MEASURING THE EFFECTIVENESS OF GROUNDWATER MANAGEMENT POLICIES FOR THE CARRIZO-WILCOX AQUIFER OF TEXAS

A Dissertation

by

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ABSTRACT

In the United States, more than 80% of the population now lives in urban areas. By 2050, a significant portion of that population will live in *megaregions* consisting of two or more metropolitan areas linked with interdependent environmental systems, a multimodal transportation infrastructure, and complementary economies. The Texas Triangle Megaregion, one of 8 to 10 such regions in the United States, is spatially delineated by the metropolitan areas of Dallas/Fort Worth, Austin, San Antonio, and Houston, with a total land size of nearly 35,435 square kilometers.

Supporting the modern industrial infrastructure of a major metropolitan megaregion has required extensive water-related modifications to the critical zone. These modifications come in the form of an extensive network of dams and reservoirs; a high-density matrix of wells for extracting water, oil, and gas from the critical zone; significant alterations of land cover; and interbasin transfer of ground and surface water. Progressive depletion of critical zone reserves threatens sustainable development in the heavily groundwater-dependent Texas Triangle and requires robust and effective water resource policy for the megaregion to remain economically viable.

Facing growth that is expected to double the population of the state to more than 46 million by 2060, Texas has increased its efforts to implement comprehensive water resources planning during the past decade. State policy in Texas dictates that groundwater management is best accomplished through locally elected, locally controlled groundwater conservation districts (GCD).

This study examined the effectiveness of GCDs as a water resource management tool in Texas. This research demonstrated no measurable difference in the annual rate of decline in groundwater levels in the Carrizo-Wilcox Aquifer in Texas after establishment of a GCD. The data did not show a correlation between the water allocation method used and the impact on average annual drawdown of the aquifer. The study was not able to demonstrate a relationship between the length of time a GCD has been in existence and the average annual drawdown rates in the aquifer.

DEDICATION

"Children of a culture born in a water-rich environment, we have never
really learned how important water is to us. We understand it,
but we do not respect it" (Ashworth, 1982, p. 1).

This dissertation is dedicated to my wife, Rita, who kept me motivated
and focused every time I was ready to give in or give up, and
to my dad, who has shown me that life-long learning
is the real fountain of youth.

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NOMENCLATURE

GCD	Groundwater Conservation District
LSD	Distance from Land Surface
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
UWCD	Underwater Conservation District

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CHAPTER I

INTRODUCTION

Water resources—lakes, streams, groundwater or wetlands—are critical to economic and general wellbeing (Rao & Yang, 2010). If one ignores water frozen in glaciers and polar ice, groundwater alone comprises more than 95% of all freshwater resources (Alley, 2006). An average of 85 billion gallons of groundwater are withdrawn daily in the United States and more than 90% of these withdrawals are used for irrigation, public supply (deliveries to homes, businesses, industry), and self-supplied industrial uses (Alley, 2006).

In many areas, the groundwater reservoir is a significant part of the hydrologic system, and its utilization offers many alternatives for effective development of the water resource (Moore, 1979). Groundwater for irrigation has transformed large areas of land with limited agricultural potential into regions of high productivity, leading to unprecedented economic development (Molina, Bromley, Garcia-Aróstegui, Sullivan, & Benavente, 2010). As a result, groundwater depletion has spread from isolated pockets to large areas in many countries throughout the world during the past 50 years, including in Texas.

The groundwater resources of Texas aquifers provide 60% of the freshwater needs of the state today (Vaughn et al., 2012). In the coming years, Texas will face significant challenges as the population is expected to grow by 46% and water demand is projected to grow by more than 20% before 2060 (Texas Water Development Board [TWDB], 2007; Vaughn et al., 2012). These changes will unfold during a period of uncertainty intensified by global climate change, potentially increasing these critical resource challenges. As a result, the impact of present groundwater management policies must be understood and these policies must be modified where required to maximize groundwater availability.

Understanding the regional-scale vulnerabilities of groundwater resources is important to ensure sustainable water resources management and land use development (Uddameri & Honnungar, 2007) because unmanaged groundwater extraction and inadequate aquifer recharge are the major causes of groundwater depletion in various parts of the world. As a result, groundwater management and conservation at watershed level have gained worldwide importance (Gaur, Chahar, & Grailot, 2011).

As groundwater becomes an increasingly important part of available freshwater resources, a variety of problems can be anticipated (Moore, 1979). Specifically, groundwater supplies will become progressively depleted, stream flows will be reduced, and the overall water quality will deteriorate. A growing awareness of groundwater as a critical natural resource is already resulting in political leaders and resource managers asking basic questions (Alley, 2006): How much groundwater do we have left? Are we running out? Where are groundwater resources most stressed? Where are they most available for future supply?

Providing answers to these questions presents an excellent opportunity to bridge the boundaries between science and public policy by developing and incorporating software, models, geographic information systems, and decision support systems with established policy to sustain people in an increasingly resource-constrained world.

The focus of this dissertation research was to integrate hydrogeology with public policy planning methods to develop an understanding of the links between specific groundwater management policies and the resulting impacts on the underlying aquifer. This study identifies how groundwater management policies affect groundwater levels and provide water resource planners additional tools and insight to meet 21st-century water resource challenges in Texas.

Background of the Problem

Groundwater Management in Texas

Unlike scientists, who recognize that all water is interconnected, Texas law distinguishes between surface water and groundwater for the purpose of regulation with different rules governing each class (Kaiser, 1988; Vaughn et al., 2012). The state recognizes that a landowner owns groundwater (fresh and brackish) underlying his or her land as real property (Combs, 2014). In contrast, with the exception of diffused water, such as storm water runoff, all surface water, including streams, rivers, and lakes, is “held in trust” by the state and appropriated to users through permits or “water rights.” (Fipps, 2002). The complicated system in Texas arose from Spanish and English common law, the laws of other Western states, and state and federal case law and legislation (Vaughn et al., 2012).

Commonly known as the *Rule of Capture*, groundwater law in Texas is based on the English common law doctrine that says that the landowner may withdraw groundwater without limitations and without liability for losses to neighbors’ wells as long as water is not wasted or taken maliciously (Combs, 2014; Fipps, 2002; Kaiser, 2005). The Texas Supreme Court in its 1904 decision *Houston & T. C. Railway Co. v. East* adopted this "rule of capture" doctrine in part because the science of quantifying and tracking the movement of groundwater was so poorly developed at the time that it would have been practically impossible to administer any set of legal rules to govern its use (Kaiser, 1988; Vaughn et al., 2012).

The right of landowners to capture and make "non-wasteful" use of groundwater has been upheld by Texas courts over the years with only a few exceptions: drilling a well on someone else's property, or drilling a "slant" well on adjoining property that crosses the property line ("trespass"); pumping water for the sole purpose of injuring an adjoining landowner ("malicious or wanton conduct"); and causing land subsidence on adjoining land from negligent overpumping (Fipps, 2002). Texas groundwater law has often been called the "law of the biggest pump" because the deepest well and most powerful pump get the water (Fipps, 2002; Kaiser, 1987).

In Texas, all surface water is held in trust by the state, which grants permission to groups and individuals to use the water (Vaughn et al., 2012). The state owns all waters flowing on the surface of Texas (Combs, 2014; Kaiser, 2005). The Texas Commission on Environmental Quality (TCEQ) issues and manages permits based on a "first in time, first in right" principle, meaning that those holding the oldest permits have first access to available water (Combs, 2014).

Texas recognizes two basic doctrines of surface water rights: the *riparian* doctrine and the *prior appropriation* doctrine. Introduced more than 200 years ago when Spanish Settlers arrived in Texas, the riparian doctrine permits landowners whose property is adjacent to a river or stream to make reasonable use of the water (Kaiser, 1988). First adopted in Texas in 1895, the prior appropriation system has evolved into the modern system used today (Vaughn et al., 2012). Under prior appropriation, landowners who live on many of the water bodies in the state are allowed to divert and use water for domestic and livestock purposes, not to exceed 247,000 cubic meters (200 acre-feet) per year (Kaiser, 1988; Vaughn et al., 2012).

Managing Water Use Through Water Planning

In response to the most severe drought of record in Texas in the 1950s, the Texas Water Planning Act of 1957 created the TWDB with authority to develop a State Water Plan (J. E. Brown, 1997). Although the state had legislated the water planning process in 1957, it had taken little or no action on the water plans developed in 1961, 1968, 1987, 1990, and 1992 (J. E. Brown, 1997). In 1997, once again acting in response to a drought (1995-1996), the TWDB, in conjunction with the Texas Natural Resources Conservation Commission and the Texas Parks and Wildlife Department, developed the first "consensus-based" plan (J. E. Brown, 1997).

Recognizing that water is the single most important factor for the future economic viability of Texas (Vaughn et al., 2012), the legislature passed Senate Bill 1, the Comprehensive Water Management Bill, which was signed into law on June 19, 1997 (J. E. Brown, 1997). Senate Bill 1 put in place the "bottom-up" approach to water planning rooted in local, consensus-based decision making that Texas uses for water planning today (Combs, 2009). Senate Bill 1 resulted in designation of water planning regions based on geographical, hydrological, and political boundaries; water utility development patterns; and socioeconomic characteristics (J. E. Brown, 1997).

Managing Groundwater Through Conservation Districts

State policy in Texas dictates that groundwater management is best accomplished through locally elected, locally controlled groundwater conservation districts (GCDs), suggesting that any modification or limitation on the rule of capture will be made by local groundwater districts (J. E. Brown, 1997). In 1949, the Texas legislature first provided for the voluntary creation of GCDs over any groundwater reservoir designated by the state (Fipps, 2002). While continuing to acknowledge the “rule of capture” of groundwater by landowners, the legislature passed additional legislation in 1985 and 1997 to encourage establishment of GCDs and, in limited cases, to allow for the creation of districts by state initiative (Fipps, 2002).

As of April 2014, a total of 101 GCDs had been created in the state: 98 established (i.e., confirmed) districts and 3 unconfirmed districts. The 98 established districts cover all or part of 179 of the 254 counties in the state. The Texas Triangle Megaregion (TTMR) has 50 GCDs in place (TWDB, 2014a), and 24 GCDs overlie the Carrizo-Wilcox Aquifer.

GCDs are charged to manage groundwater by providing for conservation, preservation, protection, recharging, and prevention of waste of groundwater resources within their jurisdictions (Fipps, 2002). GCDs can be created by one of four procedures: (a) established through action of the legislature, (b) created through a landowner petition procedure based on state law in Subchapter B, Chapter 36 of the Texas Water Code, (c) created by the TCEQ on its own motion in a designated Priority Groundwater Management Area (PGMA) through a procedure similar in principle to procedure (b) above but in which action is initiated by the TCEQ rather than by petition, or (d) alternative to creating a new GCD, adding territory to an existing district if the existing district is willing to accept the new territory (Lesikar, Kaiser, & Silvy, 2002).

GCDs are authorized by the state with powers and duties that enable them to manage groundwater resources. The three primary GCD legislatively mandated duties are (a) permitting water wells, (b) developing a comprehensive management plan, and (c) adopting necessary rules to implement the management plan (Lesikar et al., 2002).

The Texas Water Code Section 36.116 (a) (Texas, 2005) provides broad regulatory authority to GCDs (Porter, 2014) as indicated below:

> To minimize as far as practicable the drawdown of the water table or the reduction of artesian pressure, to control subsidence, to prevent interference between wells, to prevent degradation of water quality, or to prevent waste, a district may regulate:
>
> The spacing of wells by:
>
> Requiring all water wells to be spaced a certain distance from property or adjoining wells;
>
> Requiring wells with certain production capacity, pump size, or other characteristic related to the construction or operation and production of and production from a well to be spaced a certain distance from property lines or adjoining wells; or

Imposing spacing requirements adopted by the board; and

The production of groundwater by:

Setting the production limit on wells;

Limiting the amount of water produced based on acreage tract size;

Limiting the amount of water that may be produced from a from a defined number of acres assigned to an authorized well site;

Limiting the maximum amount of water that may be produced the basis of acre-feet per acre or gallons per minute per well site per acre;

Managed depletion; or

Any combination of the methods listed above in Paragraphs (a) through (e).

The principle power of a GCD to prevent waste of groundwater is to require that all wells, with certain exceptions, be registered and permitted. Wells with permits are subject to GCD rules governing spacing, production, drilling, equipping, and completion or alteration. Even exempt registered wells are subject to GCD rules governing spacing, tract size, and well construction standards to prevent unnecessary discharge of groundwater or pollution of the aquifer. Permits may be required by a GCD for all wells except for wells specifically exempted by a GCD and statutorily exempt wells (i.e., wells used solely for domestic use or for providing water for livestock or poultry purposes; the drilling of a water well used solely to supply water for a rig actively engaged in drilling or exploration operations for an oil or gas well permitted by the Railroad Commission of Texas [RRC]; and the drilling of a water well authorized by the RRC for mining activities; Lesikar et al., 2002).

In 1985 the Texas legislature passed House Bill 2, containing provisions for the Texas Water Commission (TWC; a predecessor to the TWDB) to identify areas of the state that had critical groundwater problems, such as aquifer depletion, water quality contamination, land subsidence, or shortage of water supply. Accordingly, beginning in 1986, the TWC and the TWDB identified possible critical areas and conducted further studies (Fipps, 2002). Portions of 11 groundwater management agencies are located within the TTMR (TWDB, 2014b).

> Groundwater Management Areas were created "to provide for the conservation, preservation, protection, recharging, and prevention of waste of the groundwater, and of groundwater reservoirs or their subdivisions, and to control subsidence caused by withdrawal of water from those groundwater reservoirs or their subdivisions and to control subsidence caused by withdrawal of water from those groundwater reservoirs or their subdivisions, consistent with the objectives of Section 59, Article XVI, Texas Constitution, groundwater management areas may be created. (Texas Water Code §35.001, Added by Acts 1995, 74th Leg. ch. 933 §2, eff. Spet. 1, 1995)

Beginning in 2005, Texas required, through legislation, that staff of GCDs meet regularly and define the "desired future conditions" of the groundwater resources within designated management areas (Vaughn et al., 2012). Based on these desired future conditions, TWDB delivers modeled values of available groundwater to GCDs and regional water planning groups for inclusion in their plans.

The above discussion illustrates how controlled surface water and groundwater are in the critical zone in Texas, especially in the TTMR. Despite this control regime, waters in the critical zone are being depleted and degraded at an alarming rate. Texas has implemented a management regime for groundwater, but the effectiveness of this regime is uncertain.

Statement of the Problem

Water resources in the United States have been increasingly stressed over the past decades and nearly every region in the country has experienced water shortages in the past 5 years (Wang, Small, & Dzombak, 2014). Growing human population, increasing per capita water usage, and accelerating climate change drive these shortages (Dellapenna, 2013). Texas is no exception to these shortages or the causes. Texas is experiencing extended drought and, as a result of a rapidly growing population, may be reaching the limits of its available water resources (Combs, 2014). This is particularly true in the TTMR. Groundwater will play a central role in resolving these shortages because the majority of fresh water on Earth is found underground (Dellapenna, 2013); but in many places, groundwater is being used much more quickly than it can be recharged (Combs, 2014).

Regarding groundwater, Texas is one of the few remaining states that subscribes to the “Rule of Capture” (Dellapenna, 2013). This common-law rule allows landowners to draw as much water as they can capture so long as the water is not wasted or taken maliciously (Combs, 2014). Groundwater can be taken without liability for losses to neighbors’ wells, subject to reasonable GCD regulations (Combs, 2014). In an attempt to balance the interests of landowners with limited groundwater resources, in 1949 the Texas legislature authorized creation of GCDs for local management of groundwater (Vaughn et al., 2012). Very little research has been done to measure the effectiveness of these GCDs in managing this critical natural resource.

Purpose of the Study

The purpose of this study was to investigate how to optimize groundwater use to achieve sustainable levels in the Carrizo-Wilcox Aquifer. The first objective of this study was to develop a thorough understanding of the hydrogeology of the Carrizo-Wilcox Aquifer. Specific management policies were then identified based on a comprehensive analysis of the plans developed by agencies that collectively manage groundwater withdrawals from the Carrizo-Wilcox Aquifer. Specific groundwater management policies were correlated with the impact on the hydrogeology of the underlying aquifer.

Significance of the Study

Texas efforts in water resource planning will be increasingly integrated on regional and aquifer levels. This integration will be possible only if water resource planners have additional management tools based on a solid understanding of the underlying hydrogeology of the aquifers that they are trying to manage. This study begins to fill a significant gap in knowledge by linking the impact of specific policies of groundwater management with the resultant impacts on underlying aquifer—knowledge that will allow Texas water planners to manage more efficiently and effectively the groundwater resources critical to the economic well-being of the state in the 21st century.

This research correlates the effects of specific groundwater management policies with the impact on the underlying Carrizo-Wilcox aquifer. This knowledge is extremely important because, according to the TWDB, water is the single most significant limiter to future economic growth in Texas (Vaughn et al., 2012). Without action, the state could face economic losses exceeding $98.4 billion annually by 2060 and 85% of the population of Texas will not have enough water during drought conditions (TWDB, 2007).

Research Questions

Sustainable management of constrained groundwater resources is critical to the long-term economic viability of rapidly growing urban areas of Texas. This study investigates methods to optimize groundwater use to achieve sustainable levels in the Carrizo-Wilcox Aquifer. Four research questions were addressed in this study.

1. Does a measurable difference exist in the rate of decline in aquifer levels after the establishment of a GCD?

2. Do individual groundwater allocation methods implemented by GCDs produce measurable decreases in the rates of decline in aquifer levels?

3. Does the length of time a GCD has been in effect result in a measurable decrease in the rate of decline in aquifer levels?

4. What is the impact of urbanization on groundwater resources of the Carrizo-Wilcox Aquifer?

Hypotheses

1. If GCDs are effective organizational structures for managing groundwater resources in Texas, then a measurable decrease should occur in the rate of decline of aquifer levels after establishment of a GCD.

2. If GCDs are effective organizational structures for managing groundwater resources, then a measurable difference should exist in the rate of decline in aquifer levels when compared to areas utilizing "rule of capture."

3. If groundwater allocation methods utilized by GCDs are effective, then a specific allocation method should produce similar results when applied by different GCDs.

4. If some groundwater allocation methods are more effective than others, then there should be a measurable difference in the rate of decline in aquifer levels that result from implementation of the various groundwater allocation methods.

5. If increased urbanization has a detrimental effect on aquifer levels, then an increase in urbanization should result in corresponding decrease in aquifer levels.

Literature Review

A very limited amount of published research exists dealing specifically with the subject of groundwater conservation districts in Texas. The literature contains an even smaller subset that addresses the topic of the efficiency of GCD policies.

Groundwater Management Regimes

From a historical perspective, the development of groundwater resources for beneficial use by the public has largely been a matter of individual users acting in an uncoordinated manner without regard to the needs or desires of other users (Smith, 1956). Notably, even when the Smith article was written more than a half-century ago, the author identified the increasing importance of groundwater as a matter of public concern and cited the organization of groundwater management districts at the local level as the preferred method for groundwater management in Texas (Smith, 1956).

Burt's (1964) article pioneered incorporation of dynamic programming into a study applied to groundwater allocation by examining the optimal temporal allocation of a fixed or constrained resource. Burt developed a functional equation to derive rough decision rules for resource allocation with results applied to control of groundwater storage.

Burt (1966) also developed decision rules to optimize groundwater policy based on expected present value of groundwater production output or the maximization of social benefits. He published additional work on temporal allocation of groundwater (Burt, 1967) and on the impact of institutional restrictions on groundwater storage control (Burt, 1970). These important articles provide a substantial foundation in the economics of groundwater management.

Foster (2008, 2009) examined specific policies used by groundwater districts to determine which, if any, are effective and considered the temporal differences introduced by the establishment of GCDs on aquifer levels. The scale of Foster's work was very broad and covered the entire state of Texas. Given the broad approach that Foster took, he was not able to examine any single aquifer or GCD in detail. Even so, Foster's work begins to fill the gap in the literature by applying econometric methods to controls implemented by GCDs; however, it leaves many questions unanswered. Foster did not include an in-depth analysis of the type of aquifer in his research nor did he account for the impact of all groundwater management policies on rates of aquifer depletion.

Johnson, Johnson, Segarra, and Willis (2009) examined the impact of two water conservation policies (quotas and pumping fees) on aquifer levels and evaluated the economic impact associated with these policies. The study determined that quotas were most effective in conserving aquifer levels but also had a negative economic impact on regional economies. This was an entirely econometric study and did not examine the hydrogeology of the underlying aquifer.

Somma (1997) examined West Texas groundwater districts, noting the autonomous nature of GCD management and declaring GCDs to be an "unintended experiment in commons resource management" (p. 1). Somma presented a model to corroborate his claim that GCDs have a positive impact on reducing rates of aquifer depletion. The main feature of Somma's model was a dummy variable representing the presence of GCDs to allow differentiation in rates of depletion based on whether an aquifer was managed by a groundwater district. Somma regressed Ogallala Aquifer water levels on the groundwater district dummy variable, together with a series of control variables, to provide an initial examination of the impact of GCD management policies on aquifer levels. This was the same approach later used by Foster (2008, 2009).

Apart from Somma and Foster, much of the remaining groundwater literature is focused on depletion issues or establishing optimal controls on groundwater use. Smith

(1956) provided an important analysis of the problems associated with the use of groundwater management districts in the United States. Provencher and Burt (1993, 1994) focused on the use of dynamic programming to develop decision rules for optimizing groundwater policy. Gardner, Moore, and Walker's (1997) study examined strategic behavior in groundwater depletion in the setting of state governance of groundwater resources.

Provencher (1993) applied dynamic programming to the private property rights regimes used to maintain groundwater aquifers at steady state. In an empirical study of Madera County, California, Provencher demonstrated that private property rights regimes could recover 95% of the potential gain from groundwater management. He co-authored two articles with Burt, both of which, like his 1993 article, utilized dynamic programming models applied to Madera County. Provencher and Burt (1993) contrasted the effects of pumping groundwater under centralized control with those obtained by utilizing the same private property rights regime that Provencher had used in his 1993 article. In the second article, Provencher and Burt (1994) presented two methods for stochastic optimization of groundwater pumping policy for interrelated aquifers with conjunctive use of surface water.

Another article of significance to this study was one by Gardner et al. (1997) on strategic behavior in groundwater depletion. The authors focused on three legal regimes in developing a dynamic, common-pool resource model. They examined behavior under "rule of capture," prior appropriation, and correlative rights doctrines in the Western

United States and studied the effects of property rights and regulations on individual behavior.

Groundwater Models

Virtually all authors of global groundwater assessments have highlighted the problems of data availability and quality and have placed important caveats on the accuracy of the accompanying numbers (Giordano, 2009). If data on groundwater resources are of questionable quality, data on its use are even less reliable (Giordano, 2009).

Even as early as the 1970s, about 250 digital models were being used to evaluate groundwater problems (Moore, 1979). Analysts have developed models that portray groundwater systems and predict changes with varying degrees of accuracy (Moore, 1979).

The output of a model might include statistics, graphs, maps, images, and animations, all of which require expert interpretation and evaluation in the context of the model setup or implementation (Reitsma, 2010). The results of water resource models can be used to support decision making and drive government policy, transforming scientific explanation and demonstrating cause-and-effect links to support decisions or policies (Reitsma, 2010).

Groundwater models come in several forms with specific functions and outputs:

1. Raster and vector data models deal with space in slightly different ways but have fundamentally similar underlying abstractions. They represent an attribute at a

specific location in space at a particular instant in time, using a pixel or point (Reitsma, 2010).

2. Spatio-temporal extensions typically involve extension of spatial objects through time (Reitsma, 2010).

3. Data models with behavior: One of the best examples of modeling that implements a data model incorporating behavior is agent based modeling (ABM). ABM is a simulation methodology focused on mobile individuals and the interaction and is used to study complex systems arising from the interaction of many independent parts such as ecological systems and cities (Reeves & Zellner, 2010). Reeves and Zellner linked agent-based land use models to MOD-FLOW to study the complexity inherent in land use change and its effect on groundwater resources. The Water-Use/Land-Use Model (WULUM) was developed and applied to study the potential effectiveness of zoning to control the effect of urbanization on groundwater resources.

4. Event-based data models accommodate dynamics and change within a geographic information system (GIS), changing the unit of focus from objects and fields to temporally extended events. A conceptual model for incorporating events into the traditional object- and field-focused models of the world is the GEM model proposed by Worboys and Hornsby (2004). The GEM model includes geo-spatial entities such as objects and events that are situated within a spatial, temporal, or spatio-temporal setting (Reitsma, 2010).

5. A process-based data model builds on the event approach, using the process rather than static things to represent states of the system at a given point in time.

Process-based models have the advantage of facilitating analysis of processes rather than merely attempting to infer them (Reitsma, 2010).

Integration of Geographic Information Systems

Whereas these models were a major step forward in the ability to supply the information that water resources managers need in their efforts to develop effective policy, they fall short in their ability to provide answers to many of the most important questions. Despite their location or the level at which they operate, water resource managers consistently ask similar questions when examining problems (Strager et al., 2010). What is the extent of the water quality problem? Where are the problems occurring in the watershed? Where should sampling or monitoring locations be established to assess the problem more accurately? Where should we focus best management practices or reclamation plans to address the problems? The abundance of “where’’ questions points out the spatial nature of water resource management (Strager et al., 2010) and suggests the need for integration of water models with GISs.

A recent trend in groundwater modeling is to integrate groundwater modeling with GIS technology and allow the modeler to import, create, and automatically convert geographic “map layers” into “grid layers” for numerical modeling (Pint & Li, 2006). These GIS techniques, coupled with numerical modeling, create a unique opportunity to improve groundwater management (Chenini & Ben Mammou, 2010). This provides water resource managers the ability to answer the “where” questions posed by Strager et al. (2010).

GIS integration provides advantages over older and improved geo-referenced thematic map analysis and interpretations because, unlike conventional methods, GIS methods take into account the diversity of factors that control groundwater recharge (Strager et al., 2010).

Software packages, such as ModTech in conjunction with GeoLink, make it significantly easier to use available geo-referenced surface water and ground water information and enhance a resource manager's ability to simulate complex groundwater systems (Pint & Li, 2006). The underlying numerical engine of ModTech is a finite-difference model. It facilitates transient three-dimensional (3D) flow and solute transport modeling. The flow simulator implemented in ModTech is similar to the USGS MOD-FLOW code (Pint & Li, 2006). GeoLink GIS provides high-quality visualization of model outputs suitable for reports and publications (Pint & Li, 2006). The program also permits exporting model results as geographic objects that can be presented and visualized in an integrated fashion with other data layers. This allows analysis and interpretation of results and basic 3D volume visualization (Pint & Li, 2006).

DRASTIC (D: Depth to water table, R: aquifer Recharge, A: Aquifer media, S: Soil media, T: Topography, I: Impact of vadose zone, C: hydraulic Conductivity) has also been integrated with GIS and remote sensing tools for easy visualization of water resource data (Uddameri & Honnungar, 2007).

Rao and Yang (2010) used AVSWAT (ArcView SWAT), a hydrologic/watershed modeling extension for ArcView GIS to define the watershed and calculate groundwater recharge for hydrologic response units in Oklahoma. Rao demonstrated the utility of GIS to understand spatial dynamics through visual analysis, as well as to understand spatial linkages between land use and environmental impacts. Understanding the linkages between land use and the environmental impacts is critical for policy formulation and optimal management of groundwater quantity and quality in the southwestern United States (Rao & Yang, 2010).

Santini, Caccamo, Laurenti, Noce, and Valentini (2010) developed methodologies for integrating GIS with existing models to analyze the spatio-temporal aspects of desertification. Santini's Integrated Desertification Index (IDI) balances model sophistication and complexity by integrating results of various types of models with GIS to simulate environmental processes using different degrees of coupling strength. In particular, this tool allows production of desertification risk maps that are easily read and easily repeated for nonexpert GIS users (Santini et al., 2010).

Gaur et al. (2011) combined GIS-based potential zone analysis and groundwater modeling to study groundwater behavior and identify best management practices at the watershed level. Gaur's methodology can be used for both agricultural and water resources analysis.

Diodato, Ceccarelli, and Bellocchi (2010) used an upscaling procedure to combine GIS and geoindicators (e.g., topographical and vegetation indices) in the development of climatological baseline estimations of actual evapotranspiration at the subregional basin scale.

A watershed characterization and modeling system (WCMS) was developed by Strager et al. (2010) to support decision making and management of water resources at a statewide level. Running as an extension of ArcGIS 9.x using the spatial analyst, the components of the WCMS application include an overland flow model that provides insight into optimum water quality and a watershed-ranking model to prioritize where to focus remediation programs (Strager et al., 2010). WCMS uses geographic data within a multiple-criteria decision-making framework and can be incorporated into projects that require identification or prioritization of alternative management scenarios among conflicting goals and objectives (Strager et al., 2010).

Standard statistical packages are also increasingly being linked to GIS for exploratory data analysis and statistical analysis and hypothesis testing (Burrough, 2000) Geostatistics addresses the need to make predictions of sampled attributes (i.e., maps) at unsampled locations from sparse, often expensive data (Burrough, 2000).

Groundwater Use

Wang et al. (2014) explored factors influencing changes in water industrial sector withdrawals the United States between 1997 and 2002 and found that changes in population, gross domestic product (GDP) per capita, and water use intensity led to increased water withdrawals, while changes in production structure and consumption patterns resulted in decreased water withdrawals.

CHAPTER II

NATURAL AND ANTHROPOGENIC FACTORS AFFECTING GROUNDWATER IN THE CRITICAL ZONE OF THE TEXAS TRIANGLE MEGAREGION

Rapid changes occurring on Earth since the beginning of the Industrial Revolution are leading to a new geological epoch referred to as the Anthropocene (Amundson, Richter, Humphreys, Jobbágy, & Gaillardet, 2007; Crutzen, 2002). The Anthropocene (~250 y BP to present) encompasses some of the most pronounced changes in the history of Earth by any measurement: rates of erosion, deforestation, extinction, extent of climate change, and so forth (Amundson et al., 2007).

In less than three centuries, 1.86 million hectares (46 million acres) of the virgin landscape in the United States has been converted to urban uses; in the next 25 years that area will more than double to 45.32 million hectares (112 million acres; Carbonell & Yaro, 2005). During this time period, more than half of the land surface has been "plowed, pastured, fertilized, irrigated, drained, fumigated, bulldozed, compacted, eroded, reconstructed, manured, mined, logged, or converted to new uses" (Richter & Mobley, 2009, p. 1067). Activities like these have far-reaching impacts on life-sustaining processes of the near-surface environment, recently termed the "critical zone" (Richter & Mobley, 2009).

The "critical zone" is the vertical and spatial zone of the surface and near-surface systems that extends from bedrock to the atmosphere boundary layer (Anderson et al., 2010; National Research Council [NRC], 2001). The critical zone lies at the interface of the lithosphere, atmosphere, and hydrosphere (Amundson et al., 2007) and encompasses soils and terrestrial ecosystems. Although not usually recognized in definitions of the critical zone (Anderson et al., 2010; NRC, 2001), this zone also includes human systems. Thus, the critical zone is a complex mixture of air, water, biota, organic matter, earth materials, energy, human capital, and associated infrastructure and alterations (Brantley, Goldhaber, & Ragnarsdottir, 2007).

The critical zone has been defined as “the heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources” (Lin, 2010, p. 25). It has evolved as a dynamic and generally self-sustaining system (Amundson et al., 2007). This thin, fragile envelope that includes the land surface and its canopy of vegetation, rivers, lakes, and shallow seas (Wilding & Lin, 2006) is critical from a human perspective because it is the environment in which most people live and work (Graf, 2008).

Future global change has implications for the critical zone because of changes in such phenomena as rates of evapotranspiration, precipitation characteristics, plant distributions, and human responses (Goudie, 2006). Global climate models predict a warmer planet (Bradley, Alverson, & Pedersen, 2003). For Texas, this could mean changes to its climate—specifically temperature, evaporation, rainfall, and drought (Mace & Wade, 2008). At the same time, rapidly growing demands for water in urban areas are already straining local and regional water supplies. Concerns about the scarcity of urban water in the United States are becoming more prominent (Levin et al., 2002;

Padowski & Jawitz, 2012). Water shortages in Atlanta, Georgia, in 2008, and San Francisco, California, in 2006-2007 (Dorfman, Mehta, Chou, Fleischli, & Rosselot, 2011; Padowski & Jawitz, 2012) are illustrative of the potential impacts of climate change on population growth, environmental regulation, and water supplies.

In the United States, more than 80% of the population now lives in urban areas, compared to 64% in 1950 (Padowski & Jawitz, 2012). Further, population in the United States will likely increase by 40% by 2050 with the growth concentrated in 8 to 10 megaregions (Dewar & Epstein, 2007). A *megaregion* consists of two or more metropolitan areas linked with interdependent environmental systems, a multimodal transportation infrastructure, and complementary economies (Butler, Hammerschmidt, Steiner, & Zhang, 2009; Zhang, Steiner, & Butler, 2007). Ensuring that cities have an adequate supply of water will become increasingly important as human populations continue to concentrate in these highly urbanized megaregions. Thus, interaction between humans and the other natural systems in the critical zone will become more complex.

As populations continue to increase during a period of rapid global change, far-reaching impacts will occur within the critical zone. It will be increasingly important to understand these changes to the critical zone to mitigate them effectively. The purpose of this chapter is to examine the potential impact of anthropogenic changes on the critical zone. The point is illustrated by focusing in one area of Texas that is experiencing exceptionally dynamic alterations to the critical zone.

Identification of the Study Area

The TTMR is one of the emerging megaregions initially identified by the University of Pennsylvania with the Regional Plan Association and the Lincoln Institute (Zhang et al., 2007). The region is spatially delineated by the metropolitan areas of Dallas/Fort Worth, Austin, San Antonio, and Houston, with a total land size of approximately 155,000 square kilometers (59,900 square miles) encompassing 65 of the 254 counties in the state (Butler et al., 2009; Neuman, Bright, & Morgan, 2010; Zhang et al., 2007). The metro areas of Dallas/Fort Worth, Houston, and San Antonio form the vertices of the TTMR (Figure 1), which measure 701, 531, and 624 kilometers (436, 319, and 388 miles), respectively (Butler et al., 2009).

The Texas Triangle is a singular, new, complex, and important urban phenomenon (Neuman et al., 2010). One of the most dynamic urban regions in the nation, with a present population of more than 17 million, the TTMR represents a new urban phenomenon: a “triangular megalopolis whose development is not linear and contiguous, like prior megalopolises” (Neuman et al., 2010). This region has been characterized as the “core area of Texas,” a single mega-city forming the nucleus of Texas and rivaling New York and Los Angeles (Neuman & Bright, 2008).

The Triangle includes 70% of the population of the state, 80% of the employment, and 85% of the wages (Neuman et al., 2010). Based on the 2010 U.S. Census Bureau TIGER Data, the region contains 109 urbanized area clusters and 17 urbanized areas totaling 16,312 square kilometers. The region is emerging as a new urban megaregion in its own right (Neuman et al., 2010).

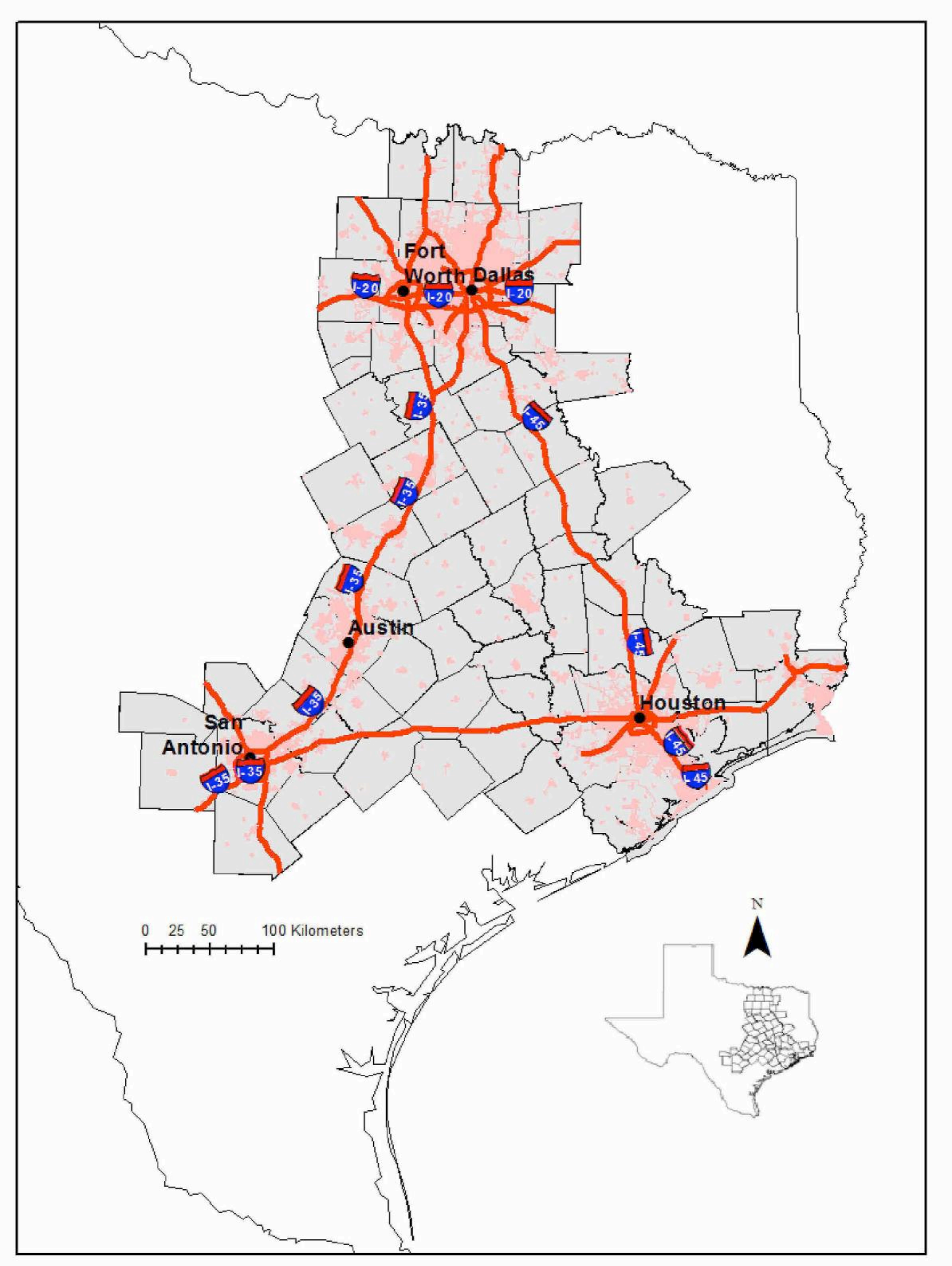

Figure 1. The Texas Triangle Megaregion (TTMR).

Physical Divisions and Ecoregions

The TTMR contains a diverse landscape including portions of four of Bailey's Ecoregions (Bailey, U.S. Fish and Wildlife Service, & U.S. Forest Service, 1980): from west to east, the Southwest Plateau and Plains Dry Steppe and Shrub Province, the Prairie Parkland (Subtropical) Province, the Southeastern Mixed Forest Province, and the Outer Coastal Plain Mixed Forest Province (Figure 2).

Southwest Plateau and Plains Dry Steppe and Shrub Province

This region of flat to rolling plains and plateaus is occasionally dissected by canyons at the western end of the Gulf Coastal Plain and the southern end of the Great Plains (Bailey et al., 1980). The Balcones Fault Zone and Escarpment sharply delineates the Southwest Plateau ecoregion from the prairielands to the east. This area is characterized by hilly limestone terrain dissected by spring-fed streams of tremendous ecological, recreational, and aesthetic importance (Butler et al., 2009; Zhang et al., 2007). Within the TTMR, elevations range from sea level to 1,100 meters (3,600 feet) on the Edwards Plateau (Figure 3).

