Quantifying Effects of Natural and Anthropogenic Stresses on Long-Term Saltwater Intrusion in a Coastal Aquifer

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ABSTRACT
A variable-density groundwater flow and solute transport model representing the Pompano Beach area in southeastern Florida was developed to simulate the historical pattern of saltwater intrusion in response to drainage and wetland reclamation, groundwater withdrawals, rainfall, and water-management practices. Simulations of the past century (1900-2005) produce water-quality trends that closely correspond to historical chloride concentrations measured at observation wells. Sensitivity analyses indicate that the position of the saltwater intrusion line is most sensitive to changes in groundwater withdrawals and to decreases in rainfall.

INTRODUCTION
Saltwater intrusion has occurred near the Pompano well field, which is located in northern Broward County, Florida. Identifying the cause of saltwater intrusion in this area is not straightforward due to the complex interaction between various hydrologic stresses. During the past century, for example, sea level has risen and extreme variations in rainfall have occurred. In addition, a century of agricultural and urban development has changed the hydrologic landscape from a system dominated by the freshwater wetlands of the Everglades to one controlled by a highly managed network of canals used primarily for drainage. This development has resulted in inland water levels that are several meters lower than predevelopment elevations. Moreover, current municipal withdrawal rates in Broward County from the shallow surficial aquifer system (SAS) represent a 90-fold increase since the mid-1940s when saltwater intrusion was first recognized as a critical water-resource issue (Renken and others, 2005). Because many of these events overlapped in time, it is difficult to identify which anthropogenic and natural factors have had the greatest influence on saltwater intrusion.

To address these issues, a variable-density groundwater flow and solute transport model was developed to investigate the causes of saltwater intrusion over the past 105 years in northeastern Broward County, Florida (Figure 1). Parameter estimation was used to calibrate the numerical model to water levels and salinities observed in monitoring wells. This paper presents preliminary findings from numerical simulations, including sensitivity analyses designed to quantify the relative importance of natural stresses induced by rainfall and sea-level change, and anthropogenic stresses induced by groundwater withdrawals and canal management.

MODEL DEVELOPMENT AND RESULTS
A variable-density numerical model was developed using the SEAWAT computer code (Langevin and others, 2003). The model is based on many of the assumptions used in other numerical models of Broward County (Dausman and Langevin 2004; CDM/DHI, 2005) and on local hydrologic and geologic data. The simulation period extends from

1900 to 2005; the first 41 years were divided into three stress periods, whereas the remainder of the simulation used monthly stress periods.

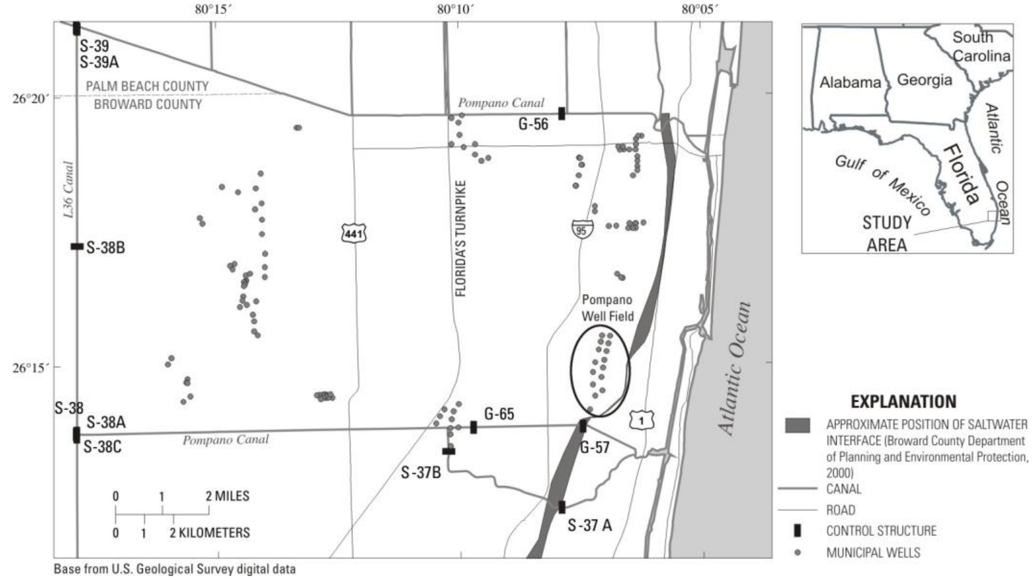

Figure 1. Northeastern Broward County, Florida, showing important hydrologic features and the approximate position of the saltwater intrusion line based on 1994 data.

A uniform finite-difference grid containing 115 rows and 160 columns (150 x 150 m cell size) was used to discretize the study area. The model consists of nine layers of varying thickness that extend from land surface to the base of the SAS. Canal heads were specified using historical field data. Heads used for the Atlantic Ocean were based on historical Atlantic Ocean stage data, which show a gradual increase of 24 cm over the past century. The salinity of the ocean boundary was held constant at 35,000 mg/L. Detailed pumping records were obtained for each municipal well field, and where possible, a time-varying pumping rate was used for individual pumping wells.

