The Three Scales of Submarine Groundwater Flow and Discharge across Passive Continental Margins

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ABSTRACT

Increased study of submarine groundwater systems in recent years has provided a wealth of new data and techniques, but some ambiguity has been introduced by insufficient distinguishing of the relevant spatial scales of the phenomena studied. Submarine groundwater flow and discharge on passive continental margins can be most productively studied and discussed by distinct consideration of the following three spatial scales: (1) the nearshore scale, spanning approximately 0–10 m offshore and including the unconfined surficial aquifer; (2) the embayment scale, spanning approximately 10 m to as much as 10 km offshore and including the first confined submarine aquifer and its terminus; and (3) the shelf scale, spanning the width and thickness of the aquifers of the entire continental shelf, from the base of the first confined aquifer downward to the basement, and including influences of geothermal convection and glacio-eustatic change in sea level.

Introduction

Following the publication of several important papers in the 1990s, especially those by Moore (1996, 1999), and the formation of the Scientific Committee on Ocean Research (SCOR) working group on submarine groundwater discharge (SGD) in 1997 (Burnett 1999), the study of submarine groundwater discharge and related phenomena expanded rapidly. Among the issues that have motivated the development of a better understanding of this topic are balancing of ocean elemental budgets (Shaw et al. 1998; Charette et al. 2005), remediating eutrophication and other types of contamination of coastal water bodies (Giblin and Gaines 1990; Portnoy et al. 1998), protecting coastal groundwater supplies from saltwater intrusion (Barlow 2003), and ensuring the health of groundwater-dependent coastal ecosystems (Valiela et al. 1990). Given rapid growth in this field, however, hydrogeologic processes that may be similar in terms of physics but that operate at different spatial scales have not always been adequately distinguished from each other.

Burnett et al. (2003) defined 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" (p. 6), and Moore (2010) modified this to "the flow of water through continental margins from the seabed to the coastal ocean, *with scale lengths of meters to kilometers*" (p. 71; emphasis added) to exclude shear flow and flow driven by benthic fauna. While these definitions have clarified the full scope of what some of the leaders in the field consider to fall under this umbrella term, the nomenclature of the component parts is still unstable. Various terms, acronyms, and units have been proposed to differentiate and quantify distinct parts of the submarine aquifer and discharge system. These include submarine fresh groundwater discharge (SFGD), recirculated saline groundwater discharge (RSGD), and submarine groundwater recharge (SGR; Taniguchi et al. 2002); deep pore water upwelling (DPU; Moore 2010); the shallow and deep salinity transition zones (STZs; Kroeger and Charette 2008); the freshwater-saltwater interface (FSI; various authors); and discharge units of volume per unit time, volume per unit time per unit length of shoreline, and volume per unit time per unit area of seafloor (Taniguchi et al. 2002).

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Consensus on how to properly describe or discuss some SGD-related concepts and on the appropriate use of terms, acronyms, and discharge units does not yet exist in the field. This can create confusion and can make comparison of results from related studies difficult. Some of this confusion and lack of consensus is likely the result of rapidly evolving understanding of SGD-related phenomena due to new data and simultaneous development of new measurement techniques and changing interpretations of previous measurements.

More explicit consideration of different spatial scales in submarine groundwater investigations rather than a strictly process-based focus may improve clarity and understanding. This would facilitate incorporation of important aspects of hydrogeology (Kazemi 2008; McCoy and Corbett 2009), including submarine flow paths and travel time, as well as distinct ecological aspects of the interaction of submarine groundwater with surface water (hydroecology) that are not driven exclusively by organisms themselves. Such conceptualization would likely impact both motivations for and methods of study. Here I will attempt to clarify the most appropriate subdivisions of scale in submarine groundwater studies, with the ultimate aim of fostering clarity in both the formulation of SGD-related research plans and the presentation of results such that separate processes and phenomena are not conflated. The scope of the discussion will be intentionally limited, ignoring the vast areas of saline groundwater or sediment pore water with very limited flow that are believed to exist under much of the open ocean, as well as the hydrothermal systems of vigorous groundwater circulation that occur at plate boundaries, and paying particular attention to the U.S. Atlantic margin as a representative illustration. The widths and thicknesses of the zones of flow and discharge in the included schematic figures are shown for reference only and would vary significantly on the basis of local conditions.

