4.4 Recharge

Recharge refers to water that enters the saturated zone at the water table (Freeze, 1969). Potential controls on recharge include climate (precipitation, evapotranspiration), vegetation and land use, soil type, and topography (Keese and others, 2005). Sources of recharge to the Haskell-Knox-Baylor pod of the Seymour Aquifer include precipitation and irrigation return flow and, to a much lesser extent, streams. In a natural system unaffected by anthropogenic activities, an aquifer should be in a steady-state condition where aquifer recharge is balanced by natural aquifer discharge resulting in no net change in groundwater storage. Due to the low permeability of the Permian-age sediments, recharge on the Permian outcrops was assumed to be zero. The following discussion relates to the development of recharge estimates for the Seymour Aquifer.

Several changes in land use over the Seymour Aquifer have resulted in changes in the balance between aquifer recharge and natural aquifer discharge and have caused associated changes in water levels in the aquifer. The Seymour Aquifer was at steady state prior to 1880. The native vegetation at that time consisted of tall grass prairie with small pockets of timberland, primarily mesquite, in riparian zones. Grass species included wild rye, fescue, buffalo, grama, and needle grass, which ranged in height from 1.5 feet to over 3 feet with rooting depths that could have extended 5 feet (Sherrill, 1965; Weaver, 1926).

In about 1880, large herds of domestic livestock were brought into the area, which resulted in overgrazing of the land and two significant changes that affected water levels in the aquifer. First, overgrazing damages surface soil such that runoff increases and infiltration of precipitation decreases, resulting in less recharge (Warren and others, 1986; Wilcox and others, 2008). Second, overgrazing results in the expansion of honey mesquite into open grassland through the dispersal of seeds (Wilson and others, 2001), resulting in increased water-table evapotranspiration. The time period associated with overgrazing of the land is estimated to be from 1880 to about 1910 based on historical records in Sherrill (1965) and Texas State Historical Association (2008). In addition to reductions in recharge due to land-use changes, Sherrill (1965) reports that Haskell County experienced two years of major drought (1886 and 1896) and several years of light rainfall (1890 through 1893, 1901, 1904, and 1910) between 1880 and 1910, which could have contributed to a reduction in recharge during this time.

Significant changes in land use occurred again from about 1900 to 1910 due to increased farming in the area as a result of agricultural booms from about 1900 to 1910 and then again from about 1920 to 1930. Historical farming practices included deep plowing, row cropping, and long fallow periods during the winter months (Ogilbee and Osborne, 1962). Deep plowing of bare soil during the spring months could increase the potential for recharge by increasing the permeability of the soil and, thus, increasing infiltration into the subsurface. Terracing and contour farming became popular in the region in about 1929 to reduce soil erosion and likely increased recharge by reducing the amount of overland flow and enabling more precipitation to infiltrate (Ogilbee and Osborne 1962; Sherrill, 1965). In addition, clearing the land of woody vegetation and replacing it with crops resulted in decreased evapotranspiration due to fallow periods when crops are not grown and shallower rooting depths associated with short growth cycles for crops. These factors likely resulted in significant increases in recharge to the aquifer.

Historical accounts indicate that (1) the Seymour Aquifer had some saturated thickness under steady-state conditions prior to 1880 as evidenced by the existence of springs (Brune, 2002), (2) the aquifer was saturated in some areas and unsaturated in others prior to agricultural activities in the early 1900s (Gordon, 1913; Bandy, 1934, Ogilbee and Osborne, 1962; R.W. Harden and Associates, 1978), and (3) the saturated thickness of the aquifer increased dramatically in some areas due to the development of the land for agricultural purposes between about 1910 and the 1940s (Bandy, 1934; Ogilbee and Osborne, 1962; R.W. Harden and Associates, 1978). Prior to 1880, a natural, predevelopment condition is thought to have existed whereby some amount of recharge was in balance with natural discharge and the aquifer exhibited some degree of saturated thickness. Overgrazing of the land between about 1880 and 1910 resulted in recharge rates overcome by natural discharge resulting in a reduction in saturated thickness, with some areas of the aquifer becoming dry. Development of the land for agricultural purposes resulted in greater aquifer recharge than natural aquifer discharge, resulting in an increase in the saturated thickness of the aquifer.

The land use in 1992 by percentage of cultivated area (Figure 4.4.1) included 77 percent rainfed agriculture, dominated by wheat production, 13 percent irrigated agriculture, dominated by cotton production, 2 percent shrubland, 5 percent grassland, 1 percent urban, 1 percent water, and less than 1 percent forest. The area over the Seymour Aquifer that is flood irrigated, labeled as irrigated agriculture on Figure 4.4.1, was inferred from agricultural fields that display strong infrared signals and was estimated to be about 4 percent. The remaining categories of cultivated land were determined by combining land cover data from the United States Geological Survey (1992) as summarized in Table 4.4.1. Note that irrigated agriculture took precedence over all land cover data. Although, historically, the dominant crop grown in the region was cotton, over the last 30 years, it has been replaced with winter wheat. The United States Department of Agriculture (2006) indicates that the mean cultivated area for wheat was 56 percent, with a range of 30 to 70 percent, from 1973 to 2006. Cotton is still the second most produced crop in the region having a mean cultivated area of 34 percent, with a range of 23 to 50 percent, from 1973 to 2006 (United States Department of Agriculture, 2006). Other crops include alfalfa hay, corn, sorghum, oats, and peanuts. Irrigation did not become popular in the area until 1951, with the number of irrigation wells increasing from 25 to 1,100 over the period of 1951 to 1956. Table 4.4.2 provides the number of irrigation wells, estimated irrigation pumpage, and estimated acres irrigated for the years 1950 through 1956 as reported in Ogilbee and Osborne (1962). Current center pivot irrigation represents about 9 percent of the land surface over the Seymour Aquifer based on estimates calculated from 2006 county mosaics from the United States Department of Agriculture (2006).

The clay content in the upper 3 to 6 feet of the surface soil ranges from 10 to 55 percent with a mean of 32 percent based on the Soil Survey Geographic database (United States Department of Agriculture, 2007). The mean clay content is lowest in the alluvium along the Brazos River and in the sand hills in the northwestern part of Haskell County and highest along the eastern and southern edges of the aquifer in Haskell County (Figure 4.4.2). Note that the areas with the highest clay content in the surface soil generally coincide with areas of the aquifer that are dry (see Section 4.1).

The long-term mean annual precipitation, based on data from 1900 to 2007 in the city of Haskell, is 24.5 inches, with 81 percent of that occurring during the growing season of March to October

(National Climatic Data Center, 2008) (Figure 4.4.3). The coefficient of variation for this precipitation is 0.11.

