Incorporating Surface-Water/Groundwater Interaction in a Texas Central Gulf Coast Water-Demand-Forecasting Flow Model

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ABSTRACT

Previous efforts to simulate regional groundwater flow in the Texas Gulf Coast aquifer did not include explicit representation of streams and their interaction with groundwater, but instead used a model-calibrated effective recharge value. However, historical data indicates a considerable amount of surface water/groundwater interaction throughout the Central Gulf Coast (CGC) region. Using the MODFLOW STR package, streams were incorporated into a recently developed, 24,000 mi^2 CGC groundwater flow model as part of the Texas Water Development Board's Groundwater Availability Modeling initiative. The model will be used to anticipate impacts of future groundwater demands in the CGC region. Parameter values for the STR package were obtained from EPA and USGS data sets. Incorporation of the streams into MODFLOW presented the typical logistical challenges involved with moving large amounts of GIS data into MODFLOW. The stream network provides a mechanism for Theis' "rejected recharge", and reproduces the high level of surface water/groundwater interaction. Fluxes between the streams and aquifer are large, but the net contribution to the aquifer is much smaller. Simulation results indicate that stream/aquifer interaction is a significant component of the groundwater budget in the CGC.

INTRODUCTION

Regional groundwater flow models are important tools for planning future development and anticipating the impact of policy changes and drought. This paper presents a groundwater flow model of the Central Gulf Coast (CGC), developed as part of the Texas Water Development Board's (TWDB) Groundwater Availability Modeling initiative. Final TWDB approval of the model is pending: results presented should be considered preliminary and may change. The model includes representation of the stream network. This work presents the model and examines the impact of historic changes in groundwater pumping and the impact that incorporating streams might have on the overall water budget. The results demonstrate the benefits of, (1) explicitly accounting for streams in a system with a high level of stream/aquifer interaction, and (2) careful examination of the water budget to assess changes in the system with changing stresses.

The CGC aquifers simulated in this work are part of the Gulf Coast aquifer that forms a wide belt along the Gulf of Mexico from Florida to Mexico (Figure 1). The Miocene and younger sediments have a southeast regional dip and increase in thickness downdip. Four hydrogeologic units have been identified: three aquifers, from the surface downward, the Chicot, Evangeline and Jasper, respectively, and the Burekville confining unit between the Evangeline and Jasper (Baker 1979; Carr et al., 1985; Ryder and Ardis, 1991). All four aquifers outcrop, with the Chicot covering more than half of the model domain. The conceptual model consists of higher recharge rates in the updip forcing flow down dip and deeper into the system. As flow continues downdip it eventually encounters the salt-water interface and is forced towards the surface.

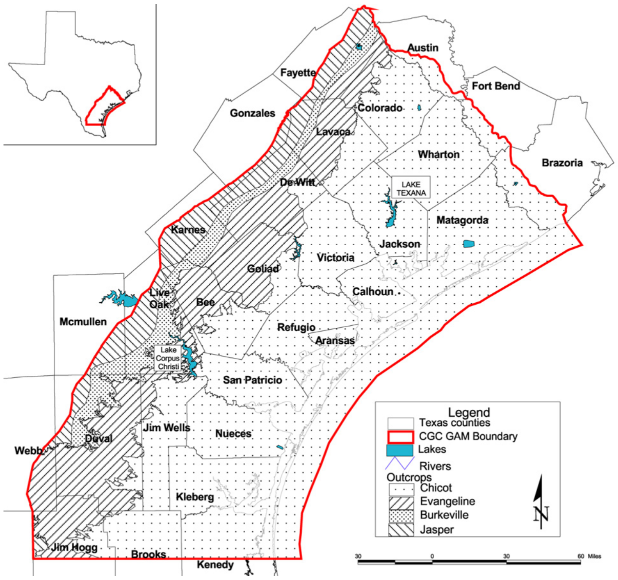

Figure 1. Aquifer outcrops of the Texas Central Gulf Coast Aquifer.