At steady state, the water table elevation and position of the fresh-saline interface in a homogeneous coastal aquifer can be determined reasonably well by a Dupuit-Ghyben-Herzberg analysis that is modified to incorporate an outflow face (Vacher 1988). Such analyses, however, are inadequate to describe many of the temporal and spatial complexities of natural and perturbed coastal and submarine aquifer systems investigated in recent years. For example, many important aspects of shallow coastal aquifers and their interactions with the coastal ocean are transient and cannot be usefully approximated by steady-state assumptions. These phenomena would include influences of sea-level fluctuations due to tides, waves, and storms (Robinson et al. 2006, 2007; Li et al. 2008). They would also include water table fluctuations due to seasonal variations in recharge and evapotranspiration as well as during recharge pulses caused by heavy rainfall (Smith et al. 2008) or rapid snow melt, or disturbance by sustained onshore pumping (McAuley et al. 2001; Foyle et al. 2002).

Simulation also becomes more complicated where the common situation of confined or semiconfined offshore flow occurs (Bratton et al. 2004, 2009; Bratton 2007; Li et al. 2007). Field studies and related variable-density flow models are now showing that the typical configuration along mesotidal coasts is best described by multiple, stacked, saline to brackish recirculation cells and discharge of fresh to brackish water in multiple shore-parallel bands, alternating shore-perpendicular zones of low discharge and high discharge, or discrete submarine springs. While numerical techniques exist to address all of these situations, appropriate offshore data are generally rare, and this conceptual framework is not yet widely appreciated by many coastal scientists and managers. To help remedy this, a reasonable way to organize consideration of submarine groundwater flow and discharge phenomena on passive continental margins is presented here. It consists of separation of margin hydrogeology into three spatial scales: (1) the nearshore scale, (2) the embayment scale, and (3) the shelf scale.

Nearshore Scale

For several reasons, the nearshore zone (fig. 1), located within approximately 10 m of shore, extending down to the first confining unit, and including the intertidal zone, has received the most research attention in recent years. This is likely due to its accessibility, the presence of observable discharge at low tidal stages, and its direct association with the unconfined surficial aquifer and topographically driven flow (Wilson 2005). Nearshore groundwater discharge can also have significant direct impact on shallow coastal ecosystems. Studies that began with manual subtidal seepage meters eventually expanded to incorporate the use of tools such as intertidal seepage meters, automated seepage and salinity meters, offshore piezometers and wells, piezomanometers, thermistors and fiber-optic distributed temperature sensing cables, water quality and radioisotope time series instruments, aerial infrared imaging, and stationary electrical resistivity arrays. The numerous studies that have been conducted to document groundwater dynam-

