SALTWATER IN COASTAL CAROLINA AQUIFERS

Christopher Paul Foldesi[1], P.G., Richard K. Spruill [3], P.G., PhD, and James K. Holley, P.G[3].

AUTHORS [1]Project Hydrogeologist, Groundwater Management Associates, Inc., 4300 Sapphire Court, Suite 100, Greenville, North Carolina 27834; [2]Associate Professor of Geology, East Carolina University, Greenville, North Carolina 27858; [3]Senoir Hydrogeologist, Groundwater Management Associates, Inc., 4300 Sapphire Court, Suite 100, Greenville, North Carolina 27834.

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Abstract. Groundwater in the coastal aquifers of the Carolinas is the predominant source of water supply for public, agricultural, and industrial purposes. The development of sustainable supplies in coastal areas must consider the position of the boundary between freshwater and saltwater in aquifer systems. This boundary, called the freshwater/saltwater interface, is complex in terms of its position and orientation. As used in this manuscript, saltwater is defined as water that is not fresh and contains chloride concentrations that exceed the Environmental Protection Agency's (EPA) secondary drinking water standard of 250 milligrams/liter (mg/L). Brackish water is defined as water that is not fresh (>250 mg/L chloride concentration) and contains less than 5,000 mg/L of total dissolved solids (Ela, 2007). Water-supply wells have been developed intentionally in both the fresh and brackish portions of coastal aquifers. Many freshwater wells are operated in a manner that does not cause the migration of the interface, but examples of saltwater intrusion abound. The source of saltwater may be fossil groundwater (groundwater with considerable age), modern saltwater from surface water, or a combination of both.

We present case studies of wellfields that are located: 1) initially within the freshwater zone, but are in danger of being contaminated by vertical and/or horizontal saltwater intrusion, and 2) intentionally within the saltwater zone as supplies for membrane treatment plants.

Large-scale withdrawals of groundwater from the Floridan Aquifer System (FAS) at Savannah, GA, have resulted in the reversal of the groundwater flow direction and lowered the hydraulic head across Hilton Head Island, SC. Thin or absent confining beds above the FAS are now conduits for downward migration of saltwater from surface water bodies, most notably Port Royal Sound. A newly discovered plume of saltwater is entering the groundwater system from Broad Creek, threatening the FAS near the center of the island.

Production wells in the Castle Hayne and Peedee Aquifers at Carolina Beach, and in the Castle Hayne Aquifer (CHA) at Topsail Island, NC, have been affected by saltwater intrusion. This is due to their proximity to river channels or intercoastal waterways, where dredging has potentially increased the hydraulic connection between the aquifer and brackish surface water.

Migration of saltwater from a Pleistocene paleo-channel may be responsible for contamination of wells near the west end of Bogue Banks, NC. The saltwater is entering near the up-dip limit of the aquifer in response to withdrawals from the CHA. Near the eastern end of Bogue Banks, saltwater has entered the aquifer from overlying aquifers, and the position of the freshwater/saltwater is inadequately understood.

Water resource developers intentionally targeted brackish portions of Tertiary aquifers at Ocracoke Island, NC, because fresh groundwater supplies were not sufficient for projected demands. Poor water quality and low permeability of major aquifers in the northeastern counties of NC, such as Pasquotank County, have resulted in the development of brackish portions of deep aquifers.

There are many proven management techniques that can be utilized to slow or reverse saltwater intrusion. We present examples of these techniques, including the utilization of brackish water withdrawal wells and Aquifer Storage Recovery (ASR) wells. Proper management of existing freshwater resources should include efforts to balance groundwater withdrawals with the amount of freshwater recharge that is entering the aquifer system.

INTRODUCTION

Saltwater occurs in coastal aquifer systems both as fossil water and as water that has been introduced into the aquifer by human activities. Activities that induce saltwater intrusion include sustained withdrawals of freshwater that exceed natural freshwater recharge, dredging activities that can result in the removal of confining layers that protect aquifers from overlying saltwater, and improper well construction activities that result in inter-aquifer contamination.

Stabilization of a cone of depression resultant from groundwater pumping can only occur when withdrawals from the groundwater system are balanced by an increase in recharge, and/or a decrease in discharge (Theis, 1940). If the new balance has been achieved by increasing recharge from a saltwater source, then any increases in withdrawals from the groundwater system will shift the groundwater system towards non-equilibrium, and the interface will begin to migrate.

Development of coastal aquifer systems as sole sources of water supply for industries and municipalities presents several interesting challenges. First and foremost is the determination of the sustainable limit of withdrawal. The volume of water that can be withdrawn from a coastal aquifer without causing degradation of the water quality in the aquifer should be determined by detailed analysis of hydraulic properties of the aquifer, and by analysis of data regarding the position of the freshwater/saltwater interface, both laterally and vertically. When the sustainable limit of withdrawal is exceeded, changes in water quality can occur, and the damage may be long lasting, if not irreversible.