The CGC aquifer is an important source of groundwater to industry, municipalities and agriculture in the Texas CGC. The surface of the CGC is primarily flat, low-lying coastal plains that rise inland to low rolling hills. Annual mean precipitation increases from southwest to northeast (22.5 - 55 in) due to the prevailing weather patterns along the CGC. Precipitation varies throughout the year with typically dry winters, moderately wet springs, dry summers and moderate to very wet falls. The net recharge to the CGC aquifer is a combination of recharge, associated with precipitation, and the net contribution from streams. Most of the streams follow the general direction of the shallow structural dip, flowing primarily from the hills along the northwest boundary to the coast along the southeast boundary (Figure 2). Upper reaches tend to be more incised within valleys between the uplands. Previous work (e.g., Brune, 1981; Slade et al., 2002) has documented considerable surface water/groundwater interaction. Slade et al. (2002) compiled measurements of stream/aquifer interaction and found that the interaction varies dramatically with location. For example, measured values along a study segment of the Colorado River fluctuate between gaining and contributing considerable amounts of water to the Chicot Aquifer and that, with time, baseflow supplied to streams has decreased. These temporal changes are supported by the general trend in declining water tables and spring flows (Brune, 1981).

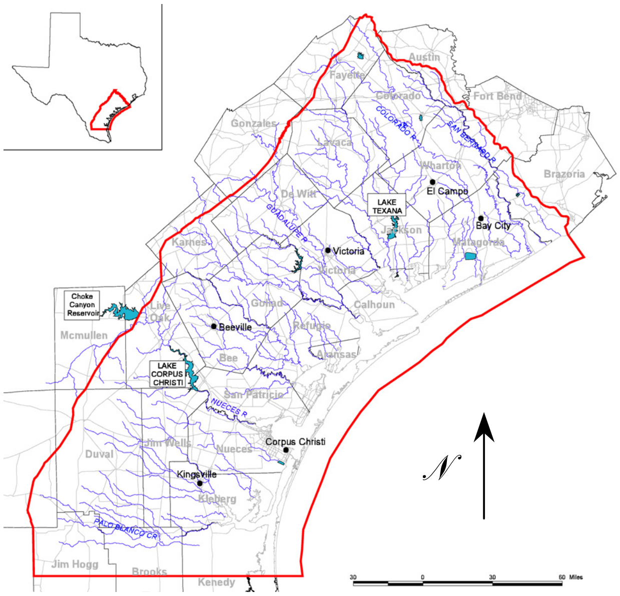

Figure 2. Streams of the Texas Central Gulf Coast.

Previous regional models include the Region N model developed by Hay (2000) and the USGS Regional Aquifer-System Analysis (RASA) model (Ryder and Ardis, 1991). The Region N model provided steady-state simulation of the CGC region, using constant head boundaries along the updip limit of each aquifer to represent recharge into the system. The RASA model covered a much bigger region, had a 5-mile square grid, used a model-calibrated net-recharge value, and provided insight on the mechanisms of subsidence and saltwater intrusion, the most dramatic impacts of which occurred beyond the extent of the CGC. This work presents a CGC groundwater flow model that, in an effort to provide an improved water resources planning tool, incorporates explicit representation of the stream network allowing the evaluation of changes in stream/aquifer interaction. Direct comparison of results to previous models was beyond the scope of this work and would not have been practical because of differences including model grid size and stress representation, and access to simulation results.

METHODS

Model Overview

The groundwater flow model MODFLOW96 (Harbaugh and McDonald, 1996) was used to simulate groundwater heads and flow. The grid had one-mile square cells, with 269 columns and 177 rows. Four layers were used to represent the three aquifers, and the confining unit. The model had a total of 56,736 active cells. The updip limits of the formations provided no-flow boundaries to the northwest. Regional flow lines along the northeastern and southern boundaries made no-flow boundaries a reasonable choice along those borders. General head boundary cells in the top layer were used to represent discharge along the coast. The model was first evaluated for predevelopment conditions: conditions prior to 1940, which was prior to the onset of significant pumping. Transient, stressed conditions from the 1980s were used for the calibration period, and data from the 1990s was used for the verification period.