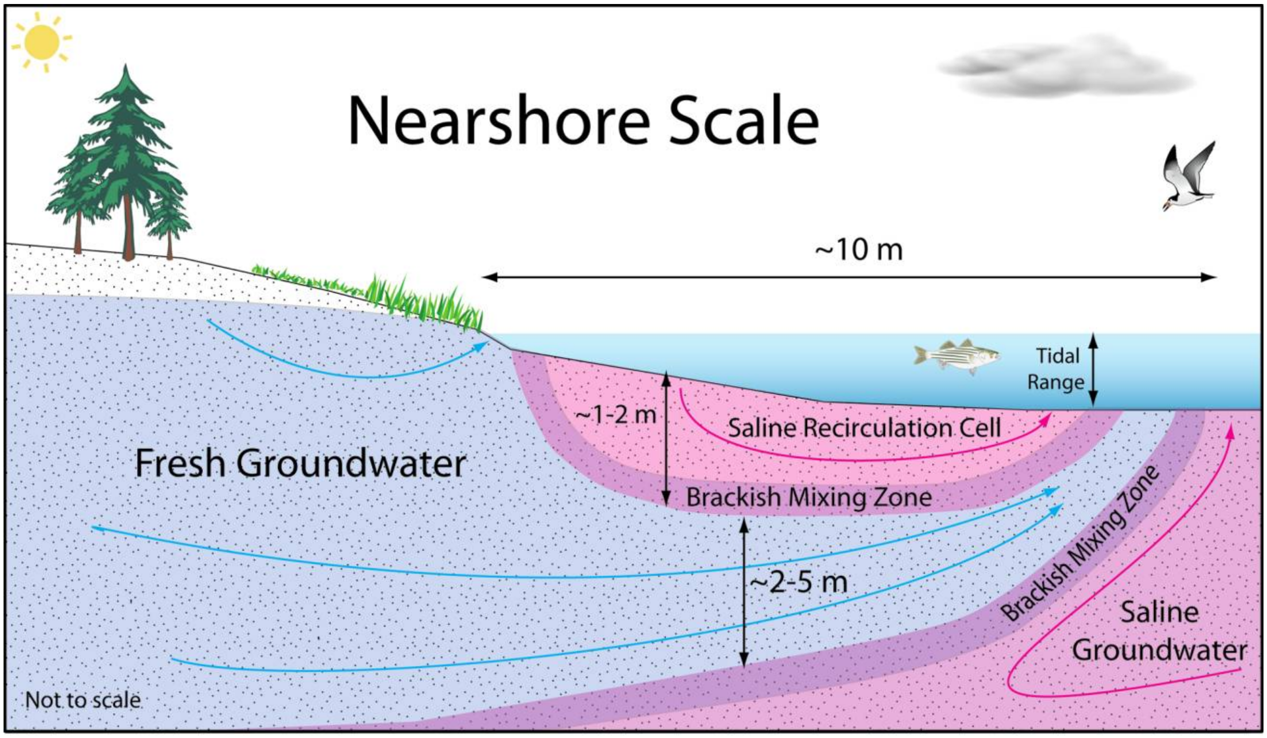

Figure 1. Schematic diagram of the nearshore scale of submarine groundwater flow and discharge showing the intertidal recirculation cell and the zone of discharge of reduced-salinity water beyond the low-tide line. The widths and thicknesses of the zones of flow and discharge shown could vary significantly on the basis of local conditions.

ics at this scale (e.g., Burnett et al. 2006) came to dominate publications on the topic; by comparison, other scales were relatively understudied during this time.

One important finding of studies of nearshore-scale phenomena, which has only recently been well documented and modeled (Michael et al. 2005; Robinson et al. 2006, 2007; Li et al. 2008), was that nearshore systems with significant tides tend to form shallow saline recirculation cells. These cells are flushed with saline seawater over periods of hours to days and tend to result in a displacement toward deeper water of the lower part of the fresh seepage face by several meters.

A recent development that was particularly relevant to nearshore SGD studies was more widespread appreciation of the fact that elevated activities of short-lived radium isotopes in surface water were not primarily derived from fresh discharge but rather from recirculated brackish to saline discharge (Moore 1996; Mulligan and Charette 2006). This meant that radium-derived values interpreted by some as quantifying fresh discharge were often too high, sometimes by an order of magnitude or more. It also meant that radium sources other than groundwater, such as fluvial inputs to estuaries and water from the open shelf advected into shallower water, as well as local temporal and spatial variations in the radium activities of discharging groundwater itself, needed to be taken more explicitly into account in the development of radium-derived budgets of groundwater discharge. Uncertainties in the application of radium isotopes in SGD studies are decreasing, and recent studies continue to provide novel and significant results, especially at larger scales (e.g., Moore et al. 2008).

Radon has also been used as a radiogenic tracer of submarine groundwater discharge in nearshore settings. Radon-222, which has a short half-life of 3.8 d, is often concentrated in fresh groundwater relative to both shallow saline groundwater and marine surface water, so it can be measured in surface water and used to calculate the amount of low-salinity groundwater that has recently discharged to an estuary or bay (Cable et al. 1996; Burnett et al. 2001; Crusius et al. 2005). Care must be taken, however, to properly constrain the radon activity of the groundwater end-member in order to use this method (Mulligan and Charette 2006; Burnett et al. 2007).

