Estimation of Groundwater Recharge to the Gulf Coast Aquifer in Texas, USA

Final contract Report to Texas Water Development Board

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US Geological Survey - Sioux Falls, South Dakota

Appendix A

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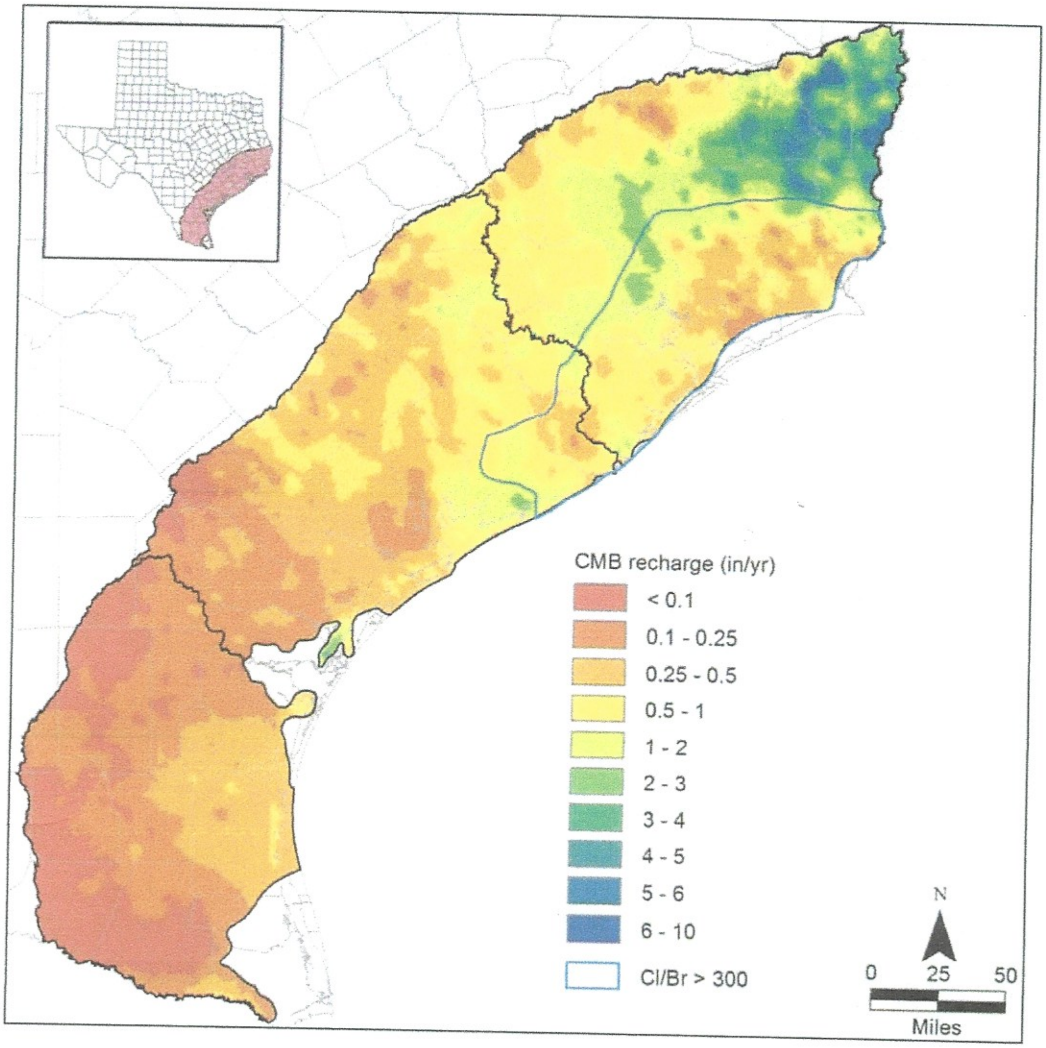

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Texas Water Development Board

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Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin

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Dr. Scanlon was responsible for the introductory material and parts of the methods and discussion. The seal appearing on this document was authorized October 31, 2011, by

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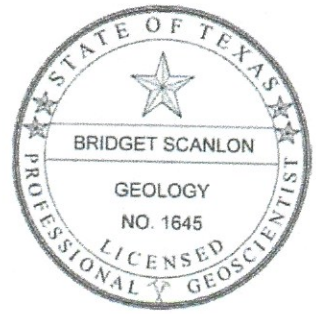

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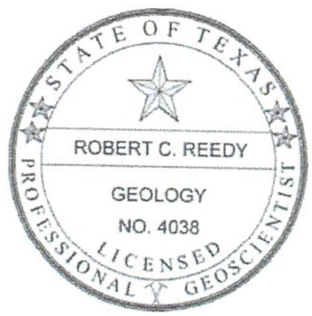
Mr. Reedy was responsible for project field work, data analysis, and parts of the methods and discussion. The seal appearing on this document was authorized October 31, 2011, by

Robert C. Reedy



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Executive Summary

Quantifying groundwater recharge is essential for managing water resources in aquifers. The objective of this study was to quantify spatial variability in recharge in the outcrop zones of the Gulf Coast aquifer in Texas. Regional recharge was estimated using the chloride mass balance approach applied to groundwater chloride data from the TWDB database in 10,530 wells, which represented the most recent samples from wells located in the region. Regional groundwater recharge was also estimated using streamflow hydrograph separation in 59 watersheds using USGS unregulated gage data. Recharge was also estimated by applying the chloride mass balance approach to unsaturated zone chloride data from 27 boreholes that represented a range of precipitation, land use, and soil texture settings in the central and southern Gulf Coast regions.

Groundwater chloride concentrations generally decrease from the southern to the northern Gulf Coast, qualitatively indicating increasing recharge in this direction with increasing precipitation. Ratios of chloride to bromide are < 150 to 200 throughout most of the Gulf Coast, suggesting a predominantly meteoric source for groundwater chloride. Recharge rates based on the chloride mass balance approach range from <0.1 in/yr in the south to 10 in/yr in the north, correlated with increasing precipitation. Stream flow ranges from ephemeral in parts of the southern Gulf Coast to perennial throughout the rest of the Gulf Coast based on flow duration curves. Hydrograph separation using Base-Flow Index (BFI) showed that recharge increased from south to north, similar to increases in recharge based on groundwater chloride data. Unsaturated zone profiles show high local variability in chloride concentrations, with mean concentrations below the root zone ranging from 7 to 10,200 mg/L. Resultant percolation rates below the root zone based on the chloride mass balance approach range from <0.1 to 6.8 in/yr. In some areas, variations in percolation rates are related to differences in soil texture whereas in other regions, they are related to differences in land use. However, there is no systematic variation in percolation rates throughout the region, unlike the trends in recharge with regional precipitation from groundwater chloride data and stream hydrograph separation.

Recharge rates based on groundwater chloride data can be considered to provide a conservative lower bound on actual recharge because many processes can add chloride to the system, resulting in lower recharge rates whereas there are no processes that can remove chloride from the system in the Gulf Coast. Stream hydrograph separation provides recharge rates in contributing basins that do not cover the entire Gulf Coast region. Recharge estimates from the chloride mass balance applied to groundwater and perennial stream hydrograph separation are highly correlated (r = 0.96) and differences between these two sets of recharge

estimates can be used to evaluate uncertainties in recharge rates in contributing basins to the stream gages. Recharge rates from groundwater chloride and streamflow hydrograph separation can be used to provide a range of recharge rates for future groundwater models of the Gulf Coast aquifer.