As treatment technology has evolved, water suppliers seem to have developed the management philosophy that over-pumping of aquifers, and the resulting degradation of water quality in coastal aquifers, are acceptable. It has been deemed acceptable because the technology exists to treat the water after mismanagement has reduced the water quality.

Technological advances in membrane filtration have been impressive in recent years, and we now have the ability to treat saltwater in a more cost-effective manner. While we applaud the advances in technology, we advocate that our fresh groundwater resources should be developed and managed such that withdrawals are in balance with fresh water recharge to the aquifer, and saltwater intrusion is minimized or does not occur. We should not intentionally manage our fresh groundwater resources in a manner that degrades the water quality of the aquifer system, simply because we have the technology to treated degraded water.

BACKGROUND

Saltwater intrusion is an issue for public utilities, agriculture, and industries that rely on groundwater as their primary source of water supply. We provide examples of several different types of saltwater intrusion in the Coastal Carolinas and potential management strategies that can be utilized to make best use of freshwater supplies, while making efforts not to cause further degradation to the water quality of the groundwater system.

Upper Floridan Aquifer At Hilton Head Island, South Carolina. Withdrawals from the Upper Floridan Aquifer (part of the FAS) at Savannah began in the late 1890's, when Savannah stopped using surface water from the Savannah River as a source of raw water supply (Krause and Clarke, 2001). Steady increases in withdrawals occurred in the Savannah area until they peaked in 1988 at 88 million gallons per day (MGD) (Krause and Clarke, 2001).

Significant withdrawals from the Upper Floridan Aquifer at Hilton Head Island began in the 1960s when the Island began to develop as a resort area. Capacity use area regulations developed by the SCDHEC now enforce a 9.75 MGD Island-wide limit on withdrawals from the Upper Floridan Aquifer at Hilton Head Island.

Predevelopment (prior to the early 1900s) equipotential maps published by the United States Geological Survey (USGS) clearly demonstrate that water levels in the Upper Floridan Aquifer were above mean sea level at Hilton Head Island, and that groundwater flowed from the mainland to the northeast end of Hilton Head Island where it discharged primarily at Port Royal Sound (Aucott and Speiran, 1985). The freshwater/saltwater interface in the Upper Floridan Aquifer was located to the northeast of Hilton Head Island under predevelopment conditions. The natural balance between recharge to the Upper Floridan Aquifer and discharge from the aquifer served to establish the position of the freshwater/saltwater boundary offshore.

The high volume of groundwater withdrawn from the Upper Floridan Aquifer at Savannah has created a regional cone of depression that extends over the majority of the Georgia Coastal Plain, extending into northern Florida, and into South Carolina across Hilton Head Island. The cone of depression associated with withdrawals in the vicinity of Savannah is defined as the area under the influence of pumping where water levels have been significantly depressed when compared with pre-pumping water levels.

Saltwater intrusion has been well documented at the northern end of Hilton Head Island since the early 1980s (Burt and others, 1987). Early reports addressed the imbalance in withdrawals at Savannah and indicated that saltwater intrusion was beginning to occur northwest of Hilton Head Island near Pinckney Island and the Colleton River (Counts and Donsky, 1959). Numerous studies have presented detailed information about the saltwater intrusion that is occurring at the northern end of Hilton Head Island, and several computer models have been completed that address the potential for further saltwater intrusion (Burt and others, 1987, Smith, 1993, and Landmeyer and Belval, 1996). Analysis of laboratory samples obtained in the early 1980s from monitoring wells in the Upper Floridan Aquifer at the northern end of Hilton Head Island indicated that chloride concentrations exceeded the secondary drinking water standard of 250 mg/L (Krause and Clarke, 2001). Chloride concentrations have continued to rise in the Upper Floridan Aquifer at Hilton Head Island, and have been recently recorded in excess of 10,000 mg/L at the base of the Upper Floridan Aquifer (SCDHEC, 2005).

More recently, a new plume of saltwater has been discovered in the South Island Public Service District wellfield (Figure 1). The source of the plume is believed to originate beneath Broad Creek, an estuary that bisects Hilton Head Island. GMA fully expects that new plumes of saltwater will appear in the future in the Hilton Head Island area, as long as the conditions which are causing saltwater intrusion remain unchanged.

Castle Hayne and Peedee Aquifers At Carolina Beach, North Carolina. Saltwater intrusion has been recognized in the Carolina Beach wellfield, and chloride concentrations in some wells are close to the secondary drinking water standard of 250 mg/L. GMA has identified a correlation between high pumping rates and increased concentrations in chloride (GMA, 2007). This correlation often suggests that an additional mechanism for saltwater intrusion may include upconing (vertical intrusion) from deeper aquifer zones, in addition to lateral intrusion.

