Biogeochemical Consequences of Seawater Intrusion into Coastal Aquifers

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EXTENDED ABSTRACT

Coastal populations are expanding rapidly, while potable coastal water supplies are decreasing due to sea water intrusion into coastal aquifers. This is a global problem that affects almost all coastlines of the world. Although over-pumping of coastal aquifers is the primary cause of sea water intrusion, several other factors must also be considered. Sea level rise, drainage of coastal wetlands, replacement of permeable surfaces with hard surfaces (roads, parking lots, buildings, etc.), dam construction, breaches of confining layers by coastal dredging and pilings all contribute to sea water intrusion.

This talk is not about potable water supplies. Instead I will focus on some of the biogeochemical consequences of sea water intrusion into coastal aquifers. I will discuss how replacing fresh water with sea water in coastal aquifers changes the biogeochemical reactions that occur within these systems. Finally I will show that these aquifers, which we call subterranean estuaries, exchange reaction products with the coastal ocean. The flow into the ocean is called submarine groundwater discharge (SGD).

During the past 15 years there has been considerable new research on SGD (e.g. Moore 2010). Investigators in this field recognize that SGD is not simply fresh groundwater flowing into the ocean, but represents mixing of salt water and freshwater in coastal aquifers, accompanied by biogeochemical reactions. To emphasize the processes of salt water-freshwater mixing and reactions with aquifer solids, these coastal aquifers are called subterranean estuaries (Moore 1999). Fluids in subterranean estuaries are enriched in the products of these biogeochemical reactions, including nutrients, carbon, and metals (Moore 2010). Thus, SGD transports these products to surface estuaries and the coastal ocean. There are over 100 studies of the role of SGD in supplying nutrients, carbon, and metals to coastal waters; most conclude that SGD is a more important source of these materials than local rivers (Moore 2010).

As salt water intrudes into coastal aquifers, the subterranean estuary expands inland. For example in the early 1900's there was a 100-500 m zone of brackish water at the base of the Biscayne aquifer in southern Florida (Barlow and Reichard 2010). By 1946 canals had been installed to drain the coastal wetlands. The zone of brackish water in the aquifer moved inland 2-16 km, primarily beneath the canals, increasing the size of the subterranean estuary along this 25 km coastline from ~20 to over 120 km^2 (Barlow and Reichard 2010). Subsequent canal construction through 1995 did little to change the extent of seawater intrusion because the early canals removed most of the standing water. This example has been repeated along coastlines worldwide.

Replacement of permeable sediments with hard surfaces has a similar effect to wetland drainage. To control the water that accumulates on such surfaces, storm drains are required to channel the water. As surface water is directed to storm drains and to the ocean, surface water infiltration is reduced and groundwater levels decrease, leading to sea water intrusion.

Industrial use of groundwater places a major demand on coastal aquifers. For example prior to October 1962, the Upper Floridan aquifer below the city of Brunswick, GA, had a head of +3 to +5 m. In 1963 a paper mill began pumping about 1.4 x 10^5 m^3 freshwater day^{-1} from the aquifer. Within 14 months the head in the aquifer had dropped to -3 m (Wait and Gregg 1973). Within 30 years a 5 km^2 subterranean estuary developed beneath the city, rendering the city wells non-potable due to 1-2.5 g/L chloride concentrations (Joiner 1991).

Depletion of groundwater has accelerated during the past 50 years. For example prior to 1950 less than 1 km^3 yr^{-1} of groundwater was pumped from the U.S. Gulf and Atlantic coastal plains; by 2008 this had increased to almost 9 km^3 yr^{-1} (Konikow 2011).

Salt water intrusion along the coastline of the Laizhou Gulf in Shandong, China, covered a total area of 16 km^2 in 1979; by 1989, the salt water intrusion area became a continuous zone covering an area of 238 km^2 (Xue et al. 1993). By 2009 the extent of salt water in the aquifer reached 4200 km^2 (Cao 2012). During the past century these examples have been repeated with similar consequences along most populated coastlines of the world. There is no doubt that the subterranean estuary is rapidly expanding inland as freshwater in the aquifer is replaced by salt water.

The subterranean estuary is a distinct coastal environment. It contains a mixture of sea water and fresh water out of contact with the atmosphere, but in intimate contact with aquifer solids. These solids often contain organic carbon, both ancient and recent. During sea water intrusion, solids that have not been exposed to sea water for thousands of years are inundated with salt water. The immediate consequence is the desorption of surface-bound ions into the fluid phase. Such things as phosphate, ammonia, barium, radium, cesium, and others are displaced from the solids by the major ions in seawater. A longer term consequence is the oxidation of organic carbon. The most powerful oxidizing agent in most natural systems is oxygen. However its oxidizing capacity is limited by its solubility in water, a maximum about 0.28 mmol per liter in most near-surface waters. Once oxygen is depleted, a number of chemical species can serve as electron acceptors to facilitate carbon oxidation. Among these, sulfate ion is the most prominent as its concentration in sea water is about 29 mmol per liter. As SO_4^{2-} is converted to H_2S, S gains 8 electrons; as O_2 is converted to CO_2, it only gains 4 electrons. Thus a liter of sea water has potentially 50 times more oxidizing capacity than a liter of fresh water.

The reaction products of sulfate oxidation of organic matter include both inorganic and organic forms of dissolved N, P, and C as well as sulfide. The ensuing reducing conditions in the aquifer lead to reduction of iron and manganese oxides. This results in increased concentrations of Fe^{2+} and Mn^{2+} as well as other metals, plus the release of ions that were attached to the oxides. As this chemically-altered fluid exchanges into coastal waters, it carries high dissolved concentrations of nutrients, carbon, and metals.

Continued over utilization of fresh water in coastal aquifers and other anthropogenic changes will lead to greater inland expansions of subterranean estuaries. Although sea water intrusion may reduce fluxes of fresh groundwater through SGD, the biogeochemical reactions of the fluids and aquifer solids may increase concentrations of the desorption and oxidation reaction products. Thus, the expansion of the subterranean estuary may lead to greater total SGD fluxes of nutrients, carbon, and metals because the biogeochemical reactions that affect their concentrations may operate over larger spatial scales and affect aquifers that have not been in contact with seawater for thousands of years.

References

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