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Hydrogeologic modeling of submarine groundwater discharge: comparison to other quantitative methods

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Abstract. Submarine groundwater discharge (SGD) is approached differently by terrestrial hydrogeologists and marine scientists, including whether to incorporate recirculated seawater with freshwater in the definition. This paper focuses on the major hydrogeologic modeling/calculational methods, what component of SGD they quantify and on what scale. It then compares the modeling methods to direct measurement and geochemical techniques used by marine scientists. Hydrogeologic modeling methods focus primarily on freshwater, but recirculated seawater can be examined with density-dependent, solute transport numerical modeling. Direct physical measurements and geochemical tracers performed in the marine environment can quantify fresh, brackish, or seawater fluxes, so that they are not always comparable to the results of modeling. Because of differences in the geochemistry (nutrients and other dissolved species) of fresh and saline waters, for many applications it may be necessary to distinguish between the fresh and recirculated seawater components of SGD.

Introduction

Submarine groundwater discharge (SGD) has been recognized to be a potentially significant source of freshwater and of nutrients and other dissolved chemical species (e.g. nitrogen, phosphorus, dissolved inorganic carbon) to the coastal zone (Johannes 1980; Simmons 1992; Uchiyama et al. 2000; Bradley & McKee 2002). In some locations, the groundwater input may be comparable to input from streams and ocean upwelling (Johannes 1980; Garrison et al. 2003) and play a major role in coastal productivity or eutrophication (Sewell 1982; Valiela and Costa 1988; Staver and Brinsfield 1996).

Quantifying SGD is inherently difficult because the methods are often indirect, requiring a series of assumptions, or rely on data with large uncertainties. To increase confidence in the SGD value determined, multiple methods including hydrogeologic modeling are often used so that resulting estimates can be compared (Gilbin and Gaines 1990; Oberdorfer et al. 1990b; Millham 1993; Robinson 1996; Rasmussen 1998). Recently, intercomparison experiments (Burnett & Turner 2001; Burnett et al. 2002) have tested multiple quantification approaches synchronously at a single site. While much valuable data have been obtained, it is necessary to clarify what these measurements represent so that it is clear which comparison between methods are valid and which could be misleading. This overview of modeling techniques with its focus on comparison to other techniques is offered within this special issue to provide a perspective to articles presented here. The term ‘model’ is used here in a broad sense as mathematical or numerical calculations that are commonly used to represent hydrogeologic processes and to distinguish those calculations from the direct measurements or geochemical tracers used by marine scientists.

One of the strengths of these intercomparison experiments is that they have brought together two diverse groups: hydrogeologists and marine scientists. This collaboration has brought a broad range of techniques to be applied to the problem of quantifying SGD. These scientists, however, approach the problem literally from opposite directions. The hydrogeologists are accustomed to working on land quantifying the movement of fresh groundwater or examining saltwater intrusion into freshwater aquifers. The marine scientists work primarily on the seawater side of the coast and so are usually dealing with some mixture of fresh SGD and recirculated seawater SGD. Thus the two groups have not always been working with the same definition of SGD, specifically whether SGD should include recirculated seawater along with the fresh groundwater discharge.

These two components of SGD are distinct phenomena with distinct forcing functions. The driving force for fresh SGD is relatively simple and well understood. It consists of the existence of a higher hydraulic head (water level) inland than at the coast (Fig. 1). This higher hydraulic head drives groundwater towards the coast where it discharges. The driving forces for recirculated seawater are not as well understood and are varied: dispersive entrainment of seawater into the mixed transition zone at the bottom of the freshwater body (Fig. 1), tidally induced fluxes in response to changes in position of the freshwater/seawater interface, and wave-induced pumping into and out of shallow sediments. Distinguishing between these two components of SGD can be important depending on the questions being addressed in a particular instance.

