Fresh and saline groundwater interaction in coastal aquifers: Is our technology ready for the problems ahead?

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Introduction

Coastal aquifers are the subsurface equivalents of coastal areas where continental fresh groundwater and seawater meet. They can be composed of a variety of rock types including karstified limestone, fractured rock and unconsolidated sands. Their thickness varies from a few meters to over a kilometer. At the surface, conditions of land use, topography and climate can be highly variable. Despite a seemingly endless variety of possible aquifer characteristics, coastal aquifers share some common hydrogeological features. For instance, flow is typically influenced by density gradients and due to the characteristic composition of the fresh and seawater end members, distinct water quality patterns develop in mixing zones. Being located in geologically active environments, the distribution of water types is often influenced by long-term geological processes (e.g., sea level fluctuations). From a water management point of view, coastal aquifers are vulnerable to salinization of fresh ground water by seawater intrusion and upconing. The future does not look too bright. The rising demand for fresh water, disruption of natural hydrological conditions, climate change and groundwater contamination will increase the stress on available water resources and valuable ecosystems. This essay will explore the present state of coastal aquifers, common problems and how hydrogeology as a scientific discipline can contribute to develop sustainable solutions.

Present state

Coastal areas are the most densely-populated areas in the world. Half of the world's population lives in coastal areas and 8 of the 10 largest cities in the world are located at the coastline (source: UN Atlas of the oceans, http://www.oceansatlas.org/). Consequently, the high demand for water poses tremendous pressure on groundwater resources. At the same time, these are threatened by the disposal of waste and sewage and leaching of contaminants. The lowering of piezometric heads can also cause land subsidence. Problems are especially felt in arid or semi-arid areas where groundwater is the only source of fresh water and the periods of highest demand (e.g., the growing and tourist seasons) coincide with the periods of lowest recharge. These problems, however, are not unique to coastal aquifers. What sets them apart from other aquifers is the risk of salt water intrusion due to overexploitation.

There exists no comprehensive review of the extent of salt water intrusion problems around the world. Well documented cases, however, include for example the Hawaiian, Californian, Floridian, Atlantic and Gulf coastal plains in the United States (Konikow and Reilly 1999) and the Mediterranean coastal aquifers (López-Geta et al. 2003). A recent inventory by the European Environmental Agency revealed that in Europe at least 100 areas have been affected by marine intrusion (Scheidleger et al. 2004). As another example, in The Netherlands, which has ample fresh-water input from rivers and precipitation, 20 well fields had to be closed due to salinization and 9 had to resort to artificial recharge between 1880 and 1992 (Stuyfzand et al. 2004).These figures show that salt water intrusion is truly a global phenomenon. Moreover, aggravation of the problem is expected in the next decades due to population and economic growth, deterioration of water quality by pollution, reduced infiltration capacity as a result of urbanization, declining river discharge and climate change. The anticipated sea level rise and decreased groundwater recharge rates in some areas could lead to further inland movement of seawater, thereby contaminating the already scarce freshwater resources.

Possible solutions

As in any other aquifer under stress, management of coastal groundwater involves balancing the demand and the renewable supply of water. The unique aspect of coastal aquifer management is that pumping schemes must be optimized to prevent or at least minimize upconing or lateral migration of saline groundwater. In many cases, demand will exceed supply and pumping scheme optimization must be complemented by other measures to ensure sufficient availability of water. Such measures may include long distance water transfer from more humid regions, artificial recharge of surplus water during wet periods, recycling of water, desalinization and water rationing. Given the anticipated shortage in the near future, the use of water of marginal quality, such as brackish groundwater and treated sewage water, will increase. A differentiation of types of use needs to be established so that water of a specific quality can be allocated to different users (e.g., why use valuable fresh water for industrial purposes such as cooling?). The best practice for a specific area is dependent on a variety of socio-economic, legislative, environmental and hydrogeological factors. Hydrogeologists will play an important role in evaluating the feasibility and the impact of the measures to be taken. But are the latest hydrogeological tools and insights sufficient to address the questions that need to be answered for optimal groundwater management in coastal zones? And what are the remaining scientific questions?

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Scientific challenges

One could say that coastal hydrogeology was established as a separate discipline of hydrogeology with the publication of the works of Badon Ghijben (1888) and Herzberg (1901). During subsequent decades, numerous field studies have been conducted that, together with complementary theoretical analysis, led to the development of the basic concepts of groundwater flow and salinity distribution in coastal aquifers. Since the early 1970s numerical models have been developed. As a result of a massive increase in computational power, simulation of realistic aquifer properties, such as three-dimensional flow, heterogeneity and anisotropy, as well as transient effects can now be applied on a routine basis.

Important progress was also made with respect to understanding groundwater quality patterns in coastal aquifers. Versluys (1916) was the first to recognize the importance of cation exchange to the chemical composition of moving fresh and saline groundwater bodies. The resultant development of chromatographic patterns, which are characteristic for coastal aquifers, was studied extensively during the 1980s and 1990s. Chemical processes due to the mixing of seawater and fresh water, such as for example calcite dissolution, have also been investigated in detail. Finally, isotopic measurements have been used in many studies to discriminate between different sources of salt water and to date groundwater bodies.

