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Submarine Groundwater Discharge: Its Measurement and Influence on the Coastal Zone

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ABSTRACT

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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 topographic flow may occur anywhere on the shelf where permeable sediments are present. The terrestrial and oceanic forces overlap spatially and thus measured fluid flow through coastal sediments may be a result of composite forcing. Since we cannot always determine the forcing functions, we define "submarine groundwater discharge" (SGD) as any flow out across the seabed, regardless of composition or driving force. We discuss here what is included in SGD, how it may be measured by natural isotopic tracing techniques, and some coastal management implications of the process. SGD is characterized by low specific flow rates that make detection and quantification difficult. Because such flows (both recharge and discharge) occur over large areas, the total flux is significant. "Groundwater" is thus be an important source of biogeochemically important constituents to coastal waters. When derived from land, groundwater-seawater interactions represent a pathway for new material fluxes to the coastal zone and may result in diffuse pollution in areas where contaminated groundwaters occur.

ADDITIONAL INDEX WORDS: *Tracers, radon, radium, management*.

INTRODUCTION

Knowledge concerning the undersea discharge of groundwater has existed for many centuries. The Roman geographer, Strabo, who lived from 63 B.C. to 21 A.D., 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, 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.). Thus, while the existence of submarine springs has been realized for centuries, the information was largely anecdotal. The subject has been neglected scientifically because of the difficulty in finding and measuring groundwater discharges. This led KOHOUT (1966) to say that "...these marvels of the sea are justifiably classified as neglected phenomena of coastal hydrology." Therefore, the direct discharge of groundwater into the ocean has not been quantified in terms of the global water and material cycle on Earth.

"Submarine groundwater discharge" (SGD) is a term that may be applied to more than one phenomenon and needs to be defined clearly. In its broadest sense, it is used to mean the flow of water upwards across the sea floor, from the pore waters of the ocean bottom into the overlying water. Since flow can also occur in the opposite direction, an even more general term "Submarine Pore Water Exchange" (SPE) may be used to describe any fluid movement across the sea floor (BURNETT *et al.*, 2003). Groundwater discharge may be pure freshwater entering the ocean from a coastal aquifer, or it may be recirculated seawater or some combination of the two. In a more narrow sense, it is sometimes used to mean only the freshwater component of that outflow. We use the term SGD to represent all direct discharge of subsurface fluids across the seafloor (Figure 1). So SGD has two components, the net (fresh) groundwater discharge (driven by terrestrial hydraulic gradients), and recirculated seawater, which results from entrainment by the fresh water discharge, wave set-up, tidally driven oscillations, density-driven convection, thermal convection, and other processes. In the marine environment, submarine groundwater recharge (SGR) also occurs as a consequence of tides, waves, currents, sea level fluctuations, and density differences that force seawater into the sea floor. This water eventually must leave the sediment and, in some cases, it is discharged locally but, in others, it can emerge far from the source. Noting the similarities to surface estuaries, MOORE (1999) has advanced the concept that many coastal aquifers are "subterranean estuaries." Understanding the magnitude and consequences of fluxes from these systems and the factors that regulate the exchange are major challenges.

MAGNITUDE AND ASSESSMENT OF FLOW

How large is SGD? There are many ways to answer this question. Globally, fresh groundwater discharge to the ocean has been estimated to be a few percent of the total freshwater flux. One recent estimate (ZEKSTER, 2000) suggests 2400 km^3 discharge per year (~6% of the world's river discharge) with 1500 km^3 per year from the continents, and 900 km^3 per year being contributed from the world's islands. Regionally, the groundwater flux has been estimated to be equivalent to 20 to

