In Hot Water? How Climate Change May (or May Not) Affect the Groundwater Resources of Texas

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ABSTRACT

The 2007 report by the Intergovernmental Panel on Climate Change suggested that Texas is likely to see a warmer climate, a decrease in mean annual runoff, an increase in flow seasonality, and an increase in the number of extreme drought events. All of these are likely to affect the water resources of Texas, including the groundwater resources. In our assessment of the susceptibility of Texas's aquifers to climate change, how quickly an aquifer recharges, the geologic setting, and land and water use will dictate how climate change may affect any given aquifer. Groundwater resources with high recharge rates, such as karstic aquifers like the Edwards (Balcones Fault Zone) Aquifer, and highly permeable clastic aquifers, like the Lipan Aquifer, are very susceptible to changes in climate while others with much slower recharge rates would not show effects for decades if not centuries. The groundwater resources in dipping clastic aquifers—aquifers with an unconfined recharge zone updip and a confined zone downdip, such as the Trinity Aquifer north of the Colorado River, the Carrizo-Wilcox Aquifer, and the Gulf Coast Aquifer—are unlikely to be affected by climate change influenced recharge as long as the flux of water moving downdip remains less than the total recharge rate. General municipal and agricultural water use is expected to increase due to changes in climate; however, increases in water use due to expected increases in population in Texas are expected to be far greater. Nonetheless, climate change could induce greater reliance on groundwater if surface water resources become less reliable, and increases in agricultural usage would increase the depletion rate of the Ogallala Aquifer and lower water levels in other aquifers. More research is needed to better understand what the climate models suggest for Texas and recharge processes.

INTRODUCTION

Global climate models predict a warmer planet. For Texas, this could mean changes to our climate—specifically temperature, evaporation, rainfall, and drought. Changes in climate will also likely affect the availability of our water resources and our plans to meet expected demands for water in the future. For surface water resources, the connection between climate and water availability is clearer and more immediate, although it does have its complications, such as changing land use associated with climate change. With the exception of karstic aquifers and highly permeable clastic aquifers—which are similar to surface water systems in their responsiveness to climatic variation—much less study and attention has been given to the effects climate change may have on groundwater resources.

The purpose of this paper is to (1) summarize how climate change may affect Texas, (2) discuss how climate change may affect groundwater, (3) hypothesize how climate change may directly and indirectly affect the aqui-

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fers of Texas, (4) present modeling results on how climate change may affect the Edwards (Balcones Fault Zone) Aquifer, and (5) discuss areas of future research needs. We base our comments on a review of the most recent Intergovernmental Panel on Climate Change (IPCC) reports, a review of literature specific for Texas, and our understanding of the state's aquifers—especially with respect to modeling them—over the past decade.

CLIMATE CHANGE AND TEXAS

The most recent report from the IPCC stated that "[w]arming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" (Bernstein et al., 2007, p. 2). As far as implications for water resources, the IPCC stated that there will be (1) a "very likely increase in frequency of hot extremes, heat waves, and heavy precipitation," (2) a "likely increase in tropical cyclone intensity," and (3) "very likely precipitation increases in high latitudes and likely decreases in most subtropical land regions" (Bernstein et al., 2007, p. 8).

The IPCC does not specifically address climate change in Texas; however, the report does include a section that focuses on the North American continent. We used the maps in this section to discern what the IPCC report projects for Texas. The IPCC projects a 2.5-3.5°C (4.5-6°F) increase in surface temperature for much of the United States, including Texas, by 2090 to 2099 relative to average temperatures between 1980 and 1999 (based on Bernstein et al., 2007, their Figure SPM-6). Several climate models suggest a 10 to 30 percent decrease in mean annual runoff in Texas by the 2050s although one model suggests little effect with a greater than 30 percent increase in the southern part of the state (based on Kundzewicz et al., 2007, their Figure 3.3, which in turn is based on Arnell, 2003). An ensemble of 12 climate models suggests that mean annual runoff may decrease 0 to 10 percent for much of Texas by 2050 with little change along the Gulf Coast (based on Kundzewicz et al., 2007, their Figure 3.4, which in turn is based on Milly et al., 2005). Many studies suggest that flow seasonality may increase (Kundzewicz et al., 2007) with more of the total precipitation arriving during the wet season.

In a recent presentation of preliminary results of statistically downscaled global climate models for Texas, Charles Jackson with the University of Texas noted that climate models suggest an average increase in temperature of about 1.7°C (3°F), an average increase in precipitation of about 1 in (2.5 cm) per year along the Gulf Coast and an average decrease of about 0.5 in (1.3 cm) per year for most of the rest of the state (Jackson, 2008). Jackson also noted that there is quite a bit of variation between the different climate models on what may be in store for Texas, with some models projecting increases in precipitation for the entire state.

