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Editorial:

Coastal Aquifers: Scientific Advances in the face of Global Environmental Challenges

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Introduction

Coastal aquifers embody the subsurface transition between terrestrial and marine systems, and form the almost invisible pathway for tremendous volumes of freshwater that flow to the ocean. Changing conditions of the earth's landscapes and oceans can disrupt the fragile natural equilibrium between fresh and saltwater that exists in coastal zones. Among these, over-abstraction of groundwater is considered the leading man-made cause of seawater intrusion. Moreover, many of the world's largest urban settings, where sources of contamination are profuse, have been built over the freshwater in coastal aquifers. Thus, coastal aquifers are important receptors of human impacts to water on Earth (Michael et al., 2017). This Special Issue on 'Investigation and Management of Coastal Aquifers' contains current scientific advances on the topic, dealing with the storage and quality of water, affected by stressors ranging in scale from point source contamination to global climate change.

At the time of preparation of this Special Issue, the world appears to be in a transformative phase of human history. An unprecedented number of refugees flee nationwide conflicts, and acts of terrorism are on the rise and instil fear across the globe. New administrations challenge existing governance, international collaboration structures, and sometimes the scientific foundations underpinning strategies for addressing contemporary global challenges. In the meantime, and perhaps less noticeable, the global population continues to grow, and as millions rise out of poverty, consumption levels soar worldwide. In many places, food is available in abundance and with enormous variety, thanks to the global trade of agricultural products, facilitated by trade agreements and high-tech supply chains. Yet at the same time, millions suffer from malnutrition, or face the threat of starvation in regions suffering from drought, war, and/or economic mismanagement. The year 2016 saw the rising of the atmospheric CO_2 concentration above 400 ppm, and was the hottest year since systematic temperature measurements began. Worries are mounting over the effects on sea level of accelerating ice sheet disintegration, and the Great Barrier Reef is experiencing alarming levels of coral bleaching. And yet, despite the overwhelming scientific consensus about human-induced global warming, and the signing of the historical Paris climate treaty in 2015, some governments remain reluctant or even opposed to reduce greenhouse gas emissions.

The impacts of these global events and developments are amplified in coastal zones, where population densities are highest and where landscape and oceanic changes act in combination. Original coastal landscapes have become unrecognizable in merely a few decades due to the rise of coastal mega-cities, mass tourism, fisheries, harbors, land reclamation, land drainage, coastline protection, and agriculture. The growing demand for natural resources and urban space requirements has severe environmental consequences, to the detriment of precious ecosystems. These stresses, coupled with poor waste management, have led to the degradation of coastal surface and subsurface water bodies.

The problems in coastal areas of the 21st century are part of a complex global web of migration, trade and environmental fluxes. The accelerated rise of sea level is just one example of an environmental problem caused at a much larger scale than the coastal water management jurisdictions it will be affecting. The global food trade makes that the demand for products in one area can lead to water problems in another, which can be thousands of kilometres away. Fears over terrorism focuses tourist streams to regions being perceived as safe, leading, for example, to record numbers of people visiting Spain in 2016, a country whose coastal zones were already suffering from water shortages in summer.

Additionally, continental runoff that discharges within coastal zones represents the culmination of processes over significant distances and timescales, and thus coastal freshwater commonly reflects the integration of impacts to surface and subsurface catchments. On top of this, freshwater reserves in coastal areas are particularly vulnerable because of the risk of seawater intrusion, and this requires special forms of water management. The advances of coastal hydrogeology since its inception as a scientific specialization around the end of the 19th century have provided much of the underpinnings that allow sustainable management. Nevertheless, critical challenges remain. This Special Issue brings together a group of 17 papers that provide a sample of the latest scientific advances within the field.

Overview of research

We categorised the articles into three different categories: (i) research of the fresh-saltwater interface, (ii) natural disasters, and (iii) management and measurement.

Research of the fresh-saltwater interface

Werner (2017) proposes three categories for the classification of seawater intrusion: active, passive and passive-active. Parameter combinations are offered to distinguish the transitions from one form to another, and the key characteristics of each type of seawater intrusion (SWI) is described based on the results from numerical simulations. Active seawater intrusion, which arises when the coastal groundwater hydraulic gradient slopes downwards in the inland direction, is the subject of further investigation by Badaruddin et al. (2017). They used numerical modelling to provide the first systematic characterization of active seawater intrusion. Sensitivity analyses highlight the influence of the main hydrogeological parameters on the rate of active SWI, the mixing zone thickness and slope, and SWI response time-scales.