Introduction

Recharge is critical for estimating groundwater availability. Most models used to simulate groundwater availability require recharge rates as input and often calibrate the models by varying the recharge rates (Chowdhury and Mace, 2003; Chowdhury et al., 2004; Kasmarek and Robinson, 2004). The Gulf Coast aquifer is typical of dipping confined aquifers found along the Gulf Coast. Conceptual models of recharge in these aquifers generally include local and intermediate flow systems in the outcrop zones and regional flow systems into the deeper confined portions of the aquifers, based on Toth's original conceptual model (Toth, 1963). Much of the recharge occurring in local and intermediate flow systems discharges to streams, sometimes referred to as "rejected recharge". The remaining recharge moves downdip into confined aquifers and is sometimes termed "deep recharge".

Recharge can be derived from a variety of sources, including precipitation, irrigation return flow, and stream flow. In the Gulf Coast system, precipitation is the dominant source of recharge in the outcrop zones. Irrigation is mostly sourced by surface water near the Rio Grande and Colorado River, and return flow in these regions provides an additional source of groundwater recharge. Groundwater is also used for irrigation, primarily in Wharton and Matagorda counties near the Colorado River; however, return flow from groundwater-fed irrigation is simply recycling of water. Streams in the southern Gulf Coast are generally ephemeral and recharge the aquifer also.

Primary controls on recharge include precipitation, soil texture, and vegetation. To assess the maximum potential recharge in a region, Keese et al. (2005) simulated recharge using local climatic forcing (1961 – 1990 data) in sandy soil. Because finer textured soils, layering of soils, and vegetation all reduce recharge, omitting these in the simulations should result in the maximum potential recharge in response to climate forcing. Maximum recharge rates ranged from 50% of precipitation in Starr county in the south, 54% in Victoria County in the central region, and 60% in Liberty county in the north. These recharge estimates provide an upper bound on recharge in the system. Adding layered soils based on data from SSURGO reduced these recharge rates as a percentage of precipitation to 29% (Starr county), 10% (Victoria county), and 19% (Liberty county). Vegetation further reduced recharge rates to 5% (Starr county), 3% (Victoria county), and 10% (Liberty county). These simulations provide an indication of the relative importance of different controls on recharge rates. Many studies have shown that cultivating land can exert an important control on groundwater recharge (Scanlon et al., 2007). However, reconstructing past land use is difficult because records generally only extend back to the 1950s or 1960s (National Agricultural Statistics Services, Texas Agricultural Statistics Services).

A variety of techniques are available for estimating recharge. Techniques vary in the space/time scales covered, range of recharge rates that can be estimated, and reliability of recharge (Scanlon et al., 2002). Recharge rates for assessing groundwater availability generally require techniques that cover large spatial scales and decadal timescales. The range of recharge rates that can be estimated using different approaches varies. Depending on the level of *a priori* information on recharge rates in a region, it may be difficult to match appropriate techniques to actual recharge rates and an iterative approach may be required with reconnaissance estimates initially followed by more detailed studies. Recharge estimates based on different techniques vary in the reliability of their estimates. Potential recharge rates can be derived from surface-water and unsaturated-zone techniques, whereas actual recharge rates are based on groundwater data. Techniques for estimating recharge can be categorized as physical, chemical, and modeling techniques, and according to the source of data, including surface water, unsaturated zone, and groundwater (Scanlon et al., 2002). Water budgets are widely applied to develop a conceptual understanding of recharge in a system. However, recharge rates based on water budgets may have large uncertainties. Assuming a simplified system where the components of the water budget can be estimated within ±10% and using the following values results in (P (40±4 in/yr) – Roff (4±0.4 in/yr) - ET (33±3.3 in/yr) = R (3±5 in/yr). This calculation shows that the resultant recharge estimate has an uncertainty of 170%. Groundwater recharge can also be evaluated by examining groundwater discharge as baseflow to streams through hydrograph separation, using codes such as baseflow index (BFI) (Wahl and Wahl, 1995). The reliability of recharge estimates from streamflow hydrograph separation depends on the validity of the assumption that most baseflow equates to groundwater discharge. However, groundwater also discharges through pumpage and evapotranspiration while bank storage and wetlands can also contribute additional flow to the system during low flow periods (Halford and Mayer, 2000). However, previous analyses suggest that recharge estimates based on BFI may overestimate actual recharge rates because of impacts of bank storage (Halford and Mayer, 2000). Groundwater table fluctuations are also used to quantify recharge (Healy and Cook, 2002). The most widely used environmental tracer for recharge estimation is chloride, which can be used with groundwater or unsaturated zone chloride data. However, other stable and radioactive isotopes can also be used. Because recharge is difficult to estimate, it is important to apply as many different approaches as possible to constrain uncertainties.

There are certain issues that should be considered with respect to recharge for groundwater models. Because most groundwater models are only calibrated with hydraulic head data, these models can only estimate the ratio of recharge to hydraulic conductivity (R/K); therefore, reliability of recharge estimates from models depends on the accuracy of hydraulic conductivity data. The entire water budget is important for groundwater availability analysis. In some cases, high recharge rates are simulated during predevelopment, i.e. before large scale pumpage. Heads are matched by discharging most of the groundwater as ET and baseflow to streams. While this approach may not be a problem for predevelopment conditions, groundwater pumpage during aquifer development may capture water that was previously discharged as ET and this approach may overestimate water availability during development. Therefore, knowledge of ET is also important.

The objective of this study was to quantify spatial variability in recharge in the outcrop areas of the Gulf Coast aquifer. Unique aspects of the study include application of different approaches to estimate recharge, primarily chloride mass balance applied at regional groundwater scales and local unsaturated zone scales and streamflow hydrograph separation applied to streamflow gages, representing recharge to contributing groundwater basins. Comparison of recharge estimates from the different techniques provides information on the reliability of the recharge estimates. This study should significantly advance our understanding of recharge to the Gulf Coast aquifer. Quantitative estimates of recharge will improve reliability of future groundwater availability models of these aquifers.

Materials and Methods

Study Area

General Information

The Gulf Coast aquifer area is subdivided for the purposes of this study into three zones (southern, central, and northern) because of the large variability of climate conditions and other factors. The southern region is bounded by the Rio Grande River and the Nueces River, The central region is bounded by the Nueces River and the Brazos River, and the northern region is bounded by the Brazos River and Sabine River (Figure 1). The climate in the Gulf Coast ranges from subtropical subhumid to subtropical humid (Larkin and Bomar, 1983) with mean annual precipitation ranging from 21 to 62 in/yr (1971 – 2000; PRISM www.prism.oregonstate.edu) (Figure 1). Median annual precipitation is 26 in/yr in the southern region, 41 in/yr in the central region, and 53 in/yr in the northern region. The seasonal distribution in precipitation is dominated by precipitation from March through October in the southern and central regions whereas precipitation remains relatively high through the winter in the northern region (Figure 2). Precipitation is double peaked in the south and central region with peaks in May-June and September, whereas precipitation in the north is dominated by a peak in June. Winters are generally drier (20-30% of annual precipitation Nov–Feb). Precipitation is derived primarily from the Gulf of Mexico in the summer. Hurricanes from the Gulf of Mexico frequently result in heavy precipitation in the summer and early fall. In the winter, Pacific and Canadian air masses bring limited to moderate precipitation. Mean annual temperature decreases from 74°F in the south to 64°F in the north (Figure 3; PRISM 1971 – 2000).

Soil clay content in the Gulf Coast ranges from < 15% to 78% (Figure 4; SSURGO, USDA 1995). Soils are generally coarser grained in the south. More clay rich soils are found in the central and northern regions, primarily near the coast. Another band of finer grained soils is found near the inland margin in the central and northern regions of the Gulf Coast aquifer.

