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Special Section:
Earth and Space Science is Essential for Society

Key Points:

- Coastal hydrogeology addresses important societal problems
- Scientific advances have created tangible societal benefits
- Collaborations between scientists, policymakers, and the public are essential for coastal water resource sustainability

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Science, society, and the coastal groundwater squeeze

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Abstract Coastal zones encompass the complex interface between land and sea. Understanding how water and solutes move within and across this interface is essential for managing resources for society. The increasingly dense human occupation of coastal zones disrupts natural groundwater flow patterns and degrades freshwater resources by both overuse and pollution. This pressure results in a "coastal groundwater squeeze," where the thin veneers of potable freshwater are threatened by contaminant sources at the land surface and saline groundwater at depth. Scientific advances in the field of coastal hydrogeology have enabled responsible management of water resources and protection of important ecosystems. To address the problems of the future, we must continue to make scientific advances, and groundwater hydrology needs to be firmly embedded in integrated coastal zone management. This will require interdisciplinary scientific collaboration, open communication between scientists and the public, and strong partnerships with policymakers.

1. Overview and Societal Relevance

Coastal zones are at the complex and dynamic interface between the land and the sea. These zones are occupied by dense human populations, many living in rapidly growing mega-cities; highly productive but increasingly threatened coastal ecosystems; and surface waters that support critical fisheries. Understanding how water and solutes move within and across this interface is essential for managing and protecting these resources.

Coastal hydrogeology is the study of groundwater processes in aquifer systems connected to the sea. It is a subfield within hydrology and incorporates aspects of geology, oceanography, engineering, biogeochemistry, and ecology. The foundations of coastal hydrogeology were laid in the late nineteenth century when the search for freshwater reserves for drinking water supply systems highlighted the need for a better understanding of groundwater processes near the coast. The delicate equilibrium between fresh and saline groundwater was recognized, and it was soon realized that pumping at too high a rate leads to an influx of saline water into wells [*Houben and Post*, 2017]. More than a century later, seawater intrusion remains a severe threat to coastal water supply systems and is one of the world's leading causes of groundwater contamination.

Just as the landward movement of seawater contaminates fresh groundwater resources on land, the seaward discharge of contaminated groundwater can wreak havoc on fragile coastal ecosystems such as estuaries [*Johannes*, 1980; *Valiela et al.*, 1990] and coral reefs [*Amato et al.*, 2016]. Humans are also altering coastal hydrology and ecological systems in other ways, by clearing vegetation, farming, filling marshes, building dikes, and accelerating erosion. Sea-level rise is creating additional pressures by increasing salinity and flooding. Ecosystem degradation is particularly worrisome because coastal ecosystems sustain a huge variety of life, humans included, and provide natural services such as protection against storm surges and sequestration of atmospheric CO_2 [*McLeod et al.*, 2011; *Woodroffe et al.*, 2015].

All but a few coastal cities are set for growth over the next few decades [*GRID-Arendal and UNEP*, 2016]. This growth, combined with the worldwide growth in tourism, is increasing the demand for water in urban areas. Concentrated pumping in population centers enhances the risk of seawater intrusion, and wastewater and industrial activities contribute contaminants. Coastal agricultural regions, though less populated, are also at

