LITERATURE SURVEY OF METHODS TO CONTROL SALT WATER INTRUSION INTO THE FLORIDAN AQUIFER

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Abstract. Under contract to the Georgia Geologic Survey, Golder Associates Inc. performed a literature search to identify methods to control horizontal and vertical salt water intrusion into coastal water supply aquifers. Golder searched databases of scientific, engineering, environmental, social, and water management literature (Dialog), reviewed other reference sources [e.g. SaltNet bibliography and the references listed in Atkinson et al. (1986) and Bear et al. (1999)], searched the Internet for relevant websites, and conducted personal interviews via phone, email, and post. Approximately 5000 literature citations were retrieved that contain variants of the key words "salt water" and "aquifer" or "ground water." These citations were reviewed, cross-referenced with other bibliographic sources, and sorted to produce a list of more than 300 pertinent references, from which 168 titles were selected by the State Geologist for further review. Review of the citations and conversations with experts indicates that some combination of demand reduction, pumping management, and hydraulic barriers are the most commonly employed methods of salt water intrusion control and are most likely to be successful in coastal Georgia. Additionally, desalination is used in a variety of municipal and industrial applications and may be useful in certain situations in Brunswick or Hilton Head Island. Finally, aquifer storage and recovery is being employed in Florida, South Carolina, and other locations, and it should be considered as a potentially useful water supply management tool in coastal Georgia.

INTRODUCTION

The Georgia Department of Natural Resources Environmental Protection Division (GAEPD) has identified intrusion of salt water into the Upper Floridan Aquifer as a significant environmental and economic concern. In April 1997 GAEPD published the *Interim Strategy For Managing Salt Water Intrusion in the Upper Floridan Aquifer of Southeast Georgia.* The primary goal of this strategy is to stop intrusion of salt water before municipal wells in Hilton Head and Savannah are affected and to prevent the salt water contamination problem in Brunswick from worsening. Additionally, it initiates a process for water supply planning in a 24 county coastal region. The target date for issuing the final salt water intrusion management strategy is 31 December 2005.

In August 1997 a technical working group composed of industry, regulatory, municipal, environmental, and academic representatives issued *Recommendations of the Upper Floridan Technical Advisory Committee to the Joint Senate-House Ground-Water Study Committee regarding Scientific Studies and Costs to Protect Coastal Georgia From Salt Water Intrusion.* These recommendations described a comprehensive scope of work for scientific studies needed by GAEPD to develop the final strategy for protecting the Upper Floridan Aquifer from salt water intrusion.

BACKGROUND

Three aquifer systems are used as groundwater sources in the coastal area of Georgia: the surficial aquifer, the Upper and Lower Brunswick Aquifers and the Upper and Lower Floridan Aquifers. The Upper Floridan is one of the most productive aquifers in the United States and is the principal source of water for all uses in coastal Georgia. In 1987, ground water withdrawals in coastal Georgia totaled about 321 Mgal/d, almost all of which came from the Upper Floridan Aquifer (Peck et al., 1990).

As early as 1905, State Geologist S. W. McCallie noted that groundwater withdrawals had suppressed the potentiometric surface in the vicinity of Savannah and Brunswick, noticeably reducing the flow from deep artesian wells penetrating Eocene rocks (McCallie,

1908). Due to lowering of the potentiometric surface, modern ocean water is laterally intruding into the upper Floridan Aquifer at the northern end of Hilton Head Island, South Carolina and migrating toward Savannah, Georgia. Modeling by the U.S. Geological Survey indicates that Upper Floridan wells in Savannah could be contaminated by saline ground water in 100 to 300 years (Krause, 1999).

Salt water has moved upward into the Upper Floridan Aquifer in Brunswick, Georgia, most likely through nearly vertical faults that have breached the underlying confining units. The source of the saltwater is the Fernandina permeable zone, which is below the Lower Floridan Aquifer and has a chloride concentration of about 30,000 mg/l. Upper Floridan ground water within a 5 square mile area in the City of Brunswick has a chloride concentration above 250 mg/l, with a maximum of approximately 2000 mg/l (Clarke et. al., 1990).