Walther et al (2017) investigate the effect of the representation of the sea-side boundary slope on numerical model results of variable-density flow in a coastal aquifer. The seaside slope has stronger influence on seawater intrusion, submarine groundwater discharge and residence times in aquifers with higher freshwater discharge or dispersion coefficients. The additional effort to implement a sloped sea-side boundary may thus have a significant impact for assessing coastal water resources with computer models, and its influence may be of a similar magnitude as that of other common uncertainties in numerical modelling.

Bakker et al (2017) present an update to a previous analytical solution for estimating the offshore extent of fresh groundwater in leaky aquifers beneath the sea. The new solution offers a wider choice of onshore boundary conditions and aquifer types relative to the original formulae. Python scripts are provided for solving the complex mathematics to encourage wider application of the method.

Levanon et al. (2017) measured the fluctuation of salinity and groundwater level in a coastal aquifer in Israel. They find that the time lag of groundwater salinity with respect to the tide in the open sea is on the same order as the time lag of the water table, but much larger than of the hydraulic head at the same depth. They link the change in salinity to the displacement of water in the capillary fringe, which causes a vertical shift of the water column in the saturated zone.

Natural disasters

Gingerich et al. (2017) use data and modelling to investigate the recovery to potable water quality of the groundwater supply on the atoll island of Guam after a flooding event. They focus in particular on the effect of recharge conditions and on management scenarios following ocean overtopping. Artificial recharge of rainwater is found to be an effective measure to shorten the recovery period. Using a similar combination of data and modelling, Post and Houben (2017) investigate a case of seawater inundation on the island of Baltrum (Germany) following a storm event. The salt flux rates were estimated, along with salinization and freshening mechanisms. Density-driven flow is shown to dominate the overall system behaviour, and unlike Gingerich et al. (2017), it is found that the recharge conditions are of secondary importance only.

Kovacs et al. (2017) report on four years of groundwater level and salinity measurements from cave systems on the Yucatan Peninsula. These are interpreted in the context of climatic drivers and primary controlling factors. Freshwater-seawater mixing is influenced by the scale of precipitation events, with larger storms inducing turbulent mixing. While the tidal signal appears stronger during wet rather than dry periods, tidal pumping effects are suppressed during very large rainfall events. Coutino et al. (2017) also studied Yucatan Peninsula cave systems. They conducted field measurements, laboratory experiments and numerical modelling to explore mixing processes in relation to open sinkholes, and the subsequent propagation of the freshwater-seawater mixture into surrounding cave passages. The mixing that accompanied severe meteorological events (hurricanes) led to unstable salinity stratification for several months. The results indicate that most freshwater-seawater mixing occurs within the open cenotes, rather than within the aquifer system.

Management and measurement

Regional mapping of SWI vulnerability was undertaken by Klassen and Allen (2017) for bedrock island aquifers in British Columbia, considering climate-change related hazards, pumping well distributions, and chemical indicators of SWI. The risk was considered a combination of SWI vulnerability and losses accompanying SWI, where economic loss was based on the cost to replace the water supply and on agricultural impacts. Financial and ecological risk were found to be significantly different.

Goebel et al. (2017) conducted geo-electrical measurements along a 40 km stretch of the Monterey coast and obtained resistivity data up to a depth of nearly 300 m. They interpret the data in terms of groundwater salinity, and provide explanations for the observed variability using known information about geology, groundwater abstraction and recharge. In a similar study, but on a smaller scale, Pauw et al. (2017) used cone penetration test (CPT) data to establish the presence of freshwater in a confined aquifer at the low water line in the intertidal area along the western coast of the Netherlands. The CPTs provide high-resolution vertical data that show the close link between lithological variability and variations in salinity, which illustrates the potential of this technology in studies of beach hydrology elsewhere. Freshwater in the confined aquifer is confirmed at all measurement locations, and its offshore continuation is assessed using the analytical model of Bakker (2006).