While additional applications may become important in the future, the primary uses to date for SGD determinations have been for calculating nutrient fluxes, and a major reason for doing so has been to mitigate anthropogenic impacts on coastal environments. For scientists needing to know the SGD

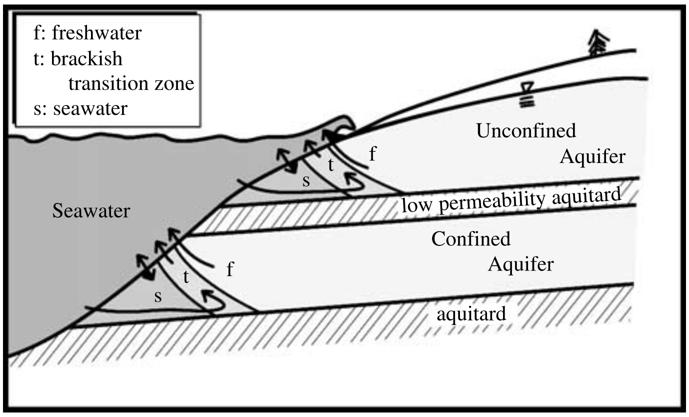

Fig. 1. Processes involved in SGD.

contribution to the nutrient budget, both the fresh and seawater components are important since they both can contribute significant amounts of nutrients to the coastal area. These two components are likely to have very different nutrient concentrations, however, making it necessary to distinguish between them so that separate freshwater and seawater SGD nutrient loads can be calculated. Coastal planners are interested primarily in the freshwater SGD to coastal areas, since that is the portion primarily affected by anthropogenic activities and thus the portion subject to regulatory mitigation. Additionally, biogeochemists may be interested in knowing the freshwater input from groundwater for species that are sensitive to salinity.

In these cases, it is necessary to separate the freshwater from the seawater component of SGD. This paper will focus on the techniques used by hydrogeologic modelers to quantify SGD, particularly focusing on which portion of SGD each technique quantifies and the scales on which each works. The modeling techniques will then be compared to the approaches of non-modeling methods to evaluate what each measures with respect to freshwater and recirculated seawater and the scale of that measurement. Scientists need to understand what they are measuring so that they know whether or not they can compare results between different methods.

Hydrogeologic modeling methods for calculating SGD

Modeling methods are primarily employed by hydrogeologists whose work focuses on the landward side of SGD. The major assumption made is that fresh groundwater flowing towards the shore will discharge into the marine

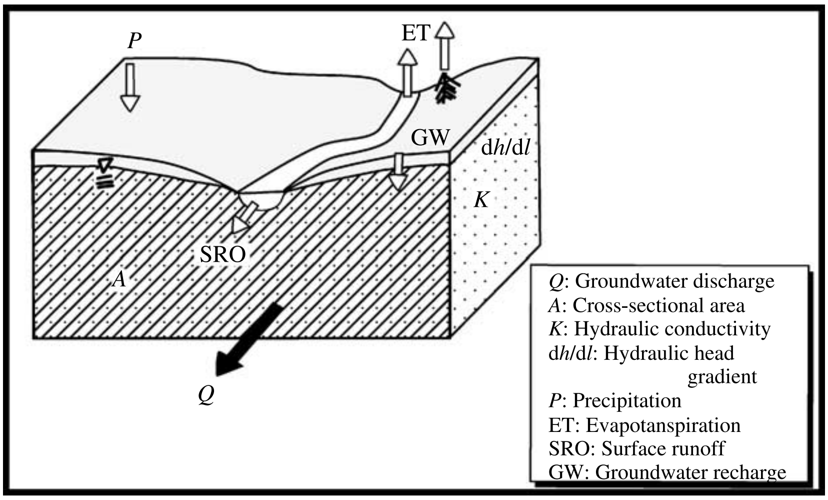

Fig. 2. Components of hydrogeologic models.

environment and therefore constitutes SGD. The four major modeling methods for quantifying fresh SGD will be presented, followed by a discussion of how one of those methods can be utilized to examine recirculated seawater SGD.

