GROUNDWATER AND SALT WATER MODELING IN COASTAL AREAS

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Abstract. Coastal aquifers are susceptible to a variety of salt water intrusion forms, including lateral intrusion, upconing, and downward infiltration of brackish water. Recent advances in the development of practical integrated groundwater models now make it possible to simulate these forms of salt water intrusion in support of coastal water supply planning and coastal aquifer management programs. Three dimensional groundwater flow models, dual phase sharp interface intrusion models, and single phase contaminant transport models are being successfully applied around the country to meet regulatory permit requirements, and to develop coastal groundwater management plans.

BACKGROUND: COASTAL WELL ISSUES

Fresh groundwater is an important source of drinking and industrial water for coastal communities. In many cases, it is the only viable source of drinking water locally available, and must be protected from the threat of contamination caused by salt water intrusion. Fresh groundwater has a slightly lower density than salt water. As the fresh groundwater system onshore meets the saline groundwater system offshore, the point at which they meet is defined as the salt water interface (Fig 1). Because of the differing densities of the two fluids, the two systems tend not to mix, except for a relatively thin zone of transition. Usually, the location of the interface is stable relative to the shoreline. Under certain conditions, however, it begins to move landward. This landward movement of the interface is known as salt water intrusion.

Salt water intrusion takes several forms. Horizontal intrusion occurs as the saline water from the coast slowly pushes the fresh inland groundwater landward and upward. This type of intrusion can be regional in scale, and results in the characteristic "wedge" of salt water at the bottom of an aquifer above an aquitard. Its cause can be both natural (due to rising sea levels) and man induced (pumping of fresh water from coastal wells, see Fig. 1). Pumping from coastal wells can also draw salt water downward from surface sources such as tidal creeks, canals, and embayments (Fig. 2). This type of intrusion is usually more local in nature. It typically occurs within the zone of capture of pumping wells where significant drawdown of the water table causes induced surface infiltration. A third type of intrusion is called "upconing". Upconing also occurs within the zone of capture of a pumping well, with salt water drawn upward toward the well from salt water existing in deeper aquifers. This form of intrusion resembles an inverted funnel, hence the name "upconing" (Fig. 3).

Long range planning in coastal areas is still the exception rather than the rule. This may be partly due to a lack of understanding of the mechanism of salt water intrusion. In many coastal areas, the onshore and offshore aquifer systems are highly stratified, with thick, confining units creating deep, confined aquifers. The existence of such confining units can result in large amounts of fresh water trapped in confined aquifers up to several miles offshore. This represents a remnant of conditions during earlier Ice Ages, when the coast was exposed during times of significantly lower sea levels. At the present sea level, this water will slowly be replaced by salt water, a process that can take tens of thousands of years under natural conditions. Pumping along the coast accelerates the process significantly. What many coastal suppliers fail to fully understand, however, is that a significant portion of the water they are withdrawing comes from this trapped, offshore fresh water. As water is withdrawn, it is replaced by salt water. By pumping along the coast, they are, in essence, mining offshore fresh water. Coastal suppliers can often withdraw water from wells under these conditions for many years, even decades, before the offshore supply of fresh water is exhausted. Once this occurs, however, the wells begin to withdraw saline water, and chloride concentrations usually rise rapidly to concentrations approaching those of sea water.

APPLICABLE MODELING APPROACHES

The aquifer system and the behavior of salt and fresh water is highly complex. For this reason, practical approaches to modeling and analysis rarely attempt to simulate fully three-dimensional, density-dependent miscible fluid flow in a porous medium. Rather, a number of simplifying assumptions are made to enable reasonable but practical solutions that can quantify the relationships, increase our understanding of the mechanism of intrusion, and make reasonable predictions about the response of the system to future conditions. The most important assumption concerns the ability of the fresh water and the salt water to mix. Under many coastal conditions, these two fluids can be considered as immiscible, separated by a sharp interface or boundary. This assumption of a sharp interface has been used successfully in many studies, and significantly simplifies the mathematical formulation describing the physical process (Reilly et al, 1985).

Fully three dimensional models of salt water intrusion, effective use of available analytical approximations of salt water upconing, and innovative use of particle tracking contaminant transport models can be combined to provide very effective planning and permitting tools for coastal water suppliers and regulatory agencies. These tools are particularly effective when fully integrated as a set of interrelated models.