The above summary of the developments in coastal hydrogeology is very brief but nevertheless testifies to the tremendous progress that has been made, which has been indispensable to tackle complicated management problems. Still, issues remain that warrant further research. These concern conceptual understanding of coastal hydrogeological systems, development of mathematical models and characterization of subsurface hydrogeological and geochemical properties.

Conceptual understanding

The traditional conception of the spatial distribution of fresh and saline groundwater in a coastal aquifer basically comprises a fresh water body overlying a salt-water wedge on land and saline groundwater below the sea floor. Application of this concept is restricted to areas where the position of the coastline has remained stable sufficiently long to reach equilibrium. This situation, however, is the exception rather than the rule as global sea level fluctuates and coastlines consequently migrate. Notably the effects of the sea level low stand during the last glaciation (110–10 ka BP) and the subsequent sea level rise during the Holocene (10 ka BP—present) are still recognized in coastal groundwaters today (e.g., Edmunds 2001). As a result, fresh groundwater is sometimes found up to tens of kilometers offshore. Conversely, saline groundwater may be encountered far inland from the current coastline.

Understanding the processes and factors that control the paleohydrological evolution of saline water in the subsurface remains an academic challenge and is at the same time of important practical use for water resource evaluation and salt water intrusion studies. The presence of fresh water offshore should be considered in calculations of sustainable yield and complicates the selection of initial and boundary conditions for numerical models. For example, it is common to assume a fixed (seawater) concentration, hydrostatic boundary condition at the coastline, which is an invalid assumption if fresh water extends below the seafloor.

As the present-day distribution of fresh and saline groundwater in coastal aquifers still reflects former environmental conditions, it is often unclear to what extent the current situation is the result of long-term effects or recent (anthropogenic) changes. This problem also arises in the investigation of submarine groundwater discharge (Kooi and Groen 2001). The realization that groundwater discharge offshore contributes significantly to the nutrient loading and contamination of coastal waters is recent insight and much work remains to be done in this field. Methodologies need to be developed for reliable quantification of discharge fluxes at the outflow face below the sea (i.e., upscaling of point or local-scale measurements). Geochemical processes due to groundwater–seawater interactions need to be evaluated in order to be able to predict the fate of nutrients and contaminants that leach into the sea. In this respect, coupled multi-component reactive transport models with the capability to simulate variable-density flow (see below) will prove indispensable.

Disruption of natural hydrological systems is another factor that threatens fresh water groundwater in coastal areas. For example, the upstream intake of water from rivers reduces their discharge to a considerable extent. This can lead to upstream migration of seawater in the river mouth and shoreline retreat due to the reduction of the sediment load to the coastal zone. Examples include the river Murray in Australia and the river Nile in Egypt, where at some locations the shoreline is retreating at a dramatic rate of tens of meters per year (Frihy et al. 2003). Obviously, this poses a threat to inland fresh water resources.

The predicted climate change and concomitant sea level rise will affect the flow regime of coastal aquifers (i.e., Oude Essink 2001). Aggravation of the problem of salt water intrusion and shrinkage of fresh water lenses below islands is expected due to sea level rise and the magnitude (and the associated uncertainty) of this effect needs to be more accurately quantified, especially in the longer term, to adequately inform water managers. The same holds for changes in the aquifer recharge regime that will affect the inland extension of seawater wedges and submarine groundwater discharge rates. Such predictions require sound conceptual knowledge and reliable modeling tools.

Mathematical models

Modeling of groundwater flow and solute transport in coastal areas inherently involves taking into account density differences. An in-depth discussion of the future of variable density groundwater flow is presented in this issue by Simmons (2005). Here, only topics that are relevant to coastal aquifers in particular will be addressed.

A well-known drawback of numerical codes that simulate density-driven flow is that few analytical solutions and laboratory experiments exist that can provide confident verification. With respect to existing benchmark tests unresolved issues remain. For example, in the Elder problem, which simulates unstable flow below a salt source overlying a fresh-water aquifer, the propagation of instabilities appears to depend on both spatial and temporal discretization (Diersch and Kolditz 2002).

Codes that simulate variable-density groundwater flow on the one hand and geochemical codes on the other are currently being integrated to provide a full description of the coupled flow and hydrochemical system (Freedman and Ibaraki 2002; Langevin et al. 2004). Already available coupled models differ in the way the coupling is implemented, solution method and the level of sophistication of the geochemical reactions. The development of these codes has only just begun and will be an area of ongoing research. Multi-component reactive transport models will find application for example in coastal areas where migration of contaminant plumes is influenced by variable density flow or in cases where salt water intrusion induces reactions such as cation exchange, mineral dissolution/precipitation and redox reactions. Chemical reactions may also affect groundwater density and thus the flow field. The importance of these models will increase even further with the expected increasing use of brackish groundwater for desalinization as the design of desalinization plants requires accurate prediction of the composition of the pumped groundwater.

