First International Conference on Saltwater Intrusion and Coastal Aquifers—
Monitoring, Modeling, and Management. Essaouira, Morocco, April 23–25, 2001

Effective Modeling of Coastal Aquifer Systems

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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 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, radial upconing models, and single phase contaminant transport models are being successfully applied to meet regulatory permit requirements, to develop coastal aquifer management plans, and to support water supply planning.

This paper discusses salt water intrusion modeling and its successful application for both water supply planning and consumptive use permitting. A case study is discussed to highlight some of these techniques in a project situation. The study highlights salt water intrusion modeling for a water supply company in the western part of Florida. Relying on wells located along the coast of the Gulf of Mexico tapping the limestone formations of the Floridan Aquifer, the supplier is vulnerable to both lateral salt water intrusion in the Upper Floridan Aquifer, as well as upconing of salt water from the saline Lower Floridan Aquifer. The Northwest Florida Water Management District (NWFWMD) required extensive, regional groundwater flow modeling, sharp interface salt water intrusion modeling, and the development of well field specific upconing models to support an application for a new well permit. An integrated suite of models was used to assess the threat to the coastal wellfield, to locate potential new well locations, and to provide the required estimates of the vulnerability of the selected new wellfield sites to eventual salt water intrusion.

BACKGROUND: COASTAL WELL ISSUES

In many coastal areas, groundwater is the only fresh source of potable water, and must be used in a responsible manner. Coastal aquifers are subject to contamination from the same types of surface sources that potentially threaten all groundwater systems, however, they also must be protected from the unique threat of salt water intrusion. Fresh groundwater has a slightly lower density than salt water, and floats on top of salt water. 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.

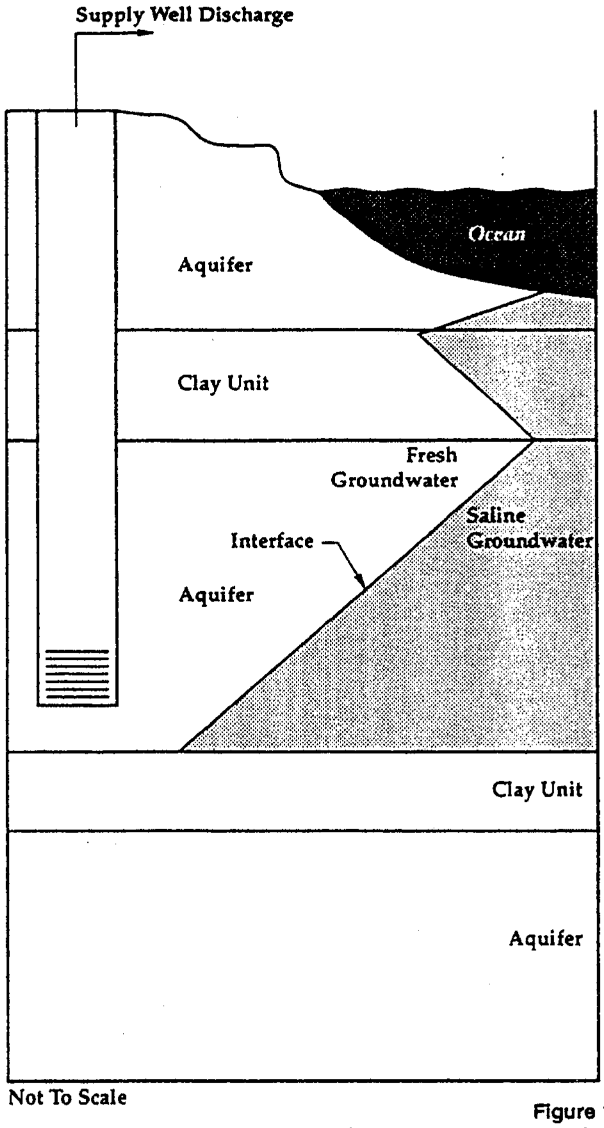

Figure 1
Horizontal Salt Water Intrusion Towards A Supply Well

Salt water intrusion takes several forms. Horizontal intrusion, shown in Fig, 1, 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). Pumping from coastal wells can also draw salt water downward from surface sources such as tidal creeks, canals, and embayments. This type of intrusion, shown in Fig. 2, 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.