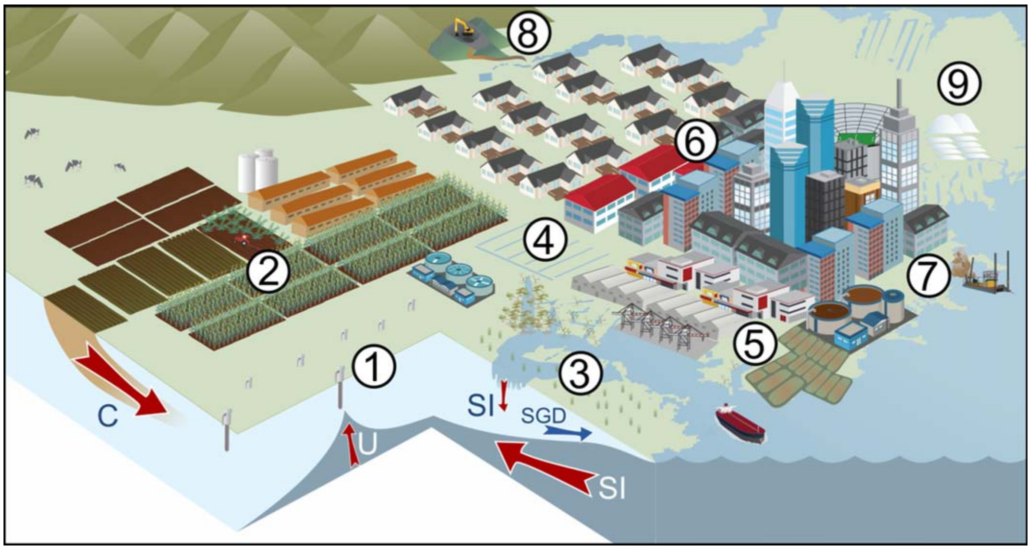

Figure 1. Diagram showing contributors to the "coastal groundwater squeeze." (1) Groundwater overpumping for agricultural and domestic water use causes saltwater upconing (U) and seawater intrusion (SI), as well as a reduction of submarine groundwater discharge to ecosystems; (2) contamination (C) by the use of fertilizer, pesticides and antibiotics for intensive agriculture; (3) vertical seawater intrusion caused by flooding of low-lying areas by seawater; (4) land subsidence caused by drainage for urban development; (5) nutrient and antibiotics use in aquaculture; (6) urban expansion causing increased water demand and pollution; (7) dredging for land reclamation and navigation; (8) mining-induced water table drawdown and pollution; (9) local salt storage causing salinization. Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

risk because irrigation places a higher demand on water than domestic use, and nutrient contributions are intense—fertilizers contribute 80% of reactive nitrogen produced worldwide [*Erisman et al*., 2008]. Sea-level rise is causing shorelines to migrate landward [see *Vitousek et al.*, 2017]. Thus, the term "coastal squeeze" that is used in ecology to indicate the habitat loss in intertidal zones [*Pontee*, 2013] appears to be equally applicable to coastal groundwater resources. Potable freshwater volumes are thin veneers, threatened by contaminant sources at the land surface and saline groundwater at depth (see Figure 1).

The current water and land use in many coastal zones (see Figure 1) is unsustainable. An example is the aquifer system of the North China Plain, which supports 200 million people, including the mega-city Beijing. Groundwater has been the primary water source for extensive population and economic growth over the last three decades, resulting in dramatic declines in water levels, seawater intrusion, and contamination from wastewater [*Foster et al*., 2004; *Liu et al*., 2008]. It is estimated that without management intervention, continued unsustainable groundwater use could lead to more than 800 million dollars per year in agricultural losses alone [*Foster et al*., 2004]. In this and many other coastal areas, landmark changes in land and water management practices will be required to avoid severe detrimental impacts on economy, health, and environment, even without taking future pressures, for example those caused by sea-level rise, into consideration. These measures should be proactive rather than reactive, since prevention is generally much less expensive than remediation. Effective, integrated coastal zone management is multidisciplinary and multisectoral, but is only feasible provided that sufficient knowledge and understanding of the groundwater processes is available.

2. Scientific Progress

Coastal aquifer systems are distinguished from terrestrial systems by the influence of the sea on the composition of the groundwater, in particular on its salinity. In these systems, water quantity and quality are closely connected—as freshwater is depleted inland, seawater intrudes. Moreover, the density difference between fresh and saline water, even a mere 2.5%, has a strong influence on the flow of groundwater and typically leads to a wedge of saltwater below a lens of freshwater. These coupled flow and transport processes present a special scientific and management challenge because groundwater flow can only be interpreted from water levels in wells if the distribution of subsurface salinity is known. This challenge is compounded by several factors. First, the spatial scale over which complex solute transport processes must be considered compared to contaminant plumes is tremendous—the contaminant source is the ocean (in the case of seawater intrusion) and the entire aquifer (in the case of submarine groundwater discharge). Second, hydrologic forcings operate over a range of different timescales. Coastal groundwater systems are influenced by tidal and wave dynamics operating over weeks to seconds, interannual and seasonal hydrologic variations, as well as sea-level changes and aquifer deposition occurring over millennia.

These distinctive physical aspects of coastal systems are accompanied by similarly distinctive biogeochemical characteristics [*Sawyer et al*., 2016]. Coastal aquifers are a mixing ground for solutes sourced from land and sea, driving reactions and fluxes within constantly moving interfaces. Thus, coastal aquifers are also fascinating natural laboratories for studying complex interactions between multiple physical and biochemical components.

Quantitative models of groundwater flow and salinity are critical in managing coastal groundwater resources. Simple analytical modeling began in the late 1800s [*Drabbe and Badon Ghyben*, 1888; *Herzberg*, 1901] and methods continue to be developed to provide rapid and easily applied guidance today. Beginning in the 1970s, numerical models that enable more realistic aquifer representation were developed and are now routinely used to support water management. Some of the most established codes, such as SEAWAT [*Langevin et al*., 2007] and SUTRA [*Voss and Provost*, 2002], are available free of charge. The same is true for codes to simulate chemical processes in groundwater, such as PHREEQC [*Parkhurst and Appelo*, 2013] and PHT3D [*Prommer and Post*, 2010].