APPROACH

Consistent with the recommendations of the Upper Floridan Technical Advisory Committee, in March 2000 Golder Associates Inc. (Golder) was contracted by the GAEPD Geologic Survey Branch (GGS) to perform a literature review of engineered and non-engineered methods to control salt water intrusion. The intent was to provide the GGS with a bibliographic source for relevant information that could be reviewed by other researchers. Therefore, the work did not include actually reading all selected references or determining the most effective methods of controlling salt water intrusion.

In order to identify information sources for methods of controlling salt water intrusion, Golder searched databases of scientific, engineering, environmental, social, and water management literature; reviewed published bibliographies; searched for relevant Internet sites; interviewed individuals; and examined other resources:

- Citations of interest were extracted from the bibliographies and abstracts of Atkinson et al. (1986) and Bear et al. (1999), the two most recent comprehensive reviews of salt water intrusion research.

- The library of the U.S. Geological Survey (USGS) Water Resources Branch in Doraville, Georgia was examined for relevant reports. Pierre Lacombe provided a list of USGS publications pertaining to New Jersey and containing the key words "saltwater" or "chloride."

- SaltNet (http://www.ce.udel.edu/faculty/cheng/saltnet/index.html), a scientific resources network for saltwater intrusion and coastal aquifers maintained by Dr. Alexander Cheng of the University of Delaware was searched.

- A Golder librarian searched the Dialog on-line databases for variants of the key words: "salt water" or "sea water" plus "aquifer" or "ground water." Dialog is the world's largest on-line provider of science, technology, and business information. Golder performed a comprehensive search of 27 engineering, environmental, business, and social sciences databases, including:

  NTIS
  EI Compendex
  Environmental Bibliography
  Water Resources Abstracts
  WATERNET
  GeoRef
  Wilson Applied Science & Technology Abstracts
  Dissertation Abstracts Online

- Golder attempted to identify relevant sites on the worldwide web. Four Internet search engines were queried for key words including variants of "salt water" combined with variants of control method key words.

- More than 150 persons were identified as potentially being knowledgable about projects or methods of controlling salt water intrusion. Most of these individuals were listed in the SaltNet directory or were referred by other contacts. A questionnaire was submitted to each person in the SaltNet directory. Other persons were contacted by phone, including persons associated with organizations known to be involved in the control of salt water intrusion (e.g. Orange County, California; South Florida Water Management District; South Carolina Department of Health and Environmental Control; Savannah Water and Sewer Authority; and the U.S. Geological Survey).

LITERATURE REVIEW RESULTS

More than 10,000 citations were identified from the various sources. Eliminating duplicates and preliminary screening by a technical reviewer yielded approximately 5000 references. Cross-referencing the bibliographies of Atkinson et al. (1986), Bear et al. (1999), and SaltNet and then carefully screening the titles and keywords for relevance to control methods yielded 344 references which were then sorted by method and geography. Typically, rejected references were purely theoretical modeling studies, were hydrogeologic or geochemical descriptions of salt water intrusion in a particular aquifer, were very general in nature (e.g. national study plans), or pertained to salt water intrusion into surface water systems. Dr. William McLemore, State Geologist, selected 168 literature citations for further review. Keywords, abstracts and other readily available information were examined and the references were sorted according to their direct applicability to salt water intrusion management in coastal Georgia. 43 references appear to be directly applicable, with the remaining references being of lesser interest.

Overall, the literature on salt water intrusion is abundant, but only about 10 to 20 per cent addresses methods of controlling salt water intrusion into coastal water supply aquifers. The quality of the information included in the literature is difficult to determine, since only titles and/or abstracts were reviewed. In fact, many of the retrieved abstracts appear to have been written by independent contractors rather than the authors, and they demonstrate a lack of first-hand familiarity with the subject.