Embayment Scale

At the next level above the nearshore scale is the embayment or inner continental shelf scale (fig. 2), operationally defined as extending 10 m to 10 km offshore and to depths of about 5–50 m below the seafloor, including the first confined or semiconfined portion of a submarine flow system. A strict definition of the outer edge of this zone is not possible because it is not directly controlled by oceanographic phenomena such as wave base or seafloor morphology. Rather, it extends to the outer edge of the shallowest submarine-confined aquifer, including its discharge zone. The shallowest submarine confining unit (Bratton 2007) permits primarily topographically driven regional flow of fresh or brackish water offshore beneath the nearshore zone and sometimes entirely beneath lagoons, shallow estuaries, embayments, and barrier islands (Bratton et al. 2009). The origin of the shallowest confining unit can vary, but it is commonly a fine-grained deposit laid down during the sea-level highstands of the last interglacial interval, especially Marine Isotope Stage 5e, or a more recent trangressional unit consisting of estuarine and tidal flat muds, as well as peat from drowned salt marshes or mangroves. At high latitudes, submerged permafrost may also play a significant role in submarine aquifer systems at these scales (Harrar et al. 2001; Rachold et al. 2007). When compared with the nearshore zone, relatively little is known about the dynamics of submarine groundwater systems at this scale. Striking examples terminate in offshore springs, particularly in carbonate settings (Colbourne and Hay 1990; Swarzenski et al. 2001; Fleury et al. 2007).

Some embayment-scale flow systems that terminate abruptly at offshore paleochannels or other erosional truncations or depositional terminations in the shallow subsurface have been documented by continuous resistivity profiling and barge-based or jack-up rig drilling (Foyle et al. 2002; Manheim et al. 2004; Bratton et al. 2009). The exact nature of discharge in most of these cases (e.g., diffuse vs. focused in lines of springs) is not well documented, but the volumes of water involved are potentially substantial. The discharging water can favorably alter salinity, water chemistry, and temperature for certain organisms. Because of the longer flow paths

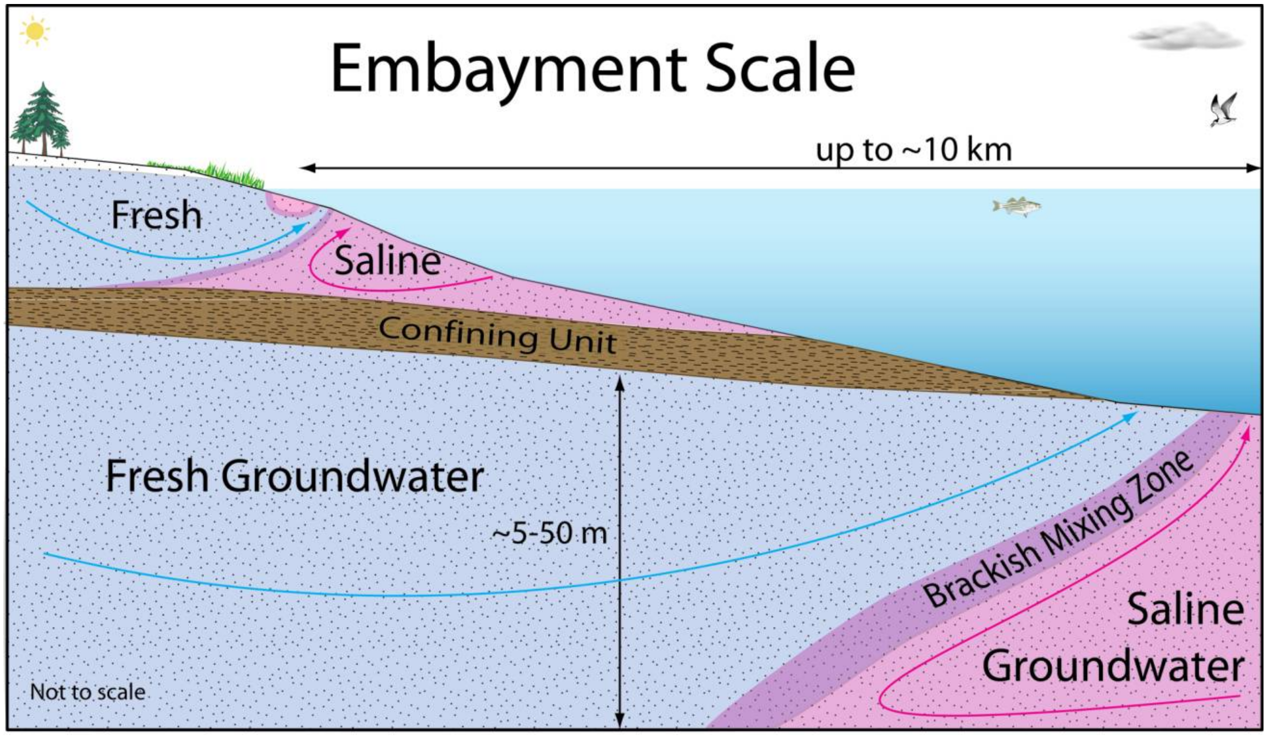

Figure 2. Schematic diagram of the embayment or inner-shelf scale of submarine groundwater flow and discharge showing submarine flow of low-salinity water in the first confined aquifer and the zone of offshore discharge beyond the edge of the submarine confining unit.