Current land use includes grass/pasture (31%), shrubland (18%), water/wetlands (17%), forest (12%), crops (12%) and developed areas (9%) (Figure 5; USGS National Land Cover Data, 2001). The distribution of these different land use/land cover types varies, with predominantly shrubland, grassland and cropland in the southern region, cropland, forest, and water/wetlands in the central region, and urban, forest, and water in the north. EPA has also defined ecoregions for the Gulf Coast, that include the Lower Rio Grande Alluvial Floodplain, Lower Rio Grande Valley, Coastal Sand Plain, Southern Subhumid and Northern Humid Gulf Coastal Prairies, floodplains and low terraces along the rivers, and flatwoods in the north (Griffith et al., 2004).

Geology

The geology of the different aquifers is summarized in Figures 6 and 7. The Gulf Coast aquifer consists of interbedded sands, silts, and clays of fluvial and marine origin (Ashworth and Hopkins, 1995). The hydrogeologic units crop out parallel to the coast and thicken downdip. The correspondence between the hydrogeologic and stratigraphic units is derived from Baker (1979) and the ages of the formations are based on Galloway et al. (2000).

The Gulf Coast aquifer deposits are underlain by sediments deposited from shallow inland seas during the Cretaceous that formed broad continental shelves covering most of Texas. In the Tertiary (starting 65 million years ago), the Rocky Mountains to the west started rising, and large river systems flowed toward the Gulf of Mexico, carrying abundant sediment, similar to today's Mississippi River. Most of Texas, particularly west Texas, was also uplifted, generating a local sediment source. Six major progradational events occurred where sedimentation built out into the Gulf Coast Basin. These progradational sequences include the most recent Vicksburg-Catahoula-Frio, Oakville-Fleming, and Plio-Pleistocene sand-rich wedges. Hydrostratigraphic units are defined in terms of flow (i.e., in terms of "shales" vs. "sands") and do not necessarily correspond to stratigraphic units which are defined in terms of age (Figure 7). The Gulf Coast aquifer system includes three main aquifers: the Jasper, Evangeline, and Chicot aquifers that broadly correspond to the Oakville Sandstone, the Goliad Sand, and Quaternary units, respectively. The Fleming Fm. is a confining unit between the Jasper and Evangeline aquifers and is named the Burkeville confining unit.

The component geologic units of the Gulf Coast aquifer are, from oldest to youngest, (1) Catahoula Fm., (2) Oakville Sandstone/Fleming Fm., (3) Goliad Fm., (4) Pleistocene formations (Willis Fm., Lissie Fm., and Beaumont Fm.), and (5) Quaternary terrace deposits and alluvium (Doering, 1935; Baker, 1979).

<u>Catahoula (Gueydan) Formation</u> is equivalent to the Catahoula Confining System. The Catahoula Fm. has a different lithology and provenance in the southwestern Gulf Coast than it does in the northeastern Gulf Coast. Baker (1979) noted that this unit is referred to as Catahoula Tuff in the southwest and Catahoula Sandstone to the northeast of the Colorado River, where it contains more sand and less volcanic material than in the southwest. In the southwest the Catahoula/Gueydan formations are unconformably overlain by either the Oakville Fm. or the Goliad Fm., whereas in the northeast they are overlain by the Fleming Fm. (Aronow et. al., 1987; Shelby et. al., 1992). Galloway (1977) described the Catahoula Fm. as being deposited by two separate fluvial systems, Gueydan in the southwest and Chita-Corrigan in the northeast parts of the Gulf Coast. The Gueydan bedload fluvial system was deposited in the Rio Grande embayment. The Chita-Corrigan mixed-load fluvial system was deposited in the Houston Embayment. Both depositional systems contain volcanic ash; however, Galloway (1977) cites differences in alteration clay minerals as evidence that Gueydan deposition occurred in an arid environment, whereas the depositional environment of Chita-Corrigan was more humid.

<u>Oakville Sandstone/Fleming Formations</u> – These two units are commonly grouped because they are both composed of varying amounts of interbedded sand and clay. In the central part of the Gulf Coast (Brazos River to central Duval County) they are easily recognized as

stratigraphically adjacent units because the Oakville is sand-rich and the Fleming is more clay-rich. To the northeast of the Brazos River, the two units are indistinguishable. Baker (1979, 1986) assigned the Miocene Oakville/Fleming geologic units to the Jasper aquifer, which has been best characterized along the northeastern Texas Gulf Coast, north of the Brazos River. Galloway et al. (1982) described the Oakville in the southwest Gulf Coast as a sand-rich fluvial system overlying the Catahoula Fm. They associated the Oakville Sandstone with the Jasper aquifer and stated that the Evangeline aquifer includes most of the Fleming Fm.

Goliad Formation – The Goliad Fm. is only present at surface as far as Lavaca County, just south of the Colorado River as seen on the Seguin GAT sheet (Proctor et. al., 1974) and is absent farther to the northeast (not present on the Beaumont GAT sheet (Shelby et. al., 1992)). The Goliad Fm. was deposited during the Pliocene or as recently as 5 Ma. Hoel (1982) found the Goliad Fm. to be genetically and compositionally similar to the underlying Oakville and Catahoula formations as they exist in the southwest Gulf Coast. Hoel (1982) noted a distinct change in character of the Goliad Fm. along a line perpendicular to the coast, just north of the Nueces River roughly coincident with the San Patricio-Refugio county line. Southwest of this line the Goliad Fm. was deposited by rivers carrying bed load or very coarse sediments containing a large proportion of orthoclase and plagioclase feldspar crystals and volcanic rock fragments from a "distant western source." Northeast of this line the rivers carried finer grained sediments composed primarily of calc-lithic particles presumably derived from Edwards Plateau rocks of central Texas.

The Evangeline aquifer is composed of water-bearing zones primarily within the Goliad Sand and secondarily in underlying portions of the Fleming Fm. (Ryder and Ardis, 1991) The Goliad Sand is only identified as an aquifer unit in the TWDB well database within and to the south and west of Lavaca and Jackson counties. However, the Evangeline aquifer is present throughout the Gulf Coast aquifer in the northeast into Louisiana. Clearly there is a difference in the geologic units that compose the Evangeline aquifer in the southwest and northeast sections of the Gulf Coast aquifer. According to Baker (1979), the Evangeline aquifer was originally only defined as far west as Austin, Brazoria, Fort Bend, and Washington counties in Texas. He stated that extending the Evangeline farther west is speculative; however, in 1976 the USGS decided to extend the Evangeline to the Rio Grande.

Pleistocene and Recent Alluvial Deposits – Since Pleistocene time, packages of fluvial sediments representing successively younger progradational cycles have been deposited along the Texas Gulf Coast (Blum, 1992). The fluvial sediments range in texture from gravel to clay and are commonly poorly indurated. Decreasing dip of the strata toward the coast through time reflects changes in relative uplift of inland areas (southern Rocky Mountains, Great Plains, and the Edwards Plateau) and subsidence in the Gulf of Mexico (Doering, 1935; Blum, 1992). The older portions of this depositional sequence are coarser grained and dip 3 to 7 m per mile (Willis Sand), whereas the younger units are finer grained and dip only approximately 2×10^{-4} (1 ft/mi) (Beaumont Fm.) (Doering, 1935). Major Pleistocene to Recent formations along the Texas Gulf Coast, listed from oldest to youngest, include Willis Fm., Lissie Fm., Beaumont Fm., and Quaternary terrace deposits and alluvium (Doering, 1935; Baker, 1979). These units plus Quaternary alluvial deposits are all assigned to the Chicot aquifer.