Darcy's law. Darcy's law can take forms ranging from simple to complex. In its simplest form it is written as: $Q = -KA\,\mathrm{d}h/\mathrm{d}l$, which states that the discharge through the aquifer (Q, $\mathrm{L}^3\mathrm{T}^{-1}$) is equal to the hydraulic conductivity (K, LT^{-1}) of the geologic materials and fluid, multiplied times the area (A, L^2) cross-sectional to flow, multiplied times the hydraulic head gradient ($\mathrm{d}h/\mathrm{d}l$, dimensionless), which can be thought of as the slope of the water surface. These terms are illustrated in Fig. 2. The hydraulic head gradient provides the driving force for flow and the hydraulic conductivity represents the ability of the fluid (in this case, water) to travel through the geologic materials in the aquifer. The greater the hydraulic conductivity, area, and hydraulic gradient, the greater the discharge through the aquifer is. The hydraulic head is measured as the elevation of groundwater in wells, and water levels in at least three wells are necessary to determine the hydraulic gradient. The area cross-sectional to flow is determined from geologic mapping and well logging and is usually limited to the area of the more permeable geologic materials. The hydraulic conductivity is determined by performing aquifer tests, such as by pumping on the aquifer and monitoring aquifer water level response. Generally, sediment with large pore spaces (sand and gravel) or rocks with large fractures are more permeable than sediment with small pore spaces (silt and clay) or unfractured rock. Darcy's law calculations are generally done on a regional scale (Oberdorfer et al. 1990b; Robinson 1996) but can also be performed on a local scale (Gilbin & Gaines 1990; Harvey & Odum 1990). Since the calculation is generally done inland from the shoreline, Darcy's law calculates the amount of fresh groundwater migrating towards the coast. An essential assumption of this approach is that the water migrating towards the coast will then discharge there as SGD.

Water budget. A water budget calculates the freshwater inputs and outtakes from a groundwater system. In its simplest form, the volumetric water budget for a specific time period can be expressed as: $\mathrm{GW} = P - \mathrm{SRO} - \mathrm{ET}$, which states that the groundwater flow (GW) is equal to the precipitation (P) coming in minus the water that flows out as surface runoff (SRO) and minus the water evaporated off and transpired off by plants (ET). These terms are illustrated in Fig. 2. Precipitation is measured by rain gages, surface runoff is measured by stream gages, and evapotranspiration (ET) is generally estimated by a variety of equations using parameters such as temperature, insolation, and wind speed. This approach deals exclusively with the freshwater inputs to the groundwater system and assumes that what goes into a coastal aquifer must discharge as freshwater at the coast. These studies are almost always done on a regional scale, including when applied to estimating SGD (Kanehiro & Peterson 1977; Oberdorfer et al. 1990b).

Hydrograph separation. The baseflow of a stream or river is the discharge to the stream from groundwater and can be determined on the streamflow hydrograph (plot of stream discharge as a function of time) during prolonged periods without precipitation when all the flow in that stream is assumed to result from the seepage of groundwater. The hydrograph separation technique for quantifying SGD is based on the assumption that if one can determine the discharge of groundwater to streams by determining the baseflow, one can infer that discharge to be the same as the discharge along the adjacent shoreline. This technique has been used by Russian scientists (Zektser et al. 1973; Zektser & Dzhamalov 1981) to estimate continental or global inputs of SGD. It estimates only freshwater flows and only those flows issuing from the shallowest aquifers that are the only ones hydraulically connected to the streams. It does not include fresh SGD from deeper, confined aquifers (Fig. 1).

Numerical modeling. Numerical modeling solves the groundwater flow equation (Darcy's law combined with an equation for the conservation of fluid mass) using finite difference or finite element numerical methods by converting the partial differential governing equation into an algebraic approximation. These methods divide space and time into discrete intervals and solve the flow equation for hydraulic head for each interval. Groundwater discharge can be calculated based on the distribution of hydraulic head and the hydraulic conductivity of the aquifer. This approach is generally applied, much the same way as the simple version of Darcy's law described above, to look at regional scale freshwater flow, with the addition that the numerical modeling techniques can incorporate spatial variability in aquifer geometry and hydraulic parameters (such as hydraulic conductivity, K) and determine spatial and temporal variations in SGD. The added complexity of numerical modeling is only justified to the degree that there are good spatial data on hydraulic parameters to use as inputs. A good spatial (and often temporal) distribution of hydraulic head data is also needed for the process of calibration of the model, in which the model is evaluated for its ability to reproduce the field data. When simulating coastal aquifers using numerical methods, the solution is generally quite dependent on the corresponding water budget. Assumptions about recharge to the aquifer (inputs minus outtakes) will almost always determine the SGD at the coast. Modification to the water budget will produce a similar alteration to the SGD simulated, although the location of that discharge may vary. Numerical modeling of coastal aquifers is generally performed on a regional scale (e.g. Johnson 1988; Rasmussen 1998).