The challenge is to have adequate data to constrain these models and judge their worth in answering scientific and practical questions. Networks of hydrologic and geochemical monitoring data collected over long periods of time (i.e., the US Geological Survey Groundwater and Streamflow Information Program and the National Water Quality Assessment Program) are critical sources of information that cannot be collected on a project-by-project basis. The spatial density of geologic and geochemical data required is generally much greater than that of hydrologic data, however, and the development of geophysical tools to map the distribution of fresh and saline groundwater has been critical to providing a 3-D window to the subsurface. Remarkable new data sets can now be collected. The latest land-based measurement systems can reach to nearly 300 m below sea level and stretch tens of kilometers along the coastline [*Goebel et al*., 2017]. Airborne methods provide data of unprecedented resolution over vast areas [*Siemon et al*., 2016]. Many of these data sets are now available to the general public, efficiently disseminated through the internet.

Improved sampling techniques and analytical methods allow environmental tracers (i.e., naturally occurring dissolved substances and isotopes) and pollutants to be measured with increased resolution and accuracy. They can be used to discriminate between different water types, distinguish water origin, trace hydrological processes, and identify anthropogenic impacts [e.g., *Rocha et al*., 2016; *Baskaran et al*., 2016; *Stalker et al*., 2014]. Other tracers, such as fluorescent dissolved organic matter, have also been used to identify biogeochemical processes [*Nelson et al*., 2015; *Suryaputra et al*., 2015]. Efforts have built on work in streams to use heat as a tracer to detect submarine groundwater discharge and subseafloor flow [*Savidge et al*., 2016; *Wilson et al*., 2016]. Geochemical tracers, such as Ra and Rn radioisotopes, can complement traditional hydrogeological tools, such as seepage meters and piezometers, and have enabled estimation of submarine groundwater discharge on larger spatial scales. These various measurements have shown that groundwater discharge to the ocean is a significant component of the global hydrologic cycle [*Moore*, 2010]; the flux of fresh and saline groundwater to the ocean could be up to 4 times the freshwater discharge from rivers [*Kwon et al*., 2014].

Research has identified best practices to arrest or even reverse the decline of freshwater resources [*Werner et al*., 2011], providing tangible societal benefits. An example is the alternating pumping regime of the Chalk aquifer of the English South Downs, where wells close to the coast intercept freshwater discharge to the sea in winter, and wells further inland are pumped only during summer [*Robins et al*., 1999]. Another example is the freshwater lens in Bonriki Island (Kiribati), where decades of hydrogeological studies and data have informed pumping limits and the design and implementation of skimming wells, allowing the resource to be utilized in the most sustainable manner [*White and Falkland*, 2010]. Technologically, the management solutions in these examples are not very complex, but their success is contingent upon science-based aquifer exploration methods and sustained monitoring.

A more sophisticated (and expensive) mitigation strategy is the artificial recharge of aquifers to restore freshwater reserves. This has been successfully applied to reverse seawater intrusion and secure the water supply to the city of Amsterdam in the Netherlands [*Stuyfzand*, 1999], and to restore water levels and improve salinities in the Korba-Mida aquifer of Tunisia [*Gaaloul et al*., 2012]. One critical aspect with this technology is the quality of the recharge water and the risk of mobilizing naturally occurring contaminants. Here reactive transport tools play an important role in assessing the effects of hydrochemical processes and predicting water quality [*van Breukelen et al*., 1998; *Wallis et al*., 2011].

"Hard-engineering" approaches have also been developed and implemented, including the use of physical barriers to reduce the impacts of seawater intrusion. For example, the Komesu subsurface dam (Japan) has reduced seawater intrusion into fresh coastal groundwater [*Nawa and Miyazaki*, 2009]. Perhaps the most ambitious and successful project to mitigate seawater intrusion impacts is the West Coast Basin Barrier Project (i.e., the Dominguez Gap and Alamitos Barrier Projects), where extensive artificial recharge to create hydraulic barriers against the salinization of water supply wells has been implemented in Los Angeles County (USA) [*Johnson and Whitaker*, 2003].

Research has also advanced our ability to identify sources of groundwater-borne pollutants to coastal waters such that they can be mitigated or efficiently managed. High levels of nutrients are a major societal concern because stimulation of productivity leads to harmful algal blooms, anoxia, and associated adverse effects on fisheries and recreation. Nutrient fluxes from groundwater to estuaries and the ocean have been quantified all over the world [e.g., *Slomp and Van Cappellen*, 2004]. Through the use of groundwater age tracers and numerical models to determine how long fresh groundwater remains in aquifers before discharge, scientists and managers are able to better understand and predict the lag between implementation of nutrient management measures and improvement in estuarine water quality [e.g., *Meals et al*., 2010; *Sanford and Pope*, 2013]. These techniques provide managers with information essential for designing nutrient mitigation policy, leading to ecosystem recovery. For example, the Tampa Bay Estuary experienced a 25% increase in eelgrass acreage as a result of the science-based Nutrient Management Strategy in the watershed [*Greening and Janicki*, 2006].