The PEST parameter estimation program (Doherty, 2007) was used to calibrate the model to observed heads and salinities. The estimated parameters included horizontal and vertical hydraulic conductivity, effective porosity, specific storage, specific yield, and net recharge. Calibration of the 105-year simulation (described herein as the base historical simulation) produced a reasonable representation of the measured trends in hydraulic head and chloride concentrations. The saltwater intrusion line, defined here as the inland extent of groundwater with salinity greater than or equal to 1,000 mg/L, for the base historical simulation is shown in Figure 2. Model results are generally consistent with historical observations in that the greatest encroachment occurred in the mid-1980s, which coincides with peak rates of coastal pumping and an extended period of drought. The model also captures the seaward movement of the saltwater intrusion line during the early 1990s. The seaward movement of the saltwater intrusion line is due to several factors. Withdrawals at the Pompano well field decreased and were reassigned to a well field located further inland. In addition, canal management strategies were refined to move water into coastal areas and raise the water table. The temporal and spatial extents of saltwater intrusion and subsequent flushing appear to be represented by the calibrated model.

Seven scenarios were performed to quantify the relative effects of sea-level rise, groundwater withdrawal rates, rainfall, and boundary canal levels on the position of the saltwater intrusion line. The scenarios were formulated as follows: no sea-level rise, no groundwater withdrawals, 100% increase in groundwater withdrawals, 16% increase and decrease in rainfall, and 0.5-m increase and decrease in boundary canal levels. Figure 2 presents the results for the scenarios that showed a substantial difference from the base historical simulation. Although results from the other scenarios are not presented here, Zygnerski and Langevin (2007) showed that the combined effects of multiple hydrologic stresses can have a large effect on the position of the saltwater intrusion line. A qualitative comparison suggests that groundwater withdrawals and drought conditions had the largest effect on the position of the saltwater intrusion line over time (Figure 2). For the base historical simulation, the saltwater intrusion line moved inland a maximum distance of about 500 m. For the scenarios with a 100% withdrawal increase and a 16% decrease in rainfall, the saltwater intrusion line moved inland a maximum distance of 2110 m and 710 m, respectively. Conversely, the saltwater intrusion line advanced only 160 m when withdrawals where eliminated altogether.

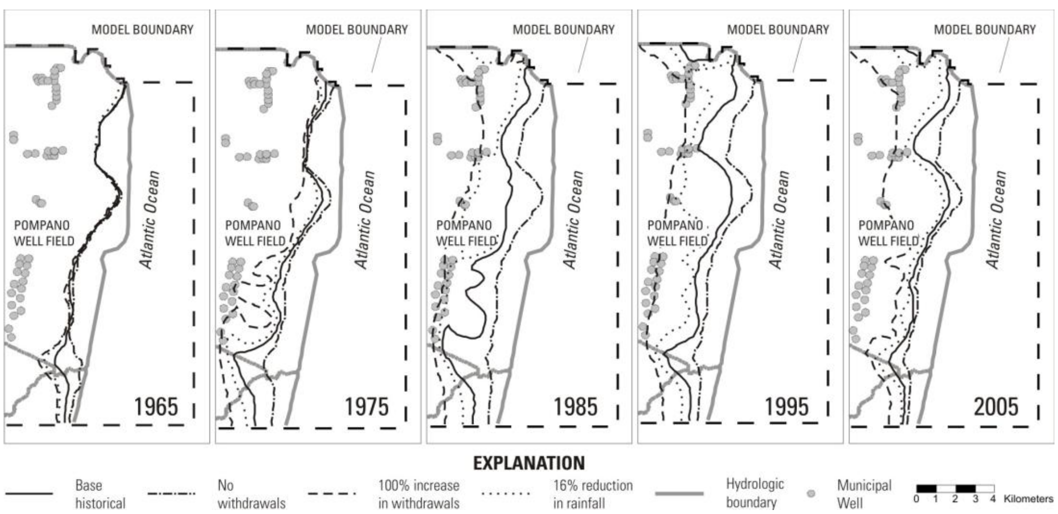

Figure 2. Lines depicting the landward limit of groundwater having salinity of 1,000 mg/L or greater. Lines are for model layer 3, which corresponds to the top of the primary production zone.

CONCLUSIONS

The Pompano well field, located in northern Broward County, withdraws groundwater from the shallow SAS. Chloride data collected at monitoring wells located between the well field and the Atlantic Ocean indicate that the saltwater intrusion line moved inland during the 1970s and 1980s toward the well field and retreated during the 1990s. A numerical model was developed for the northern part of Broward County, Florida, to quantify the effects of natural and anthropogenic stresses on the movement of the saltwater intrusion line in the SAS. Simulations were performed using the SEAWAT computer program, which represents variable-density groundwater flow and dispersive solute transport. The approach used involved calibrating the model to conditions observed over the past century and then using the calibrated model to evaluate the relative importance of selected hydrologic stresses.

When compared with the calibrated model, the hypothetical scenarios provide insight into the relative importance of several hydrologic stresses. Well-field withdrawals and periods with prolonged decreases in rainfall were identified as the factors that resulted in the most noticeable shift in the saltwater intrusion line. Although the decreased rainfall simulation proved to substantially affect the position of the saltwater intrusion line, the increased rainfall simulation did not show a large effect. This difference is probably due to the canal system, which prevents the water table from rising more than it could drop during the decreased rainfall simulation. Another important result is that the 100% withdrawal increase scenario shows the saltwater intrusion line within the well field in 1985 and 1995; however, due to the reassignment of pumping to an inland well field, results suggest that a 100% increase in withdrawal would not cause the saltwater intrusion line to move into the well field under 2005 conditions.

This paper presents an important step in quantifying the causes of saltwater intrusion in northern Broward County. A quantitative understanding of the various causes of saltwater intrusion, their individual effects, and their combined effects is expected to provide a foundation for future management practices of coastal aquifers.

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