A New Focus on Groundwater–Seawater Interactions
(Proceedings of Symposium HS1001 at IUGG2007, Perugia, July 2007). IAHS Publ. 312, 2007.

BACKGROUND AND SUMMARY

A new focus on groundwater–seawater interactions

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INTRODUCTION

Water and chemical fluxes across the sea floor provide an important linkage between terrestrial and marine environments. Oceanographers recognize that these fluxes may act as a source of nutrients or other harmful contaminants to marine systems (e.g. Johannes, 1980; Valiela *et al*., 1990). These fluxes may also act as a beneficial source of freshwater for coastal marine estuaries that require relatively low salinities. Hydrologists and hydrogeologists recognize that fluxes across the sea floor comprise an important part of the water balance for coastal aquifers. Most fresh groundwater discharge to the ocean is derived from terrestrial aquifer recharge. Management of coastal aquifers requires careful estimates of recharge and other hydrological components, such as groundwater discharge. These estimates are commonly combined into a comprehensive water budget to evaluate how much groundwater might be available for municipal uses and whether saltwater intrusion may be a potential concern. Excessive groundwater withdrawals can cause saltwater intrusion by intercepting the seaward flux of freshwater that prevents saltwater from intruding a coastal aquifer. Quantitative estimates of fresh groundwater discharge toward the coast can provide a basis for determining safe withdrawal rates. Oceanographers, marine scientists, and those studying and managing saltwater intrusion in coastal aquifers, share a common goal of quantification and understanding of groundwater and seawater interactions.

Submarine groundwater discharge, or SGD, has become a popular term in the literature for describing the flux of water across the sea floor. Burnett *et al*. (2003) specifically define SGD as the discharge of aquifer porewater across the sea floor and into the ocean. They define flow in the opposite direction as submarine groundwater recharge (SGR). SGR is the recharging flux of seawater into the aquifer. The presence of SGR does not necessarily indicate saltwater intrusion, which occurs when saline water moves into parts of the aquifer previously occupied by freshwater. Figure 1 shows a conceptual model of the types of flow patterns that are expected to exist in

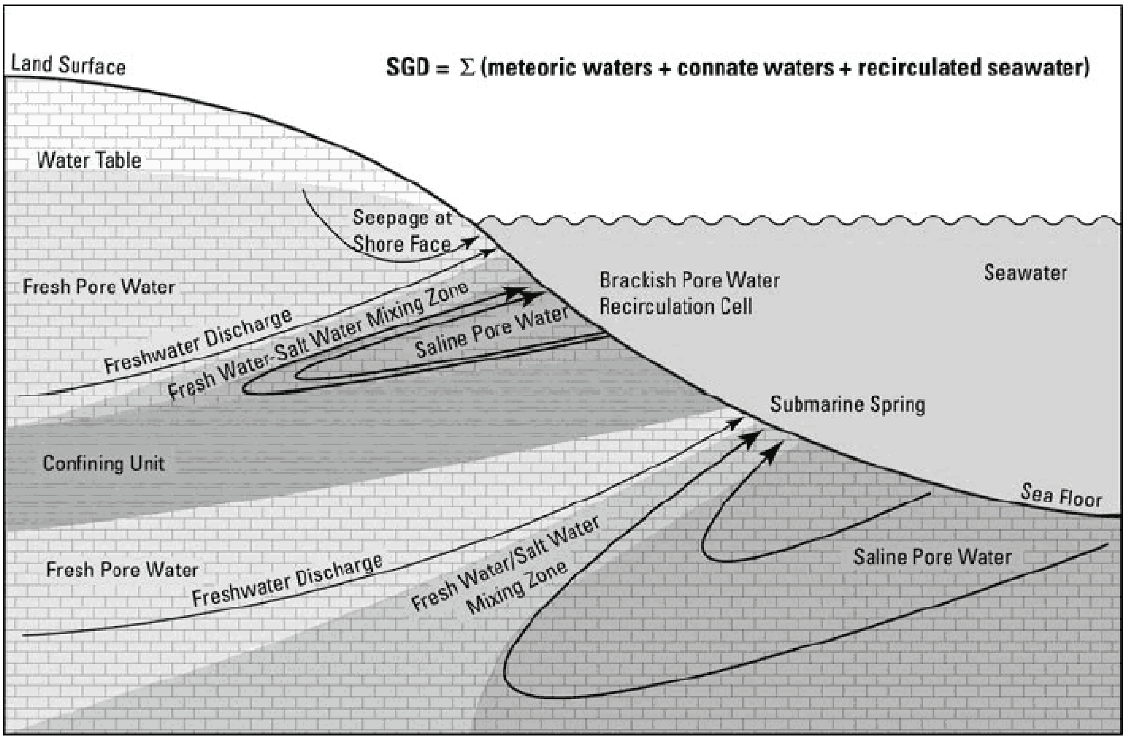

Fig. 1 Schematic showing various components of submarine groundwater discharge (SGD), from Swarzenski *et al.* (2004).