CLIMATE CHANGE AND WATER—GLOBAL PERSPECTIVE

Transferring the results from global climate models into water resources models can be problematic. The IPCC states that "quantitative projections of changes in precipitation, river flows, and water levels at the river-basin scale remain uncertain" (Kundzewicz et al., 2007, p. 175). Climate projections from global climate models are not easy to incorporate into hydrological studies (Allen and Ingram, 2002; Kundzewicz et al., 2007) because of significant uncertainties in the modeling process (Mearns et al., 2001; Allen and Ingram, 2002; Forest et al., 2002; Stott and Kettleborough, 2002; Kundzewicz et al., 2007). The various global climate models tend to agree more on geographical changes in temperature than on rainfall (Meehl et al., 2007; Kundzewicz et al., 2007). Surface water studies in Great Britain suggest that uncertainty in global climate model structure was the greatest uncertainty in predicting flood statistics followed by uncertainty in future CO_2 scenarios followed by uncertainty in hydrologic modeling (Kay et al., 2006, and Prudhomme and Davies, 2007, both as cited in Kundzewicz et al., 2007).

Nonetheless, scientists have looked at where the climate models tend to agree to suggest how climate change may affect water resources. The IPCC stated that (1) "[t]here is high confidence that by mid-century, annual river runoff and water availability are projected to increase at high latitudes (and in some tropical wet areas) and decrease in some dry regions in the mid-latitudes and tropics" and (2) "[t]here is also high confidence that many semi-arid areas (e.g., Mediterranean basin, western United States, southern Africa and northeast Brazil) will suffer a decrease in water resources due to climate change" (Bernstein et al., 2007, p. 8). It is also "very likely" that the frequency of heavy precipitation events will increase leading to adverse effects on surface water and groundwater quality although water scarcity may be relieved (Bernstein et al., 2007).

The IPCC stated with high confidence that the western United States will suffer a decrease in water resources due to climate change (Kundzewicz et al., 2007). Seager et al. (2007) predicted a new baseline for the southwestern United States within the next 100 years that looks like the dust bowl years (with the western half of Texas included in his definition of the southwest). Global climate models predict that larger parts of the planet will be under drought conditions at any given time, from 1 to 3 percent currently to 30 percent by the 2090s, and that the number of extreme drought events per 100 years will likely increase 2 to 6 times by the 2090s (Burke et al., 2006, as referenced by Kundzewicz et al., 2007).

CLIMATE CHANGE AND WATER—TEXAS

There have been several studies on how climate change might affect the water resources of Texas, some of which are included in North et al. (1995), a book focused on climate change and Texas (and in the process of being updated with more recent analysis). Ward (1993, as referenced by Ward and Valdes, 1995), assuming a 2° C increase in temperature and a 5 percent decrease in precipitation, projected a 2 percent decrease in evapotranspiration, a 12 percent increase in lake evaporation, a 26 percent decrease in runoff, a 16 percent increase in water consumption, and a 36 percent decrease in flows to the coast, all for normal conditions.

There have also been studies concerning the potential effects of climate change on:

- the reservoirs in the Trinity, Colorado, and Rio Grande river basins (Schmandt and Ward, 1991, as referenced by Ward and Valdes, 1995),
- the Upper Brazos River (Dorman, 2003),
- the Gulf Coast (Twilley et al., 2001),
- the Big Bend region (Herbert, 2004),
- the Brazos River Valley (Wurbs et al., 2005), and
- general rainfall and temperature across the state (Amick, 2005).

There has been limited work on how climate change might affect groundwater in Texas. EPA (1997) noted that there could be less recharge to the aquifers of Texas because of climate change. Much of the rest of the work is, not surprisingly, focused on the Edwards Aquifer, a karstic aquifer with a quick response time to changes in precipitation. Loáiciga et al. (1996) noted that the Edwards Aquifer area including the Guadalupe River basin (something he referred to collectively as a "regional watershed") is one of the most vulnerable to climate-change impacts in the United States. Loáiciga et al. (2000) noted that pumping would need to be reduced to 140,000 acre-ft per year to keep Comal Springs flowing at 100 ft^3 (3 m^3) per second for a repeat of the drought of the 1950s (as compared to 165,000 acre-ft per year proposed by Thorkildsen and McElhaney, 1992, for historical conditions).

Chen et al. (2001) also looked at the possible effects of climate change on the Edwards Aquifer and projected a 1.5 to 3.5 percent increase in municipal demand, 31.3 percent increase in irrigation water requirements, a 20 to 30 percent decrease in recharge, a 10 to 16 percent decrease in flow at Comal Springs by 2030, and a 20 to 24 percent decrease in flow at Comal Springs by 2090. Chen et al. (2001) also noted that trigger levels to protect spring flow for endangered species may have to be reduced by 35,000 to 50,000 acre-ft per year by 2030, and by 55,000 to 80,000 acre-ft per year by 2090.