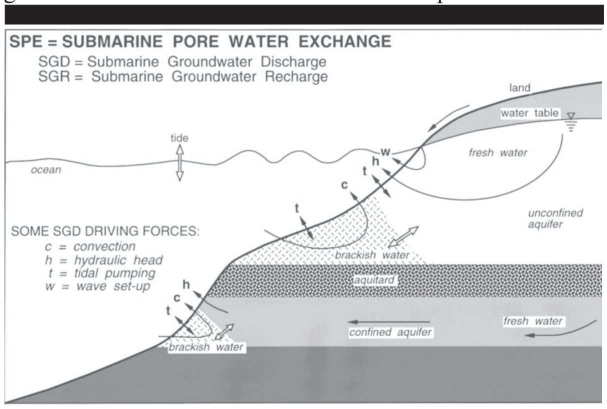

Figure 1. Nomenclature of fluid exchange and schematic depiction (no scale) of processes associated with submarine groundwater discharge. Arrows indicate fluid movement.

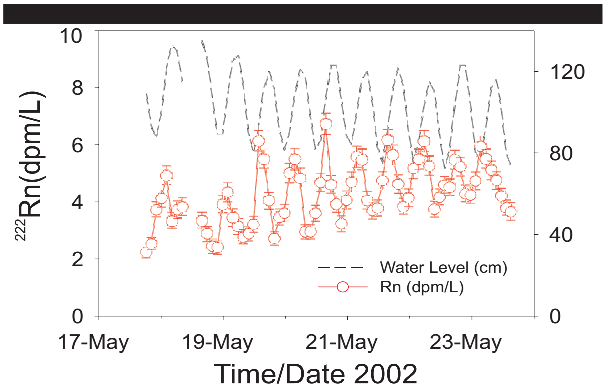

Figure 2. Example of a continuous ^{222}Rn record from coastal waters of Shelter Island (New York) with the tidal record from an SGD assessment intercomparison experiment held in May 2002.

35% of the total freshwater inflow along the coast of Long Island, 30% off the south coast of Cape Cod, Massachusetts, and 40% off the Carolina coast. SGD in many of these estimates includes not only freshwater from the land but also seawater that is recirculated through the sediments by the groundwater discharge. SGD, therefore, may range from nearly entirely fresh water to undiluted, albeit chemically altered, seawater. Confusion concerning what is meant by SGD has resulted in several misunderstandings. See, for example, the comment (YOUNGER, 1996) regarding the paper by MOORE (1996) that suggests SGD is equivalent to ~40% of the river flow in the southeast Atlantic Bight.

There are three basic 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 balance calculations through to comparatively complex numerical models of sub-surface flow. Direct physical measurements are typically limited to seepage flux meters (although several variations in design of these meters have been developed) and measurement of the direction and magnitude of hydraulic gradients across the sediment-water interface. Tracing techniques may make use of either natural geochemical species or artificial tracers (MOORE, 1996; BURNETT *et al.*, 2001a).

Unfortunately, there are two fundamental problems in the manner that direct measurements of SGD are currently 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. The difficulties in making precise estimates of SGD led BUDDEMEIER (1996) to state that "Measurements or estimates of groundwater and associated chemical fluxes, especially over substantial areas or time periods, are notoriously uncertain."

In response to this need, a team of scientists sponsored by the Intergovernmental Oceanographic Commission (IOC) and International Hydrological Project (IHP) of UNESCO has organized a series of field SGD intercomparison experiments in various hydrogeologic environments to compare methodologies on a level playing field. The experimental sites are being selected based on a variety of criteria including background information, amount of SGD expected, logistics at the site, and the specific hydrological and geological characteristics. Each intercomparison exercise involves as many methodologies as possible including various modeling approaches, "direct" measurements (seepage meters of varying design, piezometers), natural tracer studies (radium isotopes, radon, methane, etc.), and artificial tracers. The first intercomparison experiment was held at a site on the coastline of the northeast Gulf of Mexico (BURNETT *et al.*, 2002) and subsequent experiments have been held in Australia (BURNETT and TURNER, 2001) and Shelter Island, New York. Additional exercises are planned including one in Ubatuba, Brazil in 2003.