many coastal aquifers at the terrestrial–marine boundary. Through a detailed field study, Kohout (1960) showed that as fresh groundwater flows seaward, it meets and mixes with saline groundwater before discharging into the ocean. Because of this mixing and subsequent discharge to the ocean, seawater is drawn into the aquifer to replace the saline groundwater that discharged to the ocean. Seawater drawn into the aquifer is sometimes referred to as recirculated seawater. Michael *et al.* (2005) suggest that the seasonality of terrestrial recharge may also act as a mechanism for recirculating seawater through a coastal aquifer. As the mixing zone moves landward and seaward in response to seasonal fluctuations in recharge, seawater may be drawn in and flushed out of the aquifer over the course of a year. SGD can also occur at the bottom of the open ocean, even in the absence of a terrestrial connection. Waves, tides, and ocean currents can create hydraulic gradients that pump seawater across the sea floor.

Interest in groundwater–seawater interactions continues to receive a significant amount of attention in the literature. Saltwater intrusion, freshwater deliveries to marine estuaries, and nutrient loading are persistent problems of global importance. The problems are difficult to address, however, because of the elusive nature of SGD. Fortunately, the science is advancing. The journal *Biogeochemistry*, dedicated the entire November 2003 issue to the subject of SGD as did the journal *Ground Water*, in the December 2004 issue. Zektser & Dzhamalov (2007) released a comprehensive review on the subject of SGD and groundwater–seawater interactions in a new book: *Submarine Groundwater*. In their book, they suggest that SGD and related studies should be categorized into a new field called “Marine Hydrogeology”. The concentrated efforts of numerous researchers from a wide range of disciplines have led to substantial advancements in characterizing SGD, but there is still more work to be done.

This IAHS volume contains 38 papers presented at the symposium on groundwater–seawater interactions. This introductory paper briefly introduces the topic by describing and characterizing the approaches used to measure SGD, and presents a brief summary of each paper. The concept of integrating the efforts of those studying SGD from the marine perspective and those working from the terrestrial side is promoted here as a "new focus on groundwater–seawater interactions".

APPROACHES FOR MEASURING SUBMARINE GROUNDWATER DISCHARGE

Unlike rivers and streams where discharges to the ocean can be observed and quantified using proven techniques, estimates of SGD are much more difficult to obtain. Not only are there issues with making accurate field measurements in difficult environments where wind, waves and storms pose logistical concerns, but upscaling field measurements to other spatial and temporal scales significantly increases the uncertainties associated with those estimates. SGD can occur as widespread diffuse flow across the sea floor, or as channelized flow through fractures, breaches in low-permeability marine sediments, karst conduits, or through other preferential flow zones. As one might expect, the presence of heterogeneities can complicate upscaling of even the best point measurements of SGD. To overcome some of these inherent complications with measuring SGD, a diverse suite of methods and approaches have evolved to characterize, quantify, and better understand the exchange of water and chemicals across the sea floor. Following a classification scheme by Burnett *et al.* (2003), these approaches can be loosely grouped into categories that are based on physical measurements, chemical tracers, and modelling.

Physical measurements of SGD are typically made using seepage meters; however, Darcy-based calculations using field data or qualitative estimates based on results from geophysical surveys are also included here in the category of physical measurements. These approaches based on physical measurements have continued to improve as viable methods for assessing SGD. For example, the Lee-type seepage meter (Lee, 1977), which is based on measurements of SGD that has been funnelled into a plastic bag, has served as a model for the development of more sophisticated meters. Today's (2007) seepage meters are capable of digitally logging seepage rates at frequent intervals and use high-precision thermal, electromagnetic, and ultrasonic technologies to measure fluxes.