HOW CLIMATE CHANGE MAY AFFECT GROUNDWATER

There has been very little research on the impact of climate change on groundwater (Alley, 2001; Kundzewicz et al., 2007). The IPCC noted that there is no ubiquitous trend in groundwater systems that can be directly correlated to climate change, primarily because of the lack of data (Kundzewicz et al., 2007). We believe this is due, in part, to the uncertainties in estimating recharge and teasing out what component of recharge is natural or influenced by land use change let alone changes in climate, especially when those changes, current and projected, are of a much less magnitude than natural variations. Furthermore, in many aquifers, it takes time for water to reach the water table, and the water that reaches the entirety of the water table represents an integration of past climatic conditions over years, decades, and perhaps centuries.

Climate change could affect groundwater resources by affecting recharge, pumping, natural discharge, and saline intrusion. Some of these effects are direct, and some are indirect. Recharge is an obvious parameter that is affected by climate change as it is closely tied to precipitation. If there is more precipitation, there will probably be more recharge, and if there is less precipitation, there will probably be less recharge. According to a global study, recharge is expected to increase 2 percent worldwide (Döll and Flörke, 2005). There is an overall increase in recharge because it is expected that there will be an overall increase in global precipitation (more water is in global water cycle because of melting ice). However, just as there will likely be areas with increased precipitation and areas with decreased precipitation, there will be areas with increased and decreased recharge depending not only on the precipitation patterns but also on the local hydrogeology.

The IPCC stated, with high confidence, that groundwater recharge will decrease considerably in the western United States (Kundzewicz et al., 2007), although Döll and Flörke (2005) showed that recharge in the southwestern United States is expected to increase 30 percent or more by the 2050s. For Texas, recharge might decrease 10 to 30 percent by the 2050s (based on Kundzewicz et al., 2007, their Figure 3.5, which is from Döll and Flörke, 2005). However, the analysis by Döll and Flörke (2005) is quite coarse and is, in our opinion, of limited value of projecting recharge changes at a regional or local—if not global—basis.

Effects of climate change on recharge need to consider changes in precipitation variability and inundation (Khiyami et al., 2005). Locally, recharge is a function of the precipitation, both in amount and timing, the soil and vadose zone properties, evaporation, and transpiration. Recharge can also be greatly affected by changes in land use, such as going from grassland or woodland to agriculture. Outside of soil and vadose zone properties, climate change is expected to affect all of these factors. The amount and timing of precipitation was previously discussed. Increases or decreases in evaporation are a function of temperature as well as humidity, which is tied to precipitation. Globally, increased CO_2 in the atmosphere is expected to decrease transpiration (Betts et al., 2007, and Leipprand and Gerten, 2006, both as cited by Kundzewicz et al., 2007); however, transpiration will vary locally depending on the local changes in temperature, precipitation, and vegetation type. Local increases in evaporation and transpiration could cause increased salination of soils.

Some aquifers, particularly karstic aquifers, rely on streams and rivers for a substantial amount of recharge. In these cases, climate change effects on surface water and runoff will affect recharge to these aquifers, especially if these streams and rivers become ephemeral over time.

In dipping aquifers with local discharge in the unconfined part of the aquifer and pumping primarily in the confined part of the aquifer, climate change may have little to no effect on groundwater resources. In these aquifers, it is the effective recharge—the water that moves downdip—which groundwater production relies upon. Effective recharge is increased through pumping and the capture of intermediate and local groundwater flow paths. If the flux of water through the local flow paths is much greater than the effective recharge, then relatively small changes in total recharge will have no effect on downdip pumping. There would, however, be an effect on discharge to springs and streams and rivers, thus effecting surface water resources.

Climate change is likely to affect pumping in aquifers. Increases in temperature are expected to increase the demand for water unless increases in precipitation offset that increased demand. The increase in municipal and industrial use is likely to be less than five percent by the 2050s (Mote et al., 1999, and Downing et al., 2003, both as cited by Kundzewicz et al., 2007). Global irrigation demand is projected to increase from 1 to 3 percent by the 2020s and 2 to 7 percent by the 2070s (Kundzewicz et al., 2007). Note that these increases do not include changes in population, which is expected to double by 2060 in Texas (TWDB, 2007). Decreases in surface water supply due to climate change may also increase groundwater use (Kundzewicz et al., 2007). If surface water resources become temporarily or permanently unreliable, then groundwater, generally less susceptible to climate variations than surface water, may become the preferred water supply, thus increasing pumping.

Climate change could also affect the natural discharge of water from aquifers to springs, streams, and lakes. Setting aside, for the moment, the effects increased pumping have on natural discharge, a decrease in transpiration with increased CO_2 could result in increased spring and base flow to rivers and streams. However, depending on how and where the phreatophytes get their water (solely from the saturated zone or a combination of the saturated and unsaturated, or vadose zone), increased temperatures and decreased rainfall could increase groundwater transpiration and thus decrease spring flow and base flow. Increased pumping due to climate change could also appreciably decrease natural discharge and will very likely be the primary driver for decreased natural discharge, especially if groundwater becomes the preferred source of water.

In coastal settings, groundwater resources may be affected by rising sea levels. As sea level rises, salt water moves inland, decreasing the areal extent of the aquifer and possibly affecting water quality in nearby wells. This is particularly important for shallow aquifers, especially karstic ones.