The native vegetative cover is diverse and largely evergreen, dominated by juniper and live oak (Butler et al., 2009; Zhang et al., 2007). Live Oak-Ashe Juniper-Mesquite parks are the predominant (27%) vegetation cover in this province. Oak-Mesquite-Juniper park/woods occupy about 13% of the province within the megaregion. Thicker stands of Live Oak-Ash Juniper woods occupy approximately 12% of the area. Lesser coverage of Post Oak Woods, Forest and Grassland Mosaic (7%), Bluestem Grassland (6%), Mesquite-Blackbush Brush (5%), Mesquite Granero Woods (5%), and

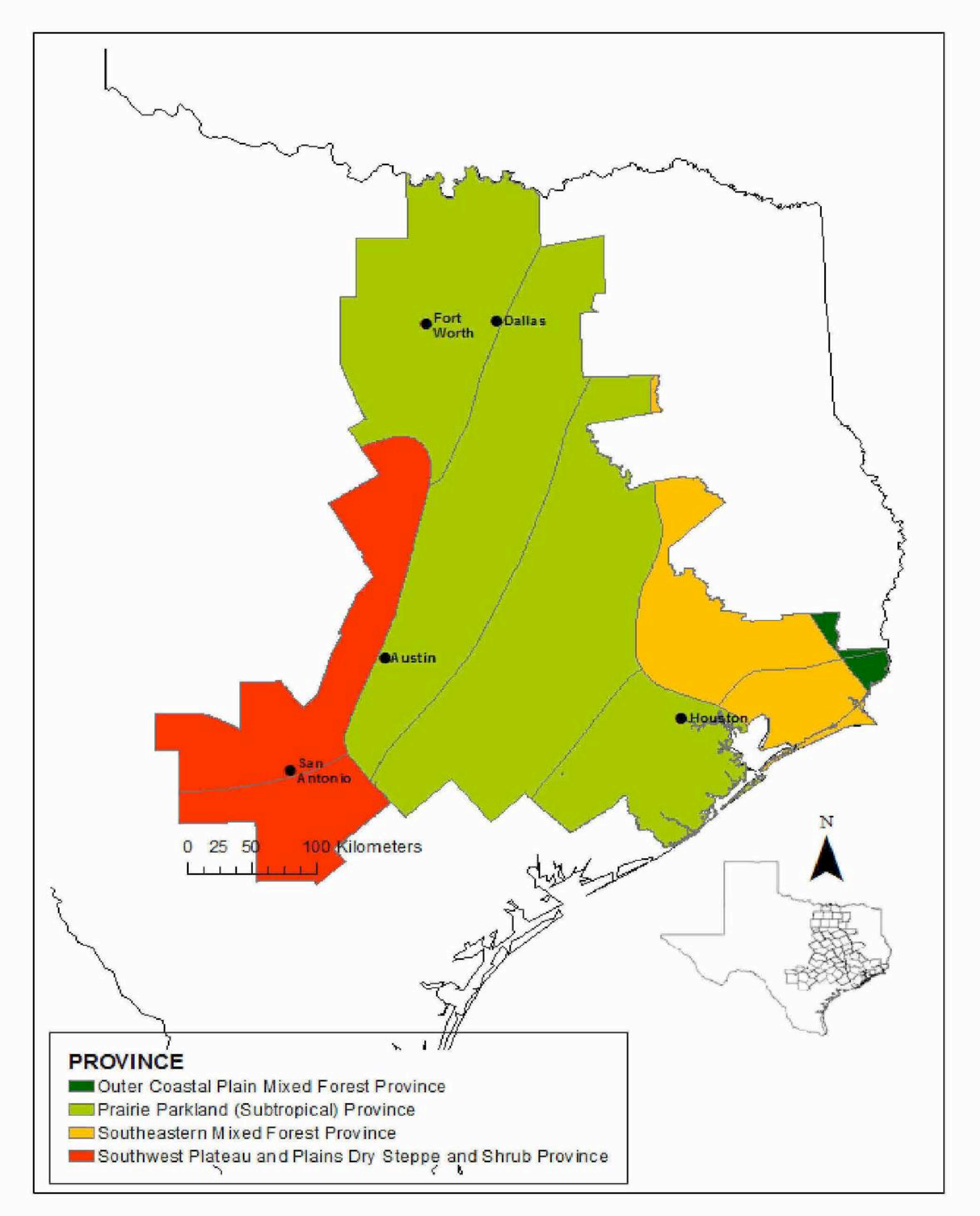

Figure 2. Bailey's Ecoregion Provinces in the Texas Triangle Megaregion (TTMR).

Figure 3. Edwards Plateau near Enchanted Rock, north of Austin, Texas. Photo by the author.

Mesquite-Live Oak-Bluewood Parks (3%) are also present. Cropland occupies about 21% of the area and surface water accounts for only 1% of the surface area in this province. The Southwest Plateau and Plains Dry Steppe and Shrub Province is summarized in Table 1.

Prairie Parkland (Subtropical) Province

The Prairie Parkland Province is the predominate ecoregion within the TTMR, occupying approximately 69% (104,152 square kilometers) of the total area. An extensive border of marshes stretches inland 8 to 16 kilometers (5 to 10 miles), sometimes farther, from the Gulf Coast of Mexico (Bailey et al., 1980) in this province, encompassing about 552 square kilometers.

Vegetation in the Prairie Parkland Province is comprised mainly of a Post Oak Parks/Woods Forest (Figure 4) and Grassland Mosaic (47%). Silver Bluestem-Texas

Table 1

Southwest Plateau and Plains Dry Steppe and Shrub Province Vegetation Cover

Cover	Area (sq. km)
Bluestem Grassland	1,260
Silver Bluestem-Texas Wintergrass Grassland	6,439
Oak-Mesquite-Juniper Parks/Woods	2,453
Live Oak-Mesquite-Ashe-Juniper Parks	288
Live Oak-Ashe Juniper Parks	318
Post Oak Parks/Woods Forest and Grassland Mosaic	33,011
Willow Oak-Water Oak-Blackgum Forest	60
Elm-Hackberry Parks/Woods	2,734
Water Oak-Elm-Hackberry Forest	1,246
Cottonwood-Hackberry-Saltcedar Brush/Woods	118
Pecan Elm	1,764
Young Forest/Grassland	97
Pine Hardwood	2,652
Marsh Barrier Island	552
Crops	11,187
Urban	3,852
Surface Water	1,728
Total Area	69,759

Figure 4. Example of Post Oak Park/Woods. Photo courtesy of Tarleton State University.

Wintergrass Grassland make up approximately 11% of the province within the TTMR. Oak-Mesquite-Juniper Parks/Woods and Water Oak-Elm-Hackberry Forests/Woods make up lesser percentages of the vegetation cover in this area. Surface water occupies about 2% of the area.

The urban areas of Austin, Fort Worth, Dallas, and Houston are contained within this province of the TTMR and account for approximately 6% of the total land area of the province. The metropolitan areas of Dallas and Austin are located in and along the interface between the Blackland Prairie and Edwards Plateau (Butler et al., 2009; Zhang et al., 2007). These ecoregions are generally perpendicular to the Gulf Coast margin and to the major watersheds and river corridors, as they extend to the coast (Zhang et al., 2007). The Houston metropolitan area and its associated communities, closer to the Gulf Coast, are located on terrain that is very flat and predominately covered in grassland, with forest or savannah-type vegetation in areas further inland (Zhang et al., 2007).

The Prairie Parkland ecoregion is highly fertile and agriculturally productive, comprised of fine textured clay soils and only small remnants of a formerly extensive natural prairie (Butler et al., 2009; Zhang et al., 2007). A considerable portion of agricultural land (about 16%) still exists, although urban and industrial growth and development is a persistent challenge to the preservation of the intrinsic resources in the region (Zhang et al., 2007). The Prairie Parkland (Subtropical) Province is summarized in Table 2.

Southeastern Mixed Forest Province

The Southeastern Mixed Forest Province occupies 12% or 17,730 square kilometers (6,846 square miles) of the TTMR. Local relief is 30 to 180 meters (100 to 600 feet) on the Gulf Coastal Plains. The flat Coastal Plains have gentle slopes and local relief of less than 30 meters (100 feet). Most of the numerous streams move slowly; marshes, lakes, and swamps are numerous (Figure 5).

Approximately half (48%) of the vegetation in this province is Pine Hardwood (Figure 6). Lesser amounts (about 11% total) of Young Forest/Grassland, Willow Oak-Water Oak-Blackgum Forest and Bald Cypress-Water Tupelo Swamp make up the remainder of the native vegetation in this province in the TTMR. Marsh Barrier Islands make up nearly 7% of the area. Cropland occupies about 20% of the land surface here. Urban areas comprise only 2% of the land area. Surface water accounts for about 2.5% of the area. The Southeastern Mixed Forest Province Vegetation Cover is summarized in Table 3.

Table 2

Prairie Parkland (Subtropical) Province Vegetation Cover

Cover	Area (sq. km)
Bluestem Grassland	1,645
Mesquite-Blackbrush Brush	1,184
Mesquite-Granjeno Woods	1,371
Mesquite-Live Oak-Bluewood Parks	767
Oak-Mesquite-Juniper Park/Woods	3,284
Live Oak-Ashe Juniper Parks	7,155
Live Oak-Mesquite-Ashe Juniper Parks	3,255
Post Oak Woods, Forest and Grassland Mosaic	1,927
Pecan Elm	46
Crops	5,529
Other	17
Urban	73
Surface Water	189
Total Area	26,442

Outer Coastal Plain Mixed Forest Province

Representing only 12% (1,259 square kilometers) of the TTMR, the Outer Coastal Plain Mixed Forest Province is restricted to flat and irregular southern Gulf Coastal Plains and is located in the far southeastern corner of the TTMR. The area is gently sloping, with relief typically less than 90 meters (300 feet; Bailey et al., 1980).

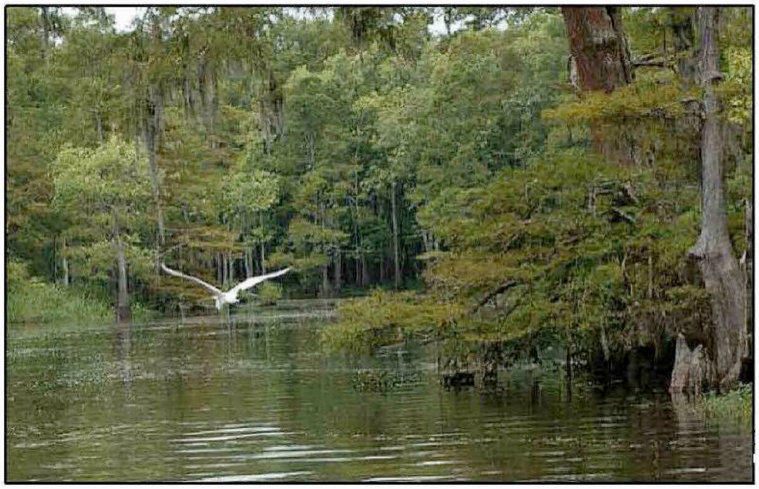

Figure 5. Mixed hardwood forest and swamp typical of the Southwestern Mixed Forest Province. Photo courtesy of the U.S. National Parks Service.

Figure 6. Pine hardwood forest. Photo courtesy of Texas Parks and Wildlife Department.

most of its numerous streams are sluggish; marshes, swamps, and lakes are numerous (Bailey et al., 1980).

Table 3

Southeastern Mixed Forest Province Vegetation Cover

Cover	Area (sq. km)
Bluestem Grassland	192
Post Oak Woods, Forest, Grassland Mosaic	63
Willow Oak-Water Oak-Blackgum Forest	807
Bald Cypress-Water Tupelo Swamp	97
Young Forest/Grassland	783
Pine Hardwood	8,529
Marsh Barrier Island	1,157
Crops	3,532
Other	1,811
Urban	296
Surface Water	441
Total Area	17,708

Soils in this region tend to be wet, acidic, and low in major plant nutrients, having been derived mainly from Coastal Plain sediments, ranging from heavy clay to gravel (Bailey et al., 1980). Soil is comprised predominantly of sandy materials, with silty soils occurring mainly on expansive level areas (Bailey et al., 1980). Vegetation is predominately pine hardwood (51%), with the other native vegetation comprised mainly of Willow Oak-Water, Oak-Blackgum Forest, Bald Cypress-Water, Tupelo Swamp, and Young Forest Grassland (17% combined). Approximately 15% of the province is cropland. Marsh barrier islands make up approximately 13% of the area. Urban areas occupy 4% of the area. Surface water as a percentage of total land cover is negligible in this province. The Outer Coastal Plain Mixed Forest Province is summarized in Table 4.

Table 4

Outer Coastal Plain Mixed Forest Province Vegetation Cover

Cover	Area (sq. km)
Willow Oak-Water Oak-Blackgum Forest	83
Bald Cypress-Water Tupelo Swamp	25
Young Forest/Grassland	96
Pine Hardwood	636
Marsh Barrier Island	163
Crops	189
Urban	57
Surface Water	2
Total Area	1,251

Aquifer Structure and Stratigraphy

According to the 2012 Texas State Water Plan, published by the TWDB, groundwater represents 60% of the total water used statewide (Vaughn et al., 2012). The amount used in the TTMR roughly mirrors the statewide water use data. In the TTMR, groundwater is supplied by numerous aquifers capable of providing groundwater in quantities sufficient to support household, industrial, municipal, and irrigation needs throughout the region (Kelley, Deeds, Fayer, & Senger, 2009; Vaughn et al., 2012)

Texas recognizes 30 aquifers (Figure 7), 21 one of which are defined as “minor” and 9 of which are defined as “major,” based on production (C. R. Brown & Farrar, 2008). Portions of four major aquifers underlie the TTMR (Figure 3): Trinity, Carrizo-Wilcox, Gulf Coast, and Edwards. The characteristic lithology of the karstic Edwards Aquifer and the Trinity Aquifer north of Austin are primarily massive limestones, sands, clays, gravels, and conglomerates (George, Mace, & Petrossian, 2011). The characteristics of the Carrizo-Wilcox and Gulf Coast aquifers differ significantly from the limestone aquifers. They dip and are principally confined clastic aquifers (Mace & Wade, 2008; Pearson & White, 1967). The age of groundwater in downdip areas of the Carrizo-Wilcox Aquifer can be more than 30,000 years (Mace & Wade, 2008; Pearson & White, 1967).

Carrizo-Wilcox Aquifer

The Carrizo-Wilcox Aquifer ranks third in the state for water use of 555 million cubic meters (450,000 acre feet) per year in 2003 behind the Gulf Coast Aquifer and the Ogallala Aquifer (Kelley et al., 2009). The Carrizo-Wilcox has been identified as a potential groundwater source to serve growing demands along the IH 35 corridor. The aquifer extends from the Rio Grande in south Texas northeastward into Arkansas and Louisiana, generally parallel to and east of IH 35.

The Carrizo-Wilcox is a hydrologically connected system consisting of the Wilcox Group and the overlying Carrizo Formation of the Claiborne Group of

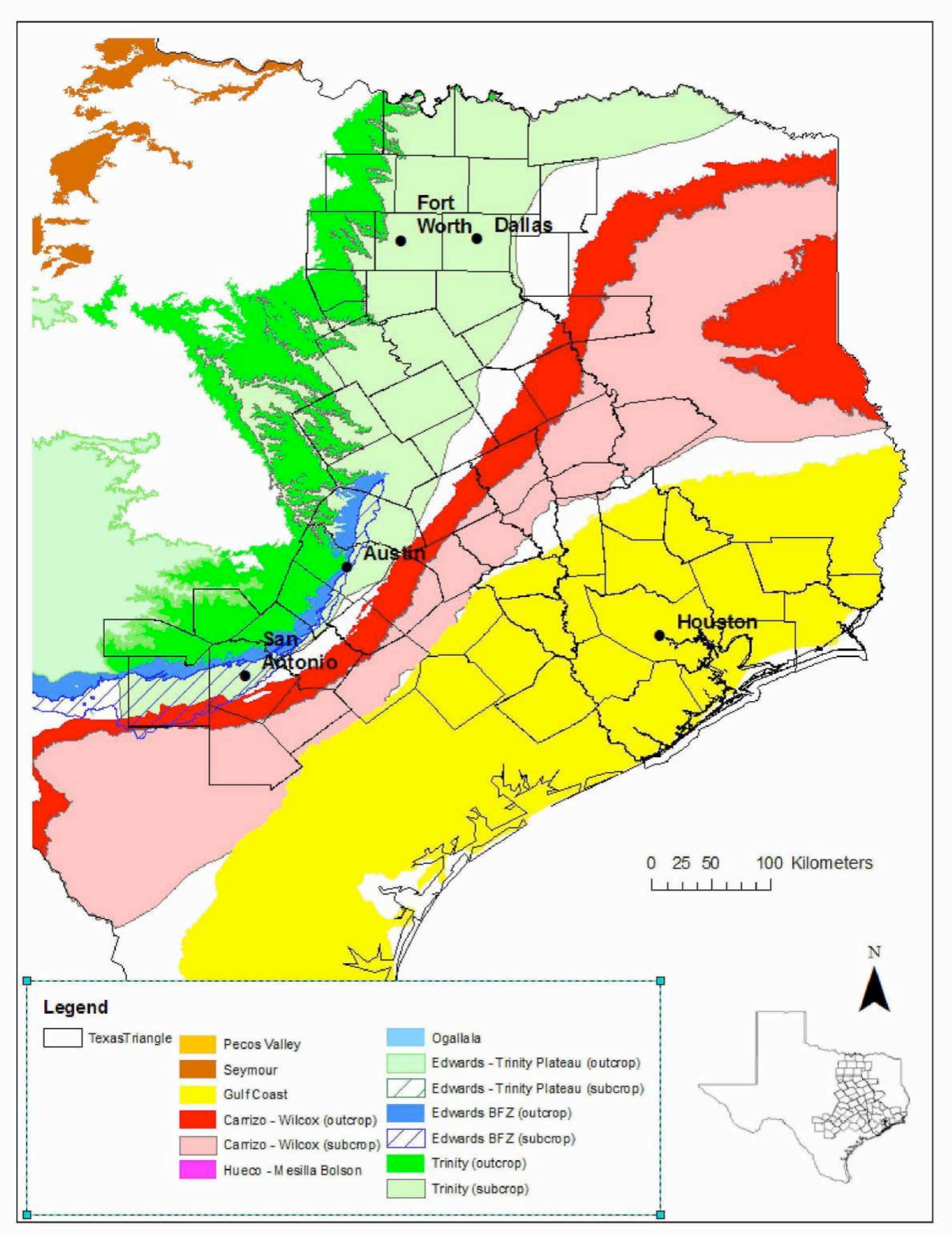

Figure 7. Major aquifers of Texas. Source: Texas Water Development Board.

fluvio-deltaic origin (Ashworth & Hopkins, 1995). The Wilcox Group contains a complex distribution of shale and sand facies that were deposited by ancient river systems (Fisher & McGowen, 1969; Thorkildsen, Quincy, & Preston, 1989). Because the sands of the Wilcox Group are locally hydraulically connected with the Carrizo Sand, both aquifers are jointly referred to as the Carrizo-Wilcox Aquifer (Green et al., 2011; Klemt, Duffin, & Elder, 1976).

Underlying the Carrizo-Wilcox Aquifer, the Paleocene Midway Formation acts as a regional confining unit (Kelley et al., 2009). Deposits of the Claiborne Group overlying the Carrizo-Wilcox Group include the fluvio-deltaic Queen City and Sparta formations separated from the Carrizo Wilcox Aquifer by the Reklaw Formation, a marine shale unit (Kelley et al., 2009), as shown in Figure 8.

The Carrizo-Wilcox aquifer is predominantly composed of sand locally interbedded with gravel, silt, clay, and lignite deposited during the Tertiary. South of the Trinity River and north of the Colorado River, the Wilcox Group is divided into three distinct formations: Hooper, Simsboro, and Calvert Bluff. Of the three formations, the Simsboro typically contains the most massive water-bearing sands. Aquifer thickness in the downdip portion ranges from less than 61 meters (200 feet) to more than 914 meters (3,000 feet; Ashworth & Hopkins, 1995). Although the Carrizo-Wilcox Aquifer reaches 914 meters (3,000 feet) in thickness, the freshwater saturated thickness of the sands averages 204 meters (670 feet; George et al., 2011).

The Carrizo Sand and Wilcox Group outcrop along a narrow band that parallels the Gulf Coast and dips beneath the land surface toward the coast. The Carrizo-Wilcox

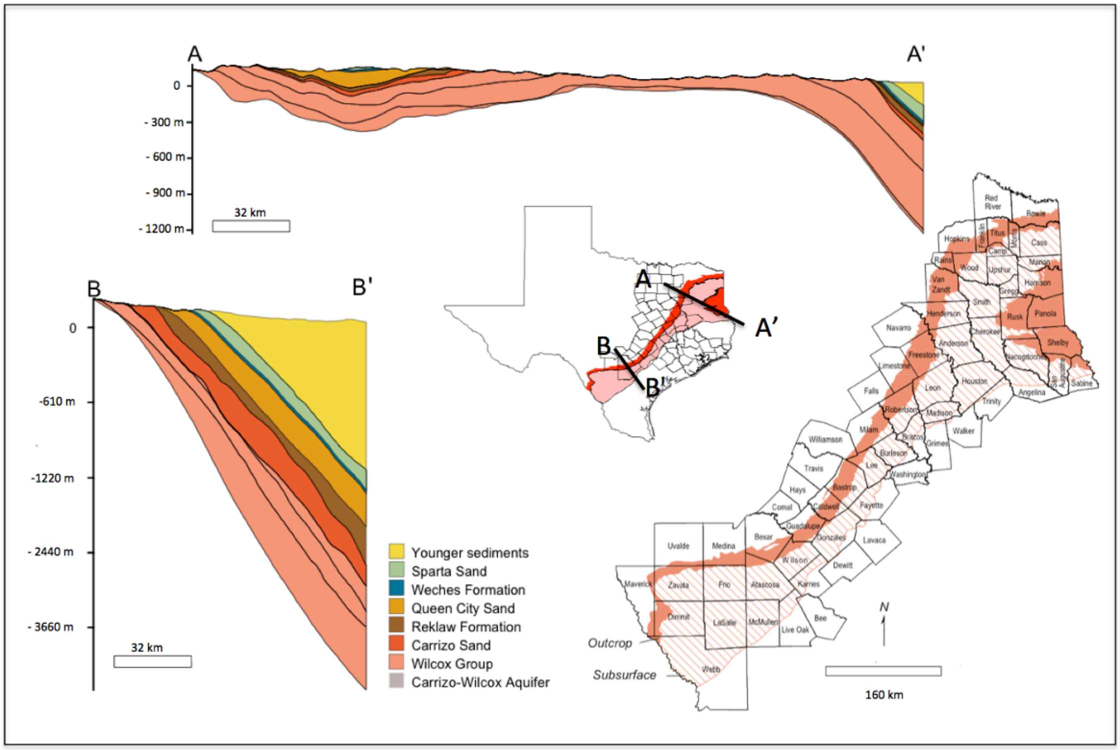

Figure 8. Carrizo-Wilcox structural cross section. Modified from *Aquifers of Texas,* by P. G. George, R. E. Mace, & R. Petrossian, 2011, Austin, TX: Texas Water Development Board.

Aquifer has three principal sources of recharge: subsurface interformational flow from other stratigraphic units, distributed recharge from precipitation over the Carrizo-Wilcox Aquifer recharge zone, and focused recharge in stream and river channels (Green et al., 2011). Irrigation pumpage during the drought has increased substantially in the Wintergarden area of southwest Texas, as has pumping of groundwater to support oil and gas exploration and production activities associated with the Eagle Ford Shale (Neffendorf & Hopkins, 2013). Water-level changes in the 11 Carrizo-Wilcox Aquifer recorder wells, managed by the TWDB, ranged from +2.62 meters (8.6 feet) in the Bastrop County well to -22 meters (-72.2 feet) in the LaSalle County well during the period 2011–2012 (Neffendorf & Hopkins, 2013). The median water-level change was -0.27 meters (-0.9 feet) and the average change was -2.74 meters (-9.0 feet; Neffendorf & Hopkins, 2013).

Gulf Coast Aquifer

The Gulf Coast aquifer forms a wide belt paralleling the Gulf of Mexico from the Louisiana border to border of Mexico (George et al., 2011). In Texas, the aquifer provides water to all or parts of 54 counties and extends from the Rio Grande northeastward to the Louisiana-Texas border. Municipal and irrigation uses account for 90% of the total pumpage from the aquifer. The greater Houston metropolitan area is the largest municipal user, where well yields average about 6,056 liters (1,600 gal) per minute (Ashworth & Hopkins, 1995).

The Gulf Coast Aquifer (Figure 9) consists of several aquifers, including the Chicot, Evangeline, and Jasper Aquifers (George et al., 2011). The aquifer consists of a complex of interbedded clays, silts, sands, and gravels of Cenozoic age, which are hydrologically connected to form a large, leaky artesian aquifer system (Ashworth & Hopkins, 1995). This system comprises four major components, consisting of the following generally recognized water-producing formations. The deepest is the Catahoula, which contains groundwater near the outcrop in relatively restricted sand layers. Above the Catahoula is the Jasper Aquifer, primarily contained within the Oakville Sandstone (Ashworth & Hopkins, 1995). The Burkeville confining layer separates the Jasper from the overlying Evangeline Aquifer, which is contained within the Fleming and Goliad sands. The Chicot Aquifer, or upper component of the Gulf

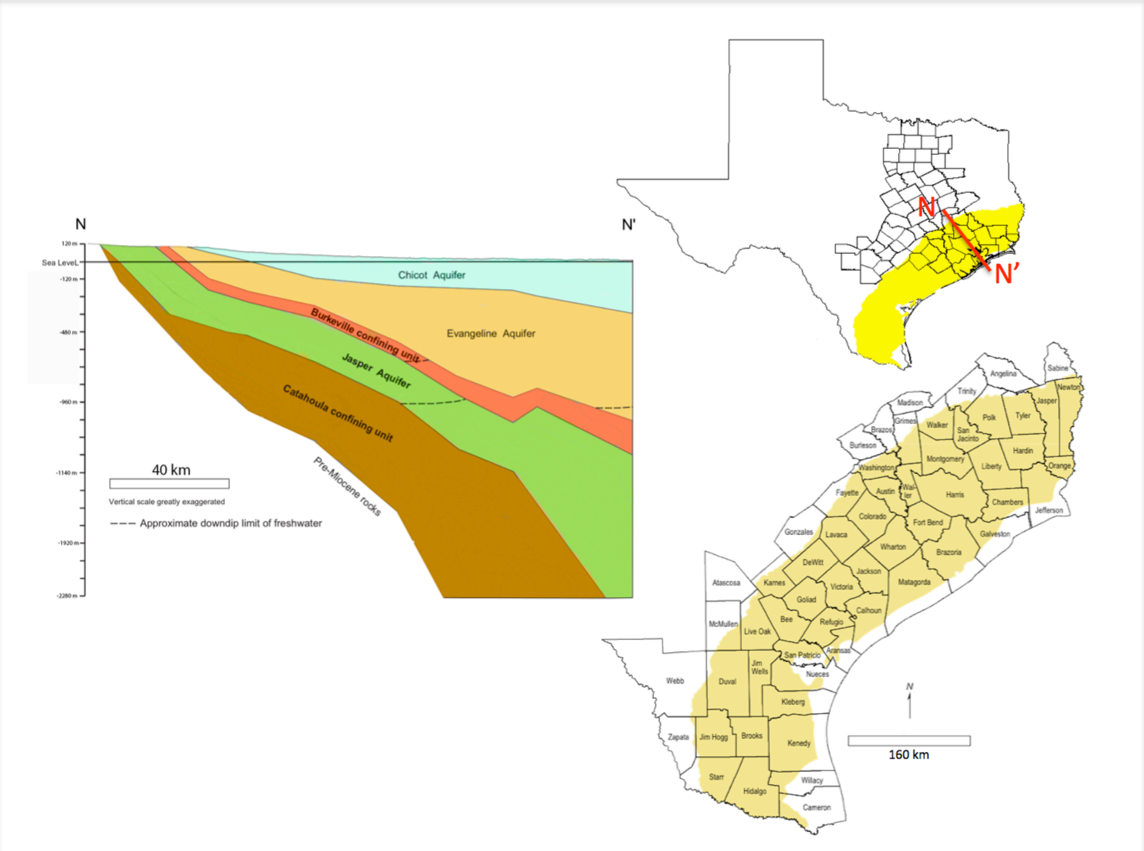

Figure 9. Gulf Coast Aquifer location and cross structure.

Coast Aquifer System, consists of the Lissie, Willis, Bentley, Montgomery, and Beaumont formations, and overlying alluvial deposits. Not all formations are present throughout the system, and nomenclature often differs from one end of the system to the other (Ashworth & Hopkins, 1995). Maximum total sand thickness ranges from 213 meters (700 feet) in the south to 396 meters (1,300) feet in the northern extent (Ashworth & Hopkins, 1995; George et al., 2011). Freshwater saturated thickness averages about 304 meters (1,000 feet; George et al., 2011).

The aquifer is used for municipal, industrial, and irrigation purposes (George et al., 2011). Years of heavy pumpage for municipal and manufacturing use in portions of the aquifer have resulted in areas of significant water-level decline (Ashworth & Hopkins, 1995). Declines of 61 meters (200 feet) to 91 meters (300 feet) have been measured in some areas of eastern and southeastern Harris and northern Galveston counties (Ashworth & Hopkins, 1995). In Harris, Galveston, Fort Bend, Jasper, and Wharton counties, water-level declines of as much as 107 meters (350 feet) have led to land subsidence (George et al., 2011). From 2011 to 2012, water-level changes in the 11 Gulf Coast Aquifer recorder wells ranged from 6 meters (+19.7 feet) in the Karnes County well to -5.1 meters (16.7 feet) in the northernmost Wharton County well, with a median change of 15.24 centimeters (0.5 feet) and an average change of 27.4 centimeters (0.9 feet; Neffendorf & Hopkins, 2013).

Edwards Aquifer

The Edwards (Balcones Fault Zone, or BFZ) Aquifer covers approximately 11,266 square kilometers (4,350 square miles) in parts of 11 counties (Ashworth & Hopkins, 1995). The aquifer forms a narrow belt extending from a ground-water divide in Kinney County through the San Antonio area northeastward to the Leon River in Bell County.

A poorly defined ground-water divide near Kyle in Hays County hydrologically separates the aquifer into the San Antonio and Austin regions. The name Edwards (BFZ) distinguishes this aquifer from the Edwards-Trinity (Plateau) and the Edwards-Trinity (High Plains) aquifers (Ashworth & Hopkins, 1995).

Consisting of partially dissolved limestone formed during early Cretaceous, the highly permeable aquifer exists under water-table conditions in the outcrop and under artesian conditions where it is confined below the overlying Del Rio Clay (Ashworth & Hopkins, 1995; George et al., 2011). The Edwards aquifer consists of the Georgetown Limestone, formations of the Edwards Group (the primary water-bearing unit) and the equivalents, and the Comanche Peak Limestone where it exists (Ashworth & Hopkins, 1995). Thickness ranges from 61 meters (200 feet) to 183 meters (600 feet; Ashworth & Hopkins, 1995). The Edwards Aquifer is delineated in Figure 10.

The Edwards Aquifer responds rapidly to rainfall events and periods of drought (Mace & Wade, 2008; Pearson & White, 1967). Recharge to the aquifer occurs primarily by the downward percolation of surface water from streams draining off the Edwards Plateau to the north and west and by direct infiltration of precipitation on the outcrop (Ashworth & Hopkins, 1995). This recharge reaches the aquifer through crevices, fractures, faults, and sinkholes in the unsaturated zone. Unknown amounts of groundwater enter the aquifer as lateral underflow from the Glen Rose Formation (Ashworth & Hopkins, 1995).

Water from the aquifer is used primarily for municipal, irrigation, and recreational purposes. San Antonio obtains almost all of its water supply from the Edwards (BFZ) Aquifer (George et al., 2011). Water is also discharged artificially from hundreds of pumping wells, particularly municipal supply wells in the San Antonio region and irrigation wells in the western extent. In the four Edwards Aquifer (BFZ) recorder wells monitored by the TWDB, changes from 2011 to 2012 ranged from +0.76

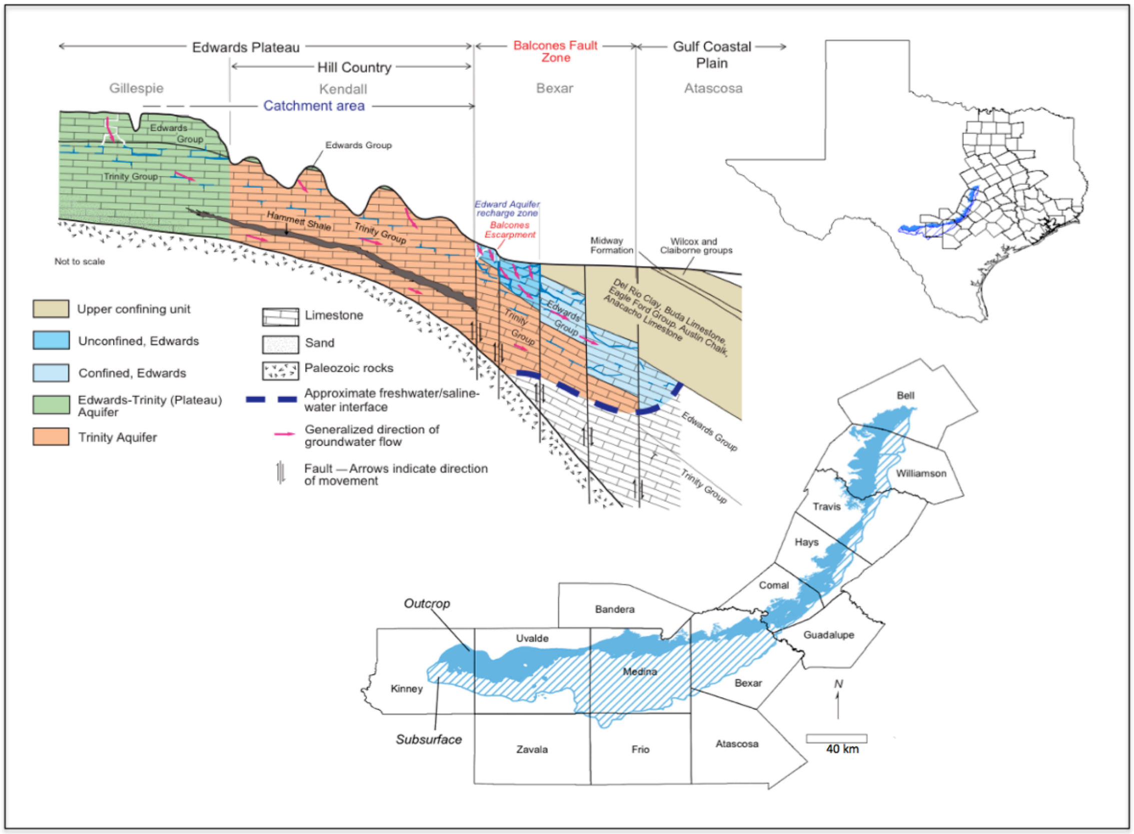

Figure 10. The Edwards Aquifer (Balcones Fault Zone). Modified from *Aquifers of Texas,* by P. G. George, R. E. Mace, & R. Petrossian, 2011, Austin, TX: Texas Water Development Board.

meters to -3.26 meters (+2.5 feet to -10.7 feet) with a median change of +27.4 centimeters (+0.9 feet) and an average change of -1.0 meter (-3.3 feet). From 2010 to 2011, changes ranged from + 3.04 meters to -6.52 meters (+10.4 to -21.4 feet) with a median change of -1.07 meters (-3.5 feet) and an average change of -1.37 meters (-4.5 feet; Neffendorf & Hopkins, 2013).

Trinity Aquifer

Extending across much of the western portion of the TTMR, the Trinity Aquifer consists of early Cretaceous age formations of the Trinity Group where they occur in a band extending through the central part of the state in all or parts of 55 counties, from the Red River in North Texas to the Hill Country of south central Texas (Ashworth & Hopkins, 1995. The aquifer is delineated in Figure 11. Trinity Group deposits also occur in the Panhandle and Edwards Plateau regions where they are included as part of the Edwards-Trinity (High Plains and Plateau) aquifers (Ashworth & Hopkins, 1995). The aquifer is one of the most extensive and highly used groundwater resources in Texas (George et al., 2011).

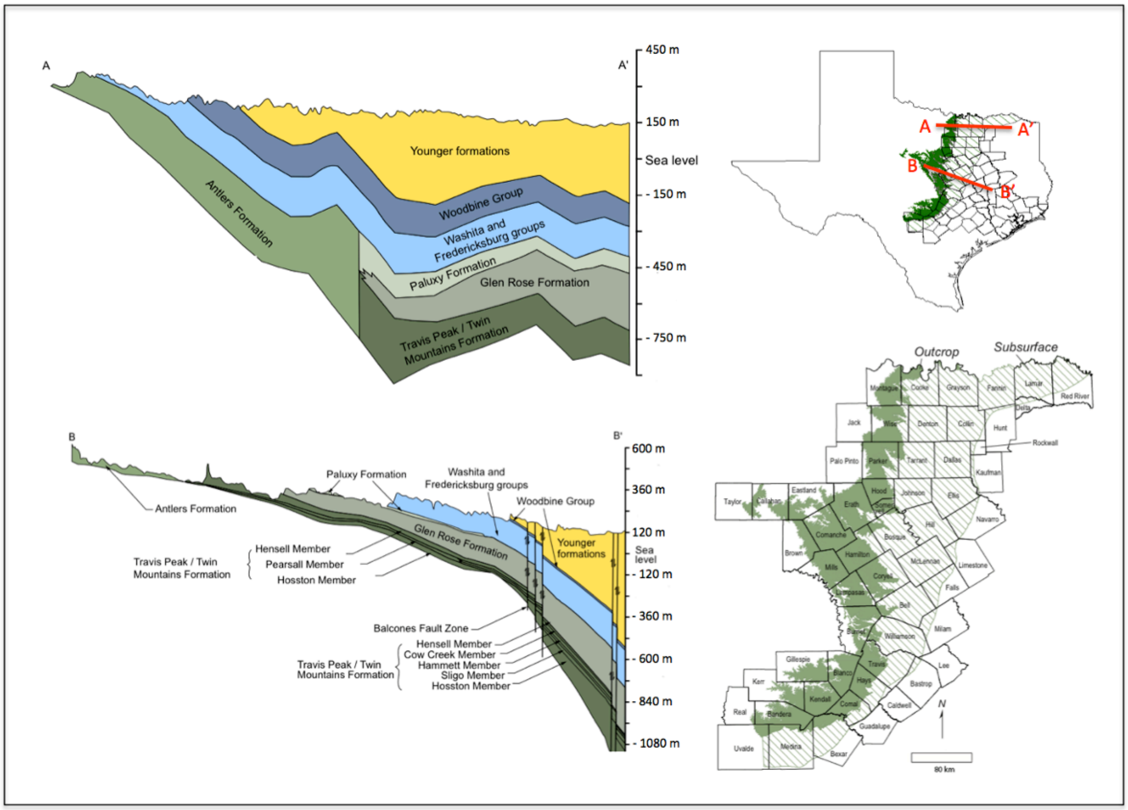

Figure 11. Trinity Aquifer location and cross structure. Adapted from *Aquifers of Texas,* by P. G. George, R. E. Mace, & R. Petrossian, 2011, Austin, TX: Texas Water Development Board.

The Trinity Group is comprised of (from youngest to oldest) the Antlers, Glen Rose, Paluxy, Twin Mountains, Travis Peak, Hensell, and Hosston aquifers (George et al., 2011). Updip, where the Glen Rose thins or is missing, the Paluxy and Twin Mountains coalesce to form the Antlers Formation (Ashworth & Hopkins, 1995). Forming the upper unit of the Trinity Group, the Paluxy Formation consists of up to 122 meters (400 feet) of predominantly fine- to coarse-grained sand interbedded with clay and shale (George et al., 2011). These aquifers consist of limestones, sands, clays, gravels, and conglomerates with a combined freshwater saturated thickness averaging about 183 meters (600 feet) in North Texas and about 579 meters (1,900 feet) in Central Texas (George et al., 2011). The Antlers consists of up to 274 meters (900 feet) of sand and gravel, with clay beds in the middle section (Ashworth and Hopkins, 1995) .

The Trinity Aquifer is most extensively developed from the Hensell and Hosston Members in the Waco area, where the water level has declined by as much as 122 meters (400 feet; Ashworth & Hopkins, 1995). Water from the Antlers is used mainly for irrigation in the outcrop area of north and central Texas (George et al., 2011). Some of the largest declines in water levels range from 107 meters (350 feet) to more than 305 meters (1,000 feet) and have occurred in counties along the IH 35 corridor from McLennan County to Grayson County (George et al., 2011). Extensive development of the Trinity aquifer has occurred in the Fort Worth-Dallas region, where water levels have historically dropped as much as 168 meters (550 feet; George et al., 2011). These declines are primarily attributed to municipal pumping but they have slowed over the past decade as a result of increasing reliance on surface water (George et al., 2011).

Since the mid-1970s, many public supply wells have been abandoned in favor of a surface-water supply, and water levels have responded with slight rises (Ashworth & Hopkins, 1995). Water-level declines of as much as 30.5 meters (100 feet) are still occurring in Denton and Johnson counties (Ashworth & Hopkins, 1995).

Surface Water Resources

Texas has significant surface water resources as well as groundwater resources. The surface waters of the Texas Triangle include a vast array of streams, lakes, and reservoirs occupying more than 2,450 square kilometers (946 square miles) of surface area (Figure 12). More than 11,811 kilometers (7,339 square miles) of major streams and rivers occur in the region, including portions of 10 major river basins, including Brazos, Colorado, Guadalupe, Neches, Nueces, Red, Sabine, and San Trinity.