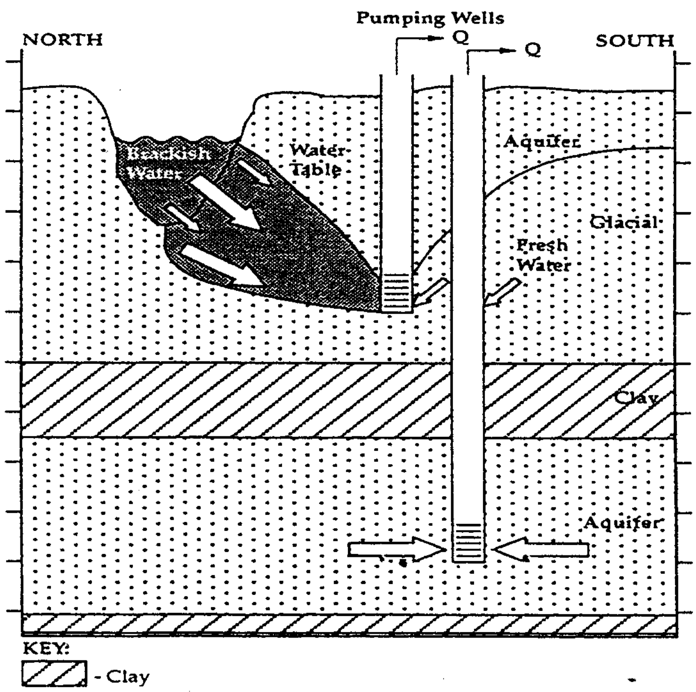

Figure 2
Induced Downward Movements Of Brackish Water In Creeks

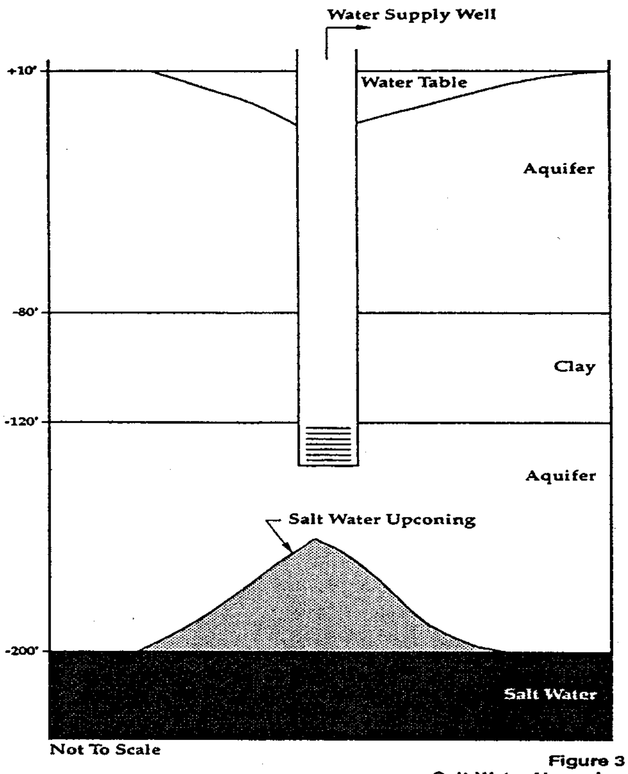

Figure 3
Salt Water Upconing Beneath A Supply Well

A third type of intrusion is called “upconing”, and is shown in Fig 3. 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”.

The threat of salt water intrusion of coastal well fields is recognized throughout the US, but surprisingly, water suppliers and regulatory agencies have been relatively slow to react. Long range planning in coastal areas is still the exception rather than the rule. Part of the problem may be related to lack of coordination and gaps in responsibility between State Agencies, Water Management Districts, Planning Authorities, and Water Suppliers. But it also may be due to a lack of understanding of the mechanism of salt water intrusion. In many coastal areas, such as along the Gulf of Mexico and the Atlantic coast of the USA, 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. Although at the present sea level, this water will slowly be replaced by salt water, the process 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.

By examining heads along the coast near pumping centers, this situation can be recognized. Heads in the fresh water system are below sea level, yet the wells continue to provide fresh water. Examples of this situation can be seen on Long Island in the deep, confined Lloyd Aquifer, and in Georgia and Florida, where suppliers take water from the confined Floridan Aquifer. 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

One effective and practical approach to modeling salt water intrusion is to apply some simplifying assumptions 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 miscible 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).