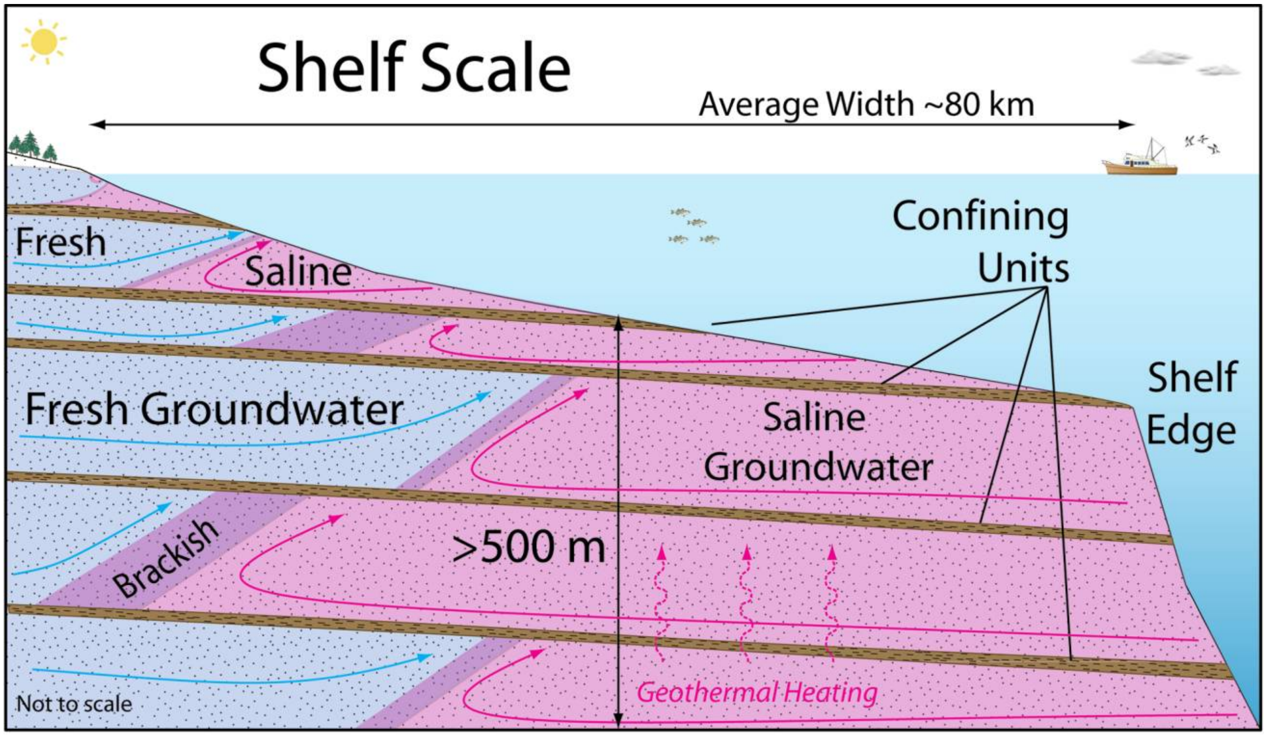

Figure 3. Schematic diagram of the continental-shelf scale of submarine groundwater phenomena showing the variable position of the fresh-saline interface in multiple confined aquifers on the shelf, the variable widths of the mixed zone at the interface, the flow of saline water inward from the exposed edges of confined aquifers, and the upward movement of saline groundwater induced by geothermal heating at depth.

that carry groundwater recharged on land into these offshore discharge zones, the water currently being discharged is often too old to have been impacted by common anthropogenic pollutants such as nitrate (Portnoy et al. 1998; Kroeger and Charette 2008), pesticides, solvents, or hydrocarbons. This is not the case for nearshore discharge.

