Anticipating Growth in the Texas Hill Country: Exploration of Potential for Land Application of Treated Wastewater and Further Considerations

by

Ty Stonecipher

A directed research report submitted to the Geography Department of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Applied Geography
with a specialization in Environmental Resource Science

May 2020

Committee Members:

Dr. Timothy T. Loftus

Dr. Richard Earl

Table of Contents

Table of Figures

Table of Tables

Executive Summary

The Texas Hill Country is an iconic landscape known for its unique beauty, including clear-running rivers and streams, and numerous springs both large and small. Given the rapid population growth along the I-35 corridor and west into the Hill Country, water-resource planning and management challenges are emerging that provide opportunity for an integrated or "One Water" approach to problem solving.

First, there is growing demand for water supply in a region that is also known to be drought-prone and home to many threatened or endangered species that need water too. Secondly, with increased water use comes a proportional increase in treated wastewater effluent production. Absent strong nutrient standards in permitted discharges to prevent cultural eutrophication of Hill Country streams, alternative uses of treated wastewater effluent are available that can reduce withdrawals of surface and groundwater and create new economic opportunities by using wastewater effluent as a resource rather than disposing it as a waste product.

From a larger set of Texas Hill Country cities that were based on their location relative to the Edwards Aquifer, nine were selected in a first phase analysis using a geographic information system and based on weighted criteria including population growth rate, potential site distance from a wastewater treatment plant (WWTP), and a set of land uses deemed suitable for land application of treated wastewater. These nine cities were then evaluated based on their ability to meet four criteria: 1) the target city's WWTP is located within or upstream of either the contributing or recharge zones of the Edwards Aquifer regulatory boundary, 2) the city's WTTP has a current or near future need to expand their WWTP based on reported

average daily discharge being 75 percent or more of permitted maximum daily discharge, 3) it being early enough in their planning development cycle, either hypothetically or in actual practice, that reuse infrastructure can be carefully examined and planned for at the most efficient time, and 4) having land-use scenarios suitable for land application that are within a 3-mile (maximum) radius of the WWTP. From this analysis, three cities emerged for study: Blanco, Boerne, and Leander.

A second phase of site analysis given to the three study cities is based on weighted criteria that include land use, location relative to the Edwards Aquifer regulatory boundary, distance from WWTP, and percent slope. Among results, the City of Blanco can meet 100 percent of both current and future needs for land application of TWW effluent on highest-quality sites (scores of ten) within a one-mile radius of its WWTP. The City of Boerne, can also meet both current and future needs for land application within a one-mile radius, but will need to include some sites with scores less than a ten and act with a greater sense of urgency given the current/projected growth rate. The City of Leander presents a particular challenge given its current/projected growth rate, large effluent volume expected in the future, and location and will require other reuse strategies to ensure efficient use of water and protection of local/regional water quality. Any land application within the region will thus need to respect the water quality buffers required by the Texas Administrative Code and discussed in the final sections of this report.

By applying a replicable methodology using publicly available data, this study shows promise for land application of treated wastewater effluent in the Texas Hill Country. While infrastructure and other cost considerations need to be analyzed in a future study along with refinement of site selection and a collaborative process for its execution, this study highlights the need for community officials and residents to develop a shared vision for their community's water future. The promise of reusing effluent via land application to help solve growing demand for water must also account for an equal need to protect surface and groundwater quality. Thus, an appropriate level of wastewater treatment must be engineered that fully accounts for specific site characteristics such that land application as a reuse strategy fulfills its promise while avoiding negative impacts on surface and groundwater.

Introduction

Treated wastewater (TWW) effluent is one of the most common forms of freshwater pollution in the United States (Grantham et al. 2012; USEPA 2019). This effluent is considered a pollutant, despite being treated to relatively high standards, because it has the ability to oversaturate receiving streams and lakes with major nutrients that are typically limiting in aquatic ecosystems: Phosphorus (P) and Nitrogen (N). Unless tertiary wastewater treatment procedures are implemented to reduce nutrient levels in TWW effluent, high P & N loading can lead to cultural or artificial eutrophication in the receiving waterbody (Horne and Goldman 1994).

Eutrophication describes the trophic status of an enriched waterbody where high nutrient concentrations result in a level of productivity that leads to overabundant plant life (e.g., algal blooms), subsequent die-off that results in a drastic reduction of dissolved oxygen, and negative impacts on other aquatic life (e.g. fish, shellfish, invertebrates) in the affected body of water (Chrislock et al. 2013). Eutrophication can result from natural processes but is deemed artificial or cultural when it is the result of human-related activities (Horne and Goldman 1994).