In general terms, the sensitivity of aquifers to climate change is probably related to the residence time of water in the aquifer. Residence time is the average time water spends in the aquifer from subsurface infiltration to discharge. Aquifers with short residence times and young groundwater are likely most sensitive to climate change, while aquifers with long residence times are least sensitive. Residence time is controlled by depth to the water table, permeability of the soil and aquifer, hydraulic gradient, and travel distance. Relative residence times can be estimated from the total aquifer storage volume divided by the total volumetric recharge rate. This generalization does not account for increased pumping due to climate change, which may actually have a greater affect on groundwater availability than changes to natural recharge.

HOW CLIMATE CHANGE MAY AFFECT GROUNDWATER IN TEXAS

Major aquifers in Texas range from karstic aquifers such as the Edwards Aquifer to dipping and principally confined clastic aquifers such as the Trinity Aquifer north of Austin, and the Carrizo-Wilcox and Gulf Coast aquifers. The Edwards Aquifer responds rapidly to rainfall events and drought periods while the age of groundwater in downdip areas of the Carrizo-Wilcox Aquifer can be more than 30,000 years old (Pearson and White, 1967). The aquifers in Texas likely to be most affected by climate change are the fractured and karstic aquifers such as the Edwards, Hill Country portion of the Trinity, and the Bone Spring – Victorio Peak. The Edwards Aquifer and the upper and middle parts of the Hill Country Trinity Aquifer have thin soil and high permeability. Water levels in shallow, high-permeability, clastic aquifers such as the Seymour and the Lipan-Kickapoo are sensitive to seasonal changes; therefore, they are also likely to be affected by changes to climate. Less likely to be sensitive to climate change are the low permeability, unconfined, clastic aquifers such as the Ogallala Aquifer in the High Plains and the Pecos Valley Aquifer in West Texas. The dipping, confined aquifer systems such as the Carrizo-Wilcox and Gulf Coast aquifer systems that run from southwest to northeast Texas are also not likely to be sensitive to climate change. The regionally dipping aquifers include a recharge zone in the outcrop with a local flow system, which will likely be affected by climate change. However, most of the production comes from the deeper confined portions where groundwater is much older (Pearson and White, 1967).

Following is a discussion on how climate change may or may not affect groundwater resources from the major aquifers of Texas as well as several selected minor aquifers.

Edwards Aquifer

The Edwards Aquifer is probably Texas's most vulnerable aquifer and groundwater resource with respect to climate change and variability. The Edwards Aquifer is very responsive to changes in precipitation, which affects water levels, spring flows, and how much water can be pumped out of the aquifer. Because of protected endangered species in San Marcos and Comal springs, pumping is very unlikely to increase in response to climate change. If there is a long-term drying of the climate in south-central Texas, area groundwater users can expect to be under more drought restrictions. See our review of previous work and our own analysis in the following section for more information on how the Edwards Aquifer may be affected by climate change.

Edwards-Trinity (Plateau) Aquifer

Because of the karstic nature of the Edwards part of this aquifer, we expect the Edwards-Trinity (Plateau) Aquifer to be sensitive to changes in climate, especially in Kinney and Val Verde counties. We do not expect the Trinity part of this aquifer to be very sensitive to the direct effects of climate change, especially where it is overlain by saturated Edwards sediments; however, the aquifer as a whole may be affected indirectly by municipalities in search of groundwater if surface water resources become unreliable such as what is currently happening to San Angelo with the low conservation storage in O. C. Fisher Lake (0 percent of conservation storage) and the O. H. Ivie Reservoir (66 percent of conservation storage) (TWDB, 2008).

Carrizo-Wilcox Aquifer

Because of its dipping geology and the location of much of its pumping in the confined part of the aquifer, groundwater resources from the Carrizo-Wilcox aquifer are unlikely to be directly affected by changes in climate. However, if the climate gets drier, there could be indirect effects on pumping. For example, if the Edwards Aquifer becomes less reliable for San Antonio, the Colorado River becomes less reliable for Austin, the Brazos River becomes less reliable for Waco, and the Trinity River becomes less reliable for Dallas and Fort Worth, these cities may choose the Carrizo-Wilcox Aquifer as a conjunctive source of water (San Antonio and communities to the north and south of Austin are already looking to the Carrizo-Wilcox Aquifer as a source of water).

Gulf Coast Aquifer

Because of its dipping geology and the location of much of its pumping in the confined part of the aquifer, groundwater resources from the Gulf Coast Aquifer are unlikely to be directly affected by changes in climate. However, if the climate gets drier, there could be indirect effects on pumping. For example, if the Nueces River becomes less reliable for Corpus Christi and the Trinity River becomes less reliable for Houston, these cities could choose additional pumping from the Gulf Coast Aquifer as a conjunctive source of water. In the past, San Antonio has considered groundwater from the Gulf Coast as a source of water. Any increase in pumping from the Gulf Coast Aquifer has to consider the effects of land subsidence, especially in conjunction with rising sea levels. Over the next 100 years, we don't expect sea level rise to appreciably affect groundwater resources in the Gulf Coast Aquifer. Most groundwater production, even from areas along the coast, is from deeper parts of the aquifer that would not be affected by moderate sea level rises.