The purpose of the recharge analysis presented in this section was to determine recharge rates for the Haskell-Knox-Baylor pod of the Seymour Aquifer under modern conditions and to bound recharge estimates under pre-development, steady-state conditions and estimate recharge during the time when the aquifer was gaining water. Unsaturated zone profiles from three different land-use settings were used to estimate aquifer recharge under modern conditions and historical water-table rises were used to estimate groundwater recharge for the time period from about 1910 to the 1940s when the aquifer was gaining water and for modern conditions in the aquifer. There is currently little direct evidence of recharge under steady-state conditions due to the lack of native vegetation in the area. About 97 percent of the land overlying the Seymour Aquifer was under cultivation in 1978 (R.W. Harden and Associates, 1978) and about 90 percent in 1992 (United States Geological Survey, 1992). The following sections discuss the methods used to investigate recharge to the Seymour Aquifer, discuss the results of that investigation, and summarize estimates of recharge for steady-state conditions, conditions when water levels in the aquifer were rising, and modern conditions.

4.4.1 Methods Used to Estimate Recharge

Two methods were used to investigate recharge to the Seymour Aquifer. Modern recharge was estimated using the chloride mass balance method and the results from unsaturated zone studies conducted on the Seymour Aquifer in Haskell and Knox counties. Estimated recharge during the time period of rising water levels from about 1910 to the 1940s and under modern conditions were estimated from observed water-level changes.

4.4.1.1 Chloride Mass Balance Method

From April 2003 to January 2009, the Bureau of Economic Geology conducted unsaturated zone studies in boreholes drilled into the Seymour Aquifer to estimate recharge to the aquifer. A total of 19 boreholes were drilled in three different land-use settings in Haskell and Knox counties. Two boreholes were drilled in a natural setting, 11 in a rainfed agricultural setting, and 6 in an irrigated agricultural setting (Figure 4.4.4). The boreholes were drilled using a Geoprobe direct push drill rig and the collected cores were sealed and cold stored. Soil samples from the boreholes were analyzed in the laboratory for water content, matric potential, and chloride concentrations in soil water. Gravimetric water content was calculated by weighing each sample before and after oven drying at 105 degrees Celsius for 48 hours. Matric or water potentials were measured on soil samples to determine the vertical gradient in matric potential at the time the sample was collected. Potential gradients help to determine the direction of water movement in the unsaturated zone and can provide information on both the depth of wetting fronts and evapotranspiration. Water-extractable chloride concentrations in soil water were determined by adding approximately 40 milliliters of double-deionized water to 25 grams of the soil. The mixtures were agitated on a reciprocal shaker for 4 hours, centrifuged, and the resulting supernatant was filtered through a 0.2 micrometer filter. Extract chloride concentrations were measured using ion chromatography. Soil, pore-water chloride concentrations were then calculated by dividing the supernatant chloride concentration by the gravimetric water content and multiplying by water density. Soil texture analyses of the soil samples (sand, silt, clay fractions) were conducted by hydrometric methods.

The chloride mass balance method for estimating the rate of recharge balances inputs from precipitation (P) and chloride concentration in precipitation (Cl_P) with outputs from deep drainage or recharge (R) below the root zone and chloride concentration in soil water (Cl_{sw}):

$$P \times Cl_p = R \times Cl_{sw} \qquad \Rightarrow \qquad R = \frac{P \times Cl_P}{Cl_{sw}} \tag{4.4.1}$$

The mean precipitation was taken from the long-term, city of Haskell data, which indicates a mean value of 24.5 inches per year. The chloride concentrations in precipitation were interpolated from the National Atmospheric Deposition Program (2008), for the nearest station to Haskell and Knox counties, which is in Throckmorton County. Chloride data for this station are available for the 9 years from 1984 to 1992 and yield a mean concentration of 0.19 milligrams per liter, which was increased by a factor of two to account for dry deposition (Scanlon, 2000). These data, along with the laboratory results for the borehole soil samples, were used in the chloride mass balance method.

The time required to accumulate chloride in the flushed zone was used to estimate the timing of land-use change in profiles that had not been completely flushed. This accumulation time, t, was calculated by dividing the total mass of the chloride from the land surface to the depth of interest, z, by the chloride input:

$$t = \int_0^z \frac{\theta Cl_{sw} dz}{P \times Cl_p} \tag{4.4.2}$$

where θ is the volumetric water content. Aerial photographs and land owner records were also used to constrain the timing of the land-use change. Photographs were available for 1939 and 1972.

4.4.1.2 Water-Table Fluctuation Method

The water-table fluctuation method was used to estimate groundwater recharge for modern time and for the time period when water levels in the Seymour Aquifer rose. This method is based on the premise that water-level rises in unconfined aquifers are due to recharge water arriving at the water table. The impact of discharge is neglected. Recharge is calculated as:

$$R = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \tag{4.4.3}$$

where S_y is aquifer specific yield, *h* is water-table height, and *t* is time. The water-table fluctuation method can be applied to estimate the net change in subsurface storage, also referred to as net recharge. This method is not restricted by preferential flow paths in the unsaturated zone and, in addition, may be useful to determine estimates of recharge at the location of wells exhibiting periods with long-term water-level rises.

4.4.2 Results and Discussion

This section presents the recharge estimates determined using the chloride mass balance method and the water-table fluctuation method.

4.4.2.1 Chloride Mass Balance Method

Data for the 19 boreholes used to estimate recharge using the chloride mass balance method are summarized in Table 4.4.3. This table includes the borehole number, the land-use setting, the location, the vegetation or crop coverage, the depth, the average texture determined for the soil, the laboratory-determined values for water content, matric potential, and chloride concentration, the calculated recharge rate, and the calculated chloride accumulation times. Based on the data from the boreholes, spatial variability in water content in the vadose zone of the Seymour Aquifer appears to be primarily a function of the differences in sediment texture. Variations in water content are positively correlated with percent clay and negatively correlated with percent sand (Figure 4.4.5). Chloride concentration and matric potential results do not indicate that land use is the primary control on water content in the region (Figure 4.4.6). High matric potentials and low chloride concentrations seen in the natural boreholes on the Seymour Aquifer are not consistent with unsaturated zone studies conducted in the Texas High Plains, where large chloride bulges and low matric potentials indicate that chloride has been accumulating since the Pleistocene (10,000 to 15,000 years) or longer (Scanlon and Goldsmith, 1997; Scanlon and others, 2005; 2007). The high matric potentials measured for the boreholes drilled on irrigated sites indicate that the profiles are flushed; suggesting that the variability in chloride concentrations observed in these boreholes is due to variability in the chloride concentration in the applied irrigation water. Chloride concentrations in the Seymour Aquifer are highly variable ranging from 3 to over 6,000 milligrams per liter (TWDB, 2009c).

Estimated Recharge for Natural Rangeland

Due to intensive cultivation of the land in Haskell and Knox counties over the years, representative natural land use areas are difficult to locate. Only two boreholes were drilled in a natural rangeland setting and it is questionable whether they represent natural land use prior to the introduction of ranching and farming in the area. At both locations, the mean sediment is coarse grained, with the sand content ranging from 83 to 90 percent, and mean water contents are low, ranging from 0.04 to 0.06 kg/kg. For borehole HAS03-05, the mean matric potential in the measured profile was high at -0.8 meters and the mean chloride concentrations were low, ranging from 6 to 17 milligrams per liter. The low chloride concentrations throughout borehole

HAS03-05 indicate flushing of the profile. The mean chloride concentrations in borehole HAS04-29 varied from 11 to 132 milligrams per liter and exhibit what is likely a displaced chloride bulge at the 5 meter depth, indicating deep drainage. Assuming a root zone depth of 3 feet, estimated recharge rates for the natural rangeland setting range from 0.3 to 1.1 inches per year, with a mean and median of 0.7 inches per year, and represent chloride accumulation times ranging from 23 to 130 years.