Three dimensional, sharp interface salt water intrusion models are an ideal tool to analyze the long term sustainability of coastal wells. These models can provide insight into the horizontal advance of wedges of salt water under the influence of both sea level rise and coastal pumping. They can help estimate the rate at which fresh water is being withdrawn from offshore sources, and, provided that some information is available on the location of the offshore interface, can make accurate projections of the rate and timing of salt water advance. In this way, the long term viability of coastal well fields can be assessed, and future plans for alternative sources or treatment can be developed in a timely fashion.

In analyzing upconing of salt water, the existence of salt water in aquifers below the pumping wells is usually already documented. In this situation, it is important to calculate the maximum sustainable pumping rate that avoids salt water upconing, or to calculate the timing of eventual upconing and the expected levels of chlorides in the wells. Both sharp interface and advective transport models can be applied to this problem.

Single phase contaminant transport models are very useful in analyzing the interaction between saline surface water and groundwater where surface salt water could be drawn downward toward pumping centers from canals, bays, or tidal creeks and rivers. In this case, the water is often just brackish, and its density is not significantly different from that of the groundwater. Advective transport and dispersion then become the primary mechanism of transport towards the well, a situation that can be effectively and efficiently simulated by particle tracking codes.

Ideally the models selected should be fully integrated. The model grid, stratigraphy, hydraulic parameters, and boundary conditions developed for the flow model should be directly available for use in the single phase contaminant transport model and the dual phase, sharp interface salt water intrusion model. This is one of the most important features of the DYN-SYSTEM (CDM, 1995) models described in the case study below.

CASE STUDY

The case study presented here involves a water supplier with numerous water supply wells located along the coast of the Florida Panhandle in both Walton and Okaloosa Counties (Fig. 4). The Floridan Aquifer System in this area of the Florida Panhandle consists of several aquifers and aquitards. The surface aquifer is called the Sand and Gravel Aquifer. Beneath the surface aquifer is a thick confining unit called the Intermediate Confining Unit, consisting of clayey quartz sand and clayey limestone deposits. The Floridan Aquifer is the main water bearing aquifer throughout much of Florida, and consists of medium to highly permeable limestone formations. The Floridan aquifer is divided into the Upper Floridan Aquifer and the Lower Floridan Aquifer. The Upper Floridan Aquifer presently provides all the potable water for the water supplier, as well as all the other municipalities in the area. As a result, the potentiometric surface in the Upper Floridan Aquifer has been drawn down in some areas to more than 100 feet below mean sea level (msl). Below the Upper Floridan Aquifer is another thick confining clay unit called the Bucatunna Clay, followed by the lower Floridan Aquifer. The lower Floridan Aquifer contains saline water, and is unfit for water supply purposes without use of desalination treatment techniques.

The study was designed to serve two purposes. The first purpose was to help the supplier make decisions about the long term planning of their water supply in the face of steadily increasing water demand. The supplier was considering two basic options to increase capacity (see Fig. 4). The first was to drill deeper through the Bucatunna Clay into the Lower Floridan Aquifer within existing well fields located on the coast, supplementing supplies with brackish water in combination with reverse osmosis (RO) treatment. The second option was to develop a new well field 10 miles inland, tapping the high quality water of the Upper Floridan Aquifer and piping it to the coastal service area. In both cases, some difficult questions about potential salt water intrusion had to be answered.

Option 1: Coastal Lower Floridan Well and Reverse Osmosis Treatment

In the case of the proposed Lower Floridan coastal well in combination with RO treatment, the question was not one of capacity, but of the long term quality of the water and the associated costs of treatment. To assess this, a deep test well was drilled at the proposed location, and both pump tests and water quality sampling were performed. Water quality in the proposed zone of production at -900 feet msl was brackish, with a chloride concentration of approximately 1800 ppm. The costs associated with RO treatment were reasonable. This, however, did not address the question of the long term viability of the well. As chloride concentrations increase, the costs associated with RO rise, and the well becomes a less attractive option. To assess this possibility, a test boring was advanced deeper into the Lower Floridan Aquifer, and water samples and cores were taken at deeper intervals. At -1200 feet msl, chloride concentrations were 9000 ppm. Water samples at a depth of -1450 feet msl showed chloride concentrations of 18,000 ppm.