Tracing Groundwater Discharge via Natural Isotopic Tracers

We present here a summary of our approach for estimating rates of groundwater discharge via a combined isotopic approach using naturally occurring ^{222}Rn and Ra isotopes. The radon approach: is based on calculating radon fluxes using a mass balance approach observed changes in the measured Rn inventories over time are converted to fluxes, making allowances for losses due to atmospheric evasion and mixing with lower concentration waters offshore (BURNETT and DULAIOVA, 2003). Radon inventories over time in the coastal zone are assessed using a continuous radon monitor (Burnett *et al*., 2001b) and a recording water level meter. Mixing with offshore waters is estimated based on inspection of the calculated radon net fluxes or independently by use of short-lived Ra isotopes (MOORE, 2000). Assuming that benthic fluxes of radon are driven mainly by groundwater (pore water) advection, one can convert calculated ^{222}Rn fluxes to water fluxes by dividing by the measured radon concentration in groundwater. To make appropriate corrections for atmospheric losses and tidal fluctuations, we also continuously monitor atmospheric ^{222}Rn concentrations, water depth, water temperature, and weather conditions (wind speed, temperature, etc.). Spot measurements of ^{226}Ra are taken to correct for supported ^{222}Rn activities.

The radium model is somewhat similar. Offshore transects of the long-lived isotope, ^{226}Ra, are converted to fluxes assuming steady-state conditions and using an estimate of the residence time (MOORE, 1996). The short-lived radium isotopes (^{223}Ra, ^{224}Ra) can be used to calculate residence time (MOORE, 2000). While both the radon and radium isotopic approaches are valuable, we find that they can be particularly powerful if applied together to the same system. For example, the short-lived Ra isotopes can constrain the mixing rate in the radon model. On the other hand, the high temporal resolution possible with the radon measurements provides the ability to examine the dynamics of SGD inputs. Together, the multi-

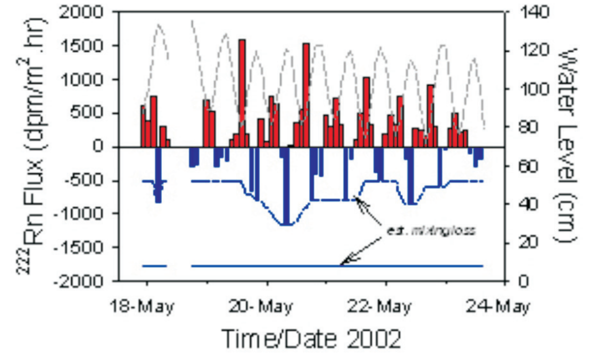

Figure 3. Calculated net fluxes based on the change in inventories per unit time after appropriate corrections for tidal effects and atmospheric evasion. A complete description of these corrections and calculations may be found in BURNETT and DULAIOVA (2003).

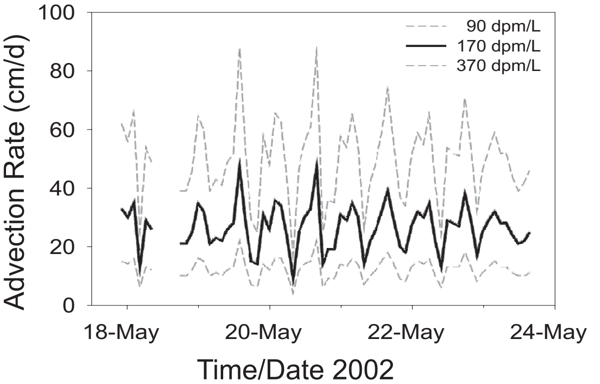

Figure 4. Fluid advection rates were assessed using the Ra-derived mixing rate and dividing the radon fluxes by various estimates of the pore water ^{222}Rn activity. The 12-hour periodicity shows that tidal modulation influences fluid fluxes.

tracer approach provides less uncertainty and more information on SGD fluxes. In addition, the tracer approach is amenable to examining a scale of up to at least tens of kilometers. Combining such information with standard water quality measurements allows one to estimate freshwater and chemical fluxes into the near-shore environment.