Naturally occurring chemical tracers such as the isotopes of radium or radon can be used to provide indirect measurements of SGD rates. Moore (1996, 1999, 2003) describes the use of four radium isotopes with different decay rates that can be used to quantify SGD rates. Burnett & Dulaiova (2003) demonstrate the use of radon to quantify SGD. The radium and radon methods are based on the general principle that groundwater is enriched with respect to these isotopes in comparison to surface waters, and can therefore be used as a quantitative indicator of SGD. An advantage of these chemical tracers is that they can provide an integrated average rate of SGD over very large areas.

Variable-density groundwater flow and solute transport models are often used to simulate saltwater intrusion, but these same models can also be used to provide quantitative estimates of SGD. Numerical modelling is a sophisticated way of distributing aquifer recharge, in space and time, to the various outflow boundaries. Use of numerical models is appealing because a simulation can provide spatially and temporally detailed estimates of SGD rates. A well-calibrated numerical model is a defensible tool for estimating SGD within an entire study area by interpolating and extrapolating field measurements in space and time. Numerical models can also be used to predict future SGD rates or rates for other hydrological conditions (e.g. predevelopment), provided a reasonable set of hydrological stresses can be assigned for those conditions. The number of reported studies using numerical models specifically for SGD continues to increase (e.g. Langevin, 2001; Smith & Nield, 2003; Smith & Zawadski, 2003).

OVERVIEW OF THE PAPERS IN THIS VOLUME

This volume contains 38 papers on one or more aspects of groundwater–seawater interactions. The papers are grouped into three categories (physical approaches, chemical approaches, and mathematical modelling approaches) based on the dominant approach used in the study. An exception to this is the three overview papers that contain information from more than one approach. These overview papers are summarized in the next paragraph. Physical approaches are those that use hydrogeological analysis of monitoring well data, seepage meters, or geophysical measurements. This volume presents eight papers in this group. Chemical approaches can be either terrestrial- or marine-based and involve analysis of marine or coastal aquifer water quality. Chemical and isotopic tracer methods, such as the use of radon and radium for estimating SGD also fall into this group. This volume presents 14 papers in this group. The last group consists of 13 papers and contains those that report the use of a mathematical model to characterize groundwater–seawater interactions. Numerical modelling with finite-difference or finite-element models is the most common approach in this group.

Three of the papers provide overviews of groundwater–seawater interactions. The paper by Zektser & Dzhamalov provides an overview of the general topic of marine hydrogeology. Water fluxes between the terrestrial and marine systems cannot be directly measured, and thus, SGD may be one of the largest sources of uncertainty in the water balance for the ocean. This new field of marine hydrogeology focuses on the subsurface water exchange between land and sea. Kontar identifies the hydrological and water quality contamination problems resulting from the December 2004 tsunami in the Indian Ocean. He also describes a study by the International Commission on Groundwater–Seawater Interaction to evaluate the processes of groundwater–seawater interactions in areas affected by the tsunami. Bratton provides an overview on the importance of shallow confining units in controlling patterns of SGD.

Physical Approaches: hydrogeological analysis, seepage meters, and geophysical methods

Freshwater resources in coastal and island aquifers continue to be of paramount importance. The paper by Bonacci & Gabric provides an overview on the status of eight brackish springs along the coast of the Croatian Adriatic Sea. They describe technical concerns with protecting these springs from saltwater intrusion. Majumdar & Das used electrical resistivity soundings and water quality measurements to characterize the chemistry and extent of fresh groundwater resources on Sagar Island, the largest island in the Ganga Delta of West Bengal, India.

Japanese researchers are actively involved with studies of SGD. Ishitobi *et al.* developed a method for using temperature measurements from a fibre-optic cable to estimate SGD rates. Results from Lee-type and heat-flow seepage meters were used to calibrate temperature measurements from the optic cable. The total SGD was estimated to be 37% of the river discharge in Osaka Bay, Japan. Miyaoka quantified the strong seasonal variability of groundwater–seawater interactions in a coastal aquifer in Japan using measurements from two sets of nested monitoring wells and electrical resistivity surveys. Shimada *et al.* conducted a comprehensive hydrological study of a small mountainous basin in the Uto Peninsula of Kumamoto, Japan. Using a variety of physical, chemical, and modelling techniques, they characterized hydrological conditions and verified the presence of SGD. Taniguchi *et al.* used heat-type automated seepage meters and electrical resistivity methods to evaluate spatial and temporal SGD patterns along the coast of Yatsushiro, Japan. Their results are presented in the context of a collection of global estimates, which indicate that SGD may be as much as 7% of the total discharge from rivers.

