Alternative Approaches for Water Extraction in Areas Subject to Saltwater Upconing

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ABSTRACT
Upconing of the saltwater interface beneath a pumping well can result when the hydrostatic balance between saltwater and the overlying freshwater is disturbed. The combination of the rate of pumping, the method of extraction, the distance from the intake of the well to the interface, the relative horizontal and vertical hydraulic conductivities of the aquifer, and the longitudinal and lateral dispersivities determine the degree of upconing. The numerical 3D, variable density model SEAWAT was used to simulate alternative methods of groundwater extraction and the resulting upconing. The model is an effective tool for predicting saltwater upconing and selecting appropriate pumping rates and the best method of groundwater development.

INTRODUCTION
Extraction of freshwater in coastal areas can lead to lateral saltwater intrusion and upconing. Lateral intrusion results from the decrease in the flux of freshwater moving seaward and impacts a relatively large area. It can be approximately modeled by simulating a decrease in the amount of recharge instead of modeling the quantity of water withdrawn (Mather, 1975). In contrast, the degree of upconing is significantly influenced by the local method of groundwater extraction. Experience has shown that pumping from a well is more likely to induce saltwater into the well than recovering the same quantity of water from a shallow extraction system (multiple shallow wells or a horizontal trench/drain) that distributes the stresses on the aquifer over a larger area. The purpose of this paper is to demonstrate a means of assessing the degree of potential upconing resulting from different groundwater extraction methods.

METHODOLOGY
The simulation of the impacts resulting from the different methods of groundwater extraction on an unconfined coastal aquifer assumes that the extraction site is located sufficiently far from the coast so the phreatic surface and the saltwater-freshwater interface are essentially parallel, and the geometry of the discharge zone does not affect the model. The less dense freshwater is in hydrostatic balance with the denser underlying saltwater in accordance with the Ghyben-Herzberg relationship. Governing equations for such a condition have been fully addressed by others (Bear, Zhou, and Bensbat, 2004; Bower, Motz, and Durden, 1999; Hamza, 2006; and Larabi, A., 2001) and will not be repeated here.

Qualitatively, the Ghyben-Herzberg hydrostatic relationship holds that one foot of drawdown in a well will result in 40 feet of rise at a sharp freshwater-saltwater interface beneath the well. Assuming adequate aquifer recharge, there is a critical pumping rate below which the upconing of saltwater will not intersect the bottom of the borehole. The total quantity of water that can be pumped from an aquifer is related to the pumping rate, the distance of the intake above the interface, and the horizontal and vertical hydraulic conductivities of the aquifer. The longitudinal and lateral dispersivities also have some impact, but are not as critical (Hamza, 2006). The thicker the transition zone, the less accurate the Ghyben-Hertzberg relationship becomes.

It seems logical that the greater the distance between the bottom of the well and the freshwater-saltwater interface, the less likely it is that the interface will rise to the bottom of the well. However, complications arise when it is considered that as the open portion of the well is shortened, the specific capacity of the well decreases. Therefore, the amount of drawdown per gallon pumped increases, thus increasing the potential for upconing of the interface.

The increase in drawdown at the individual well can be minimized by reducing the withdrawal rate at that well and simultaneously adding additional shallow wells to provide the same total quantity of water. Another alternative is to pump from a long, continuous, permeable subdrain that will skim water from the very top of the watertable with minimal drawdown.

In order to evaluate the optimum method of withdrawal, a numerical model was used to simulate a single deep well, a single shallow well, and a horizontal drain. The simulation considers stratigraphy typical of South Florida, with a moderately permeable sand overlying highly permeable oolitic limestone with an intervening layer of low permeability clayey sand.

MODELING SIMULATIONS

The three-dimensional, finite-difference, variable-density numerical model SEAWAT-2000 (Langevin, 2003) was used to simulate extraction of groundwater from the two wells and the horizontal trench. The general model consists of four layers with varying hydraulic conductivities. Additional layers were included to simulate the shallow well and the trench. The models for the deep and the shallow wells consist of 75 rows and 83 columns. In order to simulate the trench, the number of rows was increased to 119. The model domain is 6,600 meters by 3,800 meters. The row spacing ranges from 1.7 meters to 110 meters and the column spacing ranges from 1.7 meters to 200 meters. The trench model has row spacings that range from 2.2 meters to 110 meters.