Anthropogenic Factors Affecting Groundwater in the Critical Zone of the Texas Triangle Megaregion

Anthropogenic forces, ranging from population growth to physical alteration of the landscape, are driving significant changes to the critical zone in the TTMR. Population in the Texas Triangle increased more rapidly than in any other region in Texas during the last half of the 20th century (U.S. Census Bureau, 2014) and that growth is projected to continue at an accelerated rate during the first half of the 21st century (Potter & Hogue, 2011). The expanding population will result in accelerated urbanization and other land use changes that will impact the availability and quality of water resources in the region.

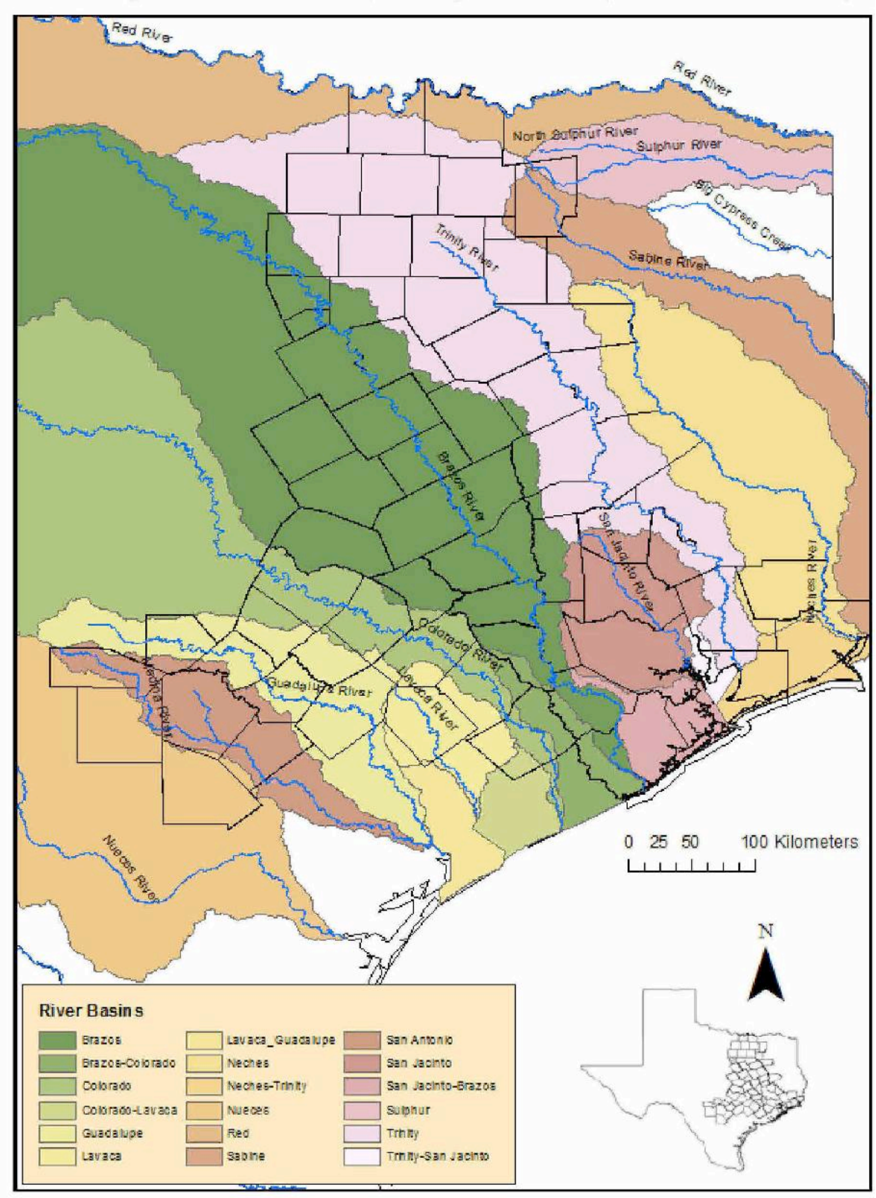

Figure 12. River basins of the Texas Triangle Megaregion (TTMR).

Population Growth

The U.S. Census Bureau has forecast that the population of the nation will grow by 40% to 430 million by 2050 (Carbonell & Yaro, 2005). Whereas the population of the United States is projected to double between 2000 and 2100, the population of Texas is projected to increase by about 2.5 times (Butler et al., 2009). As Texas continues to grow steadily, growth in the TTMR is expected to be even faster (Neuman & Bright, 2008).

Population in the TTMR is projected to increase by 57% between 2000 and 2030, above the 42% increase for the rest of the state (Neuman et al., 2010). Projections indicate that, over the next 20 years, population in the area will account for more than 80% of the total population in the state (Neuman et al., 2010). By 2070, the 65 counties of the TTMR will have a projected population of 38.5 million people.

Urbanization

This expanding Texas population will be accommodated primarily within the Texas Triangle. This has been the fastest-growing region of the state for decades (Neuman et al., 2010). The size of the city of Houston today is equal to the land area of the cities of Boston, Denver, Las Vegas, Orlando, and Philadelphia combined (Butler et al., 2009). The axis from San Antonio to Dallas is on its way to becoming fully urbanized because of the proximity of the string of cities along IH 35: New Braunfels, San Marcos, Austin, Georgetown, Temple, Killeen, and Waco (Neuman et al., 2010). In contrast, along Interstate 45 between Dallas and Houston, and along Interstate 10 between Houston and San Antonio, only small villages and towns exist (Neuman et al., 2010).

According to the 2011 National Land Cover Database (Jin et al., 2013), approximately 14% of the total surface area of the TTMR is developed to some degree, with approximately 4% of that area being medium- or high-intensity development. The area of impervious surface in the TTMR is shown in Figure 13. Table 5 depicts the major land use categories in the TTMR.

Anthropogenic Hydrological Alterations

Supporting the modern industrial infrastructure of a major metropolitan megaregion has required extensive modifications to the various components of the critical zone. These modifications come in the form of an extensive network of dams and reservoirs; a high-density matrix of wells for extracting water, oil, and gas from the critical zone; significant land-cover alterations; and inter-basin transfer of ground and surface water.

Dams and Reservoirs

More than 76 major dams and reservoirs provide a maximum storage capacity in excess of 39.47 cubic kilometers (32 million acre-feet) of water for the TTMR. Normal storage capacity for these reservoirs is approximately 16.40 cubic kilometers (13.3 million-acre feet). The largest of these reservoirs, Medina Lake in Medina County, has a maximum storage capacity of 403 million cubic meters (327,250 acre-feet). Lake McQueeny, built on the Guadalupe River in Guadalupe County, is the smallest of the reservoirs, with a maximum capacity of 6.2 million cubic meters (5,050 acre-feet).

The first of these dams and reservoirs was constructed on Shawnee Creek to form Randell Lake, which provides water for the City of Denton. The last major construction effort was completed in 1987 on the Elm Fork of the Trinity River to form Lake Ray Roberts, which provides water to Cooke, Denton, and Grayson counties.

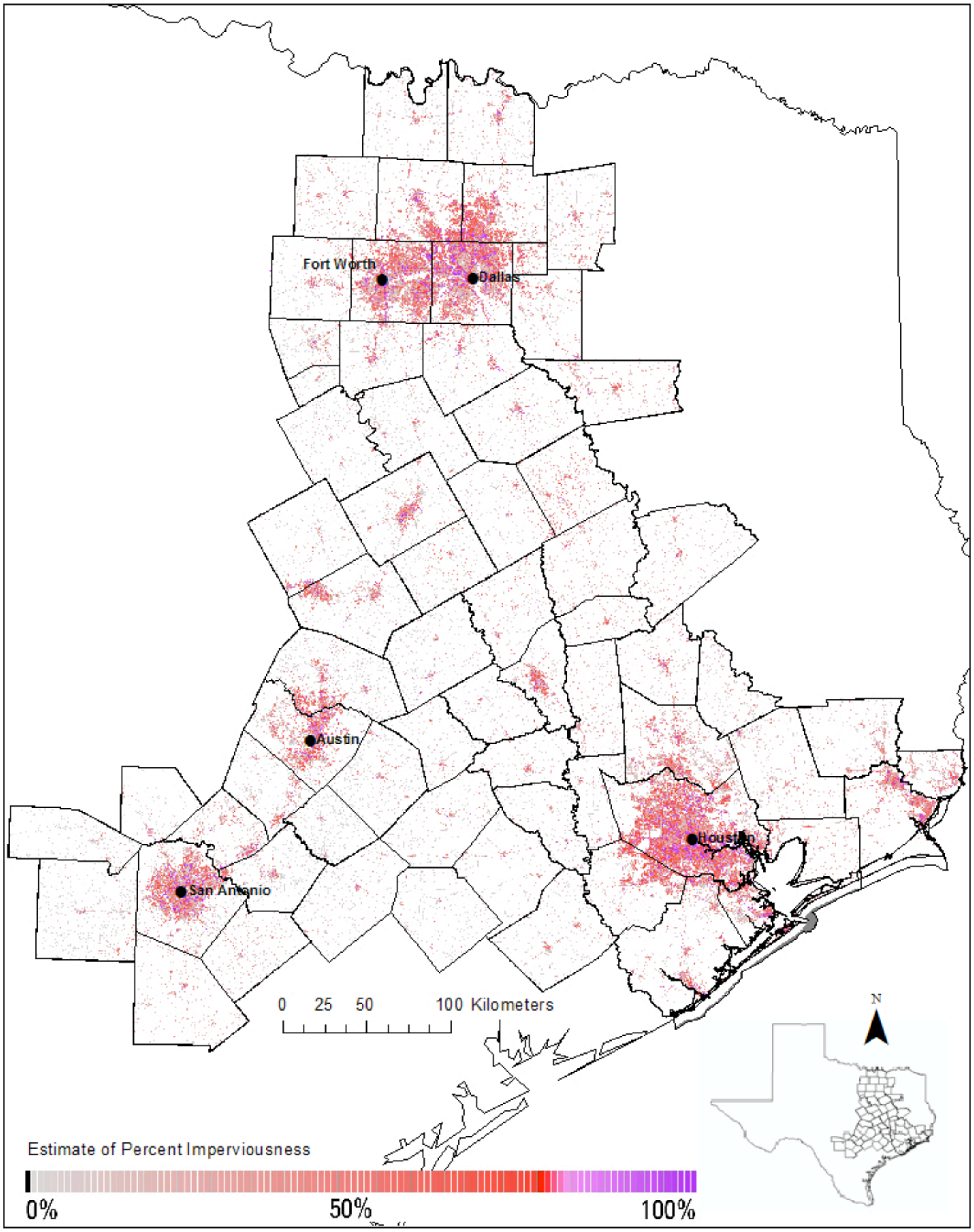

Figure 13. Map of impervious surfaces in the Texas Triangle Megaregion (TTMR).

Table 5

Texas Triangle Megaregion (TTMR) Land Use by Category

Land use category	Area (sq km)	% of total
Open Water	5,996	4
Developed, Open Space	9,558	6
Developed, Low Intensity	5,21	4
Developed, Medium Intensity	3,929	3
Developed, High Intensity	1,622	1
Barren Land (Rock/Sand/Clay)	731	0
Deciduous Forest	13,085	9
Evergreen Forest	11,436	7
Mixed Forest	3,963	3
Scrub/Shrub	15,574	10
Grassland Herbaceous	25,421	17
Pasture/Hay	31,871	21
Cultivated Crops	13,803	9
Woody Wetlands	8,387	5
Emergent Herbaceous Wetlands	2,557	2
Total	153,554	100

Most of the dams and reservoirs within the TTMR serve multiple purposes, including public water supplies, recreation, flood control, hydroelectric power generation, and irrigation. The primary purpose (34%) of these dams and reservoirs is to provide a public water supply for municipalities within the TTMR. Approximately one quarter of the reservoirs also provide a source of recreation for the region. Fifteen percent of the dams and associated reservoirs were constructed to serve a flood control function. A small percentage of the reservoirs (9%) provide a source of water for irrigation. Only 4% of the dams provide a source of hydroelectric power (Figure 14).

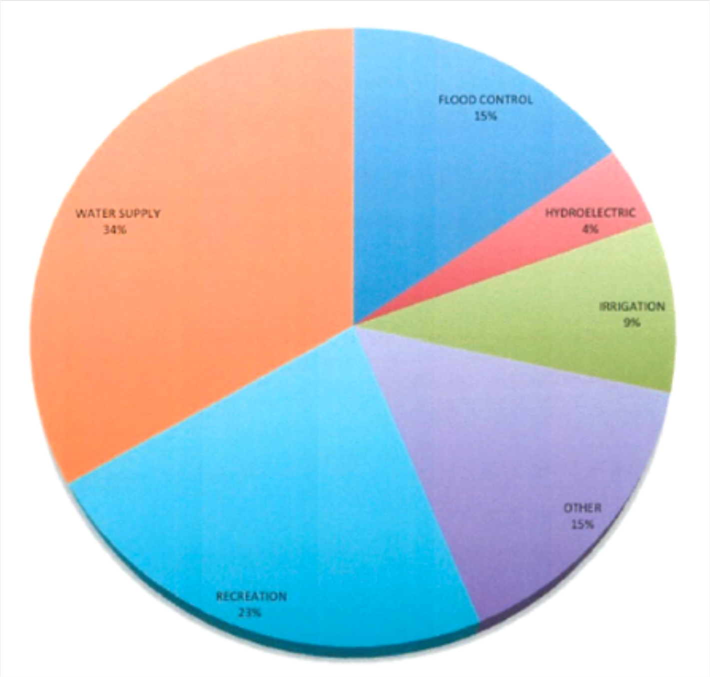

Figure 14. Major purposes of existing dams and reservoirs in the Texas Triangle Megaregion (TTMR).

Water Use

Many communities in Central Texas along the IH 35 corridor have experienced double-digit growth rates over the past 10 years, and this rate of growth is expected to continue in many communities of the region (Vaughn et al., 2012). The ability of the region to sustain this growth is largely dependent on the ability to provide adequate water supplies. According to the TWDB (Vaughn et al., 2012), municipal, industrial, and other uses for water will increase 22% by 2060 and failure to meet demand could cost businesses and workers in Texas approximately $11.9 billion per year (Combs, 2009; Vaughn et al., 2012).

Politicians and managers of water resources are increasingly recognizing the important role of groundwater resources in meeting the demands for drinking water, agricultural and industrial activities, sustaining ecosystems, and adaptation to, and mitigation of, the impacts of climate change and coupled human activities (Green et al., 2011; Kaiser & Skillern, 2000). In the next 25 years, the fastest-growing categories of use are projected to be in municipal and manufacturing use and, by the 2040s, municipal and industrial uses of water are expected to exceed agricultural use of water (Kaiser & Skillern, 2000).

Throughout Texas, landowners and municipalities have depended on groundwater as a primary water resource because of local availability and quality (Vaughn et al., 2012). Groundwater provides about 60% of the 19.86 cubic kilometers (16.1 million acre-feet) of water used in the state each year (Fipps, 2002; Levasseur, 2012; Vaughn et al., 2012). The TWDB (Vaughn et al., 2012) predicts that, over the next 50 years, agricultural use of groundwater will experience a dramatic decline because of aquifer depletion and rising energy costs. At the same time, municipal share of groundwater use will double (Kaiser & Skillern, 2000).

The increasing demand for groundwater in the region has resulted in a decrease in aquifer levels of more than 244 meters (800 feet) in the Dallas area and 122 meters (400 feet) in the Houston area in less than a century (Neuman & Bright, 2008). In the Gulf Coast Aquifer in Houston and the Carrizo-Wilcox Aquifer close to Tyler, Lufkin and College Station-Bryan water levels have dropped by more than 91.4 meters (300 feet; Neuman & Bright, 2008). It is projected that two of the five largest aquifers in the region will have less than 45% of the reservoir storage capacity remaining by 2050 (Butler et al., 2009). A recent estimate indicated a potential reduction of about 31% in the total groundwater supply in the state by the year 2060 (Chaudhuri & Ale, 2013; Vaughn et al., 2012).

Municipal Use

The TWDB (Vaughn et al., 2012) estimated that the rapidly growing population in the state will spur changes in the demand for and use of water. In 2010, irrigation was projected to account for 56% of the water use in Texas, followed by municipal use at 27% (Combs, 2014). By 2060, municipal water use is expected to become the largest category, at 38.3% of all water use, followed closely by irrigation at 38.1% (Combs, 2014). Bryan-College Station, Lufkin-Nacogdoches, Bastrop, and Tyler are the major municipalities that rely on groundwater from the Carrizo-Wilcox Aquifer (Boghici, 2008). Whereas San Antonio currently gets most of its water for municipal use from the Edwards Aquifer, it has entered into contractual negotiations with Alcoa Corporation for the rights to purchase groundwater originating from a lignite mining operation in the

Carrizo-Wilcox Aquifer more than 161 kilometers (100 miles) from the city (Neuman & Bright, 2008).

The City of San Antonio has also begun to incorporate aquifer storage and recovery as a key component of its attempt to achieve water supply diversity. The Twin Oaks Aquifer Storage and Recovery System stores up to 148 million cubic meters (120,000 acre feet) of Edwards Aquifer water that becomes available during wet periods in the Carrizo Aquifer for later use.

Irrigation

As is the case in the United States as a whole, irrigation represents the highest use of Texas groundwater (Kelley et al., 2009). Agricultural irrigation consumes about 80% of all groundwater pumped annually in Texas (Kaiser & Skillern, 2000).

Groundwater Quality

The principal type of aquifer in the TTMR is unconsolidated sand and gravel. This makes the aquifers susceptible to contamination because of the high permeability and hydraulic conductivity (Neuman et al., 2010). More than 1,250 active and former municipal solid waste sites exist within the Texas Triangle (Figure 15), with the potential to impact groundwater quality negatively. In addition, 139 permitted Industrial and Hazardous Waste Sites are present. The region is also home to 74 Environmental Protection Area Superfund sites. The TWDB (Vaughn et al., 2012) has logged 38,581 wells, each of which has the potential to impact groundwater quality negatively if not properly maintained.

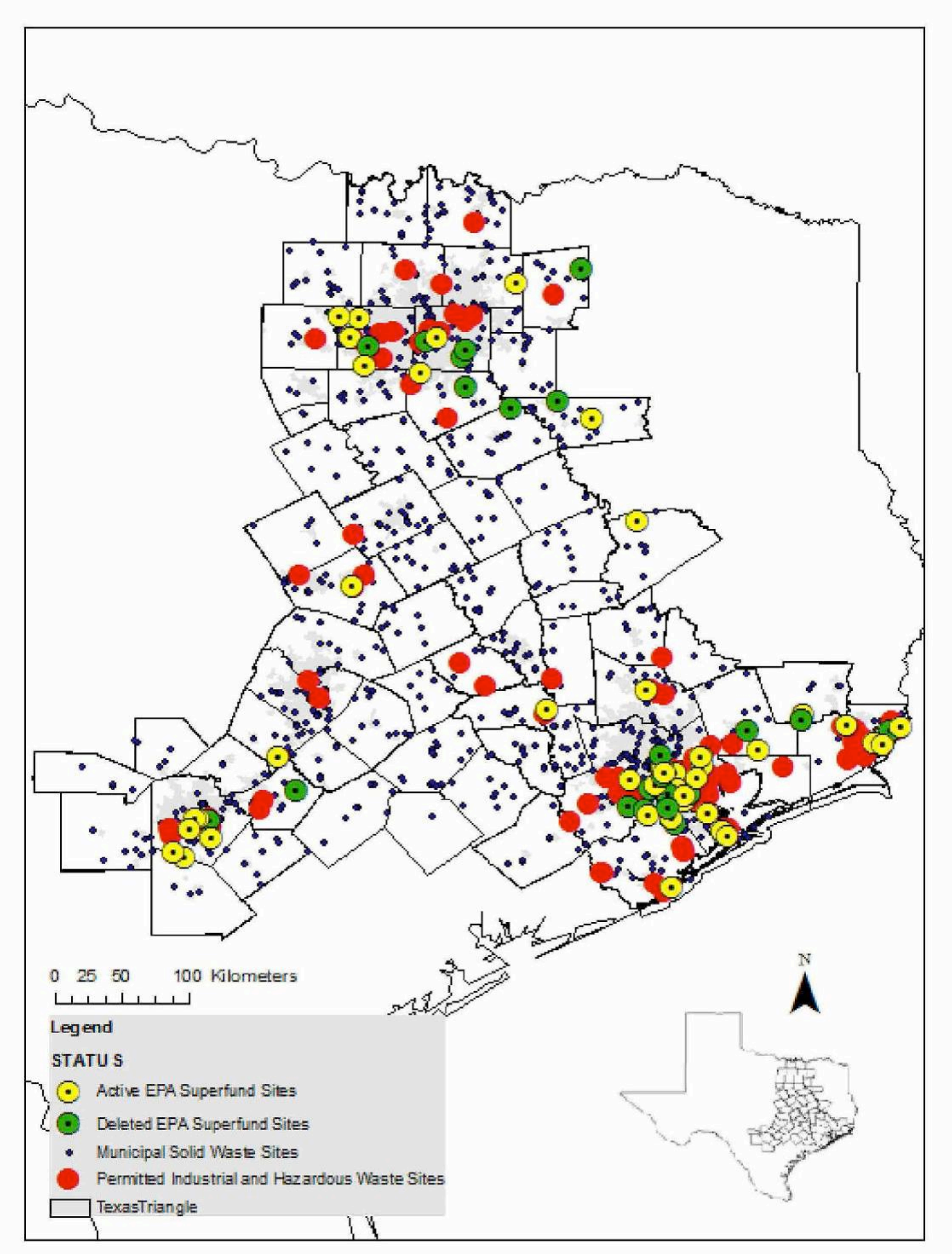

Figure 15. Municipal solid waste, industrial waste, and Environmental Protection Agency Superfund Sites in the Texas Triangle Megaregion (TTMR). Source data from the Texas Commission on Environmental Quality retrieved from http://www.tceq.texas.gov/gis/download-tceq-gis-data.

Mining Operations

The TTMR supports significant mining operations of nine major commodities, ranging from bentonite to sand and gravel, as shown in Figure 16. More than 235 active mines exist in the TTMR (Figure 17), supporting operations that mine these commodities. The vast majority of the operations mine sand and gravel (119) and crushed stone (58; U.S. Geological Survey, 2003).

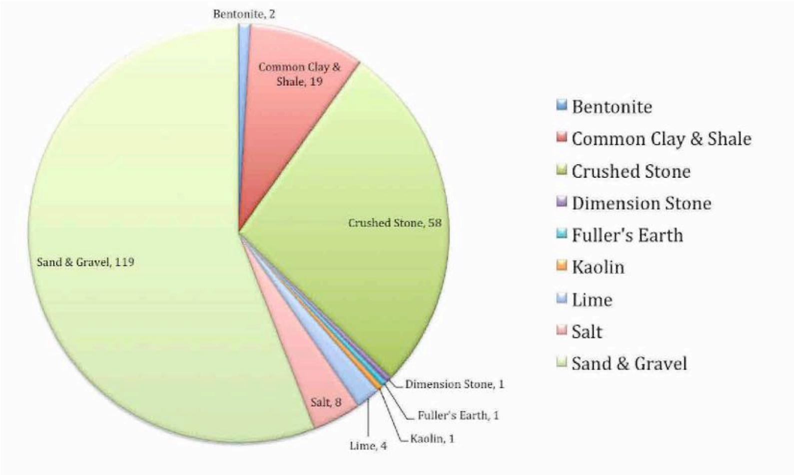

Figure 16. Mining activities in the Texas Triangle Megaregion by commodity.

Renewed interest in the Carrizo-Wilcox Aquifer and the Trinity Aquifer comes from the energy sector, particularly from companies engaged in development of oil and gas resources, such as the Eagle Ford Shale and Barnett Shale (Levasseur, 2012; Nicot & Scanlon, 2012). Investment in the unconventional reservoirs by the petroleum industry has exceeded $1 billion to date (personal communication, Carlos Dengo, Director, Texas A&M Berg-Hughes Center for Petroleum and Sedimentary Systems, July 8, 2014).

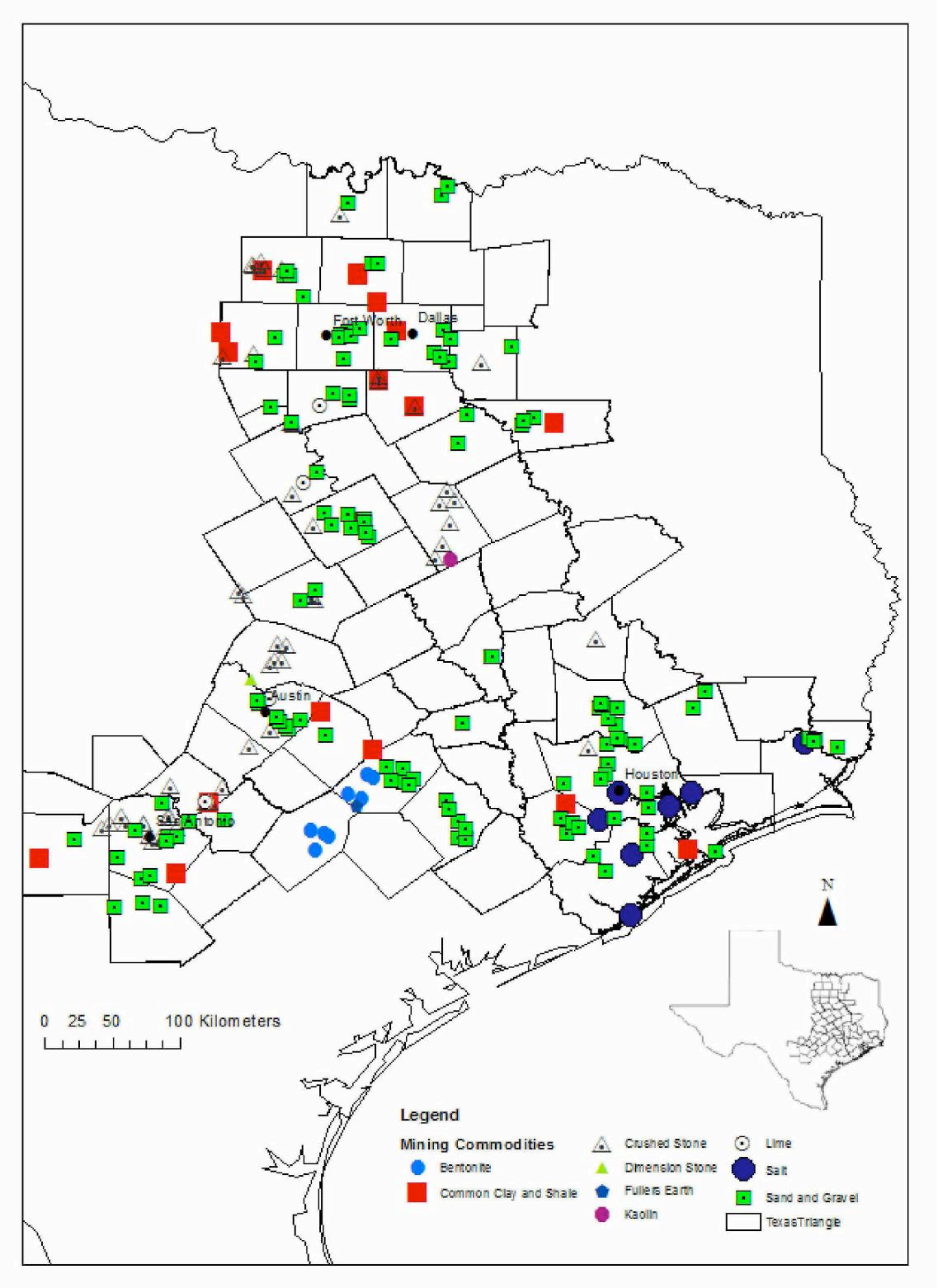

Figure 17. Mining operations in the Texas Triangle Megaregion.

Productive Mississippian Barnett Shale is found at depths of 2000 to 2600 meters (6,561 to 8,530 feet) near the Dallas-Fort Worth metroplex and in the Eagle Ford Shale play area extending over portions of 24 counties (~50,000 square kilometers or 19,305 square miles) in south Texas. Figure 18 shows the extent of the Eagle Ford.

This interest is placing new demands on groundwater in areas where the resource is already becoming constrained, particularly in the Wintergarden and Dallas-Fort Worth areas. On average, oil and gas companies utilize 5.7–11.3 million liters (1.5–3.0 million gallons) of water per horizontal well drilled and hydraulically fractured, but these estimates are largely dependent on the length and number of stages in the well design for a given formation (Nicot & Scanlon, 2012). The TWDB estimated that in 2008 about 44.16 million cubic meters (35.8 thousand acre-feet) of water was used for hydraulic fracturing (Levasseur, 2012; Vaughn et al., 2012). Fracking water use in the Barnett Shale (Figure 18) in 2010 represented approximately 9% of the 308.37 million cubic meters (250,000 acre-feet) of water used by the City of Dallas, the ninth-largest city in the United States (Nicot & Scanlon, 2012). Fracking for shale-gas production in the Eagle Ford Shale began in 2008, and wells drilled in the Eagle Ford Shale totaled 1,040, with cumulative water use of 1.8 million cubic meters (14,600 acre-feet) by mid-2011 (Nicot & Scanlon, 2012).

Whereas surface water is available in the Barnett Shale from the Trinity and Brazos rivers and reservoirs, it is not as readily available in the Eagle Ford Shale region (Nicot & Scanlon, 2012). Groundwater resources are generally available in each of the

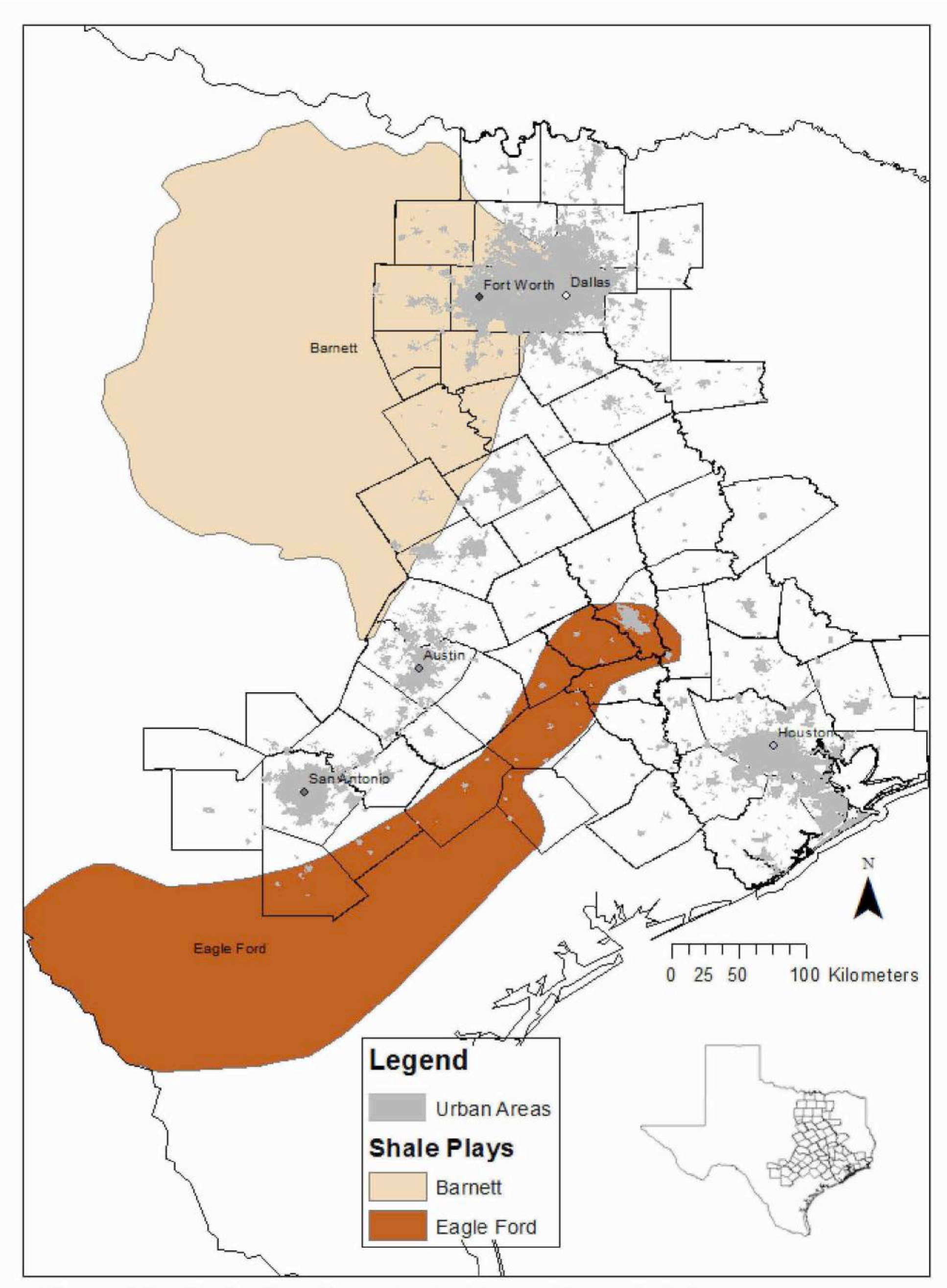

Figure 18. Shale gas plays in the Texas Triangle Megaregion (TTMR).

shale-gas plays, and, unlike surface water, groundwater is ubiquitous and generally available close to production wells. However, in the Eagle Ford Shale region groundwater has already been significantly depleted for irrigation in the Winter Garden region of South Texas, resulting in water-level declines >60 meters (197 feet) over a 6,500 square kilometer (2,510 square mile) area, disappearance of several large springs, and transition from predominantly gaining to mostly losing streams (Nicot & Scanlon, 2012). Population growth will also increase demand for this resource and possibly compound stress on the aquifer in which water levels have significantly declined in past decades (Nicot & Scanlon, 2012).

Land-Use and Land-Cover Change

According to Riebsame et al. (1994), land-use and land-cover changes are gaining recognition as key drivers of environmental change. Urbanization and industrial development in the megaregion are the primary agents of change in land use (Butler et al., 2009). In the TTMR, the most rapid urban growth and land consumption in the state is in the fringes of the Triangle cities (Neuman et al., 2010). Carbonell and Yaro (2005) estimated the need to build 50% as much housing and 100% of the commercial and retail space as were built over the past 200 years to support the growth anticipated in the next five decades in this area.

Water Management Policy in the Texas Triangle Megaregion

Unlike scientists who recognize that all water is interconnected, Texas law distinguishes between surface water and groundwater for the purpose of regulation with different rules governing each class (Kaiser, 1988; Vaughn et al., 2012). The state recognizes that a landowner owns groundwater (fresh and brackish) underlying his or her land as real property (Combs, 2014). In contrast, with the exception of diffused water, such as storm water runoff, all surface water, including streams, rivers, and lakes, is "held in trust" by the state and appropriated to users through permits or "water rights" (Fipps, 2002). The complicated system in Texas arose from Spanish and English common law, the laws of other Western states, and state and federal case law and legislation (Vaughn et al., 2012).

Commonly known as the "Rule of Capture," groundwater law in Texas is based on the English common law doctrine, which says that the landowner may withdraw groundwater without limitations and without liability for losses to neighbors' wells as long as water is not wasted or taken maliciously (Combs, 2014; Fipps, 2002; Kaiser, 2005). The Texas Supreme Court in its 1904 decision *Houston & T.C. Railway Co. v. East* adopted the "rule of capture" doctrine in part because the science of quantifying and tracking the movement of groundwater was so poorly developed at the time that it would be practically impossible to administer any set of legal rules to govern its use (Kaiser, 1988; Vaughn et al., 2012).

The right of landowners to capture and make "nonwasteful" use of groundwater has been upheld by Texas courts over the years, with only a few exceptions: drilling a well on someone else's property or drilling a "slant" well on adjoining property that crosses the property line ("trespass"), pumping water for the sole purpose of injuring an adjoining landowner ("malicious or wanton conduct"), or causing land subsidence on adjoining land from negligent overpumping (Fipps, 2002). Texas groundwater law has often been called the "law of the biggest pump" because the deepest well and most powerful pump get the water (Fipps, 2002; Kaiser, 1987).

In Texas, all surface water is held in trust by the state, which grants permission to groups and individuals to use the water (Vaughn et al., 2012). The state owns all waters flowing on the surface of Texas (Combs, 2014; Kaiser, 2005). The TCEQ issues and manages permits based on a "first in time, first in right" principle, meaning that those holding the oldest permits have first access to available water (Combs, 2014).

Texas recognizes two basic doctrines of surface water rights: the riparian doctrine and the prior appropriation doctrine. Introduced more than 200 years ago when Spanish Settlers first arrived in Texas, the riparian doctrine permits landowners whose property is adjacent to a river or stream to make reasonable use of the water (Kaiser, 1988). First adopted in Texas in 1895, the prior appropriation system has evolved into the modern system used today (Vaughn et al., 2012). Under prior appropriation, landowners who live near many of the water bodies in the state are allowed to divert and to use water for domestic and livestock purposes, not to exceed 247,000 cubic meters (200 acre-feet) per year (Kaiser, 1988; Vaughn et al., 2012).

Managing the Water Resources of Texas

Four agencies have primary responsibility for managing and enforcing water planning, water quality, and water quantity in Texas: TWDB, Texas Parks and Wildlife Department, TCEQ, and Texas Soil and Water Conservation Board.

The TWDB was created in 1959 as the primary water supply planning and financing agency. The TWDB supports the development of 16 regional water plans and is responsible for developing the state water plan every 5 years.

The Texas Parks and Wildlife Department works with regional and state water planning stakeholders and regulatory agencies to protect and enhance water quality and to ensure adequate environmental flows for rivers, bays, and estuaries. It also provides technical support to the environmental flows process and is a member of the Texas Water Conservation Advisory Council.

The TCEQ is the environmental regulatory agency for the state, focusing on water quality and quantity through various state and federal programs. The agency issues permits for the treatment and discharge of industrial and domestic wastewater and storm water, reviews plans and specifications for public water systems, and conducts assessments of surface water and groundwater quality. The TCEQ regulates retail water and sewer utilities, reviews rate increases by investor-owned water and wastewater utilities, and administers a portion of the Nonpoint Source Management Program. In addition, TCEQ administers the surface water rights permitting program and a dam safety program, designates Priority Groundwater Management Areas, creates some GCDs, and enforces requirements of groundwater management planning.

The Texas State Soil and Water Conservation Board administers soil and water conservation law in Texas and coordinates conservation and nonpoint source pollution abatement programs. The agency also administers water quality and water supply enhancement programs.

Managing Water Use Through Water Planning

In response to the most severe drought of record in Texas in the 1950s, the Texas Water Planning Act of 1957 created the TWDB and gave it authority to develop a State

Water Plan (J. E. Brown, 1997). Although the state had legislated the water planning process in 1957, it took little or no action on the first two water plans developed in 1961, 1968, 1987, 1990, and 1992. In 1997, once again acting in response to a drought (1995-1996), the TWDB, in conjunction with the Texas Natural Resources Conservation Commission and the Texas Parks and Wildlife Department, developed the first "consensus-based" plan (J. E. Brown, 1997).

Recognizing that water is the single most important factor for the future economic viability of Texas, the legislature passed Senate Bill 1, the Comprehensive Water Management Bill, which was signed into law on June 19, 1997 (J. E. Brown, 1997). Senate Bill 1 put in place the "bottom-up" approach to water planning rooted in local, consensus-based decision making that Texas uses for water planning today (Combs, 2009). Senate Bill 1 resulted in designation of water planning regions based on geographical, hydrological, and political boundaries, water utility development patterns, and socioeconomic characteristics (J. E. Brown, 1997).

Managing Groundwater Through Conservation Districts

State policy in Texas dictates that groundwater management is best accomplished through locally elected, locally controlled GCDs, suggesting that any modification or limitation on the rule of capture will be made by local groundwater districts (J. E. Brown, 1997). In 1949, the Texas legislature first provided for voluntary creation of GCDs over any groundwater reservoir designated by the state (Fipps, 2002). While continuing to acknowledge the "rule of capture" of groundwater by landowners, the Texas legislature passed additional legislation in 1985 and 1997 to encourage establishment of GCDs and, in limited cases, to allow for the creation of districts by state initiative (Fipps, 2002).

As of April 2014, a total of 101 GCDs had been created in the state. The total includes 98 established (i.e., confirmed) districts and 3 unconfirmed districts. The 98 established districts cover all or part of 179 of the 254 counties in the state. The TTMR has 50 GCDs in place (TWDB, 2014a). GCDs are charged to manage groundwater by providing for the conservation, preservation, protection, recharging, and prevention of waste of the groundwater resources within their jurisdictions (Fipps, 2002).