Texas Hill Country streams are particularly vulnerable to eutrophication because they tend to have low ambient nutrient concentrations, streambeds that support relatively few plants, low turbidity, and high benthic light availability (*personal communication*, Raymond Slade, Jr., Surface Water Specialist, Texas Office of the United States Geological Survey, retired, June 9th, 2019, conversation). Another factor that makes these iconic waterways even more vulnerable is the drought-prone nature of the region (Earl, Dixon, and Day 2006). Periods of drought can lead to decreased base and spring flows and leave less water in rivers and streams to dilute instream-nutrient concentrations from wastewater effluent.

Population growth in the Texas Hill Country is increasing water demand. If the most common wastewater treatment and disposal paradigm is followed, secondary treatment and discharge of TWW effluent into a local waterbody, then the population growth creates a positive feedback loop where increasing groundwater and surface water withdrawals leave less water available in streams to dilute high nutrient concentrations in effluent; which when paired with increased discharges of treated wastewater effluent into waterways results in increased instream nutrient levels. These factors combine to increase the likelihood of eutrophication. It is imperative, therefore, that new alternative uses for TWW effluent are found that can both prevent the discharge of nutrient-rich effluent into Hill Country streams and help mitigate the region's potential water scarcity by offsetting demand for surface and groundwater.

Land application of treated effluent has the potential to address these issues and create new economic opportunities for landowners in the region and sources of revenue for water service providers. Land application of treated wastewater, however, is not without challenges and these will be addressed in another section of this report.

Land application of treated wastewater can help address water scarcity by increasing the efficiency of water use and potentially offset existing or new withdrawals from natural water supplies. Land application of TWW turns what would otherwise be a waste product into a resource by taking nutrient-rich wastewater[1] and supplementing or replacing water and

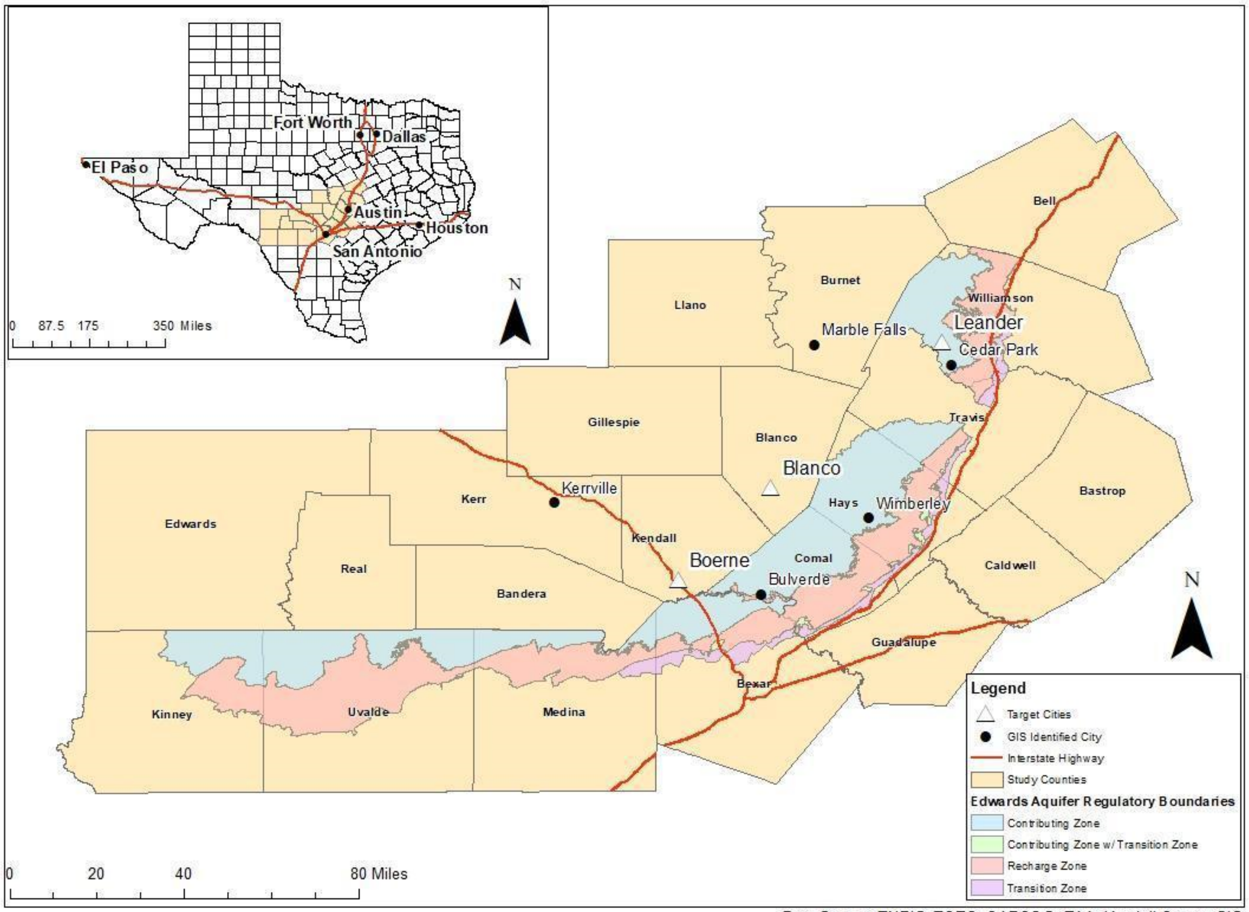
[1] Tertiary treatment, a process that is designed to minimize nutrient concentrations in effluent, will be necessary prior to land application in the study area depending on site characteristics relative to the Edwards Aquifer contributing zone.