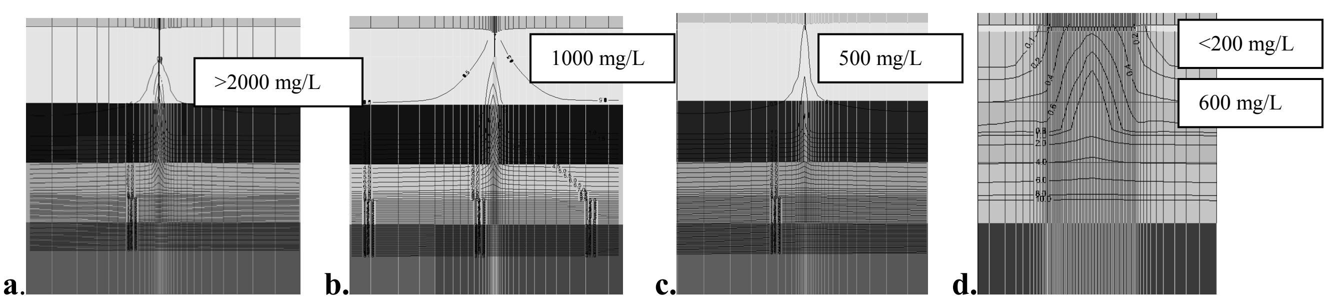
Saltwater and freshwater specified head boundaries were set on the east side and west sides of the models, respectively. The saltwater boundary was assigned an elevation of sea level and the freshwater head was assigned a concentration of zero and an elevation of one meter NGVD. The top and bottom of the model were set at elevations of 3.5 meters and –55 meters NGVD, respectively. The hydraulic conductivities were varied as follows from top to bottom of the models: Kh=25 meters/day (m/d) and Kv=2.5 m/d from 3.5 to -15 meters NGVD; Kh=100 m/d and Kv=1 m/d from –15 to –27.5 meters NGVD; Kh and Kv=0.1 m/d from –27.5 to –40 meters NGVD; and Kh=100,000 m/d and Kv=10 m/d from –40 to –55 meters NGVD. The transition from 500 mg/L total dissolved solids (TDS) to > 30,000 mg/L TDS is approximately 35 meters thick, between -15 and -50 meters National Geodetic Vertical Datum (NGVD). The freshwater in the aquifer occurs in the layer extending from the water table and a depth of approximately –15 meters NGVD. The transition from 500 mg/L total dissolved solids (TDS) to > 30,000 mg/L TDS is approximately 35 meters thick, between -15 and -50 meters National Geodetic Vertical Datum (NGVD). The model was initially run without pumping for 10,000 days until steady state was reached to establish the initial conditions for the transient pumping simulations. A uniform recharge of 0.001 m/day was used. The discharge rate in every case is 384 m^3/day.

The first simulation was constructed with a well that fully-penetrates the aquifer from 3.5 to -15 meters. The second simulation was constructed with a partially-penetrating well extending only to a depth of only –5 meters NGVD. The third model considers a horizontal trench oriented perpendicular to groundwater flow. The bottom of the trench is at elevation –0.5 meters NGVD. The trench measures 183 meter-long by 4 meters wide by 1.7 meters deep and was simulated by two methods. The first method includes 59 wells extracting at 6.51 m^3/day from the aquifer matrix. The second method uses one well extracting 384 m^3/day from a highly conductive series of cells. In the latter case, the trench was assigned a hydraulic conductivity of 10,000 m/day and a specific yield of 1. The transient simulations were subsequently run for 90 days and 900 days. The finite-difference scheme was used to solve the flow equations and the Preconditioned Conjugate-Gradient (PCG2) solver was used for the transport solution of each simulation.

FINDINGS AND CONCLUSIONS

It was found that the 90 day pumping scenario was of insufficient duration to show the impacts from the different extraction methods and demonstrates the need to consider the time required to reach a new equilibrium.

The results of the first simulation (**Figure 1a**) demonstrates that after pumping the deep fully penetrating well for 900 days, drawdown in the well will be approximately 0.9 meters (specific capacity = 427 m^3/day/m), and water containing in excess of 2,000 mg/L TDS will upcone into bottom of the well. The second simulation (**Figure 1b**) shows that after 900 days, the drawdown in the shallow well will be approximately 2.4 meters (specific capacity = 160 m^3/day/m) and water with a salinity of over 1,000 mg/L TDS will still reach the bottom of the well. The third simulation using the horizontal drain will result in less than 0.5 meters of drawdown at the middle of the trench, with less at the ends (**Figure 1c**), and has the least amount of upconing. The salinity of the water entering the trench ranges from less than 200 mg/L TDS at the ends of the trench to approximately 600 mg/L TDS at the center (**Figure 1d**). Assuming complete mixing, water with salinity on the order of 350 mg/L TDS could be withdrawn from the trench.



Fully Penetrating Well **Shallow Well** **Horizontal Drain**

Figure 1.

The concept discussed above was used for an irrigation system expansion located less than 150 meters from a saltwater canal in Naples, Florida. The system had previously pumped irrigation water from an unlined pond that was replenished from a single, 18.3 meter deep well. An increase in the Water Use Permit allocation was requested, but the South Florida Water Management District was reluctant to issue the permit due to the risk of saltwater intrusion and upconing.

As an alternative, a 192-meter long shallow drain oriented perpendicular to the direction of shallow groundwater flow along the upgradient side of the property was proposed. The invert of the perforated pipe in the drain was set at one foot above sea level. Modeling **(Figure 2)** predicted, and experience has confirmed, that the drawdown along the length of the pipe is minimal compared the single well, and the watertable quickly recovers following cessation of pumping. In spite of recent drought conditions, the system has supplied adequate quantities of irrigation water with no indications of saltwater contamination or impacts to nearby wetlands. In contrast, a nearby deep well continues to replenish a similar pond from which irrigation water is withdrawn. The salinity in that neighboring pond is more than double that in the pond with the horizontal drain, even though it is located farther from the sea.

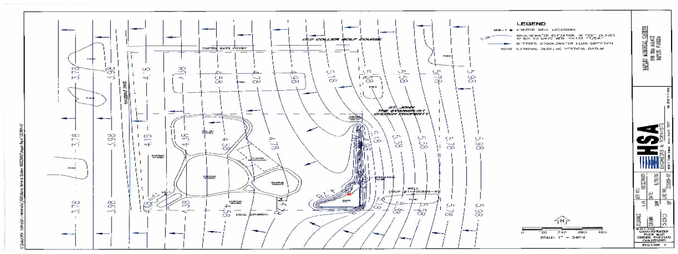


Figure 2.

Where conditions are suitable, large users of irrigation water (*esp.* golf courses, nurseries, subdivisions, cemeteries, etc.) should be encouraged to develop similar approaches to protecting groundwater resources from saltwater intrusion.

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