Because of the relative purity of some of this old, offshore water, inner-shelf aquifers such as these have been examined as potential sources of drinking water for coastal communities in many locations (Edmunds 2001). Current or imminent eutrophication from discharge of nutrients associated with these waters is generally not an issue, and it will not be for decades to centuries except where intentional injection of nutrients into these systems has been performed on a large scale (e.g., Paul et al. 1997; Hunt 2007; Maliva et al. 2007). Applying radioisotopic approaches to quantifying discharge at this scale, as was described above for the nearshore scale, is more complicated because of the greater dilution and generally more diffuse nature of SGD in open embayments or inner-shelf waters.

Shelf Scale

The next-larger scale is that of the entire continental shelf (fig. 3), which may include multiple confined aquifer systems extending below the first confined aquifer to depths of 500 m or more below the seafloor and to the outer continental shelf edges, submarine canyon incisions, and even the continental slope, especially during sea-level lowstands. The primary process driving flow at this scale is usually geothermal convection, which produces seawater recirculation through the shelf (Kohout 1967; Wilson 2005; Hughes et al. 2007, 2009). Sediment compaction and associated dewatering, as well as brine-related processes, are also important in some settings (Wilson and Ruppel 2007). It could be argued that there is actually more known about the occurrence of submarine groundwater systems at the shelf scale, including relict reduced-salinity groundwater, than is known about intermediate embayment-scale submarine aquifer systems in some settings. This is mostly a result of ancillary data collected as part of offshore oil exploration as well as scientific drilling through the

Table 1. Summary Characteristics of Each Scale of Submarine Groundwater Flow and Discharge

	Nearshore scale	Embayment scale	Shelf scale
Typical width	10 m	Up to 10 km	80 km
Typical thickness	2–5 m	5–50 m	>500 m
Dominant processes	Topographically driven flow, intertidal and subtidal saline recirculation	Topographically driven flow, subtidal saline recirculation	Geothermal convection, also compaction dewatering
Recharge	Surficial terrestrial, intertidal saline, and shallow subtidal saline	Surficial and confined terrestrial, subtidal saline	Confined terrestrial, subtidal and shelf-edge saline
Discharge	Fresh and saline/brackish, intertidal and shallow subtidal	Fresh and saline/brackish, subtidal	Saline/brackish, subtidal and shelf edge
Upper bound	Intertidal surface and seafloor	Top of uppermost confining unit and inner shelf seafloor	Base of uppermost confined aquifer, outer shelf/slope seafloor
Lower bound	Top of uppermost confining unit	Top of first confining unit below uppermost	Basement
Inner bound	Downward projection of high tide line	Downward projection of high tide line	Downward projection of high tide line
Outer bound	Intersection of uppermost confining unit with seafloor	Intersection of confining unit at base with seafloor	Downward projection of toe of continental slope

Deep Sea Drilling Program (DSDP), the Ocean Drilling Program (ODP), and the Integrated Ocean Drilling Program (IODP).

Classic work on the U.S. Atlantic shelf included studies of the Florida platform (Kohout 1966, 1967; Paull et al. 1991) as well as drilling of the Atlantic Margin Coring (AMCOR) Project and Continental Offshore Stratigraphic Test (COST) Program wells in the 1970s (Hathaway et al. 1979; Kohout 1988) and installation of submarine monitoring wells off New Jersey in 1985 (McAuley et al. 2001). Shelf-scale groundwater processes, including both development of pore fluid overpressure due to sediment compaction and submarine spring sapping, were long hypothesized to impact the geomorphology of the shelf edge, including initiating slope failures and contributing to submarine canyon formation (Johnson 1939; Robb 1984; Orange et al. 1994). Some of these phenomena and processes are now being explored more quantitatively (Dugan and Flemings 2000, 2002; Green et al. 2007; Flemings et al. 2008). Other recent work has attempted to explain anomalously fresh groundwater beneath the shelves of the North Atlantic (Edmunds 2001; Person et al. 2003) and the relative roles of terrestrial recharge, marine recharge, and geothermal convection in shelf-scale groundwater circulation (Wilson 2003, 2005). Proposals to sequester carbon dioxide in saline aquifers beneath continental shelves have recently generated renewed interest in the occurrence of submarine groundwater at this scale (Chadwick et al. 2004).