The TWDB supplied data on groundwater use, whenever possible collecting actual pumping-rate data. However, one of the primary uses of groundwater in the CGC is agricultural. Typically, pumping for agricultural purposes is not metered. As a result, a large proportion of the pumping rates were estimated using information such as land use and land cover. Historical precipitation and temperature data were combined with surface soil data to calculate recharge. Surface soil properties and precipitation patterns resulted in recharge generally increasing towards the updip, and the northeast, respectively. Calculated recharge rates were within the range of estimated and measured recharge summarized by Scanlon (2002). The present work used either an effective recharge, recharge minus evapotranspiration (ET), or only incorporated ET drawn directly from groundwater: an amount much smaller than total ET.

Incorporating Streams

The MODFLOW Stream (STR) package (Prudic, 1989) was used to represent rivers and streams in the model. Streams represented using the STR package can gain and contribute water to the aquifer, and can go dry depending on the stream stage, streambed conductance and adjacent-aquifer water levels. The network of more than 4300 miles of streams in the CGC region was defined based on the Reach File version 1.0 (RF1) database developed by the United States Environmental Protection Agency (USEPA, 1998). RF1 includes definition of the upstream-downstream connections for all streams contained in the database.

Streambed conductance is a critical parameter in determining the amount of interaction between the stream and aquifer. In general streambed conductance is highly variable, and there are considerable differences between the scale at which streambed conductance is typically measured and the scale at which it is applied in a model (Rosenberry, 2002). These facts make it extremely difficult to obtain conductance data for a large regional model. This work, and previous modeling efforts in the CGC area that incorporated streambed conductance (e.g., Dutton 1994), used values of hydraulic conductivity of the outcropping aquifer and adjusted conductance values as part of the calibration process (Dutton, 2002). Using a GIS, streams in the CGC were associated with model grid cells and their length in each cell calculated and combined with width and streambed hydraulic conductivity to produce streambed conductance. Streambed elevation was obtained from the digital elevation models (DEM): the minimum elevation within each cell was used as an approximation for the streambed elevation in each model cell. The resulting stream profile was then checked for any uphill stream segments: segments that gained elevation moving downstream. Uphill segments, typically artifacts of roundoff or DEM resolution, were flattened by replacing their streambed elevation with the adjacent upstream streambed elevation.

Temporal variations in streamflow were incorporated using stream-gage data for the calibration and verification periods. For each stream gage at each stress period, the measured value was compared to the RF1 mean stream-flow value. The ratio of the measured to the mean value was used as a deviation coefficient and applied to all stream reaches associated with that gage. Association of stream reaches to individual stream gages was done on the basis of several factors including proximity and watershed.

A global adjustment to streambed conductance was performed as part of the calibration process. The data available was not sufficient to justify adjustment of streambed conductance on per STR-segment basis. While it may have been possible to calibrate streambed conductance for individual segments within the river reaches studied by Slade et al. (2002), this would have produced calibrated values for less than 5% of the streams in the system. In addition, the data reported in Slade et al. (2002) was a composite of different studies performed at various times over a roughly 50-year period.

RESULTS AND DISCUSSION

The results presented focus on general changes in the CGC aquifer between the relatively steady-state conditions that existed during the pre-development period and more recent conditions. The water budget from the pre-development period provides insight to the hydrologic system prior to significant pumping: effective recharge accounts for about 41 % of the flow into the system and streams account for most of the remaining, 86% of the discharge is to streams and 13% flows into the ocean along the coast. Figures 3a and b show recharge, stream and pumping water-budget results for pre-development and 1984. Results from a single year in a transient simulation are not expected to reflect a new equilibrium, but do allow a comparison to the pre-development conditions. The year 1984 was selected because recharge is very similar to the pre-development rate, but pumping was significant. Water budget components not shown changed little, or were relatively small. Declining water levels associated with increased pumping had a considerable impact on stream/aquifer interaction: changes in pumping decreased the amount of rejected recharge, baseflow to streams, or decreased water levels to the point that streams switched from gaining to losing water to the underlying aquifer. These simulation results are generally supported by field observations indicating a general increase in the amount of water contributed from streams (Slade, 2002). The 1984 water budgets indicate an increase in net recharge over the pre-development period because, (1) recharge is virtually the same as during pre-development and (2) streams now have a net contribution to the system (Figure 3b). The total budget, which is not shown, also reflects this change, increasing by 40% over the pre-development amount.