fertilizer for crops and other irrigated landscapes. Thus, the opportunities of stream eutrophication from direct discharge are reduced. Here, we assume that both local land-application management is sound and the state regulatory environment is strengthened to protect water quality. Land application of nonpotable water also enables potable water to be reserved for uses that demand higher water quality. The purpose of this research project is to answer the question "What is the potential for land application of treated wastewater for three rapidly growing cities in the Texas Hill Country?"

Background

The Texas Hill Country (Figure 1) is located approximately in the center of the state. According to the Texas Water Development Board (TWDB) 2012 State Water Plan, the region has a Subtropical Subhumid climate (Larkin and Bomar 1983) that varies from semiarid in dry years to humid during wet years (Earl, Dixon, and Day 2006). The region generally receives less than 35 inches of precipitation per year, with most of the rainfall coinciding with seasonal changes in frontal patterns. The area has an average annual temperature between 60 °F and 65 °F. Summer highs can reach into the mid-90s °F, with heat indexes reaching into triple-digit temperatures. This combination of limited precipitation and high summer temperatures causes lake evaporation to be approximately 60" a year and makes the area prone to moderate to severe drought (TWDB 2012).

Figure 1. Study area location map.



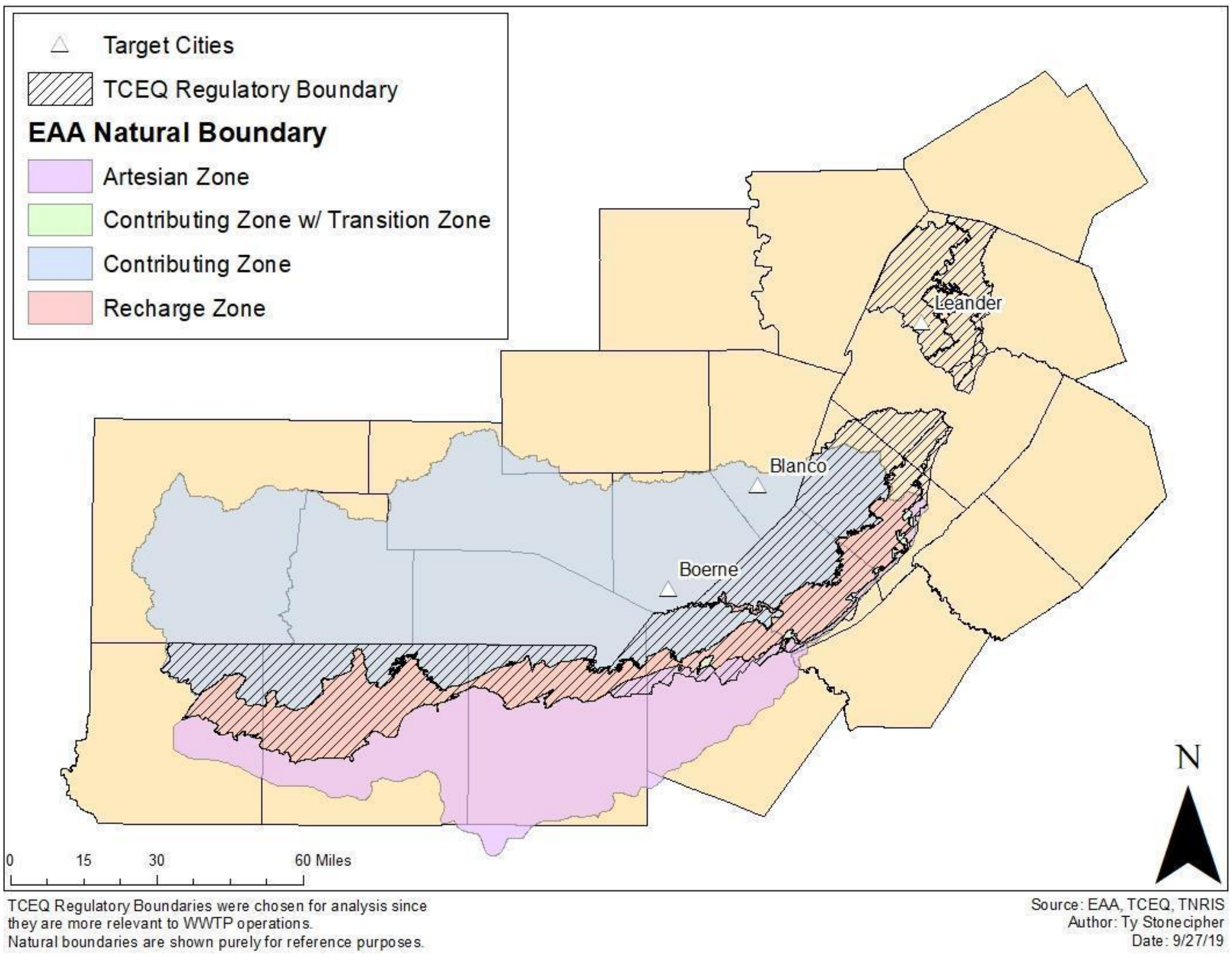
Data Source: TNRIS, TCEQ, CAPCOG, EAA, Kendall County GIS
Author: Ty Stonecipher
Date: 9/10/19