Tal et al. (2017) provide an assessment of the effect of fish ponds on the chemical composition of groundwater along the Mediterranean coast in Israel. Besides conventional hydrochemical tools, they use organic matter fluorescence measurements to trace the water emanating from the ponds. The nutrient load to the sea is found to be suppressed by nitrogen reduction by organic matter degradation. Also focusing on nutrients, Wang et al. (2017) studied the groundwater discharge to Daya Bay, China using the radon mass balance method. To increase the accuracy of their estimates, they measured time series and considered the influence of mixing, atmospheric losses, and sediment and tidal transport. The authors conclude that the influx of nutrients may be higher via subsurface than via surface water pathways, which has important consequences for the ecological management of the bay.

Geng et al. (2017) used a numerical reactive transport model to test the influence of various parameters on the degradation of benzene in a synthetic, tidally-dominated aquifer. They find that there can be significant degradation of the benzene via aerobic processes in the unsaturated zone if the capillary fringe is larger. The tidal range was particularly important to the residence time and spatial distribution of the benzene plume, and a higher hydraulic conductivity exerted a key control on the rate of benzene degradation.

The results and interpretations of field measurements from coastal dune freshwater lenses in Northern Italy highlights the impacts of anthropogenic activities (Cozzolino et al., 2017). Comparison of the hydrochemical characteristics of natural and human-impacted lenses shows that lenses are growing in undisturbed sites, while those in areas of fragmented dunes are affected by salinization processes. Replacement of the natural vegetation by pine forest has led to a reduction in recharge and a concomitant decrease of freshwater storage.

Werner et al. (2017) review the available literature to summarise the key processes, investigative techniques and management approaches relevant to atoll island aquifers. The review concludes that the freshwater lenses of atoll islands are particularly challenging to characterise, due to their dynamic nature and often limited available field measurements. Nevertheless, a handful of intensive atoll island investigations, continued over several decades, reveals important insights into freshwater-seawater mixing processes. Difficulties in reconciling field measurements and numerical models, even for well-studied sites, highlights persistent challenges for predicting the future behaviour of atoll island aquifers under increasing threats of over-use, contamination and climate-change impacts.

Summary and outlook

To a certain extent, the contributions received for this Special Issue are a reflection of the current themes and concerns of our globalized world outlined in the introduction section. For example, a number of the papers deal with natural disasters, such as the effect of hurricanes and storm surges on freshwater resources (Coutino et al., 2017; Gingerich et al., 2017; Kovacs et al., 2017; Post and Houben, 2017), which is related to the mounting concerns over future sea-level and climate. Also, a number of papers study anthropogenic contamination (Geng et al., 2017; Tal et al., 2017; Wang et al., 2017), and thereby interlink with the ongoing land use changes driven by economic development and food production in coastal areas. The growing interest in the management of island aquifers, which are especially vulnerable to environmental change, is reflected by the papers by Klassen and Allen (2017) and Werner et al. (2017).

A significant number of the submissions present new field data that show how coastal aquifers respond to forcings, such as recharge events and tides (Coutino et al., 2017; Gingerich et al., 2017; Goebel et al., 2017; Kovacs et al., 2017; Levanon et al., 2017; Pauw et al., 2017; Post and Houben, 2017). Such studies are invaluable, because while our understanding of the groundwater processes has advanced considerably, the interplay of multiple processes operating at the same time under the influence of natural heterogeneity, remains challenging to unravel. Yet, scientific understanding of aquifer systems at the field scale and forecasting changes at a decadal timescale is what is required to support water management. And this is perhaps where some of the most significant future challenges lie. For example, the system behaviour under the effects of pumping, which disturbs complex density-dependent flow systems, is exceptionally difficult to measure. Assessment of acceptable levels of pumping from a coastal aquifer, where “adverse” (considering economic, social and ecological elements) impacts are avoided, therefore remains an elusive endeavour that is compounded by changing attitudes towards sustainability. It is often unclear if present management practices are sustainable in the long-term, and it might be that for some coastal aquifers tipping points exist, beyond which the resource becomes damaged past the point of restoration at a timeframe relevant to human water supply.

The question is not only if we understand the processes in coastal zones well enough to forecast the future threats, but also if we can determine the most appropriate management responses. Groundwater is only a piece of the puzzle of environmental and socio-economic issues in coastal zones (Michael et al., 2017). We notice a general lack of articles that combine social and economic factors with biophysical aspects of coastal settings. Similarly, the interaction between the processes in coastal ecosystems with those in aquifers remains an area worthy of further research attention. Fundamental hydrogeological research remains essential, but when conducted in isolation, will not be enough to address future societal needs under projected climate change impacts and population rise, amongst other global stressors.

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