Northeast of the Colorado River, Miocene- to Pliocene-age Fleming Fm. clay is unconformably overlain by the Willis Sand, which is in turn unconformably overlain by the sand and clay of the Lissie Fm. South of the Colorado River, the Pliocene-age Goliad Fm. is overlain by the Lissie Fm., which consists of sand, silt, clay, and minor amounts of gravel. The Lissie Fm. is overlain by clay, silt, and fine-grained sand of the Pleistocene-age Beaumont Fm. throughout the Texas Gulf Coast. Although the Beaumont Fm. as a whole is much finer grained than directly underlying formations, it contains localized sand channel deposits. The base of the Pleistocene (thought to be Willis Fm. in the northeast Gulf Coast and Lissie Fm. in southwest Gulf Coast) is very difficult to identify on geophysical logs (Baker, 1979). Because of this the bottom of the Chicot aquifer, which has in the past been defined as the base of the Pleistocene, is ambiguously defined and is often lumped together with the Evangeline aquifer.

Recharge Rates from Previous Studies

Recharge rates for Gulf Coast aquifer have been determined in many previous studies. A variety of approaches were used to estimate recharge, including Darcy's Law, environmental tracers, hydrograph separation, and numerical modeling.

Recharge rates in the Trinity River Basin ranged from 0.0 – 7.2 in/yr (median 0.9 in/yr) based on Darcian pedotransfer functions, 0.0 – 5.6 in/yr (median 0.4 in/yr) based on the chloride mass balance approach applied to unsaturated zone samples, and 0.0 – 4.1 in/yr (median 0.8 in/yr) based on chloride mass balance applied to groundwater data (Nolan et al., 2007). The regional recharge rates based on groundwater chloride data were not as variable as those based on unsaturated zone chloride data. Recharge rates based on Darcy's Law range from 1.2 to 1.3 in/yr in the Chicot and Evangeline aquifers in Colorado, Lavaca, and Wharton Counties (Loskot et al., 1982).

Recharge rates in the Chico and Evangeline aquifers were estimated using tritium isotopes in groundwater by Noble et al. (1996). An upper bound on the average recharge rate of 6 in/yr was estimated using the deepest penetration of tritium (80 ft) in 41 sampled wells in the Chicot and Evangeline outcrop areas.

Variations in recharge rates among groundwater models are attributed to differences in model grid size, hydraulic conductivity distribution, and degree of aquifer development. Recharge rates based on groundwater models may be biased because of scale issues (Johnston, 1997). Grid sizes in regional models are generally ≥ 1 mi^2. Therefore, in areas with large topographic relief with recharge discharging through streams within grid blocks, total recharge will be underestimated by the model because local and possibly intermediate flow systems are not captured in the larger grid blocks because they encompass both, and oftentimes only regional flow systems can be simulated.

Because most groundwater models of the Gulf Coast are calibrated using hydraulic head data alone, they can only simulate the ratio of recharge to hydraulic conductivity (Scanlon et al., 2002). Therefore, variations in recharge among the models are generally related to hydraulic conductivity, i.e. low recharge rates (0.0004 to 0.12 in/yr) associated with low hydraulic conductivity distribution (Hay, 1999).

Ryder (1988) estimated an average recharge rate of 0.74 in/yr in the outcrop areas of the upper Gulf Coast. Calibrated recharge rates in the southern Gulf Coast ranged from 0 – 4 in/yr for Goliad sand. A later model by Ryder and Ardis (2002) reported an average recharge rate of 0.12 in/yr. Simulated recharge rates of 0.1 to 0.4 in/yr were estimated by Dutton and Richter (1990) for the Chicot and Evangeline aquifers in Matagorda, Wharton, and Colorado counties.

Simulations of the northern Gulf Coast aquifer as part of the Groundwater Availability Modeling program resulted in predevelopment recharge rates in the aquifer outcrop zones of 0.14 in/yr in the Chicot and 0.41 in/yr in the Evangeline (Kasmarek and Robinson, 2004). Simulated transient recharge rates in the aquifer outcrop zones range from 0.4 in/yr in the Chicot and 0.12 in/yr in the Evangeline in 1977. Recharge increases to 0.55 in/yr in the Chicot in 2000 and decreases to 0.11 in/yr in the Evangeline. In the central and southern Gulf Coast GAMs, groundwater recharge was calibrated in the model as a uniform percent of distributed mean annual precipitation according to soil characteristics, which resulted in higher recharge rates in the central Gulf Coast because of higher precipitation relative to the southern Gulf Coast (Chowdhury et al., 2004, Chowdhury and Mace, 2003). Calibrated recharge rates were low in the Jasper Aquifer (≤ 0.1 in/yr) and higher in the Evangeline (0.1 – 0.2 in/yr) and Chicot (0.1 – 0.3 in/yr) aquifers based on results for 1980 1990, and 1999. Recharge in the lower Rio Grande Valley is derived from precipitation (47%) and from the Rio Grande seepage (0.53%).

Methods

Actual evapotranspiration (ETa) was estimated to ensure that ET used in future groundwater models in this region does not exceed actual ET estimates. In addition, reference ET (ET_0)was also evaluated to compare with actual ET at station locations. Various techniques were used to estimate aquifer recharge. The primary techniques are chloride mass balance approach applied to groundwater and unsaturated zone chloride data, water table fluctuations, and streamflow hydrograph separation. Additional data were collected to further constrain recharge rates. For example, chemical data from streams were compared with those from groundwater during low flow conditions to evaluate reliability of baseflow discharge estimates from stream data.

Estimation of Evapotranspiration

Reference Evapotranspiration

Evapotranspiration is generally the second largest parameter in the water budget in most regions. Reference ET refers to ET that is not limited by water availability in the soil profile and is only controlled by meteorological parameters such as radiation, temperature, wind, and relative humidity. Reference ET was estimated using the Penman Monteith approach (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (1)$$

where ET_0 = reference evapotranspiration [mm day-1],

R_n = net radiation at the crop surface [MJ m^2/ d],

G = soil heat flux density [MJ/m^2 d],

T = mean daily air temperature at 2 m height [°C],

u_2 =wind speed at 2 m height [m/ s],

e_s =saturation vapor pressure [kPa],

e_a =actual vapor pressure [kPa],

Δ = slope of vapor pressure curve [kPa/°C],

γ = psychrometric constant [kPa/ °C].

Reference ET was obtained for 10 stations in and surrounding the Texas Gulf Coast region from the TexasET Network (Table 1). This network is partially supported through a federal program, the "Rio Grande Basin Initiative," and administered by the Texas Water Resources Institute of the Texas A&M University System and other groups. TexasET contains weather information, current and average ET data, and irrigation watering recommendations. The standard Penman-Monteith method is used to calculate ET_0 from the weather station data. Reference ET was also estimated using stations from The National Solar Radiation Database (NSRDB) established by the National Renewable Energy Lab (NREL). Eight class I stations in the Gulf Coast region were selected for ET_0 estimation (Table 2). Hourly data from 1991 to 2005 for each station were extracted from the archive and hourly ET_0 was calculated using Penman-Monteith equation. Annual ET_0 by station was summarized from hourly values. Monthly and annual ET_0 were calculated for all stations (Table 2).

Atmometers (2) were installed to monitor reference ET in a riparian setting adjacent to the Colorado River at La Grange, Fayette County. One atmometer was installed in a small clearing receiving full sunlight and another was installed under the tree canopy in full shade, both separated by a distance of about 150 ft. The atmometers (Model E, ETGage, Loveland, CO, www.etgage.com) consist of a reservoir of distilled water connected to a porous ceramic evaporator through an electronic measuring device that records evaporation in 0.01-inch increments. The ceramic is covered by a canvas diffusion cover designed to simulate reference ET (ET_0). The reservoir has a capacity to supply 12 in of evaporation.