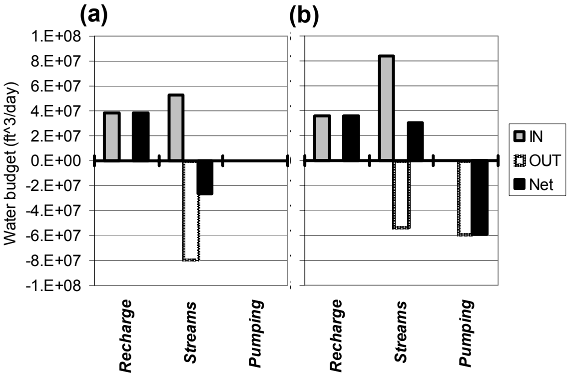

Figure 3. Recharge, streams, and pumping water-budget results for (a) pre-development and (b) 1984. Positive values indicate flow into the model.

The simulation results indicate that the system compensated for the change in pumping from pre-development to 1984, and the calibration/verification periods (1980 - 1999) in general, by increasing net recharge: recharge combined with a relatively small net contribution from storage and the net contribution from streams. The streams provided considerable buffering, decreasing the potential drop in water table by effectively increasing recharge to the system, so that the simulated amount of water taken from storage was relatively small for 1984 and fluctuated during the calibration and verification periods.

Increases in pumping, from pre-development to verification are reflected in the changes in cross-formational flow (CFF) between the Chicot and Evangeline aquifers (Figure 4). Pre-development had a net upward CFF since updip recharge penetrating downdip was eventually forced back to the surface at or before the coast. During the verification period CFF between the Chicot and Evangeline aquifers was reversed: pumping from the Chicot and Evangeline produced a net downward CFF.

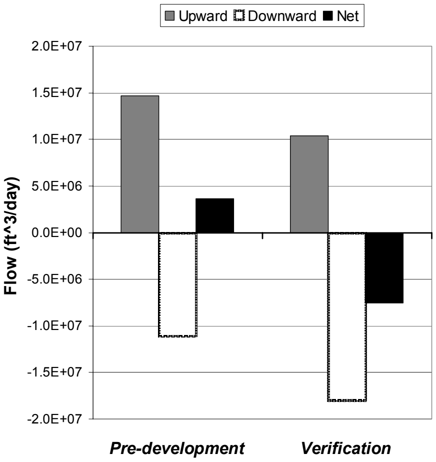

Figure 4. Cross-formational flow between the Chicot and Evangeline.

Streambed conductance was calibrated using a global adjustment that (1) produced reasonable matches between observed and simulated water levels, and (2) attempted to reproduce observed stream/aquifer interaction. Pre-development and verification-period simulated leakage-per-length values are consistent with observed rates in terms of the direction of flow. The pre-development simulated leakages provide a better match to the observed, but the verification values are still within one standard deviation of observations reported by Slade et al. (2002). However, the observed standard deviations are at least twice as large as the average rates of per-length leakage: the measurements provide some good information but they have a large amount of uncertainty, spatial variability and possibly temporal variability. In addition, the limited amount of data precludes adjusting streambed conductance on anything other than a global scale. The global adjustments to streambed conductance provided at least some potential for calibration, while factors such as stream length, width and streambed elevation allow incorporation of spatial variability in stream/aquifer interaction potential.

The results indicate that groundwater resource assessments should include, (1) considering how changes in stresses require boundary conditions capable of adjusting to those changes, and (2) understanding exactly how the groundwater system adjusts to those changes. In the CGC, preliminary simulations suggest that stream/aquifer interaction is a critical component of the water budget, especially as it adjusts to changes in stresses. Without representation of streams, simulation results would have indicated far greater reliance on storage depletion to supplement the pre-development recharge rate and provide sufficient water for the increased pumping. Given the uncertainty of estimating stream/aquifer interaction it is important to acknowledge that the contribution of surface water to the groundwater may be considerably different than these preliminary results indicate. However, regardless whether the supplemental flow is from storage, streams or other sources, the net result is a change in the total budget and the system will continue to adjust towards a new equilibrium that satisfies the existing stresses.

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