The development of multi-component reactive transport models can even be taken a step further by including the interaction between chemical reactions (e.g., precipitation/dissolution reactions and clay-swelling) with physical aquifer properties such as hydraulic conductivity and porosity (Freedman and Ibaraki 2002). Such models can be applied to test the feasibility and evaluate the effectiveness of artificial barriers against salt water intrusion by precipitation of gypsum or other minerals. Although some work has been carried out in this field it is by no means clear how this interaction should be implemented.

In terms of the water and salt budget, surface water and groundwater are interrelated. Simulation of the interaction between the two is not a trivial matter as groundwater responds much slower

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than does surface water, which presents a problem of different time scales when coupling surface water and groundwater models. Relatively little work has been carried out in this field, but the need for these models certainly exists to evaluate for example the effect of sea level rise on the salinity of canals and rivers that drain aquifers affected by salt water intrusion.

Subsurface characterization

In order to successfully apply existing and future models which describe three-dimensional flow, transport and geochemical interactions under variable-density conditions to real-world problems, detailed and accurate characterization of the subsurface is required. This presents a difficulty that is especially felt in salt water intrusion problems in which migration of seawater is largely controlled by the heterogeneity of the subsurface. While this also pertains to other hydrogeologic disciplines, such as contaminant hydrogeology, the scale of salt water intrusion problems is generally much larger. Delineation of geological structures that constitute preferential flow paths, such as paleochannels and fractures, then becomes highly important.

Mapping of hydrogeological conditions can never be based on boreholes alone as the number of observations is always too small. The same holds for the subsurface salinity distribution, which is a critical input requirement for numerical models. Effective subsurface characterization should be achieved by employing methods that provide information on lateral variations in lithology, hydraulic properties and salinity, such as two- and three-dimensional geoelectrical, airborne electromagnetic and seismic methods. These relatively novel techniques are currently finding their way into coastal hydrogeology. Moreover, sedimentological facies models will prove to be important in this respect.

Inverse methods provide another means to determine the required model input parameters. New optimization algorithms are being developed to improve the calibration of variable-density models. Recent methods incorporate both head and salinity measurements (Iribar et al. 1997), which increases the reliability of the parameter estimation process.

Despite the ever-improving techniques for subsurface characterization, uncertainty remains and needs to be accounted for. The use of stochastic models, in which parameters are characterized by statistical properties instead of being fixed as in deterministic models, allows for quantification of the uncertainty of model predictions.

There is also a need to assess the effect of small-scale heterogeneity, which is currently being implemented in regional-scale models by means of effective parameters. Mixing for instance is strongly influenced by small-scale permeability variations and is simulated through the use of a dispersion coefficient. The validity of this approach is a matter of debate and will continue to be an important topic of research in the future (Diersch and Kolditz 2002).

Adequate characterization of heterogeneity also requires quantification of groundwater recharge. It is well-known that recharge rates are highly variable in both space and time. Recharge is distributed unevenly in urban areas in particular, which occupy an increasingly larger surface area of coastal zones. New isotopic techniques such as tritium-helium dating should be applied to coastal areas to get an idea of the variability of aquifer recharge. Subsequently, this information should be used by modelers to get an idea of the sensitivity of this often highly uncertain parameter to the output of models.

Data scarcity is especially a problem in the offshore domain. Coastal aquifers always extend below the seafloor and correct modeling of salt water intrusion requires accurate representation of offshore geology. The land–sea connection has received little attention and in future studies hydrogeologists should team up with marine geologists to bridge this gap.

Conclusions

The pressure on water supplies and precious ecosystems in coastal areas is very high and will only be seen to increase in the future. The question is when the limits to population numbers and living standards posed by the availability of fresh water will be reached. Will solutions to problems provided by current technologies, like artificial recharge and recovery, desalinization and water recycling provide adequate relief? Or will natural limitations force populations to adapt or even abandon certain regions? The answers depend of course on a great number of factors. The role of hydrogeologists is to work out how to optimally manage our coastal aquifers and come up with (at least an educated guess about) the limits of sustainability.

To come back to the question in the title: Is our technology geared-up for this? The discipline of coastal hydrogeology has evolved remarkably over the past decades. Presently, models are available that are well-suited to simulate groundwater flow and solute transport under variable density conditions. Although issues like incorporation of dispersion and grid convergence in free convection problems deserve further attention, the real problems in modeling do not lie in the description of the processes but in the simulation of real-world cases. There is a strong need for better methods to characterize model input parameters that resolve the spatial variability of physical and chemical aquifer properties as well as recharge rates. Moreover, the conceptual framework needs to be strengthened: On- and offshore domains need to be linked and knowledge of long-term processes is required to predict the effects of climate change. The clock is ticking, let's keep on going.

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