GCDs can be created by one of four procedures (Lesikar et al., 2002): (a) GCDs can be established through the action of the legislature; (b) GCDs can be created through a landowner petition procedure based on state law in Subchapter B, Chapter 36 of the Texas Water Code; (c) GCDs can be created by the TCEQ on its own motion in a designated Priority Groundwater Management Area (PGMA) through a procedure similar in principle to procedure (b) above but in which action is initiated by the TCEQ rather than by petition; or (d) an alternative to creating a new GCD is to add territory to an existing district if the existing district is willing to accept the new territory.

GCDs are authorized by the state with powers and duties that enable them to manage groundwater resources. The three primary GCD legislatively mandated duties are permitting water wells, developing a comprehensive management plan, and adopting the necessary rules to implement the management plan (Lesikar et al., 2002).

The principle power of a GCD to prevent waste of groundwater is to require that all wells, with certain exceptions, be registered and permitted. Wells with permits are subject to GCD rules governing spacing, production, drilling, equipping, and completion or alteration. Even exempt registered wells are subject to GCD rules governing spacing, tract size, and well construction standards to prevent unnecessary discharge of groundwater or pollution of the aquifer. Permits may be required by a GCD for all wells except for wells specifically exempted by a GCD and statutorily exempt wells (i.e., wells used solely for domestic use or for providing water for livestock or poultry purposes; the drilling of a water well used solely to supply water for a rig actively engaged in drilling or exploration operations for an oil or gas well permitted by the RRC; or the drilling of a water well authorized by the RRC for mining activities; Lesikar et al., 2002).

In 1985 the Texas legislature passed House Bill 2, containing provisions for the Texas Water Commission (a predecessor to the TWDB) to identify areas of the state that have critical groundwater problems, such as aquifer depletion, water quality contamination, land subsidence or shortage of water supply. Accordingly, beginning in 1986, the TWC and the TWDB identified possible critical areas and conducted further studies (Fipps, 2002). Portions of 11 Groundwater Management Agencies are located within the TTMR (TWDB, 2014b).

Groundwater Management Areas were created "to provide for the conservation, preservation, protection, recharging, and prevention of waste of the groundwater, and of groundwater reservoirs or their subdivisions, and to control subsidence caused by withdrawal of water from those groundwater reservoirs or their subdivisions" (Texas Water Code §35.001, Added by Acts 1995, 74th Leg., ch. 933, §2, eff. Sept. 1, 1995).

Beginning in 2005, Texas required, through legislation, that GCDs meet regularly and define the “desired future conditions” of the groundwater resources within designated management areas (Vaughn et al., 2012). Based on these desired future conditions, TWDB delivers modeled available groundwater values to GCDs and regional water planning groups for inclusion in their plans.

The above discussion illustrates how controlled surface water and groundwater are in the critical zone in Texas, especially in the TTMR. Despite this control regime, the waters in the critical zone are being depleted and degraded at an alarming rate.

Discussion

The TTMR has become the “core area of Texas,” creating an urbanized area rivaling New York and Los Angeles and expected to accommodate more than 80% of the population of the state by 2030. By 2070, the 65 counties of the TTMR will support a projected population of almost 40 million people. This rapid growth will put significant impacts on the water resources of the region.

The TTMR has historically derived approximately 60% of its water for all major uses from groundwater from the four primary aquifers in the megaregion. Despite the significant sources of surface water within the TTMR, as the population of the region continues to grow, water managers will increasingly rely on groundwater as a reliable water source to sustain this growth.

The increasing pressure to use groundwater will result in significant alterations to the critical zone such as those already being used by the City of San Antonio. The transfer of water from the Carrizo-Wilcox Aquifer to service the City of San Antonio, which overlies the Edwards Aquifer, as well as the storage of significant amounts of water from the Edwards Aquifer in the Carrizo-Wilcox for later use represent significant anthropogenic alterations to the critical zone.

Land use and land cover changes will continue to significantly affect the critical zone in this region as well. As more land surface area is converted from a natural state or agricultural use to urban development, the increased impervious surface will impact the critical zone in a variety of ways. Increased runoff and evaporation rates will occur. Expanded urban infrastructure will result in mixing of chemicals and petroleum products with surface water, resulting in degraded water quality. The IH 35 corridor, which serves as the lifeblood of the TTMR, overlaps a significant portion of the groundwater recharge zones for the region. As the area becomes more congested and the impervious surface increases even more, the ability to recharge the aquifers in this area naturally will decrease. The enhanced runoff from the impervious surface will also pose a significant water quality hazard to surrounding surface water and groundwater sources.

Development of shale plays in the Eagle Ford and Barnett shale regions will continue to have increasing significant impacts on the critical zone of the TTMR. As these areas are further developed in the future, that development will place additional demands on groundwater resources even as these resources are receiving increased demand to supply a growing municipal population. Use of these groundwater resources to support fracturing operations introduces the added anthropogenic changes to the critical zone associated with disposal of hazardous waste generated from the fracturing process.

The increasing urbanization of the TTMR will continue to affect surface and groundwater quality in the region. In addition to water quality issues generated by a increased impervious surfaces, the potential for surface water and groundwater contamination resulting from municipal solid waste sites and permitted industrial waste sites will be ever present.

The significant anthropogenic alterations to the critical zone in the TTMR will require robust, forward-thinking laws, policies, and management structures to mitigate the negative impact on the critical zone. This is particularly true regarding groundwater management because groundwater law in Texas has changed very little since the beginning of the 20th century.

Conclusion

Life on Earth depends on the uninterrupted provision of “critical zone services,” ranging from the provision of water of a quality and in a quantity that will support human activities and ecosystems to the production of food and fiber for a growing global population (Anderson et al., 2010). Providing these critical zone services will become increasingly difficult in the TTMR as the population approaches nearly 40 million people—more than a five-fold increase from the 7.1 million people who occupied the area in 1970.

Supporting the modern industrial infrastructure of the TTMR has required extensive modifications to the critical zone in the form of an extensive network of dams and reservoirs; a high-density matrix of wells for extracting water, oil, and gas from the critical zone; significant landcover alterations; and interbasin transfer of ground and surface waters. Progressive depletion of critical zone reserves threatens sustainable development in the heavily groundwater-dependent Texas Triangle and requires robust and effective water resource policy for the megaregion to remain economically viable. According to the TWDB, demand for water will increase by 22% by 2060 and failure to meet the demand could cost businesses and workers in Texas approximately $11.9 annually (Vaughn et al., 2012).

Progressive depletion of freshwater reserves threatens sustainable development in many parts of the United States, including Texas, that are heavily reliant on groundwater resources (Chaudhuri & Ale, 2013). In a state where more than 95% of land is privately owned, the emphasis on private property rights relating to groundwater has resulted in the rule of capture being held by many to be sacrosanct (J. E. Brown, 1997). Any full-scale revision of the rule of capture in Texas will most likely arise from attitudinal changes that evolve with the growth of free-market forces on precious water resources of Texas (J. E. Brown, 1997).

The significant anthropogenic alterations to the critical zone in the TTMR will require robust, forward-thinking laws, policies, and management structures to mitigate the negative impact on the critical zone. This is particularly true regarding groundwater management because groundwater law in Texas has changed very little since the beginning of the 20th century.

CHAPTER III

AN ANALYSIS OF GROUNDWATER DRAWDOWN TRENDS RESULTING FROM IMPLEMENTATION OF GROUNDWATER CONSERVATION DISTRICTS IN TEXAS

Groundwater is a critically important water resource in the state of Texas. Facing growth that is expected to double the population of the state to more than 46 million by 2060, Texas has increased its efforts to implement comprehensive planning for water resources during the past decade (Vaughn et al., 2012). Maximizing available water resources in Texas, including groundwater, is critical to the long-term economic viability of the state (Vaughn et al., 2012).

Ranked among the top four states in the country in terms of water consumption, Texas is facing significant challenges in water resources because most of the surface water supply is already fully allocated (Wagner & Kreuter, 2004). As a result, the state will rely increasingly on groundwater to meet its freshwater needs in coming decades (Wagner & Kreuter, 2004). The challenges that Texas will face in meeting demands for freshwater will be aggravated as the state population nearly doubles to 46 million people by 2060 (TWDB, 2007; Vaughn et al., 2012). This population increase will bring with it an annual increase in water demand of 27% (TWDB, 2007; Vaughn et al., 2012). Texas will be forced to rely more and more on groundwater to meet agricultural, municipal, and industrial needs as supplies of surface water become even more limited (Johnson et al., 2009).

This paper reports results of an investigation of the impact of the creation of GCDs in Texas on aquifer levels in the Carrizo-Wilcox Aquifer. The research was designed to determine whether a measurable difference exists in the rate of decline in aquifer levels after the establishment of a GCD. If GCDs are effective organizational structures for managing groundwater resources in Texas, then a measurable decrease should occur in the rate of decline of aquifer levels after establishment of a GCD.

Background

Study Area

The Carrizo Wilcox Aquifer bisects the TTMR (Figure 19)—an area where 80% of the Texas population will live by 2030 (Neuman et al., 2010). The Carrizo Wilcox is managed through 24 GCDs covering an area of 55,567 square kilometers. The oldest of these GCDs (Evergreen GCD) was established in 1965 and the newest (Panola County GCD) was established in 2007.

The political boundaries of the GCDs in the Carrizo are largely (10 GCDs or 42%) single-county jurisdictions, whereas 29% (7) cover two counties and 29% percent (7) cover more than two counties.

The communities managed by these GCDs are predominately rural (79%) with the remaining communities being suburban. The populations of the GCDs generally range between 10,000 and 50,000 (46%), with 29% having populations between 50,000 and 100,000 and 13% having populations between 100,000 and 500,000. Only 4% percent of the communities in the Carrizo-Wilcox GCDs have populations less than 10,000 and 8% have populations above 500,000.

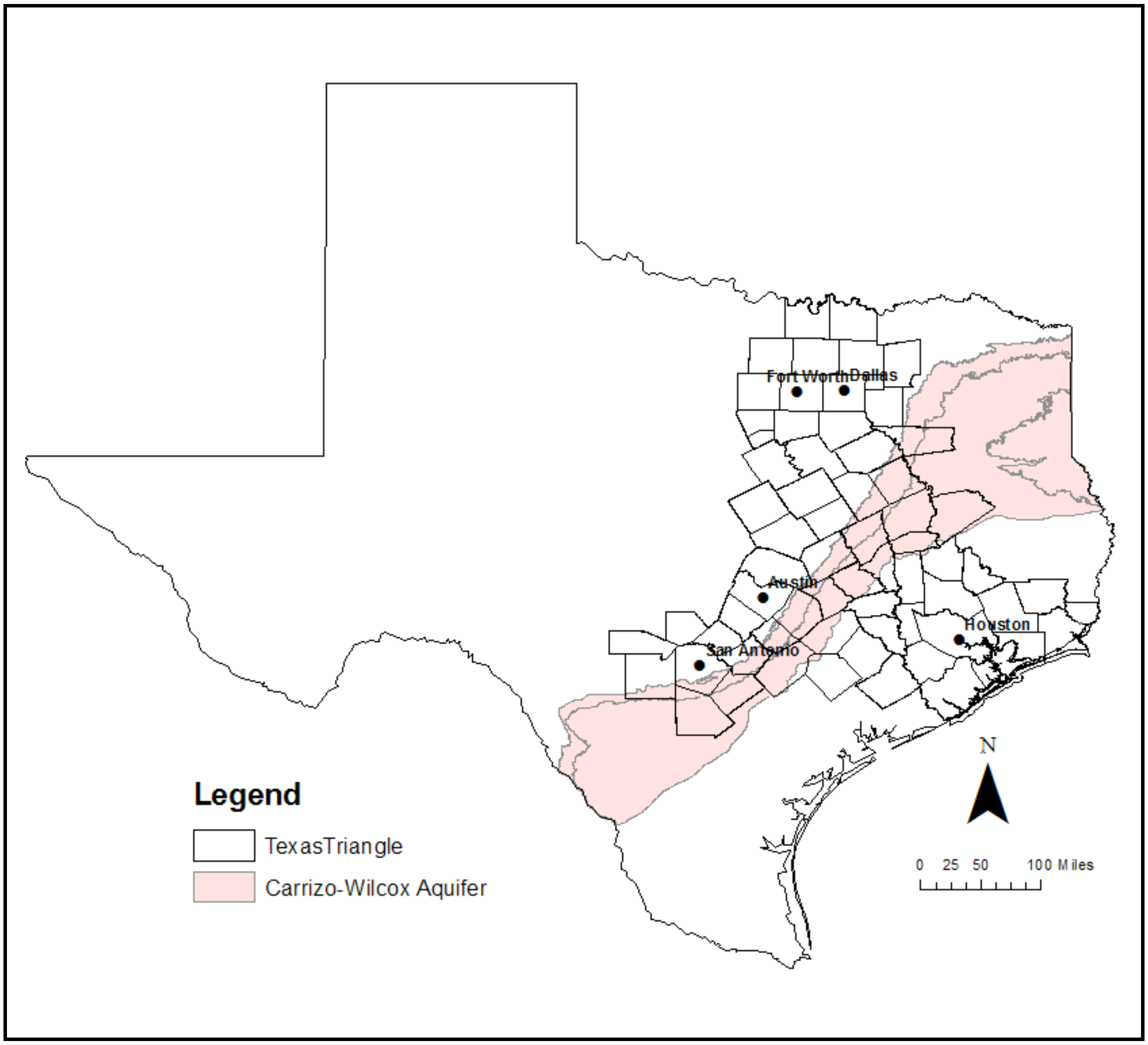

Figure 19. Carrizo Wilcox Aquifer in the Texas Triangle Megaregion.

The primary use of Carrizo-Wilcox groundwater is to supply water for public consumption (52%). Agricultural use accounts for approximately 32% of the total. Supplying water to support oil and gas activity accounts for 12% of the total and providing water for livestock is the primary use for the remaining 4%.

Groundwater Management in Texas

Unlike scientists who recognize that all water is interconnected, Texas law distinguishes between surface water and groundwater for the purpose of regulation with different rules governing each class (Kaiser, 1988; Vaughn et al., 2012). The state recognizes that a landowner owns groundwater (fresh and brackish) underlying his or her land as real property (Combs, 2014). In contrast, with the exception of diffused water, such as storm water runoff, all surface water, including streams, rivers, and lakes, is "held in trust" by the state and appropriated to users through permits or "water rights." (Fipps, 2002). The complicated system in Texas arose from Spanish and English common law, the laws of other western states, and state and federal case law and legislation (Vaughn et al., 2012).

Commonly known as the "Rule of Capture," groundwater law in Texas is based on the English common law doctrine that says that the landowner may withdraw groundwater without limitations and without liability for losses to neighbors' wells as long as water is not wasted or taken maliciously (Combs, 2014; Fipps, 2002; Kaiser, 2005). The Texas Supreme Court in its 1904 decision *Houston & T.C. Railway Co. v. East* adopted this "rule of capture" doctrine, in part because the science of quantifying and tracking the movement of groundwater was so poorly developed at the time that it would be practically impossible to administer any set of legal rules to govern its use (Kaiser, 1988; Vaughn et al., 2012).

The right of landowners to capture and make "nonwasteful" use of groundwater has been upheld by Texas courts over the years with only a few exceptions: drilling a well on someone else's property or drilling a "slant" well on adjoining property that crosses the property line ("trespass"); pumping water for the sole purpose of injuring an adjoining landowner ("malicious or wanton conduct"); or causing land subsidence on adjoining land from negligent overpumping (Fipps, 2002). Texas groundwater law has often been called the "law of the biggest pump" because the deepest well and most powerful pump get the water (Fipps, 2002; Kaiser, 1987).

In Texas, all surface water is held in trust by the state, which grants permission to groups and individuals to use the water (Vaughn et al., 2012). The state owns all waters flowing on the surface of Texas (Combs, 2014; Kaiser, 2005). The TCEQ issues and manages permits based on a "first in time, first in right" principle, meaning that those holding the oldest permits have first access to available water (Combs, 2014).

Texas recognizes two basic doctrines of surface water rights: the riparian doctrine and the prior appropriation doctrine. Introduced more than 200 years ago when Spanish Settlers first arrived in Texas, the riparian doctrine permits landowners whose property is adjacent to a river or stream to make reasonable use of the water (Kaiser, 1988). First adopted in Texas in 1895, the prior appropriation system has evolved into the modern system used today (Vaughn et al., 2012). Under prior appropriation, landowners who live near many of the water bodies in the state are allowed to divert and to use water for domestic and livestock purposes, not to exceed 247,000 cubic meters (200 acre-feet) per year (Kaiser, 1988; Vaughn et al., 2012).

Managing Groundwater Use Through Water Planning

In response to the most severe drought of record in Texas in the 1950s, the Texas Water Planning Act of 1957 created the TWDB with the authority to develop a State Water Plan (J. E. Brown, 1997). Although the state had legislated the water planning process in 1957, it took little or no action on the water plans developed in 1961, 1968, 1987, 1990, and 1992 (J. E. Brown, 1997). In 1997, once again acting in response to a drought (1995-1996), the TWDB, in conjunction with the Texas Natural Resources Conservation Commission and the Texas Parks and Wildlife Department developed the first “consensus-based” plan (J. E. Brown, 1997).

Recognizing that water is the single most important factor for the future economic viability of Texas (Vaughn et al., 2012), the legislature passed Senate Bill 1, the Comprehensive Water Management Bill, which was signed into law on June 19, 1997 (J. E. Brown, 1997). Senate Bill 1 put in place the “bottom-up” approach to water planning rooted in local, consensus-based decision making that Texas uses for water planning today (Combs, 2009). Senate Bill 1 also resulted in designation of water planning regions based on geographical, hydrological, and political boundaries, water utility development patterns, and socioeconomic characteristics (J. E. Brown, 1997).

Managing Groundwater Through Conservation Districts

State policy in Texas dictates that groundwater management is best accomplished through locally elected, locally controlled GCDs, suggesting that any modification or limitation on the “rule of capture” will be made by local GCD (J. E. Brown, 1997). In 1949, the Texas legislature provided for voluntary creation of GCDs over any groundwater reservoir designated by the state (Fipps, 2002). While continuing to acknowledge the “rule of capture” of groundwater by landowners, the legislature passed additional legislation in 1985 and 1997 to encourage the establishment of GCDs and, in limited cases, to allow for creation of districts by state initiative (Fipps, 2002).

As of April 2014, a total of 101 GCDs had been created in the state. The total includes 98 established (i.e., confirmed) districts and 3 unconfirmed districts. The 98 established districts cover all or part of 179 of the 254 counties in the state. The TTMR has 50 GCDs in place (TWDB, 2014a).

GCDs are charged to manage groundwater by providing for the conservation, preservation, protection, recharging, and prevention of waste of the groundwater resources within their jurisdictions (Fipps, 2002).

These GCDs can be created by one of four procedures: (a) established through action of the legislature, (b) created through a landowner petition procedure based on state law in Subchapter B, Chapter 36 of the Texas Water Code, (c) created by the TCEQ on its own motion in a designated Priority Groundwater Management Area (PGMA) through a procedure similar in principle to procedure (b) above but in which action is initiated by the TCEQ rather than by petition, or (d) alternative to creating a new GCD, adding territory to an existing district if the existing district is willing to accept the new territory (Lesikar et al., 2002).

GCDs are authorized by the state of Texas with powers and duties that enable them to manage groundwater resources. The three primary GCD legislatively mandated duties are permitting water wells, developing a comprehensive management plan, and adopting the necessary rules to implement the management plan (Lesikar et al., 2002).

Regulatory Methods Available to Groundwater Conservation Districts

To minimize drawdown of the water table or reduction of artesian pressure, to control subsidence, to prevent interference between wells, to prevent degradation of water quality, or to prevent waste, the Texas Water Code Section 36.116(a) provides broad regulatory authority to GCDs (Porter, 2014). The methods include permitting, spacing, production limits, regulations tailored to specific geological strata or areas, regulation based upon prioritizing types of use, regulation based on well construction standards, and regulation based upon reporting requirements (Houston, 2004). The regulatory methods are intended to minimize drawdown of the water table or reduction of artesian pressure to control subsidence, to prevent interference between wells, to prevent degradation of water quality, or to prevent waste.

Well Permitting

One of the most basic tools of a GCD is a permitting program designed to establish the foundation for future management decisions (Houston, 2004). The data collected through the permitting process provide information on the types and quantity of groundwater use. The permitting process does not place a regulatory burden on groundwater users, other than basic permitting and reporting requirements, but serves to make groundwater users more aware of waste prevention and conservation (Houston, 2004). Wells with permits are subject to GCD rules governing spacing, production, drilling, equipping, and completion or alteration. Even exempt registered wells are subject to GCD rules governing spacing, tract size, and well construction standards, to prevent unnecessary discharge of groundwater or pollution of the aquifer (Lesikar et al., 2002).

Permits may be required by a GCD for all wells except for wells specifically exempted by a GCD and statutorily exempt wells (i.e., wells used solely for domestic use or for providing water for livestock or poultry purposes; the drilling of a water well used solely to supply water for a rig actively engaged in drilling or exploration operations for an oil or gas well permitted by the RRC; and the drilling of a water well authorized by the RRC for mining activities; Lesikar et al., 2002). As the management structure of a GCD evolves and more substantive regulations are put in place, the permitting system provides the management framework for implementation of those regulations (Houston, 2004).

Well Spacing

GCDs require that wells be spaced a certain distance from property or adjoining wells and require that wells with certain production capacity, pump size, or other characteristic be spaced a certain distance from property lines or adjoining wells (Houston, 2004). The primary goal of spacing regulations is to prevent interference or encroachment between wells, thereby ensuring that the groundwater being pumped from a well is actually coming from beneath the well owner's land (Houston, 2004). The appropriateness of spacing depends largely on the hydrogeological characteristics of the aquifer; spacing is most appropriate in unconfined, relatively homogeneous aquifers; whereas in karst aquifers spacing is generally not appropriate because of different hydrogeological conditions (Houston, 2004). Spacing is generally not effective in developed or urban areas and is limited as a regulatory tool because it can be applied only to new wells (Houston, 2004). The well spacing requirements of the various GCDs overlying the Carrizo Wilcox Aquifer are described in Table 6.

Groundwater Production

The production of groundwater can be regulated by setting the production limit on wells, limiting the amount of water produced based on acreage tract size, limiting the amount of water that may be produced from a from a defined number of acres assigned to an authorized well site, or limiting the maximum amount of water that may be produced on the basis of acre-feet per acre or gallons per minute per well site per acre (Houston, 2004). The goal of these production limits is to manage or control the amount of groundwater being withdrawn from an aquifer to prevent unacceptable declines in water levels (Houston, 2004).

Production limits based on acreage or tract size establishes a correlative rights approach in which a landowner is entitled to withdraw a predetermined amount of water from beneath his property and provides certainty regarding how much water can be withdrawn from beneath each acre of land (Houston, 2004). This method is well suited to unconfined, fairly homogenous aquifers but results in aquifer mining if recharge is limited (Houston, 2004).

Production limits based on proportionate reduction are used when a GCD places a cap on withdrawals from the aquifer; once the cap is attained, all permits are proportionately reduced to facilitate new permits (Houston, 2004). The goal of this

Table 6

Spacing Requirements for Wells in Designated Groundwater Conservation Districts (GCD)

GCD	Spacing requirements
Anderson	Not available
Bee County	Wells may not be drilled within 100 feet of any property line; additional spacing requirements are based on well capacity.
Bluebonnet	No additional spacing requirements beyond state law.
Brazos Valley	Non-exempt wells must be spaced according to maximum annual production.
Duval County	Wells must be 100 feet from property lines; additional spacing requirements are based on well capacity.
Edwards	No additional spacing requirements beyond state law.
Evergreen	Wells must be 100 feet from property lines; additional spacing requirements are based on well capacity.
Fayette County	Wells must be 50 feet from property lines; additional spacing requirements are based on well capacity.
Gonzales County	Spacing requirements based on well capacity and tract size.
Guadalupe County	Distances between wells are calculated using the well's projected "area of influence." The area of influence of two wells may not overlap. Wells must be set back from property lines no less than 0.25 ft/gpm, and in no event may be closer than 100 feet to any property line.
Live Oak	Permitted wells must be at least 300 foot from property lines; additional spacing requirements are based on well capacity.
Lost Pines	New wells may must be at least 50 feet from property lines; additional spacing requirements are based on well capacity..
McMullen	Wells may not be drilled within 100 feet of any property line. In addition, well must be located so that the distance to any other existing well is at least one foot for each gallon-per-minute of production capacity of the new well. If the capacity of the well exceeds 1,000 gallons-per-minute, then the minimum spacing distance must be an additional 1/2 foot for each gallon-per-minute in excess of 1,000.

Table 6 (continued)

GCD	Spacing requirements
Medina County	No additional spacing requirements beyond state law.
Mid-East Texas	No additional spacing requirements beyond state law.
Neches/Trinity Valleys	Wells must be at least 50 feet from another well or property lines.
Panola County	Spacing requirements are based on the well’s casing size.
Pecan Valley	Exempt wells must be at least 50 feet from property lines and 50 feet from other exempt wells. Spacing requirements for non-exempt wells are based on well capacity.
Pineywoods	Exempt wells must be at least 50 feet from property lines. Non-exempt wells must be at least 150 feet from property lines.
Plum Creek	Spacing requirements are based on the aquifer and well size/capacity.
Post Oak Savannah	Spacing requirements are based on the aquifer and well size/capacity.
Rusk County	Wells must be one-half foot per gallon per minute of production capacity from the perimeter of the property and at least 150 feet from the nearest property line. Wells must be one foot per one gallon per minute of production capacity from permitted or registered wells.
Uvalde County	No additional spacing requirements beyond state law.
Wintergarden	Wells must be drilled at least 100 feet from the property line and spaced at least the distance equivalent to one foot per gallon per minute of the combined production rate of the proposed well and the nearest existing well drilled into the same formation.

method is to maintain the aquifer at a certain level by requiring proportionate reductions in usage by all permit holders until total groundwater pumpage is approximately equal to the aquifer recharge or sustainable yield (Houston, 2004). The challenge inherent in this method is that, while some permit holders may be able to simply reduce their groundwater usage through conservation, many will need to seek alternative sources of water to satisfy their total water demand (Houston, 2004).

Production limits based on protecting historical use allow existing users to continue to produce a certain amount of groundwater based on the annual amount of groundwater the user can prove that he put to beneficial, nonwasteful use at some point in the past. Existing wells, where historical use can be substantiated, are generally exempted from new production limitations. The goal of regulations on historical use generally is to place the burden of production limitations on new users in the groundwater conservation district while protecting historical users (Houston, 2004). While in some cases historical users receive a permanent, marketable groundwater right, in other cases the permit is neither permanent nor transferable (Houston, 2004). In such a case, a district could grant a historical use permit to a groundwater user for a specific historical use, such as agriculture, but if he were to sell his property, the groundwater permit would no longer be valid.

Production limits based on rate of withdrawal establish a maximum rate at which groundwater can be withdrawn from a well, typically based on gallons per minute or gallons per day (Houston, 2004). The goal of this production method is to maintain a predetermined aquifer level by limiting the maximum rate of withdrawal for each permit holder (Houston, 2004). This method is typically used in conjunction with other regulatory methods, such as spacing requirements (Houston, 2004). Production limits based on preventing well interference or unreasonable drawdown combine a number of regulatory methods and are applied on a more specific, well-by-well basis, rather than to all wells on a districtwide basis (Houston, 2004).

The Texas Water Code gives each GCD the authority to establish different rules for different aquifers, different geologic strata, or different geographic areas within the same district (Houston, 2004). The goal of this method is to improve management of groundwater resources by tailoring the rules of the district to the specific area where problems are occurring, such as areas where overpumping is occurring or specific areas of an aquifer where water levels are declining (Houston, 2004). This type of regulatory method is appropriate if a district is split geographically by more than one aquifer, or if conditions in an aquifer differ substantially from one geographic area to another (Houston, 2004).

The limitation requirements on well production by the various GCDs districts overlying the Carrizo Wilcox Aquifer are described in Table 7.

Summary of Regulatory Methods Used in the Carrizo Wilcox Aquifer

The various regulatory methods employed by GCDs overlying the Carrizo Wilcox Aquifer are listed in Table 8.

The most common method (employed by 25% of the GCDs) is a combination of production limits based on acreage or tract size and well spacing. The second most common method is production limits based on acreage or tract size alone. A summary of the regulatory methods is shown in Table 9.

Table 7

Production Limitations for Wells in Designated Groundwater Conservation Districts (GCD)

GCD	Spacing requirements
Anderson	Not available
Anderson	Not Available
Bee County	Production is capped at 10 gal/min/acre; NTE 1 acre ft/acre; Maximum capacity is 640 af/yr. A permitted well or well system may only be drilled and equipped for production of a cumulative total of 10 gpm/acre. Total annual production may not exceed 1 af/acre/year (non-grandfathered users)
Bluebonnet	Non-exempt wells that will produce greater than a certain gpm must go through an initial hydrogeological study standardized to applicable groundwater models. This initial study will produce a three-tiered area of influence, which will be used to determine if additional studies and information are needed before a production limit is set.
Brazos Valley	At this time, production limitations only apply to the amount of continuous acreage assigned to the well site. All wells are capped at a maximum of 3300 gpm.
Duval County	A permitted well or well system may only be drilled and equipped for production of a cumulative total of 10 gpm per contiguous acre owned or operated. Total annual production may not exceed 0.5 af/acre.
Edwards	Total pumping is limited to 572,000 acre-feet. Mandated drought reductions can be 44% (320,000 af) at Stage V.
Evergreen	Total pumping is limited to 652,000 gallons/acre/year. Entities that use groundwater for municipal supply to the public may claim acreage within their CCN in certain instances.
Fayette County	Excluding wells operated pursuant to a valid Existing and Historic Use Permit, in no event may a well or well system be operated such that the total annual production exceeds two acre-feet of water per contiguous acre owned or operated, or for which a person can show ownership or possession of groundwater rights, per year. Specific production limitations will be set as a condition of the granted well operating permit.

Table 7 (continued)

GCD	Spacing requirements
Gonzales County	Production limitation are based upon the aquifer; 1 af/acre/year combined total production from Carrizo, Sparta (limited to 0.5 af total), and Queen City, plus 1 af/acre/year from the Wilcox; pump size is based on a pumping rate of 0.93 gpm per acre, except irrigation well maximum pump size in gpm is determined by multiplying the actual irrigated acres by a factor of 7.54.
Guadalupe County	Permitted wells may not produce more than 1200 gpm at any given moment and may not average more than 1000 gpm. In the Carrizo, production limits are calculated by the GCD's model. In the Wilcox, production limits are 0.5 af/acre/year. Additional contractual groundwater commitments are required in some instances. Historic use permits begin a phase out period in 2025.Carrizo production is determined annually by the GCD and a production cap is established. Wlicox production is a maximum of ½ af/year using the formula $R = 74550.6\ X - 10.6667\ X^2$ Permitted wells, regardless of the formation produced or of the stipulations of the relevant permit, shall never, in any case, be produced at instantaneous rates of more than 1200 gpm or at average rates of more than 1000 gpm.
Live Oak	A permitted well or well system may only be drilled and/or equipped for the production of a cumulative total of 10 gpm/acre. Wells or well systems may not be operated such that the total annual production exceeds 16.13 af/acre/year.
Lost Pines	Reasonable Use
McMullen	A well or well system may only be permitted to be drilled and equipped for production of a cumulative total of ten (10) gallons per minute per contiguous acre owned or operated. In no event may a well or well system be operated such that the total annual production exceeds one/half (1/2) acre-foot of water per acre owned or operated per aquifer layer.

Table 7 (continued)

GCD	Spacing requirements
Medina County	Production limitations range from 0.5 af/acre/year to 2 af/acre/year, depending on aquifer. For wells capable of withdrawing water from the Carrizo-Wilcox Aquifer the maximum annual quantity of groundwater that may be withdrawn shall be no greater than the product of the applicable "water allocation" per acre set forth in the Medina County GCD Rules, multiplied by the number of contiguous acres of land within the District upon which the well is located that are owned or controlled by the well owner and that are assigned to the well. For a well that is capable of producing groundwater solely from the Carrizo-Wilcox Aquifer, the water allocation shall be two acre-feet per acre;
Mid-East Texas	Priority is given to exempt and historic/existing uses. New users must demonstrate beneficial use of the requested amounts during the permit term. The GCD's rules allow for proportional reductions under certain conditions. The production limit for a well requiring an operating permit is set at an annual amount that the District determines does not unreasonably affect existing groundwater and surface water resources or existing permit holders. In no event will the annual production amount exceed three acre feet per year per acre of surface area designated in the application as production area for the well.
Neches/Trinity Valleys	No current limitations on production listed in rules
Panola County	The District designates the quantity of groundwater authorized to be produced on an annual basis under an Operating Permit issued by the District pursuant to the conditions of the District Act, Chapter 36 of the Texas Water Code, the Desired Future Conditions established by the Groundwater Management Area (GMA) in which the District is located for the aquifers located in whole or in part within the boundaries of the District, and these Rules, provided, however, that the quantity shall not exceed an amount demonstrated by the applicant and determined by the Board to be necessary for beneficial use during the permit term as set forth in the permit issued by the District. No current limitations on production.
Pecan Valley	0.5 af/acre/year or 1 af/year if drilled deeper than 700' and no screen above 500 feet.
Pineywoods	No current limitations.

Table 7 (continued)

GCD	Spacing requirements
Plum Creek	Depends on the aquifer and the size/capacity of well; generally 0.5 af/acre/year
Post Oak Savannah	2af/acre/year
Rusk County	Determined by a formula that factors total number of contiguous acres legally assigned to the well site.
Uvalde County	Total pumping is limited to 572,000 acre-feet. Mandated drought reductions can be 44% (320,000af) at Stage V.
Wintergarden	2.5 af/acre/year. The rules allow for grandfathered production of higher rates with proof of historic production and account for connections for public water system use.

Methodology

A copy of the Groundwater Database maintained by the TWDB was downloaded from the TWDB website in Microsoft® Access® format. The database contains detailed information on nearly 28,000 wells located throughout the state. The 2,332 wells located in the Carrizo-Wilcox Aquifer (Aquifer ID Code 10) were extracted for analysis.

The entire TWDB Groundwater Database contains 675,350 records from 27,955 wells. More than 50,600 records exist from 2,332 wells in the Carrizo-Wilcox Aquifer. Of these, 1,315 (56%) contain 10 or fewer records for the entire history of the respective well. There are 358 wells in the Carrizo-Wilcox database that have at least 40 water level measurements; these were examined to determine sufficiency inclusion in the final GCD datasets.

Table 8

Categories of Regulatory Methods Used by Groundwater Conservation Districts (GCD)

GCD	Regulatory method categories
Anderson County	Rule of Capture
Bee County	Acreage or tract size
Bluebonnet	Rule of Capture
Brazos Valley	Spacing, historical use
Duval County	Spacing, acreage or tract size
Edwards	Historical use
Evergreen	Acreage or tract size; first in time, first in right
Fayette County	Preventing well interference or unreasonable drawdown
Gonzales County	Spacing, acreage or tract size
Guadalupe County	Spacing, acreage or tract size
Live Oak	Spacing, acreage or tract size
Lost Pines	Reasonable use
McMullen	Acreage or tract size; first in time, first in right
Medina County	Acreage or tract size
Mid-East Texas	Acreage or tract size
Neches/Trinity Valleys	Spacing
Panola County	Rule of Capture
Pecan Valley	Acreage or tract size
Pineywoods	Spacing, historical use
Plum Creek	Preventing well interference or unreasonable drawdown
Post Oak Savannah	Acreage or tract size, historical use, rate of withdrawal
Rusk County	Spacing, acreage or tract size
Uvalde County	Rule of Capture
Wintergarden	Spacing, acreage or tract size

Table 9

Summary of Regulatory Methods Used by Groundwater Conservation Districts (GCD)

Regulatory method	*n*	%
Production limits based upon spacing and tract size	6	25.0
Production limits based upon acreage or tract size	4	16.7
Production limits based upon Rule of Capture	3	12.5
Production limits based on tract size	3	12.5
Production limits based upon spacing and historical use	2	8.3
Production limits based upon preventing well interference or unreasonable drawdown	2	8.3
Production limits based on tract size and first in time/first in right	1	4.2
Production limits based upon reasonable use	1	4.2
Production limits based on spacing	1	4.2
Production limits based on acreage or tract size, historical use, and rate of withdrawal	1	4.2
Total	24	100.0

A separate Excel® file was created for each of the 20 GCDs in the database that manage groundwater in the Carrizo-Wilcox aquifer. Four GCDs (Bee GCD, Bluebonnet GCD, Duval County GCD, and Pecan Valley GCD) did not have any wells in the TWDB database. The number of wells available for analysis from the remaining GCDs ranged from 2 (Live Oak and Fayette County) to 1,508 wells (Evergreen).

Once separate files for each GCD had been created, a review was conducted to determine which individual state well records contained sufficient data for further analysis. To be suitable for analysis, a well was required to have 10 years of water level measurements prior to the year the GCD in which the well is located was created and 10 years of water level measurements after that creation date.

Preparation of Hydrologic Variables

After a dataset with sufficient history had been established for each GCD, the individual records were standardized by developing annual drawdown data for each well, using the depth or distance from land surface as the standard variable. This was necessary, in part, because the records in the TWDB database are extremely inconsistent. Some records have consistent annual water level data, but most have very inconsistent data and were not suitable for analysis because an insufficient number of depth measurements were available from which to calculate an average annual drawdown. In cases where data were missing for a single year, measurements were averaged from the most recent measurement to establish the average annual drawdown. If more than three consecutive annual measurements were missing from the record, that record was discarded. In cases where multiple measurements existed for the same year, they were averaged to provide a single annual data point for that well.

Selection of Groundwater Conservation Districts

Twenty-four GCDs have boundaries that either partially or fully overlie the Carrizo-Wilcox Aquifer. Four GCDs (Bee GCD, Bluebonnet GCD, Duval County GCD, and Pecan Valley GCD) did not have any wells in the TWDB database.

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Once separate files for each GCD had been created, a review was conducted to determine which individual state well records contained sufficient data for further analysis. To be suitable for analysis, each well was required to have 10 years of water-level measurements prior to the year the GCD in which the well is located was created and 10 years of water-level measurements after that creation date.

A preliminary review of the records demonstrated that only 5% of the records in the database were sufficiently complete to provide enough data for analyzing the period 10 years prior to and 10 years after creation of the GCD. Four of the GCDs (Bee, Bluebonnet, Duval County, and Pecan Valley) were eliminated from consideration for analysis because the TWDB Groundwater Database did not contain any records from these GCDs. Four GCDs (Anderson County, Fayette County, Live Oak County, and Uvalde County) were eliminated from consideration because the database contained insufficient records to result in a meaningful analysis of the GCD. When all factors regarding data sufficiency were considered, 13 GCDs were selected for this analysis: Brazos Valley, Evergreen, Gonzales County, Guadalupe County, Lost Pines, Medina County, McMullen, Mid East Texas, Neches & Trinity Valley, Pineywoods, Post Oak Savannah, Rusk County, and Wintergarden. These GCDs are depicted in Figure 20.