Although the natural rangeland present today likely does not completely represent land cover on the aquifer during the period of steady state prior to 1880, the recharge estimates for this land use provide the best estimates of recharge under steady-state conditions. It is estimated that recharge under steady-state conditions was near or less than the mean value of 0.7 inches per year estimated for natural rangeland.

Estimated Recharge for Rainfed Agriculture

A total of 11 boreholes were drilled beneath rainfed (dryland) agriculture. The profile was partially flushed in two of the boreholes and totally flushed in nine of the boreholes. Sediments in the profiles of these boreholes are generally coarse grained, with a mean sand content of 75 percent, and textures range from sandy clay loam to sandy loam. All but borehole HAS03-07 are located in the sand hills on the western side of the aquifer in northwestern Haskell County (see Figure 4.4.4). Although borehole HAS03-07 is located northeast of the sand hills, the textural variation in this borehole is not significantly different from that in the boreholes located in the sand hills (Table 4.4.3). The range in mean water content for the rainfed profiles is low, ranging from 0.07 to 0.14. Mean chloride concentrations are also low, ranging from 6 to 37 milligrams per liter, and mean matric potentials are high, ranging from -1.8 to -5.4 meters. Estimated recharge rates for rainfed agriculture range from 0.4 to 1.7 inches per year, with a mean of 1.1 inches per year and a median of 0.9 inches per year. These rates are similar to those estimated for rainfed agriculture in the Southern High Plains (Scanlon and others, 2007). Chloride accumulation times for the rainfed profiles range from 21 to 98 years.

The timing of land-use change for partly flushed borehole HAS03-07 is 60 years, which correlates well with land owner records of initial cultivation in 1945. Although the land-use transition date is not known for the other partly flushed borehole (HAS04-27), the calculated chloride accumulation time of 75 years indicates a transition date of about 1933. This date is older than the earliest available aerial photography from 1939, which indicates that the area was cultivated by that time. The profiles in the other boreholes did not extend deep enough to provide data with which the date of land-use change could be estimated.

Estimated Recharge for Irrigated Agriculture

Six boreholes from irrigated sites were evaluated. There were strong variations in the soil texture in these boreholes; three were drilled in the sand hills where the mean clay content of the surface soil is 22 percent and three were drilled where the mean clay content of the surface soil is 29 percent. The profiles in these six boreholes have mean water contents that range from 0.11 to 0.15 and high mean matric potentials that range from -1.2 to -34.2 meters. Mean chloride concentrations in the profiles are highly variable, ranging from 23 to 2,586 milligrams per liter. This variability likely represents variations in the concentration of chloride in the irrigation water. Chloride concentrations in the Seymour Aquifer are highly variable and range from 3 to over 6,000 milligrams per liter (TWDB, 2009c).

Although there are significant uncertainties associated with variability in the amount of irrigation water applied and the chloride concentrations of the irrigation water, estimates of irrigation amounts and chloride concentrations were used to calculate recharge rates using the data from the boreholes drilled beneath irrigated sites. Actual irrigation water inputs were estimated where owner records were available; otherwise, an application rate of 1 foot per year was assumed. Chloride concentrations in the irrigation water were estimated from mean chloride concentrations of water in nearby wells. The estimated chloride concentrations for the irrigation water at the six borehole locations were highly variable, ranging from 7 to 330 milligrams per liter. Estimated recharge rates for irrigated profiles range from 1.5 to 5.8 inches per year, with a mean of 3.2 inches per year and a median of 2.6 inches per year. Although there were distinct textural variations with three of the profiles located in the higher clay content soils to the northeast, calculated recharge rates did not vary systematically with soil texture. Estimated chloride accumulation times for the irrigated profiles range from 16 to 64 years.

Spatial Mean Recharge Estimate

A spatial mean recharge rate of 1.3 inches per year was estimated for the Seymour Aquifer in Haskell and Knox counties by weighting the estimated mean recharge rates for the generalized 1992 National Land Cover Data land use areas. Rainfed agriculture was weighted as 79 percent, irrigated agriculture as 13 percent, and shrubland, grassland, and forest areas were combined to form the natural land use representing the remaining 8 percent. Urban and water land cover were not included in the spatial estimate.

4.4.2.2 Water-Table Fluctuation Method

Recharge rates were calculated using the water-table fluctuation method and the water-level rises documented in Bandy (1934) and using water levels observed in three Seymour Aquifer wells having long-term data. Bandy (1934) reported several accounts of large water-level rises in wells during the period from about 1910 to 1934 from longtime residents in the vicinity of the cities of O'Brien and Rochester in Haskell County. Those rises ranged from 5 to 49 feet over time periods ranging from 4 to 23 years (Table 4.4.4). Wells located to the west of O'Brien showed a range in increase of 0.5 to 1.8 feet per year with a mean of 1 foot per year. Wells located east and southeast of Rochester showed a range in increase of 1.0 to 2.8 feet per year with a mean of 2.0 feet per year. Note that increases in two of the wells could not be used in this analysis because the date of the first measurement was not given in Bandy (1934). Assuming a specific yield of 0.15 (R.W. Harden and Associates, 1978), these water-level rises indicate recharge rates ranging from 0.8 to 5.0 inches per year, with a mean of 2.5 inches per year and a median of 2.0 inches per year. This range corresponds to 3 to 20 percent of the long-term average precipitation of 24.5 inches per year.

Long-term water-level data for three Seymour Aquifer wells in three different locations indicate varying responses to precipitation and irrigation within the aquifer (Figure 4.4.7). The water table was most responsive to precipitation events in well 21-34-902 located in the central portion of the aquifer. The water-level response was slightly reduced in well 21-42-701 located in the sand hills to the southwest, and substantially reduced in well 21-35-301 located in an area predominately covered with surface soil having a clay content of 29 percent. There are limited data available for water levels in the 1940s, but the decline in water levels from 1944 to 1951, seen in well 21-42-701 (see Figure 4.4.7), along with a decreasing trend in precipitation over that time period (see Figure 4.4.3), indicate that water levels were declining from highs seen in the 1930s. Water levels continued to decline during the 1950s, due to the drought conditions and the widespread implementation of irrigation pumpage in the region. Use of groundwater for irrigation purposes began in about 1951, when over the subsequent 5-year period the number of irrigation wells increased from 25 to 1,100. Water levels began to rise in well 21-42-701 in the late 1950s, highlighting the wells quick response to the above average precipitation that occurred in 5 out of the 8 years between 1957 and 1964. Over the same period, water levels in wells 21-35-301 and 21-34-902 showed a delayed regional response to the increased precipitation, with rises not occurring until the mid-1960s.