Clearly the decision on the viability of the well field would be determined by the potential for upconing of salt water into the well, and the expected time it would take for upconing to occur. Initially, an analytical or hand calculation solution to the problem was applied (Schmorak and Mercado, 1969) to assess whether salt water upconing was a possibility at this location. The analytical solution results, although necessarily using simplifying assumptions about the stratigraphy, suggested that pumping at 500 gpm or more would cause upconing of salt water into the well, probably within 10 years of the start of pumping. These results warranted a more sophisticated approach.

A three dimensional groundwater model (using DYNFLOW code) was developed using a radial grid. The model included all the aquifers and aquitards at the site, with the stratigraphy matching results from the test boring as well as published stratigraphies of the area by the USGS. The model was calibrated by simulating the 8 hour pump test at 250 gpm that had been carried out at the well field, and matching the drawdown measured in the field. In addition, some field data from nearby monitoring wells were available to further check the validity of the model.

Because the DYN-SYSTEM models are fully integrated, the calibrated flow model could be directly used in the dual density mode to make salt water upconing simulations. Using the sharp interface dual density model code DYNSWIM, the model simulated potential salt water upconing of saline water with a chloride concentration of 9000 ppm within one year, and upconing of full sea water within 10 to 15 years.

In order to estimate what chloride concentrations were likely to be once upconing had occurred, the same radial grid model was used in conjunction with the related particle tracking code called DYNTRACK. This was necessary because the sharp interface code cannot simulate the effects of dilution of the salt water with fresh water. The DYNTRACK simulations provided estimates of expected chloride concentration within the well. The results indicated that the salt water entering the well from below would be diluted by fresh water from shallower deposits at a ratio of 5 gallons of fresh water for every 1 gallon of salt water. The results of the modeling analysis led the water supplier to reject this option as too unreliable and potentially costly, and the second option was selected.

Option 2: Inland Wells

The second option was to develop a new well field 10 miles inland from the coast, tapping fresh water from the upper parts of the Floridan Aquifer. This required a consumptive use permit from the Northwest Florida Water Management District (NWFWMD). The permit required an extensive analysis of the potential for salt water intrusion, as well as provisions requiring an analysis of potential impacts to other users and to surface water bodies, creeks, and wetlands.

In order to meet the permit requirements, a regional three dimensional groundwater model was developed that included the Sand and Gravel Aquifer, the Intermediate Confining Unit, the Upper Floridan Aquifer, the Bucatunna Clay, and the Lower Floridan Aquifer. A variable grid spacing was selected. Areas were created with tight grid spacing to allow for simulation of well field drawdowns, movement of the salt water interface, and the interaction of the groundwater and surface water.

The permit requirements necessitated the use of three different codes. The first code, DYNFLOW, is a finite element groundwater flow model code. This code was used to calibrate the model and to simulate the proposed well field pumping, using projected pumping rates for the years 2000, 2005, 2010, 2015, and 2018. The model results showed that extensive declines in heads within the Floridan Aquifer would occur, but that the Intermediate Confining Unit was effectively protecting the surficial aquifer from pumping induced water table declines. Minimal impacts to surface water features were simulated.

In order to fulfill permit requirements regarding potential impacts to the movement of the salt water interface, the full model was also run using the DYNSWIM sharp interface salt water intrusion code. Using information gathered by the USGS and the NWFWMD, the location of the 250 ppm isochlor was plotted. This line was then used to set an initial position and elevation of the salt water/fresh water interface. The DYNSWIM model simulated the coming 50 year period, using successively higher pumping rates as projected by the water suppliers and the NWFWMD. The model results showed that the interface would advance landward under the projected pumping rates at less than 300 feet per year. Although this is a fairly slow advance, it does represent a significant increase over the less than 1 foot per year advance under natural conditions. Because of its location and the relatively slow advance of the interface, eventual impacts to