Actual Evapotranspiration

Actual ET is generally the parameter of most interest to hydrologists and is impacted by land use/land cover and soil moisture. Remote sensing is widely used to develop regional estimates of ETa A variety of codes are available to estimate ETa including SEBAL, METRIC, SSEB (Gowda et al., 2008). In this study, SSEB was used to estimate ETa in the Gulf Coast region.

All of these approaches estimate ETa or latent heat flux as the residual term in the surface energy balance equation:

$$ETa = LE = Rn - G - H \qquad (2)$$

where LE is latent heat flux (energy consumed by ET), Rn is net radiation at the surface, G is ground heat flux, and H is sensible heat flux, all in units of W/m^2. The Simplified Surface Energy Balance (SSEB) approach was developed at USGS/Center for Earth Resources Observation and Science (EROS) for operational applications (Senay et al., 2007). The SSEB approach produces ETa estimates using a combination of ET fractions generated from thermal imagery and global reference ET over homogeneous areas with similar climate zones where differences in surface temperature are mainly caused by differences in vegetation water use rates. ETa is a product of ET fraction (ET_f) and ET_0: ET_f is calculated from Moderate Resolution Imaging Spectroradiometer (MODIS) thermal image. Average 8 day MODIS data are used because of problems with cloudiness for daily data. Reference ET (ET_0) is calculated globally from assimilated meteorological datasets of the Global Data Assimilation System of NOAA (Senay et al., 2008). The 8 day average temperature of hot and cold pixels are used to calculate proportional fractions of ET on a per pixel bases based on the assumption that hot pixels have ET close to 0 (Allen and Tasumi, 2005) and cold pixels represent maximum ET. Using Normalized Difference Vegetation Index (NDVI) from MODIS, hot pixels are selected from dry and bare areas and cold pixels from well-watered, vegetated areas. The ET fraction ($ET_{f,}$) is calculated for each pixel "x" by applying the following equation to each of the 8-day MODIS land surface temperature grids.

$$ET_{f,x} = \frac{TH - Tx}{TH - TC} \quad (3)$$

where TH and TC are the averages of hot and cold pixels selected for a given scene, and T_X is the land surface T for any given pixel in the composite scene.

Theory of Recharge Estimation Approach

Chloride Mass Balance Approach

Chloride is produced naturally in the Earth's atmosphere and has been widely used to estimate recharge rates since the late 1970s (Allison and Hughes 1978). The chloride mass balance (CMB) approach is used to estimate the recharge rate in which the chloride input to the soil profile from precipitation is balanced by chloride output in percolation below the root zone which is equated to recharge at the water table. The CMB approach can be applied to unsaturated zone profiles or to groundwater chloride data:

$$P \times Cl_P = Pe_{CMB} \times Cl_{UZ} = R_{CMB} \times Cl_{UZ} \quad (4)$$

$$P \times Cl_P = R_{CMB} \times Cl_{GW} \quad (5)$$

$$R_{CMB} = \frac{P \times Cl_P}{Cl_{UZ}} = \frac{P \times Cl_P}{Cl_{GW}} \quad (6)$$

where P is precipitation, subscripts P, UZ, and GW are precipitation, unsaturated zone, and groundwater, Pe is percolation rate (in/yr), and R is recharge rate. Percolation/recharge rates are inversely related to chloride concentrations in the unsaturated zone or groundwater; high percolation/recharge rates correspond to low chloride concentrations because chloride is flushed through the system whereas low percolation/recharge rates correspond to high chloride concentrations because chloride accumulates. Therefore, chloride concentrations can be used qualitatively to assess recharge rates. Quantitative percolation/recharge estimates require application of equations 4 through 6. The accumulation time represented by chloride in unsaturated zone profiles can be determined by dividing the cumulative total mass of chloride for the depth interval of interest by the chloride input:

$$t = \frac{\int_0^z \theta \times Cl_{UZ}\, dz}{P \times Cl_P} \quad (7)$$

Chloride concentrations generally increase through the root zone as a result of evapotranspiration and then remain constant below this depth. Bulge-shaped chloride profiles in unsaturated profiles in the High Plains have been attributed to higher recharge during the Pleistocene glacial period and chloride accumulation during the drier Holocene period (Scanlon and Goldsmith, 1997).

The chloride mass balance approach assumes that precipitation is the only source of groundwater chloride. However, groundwater chloride can also be derived from underlying more saline aquifers. Mass concentration (mg/L) ratios of groundwater Cl/Br and Cl/SO_4 can be used to distinguish chloride of meteoric origin from precipitation from chloride derived from upward flow of saline groundwater from deeper aquifers, as was done in the Central High Plains (Scanlon et al., 2010).

Estimation of Recharge Rates

Chloride Deposition

Applying the chloride mass balance (CMB) approach to estimate recharge requires information on chloride input into the system. Chloride concentration data are generally obtained from the National Atmospheric Deposition Program (NADP) in the US (www.nadp.org). These data include wet chloride deposition only because the precipitation collectors are only open when it is raining. The CMB approach requires information on wet and dry chloride deposition or bulk chloride deposition. Many previous studies in the Texas High Plains doubled the wet chloride deposition as an estimate of bulk chloride deposition based on estimates of bulk chloride deposition from $^{36}Cl/Cl$ ratios below the root zone (Scanlon et al., 2010). There are no $^{36}Cl/Cl$ data available for the Gulf Coast region. We examined literature data to assess relative amounts of wet and dry deposition near coastal zones. Measurements from coastal zones in Spain showed that dry deposition accounts for up to 50% of bulk deposition.

Application of the CMB approach requires information on chloride deposition (equation 6). Many studies have indicated that chloride deposition varies markedly with distance from the coast. Blackburn and McLeod (1983) suggested exponential reduction in chloride deposition near the coast, but attributed most of the reduction to variations in dry deposition. Keywood et al. (1997) also approximated changes in chloride deposition from the coast by exponential relationships based on a W-E and N-S transects in bulk deposition and attributed the changes in deposition to a fast portion characterized by rapid removal of chloride near the coast with a decay constant of ~ 60 km and a slow portion with a decay constant of ~700 km. They also noted that reduction in precipitation from the coast is also important. Biggs (2006) suggested that a higher correlation was obtained using mass rather than volume concentrations and indicated that reductions from the coast can penetrate to 300 to 400 km from the coast. Alcala and Custodio (2008) noted that dry deposition only accounted for up to 50% of bulk deposition based on data from Spain.

As a result of these studies, we developed a relationship for chloride deposition with distance from the coast using 20 stations from the NADP. The stations are located within approximately 5 to 200 miles from the Gulf Coast and include stations in Texas, Louisiana, Mississippi, Alabama, Georgia, and Florida. The median annual deposition rate for the period of record for each station was used. Mass concentrations (kg/ha) rather than volume concentrations (mg/L) were used based on the findings from Biggs (2006). A high correlation (r^2 = 0.98) was obtained between chloride mass deposition (Cl_{PM}) and distance from the coast (x) (Figure 8). To convert wet mass deposition (Cl_{PM}, kg/ha) to concentration (Cl_P, mg/L), the following is used:

$$Cl_P = \frac{Cl_{PM}}{P} = \frac{42 - 14.6\ln x + 1.39(\ln x)^2}{P} \times 2450 \qquad (8)$$

where the second-order equation in the numerator represents a least-squares fit to NADP median mass concentration deposition versus distance from the coast is in miles, precipitation (P) is in inches, and 2450 is a units conversion factor.

