NAT. CROAT. | VOL. 21 | Suppl. 1 | 80–82 | ZAGREB | September 30, 2012

THE RECENT HISTORY AND FUTURE OF THE SUBTERRANEAN ESTUARY

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During the past century, anthropogenic forces changed the composition of water in coastal aquifers. These changes were brought about by excessive mining of coastal groundwater, dredging and pier construction, wetland draining, and hard surface expansion. These forces caused an increase of salinity in the subterranean estuary, which led to a series of biogeochemical reactions. These changes continue today.

Key words: submarine groundwater discharge, subterranean estuary, nutrients

INTRODUCTION

Recently, scientists have recognized that exchange of groundwater between land and sea is a major component of the hydrological cycle. This exchange, called submarine groundwater discharge (SGD), comprises terrestrial meteoric water mixed with seawater that has infiltrated and reacted with coastal aquifers. To emphasize the importance of mixing and chemical reaction, these coastal aquifers are called subterranean estuaries (MOORE, 1999).

REACTIONS WITHIN SUBTERRANEAN ESTUARIES

Any and all flow of water on continental margins from the seabed to the coastal ocean is called SGD, regardless of fluid composition or driving force (BURNETT *et al.*, 2003). A critical aspect of SGD is the chemical reactions, often mediated by bacteria, occurring in subterranean estuaries (MOORE, 2010). The reactions include (1) desorption of ions from adsorbed sites due to increases in ionic strength, (2) dissolution and precipitation of carbonates and other minerals, (3) remineralization of organic matter leading to carbon, nutrient, and metal release, and (4) oxidation-reduction reactions that produce and consume metal oxides, which may release or sequester other ions. It is important to recognize that sea water has a much higher oxidizing potential than does fresh water. Fresh water at 20 °C contains a maximum of ~0.28 mmol O_2 per liter, whereas sea water at the same temperature contains slightly less O_2, but also contains ~9.4 mmol SO_4^{2-} per liter. Thus, seawater-freshwater mixtures in subterranean estuaries have a great potential to oxidize organic carbon and release bound nutrients. These chemical reactions of meteoric and sea water mixtures within coastal aquifers are processes that have been largely ignored in estimating material fluxes between the land and the sea.

EFFECTS OF SGD

Hydrologists are primarily concerned with flux of fresh water due to SGD, as it relates directly to the freshwater reserve in coastal aquifers and salinization of these aquifers through sea water intrusion. Oceanographers are also interested in this question because there may be buoyancy effects on the coastal ocean associated with direct input of fresh water from the bottom. Chemical, biological, and geological oceanographers are more concerned with the material fluxes due to chemical reactions of sea water and meteoric water with aquifer solids, as it relates directly to alteration of coastal aquifers and nutrient, metal, and carbon inputs to the ocean (and in some cases removal from the ocean). The strongest evidence that SGD is a globally important process comes from the distribution of chemical tracers in the ocean. These tracers originate within coastal aquifers and reach the ocean through SGD. Tracer studies reveal that SGD provides globally important fluxes of nutrients, carbon, and metals to coastal waters. For example, the total flux of SGD to the Atlantic Ocean, as assessed with tracers, is similar in volume to the riverine flux (MOORE *et al.*, 2008). Because SGD often contains higher concentrations of nutrients, carbon, and metals than river water, it is probably more important in the oceanic budgets of these materials. Local studies have found that SGD provides a major source of nutrients to salt marshes and estuaries. PATAN *et al.* (2006) concluded that nutrient fluxes to six coral reef systems were in the same range as SGD-derived nutrient fluxes to other regions and thus represent a significant contribution of nitrogen to the reef. YOUNG *et al.* (2008) used radium tracers to differentiate two types of groundwater in Celestún Lagoon, Yucatán, Mexico, having distinct chloride, strontium, and sulfate ratios, and slightly different nutrient concentrations.

CHANGES OF SUBTERRANEAN ESTUARIES

During the past 50-100 years, subterranean estuaries have experienced considerable change due to anthropogenic pressure. Damming rivers and draining coastal wetlands have caused upstream migration of the salt front, leading to sea water intrusion into underlying aquifers. Dredging channels and pier construction have breached underlying confining layers and increased contact between surface water and subterranean estuaries. Increased groundwater usage has lowered potentiometric surfaces in aquifers and caused infiltration of seawater into these formations. Similar changes are caused by sea level rise. Expansion of hard surfaces reduces infiltration and channels precipitation into surface runoff rather than into groundwater. Additionally, new subterranean estuaries emerge in the Arctic as permafrost thaws. These processes all cause an increased rate of salinization of subterranean estuaries. Seawater sulfate facilitates a series of biogeochemical reactions, leading to increased concentrations of nutrients, some metals, and carbon (both organic and inorganic). These inland expansions of subterranean estuaries may lead to greater total SGD fluxes of nutrients, metals, and carbon 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.

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