In addition to solving the groundwater flow equation, the numerical modeling in some cases will include solutions to the solute transport equation that solves for the migration of dissolved species. With the addition of one more equation, an equation of state relating concentration of the solute being tracked (usually chloride) to fluid density, it becomes possible to simulate the density-dependent flow interactions that occur when both freshwater and seawater are present. Density-dependent flow with solute transport modeling then becomes the only one of the four modeling techniques that can potentially examine recirculated seawater near shore. The majority of numerical modeling studies of coastal aquifers (e.g. Carabin & Dassargues 1999) have concentrated primarily on the freshwater portion, examining the seawater fluxes only in relation to saltwater intrusion into freshwater aquifers. While SGD has not been the focus of saltwater intrusion studies, the modeling performed could certainly be refocused specifically to examine that aspect. It is perfectly feasible, however, to examine the saltwater fluxes and recent studies have begun the examination of recirculated seawater (Robinson 1996; Prieto 2001). These studies have generally looked at large scale forcing functions driving seawater movement, such as the dispersive entrainment of seawater into freshwater during saltwater intrusion (Souza & Voss 1987) or by tidally driven fluxes on a medium scale (Uchiyama et al. 2000) to large scale (Oberdorfer et al. 1990a). Since hydraulic head or conductivity data are almost never collected very far off shore, these studies have not been calibrated for a specific off-shore field situation, at least with regards to the recirculated seawater portion, making the results difficult to apply to a specific site for intercomparison with marine methods.

In summary, the vast majority of modeling calculations of SGD has only focused on the freshwater component rather than examining recirculated seawater. Quantifying recirculated seawater is an important topic for future research, although smaller scale forcing functions (such as wave action) may need to be incorporated into larger scale flow models as these may be quantitatively very important to recirculated seawater on the local scale measured by a number of the marine techniques.

Comparison to direct measurement and geochemical techniques

In contrast to the modeling techniques that almost exclusively quantify fresh SGD, the non-modeling methods can measure fresh SGD, recirculated seawater SGD, or some combination of the two. They can also measure SGD on vastly different scales, ranging from point measurements to values integrated over tens of kilometers of a coastal region. Direct measurements consist primarily of seepage meter determinations, while there is a wide range of geochemical tracers used. Those geochemical tracers discussed here are ones that have been used for intercomparison with hydrogeologic modeling methods.

Seepage meter. Seepage meters provide point measurements of SGD or, when arrayed in transects offshore, can give an integrated value of SGD per unit length of shoreline (Bokuniewicz 1980; Burnett et al. 2002). Typically, SGD has been observed in the seepage meters to decrease rapidly with distance from shore (Bokuniewicz 1980; Cable et al. 1997). The salinity of the water entering the seepage meter can also vary greatly, depending on where that seepage meter is located relative to the zone of freshwater discharge. For an unconfined, shallow coastal aquifer, the fresh groundwater will discharge in a narrow zone adjacent to the shoreline (Fig. 1). One of the big advantages of the seepage meters is that, based on the salinity of water entering the seepage meter, it should be possible to calculate the respective fractions of fresh and recirculated seawater SGD. Separating the two is important when making comparisons to the results of hydrogeologic modeling. In two intercomparison experiments in Florida and in Western Australia, Burnett et al. (2002) and Burnett and Turner (2001), respectively, concluded that the hydrologic modeling gave a value less than the seepage meter measurements since the modeling did not account for the recirculated seawater component measured by the seepage meters.

Radon. Since radon is produced by the decay of radioactive isotopes in the sediments, it can be flushed into the overlying marine water by either freshwater discharge or by the recirculation of seawater through the sediments. Thus, it can be a measurement of both fresh and recirculated seawater SGD, without any inherent way to distinguish between the two. Radon measured at a single station constitutes a point measurement that may represent a more spatially integrated value, depending on how well mixed the coastal zone is. It would be possible to determine the salinity of the sediment pore water at the radon sampling site, but if the coastal zone is well mixed that salinity determination would not help to determine the proportions of fresh and sea water contributing radon. At the Florida (Burnett et al. 2002) and Cockburn Sound (Burnett & Turner 2001) intercomparison experiments, the radon measurements were performed at a single location several tens of meters seaward from the region of fresh groundwater discharge (as determined by the porewater salinity within the sediments), thus the values of SGD obtained from radon measurement represent some combination of fresh groundwater and recirculated seawater.