To gain insight into the relative amount of dry deposition in the study area, precipitation collectors were installed adjacent to the two NADP stations in the Gulf Coast to collect bulk chloride deposition. Additional collectors were installed at 8 other locations (Figure 9). Unlike the NADP precipitation collectors, which open mechanically during precipitation events and are closed at other times, the deployed collectors are open at all times. The open collectors located at the NADP sites are sampled on the same schedule as the NADP wet-only collectors for direct comparison to NADP results (weekly), while open collectors at the remaining sites are sampled at intervals varying approximately from weekly to monthly. However, the region has been in a drought since installation of these collectors and there is insufficient data to modify the chloride deposition function based on the NADP data.

Unsaturated Zone Field Studies and Chemical Analysis

Field studies were designed to drill and sample boreholes in different settings to estimate percolation using the chloride mass balance approach. A total of 18 boreholes were drilled and core samples collected for analysis of texture, water content, and anion concentrations in pore water (Figure 10). In addition, results from nine boreholes drilled in a previous study in the southern Gulf Coast were used to estimate recharge in this region (Scanlon et al., 2005). Continuous soil cores were obtained using a direct push drill rig (Model 6620DT, Geoprobe, Salina, KS). Borehole depths ranged from 8.0 to 47.5 ft (Table 3). Core samples were collected in plastic sample sleeves and capped.

Subsamples of the core from depth intervals varying between 1 and 5 ft were analyzed for soil water content and texture. Chemical parameters analyzed included water-extractable anion concentrations, including chloride, sulfate, and nitrate-N in water leached from the samples. Core subsamples (25 g) were leached using 40 mL of double deionized water. The mixture was placed in a reciprocal shaker for 4 hr, centrifuged at 7,000 rpm for 20 min, and the supernatant was filtered (0.2 um). Core subsamples were then oven dried at 105°C for 48 hr to determine gravimetric water content. Ionic concentrations were analyzed using ion chromatography (Dionex ICS 2000, EPA Method 300.0). Water-extractable ion concentrations are expressed on a mass basis as mg ion per kg of dry soil and were calculated by multiplying ion concentrations in the supernatant by the extraction ratio (g water/g soil). Ion concentrations are also expressed as mg ion per L of soil pore water and were calculated by dividing concentrations in mg/kg by gravimetric water content and multiplying by water density. Soil texture analyses were conducted using hydrometer methods at the Soil Water and Plant Analysis Laboratory at the University of Arizona to determine percentages of sand, silt, and clay.

Chloride Mass Balance Applied to Groundwater Data

Groundwater chloride concentrations (Cl_{GW}) were used to estimate regional recharge rates on the basis of equation (6). Chloride data were obtained from 8,721 wells in the outcrop area of the Jasper, Evangeline, and Chicot aquifers from Texas Water Development Board (TWDB) database (www.twdb.state.tx.us). Chloride concentrations in precipitation were obtained from the National Atmospheric Deposition Program (NADP, http://nadp.sws.uiuc.edu/). Mass concentration (mg/L) ratios for subsets of the chloride data for groundwater Cl/Br (1,339 wells) and Cl/SO_4 (8,086 wells) were used to distinguish chloride of meteoric origin from precipitation from chloride derived from upward flow of saline groundwater from deeper aquifers. The chloride and sulfate concentration data represent samples analyzed between 1913 and 2009 (median 1966). The bromide concentration data for the region represent samples analyzed between 1990 and 2009 (median 2001).

Water Table Fluctuation Method

The water table fluctuation (WTF) method (Healy and Cook, 2002) was applied to groundwater level data from the TWDB database. The WTF method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. Recharge is calculated as

$$R = Sy\frac{D\Delta h}{\Delta t} \tag{9}$$

where *Sy* is specific yield, *h* is water-table height, and *t* is time (Healy and Cook, 2002). The method has been applied to groundwater level rises that occurred over several years in the High Plains aquifer (Scanlon et al., 2010). Difficulties in applying the method are related to ensuring that fluctuations in water levels are due to recharge following precipitation and are not the result of recovery after pumping, changes in atmospheric pressure, presence of entrapped air, ET, or other phenomena. Determining a representative value for specific yield can also be problematic. The method is only applicable to unconfined aquifers and is best applied to shallow water tables that display sharp water-level changes.

Wells in the TWDB database that were deeper than 50 ft were eliminated from consideration as they are more likely to be completed in confined water-bearing units. Wells were further eliminated that have a measurement frequency of greater than about 60 days, considered a minimum required to capture water level fluctuation related to precipitation events, and that had sufficient records to span at least one full year. These criteria resulted in only 30 wells out of the approximately 16,600 wells in the database. All of the selected wells are completed in the Chicot aquifer and a uniform specific yield value of 0.05 was used.

Stream Hydrograph Separation

This section presents various estimates for shallow recharge that discharges to rivers and streams within the Gulf Coast aquifer. This discharge, which is typically called baseflow, occurs when the water table in an aquifer is at a higher elevation than the water surface of the river. Under these conditions, the river is said to be gaining, because water flows from the aquifer to the river. Flow duration curves were developed to determine whether streams are gaining or losing. Baseflow represents the relatively steady portion of river flow that occurs between periods of surface runoff. By analyzing the portion of river flow that occurs as baseflow, it is then possible to determine the amount that discharges from the aquifer to the river system. Streamflow hydrograph separation was conducted using the Base-Flow Index (BFI) code developed by Wahl and Wahl (1995). BFI is an automated procedure for determining baseflow on a consistent basis from reach to reach, so that they may be compared. BFI is the ratio of baseflow to streamflow. Values of BFI range from 0 (for no baseflow contribution to streamflow) to 1 (for 100% streamflow as baseflow). This program has two options, the first is the Institute of Hydrology method (1990), and the other is referred to as the Modified method. These methods locate low points on the streamflow record (referred to as turning points) and interpolate daily values between these low points. The Institute of Hydrology method was used in this study. The parameter N, number of days, was set to 5 based on an initial sensitivity analysis using selected gage data. The turning point, F, was set to 0.9, which is the default value in the BFI code. Results were not very sensitive to the F parameter.

For this study, 59 unregulated stream gages with drainage areas intersecting the Gulf Coast aquifer were selected and hydrograph separation completed for all the years of record during the time the drainage area upstream of the gage was unregulated. Shallow areal recharge flux in inches was then calculated by dividing the estimated baseflow rate by the drainage area. With baseflow calculated for multiple years it was then possible to estimate the average baseflow at a given stream gage. While using the Base Flow Index code is a fairly simple task, several criteria must be satisfied when selecting gages to be analyzed. If one of these criteria is not fully met then the estimate of recharge may not be valid. The criteria used in this study are listed below:

1. The gage should be on a stream that is considered to be gaining.
2. The catchment area of the gage should be primarily in the aquifer.
3. If the contributing area is outside the aquifer then an upstream gage must be utilized in order to subtract the effects of the upstream area.
4. The majority of the contributing area must be unregulated.

The first criterion ensures that the baseflow separation calculation can be accomplished. For a river with perennial flow (gaining) most of the basin yield usually comes from baseflow, indicating that a large portion of the rainfall is infiltrated into the basin and reaches the stream as subsurface flow (Chow, 1988). However, if the gage was located on an intermittent stream then an estimate of baseflow would only be valid during times when the stream was flowing. The second and third criteria ensure that gains/losses are calculated for the aquifer being analyzed and the fourth criteria ensures that gains to the system are due to groundwater sources instead of discharge from reservoirs. Estimates of the time periods where a stream was regulated (influenced by reservoir discharge) are available in a USGS report (Slade et al., 2002). This report lists beginning and ending years of regulation for many active and discontinued streamflow gaging stations in Texas. Calculations of baseflow were made based on the unregulated years reported by Slade (2002). Note that Slade (2002) only lists regulated years up to the year 2000, because that was the most recent data at the time of the report. For the current study, if a gage was unregulated in 2000, it was assumed that it continued to be unregulated to the present time as no reservoirs have reportedly become active in the Gulf Coast region in the last decade.