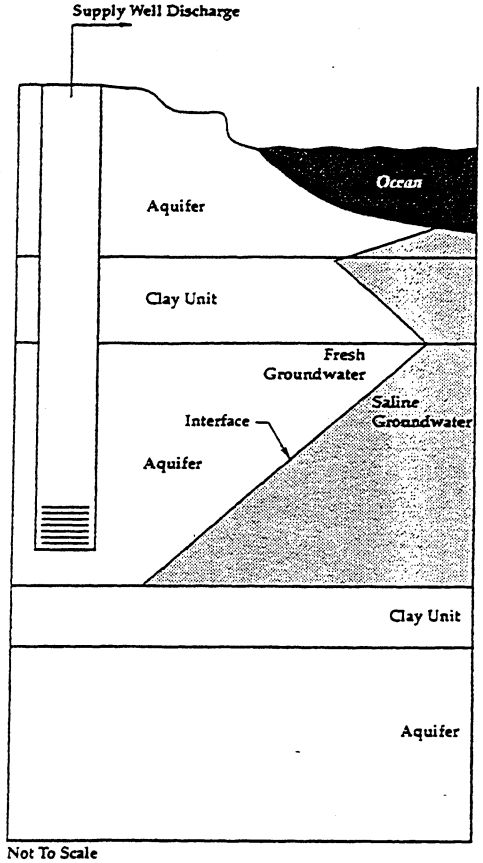

Figure 1. Horizontal salt water intrusion towards a supply well.

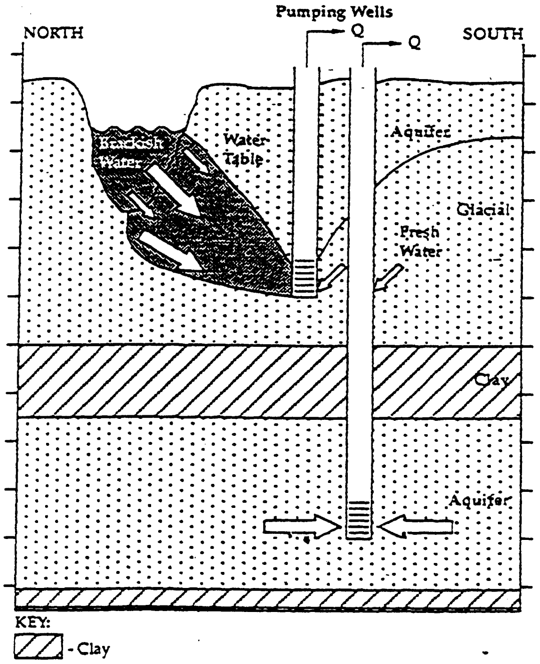

Figure 2. Induced downward movements of brackish water in creeks.

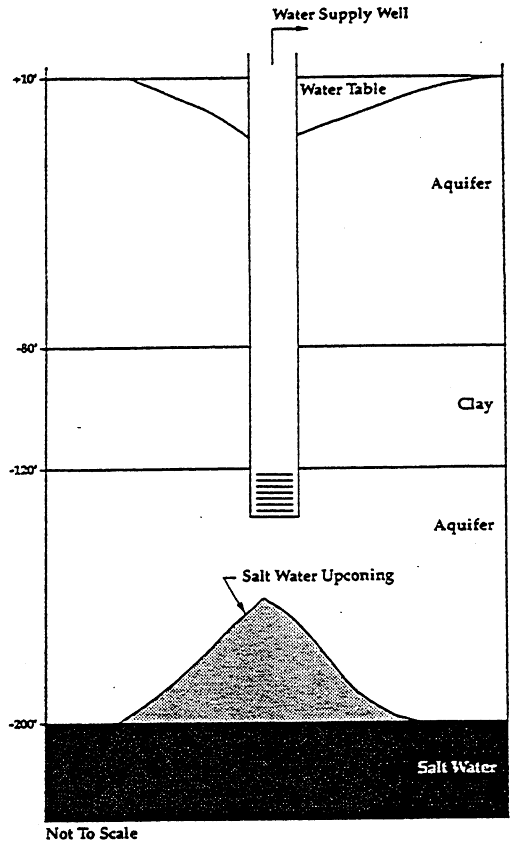

Figure 3. Salt water upconing beneath a supply well.