From 1965 to 1973, water levels in wells 21-42-701 and 21-34-902 show a general increase until 1973 due to higher than normal precipitation in 7 of the 9 years. Although increases in water level are seen during this period in well 21-35-301, the overall water level is decreasing. The decrease in water levels recorded in all three wells between 1974 and 1980 corresponds to a period when precipitation in 5 out of the 7 years fell below average. Water levels then rose until a significant decrease was seen in the mid-1990s in response to drought conditions.

The water-table fluctuation method to estimate recharge rates was applied to the long-term water-level trends in these three wells. However, heavy pumping of the aquifer could impact the recharge calculation by altering the water-table response during times of peak drawdown and well recovery. Evaluations of regional response in other localized wells were used to help constrain these impacts. Recharge rates were calculated from the documented long-term water-table rises between the periods of January 9, 1957 to December 5, 1972 and November 15, 1977 to October 14, 1986 in well 21-42-701; January 19, 1966 to January 6, 1974 and November 11, 1980 to October 12, 1987 in well 21-34-902; and January 20, 1967 to November 12, 1970, January 11, 1971 to December 7, 1972, and November 5, 1981 to October 16, 1987 in well 21-35-301 (Table 4.4.5). Using a specific yield of 0.15 (R.W. Harden and Associates, 1978), estimated recharge rates of 2 to 5.5 inches per year, with a mean of 3.5 inches per year and a median of 2.7 inches per year, were calculated. These recharge rates correspond well with the range of 0.8 to 5.0 inches per year, with a mean of 2.5 inches per year and a median of 2.0 inches per year, calculated from the water-level rises observed prior to the introduction of heavy pumping for irrigation purposes reported by Bandy (1934), as well as to the rates of 1.5 to 5.8 inches per year, with a mean of 3.2 inches per year and a median of 2.6 inches per year, calculated using data from the irrigation boreholes. These average values are higher than the 2.2 inches per year reported by R.W. Harden and Associates (1978), but may be considered an upper bound.

4.4.3 Summary and Recommendations

Historical accounts indicate that the Haskell-Knox-Baylor pod of the Seymour Aquifer had some saturated thickness, as evidenced by flowing springs, under steady-state conditions prior to 1880. Water levels in the aquifer appear to have fallen during the period of overgrazing of the land by domestic livestock from about 1880 to 1910 resulting in local areas where the aquifer was dry. Large water-table rises occurred after the area was cultivated in the early 1900s, which resulted in an increase in the saturated thickness of the aquifer.

Modern recharge rates were calculated using the chloride mass balance method and data collected from 19 boreholes located in three land-use settings and using water-level fluctuation observations in three Seymour Aquifer wells. The recharge rates calculated with the chloride mass balance method varied based on the land-use setting (Table 4.4.6). Data collected from the boreholes drilled in natural rangeland indicate a range in recharge rate of 0.3 to 1.1 inches per year with a mean of 0.7 inches per year and a median of 0.7 inches per year. Estimated recharge rates ranging from 0.4 to 1.7 inches per year, with a mean of 1.1 inches per year and a median 0.9 inches per year, were determined using data collected from boreholes drilled in the rainfed agriculture setting. Data collected from the boreholes drilled in the irrigated agriculture setting yielded a range in recharge rate of 1.5 to 5.8 inches per year, with a mean of 3.2 inches per year and a median of 2.6 inches per year. Weighting the recharge estimates by land cover area resulted in a spatial mean recharge estimate for the Seymour Aquifer of 1.3 inches per year.

Due to uncertainties associated with irrigation water inputs, the most reliable estimates are from the rainfed sites. Although recharge rates under irrigation sites were high, they are consistent with the range of values calculated using the water-table fluctuation method and long-term water-level data from three wells (range of 2 to 5.5 inches per year, with a mean of 3.5 inches per year and a median of 2.7 inches per year) as well as the values calculated using the large water-level rises reported in Bandy (1934) (range of 0.8 to 5.0 inches per year, with a mean of 2.5 inches per year and a median of 2.0 inches per year). The recharge estimates calculated using both the chloride mass balance and water-table fluctuation methods are summarized in Table 4.4.6.

A spatial distribution of modern recharge based on land use and mean clay content of surface soil was developed using the estimated recharge rates calculated by the analysis presented here. For the sand hills, which have a mean clay content of 22 percent in the surface soil, in the western portion of the aquifer in northwestern Haskell County, recharge estimates were calculated for natural rangeland, rainfed agriculture, and irrigated agriculture based on data from boreholes drilled in these three land-use settings. The medians of those calculated values were applied to the different land-use types on the areas of the aquifer with a clay content of 22 percent in the surface soils. Although data were not available to directly estimate a recharge rate for natural and rainfed land-use settings on the other surface soils, a scaling factor based on the ratio of the unsaturated soil permeability for the new soil type to the unsaturated soil permeability for the soil type on the sand hills was used to estimate values. The values for the unsaturated soil permeability were developed using the Rosetta Model (United States Department of Agricultural, 1999), which uses soil texture data to estimate unsaturated hydraulic properties. Regardless of the mean soil content in the surface soil, all irrigated land was assigned a recharge rate of 3.2 inches per year, which is the value estimated for the boreholes drilled in irrigated areas. Figure 4.4.8 shows the resultant estimated spatial distribution in recharge rates for the Seymour Aquifer under modern conditions.

Figure 4.4.8 indicates the highest recharge rates in the portion of the aquifer overlain by surface soil with a mean clay content of 16 percent. Although the higher permeability of this soil would make it conducive to recharge, the portion of the aquifer adjacent to the Brazos River is an area of natural discharge. Groundwater levels in this area are very close to land surface and any recharge there is expected to be rejected to either evapotranspiration or baseflow to the Brazos River. The recharge in Figure 4.4.8 is therefore considered an overestimate in the region adjacent to the Brazos River.

None of the estimates of recharge to the Seymour Aquifer directly apply to the time period when the aquifer was at steady state prior to 1880. However, recharge during that time was likely similar to or less than that on current locations with natural rangeland. Recharge estimates using data for the boreholes drilling in areas of natural rangeland on the sand hills, which have a mean clay content in the surface soil of 22 percent, indicate a range in recharge of 0.3 to 1.1 inches per year, with a mean and median of 0.7 inches per year. It is estimated the recharge under steady-state conditions was around 0.7 inches per year where the clay content of the surface soil is 22 percent. Estimated steady-state recharge for the remainder of the aquifer with other surface soils was developed using the ratio of the unsaturated hydraulic conductivity for the new soil type and the unsaturated hydraulic conductivity for the soil type on the sand hills.

The portion of the aquifer where large water-level rises were observed in the early 1900s lies beneath the sand hills near the cities of Rochester and O'Brian. The mean recharge rate estimated using the observed water-level rises reported in Bandy (1934) is 2.5 inches per year. That rate was assumed for the time period from about 1910 to about 1940 for areas of the aquifer with a mean clay content of 22 percent in the surface soil. Estimated recharge during this time period for the remainder of the aquifer with other surface soil types was developed using the ratio of the unsaturated hydraulic conductivity for the new soil type and the unsaturated hydraulic conductivity for the soil type on the sand hills.