3. Future Scientific Challenges to Meet Societal Needs

While advancements within the field of coastal hydrogeology have improved society's ability to protect and manage our coastal water and ecosystem resources, there are gaps in scientific understanding and missing links between science, practice, and policy that must be overcome to address the water quantity and quality problems that persist in coastal zones. One important challenge is dealing with the characteristic complexity of coastal groundwater systems. To identify the most *effective* ways to protect and manage the resources, we need to integrate understanding across geologic, hydrologic, and biogeochemical complexity. To identify the most *efficient* ways to protect and manage resources and implement policy, we must also consider human complexity, including economics, cultural values, and the factors that affect perception and decision making.

Geologic complexity—the heterogeneous spatial distribution in aquifer properties that occurs across scales—is ubiquitous and difficult to quantify. Even in the few areas where sufficient data exist to constrain both the current salinity distribution and the hydrogeologic system, it is nearly impossible to accurately predict evolution of salinity on the scale of a single well screen [e.g., *Sanford and Pope*, 2009], due in part to the inadequacy of macroscopic models of solute mixing to simulate key effects of small-scale heterogeneities. Offshore information is even more difficult to obtain, particularly stratigraphy and pore-water salinity. Because data are always limited in hydrogeological systems, we must work to better understand processes so that the most essential information can be targeted with the most effective tools.

Another complexity of coastal groundwater systems is transience caused by hydrologic forcing operating on vastly different timescales. As a result, systems are constantly out of equilibrium with current hydraulic conditions. The disequilibrium occurs in the distribution of pressures, which drive flow, and even more so in the distribution of solutes, which change much more slowly. Although substantial research has tackled individual timescales, these transient conditions are not independent [e.g., *Wilson et al*., 2016], with interactions that have yet to be identified due to the challenge of measuring and modeling across diverse timescales. For example, a suite of sophisticated age tracers has been developed to date groundwater, but the chemical and mixing processes in coastal settings preclude unambiguous interpretation of their results. This requires ongoing efforts to develop better methods to constrain the ages of water bodies and rates of processes. Changes in climate will also cause hydrologic shifts as sea level rises and groundwater recharge is altered. While research has attempted to quantify resulting changes, for example in seawater intrusion and submarine groundwater discharge [e.g., *Werner and Simmons*, 2009; *Webb and Howard*, 2011; *Michael et al*., 2013], opportunities remain to identify the nature of these hydrologic changes, and especially to forecast potential tipping points that may result in the collapse of systems under stress.

Chemical reactions add to the complexity. While our ability to quantify and predict effects of individual physical and geochemical processes has advanced remarkably, these are never decoupled in natural systems; nor are they independent of geologic heterogeneity. For example, we monitor nitrogen concentrations in wells and measure groundwater fluxes to estuaries, but the resultant nutrient load is not simply their product. Nitrogen transformations between inland wells and the ocean alter the loads in nonuniform ways that have been linked to geology, flow paths, and groundwater-surface water exchange [e.g., *Kroeger and Charette*, 2008; *Roy et al*., 2011; *Sawyer et al*., 2014]. Understanding these complexities and how they interact across space and time will enable better prediction of water quality evolution, solute loads to the ocean, and system response to hydrologic change.

To address the challenge of complexity in natural systems, we need to break down traditional disciplinary barriers. For example, while hydrogeologists and oceanographers both seek to quantify submarine groundwater discharge and associated contaminant fluxes, they bring different priorities, tools, and expertise. By working from only one side, each may miss both the complexity of and the information that can be obtained from the other side of the land-sea interface, potentially leading to knowledge gaps that could be filled by working together. This is similarly true for physical hydrogeologists and biogeochemists—the former often consider only conservative solute transport, missing the importance of chemical transformations, and the latter often overlook the influence of fluid motion on subsurface reactions. Because of the complex interlinkages between aquifers and the ocean and between physical, geochemical, and biological processes, these systems need to be understood holistically.