Hueco Bolson Aquifer

Because of its reliance on leakage from the Rio Grande for recharge, the Hueco Bolson is likely to be affected by climate change. Before there was groundwater development in the El Paso / Juarez area, the Hueco Bolson discharged to the Rio Grande. Recharge to the aquifer on the Texas side of the river before groundwater production was not significantly: about 6000 acre-ft per year (Muller and Price, 1979; Heywood and Yager, 2003). However, groundwater pumping caused the aquifer to decouple from the Rio Grande, and the Rio Grande is believed to presently contribute about 30,000 to 35,000 acre-ft per year of recharge to the aquifer in the El Paso area (Hutchison, 2006). This has been fortunate because the Hueco Bolson is currently the primary source of water to Juarez and contributes from 50 to 90 percent of the water to El Paso, depending on the flows in the river. If flows in the Rio Grande, dependant in this area primarily on snowfall in northern New Mexico and southern Colorado, decrease, it could affect recharge to the Hueco Bolson. However, in order for no water to recharge the aquifer, there would have to be no water coming down the river, which would be an extreme, if not infrequent, case. Because of the existing uncertainty of flows in the Rio Grande, El Paso is already aggressively managing in a conjunctive way and is able to rely on groundwater, including a brackish groundwater desalination plant for most of its supply if needed. Hutchison (2008) showed that El Paso Water Utilities is prepared to provide water to its customers for the next 50 years and beyond for the range of current climatic possibilities projected by the recent IPCC report.

Ogallala Aquifer

Because of the large amount of pumping relative to recharge (the rate of pumping is six times the rate of recharge) and the time it takes for water to reach the water table, the Ogallala Aquifer is presently relatively insensitive to the direct effects of climate change; however, increases in pumping due to a probable drier climate will accelerate the depletion of the aquifer. If surface water resources become less reliable, communities will become more reliant on the Ogallala Aquifer, such as what is currently happening with the low volume of water in storage in Lake Meredith (at seven percent capacity as of May 2008 [TWDB, 2008]). If the climate turns drier, recharge through dry land farming would decrease, although there would probably be an overall increase in recharge compared to pre-agricultural times because of tilling of the soil. Scanlon et al. (2007) showed that recharge has increased to the Ogallala Aquifer because of agricultural practices. In those areas currently irrigating, we don't expect much of a change in recharge because farmers would probably compensate for decreased precipitation with increased pumping at least as long as there is water to pump.

Pecos Valley Aquifer

Because of the low annual rainfall and a thick unsaturated zone comprised of eolian sands, we do not expect the Pecos Valley Aquifer, north of the Pecos River, to be affected appreciably by climate changes; however, pumping in the aquifer could be affected by nearby municipalities searching for additional water supplies if existing surface water resources become unreliable. Groundwater in the Pecos Valley Aquifer south of the Pecos River is relatively younger as shown by tritium levels greater than 2 tritium units (Jones, 2008, this volume) and therefore may be more susceptible to the affects of climate change on recharge.

Seymour Aquifer

Because of its responsiveness to precipitation and drought, the Seymour Aquifer is susceptible to changes in climate. Interestingly, agriculture created this aquifer. Bandy (1934, as cited by Harden and Associates, 1978) and Gordon (1913, as cited by Harden and Associates, 1978) noted that wells in the area in the early part of the last century had to extend into the Permian deposits below the Seymour to access water. Bandy (1934) showed that water levels were rising in the Seymour prior to the mid-1930s. Woods and Hughes (1973) and Harden and Associates (1978) hypothesized that the water level rises were attributed to cultivation. Water levels continued to rise in the 1940s, but only slightly. Then water levels fell due to the drought of the 1950s and have fluctuated with pumping and precipitation cycles since then (Harden and Associates, 1978).

Trinity Aquifer

Because of its dipping geology and the location of much of its pumping in the confined part of the aquifer, groundwater resources from the Trinity Aquifer north of the Colorado River and where it is confined, are unlikely to be affected directly by changes in climate. A drier climate could result in direct and indirect increases in pumping from the aquifer; however, artesian pressures are already greatly depleted along the length of the aquifer (Mace et al., 1994; TWDB, 2007). The upper parts of the Trinity Aquifer south of the Colorado River in the Hill Country are, similar to the Edwards Aquifer, vulnerable to climate change and variability. The Upper and Middle Trinity aquifers, composed primarily of limestone, respond rapidly to precipitation. Parts of the Hill Country already experience groundwater supply issues during droughts with current use. If the climate in the Hill Country gets drier, groundwater levels can be expected to go even lower and affect even more people. This effect probably also applies to the totality of the outcrop area of the Trinity Aquifer, including north of the Colorado River. A drier climate would also decrease natural discharge to the local rivers and streams, which in turn would decrease recharge to the Edwards Aquifer. The Lower Trinity Aquifer, because it is almost entirely confined in the Hill Country, is not likely to be directly affected by climate change; however, indirect effects of pumping—such as the City of Kerrville and others using more groundwater—could serve to increase water level declines.