In the past 8 to 10 years, successful applications of fully three dimensional models of salt water intrusion, effective use of available analytical approximations of salt water upconing, and more innovative use of particle tracking contaminant transport models have been 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 still avoids salt water upconing, or to calculate the timing of eventual upconing and the expected levels of chlorides in the wells.

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.

Critical to the successful use of these models in helping water suppliers with permit applications, however, is the ability to utilize fully integrated models. In other words, it is critical that the model grid, stratigraphy, hydraulic parameters, and boundary conditions developed for the flow model are also directly available for use in the single phase contaminant transport model and the dual phase, sharp interface salt water intrusion model. By using integrated models, once the flow model has been developed and calibrated, the same model structure, data sets, and boundary conditions are immediately available for use as a contaminant transport model or a sharp interface model with no additional model development costs. This is one of the most important features of the DYN-SYSTEM (CDM, 1995) models described in the case study below.

PERMITTING ISSUES

As awareness and knowledge of the causes and effects of salt water intrusion increase, State and Regional Regulatory Agencies are beginning to develop permitting requirements for coastal well fields that are much more stringent than similar requirements for inland wells. For example, on Long Island, the New York State Department of Environmental Conservation (NYSDEC) has identified those areas of the coast where the aquifer is considered stressed. In these areas, the NYSDEC is routinely requiring additional studies attached to all requests for new well permits, or even for requests to change pumping rates at existing wells. These studies require anything from a simple salt water upconing analysis to an exhaustive study of the response of the salt water interface to the proposed pumping. The same is true for the

Northwest Florida Water Management District (NWFWMD), which issues permits for all public supply wells. Although the language and exact requirements vary from area to area, the major requirements are usually similar. These include:

- analysis of impacts of the proposed pumping on the rate and movement of the salt water/fresh water interface
- analysis of the potential for salt water upconing beneath the well from deeper sources of salt water
- calculations of groundwater flow direction and velocity changes near the interface
- analysis of the potential downward migration of brackish water from tidal creeks and inlets, or from known areas of brackish groundwater nearby