The last, but perhaps most important, complexity is the dramatic influence of human activities and infrastructure on coastal systems. For example, canals and harbor channels cut coastal aquifers and confining units, altering natural groundwater flow systems and potentially increasing nutrient discharges [i.e., *Sawyer et al*., 2014]. The increasing prevalence of coastal ponds for aquaculture and retention ponds can strongly affect chemical cycling and fluxes [*Tal et al*., 2017]. Moreover, we need to understand how coastal groundwater systems intersect with other important societal needs. For example, coastal zones are arguably the place where the water-energy-food nexus [see *Scanlon et al.*, 2017] is most profound. Maintaining viable water supply can add a significant burden to the energy needs of coastal populations, for example through the energy required to enhance reuse of water by managed aquifer recharge and recovery. Energy demand is particularly intense in the case of desalination, which is increasingly relied upon. As a result, where population growth occurs, and the availability of fresh groundwater is increasingly insufficient due to both contamination of the available resource and rising demand, energy consumption will increase. This cost and the increasing salinity of groundwater available for irrigation may have large impacts on how land can be used and which crops can be grown. Although there have been serious efforts to determine the environmental and economic costs of desalination [*NRC*, 2008], to our knowledge there have been no published attempts to compare the cost of desalination to the cost of improved coastal groundwater management (e.g., enhanced recharge) combined with water demand management.

Holistic analyses are needed to understand all of the societal implications of interconnected and complex coastal systems so that one solution does not lead to detrimental effects elsewhere, and so that the most efficient solutions can be found; to do this, natural and social scientists must work together. While there has been some work in coastal systems, for example quantifying the value of data in decision making [e.g., *Trainor-Guitton*, 2014] and evaluating the impact of uncertainty on optimal policy [e.g., *Tsur and Zemel*, 2004], it is only scratching the surface. We need to be able to identify feedbacks between humans and coastal systems and quantify them so that integrated models can be developed. There are also opportunities to complement engineering or science-based methods to protect water resources by exploring strategies based on education and awareness that build stronger connections between communities and their water resources.

4. Ensuring that Societal Solutions Exploit Scientific Understanding

The research collaboration required to understand these complex systems and translate science to efficient societal benefit will cross fields of hydrogeology, oceanography, biogeochemistry, engineering, economics, sociology, policy, and many others. This requires a substantial investment of time on the part of investigators to communicate ideas, understand terminology, and connect often very diverse research methods. It requires a similar investment of funds to support the large, long-term projects that enable the cross-disciplinary breakthroughs that most benefit society. Further, researchers must collaborate with decision makers to better understand the problems and to move research findings to implementation. Students should be trained to become more comfortable crossing disciplines while retaining depth in hydrogeology, and we must ensure that the next generation of scientists can more readily communicate with the public and policymakers than their predecessors.

Even though science has progressed remarkably, water supply issues and environmental problems persist and in some cases are accelerating in coastal zones. On the one hand, this is because there are still important gaps in our understanding of groundwater systems, and in some cases, there is a failure to propagate research findings to groundwater practitioners. On the other hand, problems arise or persist due to ineffective management and a lack of proper governance—problems that science may or may not help solve. For example, poor regulation and/or policy enforcement result in continued unsustainable groundwater pumping in many regions, despite clear evidence of detrimental effects on the resource [*Werner et al.*, 2013]. Further, there is a need for an integrated approach to manage resources and safeguard ecosystems, but the strong interconnectedness of the terrestrial and marine natural systems is often not reflected by governance structures.

The scientific community has an important role to play to offer solutions to the problems that face coastal communities. We have an opportunity in that clean water is not only a basic human need, but in fact a basic human right [*United Nations*, 2010]. It may be more of a priority in regions of water scarcity or where treatment infrastructure is absent, but by listening to community concerns and by communicating the challenges and opportunities, we may bring the protection of water resources to the forefront of public consciousness. Improved community knowledge of coastal groundwater concepts may provide enhanced engagement in protecting coastal aquifers and dependent ecosystems. Without stronger management oversight and intervention, and community engagement, coastal settings are likely to further degrade as the populace continues to act on individual interests. Ensuring coastal water security is possible and perhaps we can follow the path of ozone layer depletion and acid rain, which with a combination of science and political will are now largely problems of the past. Only when we continue to develop fundamental science, and ensure that that science also informs policy, can we truly push against the coastal groundwater squeeze.

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References

Amato, D. W., J. M. Bishop, C. R. Glenn, H. Dulai, C. M. Smith, and J. Jolly (2016), Impact of submarine groundwater discharge on marine water quality and reef biota of Maui, edited by J. P. Meador, *PLoS One*, *11*(11), e0165825, doi:10.1371/journal.pone.0165825.

Baskaran, M., T. Novell, K. Nash, S. A. Ruberg, T. Johengen, N. Hawley, J. V. Klump, and B. A. Biddanda (2016), Tracing the seepage of subsurface sinkhole vent waters into Lake Huron using radium and stable isotopes of oxygen and hydrogen, *Aquat. Geochem.*, *22*(4), 349–374, doi:10.1007/s10498-015-9286-7.