Minor Aquifers

Texas recognizes 21 minor aquifers (TWDB, 2007). Based on geology, hydrologic setting, and water quality, we expect the following aquifers to potentially be sensitive to climate change: Bone Spring – Victorio Peak (karstic with a component of recharge dependent on precipitation, including snowfall, in the Sacramento Mountains in New Mexico and recent recharge in the plateau area [Ashworth, 1995]), Brazos River Alluvium (given its symbiotic relationship with the Brazos River), Lipan (high permeable sediments that are responsive to precipitation), Igneous (permeability based on fractures expected to be responsive to changes in precipitation), and Capitan Reef Complex (we hypothesize that at least the western wing of this karstic aquifer may be sensitive to climatic variability).

EDWARDS AQUIFER AND CLIMATE CHANGE

As mentioned earlier, Loáiciga et al. (1996) noted that the Edwards Aquifer is one of the areas most vulnerable to climate change impacts in the United States. Loáiciga et al. (2000) performed modeling analyses of the Edwards Aquifer to evaluate the changes to the aquifer assuming a doubling of atmospheric CO_2.

We used GWSIM-IV, the same finite difference groundwater modeling code used by Loáiciga et al. (2000), to investigate the possible range of effects of climate change on the San Antonio segment of the Edwards Aquifer. GWSIM-IV is based on the Prickett and Lonnquist (1971) code and has been calibrated to a range of drought and wetter than average conditions in the Edwards (Balcones Fault Zone) Aquifer (Thorkildsen and McElhaney, 1992).

We accounted for climate change in the model by scaling monthly recharge from 70 percent to 130 percent of the historical value. Scaling recharge assumes a change in average values, but not a change in seasonal distribution. We evaluated two pumping scenarios: (1) historical pumping from 1947 through 1960 (to include the 1950s drought) and (2) pumping as defined by the critical period management rules in Senate Bill 3 (see Texas Legislature, 2007) from 1947 through 1960. We also assessed the minimum discharge from Comal Springs as a function of a fixed pumping amount. Note that we ran the model from 1934 through 1989 but are only showing a subset of the results.

For historical pumping from 1947 through 1960, model-calculated discharge at Comal Springs ranges over about 100 ft^3 per second (3 m^3 per second) when recharge varies from 70 percent to 130 percent of the historical recharge (Fig. 1). During the wettest periods (Fig. 1), model calculated discharge at Comal Springs ranges over about 500 ft^3 per second (14 m^3 per second).

Even with critical period management and an assumed increase in recharge, Comal Springs would still go dry (Fig. 2). The model estimates that the springs will go dry for about two years assuming historical recharge, less than a year assuming 130 percent of historical recharge, and three years assuming 70 percent of historical recharge (Fig. 2). The critical period management scenario suggests that even if recharge is reduced to 70 percent of historical amounts during a wetter period Comal Springs will not go dry (Fig. 2 after January 1957); however, the discharge will occasionally drop below 100 ft^3 per second (3 m^3 per second).

The results of the minimum discharge versus pumping analysis indicates that if the average recharge is reduced to 70 percent of the historical value, then the estimated maximum pumping that would allow a minimum Comal Spring discharge of 100 ft^3 per second (3 m^3 per second) is about 140,000 acre-ft per year (473,000 m^3 per day) (Fig. 3). Under average conditions, the estimated maximum pumping that would allow 100 ft^3 per second (3 m^3 per second) is about 180,000 acre-ft per year (608,000 m^3 per day). With 130 percent of historical recharge, the estimated maximum pumping would increase to about 220,000 acre-ft per year (743,000 m^3 per day) (Fig. 3).

RECOMMENDATIONS FOR FUTURE STUDY

There are several items that warrant additional research to better understand how climate change may affect the groundwater resources of Texas. First, there needs to be a Texas-specific analysis of the appropriate statistically downscaled models to quantify temporal and spatial projections of temperature and precipitation. This analysis could be used as the baseline for any future assessments on climate changes' effects on groundwater. For example, our analysis of the Edwards Aquifer could better bound recharge estimates and allow them to vary by month according to projected changes in seasonality. It would also be helpful for there to be a set of projected climatic realizations to be used for assessments of impacts to water resources. Second, there should be additional recharge studies on the aquifers of Texas with a focus on the volume of recharge and the time it takes for water to percolate from the land surface to the water table. This would help quantify the relative volumetric effect on recharge and how long it would take for a change in recharge to affect the aquifer. Existing groundwater models