Sophisticated new geophysical methods are gaining popularity in studies of groundwater–seawater interactions. Ozorovich & Kontar describe the use of the MARSES TEM geophysical instrument for coastal groundwater–seawater applications. MARSES TEM is a small portable instrument, based on the transient electromagnetic method (TEM), and has been used to characterize spatial and temporal variations in the freshwater–saltwater interface at depths of up to 300 m. Swarzenski *et al.* demonstrated the use of improved, multi-channel, electrical resistivity geophysical techniques to characterize subsurface salinity patterns. A stationary resistivity profile, extending 20 m onshore and about 110 m offshore in Tampa Bay, Florida, clearly showed the presence of a shallow freshwater tongue. The tongue could be seen to depths of about 8 m and extended out beneath the bay.

Chemical Approaches: terrestrial water quality analysis, marine chemistry, and nutrients

Chemical tracer methods for quantifying SGD have been rapidly improving. Burnett *et al.* provide a discussion on some of the uncertainties that remain with using ^{222}Rn as a quantitative tracer of SGD. Difficulties in using this approach can arise when trying to assign reasonable estimates of end-member radon concentrations and atmospheric and mixing losses. This paper describes approaches for handing these difficulties and quantifying the uncertainties. Povinec describes the novel application of an underwater gamma-ray spectrometer in studies of groundwater–seawater interactions to measure ^{222}Rn activity. Tests off the coast of Sicily, Italy, and southeastern Brazil indicate that the method is capable of monitoring spatial and temporal variations of SGD. Weinstein *et al.* used seepage meters and radon concentrations to quantify SGD in Dor Bay along the southern Carmel Coast of Israel. Anomalous decreases in discharge at some seepage meters were attributed to localized seawater recharge events. Moore characterized the spatial pattern of ^{226}Ra along the southern Atlantic coasts of North and South Carolina, Georgia, and Florida, USA. Radium enrichments measured in offshore seawater samples show clear patterns of spatial and seasonal variability of regional-scale SGD. Peterson *et al.* developed a lumped-parameter box model based on water, radon, and salinity fluxes to calculate rates of SGD off the coast of Hawaii, USA. Estimated discharges from the box model show clear tidal variations with overall average rates that compare well with independent estimates.

Several papers in this volume focus on estimating nutrient fluxes and identifying their sources. Onodera *et al.* used a network of piezometers and water quality measurements to characterize nutrient transport dynamics within a tidal flat along the southern coast of Ikuchijima Island, Japan. Yasumoto *et al.* quantify nutrient inputs to Ariake Bay, Kyushu Island, Japan. Lee-type seepage meters were installed, and chemical analyses were performed to measure nutrients, major ions, and other chemical species. Results suggest that SGD may act as a significant source of nutrients to Ariake Bay. Umezawa *et al.* used a suite of physical and chemical methods to characterize SGD and associated nutrient transport in the Gulf of Thailand, just offshore from Bangkok, Thailand. Their results indicate that upward water and chemical fluxes measured in the bay could be attributed to recirculation of the overlying water.

Several authors used chemical methods to address unique research issues related to groundwater–seawater interactions. An analysis of metal chemistry and transport in the Mirim-Patos Lagoon system in southeastern Brazil was conducted by Windom *et al.* Their results suggest that SGD may act as a sink and source for metals in coastal regions. Mahara *et al.* characterized the chemical and isotopic nature of various water types collected from a coal mine in Japan that extends 8.5 km offshore and 700 m below sea level. They conclude that pore water trapped in Cretaceous formations beneath the sea floor has been isolated for over 2 million years. Using chlorine isotopic ratios, Tokunaga *et al.* concluded that diffusion is the dominant process for chloride transport beneath the sea floor in Yatsushiro Bay, Japan.

Water quality analyses are commonly employed in coastal aquifers as part of saltwater intrusion studies. For example, Bocanegra *et al.* used chemical indicators to compare and contrast the anthropogenic impacts at coastal aquifers in Argentina and Italy. Gattacceca *et al.* combined an isotopic analysis and electrical conductivity measurements from 12 monitoring wells to identify causes of saltwater intrusion in the semiconfined aquifer of the southern Venice lagoon system, Italy. Chulli *et al.* collated existing data for the coastal Gabes aquifer system in southern Tunisia to determine the causes of salinity increases.