Drabbe, J., W. Badon Ghijben (1888), *Nota in Verband Met de Voorgenomen Putboring Nabij Amsterdam*, pp. 8–22, Tijdschrift Koninklijk Instituut van Ingenieurs, The Hague, Netherlands.

Erisman, J. W., M. A. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter (2008), How a century of ammonia synthesis changed the world, *Nat. Geosci.*, *1*(10), 636–639, doi:10.1038/ngeo325.

Foster, S., H. Garduno, T. Evans, D. Olson, Y. Tian, W. Zhang, and Z. Han (2004), Quaternary aquifer of the North China Plain—Assessing and achieving groundwater resource sustainability, *Hydrogeol. J.*, *12*(1), 81–93.

Gaaloul, N., L. Cary, J. Casanova, C. Guerrot, and H. Chaieb (2012), Impact de la recharge artificielle par des eaux usées traitées sur la qualité et la quantité des eaux souterraines de la nappe côtière de Korba-Mida, Cap-Bon, Tunisie, *La Houille Blanche*, *4–5*, 24–33, doi:10.1051/lhb/2012027.

Goebel, M., A. Pidlisecky, and R. Knight (2017), Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast, *J. Hydrol.*, doi:10.1016/j.jhydrol.2017.02.037, in press.

Greening, H., and A. Janicki (2006), Toward reversal of eutrophic conditions in a subtropical estuary: Water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA, *Environ. Manage.*, *38*(2), 163–178, doi:10.1007/s00267-005-0079-4.

GRID-Arendal and UNEP (2016), *World Ocean Assessment Overview*, GRID-Arendal, Arendal, Norway.

Herzberg, A. (1901), Die Wasserversorgung einiger Nordseebäder, *J Gasbeleucht. Wasserversorg.*, *44*, 815–819.

Houben, G., and V. E. A. Post (2017), The first field-based descriptions of pumping-induced saltwater intrusion and upconing, *Hydrogeol. J.*, *25*(1), 243–247, doi:10.1007/s10040-016-1476-x.

Johannes, R. E. (1980), The ecological significance of the submarine discharge of groundwater, *Mar. Ecol. Prog. Ser.*, *3*, 365–373.

Johnson, T. A., and R. Whitaker (2003), Saltwater intrusion in the coastal aquifers of Los Angeles County, California, in *Coastal Aquifer Management-Monitoring, Modeling, and Case Studies*, pp. 29–48, CRC Press, Boca Raton, Fla.

Kroeger, K. D., and M. A. Charette (2008), Nitrogen biogeochemistry of submarine groundwater discharge, *Limnol. Oceanogr.*, *53*(3), 1025–1039, doi:10.4319/lo.2008.53.3.1025.

Kwon, E. Y., G. Kim, F. Primeau, W. S. Moore, H.-M. Cho, T. DeVries, J. L. Sarmiento, M. A. Charette, and Y.-K. Cho (2014), Global estimate of submarine groundwater discharge based on an observationally constrained radium isotope model, *Geophys. Res. Lett.*, *41*, 8438–8444, doi:10.1002/2014GL061574.

Langevin, C. D., J. Thorne, D. T., A. M. Dausman, M. C. Sukop, and W. Guo (2007), SEAWAT version 4: A computer program for simulation of multi-species solute and heat transport, *U.S. Geol. Surv. Tech. Methods, 6-A22*, 39 p.

Liu, J., C. Zheng, L. Zheng, and Y. Lei (2008), Ground water sustainability: methodology and application to the North China Plain, *Ground Water*, *46*(6), 897–909.

Mcleod, E., G. L. Chmura, S. Bouillon, R. Salm, M. Björk, C. M. Duarte, C. E. Lovelock, W. H. Schlesinger, and B. R. Silliman (2011), A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2, *Front. Ecol. Environ.*, *9*(10), 552–560, doi:10.1890/110004.

Meals, D. W., S. A. Dressing, and T. E. Davenport (2010), Lag time in water quality response to best management practices: A review, *J. Environ. Qual.*, *39*(1), 85–96, doi:10.2134/jeq2009.0108.

Michael, H. A., C. J. Russoniello, and L. A. Byron (2013), Global assessment of vulnerability to sea-level rise in topography-limited and recharge-limited coastal groundwater systems, *Water Resour. Res.*, *49*, 2228–2240, doi:10.1002/wrcr.20213.

Moore, W. S. (2010), The effect of submarine groundwater discharge on the ocean, *Annu. Rev. Mar. Sci.*, *2*, 59–88, doi:10.1146/annurev-marine-120308-081019.

Nawa, N., and K. Miyazaki (2009), The analysis of saltwater intrusion through Komesu underground dam and water quality management for salinity, *Paddy Water Environ.*, *7*(2), 71–82, doi:10.1007/s10333-009-0154-1.