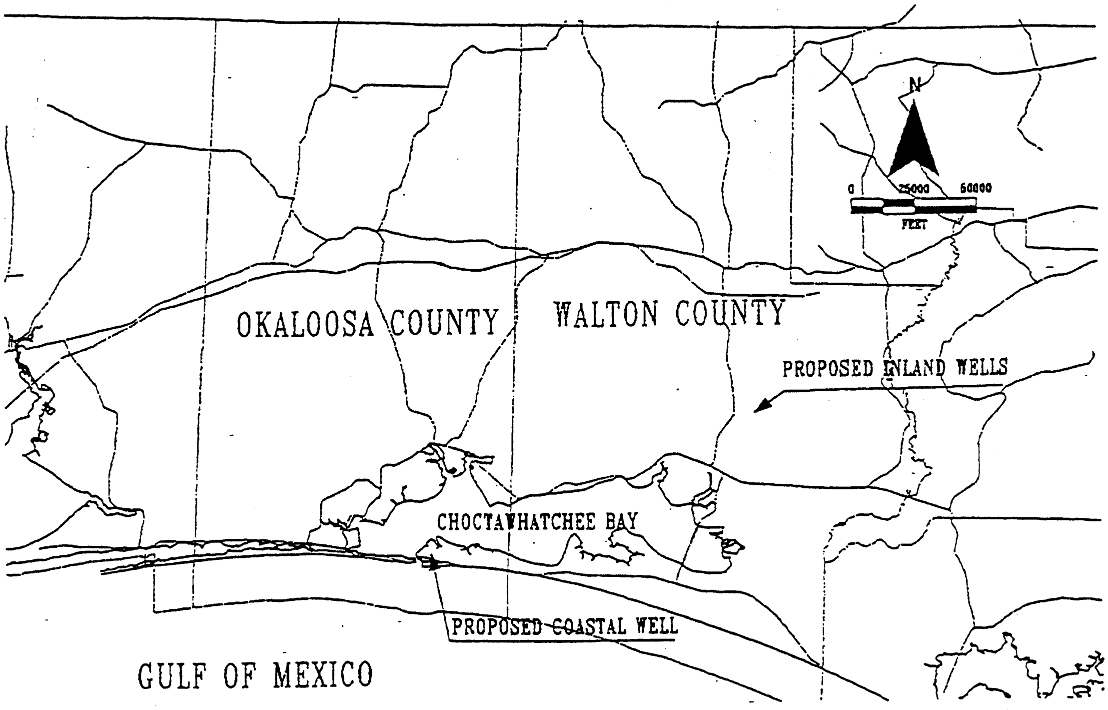

Figure 4. Case study location map.

the well field were found to be unlikely.

Additional requirements of the permit included the development of water balances showing the impacts of pumping on the flow of both fresh and salt water through the entire aquifer system. In order to show that pumping would not cause downward migration of brackish water from nearby creeks, the same basic model was again used, this time using the particle tracking code DYNTRACK. Chloride concentrations representative of the brackish water found in the nearby creeks were simulated along the creek bed, and the groundwater model was run at maximum projected pumping rates. The simulations clearly showed that, even under maximum pumping conditions, the groundwater system continues to discharge to the creeks, and no downward leakage of brackish water from the creeks would occur.

CONCLUSIONS AND RECOMMENDATIONS

Water supply wells located in coastal areas are often tapping water that was trapped offshore during periodic ice ages thousands of years ago. As coastal communities grow, pumping of coastal wells often draw the potentiometric surface of confined aquifers below mean sea level. Aquifers cannot sustain situations where heads in the fresh water system are close to or below mean sea level without eventually losing wells to salt water intrusion. This situation has been identified by the Georgia Environmental Protection Division (EPD) as occurring at several locations along the Georgia Coast, and the EPD has embarked on a coastal groundwater management program as a response.

The Georgia EPD, working with the United States Geological Survey, is developing a *Strategy for Managing Salt Water Intrusion of the Upper Floridan Aquifer*. The strategy calls for intensive field studies, water supply management plans for coastal counties, and a large scale groundwater modeling program. Computer simulation of salt water intrusion will play an important part in the development of an effective strategy. Based on the experience in a similar situation in Florida, numerical simulation techniques and modeling approaches such as those described in this paper could serve as the basis for similar efforts in Georgia.

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