Modelling Approaches: numerical, analytical, and transfer functions

Application of unique mathematical models or use of mathematical models to address unique problems has been performed by several authors. Cardenas & Wilson developed a numerical model to quantify the effects of turbulent sea currents and bedform topography on SGD. A current flowing over an irregular sea bottom can create areas of low and high pressure, which drive downwelling or upwelling through the sediments. The area and effective penetration depth of the SGD is shown to be a function of the ocean current Reynolds number. Ambient, or regional, groundwater flow can reduce the current-driven exchange. Attanayake & Sholley used an analytical flow net model to estimate hydraulic gradients at a proposed low-level nuclear waste disposal site near an island in the Taiwan Straits. Their modelling predicted that relatively stagnant conditions could be expected beneath the sea floor at the proposed disposal site. Van der Velde *et al.* used transfer function theory to predict the change in groundwater salinity in response to rainfall and dilution. An analysis using data from the Kingdom of Tonga, located in the southern Pacific Ocean, suggests that most lag times, which result from a combination of percolation times and buoyancy stabilization, are less than 2000 days (about 5.5 years).

Numerical models that include the effects of density variations can be used to provide insight into coastal hydrological processes. Fratesi *et al.* used a three-dimensional numerical model to quantify the effect of an offshore sinkhole on SGD patterns. Depending on the location of the sinkhole with respect to the freshwater–saltwater interface, as much as 20% of the terrestrially derived recharge may be routed through the sinkhole and into the ocean. Swain & Wolfert used results from an integrated surface water and groundwater model of the coastal Everglades, Florida, to show that the freshwater–saltwater interface beneath coastal wetlands is quite different from the classical interface. Rather than being located at the coastline, the top of the interface is found to be tens of kilometres inland. Dausman *et al.* used a generalized numerical model of variable density flow and solute and heat transport for southern Florida. The model was used to identify the hydrogeological conditions under which various remote detection methods (airborne electromagnetic geophysical surveys or infrared surveys) might identify SGD areas. Lee *et al.* used a numerical model to evaluate the effects of heavy rainfall events on SGD. Results show that heavy rainfall events and their effects on SGD could play an important role in delivering dissolved nutrients and other contaminants to the ocean.

Freshwater resources in coastal aquifers continue to receive widespread attention, and evaluating susceptibility to saltwater intrusion is commonly performed with a numerical model. Zhenghua *et al.* used a numerical model to characterize saltwater intrusion patterns on Xiamen Island, China, and to predict future intrusion patterns in response to the construction of a 15-km water diversion project. Model results suggest that intrusion patterns reach equilibrium after about one year of operation. Park *et al.* developed a three-dimensional numerical model for a coastal aquifer along the western coastline of Korea. They show the importance of explicitly including aquifer heterogeneity and anisotropy in saltwater intrusion models used to predict the effects of groundwater pumping. Ranjan *et al.* developed a numerical model of the Walawe River Basin, Sri Lanka. Analyses with the model suggest it is capable of predicting the effects of countermeasures designed to prevent saltwater intrusion. Sherif & Kacimov developed a numerical model of the coastal aquifer of Wadi Ham to quantify the effects of artificial recharge on saltwater intrusion. Results from the model suggest that a recharge pond could significantly improve water quality patterns in the aquifer and cause the freshwater–saltwater interface to move more than a kilometre seaward.

In addition to simulating saltwater intrusion, variable-density numerical models can be used to predict nutrient and contaminant transport to seas and estuaries. Sanford

& Pope used a numerical model to predict nitrogen loading to the Chesapeake Bay from the Delmarva Peninsula, USA. Predictions from the model suggest that nitrogen loads from SGD will continue to increase unless future surface application rates are drastically reduced. Furthermore, there appears to be a lag time of up to a decade or more before reductions in surface application rates will reduce nitrogen loads to the bay. La Licata *et al.* developed a numerical model of a coastal refinery in Italy to evaluate the chemical migration patterns to the sea. The effects of tides on chemical transport through the coastal aquifer were shown to be important under certain conditions.

SUMMARY

In summary, the papers in this volume present research by those working from the marine and the terrestrial sides of issues related to SGD and groundwater–seawater interactions. The first part of this paper provides an introduction and background information on the subject of SGD and groundwater–seawater interactions. The second part of this paper provides an overview of the 38 symposium papers and places them in context according to the methods used to quantify SGD. The papers presented in this volume describe important contributions to the literature and document a variety of investigative approaches applied over a range of conditions at locations across the globe.

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