Selection of Wells for Analysis

Table 10 depicts the total number of wells that were examined for each GCD in an initial attempt to determine which wells had sufficient data for further analysis. The

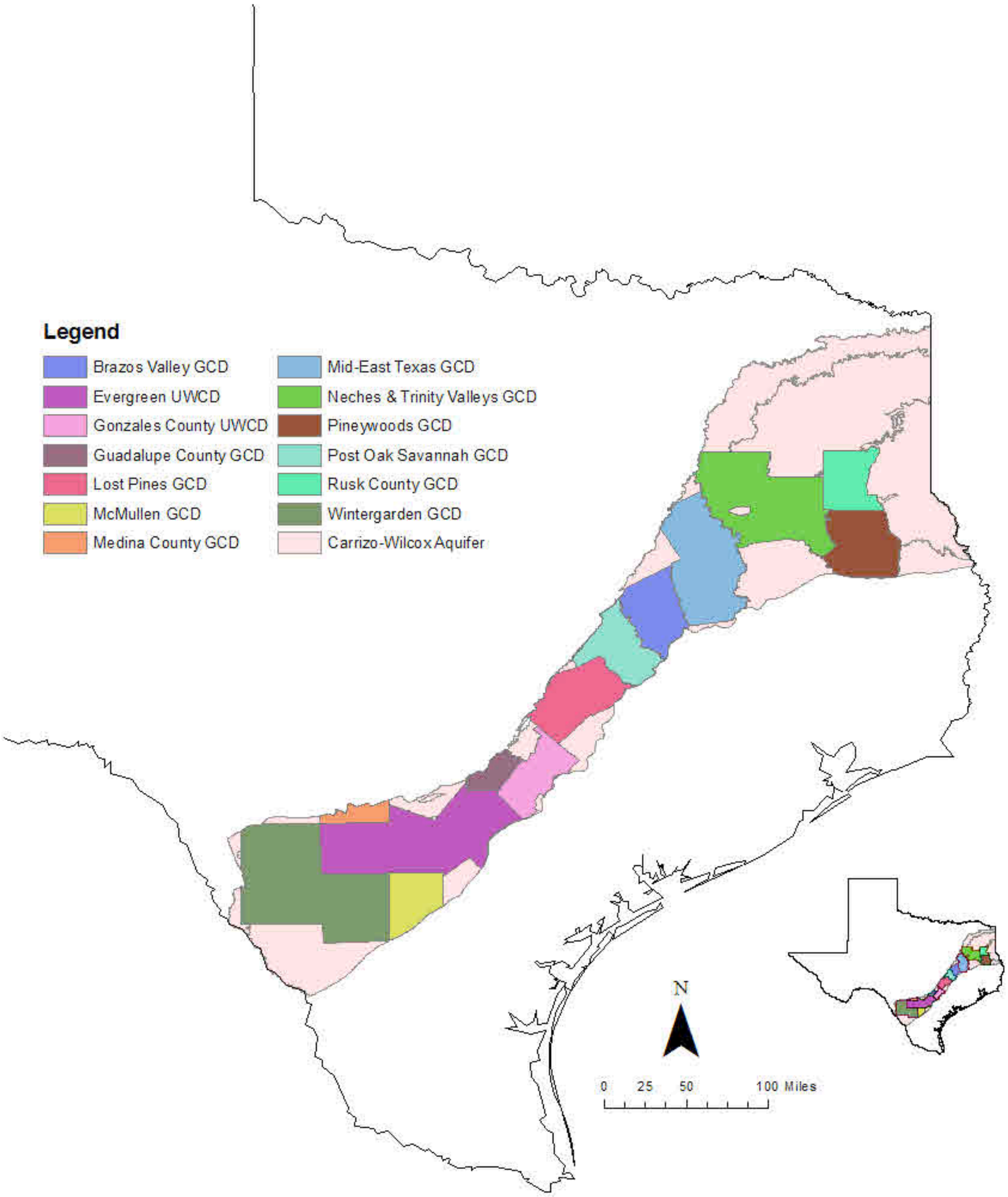


Figure 20. Carrizo-Wilcox Groundwater Conservation Districts (GCDs) selected for analysis.

Table 10

Summary of Wells Selected for Analysis, by Groundwater Conservation District (GCD)

District	Year GCD enacted	Total wells in TWDB GWDB	Total wells with > 40 measurements
Anderson County UWCD	1987	4	0
Bee GCD	-[a]	-	-
Bluebonnet GCD	-	-	-
Brazos Valley GCD	1999	266	14
Duval County GCD	-	-	-
Edwards Aquifer Authority	1996	181	6
Evergreen UWCD	1965	1,508	68
Fayette County GCD	2001	2	0
Gonzales County UWCD	1993	181	12
Guadalupe County GCD	1997	194	6
Live Oak UWCD	1989	2	0
Lost Pines GCD	1999	621	17
McMullen GCD	1999	29	4
Medina County GCD	1989	348	7
Mid-East Texas GCD	2001	517	8
Neches & Trinity Valleys GCD	2001	762	12
Panola County GCD	2007	154	7
Pecan Valley GCD	-	-	-
Pineywoods GCD	2001	347	49
Plum Creek CD	1989	195	11

Table 10 (continued)

District	Year GCD enacted	Total wells in TWDB GWDB	Total wells with > 40 measurements
Post Oak Savannah GCD	2001	271	5
Rusk County GCD	2003	371	28
Uvalde County UWCD	1993	6	1
Wintergarden GCD	1997	1,124	103

Note. TWDB = Texas Water Development Board, GWDB = Groundwater Database, GCD = Groundwater Conservation District, CD = Conservation District, UWCD = Underground Water Conservation District.

[a]No data in TWDB Groundwater Database.

table also depicts the total number of wells in each GCD that had more than 40 depth measurements. Wells with more than 40 depth measurements were then screened for inclusion in the study.

Trend Detection

Exploratory data analysis (Kundzewicz & Robson, 2012) of each of the 13 GCDs provided an advanced visual examination of the data that determined the average annual drawdown for equal periods prior to and since creation of the respective GCD. The average annual drawdown for the pre/post GCD analysis period and the average annual drawdown for the entire period of record for each well were also determined.

The average annual drawdown data for each GCD was analyzed using a t test to calculate a p value for statistical significance. The Wilcoxon-Mann-Whitney test was used for those GCDs that were determined to have nonnormal distribution of drawdown data. According to Kundzewicz and Robson (2012), this is a rank-based test that assumes that time of change is known (GCD establishment year) and looks for differences between two independent sample groups.

Application of the Methodology

This study to detect trends in average annual drawdown subsequent to the creation of a GCD examined drawdown data from the following GCDs: Brazos Valley, Evergreen, Gonzales County, Guadalupe County, Lost Pines, Medina County, McMullen, Mid-East Texas, Neches and Trinity Valleys, Pineywoods, Post Oak Savannah, Rusk County, and Wintergarden. The boundaries of all of these GCDs overlie the Carrizo-Wilcox aquifer. The periods of analysis for each GCD are listed in Table 11.

Results

Exploratory Data Analysis

Exploratory data analysis showed that drawdown decreased in 46.87% of the wells in the study in the period after establishment of the GCD, whereas in 53.13% of the wells average annual drawdown actually increased. The most favorable results were in the Evergreen GCD, where average annual drawdown decreased in 84.62% of the wells and increased in 15.38% of the wells. The least favorable results were found in the Wintergarden GCD, where average annual drawdown decreased in only 25.00% of the selected wells in the study period after creation of the GCD and increased in 75% of the selected wells. Table 12 is a summary of the exploratory data analysis. Tables 13 through 25 present the results of the exploratory data analysis for each GCD.

Table 11

Time Data Summary by Groundwater Conservation District (GCD)

District	ID	Analysis period
Brazos Valley	199912GX	1987–2011
Evergreen	196513KX	1949–1984
Gonzales County	199313LX	1983–2003
Guadalupe County	199710LX	1987–2007
Lost Pines	199912GK	1989–2009
Medina County	198913LX	1979–1999
McMullen County	199916NX	1989–2009
Mid East Texas	200111HC	1991–2011
Neches & Trinity Valley	200111IC	1991–2011
Pineywoods	200111IX	1991–2011
Post Oak Savannah	200108GY	1991–2011
Rusk County	200311IX	1993–2013
Wintergarden	199713LX	1980–2014

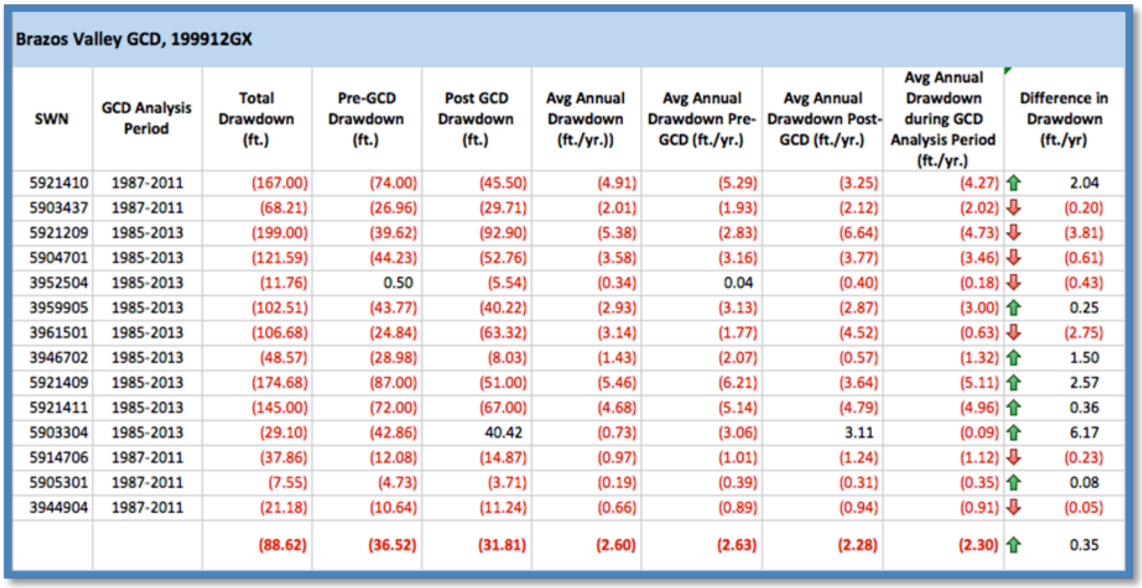
Table 12

Summary of Exploratory Data Analysis for Groundwater Conservation Districts (GCD)

District	Number of wells sampled	Number with decreased drawdown	Number with increased drawdown	% that responded as expected	% that did not respond as expected
Brazos Valley	14	7	7	50.00	50.00
Evergreen	13	11	2	84.62	15.38
Gonzales County	3	1	2	33.33	66.67
Guadalupe County	4	1	3	25.00	75.00
Lost Pines	12	4	8	33.33	66.67
Medina County	4	3	1	75.00	25.00
McMullen County	3	3	0	100.00	0.00
Mid East Texas	12	3	9	25.00	75.00
Neches & Trinity Valley	3	1	2	33.33	66.67
Pineywoods	13	10	3	76.92	23.08
Post Oak Savannah	2	2	0	100.00	0.00
Rusk County	13	5	8	38.46	61.54
Wintergarden	20	5	15	25.00	75.00
Totals	96	51	45	53.13	46.88

Table 13

Brazos Valley Groundwater Conservation District Exploratory Data Analysis

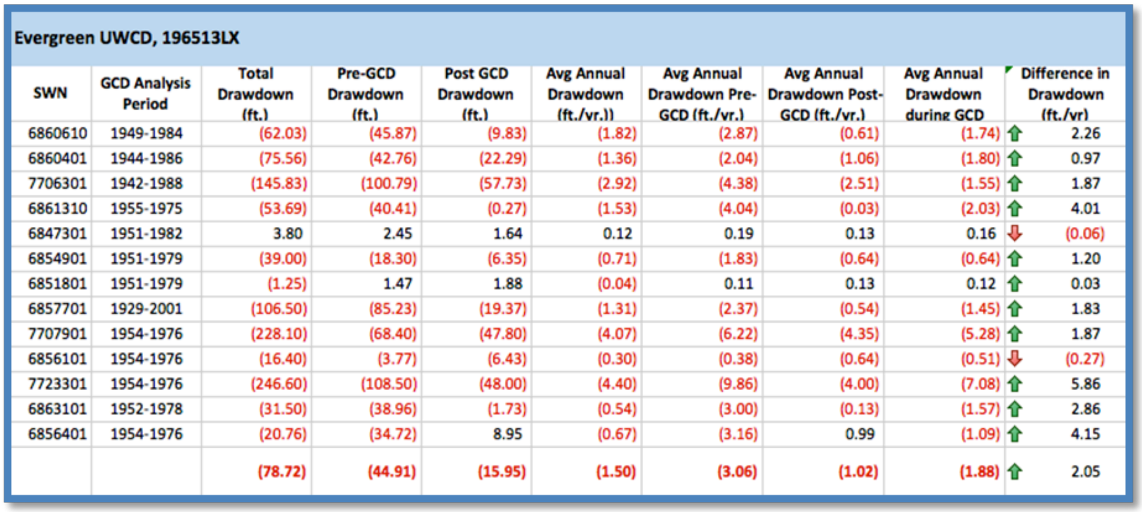


Brazos Valley GCD, 199912GX

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD Analysis Period (ft./yr.)	Difference in Drawdown (ft./yr)
5921410	1987-2011	(167.00)	(74.00)	(45.50)	(4.91)	(5.29)	(3.25)	(4.27)	⇧ 2.04
5903437	1987-2011	(68.21)	(26.96)	(29.71)	(2.01)	(1.93)	(2.12)	(2.02)	⇩ (0.20)
5921209	1985-2013	(199.00)	(39.62)	(92.90)	(5.38)	(2.83)	(6.64)	(4.73)	⇩ (3.81)
5904701	1985-2013	(121.59)	(44.23)	(52.76)	(3.58)	(3.16)	(3.77)	(3.46)	⇩ (0.61)
3952504	1985-2013	(11.76)	0.50	(5.54)	(0.34)	0.04	(0.40)	(0.18)	⇩ (0.43)
3959905	1985-2013	(102.51)	(43.77)	(40.22)	(2.93)	(3.13)	(2.87)	(3.00)	⇧ 0.25
3961501	1985-2013	(106.68)	(24.84)	(63.32)	(3.14)	(1.77)	(4.52)	(0.63)	⇩ (2.75)
3946702	1985-2013	(48.57)	(28.98)	(8.03)	(1.43)	(2.07)	(0.57)	(1.32)	⇧ 1.50
5921409	1985-2013	(174.68)	(87.00)	(51.00)	(5.46)	(6.21)	(3.64)	(5.11)	⇧ 2.57
5921411	1985-2013	(145.00)	(72.00)	(67.00)	(4.68)	(5.14)	(4.79)	(4.96)	⇧ 0.36
5903304	1985-2013	(29.10)	(42.86)	40.42	(0.73)	(3.06)	3.11	(0.09)	⇧ 6.17
5914706	1987-2011	(37.86)	(12.08)	(14.87)	(0.97)	(1.01)	(1.24)	(1.12)	⇩ (0.23)
5905301	1987-2011	(7.55)	(4.73)	(3.71)	(0.19)	(0.39)	(0.31)	(0.35)	⇧ 0.08
3944904	1987-2011	(21.18)	(10.64)	(11.24)	(0.66)	(0.89)	(0.94)	(0.91)	⇩ (0.05)
		(88.62)	**(36.52)**	**(31.81)**	**(2.60)**	**(2.63)**	**(2.28)**	**(2.30)**	⇧ 0.35

Table 14

Evergreen Groundwater Conservation District Exploratory Data Analysis

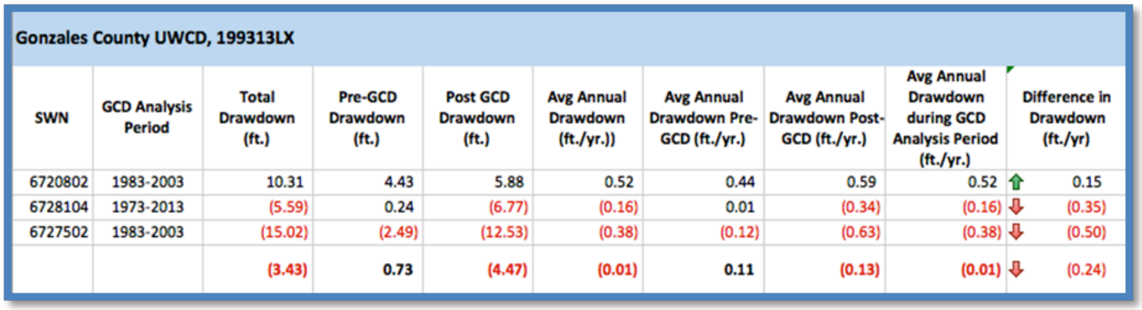


Evergreen UWCD, 196513LX

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD	Difference in Drawdown (ft./yr)
6860610	1949-1984	(62.03)	(45.87)	(9.83)	(1.82)	(2.87)	(0.61)	(1.74)	⇧ 2.26
6860401	1944-1986	(75.56)	(42.76)	(22.29)	(1.36)	(2.04)	(1.06)	(1.80)	⇧ 0.97
7706301	1942-1988	(145.83)	(100.79)	(57.73)	(2.92)	(4.38)	(2.51)	(1.55)	⇧ 1.87
6861310	1955-1975	(53.69)	(40.41)	(0.27)	(1.53)	(4.04)	(0.03)	(2.03)	⇧ 4.01
6847301	1951-1982	3.80	2.45	1.64	0.12	0.19	0.13	0.16	⇩ (0.06)
6854901	1951-1979	(39.00)	(18.30)	(6.35)	(0.71)	(1.83)	(0.64)	(0.64)	⇧ 1.20
6851801	1951-1979	(1.25)	1.47	1.88	(0.04)	0.11	0.13	0.12	⇧ 0.03
6857701	1929-2001	(106.50)	(85.23)	(19.37)	(1.31)	(2.37)	(0.54)	(1.45)	⇧ 1.83
7707901	1954-1976	(228.10)	(68.40)	(47.80)	(4.07)	(6.22)	(4.35)	(5.28)	⇧ 1.87
6856101	1954-1976	(16.40)	(3.77)	(6.43)	(0.30)	(0.38)	(0.64)	(0.51)	⇩ (0.27)
7723301	1954-1976	(246.60)	(108.50)	(48.00)	(4.40)	(9.86)	(4.00)	(7.08)	⇧ 5.86
6863101	1952-1978	(31.50)	(38.96)	(1.73)	(0.54)	(3.00)	(0.13)	(1.57)	⇧ 2.86
6856401	1954-1976	(20.76)	(34.72)	8.95	(0.67)	(3.16)	0.99	(1.09)	⇧ 4.15
		(78.72)	**(44.91)**	**(15.95)**	**(1.50)**	**(3.06)**	**(1.02)**	**(1.88)**	⇧ 2.05

Table 15

Gonzales County Groundwater Conservation District Exploratory Data Analysis

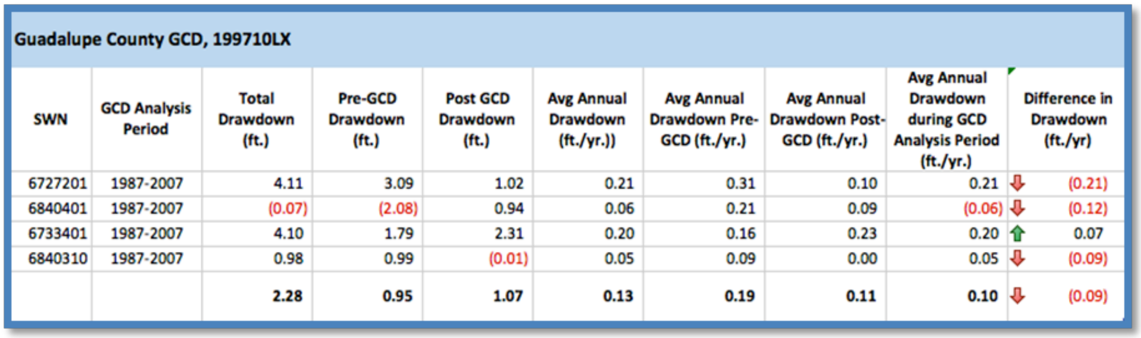


Gonzales County UWCD, 199313LX

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD Analysis Period (ft./yr.)		Difference in Drawdown (ft./yr)
6720802	1983-2003	10.31	4.43	5.88	0.52	0.44	0.59	0.52	⇧	0.15
6728104	1973-2013	(5.59)	0.24	(6.77)	(0.16)	0.01	(0.34)	(0.16)	⇩	(0.35)
6727502	1983-2003	(15.02)	(2.49)	(12.53)	(0.38)	(0.12)	(0.63)	(0.38)	⇩	(0.50)
		(3.43)	**0.73**	**(4.47)**	**(0.01)**	**0.11**	**(0.13)**	**(0.01)**	⇩	(0.24)

Table 16

Guadalupe County Groundwater Conservation District Exploratory Data Analysis

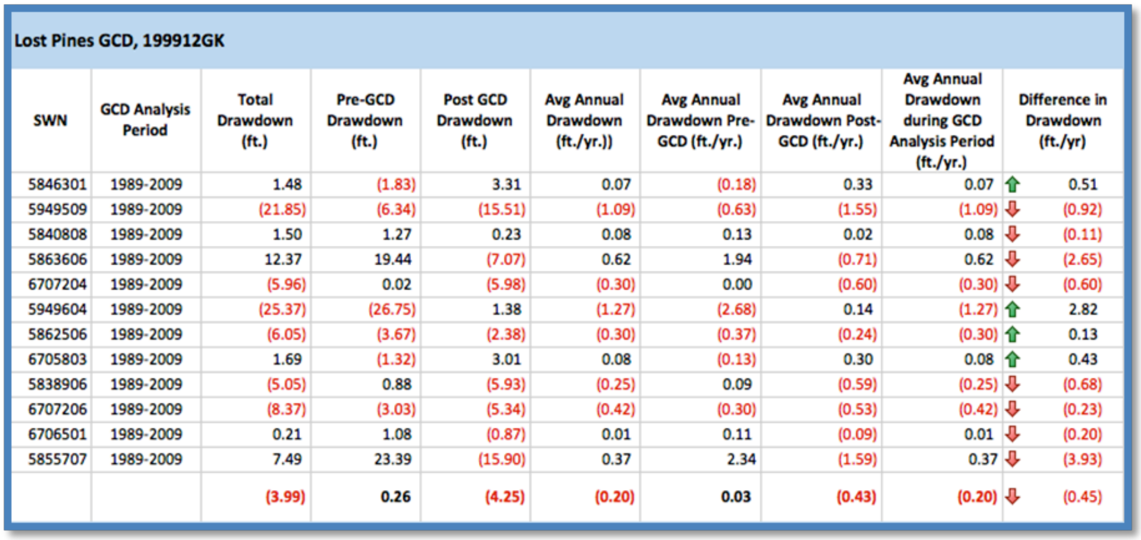


Guadalupe County GCD, 199710LX

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD Analysis Period (ft./yr.)		Difference in Drawdown (ft./yr)
6727201	1987-2007	4.11	3.09	1.02	0.21	0.31	0.10	0.21	⇩	(0.21)
6840401	1987-2007	(0.07)	(2.08)	0.94	0.06	0.21	0.09	(0.06)	⇩	(0.12)
6733401	1987-2007	4.10	1.79	2.31	0.20	0.16	0.23	0.20	⇧	0.07
6840310	1987-2007	0.98	0.99	(0.01)	0.05	0.09	0.00	0.05	⇩	(0.09)
		2.28	**0.95**	**1.07**	**0.13**	**0.19**	**0.11**	**0.10**	⇩	(0.09)

Table 17

Lost Pines Groundwater Conservation District Exploratory Data Analysis

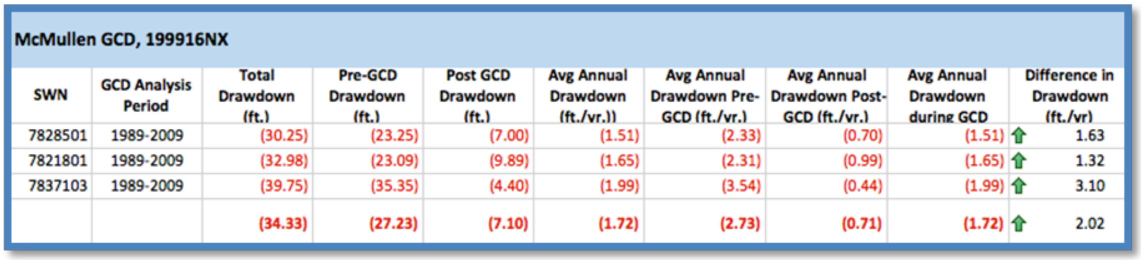


Lost Pines GCD, 199912GK

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD Analysis Period (ft./yr.)		Difference in Drawdown (ft./yr)
5846301	1989-2009	1.48	(1.83)	3.31	0.07	(0.18)	0.33	0.07	↑	0.51
5949509	1989-2009	(21.85)	(6.34)	(15.51)	(1.09)	(0.63)	(1.55)	(1.09)	↓	(0.92)
5840808	1989-2009	1.50	1.27	0.23	0.08	0.13	0.02	0.08	↓	(0.11)
5863606	1989-2009	12.37	19.44	(7.07)	0.62	1.94	(0.71)	0.62	↓	(2.65)
6707204	1989-2009	(5.96)	0.02	(5.98)	(0.30)	0.00	(0.60)	(0.30)	↓	(0.60)
5949604	1989-2009	(25.37)	(26.75)	1.38	(1.27)	(2.68)	0.14	(1.27)	↑	2.82
5862506	1989-2009	(6.05)	(3.67)	(2.38)	(0.30)	(0.37)	(0.24)	(0.30)	↑	0.13
6705803	1989-2009	1.69	(1.32)	3.01	0.08	(0.13)	0.30	0.08	↑	0.43
5838906	1989-2009	(5.05)	0.88	(5.93)	(0.25)	0.09	(0.59)	(0.25)	↓	(0.68)
6707206	1989-2009	(8.37)	(3.03)	(5.34)	(0.42)	(0.30)	(0.53)	(0.42)	↓	(0.23)
6706501	1989-2009	0.21	1.08	(0.87)	0.01	0.11	(0.09)	0.01	↓	(0.20)
5855707	1989-2009	7.49	23.39	(15.90)	0.37	2.34	(1.59)	0.37	↓	(3.93)
		(3.99)	**0.26**	**(4.25)**	**(0.20)**	**0.03**	**(0.43)**	**(0.20)**	↓	(0.45)

Table 18

McMullen County Groundwater Conservation District Exploratory Data Analysis

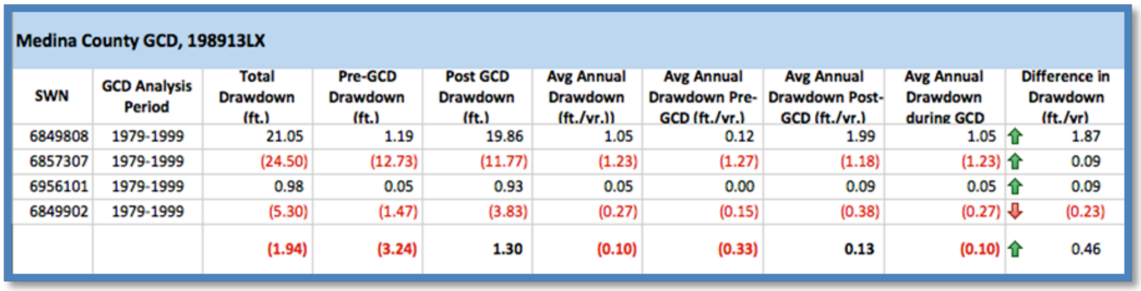


McMullen GCD, 199916NX

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD		Difference in Drawdown (ft./yr)
7828501	1989-2009	(30.25)	(23.25)	(7.00)	(1.51)	(2.33)	(0.70)	(1.51)	↑	1.63
7821801	1989-2009	(32.98)	(23.09)	(9.89)	(1.65)	(2.31)	(0.99)	(1.65)	↑	1.32
7837103	1989-2009	(39.75)	(35.35)	(4.40)	(1.99)	(3.54)	(0.44)	(1.99)	↑	3.10
		(34.33)	**(27.23)**	**(7.10)**	**(1.72)**	**(2.73)**	**(0.71)**	**(1.72)**	↑	2.02

Table 19

Medina County Groundwater Conservation District Exploratory Data Analysis

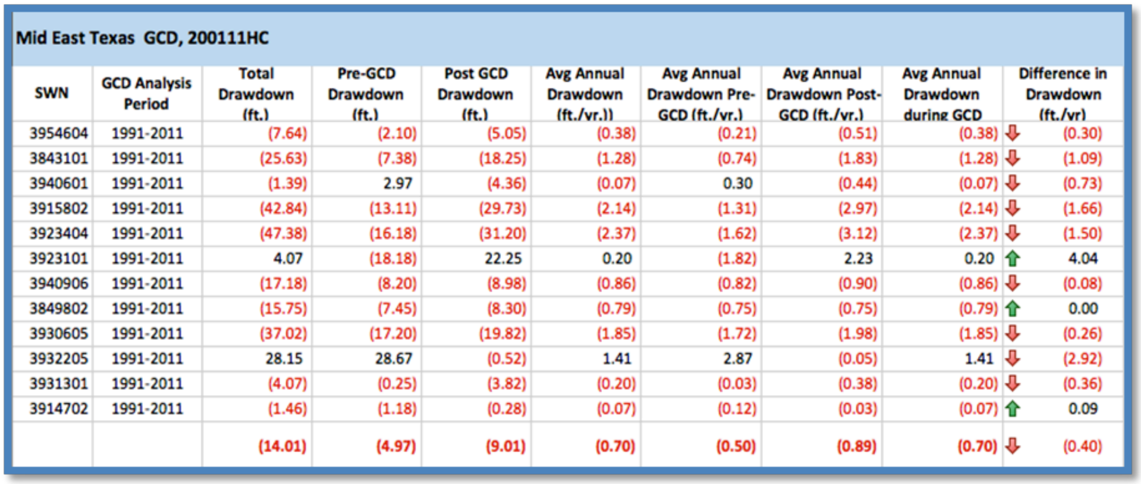


Medina County GCD, 198913LX

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD	Difference in Drawdown (ft./yr)
6849808	1979-1999	21.05	1.19	19.86	1.05	0.12	1.99	1.05	↑ 1.87
6857307	1979-1999	(24.50)	(12.73)	(11.77)	(1.23)	(1.27)	(1.18)	(1.23)	↑ 0.09
6956101	1979-1999	0.98	0.05	0.93	0.05	0.00	0.09	0.05	↑ 0.09
6849902	1979-1999	(5.30)	(1.47)	(3.83)	(0.27)	(0.15)	(0.38)	(0.27)	↓ (0.23)
		(1.94)	**(3.24)**	**1.30**	**(0.10)**	**(0.33)**	**0.13**	**(0.10)**	↑ 0.46

Table 20

Mid-East Texas Groundwater Conservation District Exploratory Data Analysis

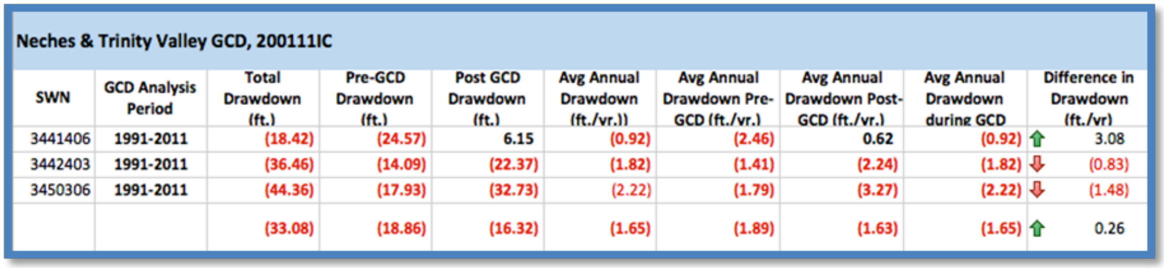


Mid East Texas GCD, 200111HC

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD	Difference in Drawdown (ft./yr)
3954604	1991-2011	(7.64)	(2.10)	(5.05)	(0.38)	(0.21)	(0.51)	(0.38)	↓ (0.30)
3843101	1991-2011	(25.63)	(7.38)	(18.25)	(1.28)	(0.74)	(1.83)	(1.28)	↓ (1.09)
3940601	1991-2011	(1.39)	2.97	(4.36)	(0.07)	0.30	(0.44)	(0.07)	↓ (0.73)
3915802	1991-2011	(42.84)	(13.11)	(29.73)	(2.14)	(1.31)	(2.97)	(2.14)	↓ (1.66)
3923404	1991-2011	(47.38)	(16.18)	(31.20)	(2.37)	(1.62)	(3.12)	(2.37)	↓ (1.50)
3923101	1991-2011	4.07	(18.18)	22.25	0.20	(1.82)	2.23	0.20	↑ 4.04
3940906	1991-2011	(17.18)	(8.20)	(8.98)	(0.86)	(0.82)	(0.90)	(0.86)	↓ (0.08)
3849802	1991-2011	(15.75)	(7.45)	(8.30)	(0.79)	(0.75)	(0.75)	(0.79)	↑ 0.00
3930605	1991-2011	(37.02)	(17.20)	(19.82)	(1.85)	(1.72)	(1.98)	(1.85)	↓ (0.26)
3932205	1991-2011	28.15	28.67	(0.52)	1.41	2.87	(0.05)	1.41	↓ (2.92)
3931301	1991-2011	(4.07)	(0.25)	(3.82)	(0.20)	(0.03)	(0.38)	(0.20)	↓ (0.36)
3914702	1991-2011	(1.46)	(1.18)	(0.28)	(0.07)	(0.12)	(0.03)	(0.07)	↑ 0.09
		(14.01)	**(4.97)**	**(9.01)**	**(0.70)**	**(0.50)**	**(0.89)**	**(0.70)**	↓ (0.40)

Table 21

Neches-Trinity Valleys Groundwater Conservation District Exploratory Data Analysis

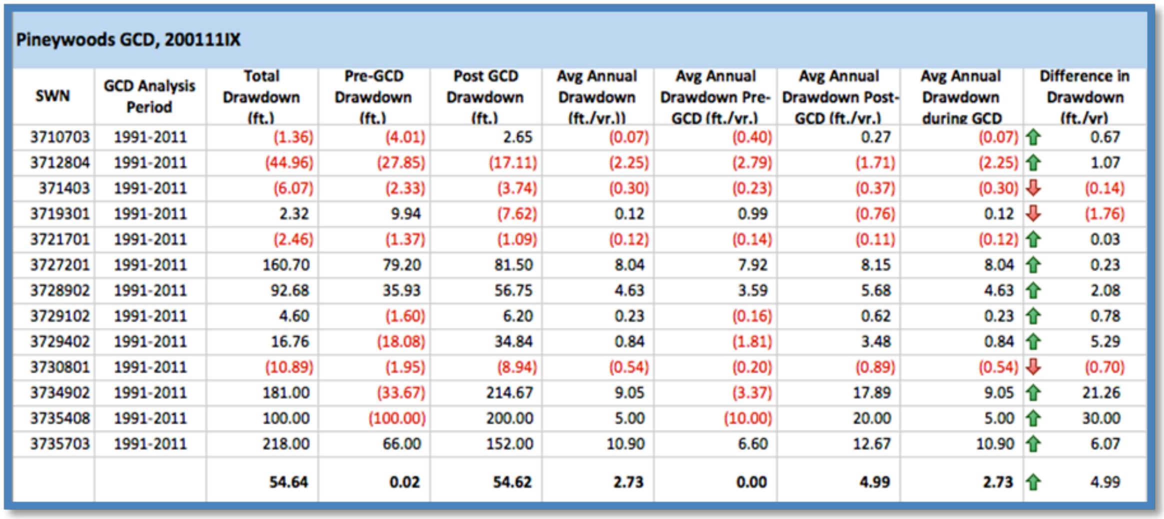


Neches & Trinity Valley GCD, 200111IC

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD	Difference in Drawdown (ft./yr)
3441406	**1991-2011**	**(18.42)**	**(24.57)**	**6.15**	**(0.92)**	**(2.46)**	**0.62**	**(0.92)**	↑ 3.08
3442403	**1991-2011**	**(36.46)**	**(14.09)**	**(22.37)**	**(1.82)**	**(1.41)**	**(2.24)**	**(1.82)**	↓ (0.83)
3450306	**1991-2011**	**(44.36)**	**(17.93)**	**(32.73)**	(2.22)	**(1.79)**	**(3.27)**	**(2.22)**	↓ (1.48)
		(33.08)	**(18.86)**	**(16.32)**	**(1.65)**	**(1.89)**	**(1.63)**	**(1.65)**	↑ 0.26

Table 22

Pineywoods Groundwater Conservation District Exploratory Data Analysis

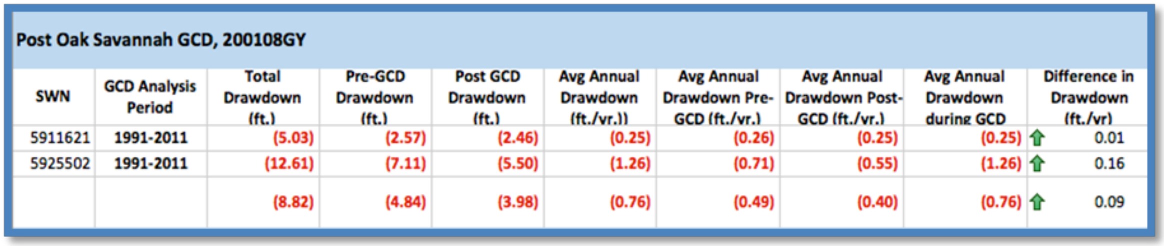


Pineywoods GCD, 200111IX

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD	Difference in Drawdown (ft./yr)
3710703	1991-2011	(1.36)	(4.01)	2.65	(0.07)	(0.40)	0.27	(0.07)	↑ 0.67
3712804	1991-2011	(44.96)	(27.85)	(17.11)	(2.25)	(2.79)	(1.71)	(2.25)	↑ 1.07
371403	1991-2011	(6.07)	(2.33)	(3.74)	(0.30)	(0.23)	(0.37)	(0.30)	↓ (0.14)
3719301	1991-2011	2.32	9.94	(7.62)	0.12	0.99	(0.76)	0.12	↓ (1.76)
3721701	1991-2011	(2.46)	(1.37)	(1.09)	(0.12)	(0.14)	(0.11)	(0.12)	↑ 0.03
3727201	1991-2011	160.70	79.20	81.50	8.04	7.92	8.15	8.04	↑ 0.23
3728902	1991-2011	92.68	35.93	56.75	4.63	3.59	5.68	4.63	↑ 2.08
3729102	1991-2011	4.60	(1.60)	6.20	0.23	(0.16)	0.62	0.23	↑ 0.78
3729402	1991-2011	16.76	(18.08)	34.84	0.84	(1.81)	3.48	0.84	↑ 5.29
3730801	1991-2011	(10.89)	(1.95)	(8.94)	(0.54)	(0.20)	(0.89)	(0.54)	↓ (0.70)
3734902	1991-2011	181.00	(33.67)	214.67	9.05	(3.37)	17.89	9.05	↑ 21.26
3735408	1991-2011	100.00	(100.00)	200.00	5.00	(10.00)	20.00	5.00	↑ 30.00
3735703	1991-2011	218.00	66.00	152.00	10.90	6.60	12.67	10.90	↑ 6.07
		54.64	**0.02**	**54.62**	**2.73**	**0.00**	**4.99**	**2.73**	↑ 4.99

Table 23

Post Oak Savannah Groundwater Conservation District Exploratory Data Analysis

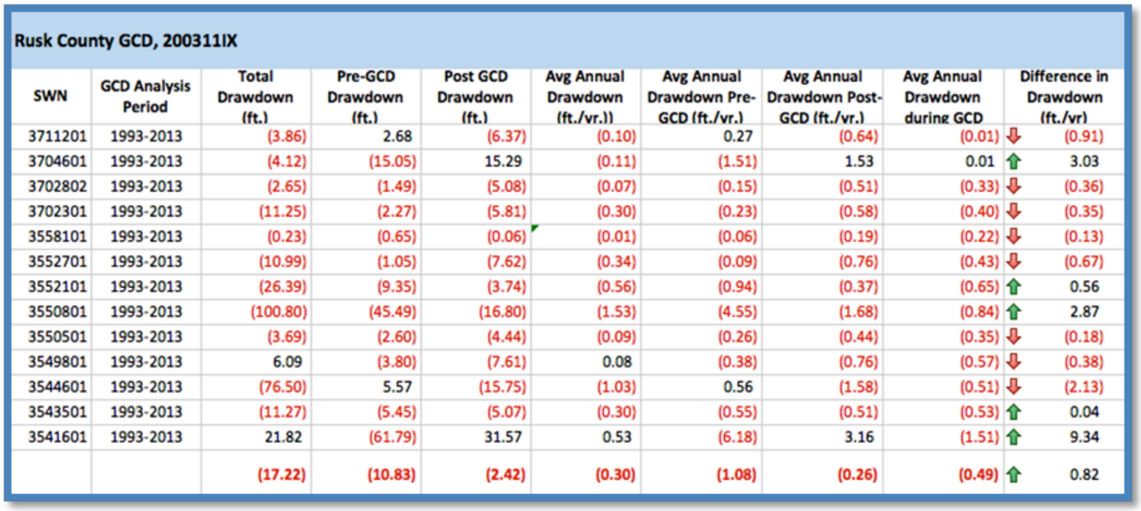


Post Oak Savannah GCD, 200108GY

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD	Difference in Drawdown (ft./yr)
5911621	**1991-2011**	**(5.03)**	**(2.57)**	**(2.46)**	**(0.25)**	**(0.26)**	**(0.25)**	**(0.25)**	↑ 0.01
5925502	**1991-2011**	**(12.61)**	**(7.11)**	**(5.50)**	**(1.26)**	**(0.71)**	**(0.55)**	**(1.26)**	↑ 0.16
		(8.82)	**(4.84)**	**(3.98)**	**(0.76)**	**(0.49)**	**(0.40)**	**(0.76)**	↑ 0.09