Integration of Scales

Although the aim here is to improve clarity by distinguishing separate scales (table 1), compartmentalized understanding is not the ultimate objective. Integrating across two or even three scales is necessary to address particular issues of scientific and societal importance, such as how best to extract fresh groundwater or petroleum from coastal and submarine areas with minimal negative consequences, or how to mitigate impacts of sea-level rise on coastal ecosystems that live at or near the submarine groundwater halocline. With this in mind, the boundaries between scales and at the upper, lower, and outer edges of the entire SGD system become especially important.

The interface between the SGD system at the nearshore and embayment scales is the uppermost confining unit. The origin, depth, composition, thickness, and lateral continuity of this unit controls vertical flow into and out of the aquifers above and below it. Similarly, the contact between embayment and shelf scales is the confining unit at the base of the uppermost confined submarine aquifer. The stacked arrangement of these com-

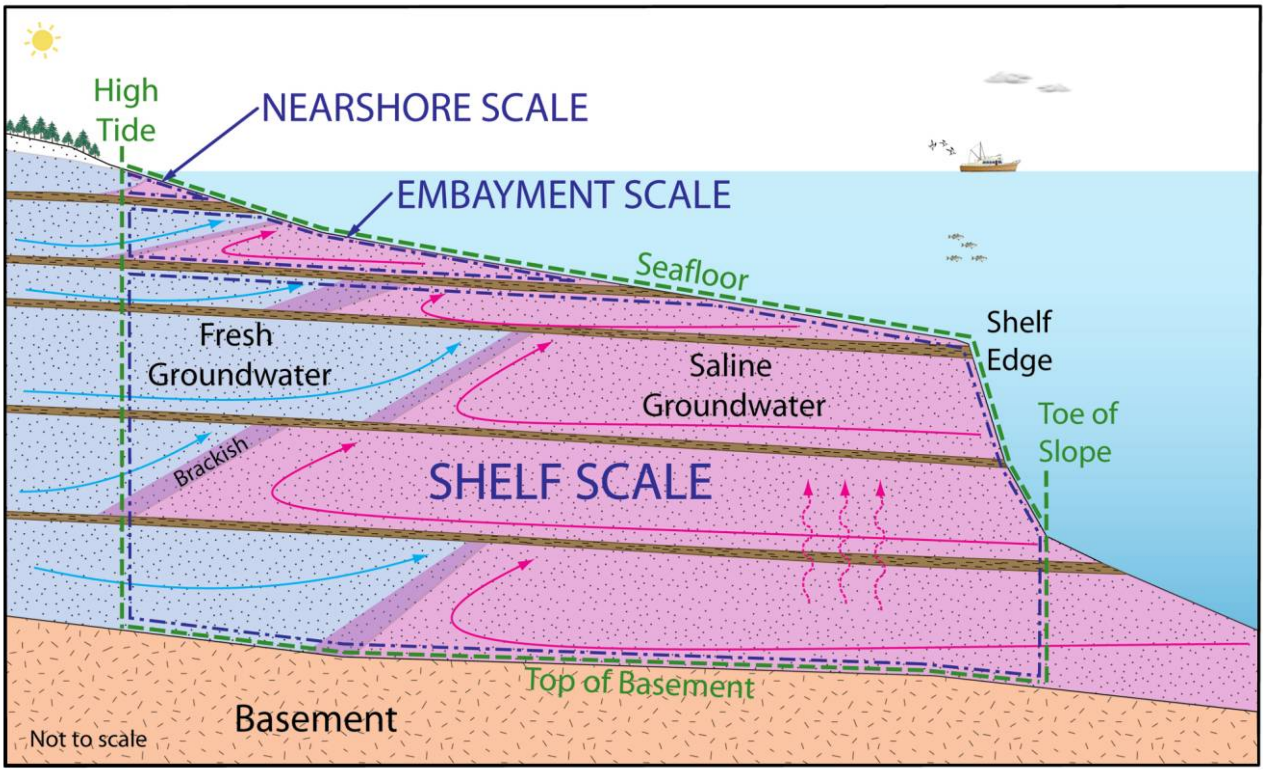

Figure 4. Summary diagram showing the three proposed spatial scales and the boundaries around the entire submarine groundwater flow and discharge system.

partments means that most SGD processes that span multiple scales are discontinuous or segmented, rather than forming a continuum. It also means that the system is dominated by anisotropy, with horizontal flow rates often exceeding vertical flow rates by an order of magnitude or more. Control of interaction between scale compartments by confining units highlights the significance of natural or engineered incision through such units or offsetting as the means by which cross-scale interaction can be greatly enhanced, at least locally. Relatively shallow incision can short-circuit barriers between the nearshore and embayment compartments. Deeper incision by submarine canyons and slides, penetration from below by diapirs, or offsetting by faults can connect flow systems of the embayment and shelf scales.