This section provides an estimate of recharge rates for the Seymour Aquifer under steady-state conditions, conditions when water levels in the aquifer were rising, and modern conditions. These estimates were developed based on limited point data from 19 boreholes drilled in the aquifer and on observed water-level rises. Therefore, their applicability to regional recharge is limited.

Table 4.4.1 Land use based on cultivated areas.

USGS (1992) Land Cover Class	Combined Land Cover Classes Based on Cultivated Area
Open water	Open water
Low Intensity Residential	Urban
High Intensity Residential	
Commercial/Industrial/Transportation	
Deciduous Forest	Forest
Evergreen Forest	
Mixed Forest	
Shrubland	Shrubland
Grasslands/Herbaceous	Grassland
Bare Rock/Sand/Clay Pasture/Hay Row Crops Small Grains Urban/Recreational Grasses	Rainfed Agriculture
Woody Wetlands	Wetlands
Emergent Herbaceous Wetlands	

USGS = United States Geological Survey

Table 4.4.2 Summary of development of irrigation pumpage in Haskell and Knox counties from 1950 to 1956 (after Ogilbee and Osborne, 1962).

Year	Number of Irrigation Wells	Estimated Irrigation Pumpage (acre-feet)	Estimated Irrigated Acres
1950	3	100	nr
1951	25	900	nr
1952	115	6,700	5,700
1953	170	9,900	8,500
1954	290	16,800	14,500
1955	600	34,800	30,000
1956	1,100	63,800	50,000

nr = no value reported in Ogilbee and Osborne (1962)

Table 4.4.3 Summary of recharge rates estimated from unsaturated zone studies in the Seymour Aquifer.

Borehole	Latitude	Longitude	Vegetation/Crop Coverage	Depth (m)	Average Soil Texture (%)			Water Content (kg/kg)			Matric potential (m)			Chloride Concentration (mg/L)			Recharge Rate (in/yr)	Chloride Accumula-tion Time (yr)
					Sand	Silt	Clay	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max		
Natural Land-Use Setting																		
HAS03-05	33.31190	-99.94210	Sage/Grass	5.79	90.2	3.1	6.9	0.06	0.01	0.15	-0.8	-1.0	-0.2	11	6	17	1.1	23
HAS04-26	33.34532	-99.90930	Mesquite/Grass	5.94	82.6	6.9	10.5	0.04	0.02	0.07	-	-	-	132	23	412	0.3	130
Rainfed Agriculture Land-Use Setting																		
HAS03-07	33.38490	-99.71950	Wheat	3.51	71.8	10.6	17.5	0.09	0.02	0.17	-	-	-	37	14	76	0.4	60
HAS04-27	33.21992	-99.88460	Wheat/Alfalfa/Cotton	5.56	75.0	13.0	12.0	0.11	0.06	0.16	-	-	-	32	6	80	0.9	75
HAS03-01	33.26880	-99.92290	Cotton/Wheat	6.10	80.9	6.2	12.9	0.07	0.02	0.12	-1.8	-4.4	-0.7	14	4	29	0.8	50
HAS03-03	33.26980	-99.91320	Cotton	6.10	78.4	7.2	14.5	0.09	0.02	0.15	-	-	-	21	6	74	0.8	59
HAS03-04	33.26360	-99.92380	Wheat	3.66	70.8	6.4	22.8	0.10	0.02	0.16	-	-	-	12	3	40	1.6	29
HAS04-30	33.19278	-99.86702	Cotton	4.57	56.8	15.1	28.1	0.14	0.10	0.16	-	-	-	7	6	9	1.4	27
HAS04-31	33.18933	-99.87683	Wheat	3.66	54.1	18.8	27.1	0.14	0.05	0.17	-	-	-	6	5	8	1.7	21
HAS04-32	33.25890	-99.88990	Cotton	9.75	78.8	8.6	12.6	0.08	0.03	0.14	-5.4	-6.8	-3.4	15	6	31	0.9	64
HAS04-25	33.21898	-99.89600	Cotton	12.19	80.7	7.5	12.3	0.09	0.03	0.17	-	-	-	19	4	66	1.1	98
HAS04-28	33.28415	-99.92400	Bermuda	10.36	79.0	5.2	15.8	0.08	0.03	0.18	-4.1	-6.2	-2.6	19	6	59	0.8	68
HAS04-24	33.21738	-99.89898	Cotton	9.60	75.5	9.2	15.3	0.10	0.03	0.15	-5.2	-6.3	-3.4	10	4	42	1.5	43
Irrigated Agriculture Land-Use Setting																		
HAS03-06	33.30910	-99.92450	Bermuda	6.10	77.3	7.6	15.1	0.12	0.05	0.15	-1.2	-2.1	-0.4	94	30	202	1.5	39
HAS04-23	33.34925	-99.89683	Peanuts	3.35	72.9	13.2	13.9	0.14	0.05	0.18	-	-	-	292	83	538	2.5	16
HAS04-29	33.21905	-99.88372	Cotton/Peanuts/Alfalfa	10.67	75.3	9.2	16.1	0.15	0.10	0.19	-	-	-	23	5	36	5.8	25
HAS07-01	33.39712	-99.66627	Cotton	6.92	46.3	23.9	29.7	0.12	0.08	0.18	-12.9	-38.2	-1.18	477	13	138	2.8	64
HAS07-02	33.43128	-99.58228	Cotton	6.40	49.4	26.4	24.2	0.14	0.05	0.19	-34.2	-71.7	-4.4	2586	1918	3956	1.6	28
HAS07-03	33.45912	-99.69360	Cotton	12.80	49.4	26.4	24.2	0.11	0.07	0.19	-3.2	-5.8	-0.5	205	132	372	4.7	19

m = meters
%= percent
kg/kg = kilograms per kilogram
mg/L = milligrams per liter
Min = minimum
Max = maximum
in/yr = inches per year
yr = years

Table 4.4.4 Average water-level rises reported in Bandy (1934) for the Rochester and O'Brien areas in Haskell County (after R.W. Harden and Associates, 1978).

Location	Well Number	Year	Depth-to-Water (feet)	Year	Depth-to-Water (feet)	Number of Years	Increase in Water Level (feet)
O'Brien	A-0	unknown	60	1934	46	unknown	14
O'Brien	A-4	1919	29	1934	22	15	7
O'Brien	Corother	1928	20	1934	15	6	5
O'Brien	A-8	1922	39	1934	17	12	22
O'Brien	Needmore School	1921	42	1934	27	13	15
O'Brien	A-30	1924	42	1934	31	10	11
O'Brien	A-37	1924	19	1934	14	10	5
Rochester	C-29	1911	51	1934	16	23	35
Rochester	C-31	1924	40	1934	30	10	10
Rochester	Cloud	1930	23	1934	12	4	11
Rochester	D-13	unknown	75	1934	6	unknown	69
Rochester	D-17	1915	60	1934	11	19	49

Table 4.4.5 Recharge rates estimated using the water-table fluctuation method and long-term water-level data for three Seymour Aquifer wells.