Table 24

Rusk County Groundwater Conservation District Exploratory Data Analysis

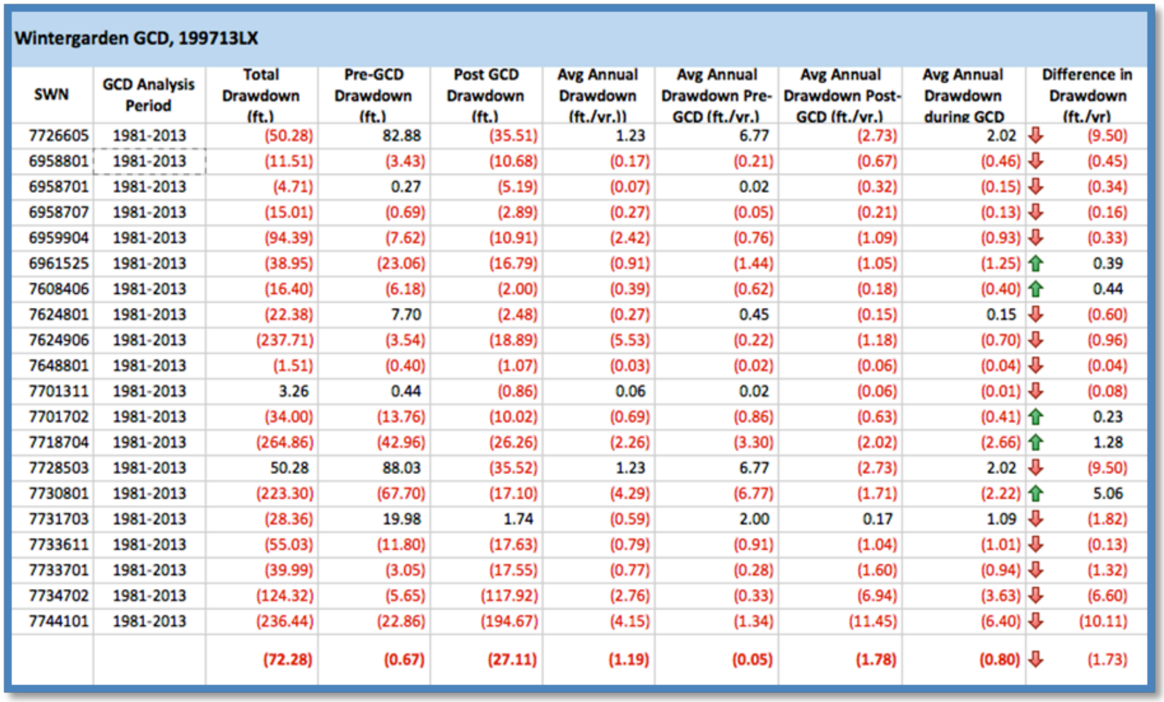


Rusk County GCD, 200311IX

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD	Difference in Drawdown (ft./yr)
3711201	1993-2013	(3.86)	2.68	(6.37)	(0.10)	0.27	(0.64)	(0.01)	⇩ (0.91)
3704601	1993-2013	(4.12)	(15.05)	15.29	(0.11)	(1.51)	1.53	0.01	⇧ 3.03
3702802	1993-2013	(2.65)	(1.49)	(5.08)	(0.07)	(0.15)	(0.51)	(0.33)	⇩ (0.36)
3702301	1993-2013	(11.25)	(2.27)	(5.81)	(0.30)	(0.23)	(0.58)	(0.40)	⇩ (0.35)
3558101	1993-2013	(0.23)	(0.65)	(0.06)	(0.01)	(0.06)	(0.19)	(0.22)	⇩ (0.13)
3552701	1993-2013	(10.99)	(1.05)	(7.62)	(0.34)	(0.09)	(0.76)	(0.43)	⇩ (0.67)
3552101	1993-2013	(26.39)	(9.35)	(3.74)	(0.56)	(0.94)	(0.37)	(0.65)	⇧ 0.56
3550801	1993-2013	(100.80)	(45.49)	(16.80)	(1.53)	(4.55)	(1.68)	(0.84)	⇧ 2.87
3550501	1993-2013	(3.69)	(2.60)	(4.44)	(0.09)	(0.26)	(0.44)	(0.35)	⇩ (0.18)
3549801	1993-2013	6.09	(3.80)	(7.61)	0.08	(0.38)	(0.76)	(0.57)	⇩ (0.38)
3544601	1993-2013	(76.50)	5.57	(15.75)	(1.03)	0.56	(1.58)	(0.51)	⇩ (2.13)
3543501	1993-2013	(11.27)	(5.45)	(5.07)	(0.30)	(0.55)	(0.51)	(0.53)	⇧ 0.04
3541601	1993-2013	21.82	(61.79)	31.57	0.53	(6.18)	3.16	(1.51)	⇧ 9.34
		(17.22)	**(10.83)**	**(2.42)**	**(0.30)**	**(1.08)**	**(0.26)**	**(0.49)**	⇧ 0.82

Table 25

Wintergarden Groundwater Conservation District Exploratory Data Analysis



Wintergarden GCD, 199713LX

SWN	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD	Difference in Drawdown (ft./yr)
7726605	1981-2013	(50.28)	82.88	(35.51)	1.23	6.77	(2.73)	2.02	⇩ (9.50)
6958801	1981-2013	(11.51)	(3.43)	(10.68)	(0.17)	(0.21)	(0.67)	(0.46)	⇩ (0.45)
6958701	1981-2013	(4.71)	0.27	(5.19)	(0.07)	0.02	(0.32)	(0.15)	⇩ (0.34)
6958707	1981-2013	(15.01)	(0.69)	(2.89)	(0.27)	(0.05)	(0.21)	(0.13)	⇩ (0.16)
6959904	1981-2013	(94.39)	(7.62)	(10.91)	(2.42)	(0.76)	(1.09)	(0.93)	⇩ (0.33)
6961525	1981-2013	(38.95)	(23.06)	(16.79)	(0.91)	(1.44)	(1.05)	(1.25)	⇧ 0.39
7608406	1981-2013	(16.40)	(6.18)	(2.00)	(0.39)	(0.62)	(0.18)	(0.40)	⇧ 0.44
7624801	1981-2013	(22.38)	7.70	(2.48)	(0.27)	0.45	(0.15)	0.15	⇩ (0.60)
7624906	1981-2013	(237.71)	(3.54)	(18.89)	(5.53)	(0.22)	(1.18)	(0.70)	⇩ (0.96)
7648801	1981-2013	(1.51)	(0.40)	(1.07)	(0.03)	(0.02)	(0.06)	(0.04)	⇩ (0.04)
7701311	1981-2013	3.26	0.44	(0.86)	0.06	0.02	(0.06)	(0.01)	⇩ (0.08)
7701702	1981-2013	(34.00)	(13.76)	(10.02)	(0.69)	(0.86)	(0.63)	(0.41)	⇧ 0.23
7718704	1981-2013	(264.86)	(42.96)	(26.26)	(2.26)	(3.30)	(2.02)	(2.66)	⇧ 1.28
7728503	1981-2013	50.28	88.03	(35.52)	1.23	6.77	(2.73)	2.02	⇩ (9.50)
7730801	1981-2013	(223.30)	(67.70)	(17.10)	(4.29)	(6.77)	(1.71)	(2.22)	⇧ 5.06
7731703	1981-2013	(28.36)	19.98	1.74	(0.59)	2.00	0.17	1.09	⇩ (1.82)
7733611	1981-2013	(55.03)	(11.80)	(17.63)	(0.79)	(0.91)	(1.04)	(1.01)	⇩ (0.13)
7733701	1981-2013	(39.99)	(3.05)	(17.55)	(0.77)	(0.28)	(1.60)	(0.94)	⇩ (1.32)
7734702	1981-2013	(124.32)	(5.65)	(117.92)	(2.76)	(0.33)	(6.94)	(3.63)	⇩ (6.60)
7744101	1981-2013	(236.44)	(22.86)	(194.67)	(4.15)	(1.34)	(11.45)	(6.40)	⇩ (10.11)
		(72.28)	**(0.67)**	**(27.11)**	**(1.19)**	**(0.05)**	**(1.78)**	**(0.80)**	⇩ (1.73)

Tests for Statistical Significance

Table 26 shows the results of *t* tests and/or Wilcoxon-Mann-Whitney tests that were performed on data from each GCD. The Wilcoxon test was used in those instances where the distribution of the data from a GCD was nonnormal. The test results were statistically significant in 4 of the 13 GCDs: Evergreen, McMullen County, Pineywoods, and Wintergarden. In the case of Wintergarden, the trend was toward significantly increased drawdown of aquifer levels after the GCD was created.

Summary of Trends

Tables 35 through 38 (Appendix) provide trend data for each well analyzed for this study. Approximately 47% of the wells recorded a decrease in average annual drawdown after the creation of a GCD and 53% recorded increased drawdown. In the case of three of the GCDs analyzed in this study (Evergreen, McMullen County, and Pineywoods), a positive impact on drawdown clearly occurred after the creation of the GCD, with a statistically significant change in drawdown recorded in approximately 85% of the wells in those GCDs. On the other hand, a statistically significant increase in average annual drawdown occurred in the Wintergarden GCD. Results of pre/post GCD comparisons in the 20 other GCDs were not statistically significant and did not demonstrate a clear trend.

Conclusions and Recommendations

The results of this study show that, generally, no difference occurred in aquifer drawdown rates after creation of a GCD. Whereas approximately 47% of the wells recorded a decrease in average annual drawdown after the creation of a GCD, 53%

Table 26

Summary of Statistical Tests

Groundwater Conservation District (GCD)	Number of wells sampled	Goodness of Fit Prov < W	*t*	Wilcoxon-Mann-Whitney	Significant?
Brazos Valley	14	0.6626	0.6535		No
Evergreen	13	0.0036	0.0313		Yes
Gonzales County	3	0.8507	0.7048	0.6625	No
Guadalupe County	4	0.8758	0.8828	0.3836	No
Lost Pines	12	0.0099	0.862		No
Medina County	4	0.1345	0.282	0.8852	No
McMullen County	3	0.4351	0.0049		Yes
Mid East Texas	12	0.0626	0.758	0.5065	No
Neches/Trinity Valleys	3	0.4697	0.4208	0.8273	No
Pineywoods	13	0.002	0.0251		Yes
Post Oak Savannah	2	0.2789	0.3915	0.4386	No
Rusk County	13	0.0001	0.223	0.626	No
Wintergarden	20	0.0001	0.0613	0.0411	Yes

Note. Significance = $p < .05$.

actually recorded increased drawdown. In the four GCDs where the results were statistically significant, there was not a common trend in the methods that the GCDs used for allocating groundwater. Both Evergreen and McMullen County GCDs established production limits based on acreage or tract size and first in time, first in right.

Pineywoods GCD established production limits based on spacing and historical use. Wintergarden GCD established production limits based on spacing and acreage or tract size. More study is required to determine whether the statistical significance of the change in drawdown was the result of rules implemented by the GCD or the result of some other economic, agricultural, or environmental change.

This study was limited by availability of consistent, long-term water-level measurement data from the TWDB groundwater database. With 2,332 wells available overlying the Carrizo-Wilcox Aquifer, approximately 5% had data with sufficient consistency and longevity to perform a meaningful assessment.

This study did not take into account environmental factors such as drought and climate change. Nor did it factor in changes in population increases, which could affect aquifer drawdown and recharge. The study was designed only to determine whether a measureable difference occurred in drawdown in pre and post GCD periods. It did not take into account the idea of managed drawdown in which the groundwater resources of a district are drawn down at a predetermined rate deemed acceptable to the GCD administrators.

Further study is required to include additional GCDs from other major aquifers in Texas. These future studies should also take into account changes in population and environmental factors to determine more accurately the utility of GCDs in Texas.

CHAPTER IV

DETECTION OF HYDROLOGICAL TRENDS RESULTING FROM IMPLEMENTATION OF GROUNDWATER CONSERVATION DISTRICTS IN TEXAS: A CASE STUDY OF THE CARRIZO-WILCOX AQUIFER

Groundwater is a critically important water resource in the state of Texas. Facing growth that is expected to double the population of the state to more than 46 million by 2060, Texas has increased its efforts during the past decade to implement comprehensive water resources planning (Vaughn et al., 2012). Maximizing available water resources in Texas, including groundwater, is critical to the long-term economic viability of the state (Vaughn et al., 2012).

Ranked among the top four states in this country in terms of water consumption, Texas is facing significant challenges in water resource management because most of the surface water supply is already fully allocated (Wagner & Kreuter, 2004). As a result, the state will rely increasingly on groundwater to meet its freshwater needs in coming decades (Wagner & Kreuter, 2004). The challenges that Texas will face in meeting demands for freshwater will be aggravated as the state population nearly doubles to 46 million people by 2060 (TWDB, 2007; Vaughn et al., 2012). This population increase will bring with it an annual increase in water demand of 27% (TWDB, 2007; Vaughn et al., 2012). Texas will be forced to rely more and more on groundwater to meet agricultural, municipal, and industrial needs in the future as surface water supplies become even more limited (Johnson et al., 2009).

This study was an investigation of the impact of GCDs in Texas on aquifer levels in the Carrizo-Wilcox Aquifer. The study was designed to determine whether a measurable difference exists in the rate of decline in aquifer levels after the establishment of a GCD. If GCDs are effective organizational structures for managing groundwater resources in Texas, then a measurable decrease in the rate of decline of aquifer levels after establishment of a GCD would be expected.

Background

Groundwater Management in Texas

Unlike scientists who recognize that all water is interconnected, Texas law distinguishes between surface water and groundwater for the purpose of regulation with different rules governing each class (Kaiser, 1988; Vaughn et al., 2012). The state recognizes that a landowner owns groundwater (fresh and brackish) underlying his or her land as real property (Combs, 2014). In contrast, with the exception of diffused water, such as storm water runoff, all surface water, including streams, rivers, and lakes, is “held in trust” by the state and appropriated to users through permits or “water rights.” (Fipps, 2002). The complicated system in Texas arose from Spanish and English common law, the laws of other Western states, and state and federal case law and legislation (Vaughn et al., 2012).

Commonly known as the “Rule of Capture,” groundwater law in Texas is based on the English common law doctrine, which says that the landowner may withdraw groundwater without limitations and without liability for losses to neighbors’ wells as long as water is not wasted or taken maliciously (Combs, 2014; Fipps, 2002; Kaiser, 2005). The Texas Supreme Court in its 1904 decision *Houston & T.C. Railway Co. v. East* adopted this "rule of capture" doctrine in part because the science of quantifying and tracking the movement of groundwater was so poorly developed at the time that it would be practically impossible to administer any set of legal rules to govern its use (Kaiser, 1988; Vaughn et al., 2012).

The right of landowners to capture and make "nonwasteful" use of groundwater has been upheld by Texas courts over the years, with only a few exceptions: drilling a well on someone else's property or drilling a "slant" well on adjoining property that crosses the property line ("trespass"), pumping water for the sole purpose of injuring an adjoining landowner ("malicious or wanton conduct"), or causing land subsidence on adjoining land from negligent over-pumping (Fipps, 2002). Texas groundwater law has often been called the "law of the biggest pump" because the deepest well and most powerful pump get the water (Fipps, 2002; Kaiser, 1987).

In Texas, all surface water is held in trust by the state, which grants permission to groups and individuals to use the water (Vaughn et al., 2012). The state owns all waters flowing on the surface of Texas (Combs, 2014; Kaiser, 2005). The TCEQ issues and manages permits based on a "first in time, first in right" principle, meaning that those holding the oldest permits have first access to available water (Combs, 2014).

Texas recognizes two basic doctrines of surface water rights: the riparian doctrine and the prior appropriation doctrine. Introduced more than 200 years ago when Spanish Settlers first arrived in Texas, the riparian doctrine permits landowners whose property is adjacent to a river or stream to make reasonable use of the water (Kaiser, 1988). First adopted in Texas in 1895, the prior appropriation system has evolved into the modern system used today (Vaughn et al., 2012). Under prior appropriation, landowners who live near many of the water bodies in the state are allowed to divert and to use water for domestic and livestock purposes, not to exceed 247,000 cubic meters (200 acre-feet) per year (Kaiser, 1988; Vaughn et al., 2012).

Managing Water Use Through Water Planning

In response to the most severe drought of record in Texas in the 1950s, the Texas Water Planning Act of 1957 created the TWDB with the authority to develop a State Water Plan (J. E. Brown, 1997). Although the state had legislated the water planning process in 1957, it took little or no action on the water plans developed in 1961, 1968, 1987, 1990, and 1992 (J. E. Brown, 1997). In 1997, once again acting in response to a drought (1995-1996), the TWDB, in conjunction with the Texas Natural Resources Conservation Commission and the Texas Parks and Wildlife Department, developed the first “consensus-based” plan (J. E. Brown, 1997).

Recognizing that water is the single most important factor for the future economic viability of Texas (Vaughn et al., 2012), the legislature passed Senate Bill 1, the Comprehensive Water Management Bill, which was signed into law on June 19, 1997 (J. E. Brown, 1997). Senate Bill 1 put in place the “bottom-up” approach to water planning rooted in local, consensus-based decision making that Texas uses for water planning today (Combs, 2009). Senate Bill 1 resulted in designation of water planning regions based on geographical, hydrological, and political boundaries, water utility development patterns, and socioeconomic characteristics (J. E. Brown, 1997).

Managing Groundwater Through Conservation Districts

State policy in Texas dictates that groundwater management is best accomplished through locally elected, locally controlled GCDs, suggesting that any modification or limitation on the rule of capture will be made by local GCDs (J. E. Brown, 1997). In 1949, the Texas legislature first provided for voluntary creation of GCDs over any groundwater reservoir designated by the state (Fipps, 2002). While continuing to acknowledge the rule of capture of groundwater by landowners, the legislature passed additional legislation in 1985 and 1997 to encourage establishment of GCDs and, in limited cases, to allow for the creation of districts by state initiative (Fipps, 2002).

As of April 2014, a total of 101 GCDs had been created in the state. The total includes 98 established (i.e., confirmed) districts and 3 unconfirmed districts. The 98 established districts cover all or part of 179 of the 254 counties in the state. The TTMR has 50 GCDs in place (TWDB, 2014a).

GCDs are charged to manage groundwater by providing for the conservation, preservation, protection, recharging, and prevention of waste of the groundwater resources within their jurisdictions (Fipps, 2002).

GCDs can be created by one of four procedures: (a) established through action of the legislature, (b) created through a landowner petition procedure based on state law in Subchapter B, Chapter 36 of the Texas Water Code, (c) created by the TCEQ on its own motion in a designated Priority Groundwater Management Area (PGMA) through a procedure similar in principle to procedure (b) above but in which action is initiated by the TCEQ rather than by petition, or (d) alternative to creating a new GCD, adding territory to an existing district if the existing district is willing to accept the new territory (Lesikar et al., 2002).

GCDs are authorized by the state with powers and duties that enable them to manage groundwater resources. The three primary GCD legislatively mandated duties are permitting water wells, developing a comprehensive management plan, and adopting the necessary rules to implement the management plan (Lesikar et al., 2002).

The Texas Water Code Section 36.116 (a) (2005) provides broad regulatory authority to GCDs (Porter, 2014) as indicated below:

> To minimize as far as practicable the drawdown of the water table or the reduction of artesian pressure, to control subsidence, to prevent interference between wells, to prevent degradation of water quality, or to prevent waste, a district may regulate:
>
> The spacing of wells by:
>
> Requiring all water wells to be spaced a certain distance from property or adjoining wells;
>
> Requiring wells with certain production capacity, pump size, or other characteristic related to the construction or operation and production of and production from a well to be spaced a certain distance from property lines or adjoining wells; or
>
> Imposing spacing requirements adopted by the board; and
>
> The production of groundwater by:
>
> Setting the production limit on wells;

Limiting the amount of water produced based on acreage tract size;

Limiting the amount of water that may be produced from a from a defined number of acres assigned to an authorized well site;

Limiting the maximum amount of water that may be produced the basis of acre-feet per acre or gallons per minute per well site per acre;

Managed depletion; or

Any combination of the methods listed above in Paragraphs (a) through (e).

The principle power of a GCD to prevent waste of groundwater is to require that all wells, with certain exceptions, be registered and permitted. Wells with permits are subject to GCD rules governing spacing, production, drilling, equipping, and completion or alteration. Even exempt registered wells are subject to GCD rules governing spacing, tract size, and well construction standards to prevent the unnecessary discharge of groundwater or pollution of the aquifer. Permits may be required by a GCD for all wells except for wells specifically exempted by a GCD and statutorily exempt wells (i.e., wells used solely for domestic use or for providing water for livestock or poultry purposes, the drilling of a water well used solely to supply water for a rig actively engaged in drilling or exploration operations for an oil or gas well permitted by the RRC, and drilling a water well authorized by the RRC for mining activities; Lesikar et al., 2002).

In 1985 the Texas legislature passed House Bill 2, containing provisions for the Texas Water Commission (a predecessor to the TWDB) to identify areas of the state that have critical groundwater problems, such as aquifer depletion, water quality contamination, land subsidence, or shortage of water supply. Accordingly, beginning in

1986, the TWC and the TWDB identified possible critical areas and conducted further studies (Fipps, 2002). Portions of 11 Groundwater Management Agencies are located within the TTMR (TWDB, 2014b).

Groundwater Management Areas were created “to provide for the conservation, preservation, protection, recharging, and prevention of waste of the groundwater, and of groundwater reservoirs or their subdivisions, and to control subsidence caused by withdrawal of water from those groundwater reservoirs or their subdivisions” (Texas Water Code §35.001, Added by Acts 1995, 74th Leg., ch. 933, §2, eff. Sept. 1, 1995).

Beginning in 2005, Texas required, through legislation, that groundwater conservation districts meet regularly and define the “desired future conditions” of the groundwater resources within designated management areas (Vaughn et al., 2012). Based on these desired future conditions, TWDB delivers modeled available groundwater values to groundwater conservation districts and regional water planning groups for inclusion in their plans.

The above discussion illustrates how controlled surface water and groundwater are in the critical zone in Texas, especially in the TTMR. Despite this control regime, the waters in the critical zone are being depleted and degraded at an alarming rate.

Methodology

A copy of the TWDB Groundwater Database was downloaded from the TWDB website in Microsoft Access format. The database contains detailed information on nearly 28,000 wells located throughout the state. The 2,332 wells located in the Carrizo-Wilcox Aquifer (Aquifer ID Code 10) were extracted for analysis.

A separate spreadsheet file was created for each of the 20 GCDs in the database that manage groundwater in the Carrizo-Wilcox aquifer. Four GCDs (Bee, Bluebonnet, Duval County, and Pecan Valley) did not have any wells in the TWDB database. The number of wells available for analysis from the remaining GCDs ranged from 2 (Live Oak and Fayette County) to 1,508 wells (Evergreen).

Once a separate file for each GCD was created, a review was conducted to determine which individual state well records contained sufficient data for further analysis. To be suitable for analysis, each well was required to have 10 years of water level measurements prior to the year the GCD in which the well is located was created and 10 years of water level measurements after that creation date.

Selection of Hydrologic Variables

After a dataset with sufficient history had been established for each GCD, the individual records were standardized by developing annual drawdown data for each well, using the depth or distance from land surface as the standard variable. This was necessary in part because the records in the TWDB database are extremely inconsistent. Some records have consistent annual water level data but most have very inconsistent data and were not suitable for analysis because an insufficient number of depth measurements were available from which to calculate an average annual drawdown. In cases where data were missing for a single year, measurements were averaged from the most recent measurement to establish the average annual drawdown. If more than three consecutive annual measurements were missing from the record, that record was discarded. In cases where multiple measurements existed for the same year, they were averaged to provide a single annual data point for that well.

The entire TWDB Groundwater Database contains 675,350 records from 27,955 wells. There are 50,620 records from 2,332 wells in the Carrizo-Wilcox Aquifer. Of these, 1,315 (56%) contain 10 or fewer records for the entire history of the respective well. Only 358 wells in the Carrizo-Wilcox database have 40 or more water-level measurements. These wells were examined to determine sufficiency inclusion in the final GCD datasets.

Selection of Groundwater Conservation Districts

Twenty-five groundwater conservation districts have boundaries that either partially or fully overlie the Carrizo-Wilcox Aquifer (Figure 20).

A preliminary review of the records demonstrated that only 5% of the records in the database were sufficiently complete to provide enough data for analyzing the period 10 years prior to and 10 years after creation of the GCD. Four of these GCDs (Bee, Bluebonnet, Duval County, and Pecan Valley) were eliminated from consideration for analysis because the TWDB Groundwater Database did not contain any records from these GCDs. Five GCDs (Anderson County, Fayette County, Live Oak, McMullen, and Uvalde County) were eliminated from consideration because the TWDB contained insufficient records to result in a meaningful analysis of the GCD. When all factors regarding data sufficiency were considered, four GCDs were selected for analysis: Brazos Valley, Evergreen, Rusk County, and Wintergarden.

Location of Wells

Table 27 depicts the total number of wells that were examined for each GCD in an initial attempt to determine which wells had sufficient data for further analysis. The table also depicts the total number of wells in each GCD that had more than 40 depth measurements. Wells with more than 40 depth measurements were then screened for inclusion in the study.

Figures 21-24 show the geographic location of each well identified by State Well Number (SWN).

Trend Detection

Exploratory data analysis (Kundzewicz & Robson, 2012) of each of the four GCDs was used to provide an advanced visual examination of the data. Data were developed to determine the average annual drawdown for equal periods prior to and after creation of the respective GCD. The average annual drawdown for the pre/post GCD analysis period and the average annual drawdown for the entire period of record for each well were also determined.

The average annual drawdown data for each GCD were also analyzed using a *t* test to provide a *p* value for statistical significance. The Wilcoxon-Mann-Whitney test was used for those GCDs that were determined to have nonnormal distribution of drawdown data. According to Kundzewicz and Robson (2012), this rank-based test that assumes time of change is known (GCD establishment year) and looks for differences between two independent sample groups.

Table 27

Summary of Wells Selected for Analysis, by Groundwater Conservation District (GCD)

District	Year GCD enacted	Total wells in TWDB GWDB	Total wells with > 40 measurements
Anderson County UWCD	1987	4	0
Bee GCD	-[a]	-	-
Bluebonnet GCD	-	-	-
Brazos Valley GCD	1999	266	14
Duval County GCD	-	-	-
Edwards Aquifer Authority	1996	181	6
Evergreen UWCD	1965	1,508	68
Fayette County GCD	2001	2	0
Gonzales County UWCD	1993	181	12
Guadalupe County GCD	1997	194	6
Live Oak UWCD	1989	2	0
Lost Pines GCD	1999	621	17
McMullen GCD	1999	29	4
Medina County GCD	1989	348	7
Mid-East Texas GCD	2001	517	8
Neches & Trinity Valleys GCD	2001	762	12
Panola County GCD	2007	154	7
Pecan Valley GCD	-	-	-
Pineywoods GCD	2001	347	49
Plum Creek CD	1989	195	11

Table 27 (continued)

District	Year GCD enacted	Total wells in TWDB GWDB	Total wells with > 40 measurements
Post Oak Savannah GCD	2001	271	5
Rusk County GCD	2003	371	28
Uvalde County UWCD	1993	6	1
Wintergarden GCD	1997	1,124	103

Note. TWDB = Texas Water Development Board, GWDB = Groundwater Database, GCD = Groundwater Conservation District, CD = Conservation District, UWCD = Underground Water Conservation District.

[a] No data in TWDB Groundwater Database.

Change-point analysis (Change-Point Analyzer© software; Taylor, 2000) was conducted on average annual drawdown data from each well. Change-point analysis is a powerful tool for detecting subtle changes in historical data. The tool is designed to detect small, sustained changes and is robust in characterizing those changes (Taylor, 2000). The procedure adopted by Taylor uses a combination of bootstrapping and cumulative sum charts (CUMSUM) to identify changes.

Application of the Methodology

This study to detect trends in average annual drawdown subsequent to creation of a GCD was performed on Brazos Valley, Evergreen, Rusk County, and Wintergarden districts. The boundaries of all of these GCDs overlie the Carrizo-Wilcox Aquifer. Figures 21 through 24 show the location of each well within the respective GCDs.

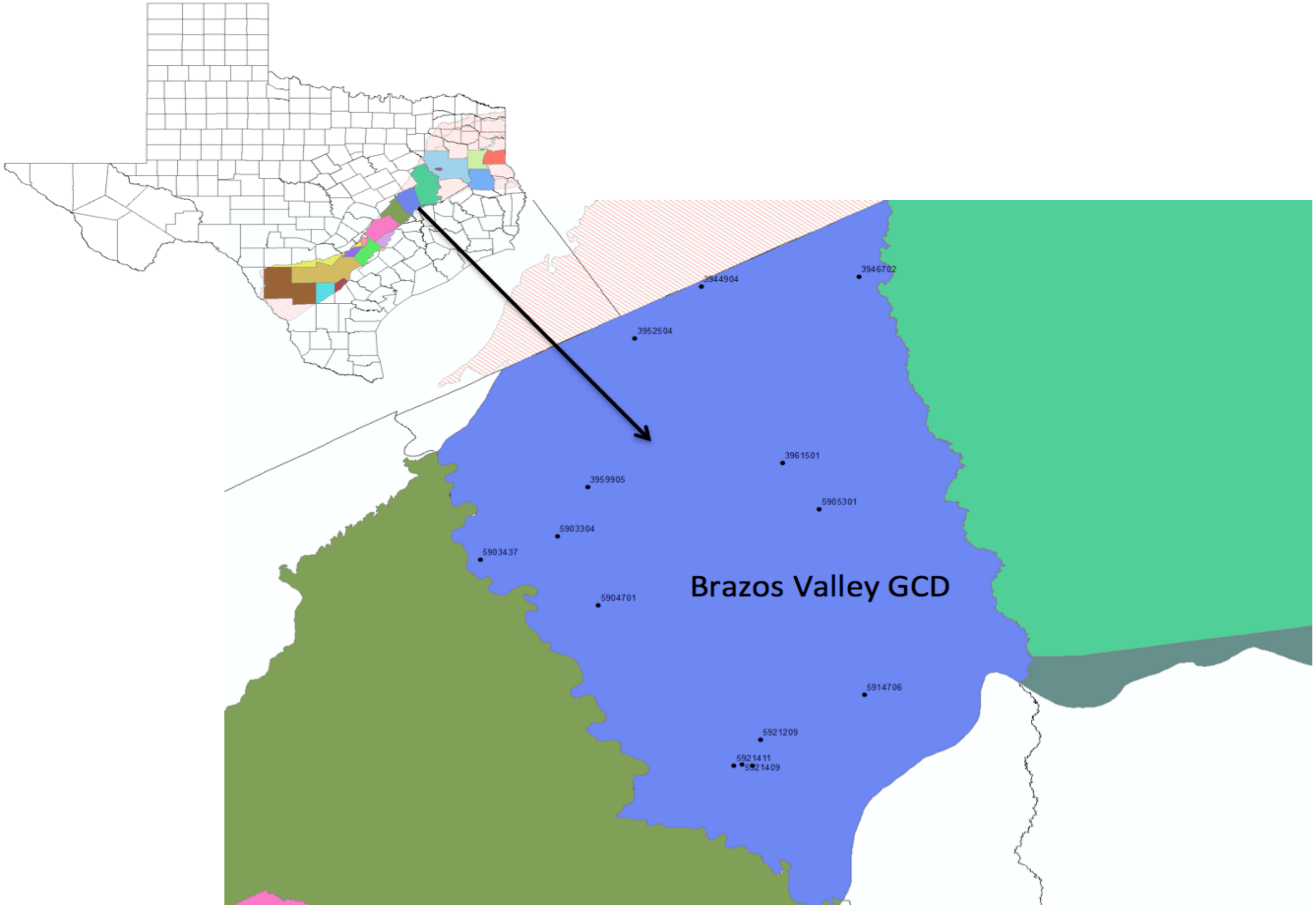


Figure 21. Map of wells analyzed in Brazos Valley Groundwater Conservation District.

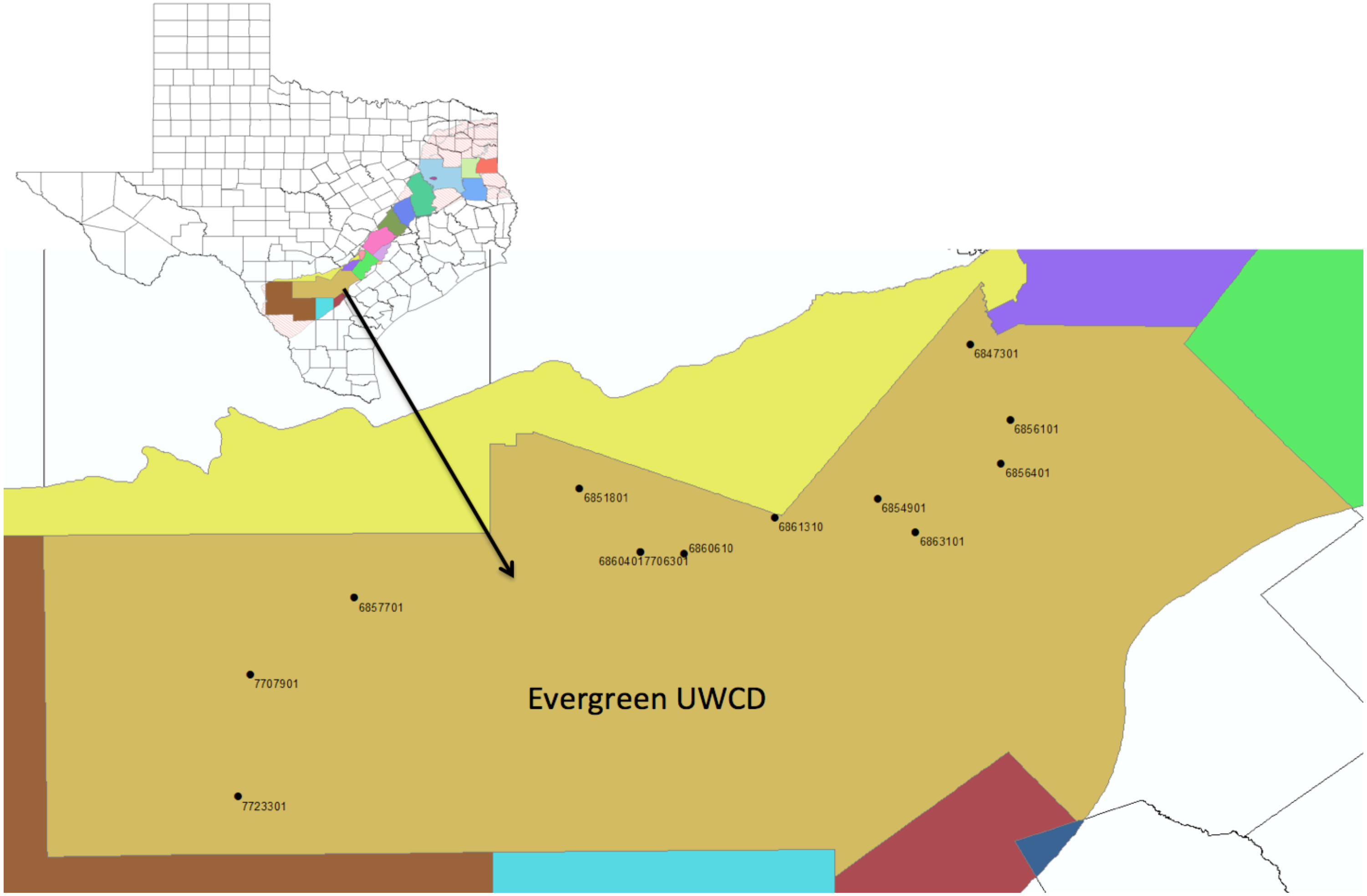


Figure 22. Map of wells analyzed in Evergreen Groundwater Conservation District.

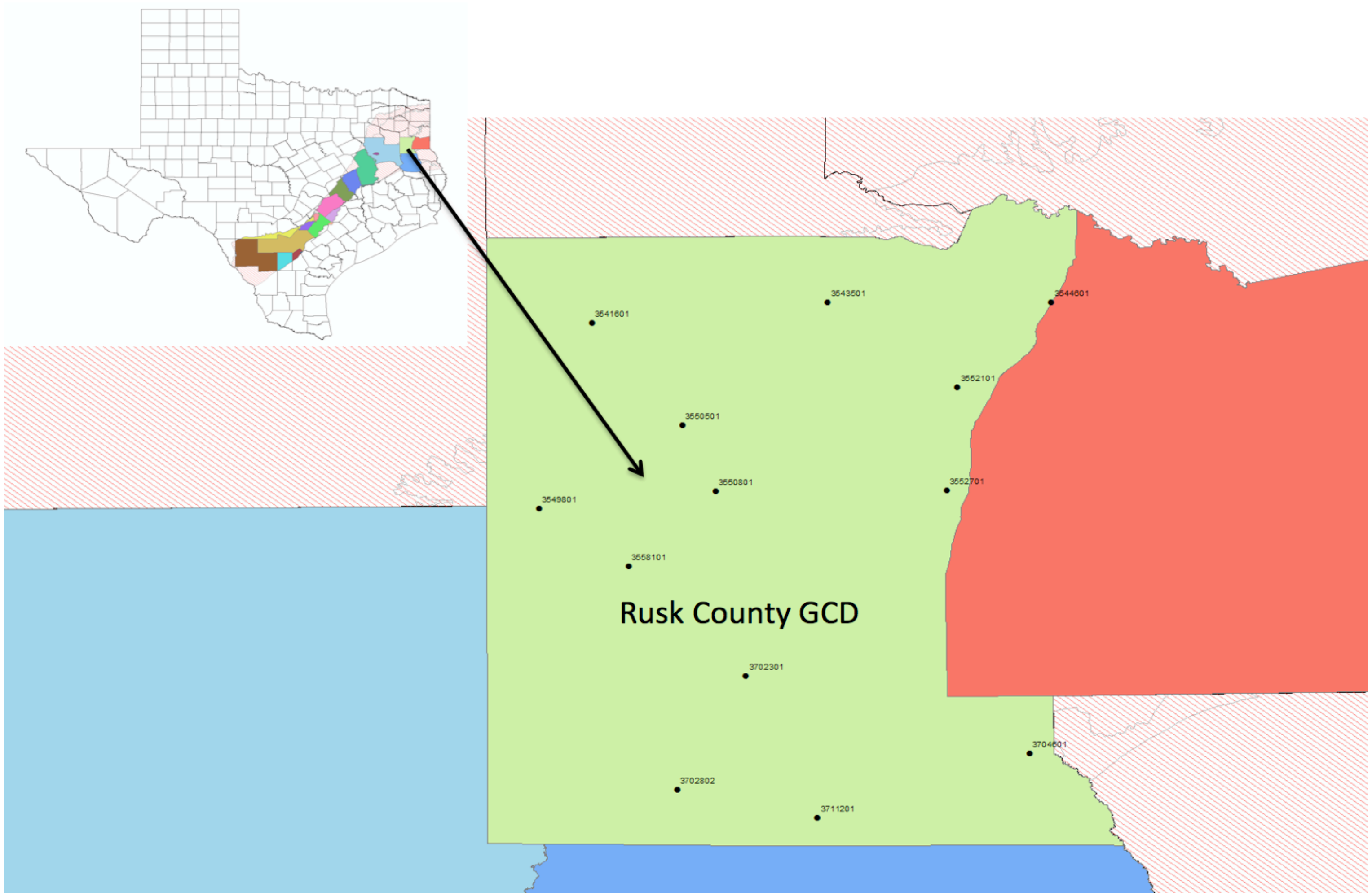


Figure 23. Map of wells analyzed in Rusk County Groundwater Conservation District.