The titles and abstracts did not always allow the specific method of salt water intrusion control to be determined. The greatest number of references were sorted into a general category of "coastal aquifer management," which includes papers focused on coastal ground water resource management as well as papers that discuss multiple methods of salt water intrusion control. Some articles appear to be useful for providing an understanding of how to design control systems (e.g. extraction or injection barriers). A few articles apparently provide a discussion of economic and legal issues. Few references were identified that seemed to be specifically focused on controlling vertical salt water intrusion, although additional sorting by the key word "upconing" might prove useful.

Most references pertaining to the southeastern United States refer to Florida. There are few references for Georgia, and these are focused on water resource management rather than specific methods of controlling salt water intrusion. The literature for California projects (Water Factory 21, Oxnard Plain, Orange County, Los Angeles County, Ventura County, Northern California) is quite extensive.

The Internet search using the Google (www.google.com) search engine located 3,585 references. The website references were not reviewed or screened after the initial search.

At least 37 individuals responded to email, phone, or post inquiry. Useful insight came from academic researchers (e.g. Dr. Jacob Bear of Technion University, Israel), consultants (e.g. Dr. Abraham Mercado), water system operators (e.g. Bert Stakelbeek, Provincial Water Supply Company of North Holland), and government scientists (e.g. Michael Bennett, South Florida Water Management District). The respondents' information was often not apparent in the literature search results produced by other means, particularly for projects that have only recently been initiated (e.g. aquifer storage and recovery in South Carolina).

SUMMARY OF SALT WATER INTRUSION CONTROL METHODS

Many methods of controlling salt water intrusion have been proposed or employed (Table 1). The most widely utilized strategies are demand reduction, pumping management, and hydraulic barriers created through various methods of artificial recharge and pumping. Desalination and induced recharge are utilized, as well. Aquifer storage and recovery is widely used as a water management tool, although more frequently as a means of meeting peak demands rather than specifically to combat salt water intrusion.

Locations where salt water intrusion control measures have actually been implemented and reported include Florida, South Carolina, California, New Jersey, Israel, The Netherlands, and Japan. Much of the salt water intrusion control in south Florida consists of controlling water levels in canals in order to prevent sea water from extending inland and contaminating the surficial Biscayne Aquifer. Orange County, California is the site of one of the best-known salt water intrusion control schemes. The Orange County Water District injects treated water from Water Factory 21 into the ground to form a hydraulic barrier to salt water drawn inward by pumping of the municipal well field. In addition, treated water is allowed to recharge the aquifer by percolation from large ponds. In South Carolina, the southern end of Hilton Head Island is

Table 1. Summary of Salt Water Intrusion Control Methods

Category	Control Method
Non-engineered Prevention	
	conservation/reduced pumpage
	leak control
	financial incentives/disincentives
	variable water rates
	pumping pattern management
Engineered Prevention	
	relocated wells - same aquifer
	relocated wells - alternative aquifer
	increased surface water use
	passive aquifer recharge
	active aquifer recharge
	induced recharge wells
	hydraulic barriers
	physical barriers - in aquifer
	electrical barriers
	saltwater interception
	flownet modification
	combined extraction/injection
	aquifer storage/recovery
Utilization of Contaminated Water	
	scavenger wells (skim freshwater from contaminated aquifer)
	desalination
	use of brine in salt-tolerant industry

supplied with water pumped from the Cretaceous Aquifer that has been desalinated.

The literature and personal contacts suggest that some combination of demand reduction, pumping management, and injection are likely to be important components of a salt water intrusion management program in coastal Georgia. Additionally, desalination may be useful in Brunswick or for treating surface water from the lower reach of the Savannah River. Additional work will be necessary to determine how injection would be best utilized in Georgia: whether for aquifer recharge, creating a hydraulic barrier, altering flowpaths, or as part of an aquifer storage and recovery scheme.

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