State Well Number	Time Period	Number of Years	Increase in Water Level (feet)	Estimated Recharge Rate (inches per year)
21-42-701	1/9/1957 to 12/5/1972	15.0	22.0	2.6
21-42-701	11/15/1977 to 10/14/1986	8.9	9.8	2.0
21-35-301	1/20/1967 to 11/12/1970	3.0	7.0	4.2
21-35-301	1/11/1971 to 12/7/1972	1.9	2.9	2.7
21-35-301	11/5/1981 to 10/16/1987	6.0	9.8	2.4
21-34-902	1/19/1966 to 1/6/1974	8.8	27.0	5.5
21-34-902	11/11/1980 to 10/12/1987	6.9	20.0	5.2

Table 4.4.6 Summary of all estimates of recharge rate for the Seymour Aquifer.

Method	Type Data	Recharge (inches per year)			
		Mean	Minimum	Maximum	Median
Chloride Mass Balance	Natural Boreholes	0.7	0.3	1.1	0.7
Chloride Mass Balance	Rainfed Boreholes	1.1	0.4	1.7	0.9
Chloride Mass Balance	Irrigated Boreholes	3.2	1.5	5.8	2.6
Water-Table Fluctuation	Long-Term Water-Level Data	3.5	2	5.5	2.7
Water-Table Fluctuation	Water-Level Rises Reported in Bandy (1934)	2.5	0.8	5.0	2.0

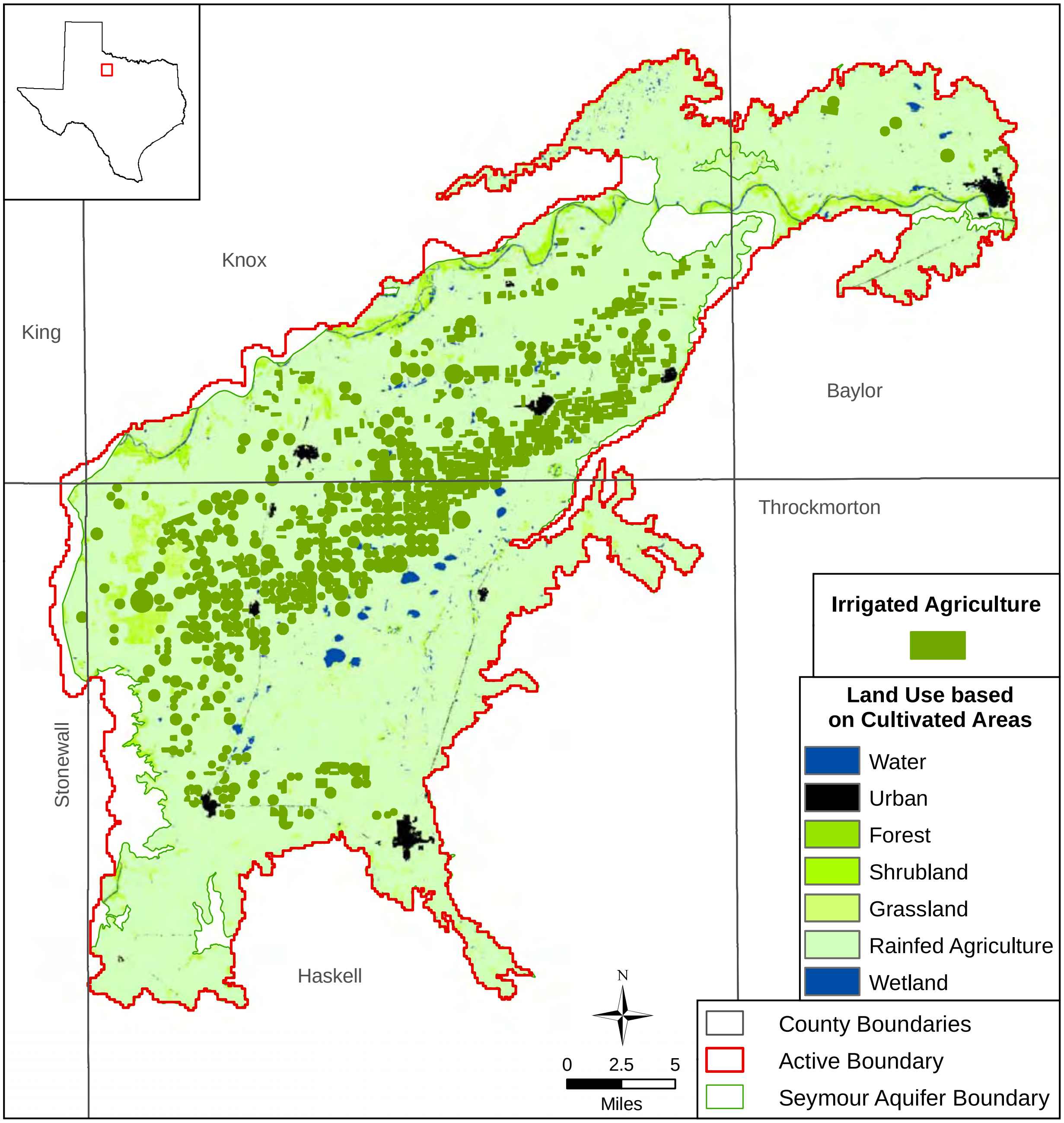


Figure 4.4.1 Land use based on cultivated areas (modified from United States Geological Survey, 1992) and irrigated agriculture.