Finally, it is also important to understand the boundaries and interfaces surrounding the entire SGD system, including the atmosphere and intertidal vadose zone (at low tide); terrestrial aquifers; estuarine, coastal, and shelf surface water, as well as deep water beyond the shelf edge; and the hot brines, weathered and fractured basement aquifers, and, eventually, supercritical groundwater that exists at depth. Practical surrounding boundaries on a passive margin could be considered to be (1) the vertical curtain underlying the high tide line (mean higher high water) at the shore, (2) the intertidal land surface and the seafloor below low tide and extending across the shelf and down the slope, (3) the vertical curtain underlying the toe of the continental slope, and (4) the basement surface (fig. 4).

Ecological Significance

Many recent studies have linked submarine groundwater discharge to the occurrence and health of important coastal ecosystems and fauna including, at the nearshore scale, salt marshes (Valiela et al. 1978; Krest et al. 2000; Charette 2007), mangroves (McGowan and Martin 2007), polychaetes (Dale and Miller 2008), bivalves (Taniguchi et al. 2008), and microbial pathogen assemblages (Boehm et al. 2004); and, at the embayment and shelf scales, coral reefs (Gagan et al. 2002; Paytan et al. 2006; Street et al. 2008), and fish (Culter 2006). The locations and chemistry of discharging water can have important impacts on benthic coastal ecosystems (Johannes 1980), particularly at the nearshore scale, even to the point of controlling their formation, their evolution, and the behavior of organisms living within them. Groundwater discharge maintains the salinity gradient in many estuaries that lack significant fluvial inputs, or where river flow is highly seasonal or episodic. At the embayment or shelf scales, especially in carbonate settings such as Florida (Swarzenski et al. 2001) or Australia's Great Barrier Reef (Stieglitz 2005), offshore springs frequented by a variety of fish species and sea turtles (Culter 2006) have been documented up to 50 km or more offshore. At the shelf scale, formation of submarine canyons, which commonly support diverse and abundant assemblages of marine organisms (e.g., Valentine et al. 1980), has been linked to groundwater processes described previously. Cold seeps in deep water are also associated with microbial mat formation and aggregations of chemosynthetic organisms such as bivalves and tube worms (Paull et al. 1984; Levin 2005).

Implications for Ancient Processes

Variation in sea level over geologic time scales has significantly modified the positions of shorelines and submarine groundwater discharge zones, shifting the three scale zones described above horizontally as well as alternately compressing and expanding the widths of the embayment and shelf zones. Highstands of sea level vertically and laterally drive seawater into continental margin aquifers, although establishment of aquifer density equilibrium usually lags behind transgression by centuries to millennia (Meisler et al. 1984) except in carbonate aquifers with high hydraulic conductivity. Land-based pumping can also affect the equilibrium position of the fresh-saline boundary in confined shelf aquifers (e.g., McAuley et al. 2001). Much of the residual impact of lowstand recharge is likely to manifest itself at the embayment scale. Adkins et al. (2002) estimated that lower sea level during the last glacial maximum allowed 4.5×10^6 km^3 of freshwater to move into continental shelf aquifers, a volume approximately 75% larger than the estimated volume of water stored in modern glacial ice in Greenland. This volume of freshwater has generally not been accounted for in ice-age water budgets and paleoceanographic investigations.

Conclusions

Three scales of submarine groundwater flow and discharge are proposed: the nearshore scale, the embayment scale, and the shelf scale. The purpose of distinguishing these scales from each other is to improve the clarity of the design and reporting of results of field and modeling studies of groundwater flow and discharge phenomena on passive continental margins by providing a conceptual spatial framework for natural subdivision of the margins. Numerous research questions remain that are relevant to the different scales discussed, as well as the task of developing such a scheme for active margins. Logical alternatives to the proposal described here are encouraged, with the ultimate goal of developing consensus within the community of scientists that study submarine groundwater in such settings.

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