Nelson, C. E., M. J. Donahue, H. Dulaiova, S. J. Goldberg, F. F. La Valle, K. Lubarsky, J. Miyano, C. Richardson, N. J. Silbiger, and F. I. M. Thomas (2015), Fluorescent dissolved organic matter as a multivariate biogeochemical tracer of submarine groundwater discharge in coral reef ecosystems, *Mar. Chem.*, *177*, 232–243, doi:10.1016/j.marchem.2015.06.026.

NRC (2008), *Desalination: A National Perspective*, Natl. Acad. Press, Washington, D. C.

Parkhurst, D. L., and C. A. J. Appelo (2013), Description of input and examples for PHREEQC version 3—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations, *U.S. Geol. Surv. Tech. Methods*, *6-A43*, 497 p.

Pontee, N. (2013), Defining coastal squeeze: A discussion, *Ocean Coastal Manage.*, *84*, 204–207, doi:10.1016/j.ocecoaman.2013.07.010.

Prommer, H., and V. E. A. Post (2010), A reactive multicomponent transport model for saturated porous media: User's manual. [Available at http://www.pht3d.org/]

Robins, N. S., H. K. Jones, and J. Ellis (1999), An aquifer management case study—The Chalk of the English South Downs, *Water Resour. Manage.*, *13*(3), 205–218.

Rocha, C., C. Veiga-Pires, J. Scholten, K. Knoeller, D. R. Gröcke, L. Carvalho, J. Anibal, and J. Wilson (2016), Assessing land–ocean connectivity via submarine groundwater discharge (SGD) in the Ria Formosa Lagoon (Portugal): Combining radon measurements and stable isotope hydrology, *Hydrol. Earth Syst. Sci.*, *20*(8), 3077–3098, doi:10.5194/hess-20-3077-2016.

Roy, M., J. B. Martin, C. G. Smith, and J. E. Cable (2011), Reactive-transport modeling of iron diagenesis and associated organic carbon remineralization in a Florida (USA) subterranean estuary, *Earth Planet. Sci. Lett.*, *304*, 191–201, doi:10.1016/j.epsl.2011.02.002.

Sanford, W. E., and J. P. Pope (2009), Current challenges using models to forecast seawater intrusion: Lessons from the Eastern Shore of Virginia, USA, *Hydrogeol. J.*, *18*(1), 73–93, doi:10.1007/s10040-009-0513-4.

Sanford, W. E., and J. P. Pope (2013), Quantifying groundwater's role in delaying improvements to Chesapeake Bay water quality, *Environ. Sci. Technol.*, *47*(23), 13,330–13,338, doi:10.1021/es401334k.

Savidge, W. B., A. M. Wilson, and G. Woodward (2016), Hydrodynamic exchange in an open shelf permeable seafloor, *Aquat. Geochem.*, *22*, 419–441.

Sawyer, A. H., O. Lazareva, K. D. Kroeger, K. Crespo, C. S. Chan, T. Stieglitz, and H. A. Michael (2014), Stratigraphic controls on fluid and solute fluxes across the sediment-water interface of an estuary, *Limnol. Oceanogr.*, *59*, 997–1010, doi:10.4319/lo.2014.59.3.0997.

Sawyer, A. H., H. A. Michael, and A. W. Schroth (2016), From soil to sea: the role of groundwater in coastal critical zone processes, *WIREs Water*, *3*(5), 706–726.

Scanlon, B. R., B. L. Ruddell, P. M. Reed, R. I. Hook, C. Zheng, V. C. Tidwell, and S. Siebert (2017), The food-energy-water nexus: Transforming science for society, *Water Resour. Res.*, *53*, doi:10.1002/2017WR020889.

Siemon, B., A. V. Christiansen, and E. Auken (2016), A review of helicopter-borne electromagnetic methods for groundwater exploration, *Near Surf. Geophys.*, *7*(5–6), 629–646.

Slomp, C. P., and P. Van Cappellen (2004), Nutrient inputs to the coastal ocean through submarine groundwater discharge: Controls and potential impact, *J. Hydrol.*, *295*(1), 64–86.

Stalker, J. C., R. M. Price, V. H. Rivera-Monroy, J. Herrera-Silveira, S. Morales, J. A. Benitez, and D. Alonzo-Parra (2014), Hydrologic dynamics of a subtropical estuary using geochemical tracers, Celestún, Yucatan, Mexico, *Estuaries Coasts*, *37*(6), 1376–1387, doi:10.1007/s12237-014-9778-5.

Stuyfzand, P. J. (1999), Patterns in groundwater chemistry resulting from groundwater flow, *Hydrogeol. J.*, *7*(1), 15–27, doi:10.1007/s100400050177.