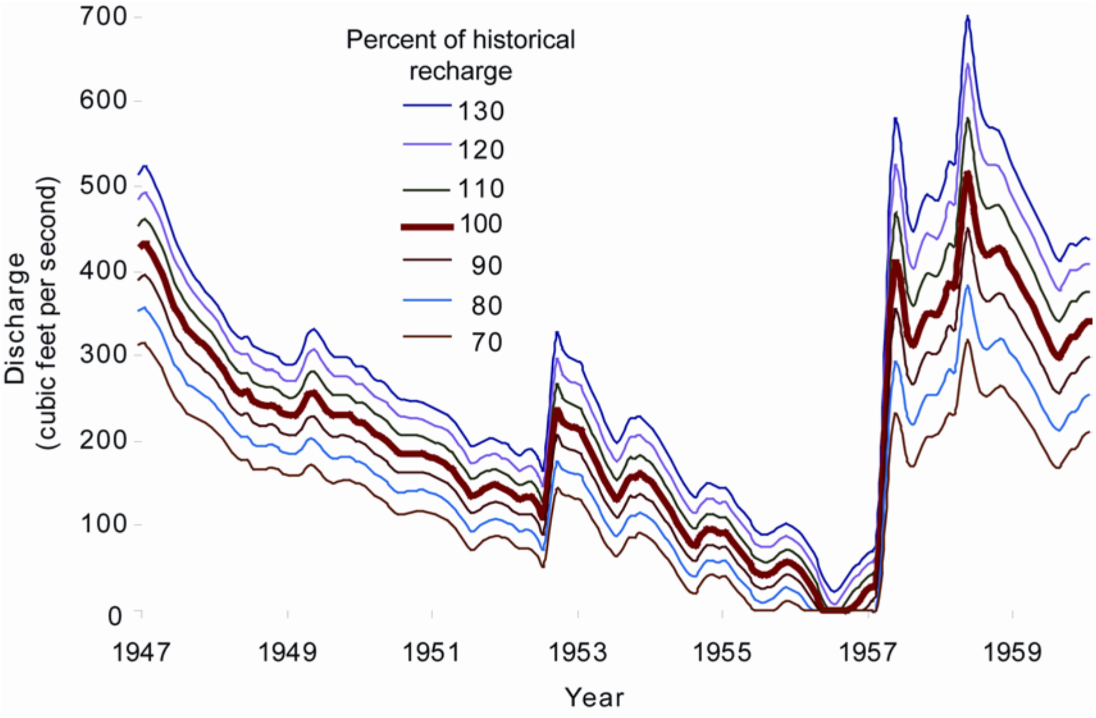

Figure 1. Model calculated discharge at Comal Springs using historical pumping with recharge ranging from 70 percent to 130 percent of historical average.

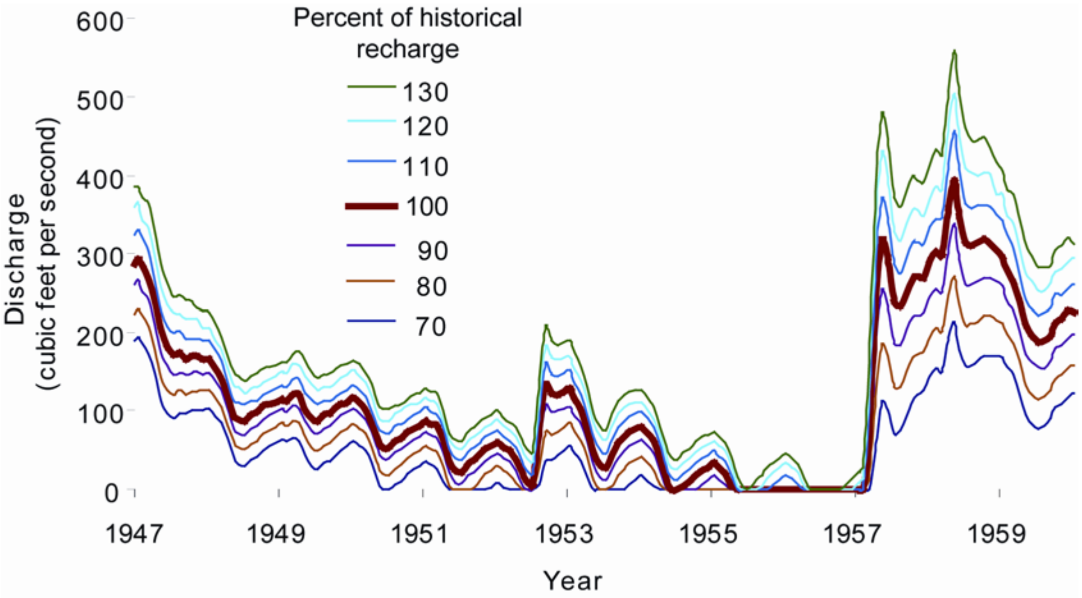

Figure 2. Model calculated discharge at Comal Springs assuming Edwards Aquifer critical period management rules with recharge ranging from 70 percent to 130 percent of historical average.