CASE STUDY

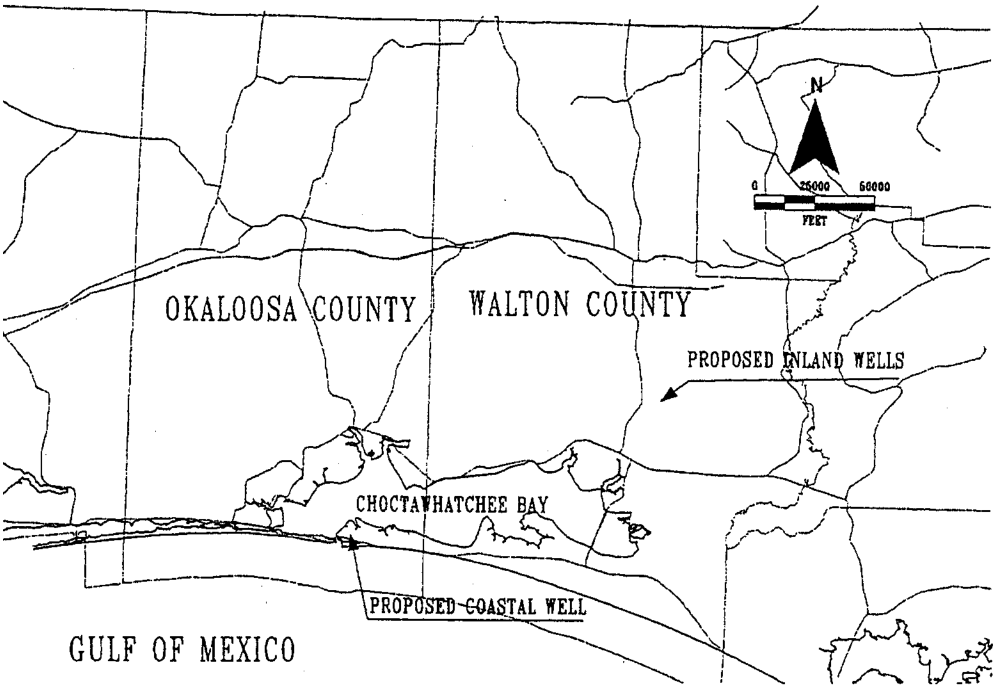

Figure 4
Case Study Location Map

The case study presented here involves a water supplier with numerous water supply wells located along the Barrier Island of the Florida Panhandle in both Walton and Okaloosa Counties (see Fig. 4). The supply wells withdraw water from the Floridan Aquifer, and have been providing high quality drinking water for many years. The Floridan Aquifer System in this area of the Florida Panhandle consists of several aquifers and aquitards, as shown in Fig 5. The surface aquifer, called the Sand

and Gravel Aquifer, is not used as a water supply due to the presence of color and organic matter causing taste and odor problems. Beneath the surface aquifer is a thick confining unit called the Intermediate Confining Unit, consisting of clayey quartz sand and clayey limestone deposits. This unit reaches a thickness of up to 200 feet in some areas, and effectively confines the Floridan Aquifer below it.

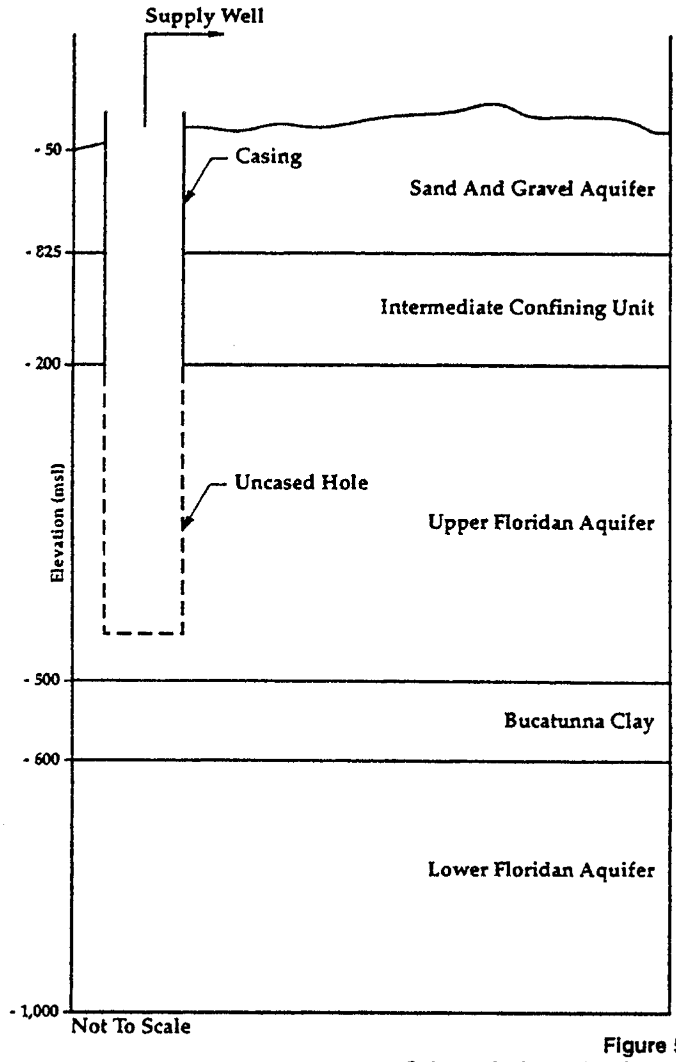

Figure 5
Schematic Cross Section Of
Floridan Aquifer System Cross Section

The Floridan Aquifer is the main water bearing aquifer throughout much of Florida, and consists of medium to highly permeable limestone formations. In this part of the state, 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 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. 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, once again tapping the high quality water of the Upper Floridan Aquifer and piping it across the Choctawhatchee Bay to the coastal service area where it is needed. 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. The pump tests indicated that potential yields were 1000 gallons per minute (gpm) or greater. 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 had risen to 9000 ppm. Between -1200 and -1250, a low permeable unit was found below which the water had a chloride concentration approaching full sea water. 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. Node spacing near the center of the grid where the proposed well was located was only 25 feet, which enabled the model to accurately simulate expected drawdowns due to pumping of the proposed well. 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 USGS and the NWFWMD. A schematic drawing of the stratigraphy is shown in Fig 5. The model was calibrated by simulating an 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. The initial position of the salt water was set at -1200 to -1250 feet msl. A second set of simulations were made with saline water set at a concentration of 18,000 ppm with a starting elevation of -1450 feet msl (see Fig. 6).