Suryaputra, I. G. N. A., I. R. Santos, M. Huettel, W. C. Burnett, and T. Dittmar (2015), Non-conservative behavior of fluorescent dissolved organic matter (FDOM) within a subterranean estuary, *Cont. Shelf Res.*, *110*, 183–190, doi:10.1016/j.csr.2015.10.011.

Tal, A., Y. Weinstein, Y. Yechieli, and M. Borisover (2017), The influence of fish ponds and salinization on groundwater quality in the multi-layer coastal aquifer system in Israel, *J. Hydrol.*, doi:10.1016/j.jhydrol.2017.04.008, in press.

Trainor-Guitton, W. J. (2014), A geophysical perspective of value of information: Examples of spatial decisions for groundwater sustainability, *Environ. Syst. Decis.*, *34*(1), 124–133, doi:10.1007/s10669-013-9487-9.

Tsur, Y., and A. Zemel (2004), Endangered aquifers: Groundwater management under threats of catastrophic events, *Water Resour. Res.*, *40*, W06S20, doi:10.1029/2003WR002168.

United Nations (2010), Resolution adopted by the General Assembly on 28 July 2010, Document A/RES/64/292, 108th Plenary Meeting, 64th Session, Agenda Item 48, 3 pp., Geneva. [Available at http://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/64/292].

Valiela, I., J. Costa, K. Foreman, J. M. Teal, B. Howes, and D. Aubrey (1990), Transport of groundwater-borne nutrients from watersheds and their effects on coastal waters, *Biogeochemistry*, *10*(3), 177–197, doi:10.1007/BF00003143.

van Breukelen, B. M., C. A. J. Appelo, and T. N. Olsthoorn (1998), Hydrogeochemical transport modeling of 24 years of Rhine water infiltration in the dunes of the Amsterdam Water Supply, *J. Hydrol.*, *209*(1–4), 281–296, doi:10.1016/S0022-1694(98)00105-X.

Vitousek, S., P. L. Barnard, and P. Limber (2017), Can beaches survive climate change?, *J. Geophys. Res. Earth Surf.*, *122*, doi:10.1002/2017JF004308.

Voss, C. I., and A. Provost (2002), SUTRA: A model for saturated-unsaturated variable-density ground-water flow with solute or energy transport, *U.S. Geol. Surv. Water Resour. Invest. Rep.*, *02-4231*, 270 p.

Wallis, I., H. Prommer, T. Pichler, V. Post, S. B. Norton, M. D. Annable, and C. T. Simmons (2011), Process-based reactive transport model to quantify arsenic mobility during aquifer storage and recovery of potable water, *Environ. Sci. Technol.*, *45*(16), 6924–6931, doi:10.1021/es201286c.

Webb, M. D., and K. W. F. Howard (2011), Modeling the transient response of saline intrusion to rising sea-levels, *Ground Water*, *49*, 560–569, doi:10.1111/j.1745-6584.2010.00758.x.

Werner, A. D., and C. T. Simmons (2009), Impact of sea-level rise on sea water intrusion in coastal aquifers, *Ground Water*, *47*, 197–204, doi:10.1111/j.1745-6584.2008.00535.x.

Werner, A. D., D. W. Alcoe, C. M. Ordens, J. L. Hutson, J. D. Ward, and C. T. Simmons (2011), Current practice and future challenges in coastal aquifer management: Flux-based and trigger-level approaches with application to an Australian case study, *Water Resour. Manage.*, *25*(7), 1831–1853, doi:10.1007/s11269-011-9777-2.

Werner, A. D., Q. Zhang, L. Xue, B. D. Smerdon, X. Li, X. Zhu, L. Yu, and L. Li (2013), An initial inventory and indexation of groundwater mega-depletion cases, *Water Resour. Manage.*, *27*(2), 507–533, doi:10.1007/s11269-012-0199-6.

White, I., and T. Falkland (2010), Management of freshwater lenses on small Pacific islands, *Hydrogeol. J.*, *18*(1), 227–246, doi:10.1007/s12237-014-9778-5.

Wilson, A. M., T. Evans, W. S. Moore, C. A. Schutte, and S. B. Joye (2015), What time scales are important for monitoring submarine groundwater discharge? Insights from a salt marsh, *Water Resour. Res.*, *51*, 4198–4207, doi:10.1002/2014WR015984.

Wilson, A. M., G. L. Woodward, and W. B. Savidge (2016), Using heat as a tracer to estimate the depth of rapid porewater advection below the sediment-water interface, *J. Hydrol.*, *538*, 743–753, doi:10.1016/j.jhydrol.2016.04.047.

Woodroffe, C. D., C. E. Lovelock, and K. Rogers (2015), Mangrove shorelines, *Coastal Environ. Global Change*, 251–267, doi:10.1002/9781119117261.ch11.