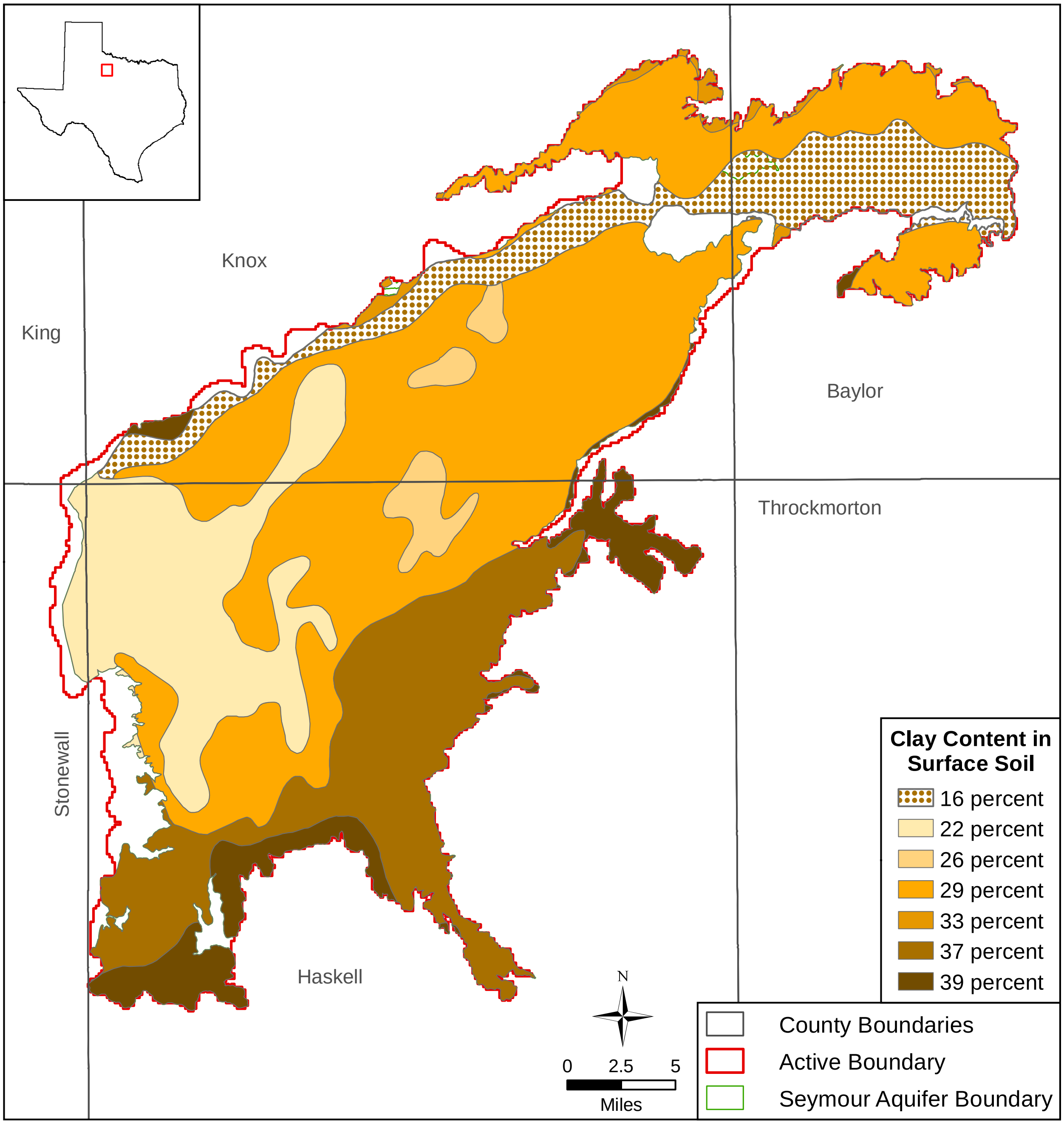


Figure 4.4.2 Clay content in surface soil (United States Department of Agriculture, 2007).

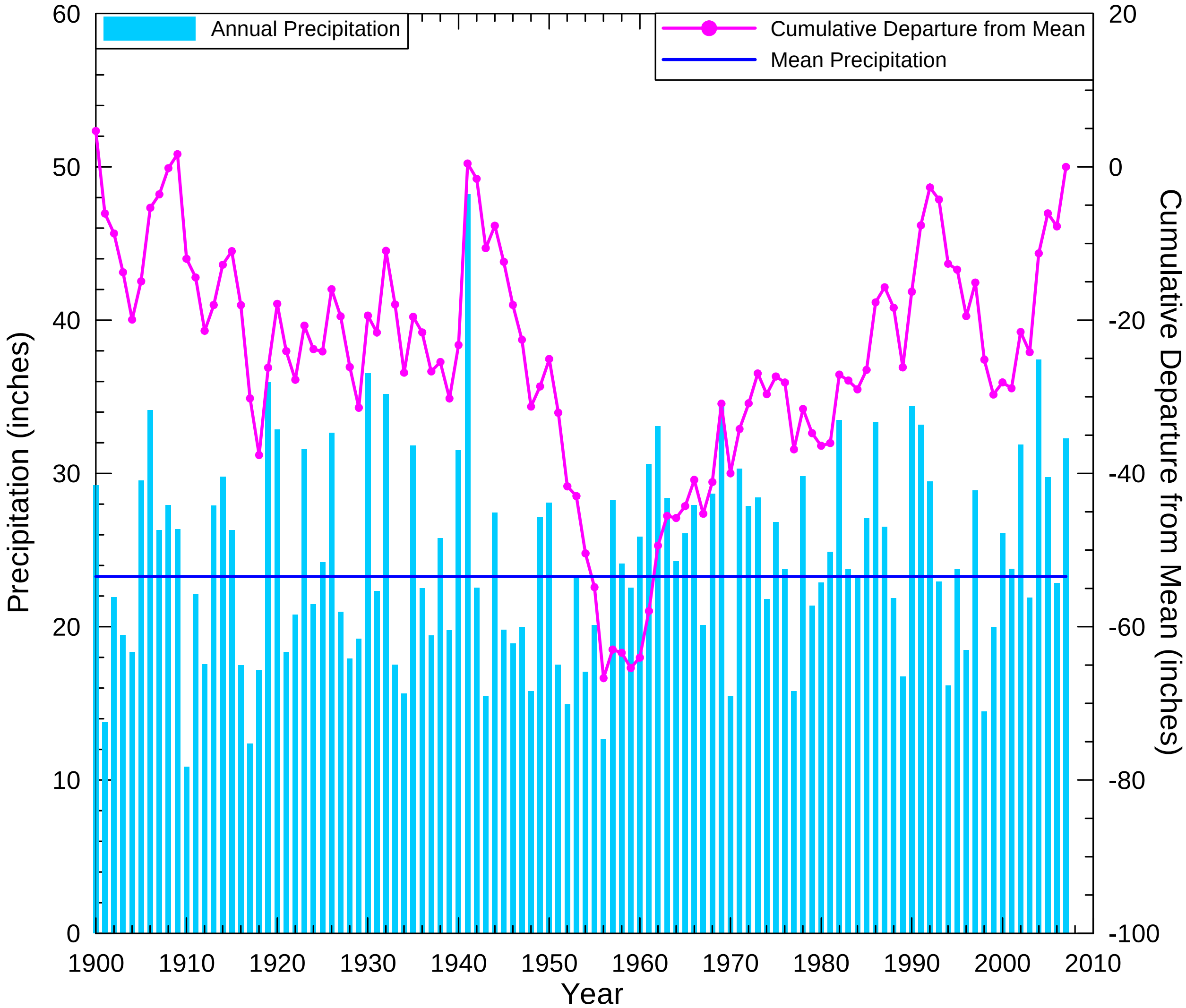


Figure 4.4.3 Annual precipitation for the city of Haskell (National Climatic Data Center, 2008).