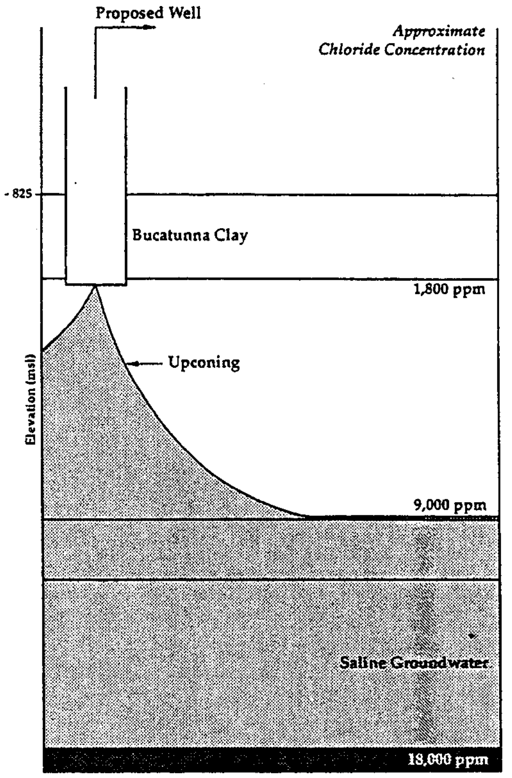

Figure 6
Schematic Cross Section Of
Proposed Well With Available Field Data

Both simulations refined the results of hand calculations, and indicated that rapid salt water upconing would occur at this location. The model indicated that it would only take about 1 to 2 years for the saline water presently at an elevation of -1250 feet to upcone into the well, causing chlorides to rise considerably higher than the 1800 ppm presently encountered. Within about 5 to 10 years, the model simulations showed that the sea water presently found at -1450 feet msl would also enter the well, further elevating the chloride levels.

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. Thus, the ability to use the same basic radial model in both a dual phase sharp interface mode as well as in a single phase particle tracking mode provided a clear picture of the projected timing of salt water upconing and the expected chloride concentrations. 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. In order to carry out this plan, however, a consumptive use permit was required from the NWFWMD. This permit contained provisions requiring 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. 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. Further away from the area of interest, grid spacing was broad, allowing the model to extend out offshore, and to the north, east, and west to suitable, natural hydrologic boundaries.

Once again, the permit required that the model be run using three different codes. The first code, DYNFLOW, is a finite element groundwater flow model code. This code was used to calibrate the model to 1990 conditions and to a well documented, 4 month transient situation where heavy agricultural pumping had caused the Floridan Aquifer heads to decline by over 80 feet during the spring of 1970. It was also used to verify the calibration against predevelopment conditions. Using the calibrated flow model, the model was able 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 continue to advance landward under the projected pumping rates. The rate of advance, however, is still relatively slow (less than 300 feet per year), although this represents a significant increase over the less than 1 foot per year advance under natural conditions. Eventual impacts to the well field are unlikely, or at most, would not occur for more than a century.

Additional requirements of the permit included the development of water balances showing the impacts of pumping on the flow of water through the entire aquifer system. These are shown in Fig 7. By examining overall fluxes of water between aquifers using the groundwater flow model, the fresh water balances could be calculated. Because the salt water intrusion model is essentially the same model as the flow model, the rate of advance of salt water along the interface could also be calculated using DYNSWIM. In this way, the rate at which salt water was displacing fresh water could easily be included in the overall water balance as required in the permit application.