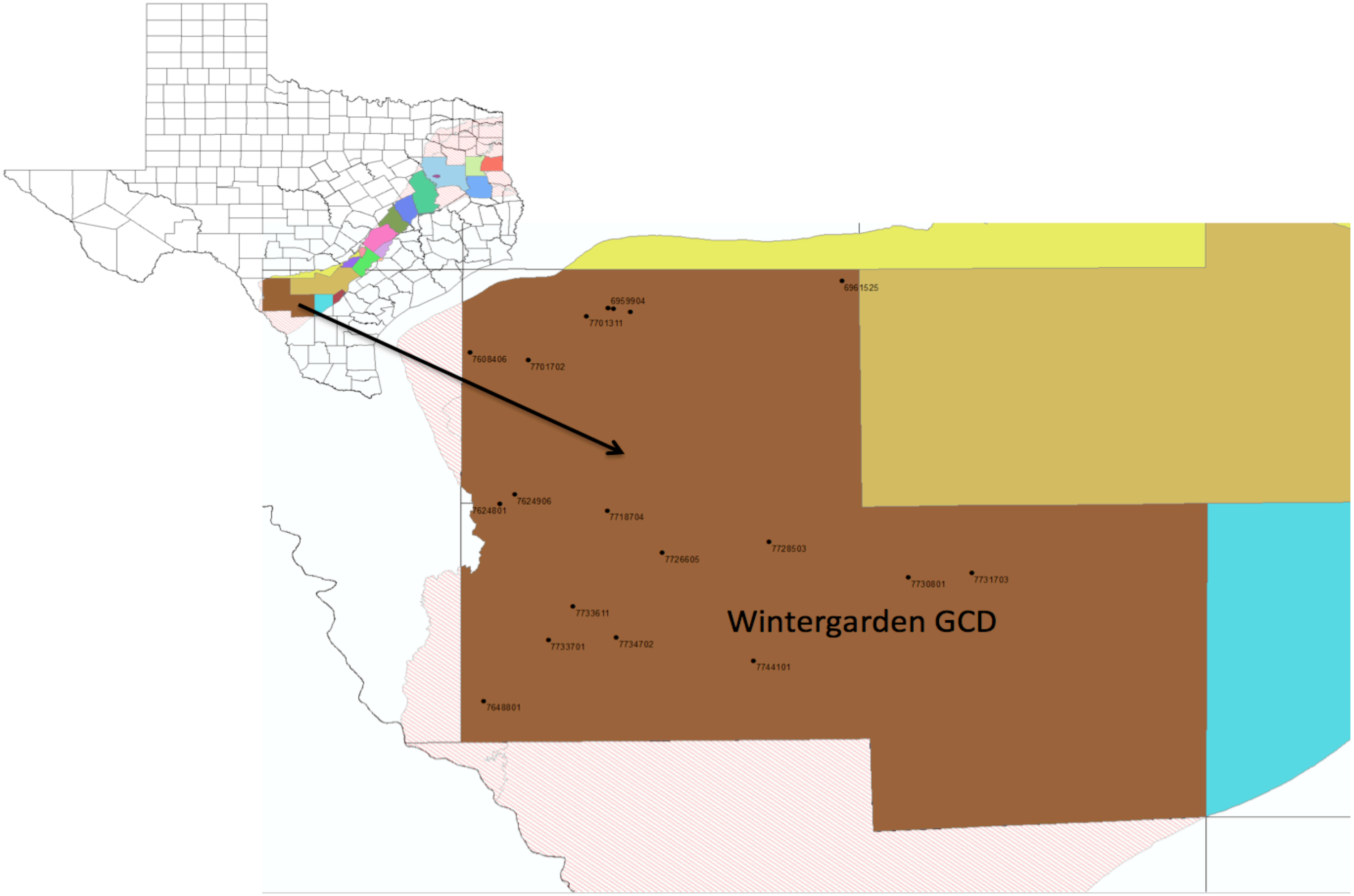


Figure 24. Map of wells analyzed in Womtergardem Groundwater Conservation District.

The periods of analysis for each GCD are listed in Table 28. If data were not available for the entire period, a shorter period of analysis was used as shown in Figures 25 through 28, which depicts detailed analysis data for each well, by SWN.

Table 28

Time Data Summary by Groundwater Conservation District (GCD)

GCD	Year created	Maximum period of well-specific record	GCD analysis period
Brazos Valley	1999	1971–2013	1985–2014
Evergreen	1965	1929–2010	1949–1984
Rusk County GCD	2003	1939–2013	1993–2013
Wintergarden GCD	1997	1930–2014	1985–2013

Results

Exploratory Data Analysis

Exploratory data analysis showed that drawdown decreased in 46.67% of the wells in the study after establishment of the GCD and increased in 53.33% of the wells. The most favorable results were in the Evergreen GCD: average annual drawdown decreased in 84.62% of the wells and increased in 15.38%. The least favorable results were in Wintergarden GCD, where average annual drawdown decreased in 25% of the selected wells and increased in 75% of the selected wells. Table 29 summarizes the exploratory data analysis. Figures 25 through 28 show results of exploratory data analysis for each GCD.

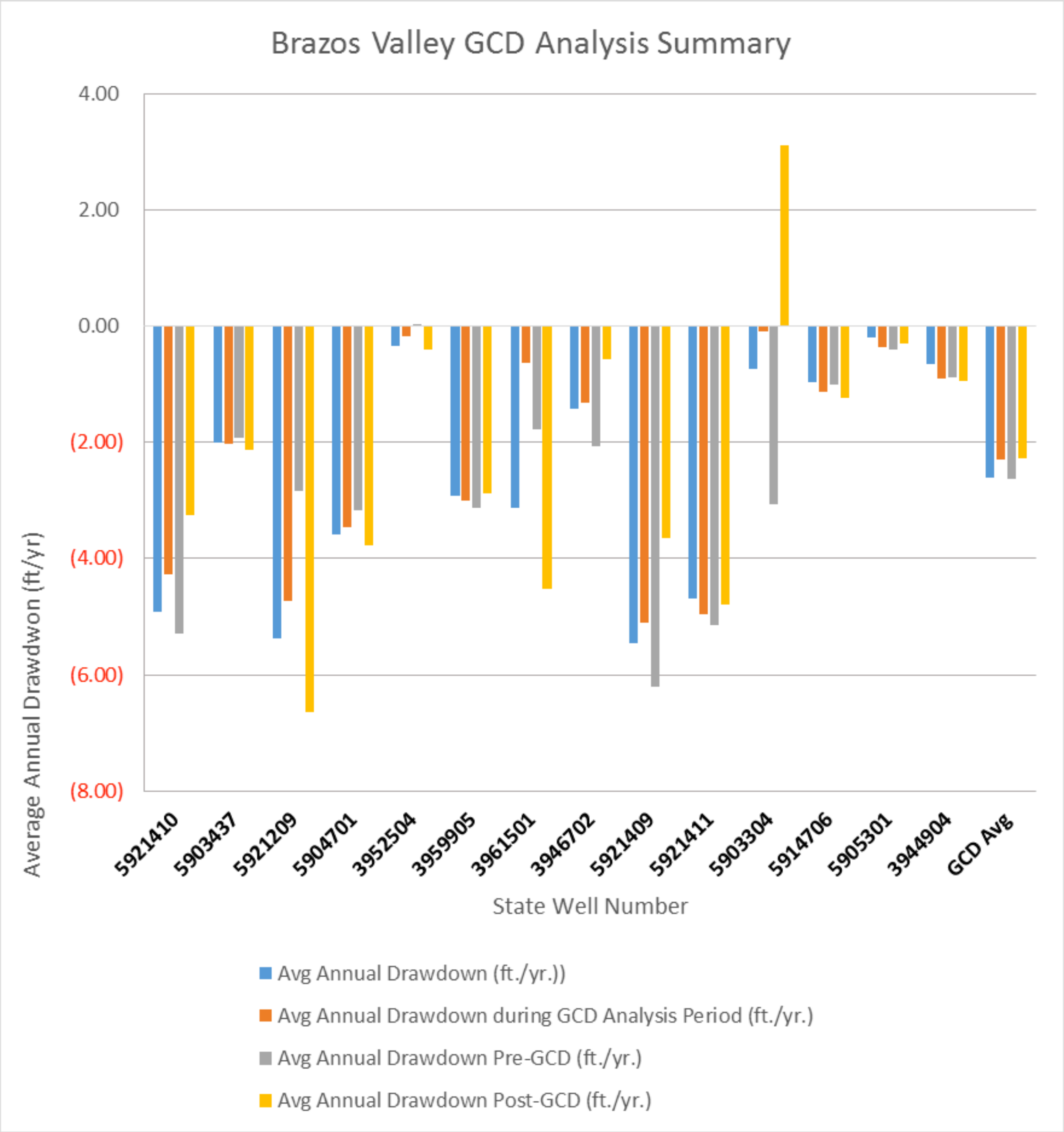


Figure 25. Brazos Valley Groundwater Conservation District analysis summary.

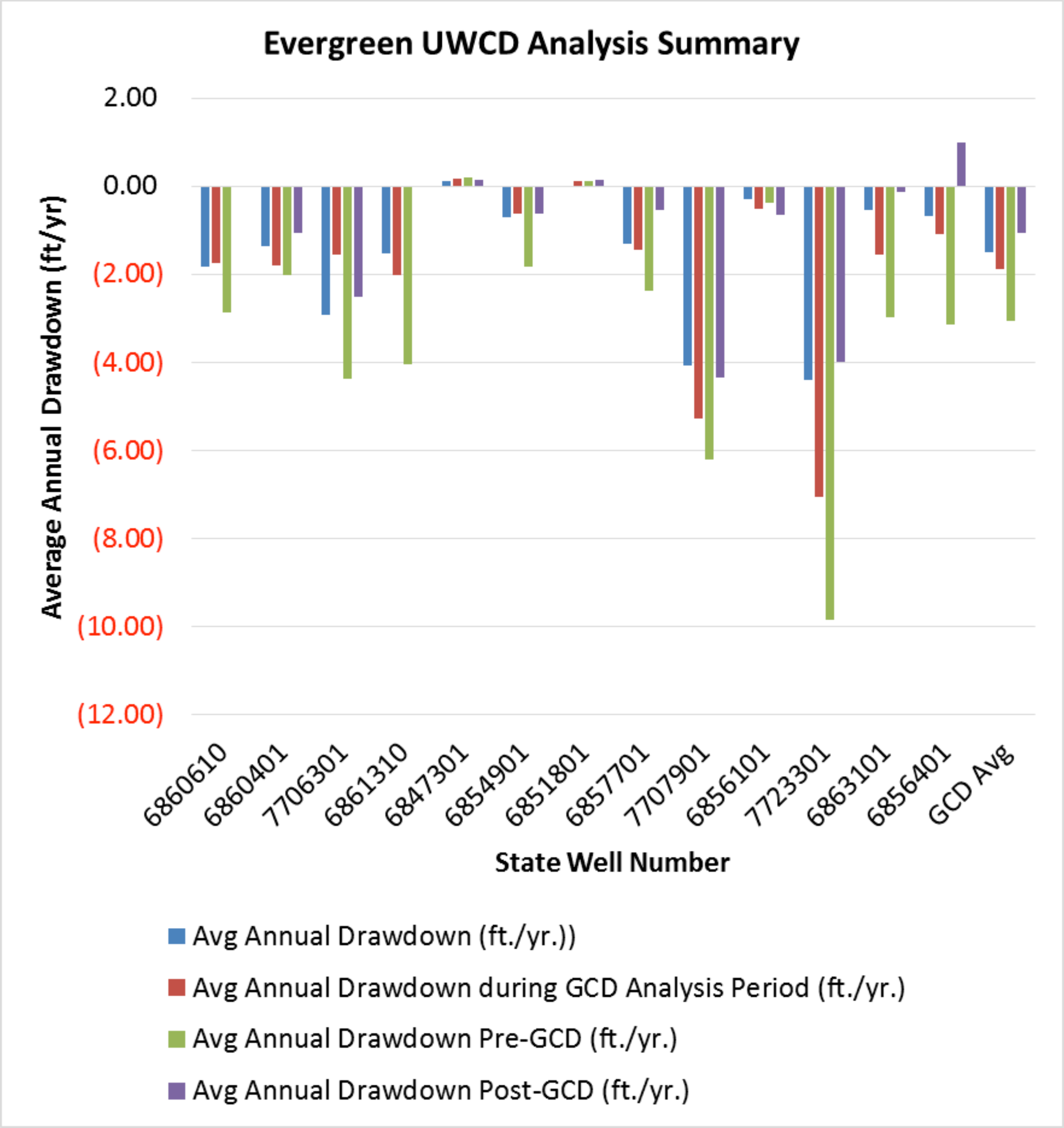


Figure 26. Evergreen Underground Water Conservation District analysis summary.

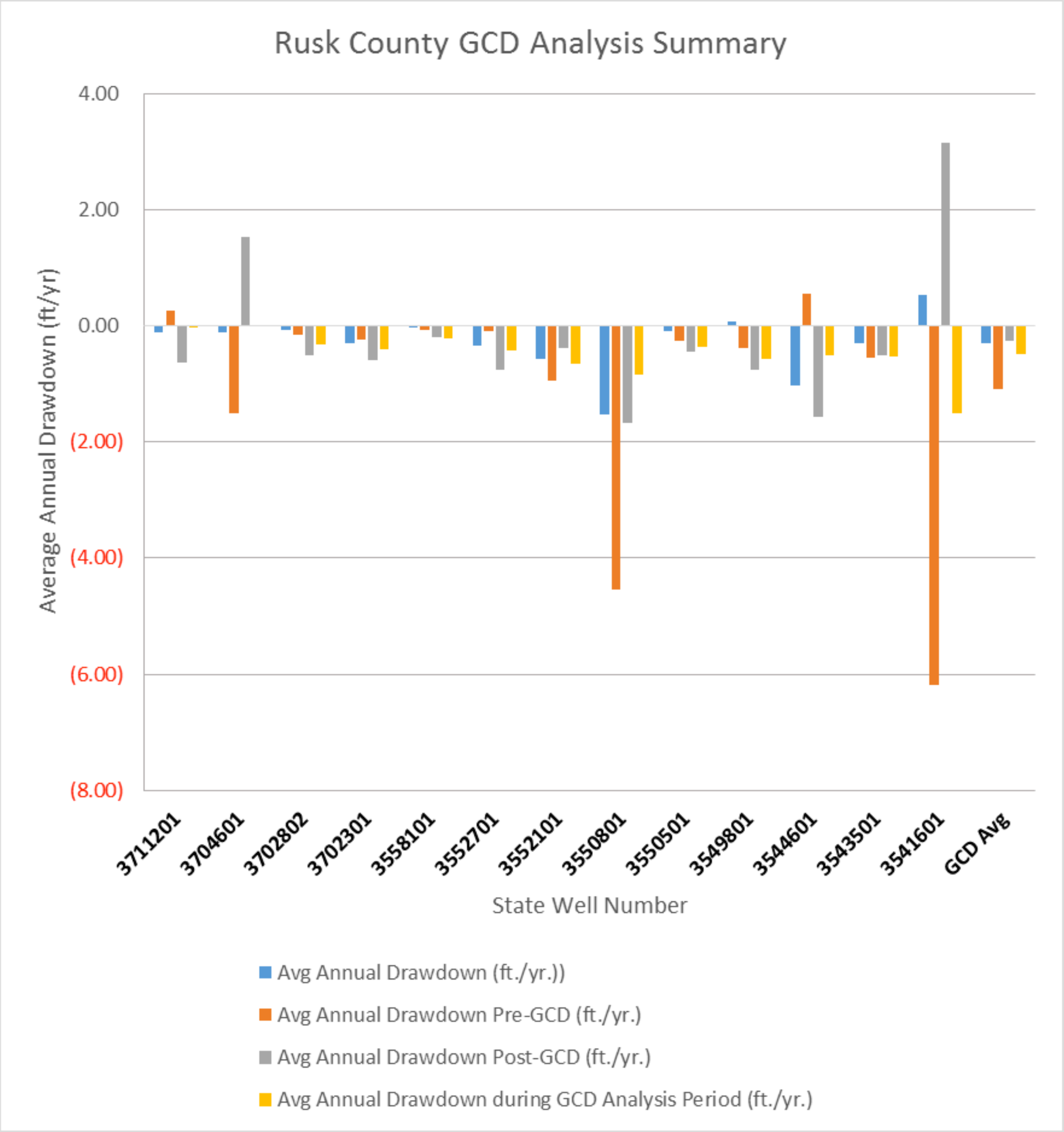


Figure 26. Rusk County Groundwater Conservation District analysis summary.

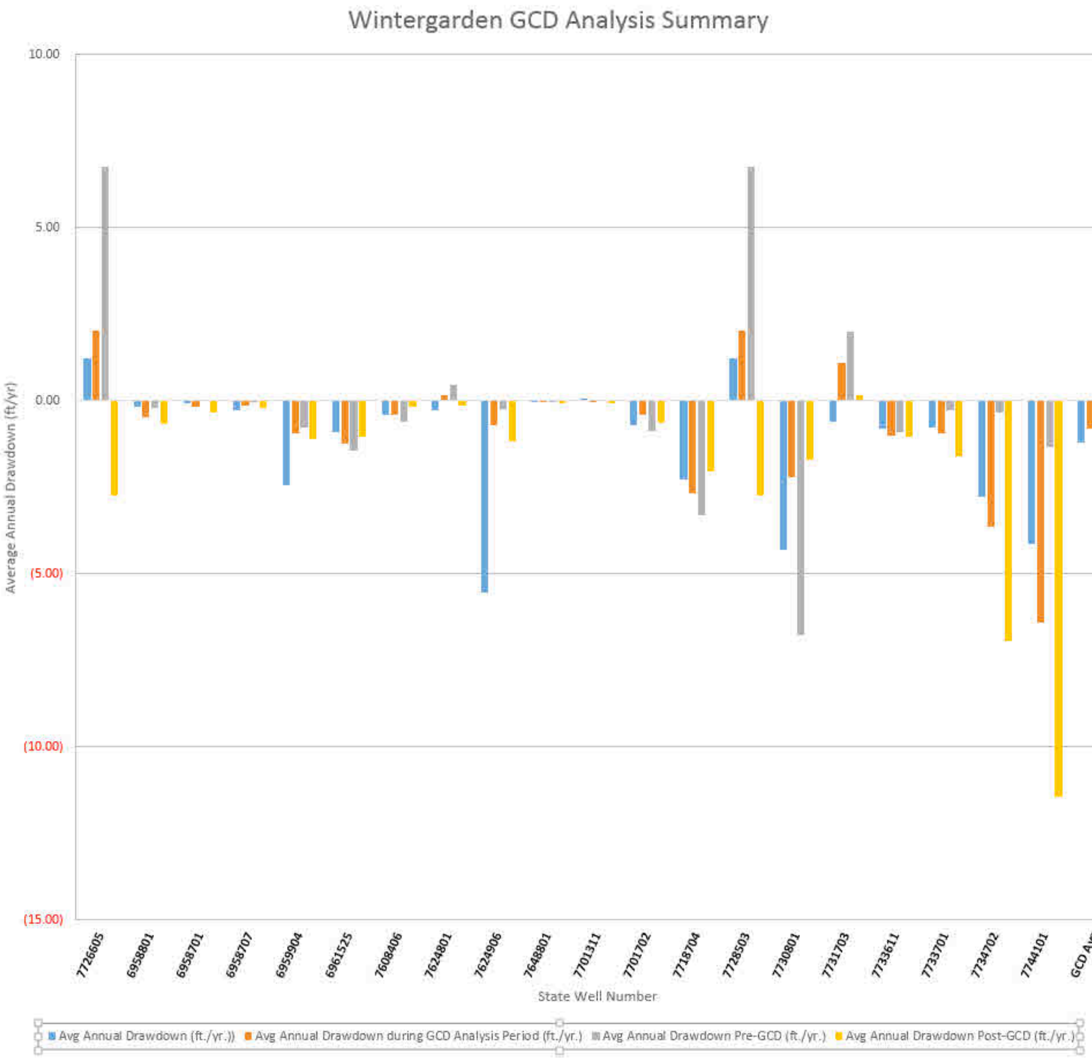


Figure 28. Wintergarden Groundwater Conservation District analysis summary.

Table 29

Summary of Exploratory Data Analysis by Groundwater Conservation District (GCD)

GCD	GCD ID	Number of wells sampled	Decreased drawdown	Increased drawdown	% with expected response	% that did not respond as as expected
Brazos Valley	199912GX	14	7	7	50.00	50.00
Evergreen	196513KX	13	11	2	84.62	15.38
Rusk County	200311IX	13	5	8	38.46	61.54
Wintergarden	199713LX	20	5	15	25.00	75.00
Total		60	28	32	46.67	53.33

Tests for Statistical Significance

Table 30 shows results of *t* tests and/or Wilcoxon-Mann-Whitney tests that were performed on data from each GCD. The Wilcoxon test was used in those instances where the distribution of the data from a GCD was nonnormal. The test results were statistically significant in two of the four GCDs (Evergreen and Wintergarden), indicating that the difference in drawdown before and after the creation of the GCD was statistically significant. In the case of Wintergarden GCD, the trend was toward significantly increased drawdown of aquifer levels after the GCD was created.

Change Point Analysis Summary by GCD

Brazos Valley GCD. Change point analysis of Brazos Valley GCD (shown in Table 31) indicated that detectable changes occurred in average annual drawdown in 4 of

Table 30

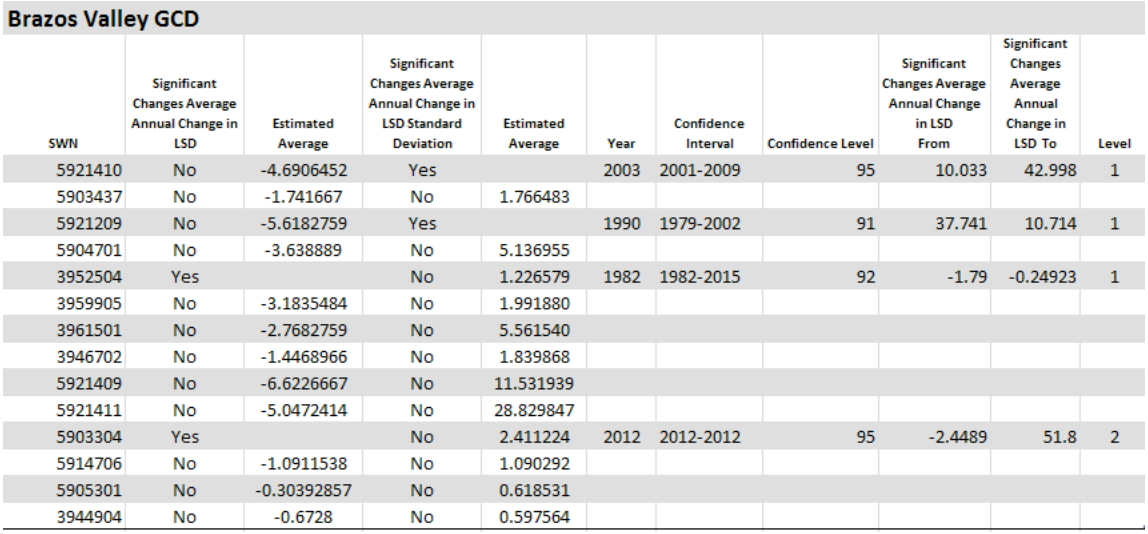
Summary of Results of Statistical Tests

Groundwater Conservation District (GCD)	Goodness of Fit Prov < W	*t*	Wilcoxon-Mann-Whitney	Significant?
Brazos Valley	.6626	0.6535		No
Evergreen	.0036	0.0313*	0.0483*	Yes
Rusk County	.0001	0.2230	0.6260	No
Wintergarden	.0001	0.0613	0.0411*	Yes

Note. Significance = $p < .05$.

Table 31

Brazos Valley Groundwater Conservation District (GCD) Change Point Analysis Summary



Brazos Valley GCD

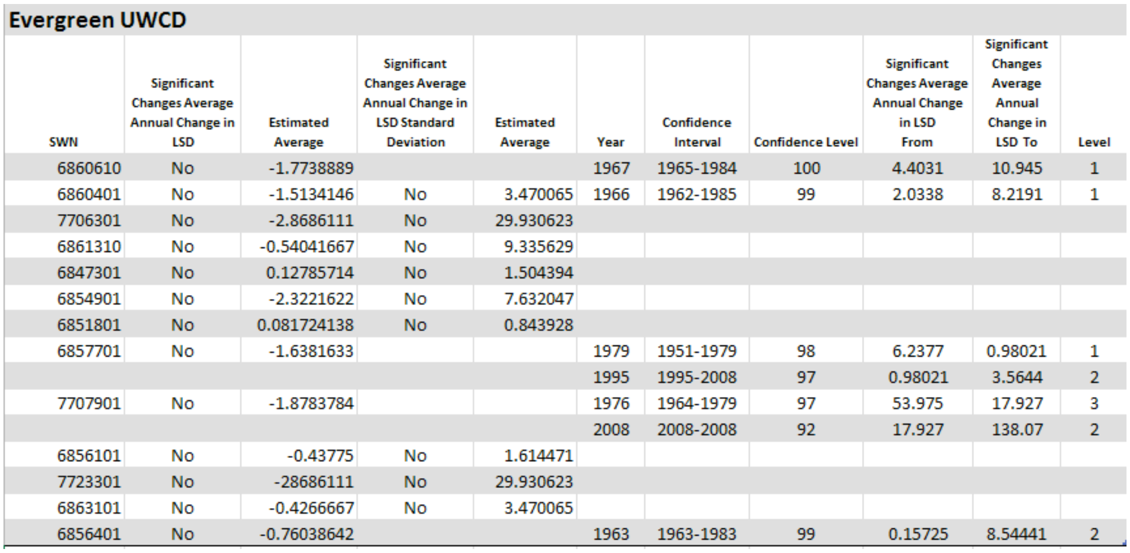
SWN	Significant Changes Average Annual Change in LSD	Estimated Average	Significant Changes Average Annual Change in LSD Standard Deviation	Estimated Average	Year	Confidence Interval	Confidence Level	Significant Changes Average Annual Change in LSD From	Significant Changes Average Annual Change in LSD To	Level
5921410	No	-4.6906452	Yes		2003	2001-2009	95	10.033	42.998	1
5903437	No	-1.741667	No	1.766483						
5921209	No	-5.6182759	Yes		1990	1979-2002	91	37.741	10.714	1
5904701	No	-3.638889	No	5.136955						
3952504	Yes		No	1.226579	1982	1982-2015	92	-1.79	-0.24923	1
3959905	No	-3.1835484	No	1.991880						
3961501	No	-2.7682759	No	5.561540						
3946702	No	-1.4468966	No	1.839868						
5921409	No	-6.6226667	No	11.531939						
5921411	No	-5.0472414	No	28.829847						
5903304	Yes		No	2.411224	2012	2012-2012	95	-2.4489	51.8	2
5914706	No	-1.0911538	No	1.090292						
5905301	No	-0.30392857	No	0.618531						
3944904	No	-0.6728	No	0.597564						

14 wells (SWNs 5921410, 5921209, 3952504, and 5903304). SWN 5921410 experienced a change in average annual drawdown from 10.033 ft/yr to 42.998 ft/yr sometime around 2003. This represents a rather sizeable increase in drawdown that came 14 years after the creation of the GCD. SWN 5921209 recorded a significant decrease in the annual drawdown rate around 1990. Since this change came approximately 10 years prior to the creation of the GCD, it cannot be attributed to policies implemented by the GCD. SWN 3952504 recorded a very modest decrease in drawdown, but the confidence interval began more than a decade prior to creation of the GCD and cannot be attributed to policies implanted by the GCD. SWN 5903304 recorded a 51.80-foot decrease in distance from land surface in 2012. Since this was the last year that a measurement was taken on that well and this single measurement is significantly outside of what is within the normal drawdown range for that particular well, the change requires further examination.

Evergreen UWCD. Change point analysis of Evergreen UWCD (shown in Table 32) indicate that detectable changes occurred in average annual drawdown in 5 of 13 wells (SWNs 6860610, 6860401, 6857701, 7707901, and 6856401). SWN 6860610 recorded a positive change in 1967, which could have been the result of GCD action because the GCD was enacted in 1965. SWN 6860401 recorded a change around 1966, but close examination of the associated CUMSUM chart suggests that the change occurred prior to implementation of the GCD. SWN 7707901 recorded two changes. The first occurred prior to creation of the GCD and the second occurred 30 years after creation of the GCD, so neither can be attributable to rules enacted by the GCD. SWN

Table 32

Evergreen Underground Water Conservation District Change Point Analysis Summary



Evergreen UWCD

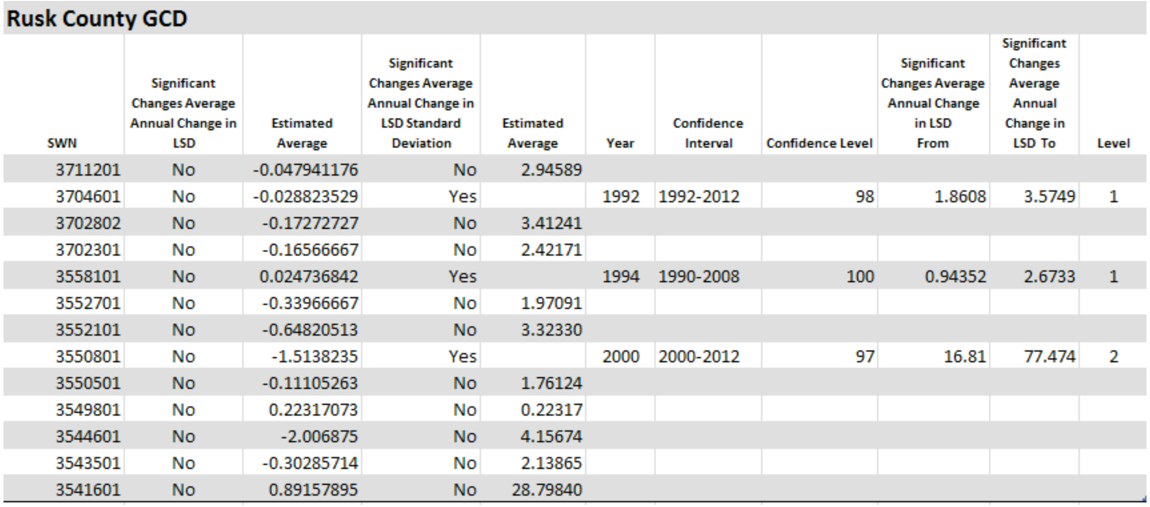
SWN	Significant Changes Average Annual Change in LSD	Estimated Average	Significant Changes Average Annual Change in LSD Standard Deviation	Estimated Average	Year	Confidence Interval	Confidence Level	Significant Changes Average Annual Change in LSD From	Significant Changes Average Annual Change in LSD To	Level
6860610	No	-1.7738889			1967	1965-1984	100	4.4031	10.945	1
6860401	No	-1.5134146	No	3.470065	1966	1962-1985	99	2.0338	8.2191	1
7706301	No	-2.8686111	No	29.930623						
6861310	No	-0.54041667	No	9.335629						
6847301	No	0.12785714	No	1.504394						
6854901	No	-2.3221622	No	7.632047						
6851801	No	0.081724138	No	0.843928						
6857701	No	-1.6381633			1979	1951-1979	98	6.2377	0.98021	1
					1995	1995-2008	97	0.98021	3.5644	2
7707901	No	-1.8783784			1976	1964-1979	97	53.975	17.927	3
					2008	2008-2008	92	17.927	138.07	2
6856101	No	-0.43775	No	1.614471						
7723301	No	-28686111	No	29.930623						
6863101	No	-0.4266667	No	3.470065						
6856401	No	-0.76038642			1963	1963-1983	99	0.15725	8.54441	2

7707901 experienced a change in 1976 and another in 2008. In both cases, the trends were not reflective of effective GCD rules if those changes can even be attributed to creation of the GCD. SWN 6856401 recorded a change in 1976 (9 years after creation of the GCD), reversing a trend of increasing drawdown that began in 1963. This could be attributed to a positive impact of the GCD.

Rusk County GCD. Change point analysis of Rusk County GCD (shown in Table 33) indicated detectable changes in average annual drawdown in 3 of 13 wells (SWNs 3704601, 3558101, and 3550801). The change in SWN 3704601 was first detected in 1992, prior to establishment of the GCD in 2003. Similarly, a change was detected in SWN 3558101 in 1994, prior to establishment of the GCD. The change detected in SWN 3550801 in 2000 was also prior to establishment of the GCD.

Table 33

Rusk County Groundwater Conservation District Change Point Analysis Summary



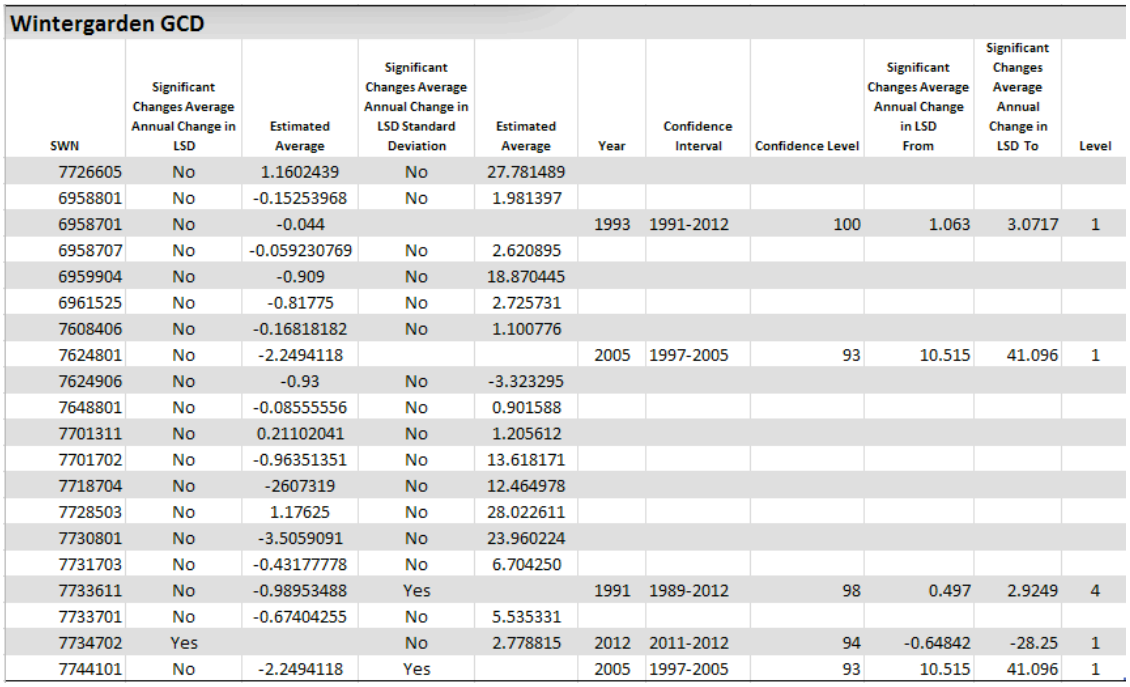
Rusk County GCD

SWN	Significant Changes Average Annual Change in LSD	Estimated Average	Significant Changes Average Annual Change in LSD Standard Deviation	Estimated Average	Year	Confidence Interval	Confidence Level	Significant Changes Average Annual Change in LSD From	Significant Changes Average Annual Change in LSD To	Level
3711201	No	-0.047941176	No	2.94589						
3704601	No	-0.028823529	Yes		1992	1992-2012	98	1.8608	3.5749	1
3702802	No	-0.17272727	No	3.41241						
3702301	No	-0.16566667	No	2.42171						
3558101	No	0.024736842	Yes		1994	1990-2008	100	0.94352	2.6733	1
3552701	No	-0.33966667	No	1.97091						
3552101	No	-0.64820513	No	3.32330						
3550801	No	-1.5138235	Yes		2000	2000-2012	97	16.81	77.474	2
3550501	No	-0.11105263	No	1.76124						
3549801	No	0.22317073	No	0.22317						
3544601	No	-2.006875	No	4.15674						
3543501	No	-0.30285714	No	2.13865						
3541601	No	0.89157895	No	28.79840						

Wintergarden GCD. Change point analysis of Wintergarden GCD (shown in Table 34) indicated that detectable changes occurred in average annual drawdown in 5 of 20 wells (SWNs 6958701, 7624801, 7733611, 7734702, and 7744101). A change recorded in annual average drawdown in SWN 6958701 occurred in 1993, prior to creation of the GCD, and the detected trend showed that average drawdown began to decrease during that period and continued through 2012. A change detected in SWN7624801 began in 2005 but the trend was toward increasing drawdown. A change was detected in SWN 7733611 in 1991, prior to creation of the GCD. A change recorded in SWN 7734702 occurred in 2012, but this trend also indicated significantly increased drawdown. A change detected in SWN 7744101 occurred in 2005, but it was toward significantly increased drawdown.

Table 34

Wintergarden Groundwater Conservation District Change Point Analysis Summary



Wintergarden GCD

SWN	Significant Changes Average Annual Change in LSD	Estimated Average	Significant Changes Average Annual Change in LSD Standard Deviation	Estimated Average	Year	Confidence Interval	Confidence Level	Significant Changes Average Annual Change in LSD From	Significant Changes Average Annual Change in LSD To	Level
7726605	No	1.1602439	No	27.781489						
6958801	No	-0.15253968	No	1.981397						
6958701	No	-0.044			1993	1991-2012	100	1.063	3.0717	1
6958707	No	-0.059230769	No	2.620895						
6959904	No	-0.909	No	18.870445						
6961525	No	-0.81775	No	2.725731						
7608406	No	-0.16818182	No	1.100776						
7624801	No	-2.2494118			2005	1997-2005	93	10.515	41.096	1
7624906	No	-0.93	No	-3.323295						
7648801	No	-0.08555556	No	0.901588						
7701311	No	0.21102041	No	1.205612						
7701702	No	-0.96351351	No	13.618171						
7718704	No	-2607319	No	12.464978						
7728503	No	1.17625	No	28.022611						
7730801	No	-3.5059091	No	23.960224						
7731703	No	-0.43177778	No	6.704250						
7733611	No	-0.98953488	Yes		1991	1989-2012	98	0.497	2.9249	4
7733701	No	-0.67404255	No	5.535331						
7734702	Yes		No	2.778815	2012	2011-2012	94	-0.64842	-28.25	1
7744101	No	-2.2494118	Yes		2005	1997-2005	93	10.515	41.096	1

Summary of Trends

Approximately 47% of the wells recorded a decrease in average annual drawdown after the creation of a GCD and 53% recorded increased drawdown. In the case of Evergreen, a positive impact on drawdown clearly occurred after creation of the GCD, with a statistically significant drawdown recorded in approximately 85% of the wells. On the other hand, there was a statistically significant increase in average annual drawdown in the Wintergarden GCD. Results of pre/post GCD comparisons in Brazos Valley GCD and Rusk County GCD were not statistically significant and did not demonstrate a clear trend.

Changepoint analysis of the average annual drawdown data for equal periods prior to and after creation of the GCD did not indicate trends that would suggest a positive correlation between establishment of a GCD and its impact on annual average drawdown. Whereas unexpected changes were detected in approximately 20% of the wells, no trends were present that would indicate a correlation between these changes and the presence of a GCD.

Conclusions and Recommendations

The results of this study showed that, generally, no difference occurred in aquifer drawdown rates after creation of a GCD. Whereas approximately 47% of the wells recorded a decrease in average annual drawdown after creation of a GCD, 53% actually recorded increased drawdown. In the case of Evergreen, a positive impact on drawdown clearly occurred after creation of the GCD. More study is required to determine whether this change is the result of rules implemented by the GCD or the result of some other economic, agricultural, or environmental change. In the Wintergarden GCD, the average annual drawdown increased in three fourths of the wells examined, suggesting that implementation of the GCD did not have a positive impact on drawdown. This could mean that the rules implanted by the GCD were not enforced, that demand for groundwater increased significantly over historical use, or that climatic conditions affected aquifer levels, among other reasons.

This study was limited by availability of consistent, long-term water-level measurement data from the TWDB groundwater database. With 2,332 wells overlying the Carrizo-Wilcox Aquifer, approximately 5% had data with sufficient consistency and longevity to perform a meaningful assessment.

This study did not take into account environmental factors such as drought and climate change. Nor did it factor in changes in land use or population increases, either or both of which could affect aquifer drawdown and recharge. This study was designed only to determine whether a measureable difference occurred in drawdown between the pre- and post-GCD establishment periods. It did not take into account the idea of managed drawdown in which the groundwater resources of a district are drawn down at a predetermined rate deemed acceptable to the GCD administrators.

Further study is required to include additional GCDs from other major aquifers in Texas. These future studies should take into account changes in population, environmental factors, and land use changes to determine the utility of GCDs in Texas.

CHAPTER V

DISCUSSION AND CONCLUSIONS

Discussion

In the United States, more than 80% of the population now lives in urban areas. By 2050, a significant portion of that population will live in megaregions consisting of two or more metropolitan areas linked with interdependent environmental systems, a multimodal transportation infrastructure, and complementary economies.

The metropolitan areas of Dallas-Fort Worth, Austin, San Antonio, and Houston, with a total land size of nearly 35,435 square kilometers, spatially delineate the TTMR, one of 8 to 10 such regions in the United States. Supporting the modern industrial infrastructure of a major metropolitan megaregion has required extensive water-related modifications to the critical zone. These modifications come in the form of an extensive network of dams and reservoirs; a high-density matrix of wells for extracting water, oil, and gas from the critical zone; significant land cover alterations; and interbasin transfer of ground and surface water. Progressive depletion of critical zone reserves threatens sustainable development in the heavily groundwater dependent TTMR and requires robust and effective groundwater water policy for the megaregion to remain economically viable.

Groundwater is a critically important water resource in Texas, making up nearly 60% of the water needs in the state (Vaughn et al., 2012). Facing growth that is expected to double the population of the state to more than 46 million by 2060, Texas has increased its efforts to implement comprehensive water resources planning during the past decade (Vaughn et al., 2012). State policy in Texas dictates that groundwater management is best accomplished through locally elected, locally controlled GCDs. Any modification or limitation to the “rule of capture”—which says that the landowner may withdraw groundwater without limitations and without liability for losses to neighbors’ wells so long as water is not wasted or taken maliciously—will be made by local GCDs (Vaughn et al., 2012).