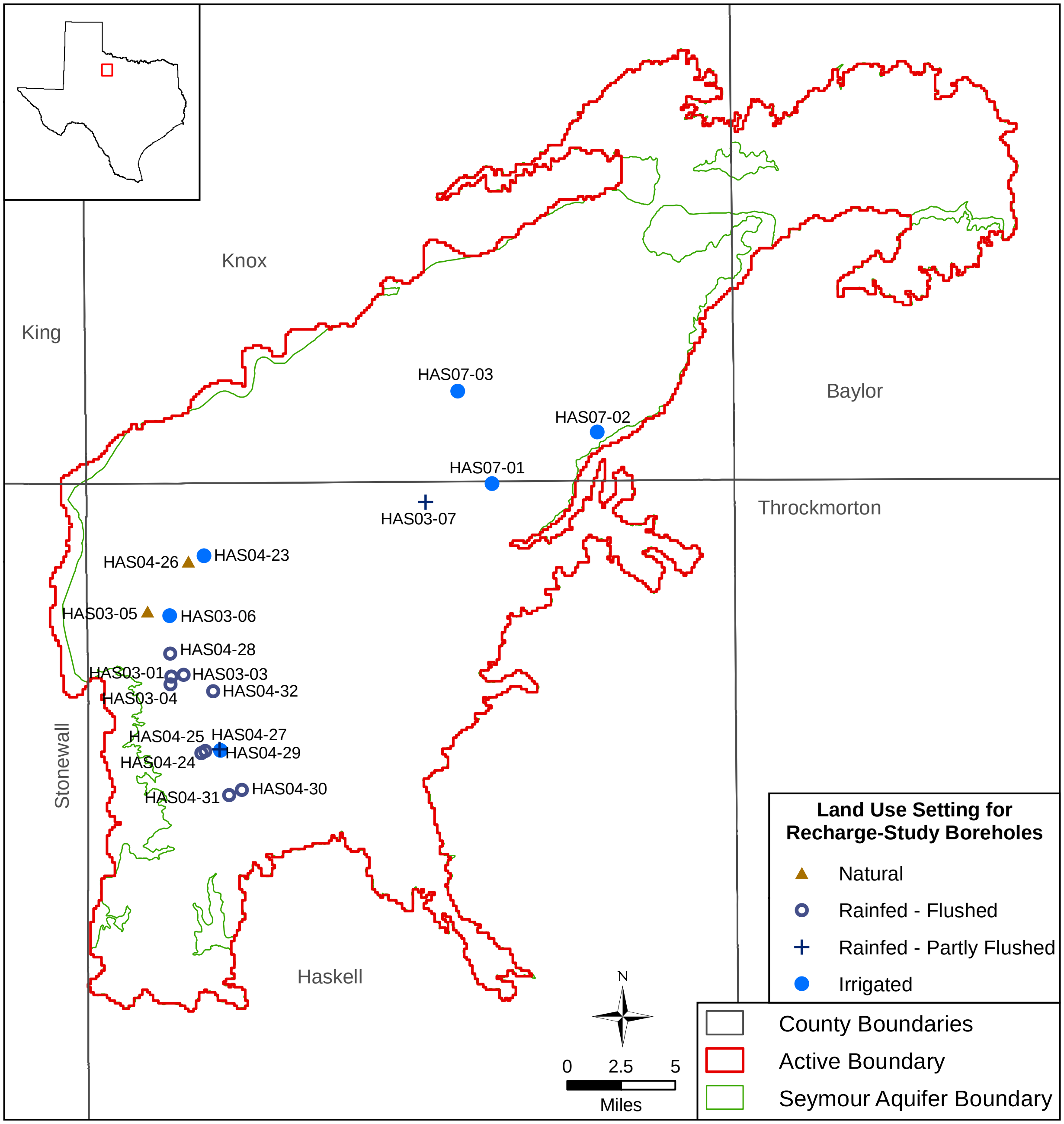
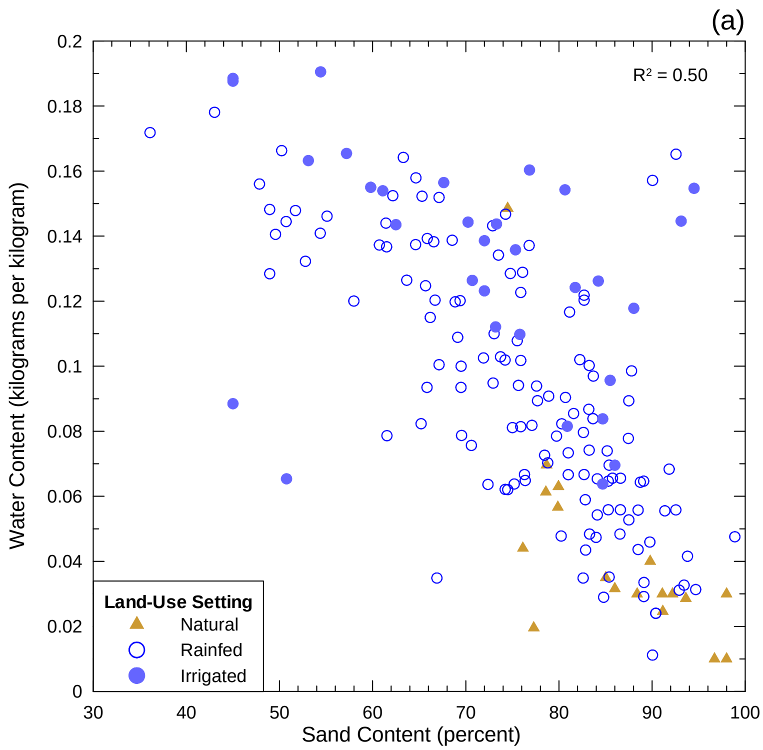


Figure 4.4.4 Location of boreholes for the unsaturated zone studies in the Seymour Aquifer.



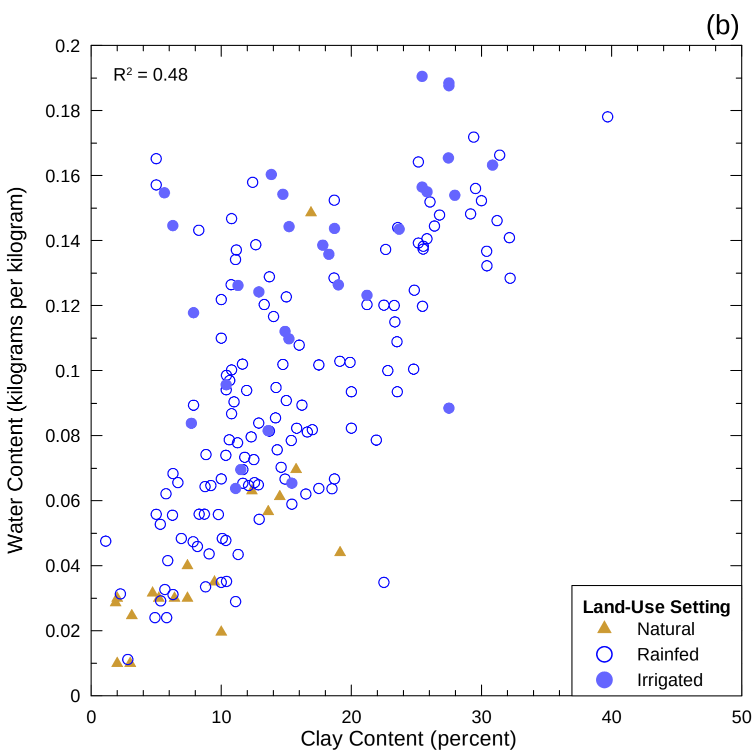


Figure 4.4.5 Relationship between (a) water content and sand content and (b) water content and clay content for boreholes in the unsaturated zone studies in the Seymour Aquifer.