Results and Discussion

Evapotranspiration

Reference ET (ET_0) refers to the ability of the atmosphere to remove water and is controlled by meteorological forcing. Reference ET refers to the maximum possible ET for fully watered vegetation. Based on historical periods of record for TexasET network stations in the region, ET_0 ranges from 52.7 to 57.0 in/yr, with an overall trend toward higher values from north to south and also increasing inland from the coast (Table 1). Seasonal ET_0 is lowest from November through February (~20% of annual total) and highest in other months (~80% of annual total), with maximum monthly totals occurring between June and August for different locations. Values of ET_0 calculated from the NSRDB database (Table 2) and from the TexasET network generally agree within ±10%.

Annual mean actual ET (ETa) ranges from 32 in/yr in the south to 36 in/yr in the central and 42 in/yr in the north region (2000 – 2009) (Figure 11). Although ETa might be expected to be greater in the south where temperatures are highest, ETa in this region is limited by water availability. In contrast, ETa is greatest in the north because precipitation and water availability are highest in this region. Interannual variability is greatest in the south, with annual ETa ranging from 24 to 42 in/yr with a coefficient of variance (CV, standard deviation divided by the mean) of 20% (Figure 12). ETa ranges from 27 to 44 in/yr in the central region (CV = 14%) and from 39 to 48 in/yr in the north (CV = 6%). Average monthly ETa varies systematically with the seasons in all regions, with minimum values (0.3 to 0.7 in) occurring in January and maximum values (5.0 to 6.5 in) occurring in July (Figure 13). Differences among regions are greatest in the summer and least during fall and early winter.

Regional Recharge Rates from Groundwater Chloride Data

Groundwater chloride concentrations range from 3 to 1,700 mg/L and decrease regionally from south to north (Figure 14). Chloride concentrations are generally highest within the southern region in areas that surround a lower concentration (100 – 300 mg/L) zone corresponding to a sand dune area (Figure 4). Within the central region, higher concentrations are generally limited to the southern coastal area and concentrations decrease toward the northeast. Chloride concentrations are lowest overall in the northern region, with regional higher concentrations limited to a narrow zone near the coast.

The CMB approach assumes that all chloride is derived from precipitation. To assess the validity of this assumption, ratios of Cl/Br and Cl/SO_4 were evaluated to determine the chloride contribution from possible upward movement of more saline water from underlying geologic units (Figures 15 and 16). Mass ratios of Cl/Br typical of precipitation range from 50 to 150, and those typical of fresh groundwater range from 100 to 200, whereas ratios in groundwater impacted by salt dissolution range from 1000 to 10,000 (Davis et al., 1998). Ratios of Cl/Br throughout much of the Gulf Coast generally range from 80 to 300, mostly within the range of those typical of precipitation and fresh groundwater; however, Cl/Br ratios in the north near the coast are generally higher (300–600) and suggest an additional source of chloride input, possibly as upward cross formational flow of saline water from deeper aquifers in this region (Figure 15). The region of elevated Cl/Br ratios is ~ 7,000 mi^2 in area and is coincident with a large cluster of salt domes (Hamlin, 2006). The high Cl/Br ratios are attributed to low Br concentrations typical of recrystallized halite. Ratios of Cl/SO_4 greater than 20 are also characteristic of this region and are generally consistent with the high Cl/Br (>300) area (Figure 16), suggesting that groundwater throughout this region may be impacted by upward cross-formational flow. Therefore, groundwater Cl data should provide a lower bound on actual recharge rates in this region.

Estimated recharge rates based on groundwater chloride concentrations range from <0.1 to 10 in/yr throughout the Gulf Coast aquifer (Figure 17). Median recharge rates range from 0.12 in/yr in the southern region, 0.39 in/yr in the central region, to 1.26 in/yr in the northern region (excluding the region with Cl/Br >300). Most recharge in the southern region falls within the range of <0.1 to 0.25 in/yr with a zone of slightly higher recharge generally corresponding to a sand dune area (Figure 4). In the central region, recharge generally ranges from 0.25 to 0.5 in/yr in the southwest to 0.5 to 1 in/yr in the northeast and near the northeast coast. Recharge in the northern region is lowest along the inland margin and is higher along a band across the center ranging from about 1 in/yr in the southwest to a maximum of about 10 in/yr in the northeast.

Estimated recharge rates in the Gulf Coast represent <0.1 to 16% of mean annual precipitation (Figure 18). Recharge rates in the southern region range from 0.1 to 2.2% (median 0.5%, mean 0.7%) of mean precipitation. Recharge rates in the central region range from 0.1 to 9% (median 1.0%, mean 1.2%) of mean precipitation. Recharge rates in the northern region range from 0.2 to 16% (median 2.6%, mean 3.5%) of mean precipitation (excluding the Cl/Br >300 region). These recharge rates are generally lower than those predicted using the precipitation model by Keese et al. (2005), which, for texturally variable vegetated soils, predicts recharge as a percentage of precipitation of 1.9% in the southern region, 5.9% in the central region, and 11% in the northern region.

Many studies have noted high correlations between groundwater nitrate concentrations and recharge to shallow aquifers (Nolan et al., 2002; Fram and Belitz, 2011). Therefore, we examined variations in groundwater nitrate concentrations to determine if these variations are related to recharge. Nitrate concentrations were generally low throughout the Gulf Coast aquifer, ≤1 mg/L NO_3-N in most of the northern Gulf Coast, ≤ 2 mg/L throughout much of the central Gulf Coast. Higher concentrations are restricted to the southern Gulf Coast (2- 13 mg/L) and are greatest near the Rio Grande (Figure 19). Generally low nitrate concentrations throughout most of the north and central Gulf Coast could reflect limited input from nitrate fertilizer application, denitrification associated with reducing conditions, or low recharge rates. To assess the distribution of anthropogenic input, the probability of nitrate concentrations exceeding 2 mg/L NO_3-N, which is considered background levels, was calculated and the data kriged. Results indicate higher probabilities in the south where recharge rates are generally low and much lower probabilities in the central and northern regions (Figure 20).

Relationships between Precipitation, Soil Texture, and Land Use with CMB Recharge

Relationships between precipitation, land use, soil texture, and groundwater CMB recharge rates were investigated using multiple linear regression. Groundwater CMB recharge rates (log-transformed) for each well were compared to long-term average annual total precipitation depth (Figure 1), soil clay content percentage (Figure 4), and land use category (Figure 5). Various combinations of these variables were modeled to characterize which, if any, might demonstrate a significant ability to predict the groundwater CMB recharge rates. The numerical values for precipitation and soil clay content at each well location were derived from the respective maps. For land use, coded variables (1's and 0's) representing the dominant land use category within 500 m of each well location were used. In this approach, the dominant land use category is assigned a value of "1" and all other categories are assigned a value of "0". Additionally, one category is implicitly omitted from the model for comparison (this is required to prevent the model from being "over-specified"). The "Pasture" category was selected for comparison as it represents the dominant land use near approximately one-third of the wells in the study area. Models were run encompassing the entire Gulf Coast region and separately for the Northern, Central, and Southern subregions. Overall model statistics including correlation (r) and standard errors of prediction were used to compare the results of the models. Results indicate that both regionally and within each subregion, precipitation has the greatest effect with $r = 0.61$ regionally and ranging from 0.37 to 0.54 for the individual subregions. The regional land use model had $r=0.40$ and ranged from 0.14 to 0.48 within subregions. The regional soil clay content model had

21) and represent from 5.7% to 20% (median 9.5%) of local mean precipitation with corresponding short chloride accumulation times ranging from 5 to 87 yr (median 27 yr) to the total depth sampled (Table 6). Sulfate concentrations were also low in these profiles (64 to 150 mg/L, median 97 mg/L), consistent with flushing. Some of the higher percolation rates may reflect recharge to shallow perched aquifers rather than to the regional system, as one profile (Fay10-04) encountered saturated conditions at a depth of 18 ft while a groundwater well approximately 300 ft distant indicated a depth to water of about 130 ft.