The hydrogeologic framework study developed by GMA, along with recent chloride sampling in the wellfield, indicates that the Cape Fear River is most likely a source of brackish recharge in the southwestern portion of the wellfield. Past and recent dredging activities may be related to saltwater intrusion at Carolina Beach by enhancing the hydraulic connection between the Cape Fear River and the underlying aquifers.

Castle Hayne Aquifer At Bogue Banks, North Carolina. The Castle Hayne Aquifer at Bogue Banks is susceptible to saltwater intrusion at locations where paleo-channels have been incised into the confining layer overlying the aquifer. These areas occur near Bogue Inlet where the Castle Hayne Aquifer, and its overlying confining layer, are relatively shallow. Withdrawals from the Castle Hayne Aquifer have resulted in the downward migration of saltwater where the confining unit is thinned or absent at these locations.

Intentional Development Of Brackish Aquifers. At several locations in the Carolinas, aquifers that are known to be brackish are being developed (e.g., Pasquotank County and Ocracoke Island). In many cases, these aquifers contain fossil water that is brackish. The availability of membrane filtration technology makes the development of these aquifers feasible. In North Carolina, brackish aquifers are being developed in areas where alternative freshwater resources are not available.

MANAGEMENT STRATEGIES

Optimizing Existing Withdrawals. Hydrogeologists have recognized that proper management of groundwater withdrawals in coastal wellfields can minimize saltwater intrusion. The redistribution of withdrawals across a wellfield can reduce cones of depression and inflections on the water-level surface. There is a increased potential for the upconing of brackish water at well locations with the large sustained withdrawals. Such management strategies reduce the potential for localized lateral and vertical saltwater intrusion and extend the life of the wellfield without the need for membrane filtration treatment.

GMA has utilized both hydraulic calculations and three-dimensional groundwater flow modeling to optimize withdrawals from existing wellfields by making recommendations for pumping rates and schedules that minimize saltwater intrusion.

Alternative Brackish Aquifer Development. In areas where fresh groundwater resources are over-utilized, steps must be taken to reduce withdrawals to minimize saltwater intrusion. The identification of alternative aquifers that can be utilized as water resources has the potential to reduce stresses on over-utilized aquifers. GMA has been involved in the development of the Middle Floridan Aquifer at Hilton Head Island. The completion of a new wellfield in the brackish Middle Floridan Aquifer has allowed the Hilton Head Public Service District to reduce its reliance on the Upper Floridan Aquifer, which is vulnerable to saltwater intrusion and significant changes in chloride concentrations.

Barriers to Saltwater Intrusion. The position and movement of the freshwater/saltwater interface in coastal aquifers is problematic for wellfield development. Withdrawal of groundwater from these aquifers can cause a change in flow patterns, and the net result is often the migration of the interface, both laterally and vertically.

One proven strategy for stabilization of the interface is the injection of water into, or the removal of water from, strategic locations near the interface. Withdrawals of saltwater from wells can be used to create a hydraulic divide to halt saltwater intrusion. In many cases, these saltwater withdrawals can be utilized as a resource due to the availability of the economically viable membrane filtration technology. It is also possible to discharge saltwater pumped from aquifers directly to the ocean.

Simply stated, a line of freshwater injection wells, or ASR wells that are properly located can be utilized to inject fresh water inland, of the freshwater/saltwater interface, and locally increase the hydraulic head around and between these wells. This forms a pressure "ridge' (a groundwater divide) that prevents the freshwater/saltwater interface from migrating. Pressure "ridges" using injection and/or ASR wells can be employed conjunctively with pressure "troughs", to provide a double barrier to saltwater intrusion.

Identifying and Abating Local Point Sources of Saltwater Intrusion. GMA is aware that human activities can result in the movement of saltwater into aquifers that are primarily fresh, creating local point-sources of contamination. These activities include dredging and improper well construction. At Roanoke Island, GMA has observed that improper well construction by residential well drillers has resulted in the migration of saltwater from a shallow aquifer downward into a confined fresh aquifer, locally contaminating the aquifer with saltwater. GMA is also aware of impacts from dredging have resulted in the saltwater contamination of previously fresh aquifers. Determining the causes of these types of local intrusions can be difficult, and enacting solutions to local point sources of saltwater intrusion may require local governmental action to protect the fresh groundwater resources. At Roanoke Island, the public water has been provided to residences so that existing private wells could be abandoned.

CONCLUSIONS

Saltwater intrusion is a common problem among coastal communities, and these problems will continue to accelerate as these communities grow. A multi-faceted approach should be used to manage surface water and groundwater resources conjunctively. The utilization of newer technologies such as ASR and membrane filtration (i.e. RO treatment) can provide extended life for existing resources and for the development of new resources, such as brackish aquifers.

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Figure 1: Cross Section Depicting Recent Chloride Contamination at Hilton Head Island