Results from the 2002 SGD assessment intercalibration experiment off Shelter Island, New York demonstrated that it is very useful to obtain short-lived radium isotopic results as well as continuous radon measurements in order to constrain the mixing rate. The continuous ^{222}Rn record (Fig. 2) shows that there is strong tidal modulation of the radon (groundwater) inputs. We converted these measurements to inventories and then fluxes, and applied corrections for tidal changes and atmospheric evasion (MACINTYRE *et al.*, 1995) to derive what we call "net fluxes" (Fig. 3). These calculations do not consider the effect of radon losses via mixing with lower concentration waters offshore. The apparent negative fluxes are a result of these mixing losses. This experiment showed that the mixing loss estimated from inspection of the radon fluxes is a lower limit (higher losses could be compensated by higher inputs during that time), and better estimates of the actual total radon fluxes (and thus advection rates) can be obtained by integrating the radium results with the radon data. Fluid advection rates in this example (Fig. 4) were assessed by using the mixing rates deduced via the short-lived Ra isotopes and by dividing the corrected total ^{222}Rn fluxes by various estimates of the groundwater ^{222}Rn concentration. Our "best" estimate (based on an average groundwater ^{222}Rn activity of 170 dpm/L) shows a pattern and range in values in good agreement with those provided by a newly developed seepage flux chamber deployed during the intercalibration by a team from Woods Hole (SHOLKOVITZ *et al.*, 2003). The isotopic tracers have the advantage of integrating the signal over a larger area than spot measurements such as are made by benthic chambers.

SGD AND COASTAL MANAGEMENT

Groundwater seepage into the coastal zone may be important for coastal area management for at least three reasons: (1) groundwater may carry dissolved solutes that result in chemical and ecological effects in the receiving waters; (2) saltwater intrusion and associated hydrologic aspects involving water resources; and (3) geotechnical aspects (as sediment stability) of the shoreline.

The direct discharge of groundwater into standing bodies of water may have significant environmental consequences as groundwaters in many areas have become contaminated with a variety of substances (e.g., nutrients, metals, organics). Because the slow, yet persistent seepage of groundwater through sediments will occur anywhere that an aquifer with a positive head is hydraulically connected to a surface water body, almost all coastal zones are subject to flow of terrestrially driven groundwater either as submarine springs or disseminated seepage (JOHANNES, 1980; CHURCH, 1996; MOORE, 1996). In addition, significant amounts of recirculated seawater pass through permeable sediments as a result of tidal pumping, topographically induced flow, and other processes (RIEDL *et al.*, 1972; LI *et al.*, 1999; HUETTEL *et al.*, 1996). The terrestrial and oceanic forces overlap spatially and thus measured fluid flow through coastal sediments is often a result of composite forcing. One may thus expect groundwater seepage to be patchy, diffuse, and temporally variable with the possibility that multiple aquifers may be involved. Furthermore, the potential for discharging groundwaters to have a significant impact on surface waters is greatest in regions where fluids may seep into a body of water having limited circulation.

Because groundwaters typically have higher concentrations of dissolved solids than most terrestrial surface waters, SGD often makes a disproportionately large contribution to the flux of dissolved constituents, including nutrients and pollutants. In addition, discharging groundwater interacts with and influences the recirculation of seawater, which can affect coastal water quality and nutrient supplies to nearshore benthic habitats, coastal wetlands, breeding and nesting grounds. Thus, one of the more important implications for coastal zone managers concerns nutrient (or other solute) loading to near-shore waters. Impacts in the coastal zone from these inputs could be the basis for land-use planning and may place limits on development.

From a management standpoint, a key issue will be the determination of whether SGD is of actual or probable importance in an area of interest. Furthermore, managers must consider the relative importance of SGD among the multiple factors considered in management activities. In this respect, coastal managers face the following problems: (1) they may not be aware of the growing realization of the importance of SGD; (2) if they are aware, they may not know how to decide whether or not SGD is relevant to their situation; and (3) if they do decide this is important, they may not know how to quantify it.