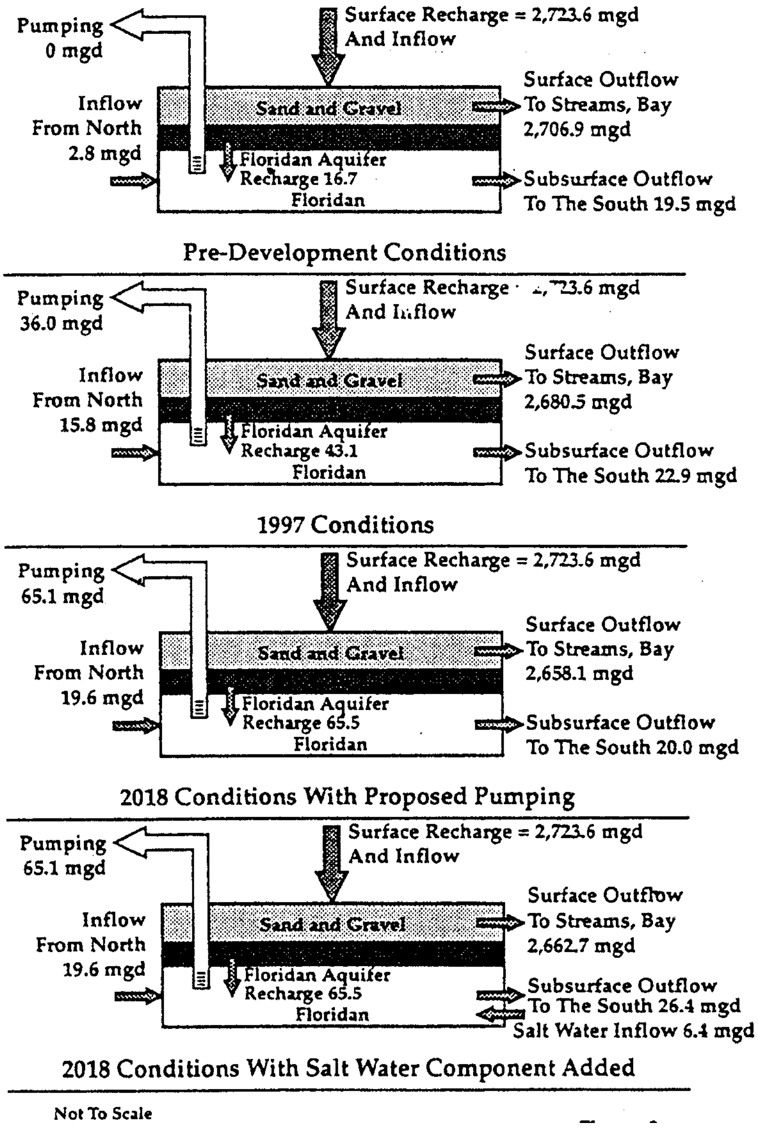

Fig. 7: Water Balances

In order to show that pumping would not cause downward migration of brackish water from nearby creeks, the same basic model was used, this time using the particle tracking code DYNTRACK. Under present day conditions, the creeks act as discharge points for the groundwater system. Thus, fresh groundwater constantly discharges to the tidal creeks, causing them to have somewhat lower chloride concentrations than the Gulf of Mexico. The question posed in the permit was to simulate whether the pumping at the proposed well field would be sufficient to reverse the groundwater flow, inducing infiltration of brackish water into the groundwater system, with subsequent transport to the wells (see Fig. 2). To do this, 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

Water supply wells located in coastal areas are usually an excellent source of drinking water for coastal communities. Wells have often been used, however, with little thought to the source of water that sustains these wells. It is now recognized that many wells are not only tapping water originating from recharge occurring in upland areas onshore, but also water that was trapped offshore during periodic ice ages thousands of years ago. As coastal populations continue to increase, an awareness of the special vulnerability of coastal wells to salt water intrusion has been growing. 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. For this reason regulatory agencies are often requiring much more extensive planning and analysis before granting well permits. Water suppliers are beginning to more effectively weigh their options, asking the right questions about long term sustainability of wells. They are looking to optimize well placement, depth, and pumping rates to minimize salt water intrusion and maximize the return on the considerable investment that a new well often represents.

Fortunately, advances in the numerical simulation of salt water intrusion make it possible to address these important issues. One approach is to utilize a fully integrated set of groundwater flow, contaminant transport, and sharp interface salt water intrusion models such as the DYN-SYSTEM models to help suppliers with long term water supply planning, as well as to respond to the more complex permitting requirements being imposed by regulatory agencies throughout the US.

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Keywords: Sharp Interface Models, salt water intrusion, water supply planning, coastal aquifer management, upconing

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