Radium. Radium is normally immobile in fresh groundwater systems because it is adsorbed onto the surfaces of the geologic materials. It becomes mobilized by desorption from sediments when seawater replaces freshwater in the pore spaces of the aquifer (Moore 1996). This generally occurs during saltwater intrusion of an aquifer, which results from the freshwater SGD having been reduced due to increased pumping withdrawals inland. Radium desorption may also occur to some extent during the formation of the mixed transition zone between the freshwater and seawater (Fig. 1), even in the absence of saltwater intrusion, although with time most of the radium would be expected to be flushed from a stable, brackish transition zone. The radium is transported to the marine environment by the mixture of fresh groundwater and recirculated seawater (primarily with that portion of the recirculated seawater actively involved in saltwater intrusion). Thus, the radium-determined value represents only a fraction of the fresh SGD and a fraction of the recirculated seawater SGD.

Since the measurements are carried out on transects carried out over tens of kilometers from shore, multiple aquifers may be involved. At the Florida and Cockburn Sound intercomparison experiments (Burnett & Turner 2001; Burnett et al., 2002), the majority of the methods were applied to SGD from the uppermost, shallow aquifer. The radium data, however, would likely include radium seepage from lower aquifers that extend and discharge further offshore. In many cases, the radium-determined SGD would reflect a contribution from multiple aquifers and, so, cannot be readily compared to the results of nearshore marine methods or of hydrogeologic modeling done only on the uppermost aquifer. This lack of comparability also holds because the radium numbers represent only a portion of the total fresh and recirculated seawater SGD.

CTD (conductivity, temperature, and depth) profiles. These measurements of electrical conductivity and temperature with depth in the marine water column are performed at a series of points. Where the electrical conductivity measured is reduced from the conductivity of nearby ocean water, that reduction is used to calculate the input of fresh SGD with a simple dilution calculation. Since this technique measures dilution of seawater by fresh SGD, the values can reasonably be compared to the terrestrial-based hydrogeologic modeling values. The CTD profiles also give a spatially integrated value, which should correspond well to the regional modeling determinations of fresh SGD.

Conclusions

In the search for a consensus value for SGD at a specific site through the use of multiple methods, it is important to determine which fluxes of water out of the sediment are being measured. Different techniques will measure fresh SGD or recirculated SGD or some combination, and, before comparisons can be made, it is important to determine what component of SGD is being measured. Recent studies (Garrison et al. 2003) have begun distinguishing the fresh and recirculated seawater components.

Determinations made by hydrogeologic modeling at sites have most commonly been for fresh SGD. Of the marine measurements, CTD profiling also measures fresh SGD so a comparison between the two is legitimate.

Seepage meter measurements can result from either fresh or recirculated seawater SGD, and so it is important that the salinity of the seepage water be determined at the same time so the components of each can be estimated. Unless only fresh SGD is being measured, it is not legitimate to compare the seepage meter derived SGD with the results of hydrologic modeling focused on the freshwater component. Since radon measurements are affected by mixing in the water column, it is more difficult to distinguish fresh and seawater input components, and, thus, more difficult to compare to modeling results. Radium measurements reflect a portion of the fresh and the recirculated seawater SGD and should not be compared to the results of modeling, unless that modeling is specifically examining issues of saltwater/freshwater mixing.

It is also necessary to take issues of scale into account. Modeling is usually applied on a regional scale, as are CTD profiles and radium determinations.

Seepage meter and radon measurements tend to be much more localized to a given portion of shoreline and so may exceed or be less than the regional average.

Ultimately, it is the purpose of the investigation that will determine which methods are most appropriate. If the focus is on terrestrial inputs to the coastal zone via SGD, then techniques that can distinguish freshwater inputs should be used. If the total inputs (terrestrial plus marine) are important, such as for a nutrient budget, it still is likely to be important to distinguish fresh from recirculated seawater SGD as each may contribute very different geochemical loads.

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