However, since SGD is essentially "invisible," the problem that arises, from both a management and scientific standpoint, is determining how to avoid the error of ignoring an important process on the one hand, and wasting valuable resources on an unimportant issue on the other. Where terrestrially driven SGD is a significant factor in maintaining or altering coastal ecosystems, coastal zone managers will need to consider management of water levels and fluxes through controls on withdrawal or alterations in recharge patterns, as well as groundwater quality management (e.g., through controls on land use, waste disposal, etc.). Such major interventions in the coastal zone management system require a sound scientific justification and technical understanding that does not currently exist.

How can a manager tell if SGD may be important in a particular area? Several potential, indirect indicators of freshwater submarine discharge have been suggested but not yet widely applied. Its color, temperature, salinity, or some other geochemical fingerprint might distinguish the water itself. Escaping groundwater, for example, might be stained red by the oxidation of iron or colored by tiny gas bubbles. Because groundwater tends to be at the average annual temperature, cold-water anomalies in the open water during the summer and warm water anomalies during the winter, as might be detected by infrared aerial photography, can be an indicator of SGD. Salinity anomalies have also long been used to identify subsea freshwater seeps, and can also be used at a variety of scales from regional water budgets to vertical profiles at specific locations.

Particular site conditions may also provide clues to the occurrence of SGD. The presence of coastal ponds or unconsolidated coastal bluffs, which may maintain a high hydraulic head near shore, may be other indicators. Growths of freshwater coastal vegetation may indicate regions of high SGD offshore. It has also been suggested that the presence of barite, oxidized shells, or beach rock may indicate the occurrence of groundwater discharges. In Great South Bay (NY, USA), there occurs a phenomenon known as "anchor ice," in which the bay floor freezes while the saline open waters of the bay are still ice-free (Bokuniewicz, pers. comm.). This is attributed to the presence of fresh water in the sediments maintained by SGD. It is also reported to occur in the Baltic. Alternatively, in coastal areas that are covered with ice in the water, like the Schlei estuary in northern Germany, ice-free spots, called "wind-spots," can be found above the SGD of relatively warm freshwater. In Eckernforde Bay (southeast Baltic Sea) pockmarks in the fine-grained sediments of the sea floor have been identified as bathymetric expressions of groundwater seeps (SCHULTER *et al.*, 2000). If the SGD is great enough the water itself can be domed up and "boiling."

Managers must consider the relative relationships and priorities of SGD among the multiple factors considered in management activities. This presents at least two ways that current approaches to the study of groundwater discharge will need to be modified if such studies are to be of use to managers: (1) The scale of emphasis would be that of management areas probably tens to hundreds of kilometers. By contrast, scientists are typically performing investigations at the lower end of this scale (although some tracer investigations work at scales of 10-100 km). (2) Scientists may study one area for years, often reflecting the typical 2-3 year grant cycle. Managers, on the other hand, will have need for relatively simple and rapid diagnostic and assessment tools to evaluate the local importance and management issues related to SGD in specific settings. The concerns could be either natural processes or human impacts (which may be extreme in some cases).

CONCLUSIONS

BUDDEMEIER (1996) has pointed out that "...The terrestrial portion of the coastal zone is an area of high human activity (agricultural, urban and industrial), with attendant perturbations and high gradients in water and contaminant fluxes. The problems of pathway identification and flux measurement become more critical at local scales. Local authorities and researchers tend to focus on the best resource or the worst problem, rather than the widely-distributed marginal-quality water that may carry most of the chemical load or system-relevant signal." Groundwater seepage often fits this "low unit flux - high overall loading" model. It is now recognized that subterranean non-point pathways of contamination may be very important in some coastal areas. Managers should be aware of these "invisible fluxes" and reliable SGD assessment approaches need to be refined and made "coastal zone manager friendly."

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