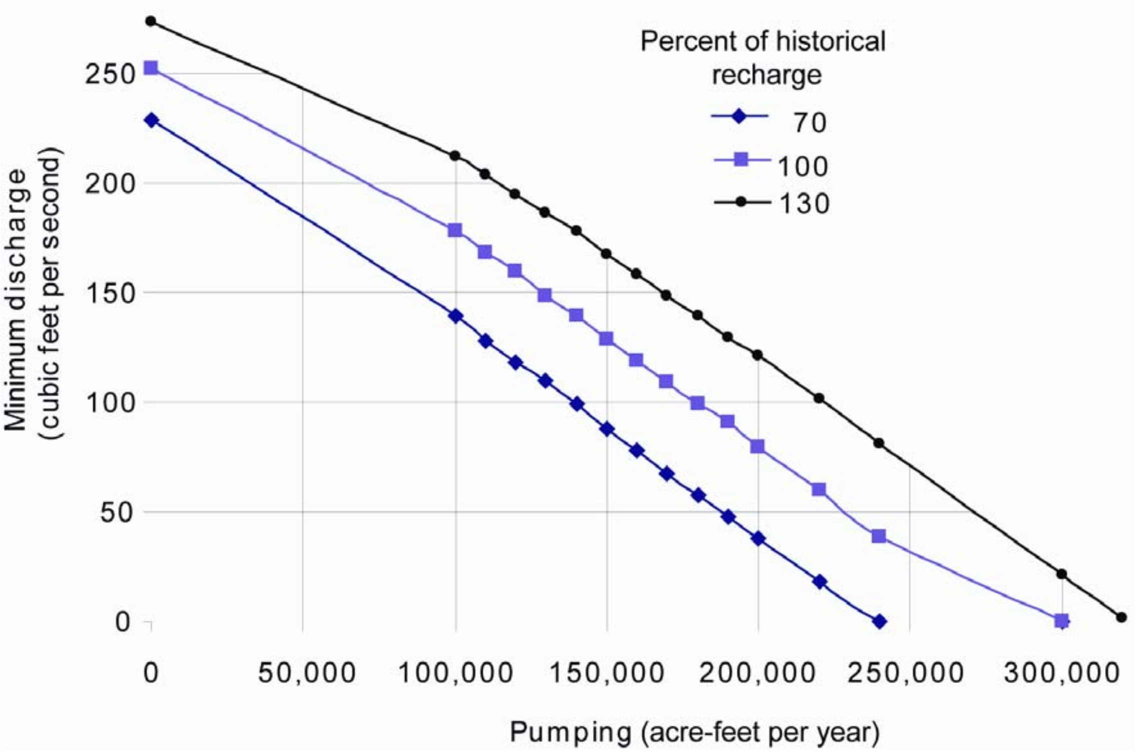

Figure 3. Minimum discharge at Comal Springs as a function of maximum pumping for 70 percent, 100 percent, and 130 percent of historical average recharge.

for Texas represent recharge as it enters the water table, not as it percolates through the unsaturated zone. Therefore, current groundwater models cannot be used to assess how long it will take for climate changes to propagate down to the aquifer. Third, it would be good to better quantify surface water and groundwater interaction to better assess how each resource affects the other. Studies on surface water and groundwater interaction now can be used as baseline information for future studies. And fourth, it would be useful to better quantify how climate change may affect drought, especially with respect to intensity and duration. For example, our Edwards Aquifer analysis assumes that the future drought will look similar to the drought of the 1950s.

These studies would help to better understand how groundwater resources are affected by climate change. However, given the natural variability of climate, the uncertainty of recharge estimates, the effects of land use changes on recharge processes, and the effects of pumping and pumping variations over time, we may never be able to discern the effects of climate change in groundwater systems except on extremely responsive aquifers.

CONCLUSIONS

Global climate models project a warmer Texas with probable changes in long-term precipitation with a preference toward drier conditions. Not surprisingly, changes in the climate can affect changes in water resources. For aquifers, climate change can affect recharge, the amount of pumping, and natural discharge with highly responsive aquifers being the most affected. There has only been limited research on how climate change may affect Texas's groundwater resources with most of the existing work focused on the Edwards Aquifer. Based on our experience with the state's aquifers, we expect that the Edwards, the upper part of the Hill Country portion and outcrop areas of the Trinity, the upper parts of the Edwards-Trinity (Plateau), the Seymour, and several responsive minor aquifers to be susceptible directly to climate change. We expect the groundwater resources from the other aquifers to be affected minimally by climate change because of their lower responsiveness, dipping geology, and/or the amount of pumping as compared to recharge. However, many of the aquifers not directly affected by climate change may be indirectly affected if cities that rely primarily on surface water resources are forced to find other sources of water. The Edwards Aquifer is particularly susceptible to climate change because it recharges so quickly and is closely tied to surface water runoff. Our modeling work with the San Antonio segment of the Edwards Aquifer suggests that pumping may have to be reduced by about 40,000 acre-ft per year to maintain minimum spring flows if recharge declines 30 percent. Additional research is needed on summarizing downscaled climate models for Texas, better representing the flow of water through the unsaturated zone to the water table, quantifying how the intensity and duration of droughts may change, and better characterizing surface water and groundwater interactions.

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