A total of five profiles have slightly higher chloride (90 to 190 mg/L, median 140 mg/L), with three of the profiles having low sulfate concentrations (110 to 180 mg/L) and the remaining two having elevated sulfate concentrations (430 and 660 mg/L) (Table 5). Calculated percolation rates range from 0.35 to 0.73 in/yr (median 0.52 in/yr) for these five profiles, representing from 1.1% to 3.4% (median 1.4%) of local precipitation (Table 6, Figure 21).

The remaining profiles (14) have high chloride concentrations (560 – 10,200 mg/L, median 2,400 mg/L) and high sulfate concentrations (550 – 15,300 mg/L, median 1,400 mg/L) (Table 5), with very low calculated percolation rates ranging from 0.01 to 0.16 in/yr (median 0.03 in/yr) and represent only 0.02% to 0.16% (median 0.1%) of local mean precipitation (Table 6, Figure 21). Accumulation times in this group are up to 13,000 yr, with a median accumulation time of 4,000 yr for boreholes between 20 and 37 ft deep. Chloride profiles show increasing or stable concentration at depth.

Nitrate is sometimes used to fingerprint water fluxes associated with cultivation and fertilization (Scanlon et al., 2010). Most profiles in the Gulf Coast have low nitrate concentrations (median 0.1 – 2 mg/L) (Table 5). A few profiles have slightly higher nitrate levels (3-8 mg/L). The remaining profiles with high mean nitrate concentrations (31 – 275 mg/L) have high levels in the shallow subsurface in some profiles (Bee10-01, Kar10-01) and high levels towards the base in other profiles (Hid05-01, and Liv10-02). The latter have increased nitrate levels coincident with chloride concentration increases, suggesting release of nitrate at the beginning of cultivation, similar to profiles in the High Plains (Scanlon et al., 2008). One of the profiles (Liv10-01) is unusual in that high nitrate extends to 6 m depth, although chloride concentrations are extremely high. The clay content in this profile is extremely high and deep penetration of nitrate may suggest preferential flow.

In summary, there are no regional trends in percolation with precipitation from unsaturated zone profiles, with low and high percolation rates found throughout the sampled region. There is no systematic variation in percolation rate with soil texture. Locally, soil texture may exert a dominant control, e.g. percolation is limited (0.01 in/yr) at a location in Nueces County by clayey soils under a rainfed agricultural setting whereas percolation is much higher (4.91 in/yr) in sandy soils in Kenedy County despite heavy forest/shrub vegetation (efficient at using water) (Figure 22). Land use also plays an important role locally in determining percolation rates. In Karnes County, two boreholes separated by about 300 ft differ only in land use history (Figure 23). One borehole (Kar10-01) is located in pastureland that was cleared of trees in 1975, is currently grassland with sparse shrubs, and has high Cl and SO_4 concentrations indicating essentially no percolation (0.03 in/yr). The other borehole location (Kar10-02) was cleared in ~1910 and was under continuous cultivation until 1972 when it was allowed to revert to pastureland, is currently covered in grasses similar to Kar10-01, and has low Cl and SO_4 concentrations indicative of flushing with a percolation rate of 5.65 in/yr.

Land use history was difficult to determine accurately for many of the pasture sites sampled because current landowners are only aware of relatively recent land use. Cotton was an important regional crop in the past and much of the current pastureland may have been previously cultivated for cotton.

Regional Recharge Rates from Streamflow Hydrograph Separation

Recharge rates from previous streamflow hydrograph analyses are provided in Appendix 2. Flow duration curves were calculated to determine whether streams are ephemeral or perennial. The curves for all gages are presented in Appendix 3. Two example flow duration curves are shown in Figure 24. From the flow duration curve for gage 8115500, in the southwestern Gulf Coast, ~65% of the time the stream at this location becomes dry and has no flow. In contrast, the flow duration curve for gage 8117500, located in the more humid Brazos River basin, terminates near 100%, which is characteristic of a perennial stream.

Streamflow hydrograph separation was conducted on stream gages whose flow duration curves indicated that they are perennial. Temporal trends in baseflow were first examined prior to estimating recharge rates for contributing basins (Appendix 4). In some areas, such as in the Lower Colorado River Basin, groundwater pumping has varied dramatically through time, and the impact may be evident in the temporal trends of baseflow. Groundwater levels in the Gulf Coast aquifer reached their minimum in the area in approximately 1985-1990 (URS, 2004).

Results from the streamflow hydrograph separation analysis are presented in Tables 7 and 8. Statistics describing baseflow temporal variability are also presented to show the standard deviation and range of values calculated for each gaging station during the period of unregulated flow. Figure 26 shows the locations of the drainage areas analyzed for baseflow recharge and the associated average recharge rates in relation to groundwater CMB recharge rates in the corresponding drainage basin areas. The results are consistent and indicate that average recharge increases from south to north with increasing precipitation, as expected. Average recharge is negligible in the south, and increases to up to 7 in/yr in the north near the Sabine River.

Comparison of Recharge Rates from Different Approaches

Regional recharge estimates from groundwater chloride data may be considered a lower bound because various processes can add chloride to groundwater whereas no process removes chloride from groundwater in the Gulf Coast. For comparison with the groundwater chloride mass balance results, the streamflow hydrograph results were grouped into four categories based on results of the hydrograph analysis, including (1) perennial streams where the flow duration curves indicate flow persisted for at least 99% of the time, (2) perennial streams as in (1) but that have BFI values below 7%, (3) perennial streams as in (1) that exhibit strong increasing temporal trends in BFI (all located in the Houston area), and (4) nonperennial streams where the flow duration curves indicate flow persisted for less than 99% of the time. Category 1 represents all hydrograph results that indicate a persistent hydraulic connection between the stream and the groundwater in the drainage area while the remaining categories indicate changing or nonpersistent connections.

The trend in groundwater CMB recharge rates is highly correlated with the 24 perennial streamflow hydrograph separations (r = 0.96, Figure 27) with most data pairs falling within about 25% of the 1:1 line. The high level of agreement between these two independent methods serves to reinforce the results of the recharge estimates for both methods. Within the remaining hydrograph categories, all of the perennial hydrographs showing strong temporal BFI trends plot above the 1:1 line while all but one of the nonperennial and low BFI hydrographs plot below the 1:1 line. Higher BFI recharge estimates in the former category suggests that these estimates may be impacted by increased streamflow over time in the Houston area while the lower BFI recharge estimates in the latter categories are indicative of basins with nonpersistent connections between surface water and groundwater.

Summary

A variety of approaches were used to assess recharge to the Gulf Coast aquifer. The techniques were primarily chosen to provide regional recharge estimates for input to future groundwater availability models of these aquifers. The chloride mass balance approach was applied to groundwater chloride data to estimate recharge throughout the Gulf Coast and