According to the TWDB, water is the single most significant limiting factor to future economic growth in Texas (Vaughn et al., 2012). Without coordinated action, the state could face economic losses exceeding $98.4 billion annually by 2060 and 85% of the population of Texas will not have enough water during drought conditions (TWDB, 2007). Even though the importance of groundwater to the health of the Texas economy is undisputed and local control of groundwater is state policy, little research has been conducted to measure the effectiveness of that policy. This study was a preliminary step in measuring the effectiveness of groundwater allocation methods used by GCDs overlying the Carrizo-Wilcox Aquifer in Texas.

Four research questions guided the study:

1. Does a measurable difference exist in the rate of decline in aquifer levels after the establishment of a GCD?

2. Do individual groundwater allocation methods implemented by GCDs produce measurable decreases in the rates of decline in aquifer levels?

3. Does the length of time a GCD has been in effect result in a measurable decrease in the rate of decline in aquifer levels?

4. What is the impact of urbanization on groundwater resources of the Carrizo-Wilcox Aquifer?

Conclusions

Analysis of the data in this study lead to four conclusions.

1. Generally, no difference in aquifer drawdown rates occurred after creation of a GCD. Whereas approximately 47% of the wells recorded a decrease in average annual drawdown after creation of a GCD, 53% actually recorded increased drawdown. In the case of three of the GCDs analyzed in this study (Evergreen, McMullen County, and Pineywoods), a positive impact on drawdown clearly occurred after creation of the GCD, with a statistically significant change in drawdown recorded in approximately 85% of the wells in those GCDs.

A statistically significant increase in average annual drawdown occurred in three fourths of the wells examined in the Wintergarden GCD. This suggests that implementation of the GCD did not have a positive impact on drawdown. The results could mean that the rules enacted by the GCD were not enforced, that demand for groundwater increased significantly over historical use, or that climatic conditions were impacting aquifer levels, among other reasons. Results of pre/post GCD comparisons in the nine other GCDs were not statistically significant and did not demonstrate a clear trend during exploratory data analysis.

2. No correlation between groundwater allocation methods and average annual rates of decline in aquifer levels could be established. In the four GCDs where the results were statistically significant, there was not a common trend in the methods that the

GCDs used for allocating groundwater. Both Evergreen and McMullen County GCDs established production limits based on acreage or tract size and first in time, first in right. Pineywoods GCD established production limits based on spacing and historical use. Wintergarden GCD established production limits based on spacing and acreage or tract size. More study is required to determine whether the statistical significance of the change in drawdown was the result of rules implemented by the GCD or the result of some other economic, agricultural, or environmental change.

3. This study did not demonstrate any correlation between the length of time a GCD had been in existence and its impact on groundwater levels. Whereas the results of analysis on Evergreen, created in 1965, showed that a statistically significant decrease occurred in average annual drawdown in 85% of the wells sampled, McMullen County GCD (established in 1999) and Pineywoods GCD (established in 2001) demonstrated similar results.

4. The impact of urbanization on groundwater resources of the Carrizo-Wilcox Aquifer will be significant. Already the fastest-growing region of Texas, the 65 counties of the TTMR will have a projected population of 38.5 million people by 2070 and will account for more than 80% of the total population in Texas (Neuman et al., 2010). According to the 2011 National Land Cover Database (Jin et al., 2013), approximately 14% of the total surface area of the TTMR is already developed to some degree, with approximately 4% of that area being medium- or high-intensity development.

Throughout Texas, landowners and municipalities have depended on groundwater as a primary water resource because of local availability and quality

(Vaughn et al., 2012). Groundwater provides about 60% of the 19.86 cubic kilometer (16.1 million acre-feet) of water used in the state each year (Fipps, 2002; Levasseur, 2012; Vaughn et al., 2012). The TWDB (Vaughn et al., 2012) has predicted that, over the next 50 years, agricultural use of groundwater will experience a dramatic decline because of aquifer depletion and rising energy costs; at the same time, the municipal share of groundwater use will double (Kaiser & Skillern, 2000). It is projected that two of the five largest aquifers in the Texas Triangle will have less than 45% of the reservoir storage capacity remaining by 2050 (Butler et al., 2009). A recent estimate indicated a potential reduction of about 31% in the total groundwater supply in the state by the year 2060 (Chaudhuri & Ale, 2013; Vaughn et al., 2012).

Limitation of the Study

This study was limited by availability of consistent, long-term water-level measurement data from the TWDB groundwater database. Of the 2,332 wells overlying the Carrizo-Wilcox Aquifer, only approximately 5% had data with sufficient consistency and longevity to perform a meaningful assessment. The study was designed so that equal periods (at least 10 years) before and after creation of the GCD were analyzed.

This study did not take into account environmental factors such as drought and climate change, nor did it factor in changes in land use or population increases, which could affect aquifer drawdown and recharge. The study was designed only to determine whether a measureable difference occurred in drawdown between the pre- and post-GCD periods. It did not take into account the idea of managed drawdown in which the groundwater resources of a district are drawn down at a predetermined rate deemed acceptable to the GCD administrators.

Future study is required to determine whether observed changes in average annual drawdown are the result of rules implemented by the GCDs or the result of some other economic, agricultural, or environmental factors. These studies should also take into account detailed changes in population, environmental factors, and land use to determine more accurately the utility of GCDs in Texas.

REFERENCES

Alley, W. M. (2006). Tracking U.S. groundwater: Reserves for the future? *Environment, 48*(3), 10-25.

Anderson, R. S., Anderson, S., Aufdenkampe, A. K., Bales, R., Brantley, S., Chorover, J. . . . Troch, P. A. (2010). *Future directions for Critical Zone Observatory (CZO)*. Retrieved from http://criticalzone.org/boulder/publications/year/2010/

Amundson, R. S., Richter, D. D., Humphreys, G. S., Jobbágy, E. G., & Gaillardet, J. (2007). Coupling between biota and earth materials in the critical zone. *Elements, 3*, 327-332.

Ashworth, J. B., & Hopkins, J. (1995). *Aquifers of Texas: Texas Water Development Board Report 345.* Austin, TX: Texas Water Development Board.

Bailey, R. G., U.S. Fish and Wildlife Service, & U.S. Forest Service. (1980). *Description of the ecoregions of the United States.* Ogden, UT: U.S. Department of Agriculture, U.S. Forest Service.

Boghici, R. (2008). The Carrizo-Wilcox Aquifer of Texas: Groundwater chemistry, origin, and ages. *Gulf Coast Association of Geological Sciences Transctions, 58,* 105-123.

Bradley, R. S., Alverson, K., & Pedersen, T. F. (2003). *Challenges of a changing earth: Past perspectives, future concerns—Paleoclimate, global change and the future.* Berlin, Germany: Springer Verlag.

Brantley, S. L., Goldhaber, M. B., & Ragnarsdottir, K. V. (2007). Crossing disciplines and scales to understand the critical zone. *Elements, 3*, 307-314.

Brown, C. R., & Farrar, B. (2008). Hole in the bucket: *Aspermont*'s impact on groundwater districts and what it says about Texas groundwater policy. *Texas Environmental Law Journal, 39*(1).

Brown, J. E. (1997). Senate Bill 1: We've never changed Texas water law this way before. *Texas Environmental Law Journal, 28*, 152.

Burrough, P. A. (2000). GIS and geostatistics: Essential partners for spatial analysis. *Environmental and Ecological Statistics, 8*(4), 361-377.

Burt, O. (1964). Optimal resource use over time with an application to ground water. *Management Science, 11*(1), 80-93.

Burt, O. (1966). Economic control of groundwater reserves. *Journal of Farm Economics, 48*, 632-647.

Burt, O. (1967). Temporal allocation of groundwater. *Water Resources Research, 3*(1), 45-50.

Burt, O. (1970). Groundwater storage control under institutional restrictions. *Water Resources Research, 6,* 1540-1548.

Butler, K., Hammerschmidt, S., Steiner, F., & Zhang, M. (2009). *Reinventing the Texas triangle: Solutions for growing challenges.* Austin, TX: University of Texas at Ausin, School of Architecture, Center for Sustainable Development.

Carbonell, A., & Yaro, R. D. (2005). American spatial development and the new megalopolis. *Land Lines, 17*(2), 1-4.

Chaudhuri, S., & Ale, S. (2013). Characterization of groundwater resources in the Trinity and Woodbine aquifers in Texas. *Science of the Total Environment, 452,* 333-348.

Chenini, I., & Ben Mammou, A. (2010). Groundwater recharge study in arid region: An approach using GIS techniques and numerical modeling. *Computers & Geosciences, 36*, 801-817.

Combs, S. (2009). *Liquid assets: The state of Texas's water resources.* Austin, TX: Texas Comptroller of Public Accounts.

Combs, S. (2014). *Texas water report: Going deeper for the solution.* Austin, TX: State of Texas, Data Services Division.

Crutzen, P. J. (2002). Geology of mankind. *Nature, 415*(6867), 23-23.

Dellapenna, J. (2013). *The rise and the demise of the absolute dominion doctrine for groundwater.* Retrieved from http://ualr.edu/lawreview/files/2013/10/Joseph-W.-Dellapenna-Absolute-Dominion.pdf

Dewar, M., & Epstein, D. (2007). Planning for "megaregions" in the United States. *Journal of Planning Literature, 22*(2), 108-124.

Diodato, N., Ceccarelli, M., & Bellocchi, G. (2010). GIS-aided evaluation of evapotranspiration at multiple spatial and temporal climate patterns using geoindicators. *Ecological Indicators, 10*, 1009-1016.

Dorfman, M. H., Mehta, M., Chou, B., Fleischli, S., & Rosselot, K. S. (2011). *Thirsty for answers: Preparing for the water-related impacts of climate change in American cities.* Washington, DC: Natural Resources Defense Council.

Fipps, G. (2002). *Managing Texas groundwater resources through groundwater conservation districts.* Retrieved from http://hdl.handle.net/1969.1/87784

Fisher, W. L., & McGowen, J. H. (1969). Depositional systems in Wilcox Group (Eocene) of Texas and their relation to occurrence of oil and gas. *AAPG Bulletin, 53*(1), 30-54.

Foster, J. R. J. (2008). Three essays on groundwater depletion and groundwater conservation districts in Texas.

Foster, J. R. J. (2009). Do Texas groundwater conservation districts matter? *Water Policy, 11*, 379-399.

Gardner, R., Moore, M., & Walker, J. (1997). Governing a groundwater commons: A strategic and laboratory analysis of Western Water Law. *Economic Inquiry, 35*, 218-234.

Gaur, S., Chahar, B. R., & Graillot, D. (2011). Combined use of groundwater modeling and potential zone analysis for management of groundwater. *International Journal of Applied Earth Observation and Geoinformation, 13*(1), 127-139.

George, P. G., Mace, R. E., & Petrossian, R. (2011). *Aquifers of Texas*. Austin, TX: Texas Water Development Board.

Giordano, M. (2009). Global groundwater? Issues and solutions. *Annual Review of Environmental Resources, 34*, 153-178.

Goudie, A. S. (2006). Global warming and fluvial geomorphology. *Geomorphology, 79*, 384-394.

Graf, W. L. (2008). In the critical zone: Geography at the U.S. Geological Survey. *The Professional Geographer, 56*(1), 100-108.

Green, T. R., Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., . . . Aureli, A. (2011). Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrolology, 405*, 532-560.

Houston & T. C. Railway Co. v. East, 98 Tex. 146, 81 S.W. 279 (1904).

Houston, J. A. (2004). *Overview of groundwater district rules and regulations in Texas.* Friendswood, TX: Harris-Galveston Coastal Subsidence District.

Jin, S., Yang, L., Danielson, P., Homer, C., Fry, J., & Xian, G. (2013). A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment, 132*, 159-175.

Johnson, J., Johnson, P., Segarra, E., & Willis, D. (2009). Water conservation policy alternatives for the Ogallala Aquifer in Texas. *Water Policy, 11*, 537-552.

Kaiser, R. (1987). *Hand book of Texas water law: Problems and needs.* College Station, TX: Texas Water Resources Institute, Texas Agricultural Experiment Station, Texas A&M University.

Kaiser, R. (1988). *Handbook of Texas water law: Problems and needs.* College Station, TX: Texas A&M University, Texas Water Resources Institute.

Kaiser, R. (2005). *Who owns the water: A primer on Texas groundwater law.* Retrieved from http://www.tamu.edu/faculty/rakwater/research/tpwd_Water_Article.pdf

Kaiser, R., & Skillern, F. F. (2000). Deep trouble: Options for managing the hidden threat of aquifer depletion in Texas. *Texas Tech Law Review, 32,* 249.

Kelley, V., Deeds, N., Fryar, D., & Senger, R. (2009). Development of regional groundwater availability models of the Carrizo-Wilcox Aquifer in Texas. *Gulf Coast Association of Geological Societies Transactions, 59,* 401-410.

Klemt, W. B., Duffin, G. L., & Elder, G. R. (1976). *Ground-water resources of the Carrizo aquifer in the Winter Garden area of Texas.* Austin, TX: Texas Water Development Board.

Kundzewicz, Z. W., & Robson, A. J. (2012). Change detection in hydrological records: A review of the methodology [Revue méthodologique de la détection de changements dans les chroniques hydrologiques]. *Hydrological Sciences Journal/Journal des Sciences Hydrologiques, 49*(1), 7-19.

Lesikar, B., Kaiser, R., & Silvy, V. (2002). *Questions about groundwater conservation districts in Texas.* Retrieved from http://www.tamu.edu/faculty/rakwater/research/GW-Conserv-Dist.pdf

Levasseur, P. G. (2012). *Current regulations, scientific research, and district rulemaking processes to protect and conserve the Carrizo-Wilcox Aquifer in Texas by groundwater conservation districts* (Master's thesis). The University of Texas at Austin, Austin, TX.

Levin, R. B., Epstein, P. R., Ford, T. E., Harrington, W., Olson, E., & Reichard, E. G. (2002). U.S. drinking water challenges in the twenty-first century. *Environmental Health Perspectives, 110*(Suppl. 1), 43-52.

Lin, H. (2010). Earth's critical zone and hydropedology: Concepts, characteristics, and advances. *Hydrology and Earth System Sciences, 14*, 25-45.

Mace, R. E., & Wade, S. C. (2008). *In hot water? How climate change may (or may not) affect the groundwater resources of Texas.* Address presented at the 2008 Joint Meeting of the Geological Society of America, Soil Science Society of America, American Society of Agronomy, Crop Science Society of America, and Gulf Coast Association of Geological Societies with the Gulf Coast Section of SEPM. *GCAGS Transactions, 2008*, 655-668.

Molina, J. L., Bromley, J., García-Aróstegui, J. L., Sullivan, C., & Benavente, J. (2010). Integrated water resources management of overexploited hydrogeological systems using object-oriented Bayesian networks. *Environmental Modelling & Software, 25*, 383-397.

Moore, J. E. (1979). Contribution of groundwater modeling to planning. *Journal of Contemporary Hydrogeology, 43,* 121-128.

National Research Council (NRC). (2001). *Basic research opportunities in earth science.* Washington, DC: National Academies Press.

Neffendorf, B., & Hopkins, J. (2013). *Summary of groundwater conditions in Texas: Recent (2011-2012) and historical water-level changes in the TWDB Recorder Network.* Austin, TX: Texas Water Development Board.

Neuman, M., & Bright, E. M. (2008). *Texas urban triangle: Framework for future growth*. College Station, TX: Southwest Region University Transportation Center.

Neuman, M., Bright, E., & Morgan, C. (2010). *Texas urban triangle: Creating a spatial decision support system for mobility policy and investments that shape the sustainable growth of Texas.* Retrieved from http://utcm.tamu.edu/publ...eports/Neuman_09-30-10.pdf

Nicot, J.-P., & Scanlon, B. R. (2012). Water use for shale-gas production in Texas. U.S. Environmental Science and Technololgy, *46*, 3580-3586.

Padowski, J. C., & Jawitz, J. W. (2012). Water availability and vulnerability of 225 large cities in the United States. *Water Resources Research, 48*(12), 16-32.

Pearson, F. F., & White, D. E. (1967). Carbon 14 ages and flow rates of water in Carrizo Sand Atascosa County Texas. *Water Resources Research, 3*(1), 251-261.

Pint, T., & Li, S.-G. (2006). ModTech: A GIS-enabled ground water modeling program. *Ground Water, 44*, 506-508.

Porter, C. R. (2014). *Sharing the common pool: Water rights in the everyday lives of Texans*. College Station, TX: Texas A&M University Press.

Potter, L. B., & Hogue, N. (2011). *Texas population projections, 2010-2050.* Austin, TX: Office of the State Demographer.

Provencher, B. (1993). A private property-rights regime to replenish a groundwater aquifer. *Land Economics, 69*, 325-340.

Provencher, B., & Burt, O. (1993). The externalities associated with the common property exploitation of groundwater. *Journal of Environmental and Economic Management, 24*(2), 139-158.

Provencher, B., & Burt, O. (1994). A private property rights regime for the commons: The case for groundwater. *American Journal of Agricultural Economics, 76*, 875-888.

Rao, M. N., & Yang, Z. (2010). Groundwater impacts due to conservation reserve program in Texas County, Oklahoma. *Applied Geography, 30*(3), 317-328.

Reeves, H. W., & Zellner, M. L. (2010). Linking MODFLOW with an agent-based land-use model to support decision making. *Ground Water, 48*, 649-660. doi:10.1111/j.1745-6584.2010.00677.x

Reitsma, F. (2010). Geoscience explanations: Identifying what is needed for generating scientific narratives from data models. *Environmental Modelling & Software, 25*(1), 93-99.

Richter, D. D., & Mobley, M. (2009). Monitoring earths critical zone. *Science, 326,* 1067-1068.

Riebsame, W. E., Parton, W. J., Galvin, K. A., Burke, I. C., Bohren, L., Young, R., & Knop, E. (1994). Integrated modeling of land use and cover change. *Bioscience, 44*, 350-356.

Santini, M., Caccamo, G., Laurenti, A., Noce, S., & Valentini, R. (2010). A multi-component GIS framework for desertification risk assessment by an integrated index. *Applied Geography, 30*, 394-415.

Smith, S. C. (1956). Problems in the use of the public district for groundwater management. *Land Economics, 32*, 259-269.

Somma, M. (1997). Institutions, ideology, and the tragedy of the commons: West Texas groundwater policy. *Publius: The Journal of Federalism, 27*(1), 1-13.

Strager, M. P., Fletcher, J. J., Strager, J. M., Yuill, C. B., Eli, R. N., Todd Petty, J., & Lamont, S. J. (2010). Watershed analysis with GIS: The watershed characterization and modeling system software application. *Computers & Geosciences, 36*, 970-976.

Taylor, W. A. (2000). *Change-point analysis: A powerful new tool for detecting changes*. Retrieved from http://www.variation.com/cpa/tech/changepoint.html

Texas. (2005). *Texas Water Code*. Retrieved from http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.26.htm

Texas Water Development Board. (2007). *Water for Texas 2007.* Austin, TX: Author.

Texas Water Development Board. (2014a.) *Groundwater conservation district information*. Austin, TX: Author.

Texas Water Development Board. (2014b). *Groundwater management areas*. Austin, TX: Author.

Thorkildsen, D., Quincy, R., & Preston, R. (1989). *A digital model of the Carrizo-Wilcox Aquifer within the Colorado River basin of Texas.* Austin, TX: Texas Water Development Board.

Uddameri, V., & Honnungar, V. (2007). Combining rough sets and GIS techniques to assess aquifer vulnerability characteristics in the semi-arid South Texas. *Environmental Geology, 51*, 931-939.

U.S. Census Bureau, Economics and Statistics Administration. (2014). *Average annual population growth 1930–2000.* Washington, DC: U.S. Department of Commerce.

U.S. Geological Survey. (2003). Active mines and mineral plants in the US. In U.S.G.S. (Ed.), *USGS minerals yearbook*—2003. Reston, VA: Author.

Vaughn, E. G., Crutcher, J. M., Labatt, T. W., McMahan, L. H., Bradford B. R., Jr., Gruver, M. C., & Gruver, M. C. (2012). *Water for Texas 2012.* Austin, TX: Texas Water Development Board.

Wagner, M., & Kreuter, U. (2004). Groundwater supply in Texas: Private land considerations in a rule-of-capture state. *Society & Natural Resources, 17*, 349-357.

Wang, H., Small, M. J., & Dzombak, D. A. (2014, November). *Factors governing change in water withdrawals for U.S. industrial sectors from 1997 to 2002.* Paper presented at the 2013 AWRA Annual Water Resources Conference, Portland, OR.

Wilding, L. P., & Lin, H. (2006). Advancing the frontiers of soil science towards a geoscience. *Geoderma, 131*(3/4), 257-274.

Worboys, M., & Hornsby, K. (2004). From objects to events: GEM, the geospatial event model. *Geographic Information Science, 3234,* 327-343.

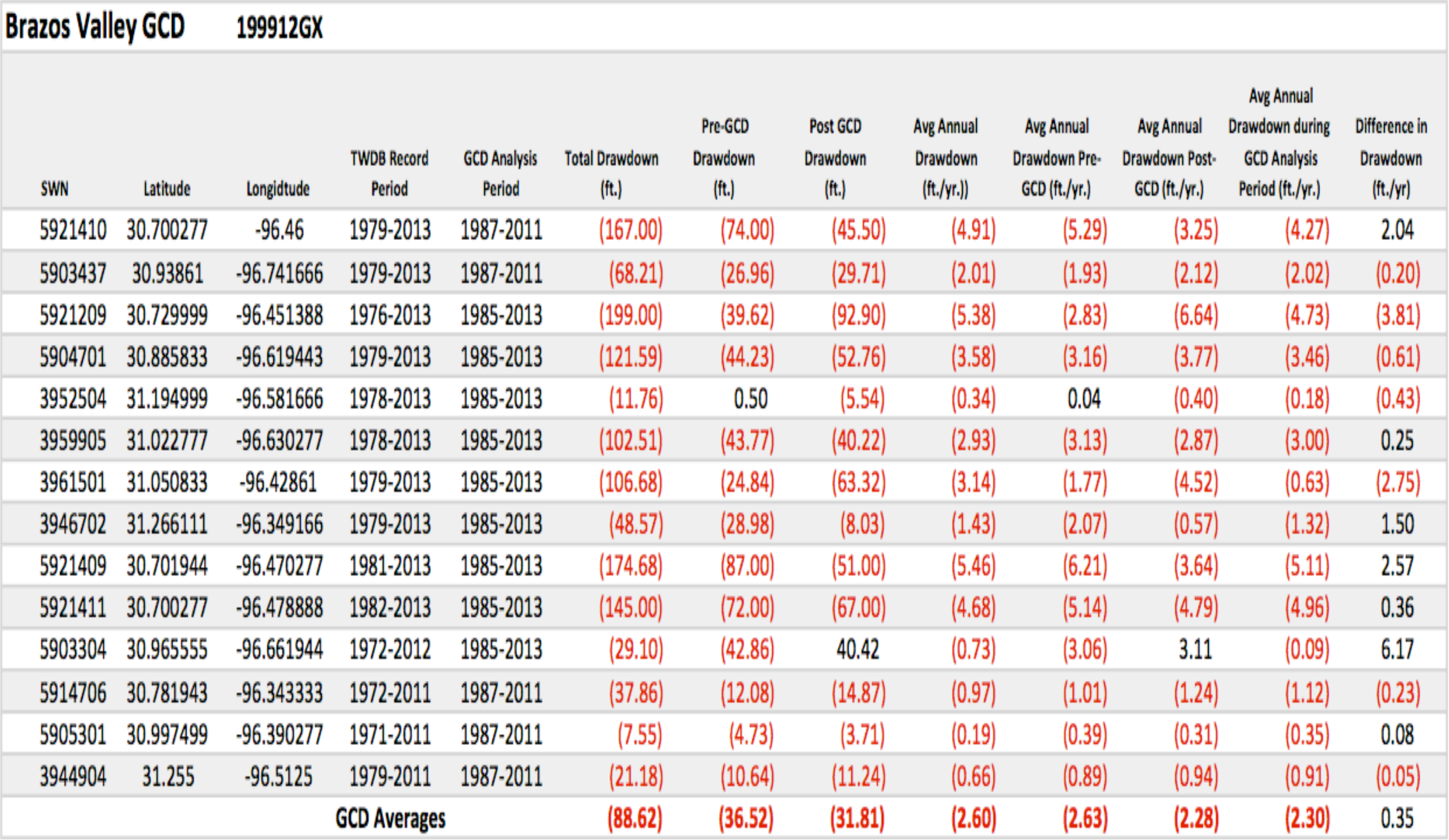
Zhang, M., Steiner, F., & Butler, K. (2007). *Connecting the Texas Triangle: Economic integration and transportation coordination.* Healdsburg, CA: Regional Plan Association & Lincoln Institute of Land Policy.

APPENDIX

MEASUREMENT SUMMARIES

Table 35

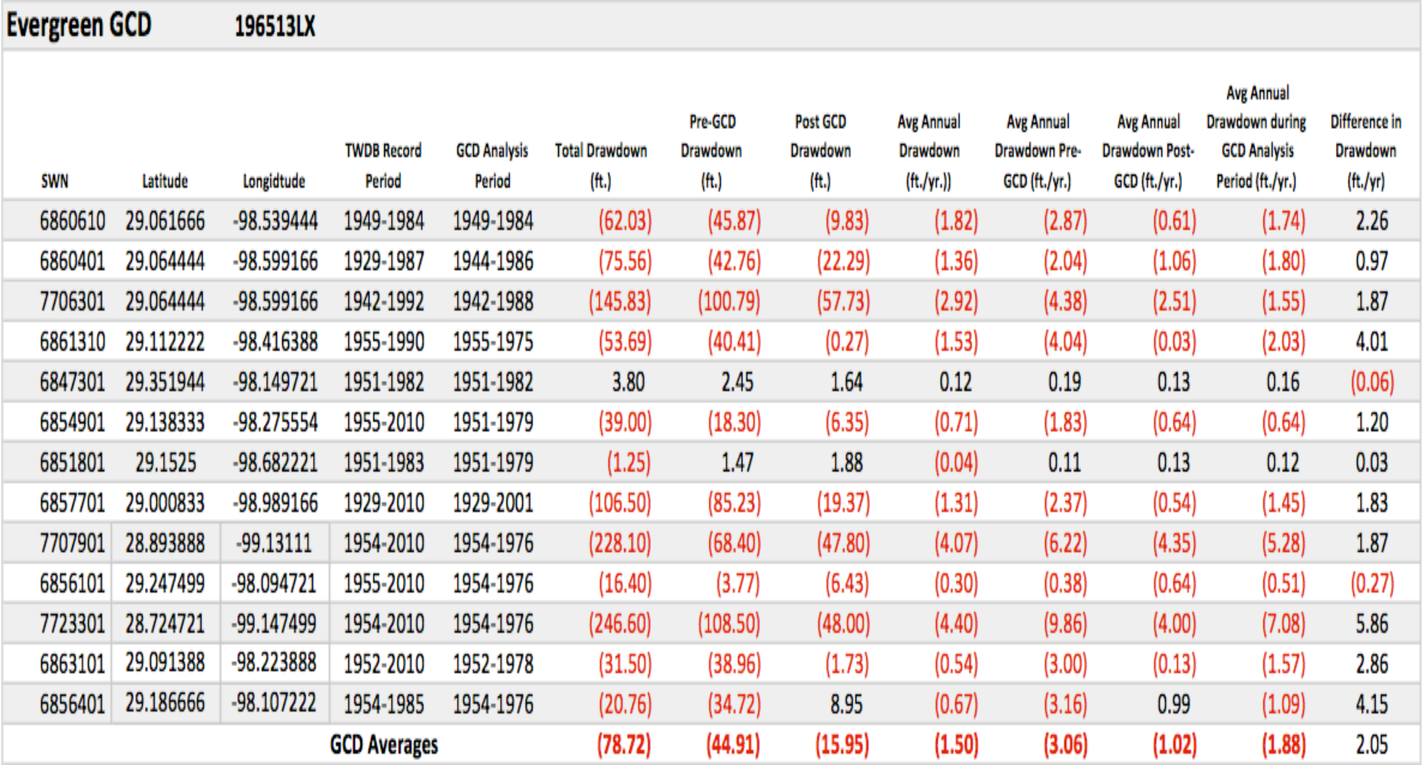
Brazos Valley Groundwater Conservation District Measurement Summary



Brazos Valley GCD		**199912GX**										
SWN	Latitude	Longidtude	TWDB Record Period	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD Analysis Period (ft./yr.)	Difference in Drawdown (ft./yr)
5921410	30.700277	-96.46	1979-2013	1987-2011	(167.00)	(74.00)	(45.50)	(4.91)	(5.29)	(3.25)	(4.27)	2.04
5903437	30.93861	-96.741666	1979-2013	1987-2011	(68.21)	(26.96)	(29.71)	(2.01)	(1.93)	(2.12)	(2.02)	(0.20)
5921209	30.729999	-96.451388	1976-2013	1985-2013	(199.00)	(39.62)	(92.90)	(5.38)	(2.83)	(6.64)	(4.73)	(3.81)
5904701	30.885833	-96.619443	1979-2013	1985-2013	(121.59)	(44.23)	(52.76)	(3.58)	(3.16)	(3.77)	(3.46)	(0.61)
3952504	31.194999	-96.581666	1978-2013	1985-2013	(11.76)	0.50	(5.54)	(0.34)	0.04	(0.40)	(0.18)	(0.43)
3959905	31.022777	-96.630277	1978-2013	1985-2013	(102.51)	(43.77)	(40.22)	(2.93)	(3.13)	(2.87)	(3.00)	0.25
3961501	31.050833	-96.42861	1979-2013	1985-2013	(106.68)	(24.84)	(63.32)	(3.14)	(1.77)	(4.52)	(0.63)	(2.75)
3946702	31.266111	-96.349166	1979-2013	1985-2013	(48.57)	(28.98)	(8.03)	(1.43)	(2.07)	(0.57)	(1.32)	1.50
5921409	30.701944	-96.470277	1981-2013	1985-2013	(174.68)	(87.00)	(51.00)	(5.46)	(6.21)	(3.64)	(5.11)	2.57
5921411	30.700277	-96.478888	1982-2013	1985-2013	(145.00)	(72.00)	(67.00)	(4.68)	(5.14)	(4.79)	(4.96)	0.36
5903304	30.965555	-96.661944	1972-2012	1985-2013	(29.10)	(42.86)	40.42	(0.73)	(3.06)	3.11	(0.09)	6.17
5914706	30.781943	-96.343333	1972-2011	1987-2011	(37.86)	(12.08)	(14.87)	(0.97)	(1.01)	(1.24)	(1.12)	(0.23)
5905301	30.997499	-96.390277	1971-2011	1987-2011	(7.55)	(4.73)	(3.71)	(0.19)	(0.39)	(0.31)	(0.35)	0.08
3944904	31.255	-96.5125	1979-2011	1987-2011	(21.18)	(10.64)	(11.24)	(0.66)	(0.89)	(0.94)	(0.91)	(0.05)
			GCD Averages		**(88.62)**	**(36.52)**	**(31.81)**	**(2.60)**	**(2.63)**	**(2.28)**	**(2.30)**	0.35

Table 36

Evergreen Groundwater Conservation District Measurement Summary



Evergreen GCD		**196513LX**										
SWN	Latitude	Longidtude	TWDB Record Period	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD Analysis Period (ft./yr.)	Difference in Drawdown (ft./yr)
6860610	29.061666	-98.539444	1949-1984	1949-1984	(62.03)	(45.87)	(9.83)	(1.82)	(2.87)	(0.61)	(1.74)	2.26
6860401	29.064444	-98.599166	1929-1987	1944-1986	(75.56)	(42.76)	(22.29)	(1.36)	(2.04)	(1.06)	(1.80)	0.97
7706301	29.064444	-98.599166	1942-1992	1942-1988	(145.83)	(100.79)	(57.73)	(2.92)	(4.38)	(2.51)	(1.55)	1.87
6861310	29.112222	-98.416388	1955-1990	1955-1975	(53.69)	(40.41)	(0.27)	(1.53)	(4.04)	(0.03)	(2.03)	4.01
6847301	29.351944	-98.149721	1951-1982	1951-1982	3.80	2.45	1.64	0.12	0.19	0.13	0.16	(0.06)
6854901	29.138333	-98.275554	1955-2010	1951-1979	(39.00)	(18.30)	(6.35)	(0.71)	(1.83)	(0.64)	(0.64)	1.20
6851801	29.1525	-98.682221	1951-1983	1951-1979	(1.25)	1.47	1.88	(0.04)	0.11	0.13	0.12	0.03
6857701	29.000833	-98.989166	1929-2010	1929-2001	(106.50)	(85.23)	(19.37)	(1.31)	(2.37)	(0.54)	(1.45)	1.83
7707901	28.893888	-99.13111	1954-2010	1954-1976	(228.10)	(68.40)	(47.80)	(4.07)	(6.22)	(4.35)	(5.28)	1.87
6856101	29.247499	-98.094721	1955-2010	1954-1976	(16.40)	(3.77)	(6.43)	(0.30)	(0.38)	(0.64)	(0.51)	(0.27)
7723301	28.724721	-99.147499	1954-2010	1954-1976	(246.60)	(108.50)	(48.00)	(4.40)	(9.86)	(4.00)	(7.08)	5.86
6863101	29.091388	-98.223888	1952-2010	1952-1978	(31.50)	(38.96)	(1.73)	(0.54)	(3.00)	(0.13)	(1.57)	2.86
6856401	29.186666	-98.107222	1954-1985	1954-1976	(20.76)	(34.72)	8.95	(0.67)	(3.16)	0.99	(1.09)	4.15
			GCD Averages		**(78.72)**	**(44.91)**	**(15.95)**	**(1.50)**	**(3.06)**	**(1.02)**	**(1.88)**	2.05

Table 37

Rusk County Groundwater Conservation District Measurement Summary

Rusk County GCD **200311IX**

SWN	Latitude	Longitude	TWDB Record Period	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD Analysis Period (ft./yr.)		Difference in Drawdown (ft./yr)
3711201	31.868332	-94.708333	1976-2013	1993-2013	(3.86)	2.68	(6.37)	(0.10)	0.27	(0.64)	(0.01)	↓	(0.91)
3704601	31.924166	-94.53111	1976-2013	1993-2013	(4.12)	(15.05)	15.29	(0.11)	(1.51)	1.53	0.01	↑	3.03
3702802	31.892499	-94.825832	1976-2013	1993-2013	(2.65)	(1.49)	(5.08)	(0.07)	(0.15)	(0.51)	(0.33)	↓	(0.36)
3702301	31.99111	-94.768332	1976-2013	1993-2013	(11.25)	(2.27)	(5.81)	(0.30)	(0.23)	(0.58)	(0.40)	↓	(0.35)
3558101	32.085833	-94.866388	1972-2013	1993-2013	(0.23)	(0.65)	(0.06)	(0.01)	(0.06)	(0.19)	(0.22)	↓	(0.13)
3552701	32.151944	-94.600277	1981-2013	1993-2013	(10.99)	(1.05)	(7.62)	(0.34)	(0.09)	(0.76)	(0.43)	↓	(0.67)
3552101	32.240555	-94.591388	1966-2013	1993-2013	(26.39)	(9.35)	(3.74)	(0.56)	(0.94)	(0.37)	(0.65)	↑	0.56
3550801	32.150833	-94.79361	1947-2013	1993-2013	(100.80)	(45.49)	(16.80)	(1.53)	(4.55)	(1.68)	(0.84)	↑	2.87
3550501	32.208055	-94.821388	1972-2013	1993-2013	(3.69)	(2.60)	(4.44)	(0.09)	(0.26)	(0.44)	(0.35)	↓	(0.18)
3549801	32.13611	-94.941388	1941-2013	1993-2013	6.09	(3.80)	(7.61)	0.08	(0.38)	(0.76)	(0.57)	↓	(0.38)
3544601	32.314166	-94.512777	1939-2013	1993-2013	(76.50)	5.57	(15.75)	(1.03)	0.56	(1.58)	(0.51)	↓	(2.13)
3543501	32.314444	-94.699721	1976-2013	1993-2013	(11.27)	(5.45)	(5.07)	(0.30)	(0.55)	(0.51)	(0.53)	↑	0.04
3541601	32.296388	-94.897221	1972-2013	1993-2013	21.82	(61.79)	31.57	0.53	(6.18)	3.16	(1.51)	↑	9.34
			GCD Averages		**(17.22)**	**(10.83)**	**(2.42)**	**(0.30)**	**(1.08)**	**(0.26)**	**(0.49)**	↑	0.82

Table 38

Wintergarden Groundwater Conservation District Measurement Summary

Wintergarden GCD **199713LX**

SWN	Latitude	Longitude	TWDB Record Period	GCD Analysis Period	Total Drawdown (ft.)	Pre-GCD Drawdown (ft.)	Post GCD Drawdown (ft.)	Avg Annual Drawdown (ft./yr.))	Avg Annual Drawdown Pre-GCD (ft./yr.)	Avg Annual Drawdown Post-GCD (ft./yr.)	Avg Annual Drawdown during GCD Analysis Period (ft./yr.)	Difference in Drawdown (ft./yr)
7726605	28.555277	-99.759444	1969-2010	1984-2010	(50.28)	82.88	(35.51)	1.23	6.77	(2.73)	2.02	↓ (9.50)
6958801	29.007222	-99.815555	1946-2014	1981-2013	(11.51)	(3.43)	(10.68)	(0.17)	(0.21)	(0.67)	(0.46)	↓ (0.45)
6958701	29.0125	-99.845555	1954-2014	1981-2013	(4.71)	0.27	(5.19)	(0.07)	0.02	(0.32)	(0.15)	↓ (0.34)
6958707	29.013611	-99.854444	1958-2014	1983-2011	(15.01)	(0.69)	(2.89)	(0.27)	(0.05)	(0.21)	(0.13)	↓ (0.16)
6959904	29.013611	-99.854444	1967-2007	1987-2007	(94.39)	(7.62)	(10.91)	(2.42)	(0.76)	(1.09)	(0.93)	↓ (0.33)
6961525	29.064722	-99.44361	1971-2014	1981-2013	(38.95)	(23.06)	(16.79)	(0.91)	(1.44)	(1.05)	(1.25)	↑ 0.39
7608406	28.930554	-100.09778	1970-2012	1986-2008	(16.40)	(6.18)	(2.00)	(0.39)	(0.62)	(0.18)	(0.40)	↑ 0.44
7624801	28.646666	-100.04583	1930-2014	1980-2014	(22.38)	7.70	(2.48)	(0.27)	0.45	(0.15)	0.15	↓ (0.60)
7624906	28.664444	-100.01917	1971-2014	1981-2013	(237.71)	(3.54)	(18.89)	(5.53)	(0.22)	(1.18)	(0.70)	↓ (0.96)
7648801	28.275832	-100.07361	1965-2014	1980-2014	(1.51)	(0.40)	(1.07)	(0.03)	(0.02)	(0.06)	(0.04)	↓ (0.04)
7701311	28.998333	-99.892777	1958-2014	1980-2014	3.26	0.44	(0.86)	0.06	0.02	(0.06)	(0.01)	↓ (0.08)
7701702	28.916111	-99.995277	1965-2014	1981-2013	(34.00)	(13.76)	(10.02)	(0.69)	(0.86)	(0.63)	(0.41)	↑ 0.23
7718704	28.633888	-99.856388	1930-2014	1984-2010	(264.86)	(42.96)	(26.26)	(2.26)	(3.30)	(2.02)	(2.66)	↑ 1.28
7728503	28.575554	-99.571388	1969-2010	1984-2010	50.28	88.03	(35.52)	1.23	6.77	(2.73)	2.02	↓ (9.50)
7730801	28.508611	-99.326388	1955-2007	1987-2007	(223.30)	(67.70)	(17.10)	(4.29)	(6.77)	(1.71)	(2.22)	↑ 5.06
7731703	28.517221	-99.215	1959-2007	1987-2007	(28.36)	19.98	1.74	(0.59)	2.00	0.17	1.09	↓ (1.82)
7733611	28.453333	-99.916388	1944-2014	1980-2014	(55.03)	(11.80)	(17.63)	(0.79)	(0.91)	(1.04)	(1.01)	↓ (0.13)
7733701	28.390555	-99.96	1956-2008	1986-2008	(39.99)	(3.05)	(17.55)	(0.77)	(0.28)	(1.60)	(0.94)	↓ (1.32)
7734702	28.394999	-99.840555	1969-2014	1980-2014	(124.32)	(5.65)	(117.92)	(2.76)	(0.33)	(6.94)	(3.63)	↓ (6.60)
7744101	28.351944	-99.598888	1957-2014	1980-2014	(236.44)	(22.86)	(194.67)	(4.15)	(1.34)	(11.45)	(6.40)	↓ (10.11)
			GCD Averages		**(72.28)**	**(0.67)**	**(27.11)**	**(1.19)**	**(0.05)**	**(1.78)**	**(0.80)**	↓ (1.73)