Physiographically, the Texas Hill Country is dominated by a karst landscape composed of various limestones (Edwards Aquifer Authority 2019a). The region is named for the valleys that have dissected the Edwards Plateau and is known for its unique water features. The Edwards Aquifer (Figure 2) has an extensive presence on the Hill Country landscape. This aquifer system, as delineated by the Edwards Aquifer Authority (2019b), includes or underlies 12 counties with a total surface area of over 3,000 square miles.[2] Almost all of the precipitation that falls on the Edwards Plateau will interact with the Edwards Aquifer in some form or

[2] The 12 counties delineated by the Edwards Aquifer Authority do not include the Barton Springs and Northern segments of the Edwards Aquifer that would add Travis, Williamson, and Bell counties.

fashion. Many of the region's streams will lose some of their water to the Edwards via percolation through limestone and serve as recharge (Edwards Aquifer Authority 2019a). Overland flow of precipitation can also be intercepted by the region's numerous caves, sinkholes, and other recharge features.

Figure 2. Regulatory vs. natural boundary of the Edwards Aquifer System.



The Edwards Aquifer is also a primary source of water for the two million people who live in the greater San Antonio metropolitan region and others situated along the I-35 corridor north to Austin. Most of the region's high-profile and crystal-clear springs, such as the San Marcos, Comal, and Barton springs, are also fed by the aquifer. The Edwards Aquifer's combination of high permeability and porosity, use as a significant water supply, and unique assemblage of threatened and endangered species make it particularly vulnerable to pollution.

The high degree of hydraulic connectivity in the Edwards Aquifer system means that any pollution in the streams of the Hill Country can be reasonably assumed to have a negative impact on the aquifer itself (Einsiedl, Radke, and Maloszewski 2010). In Texas, 30 Texas Administrative Code (TAC) §213.6 prohibits land application systems on the Edwards Aquifer recharge zone, but is otherwise silent about land application relative to the contributing zone.[3] The rules in Texas for Land Disposal of Sewage Effluent are found in 30 TAC §309.20, §309.3, and §309.4. These latter two rules also address effluent limitations for domestic WWTPs as they pertain to discharges and more. Other rules governing Use of Reclaimed Water and most pertinent to this project are found in 30 TAC §210.3, §210.22, §210.24, and §210.32. Additionally, 30 TAC §222.81 addresses Buffer Zone Requirements associated with subsurface area drip dispersal systems. For this project, site identification does not differentiate between types of land application: subsurface area drip dispersal systems vs. irrigation disposal systems.

During the course of this research the TCEQ began working on amendments to the regulatory framework for land application and beneficial reuse of TWW (TCEQ 2019). The City of Austin petitioned for changes to the rules for beneficial reuse. The proposed rule changes will eliminate the requirement that additional acreage for land application sites be made available for wastewater that is intended to be used for landscape irrigation or for nonpotable water supply in the event that said reuse is unavailable. The City of Austin is of the position that the

[3] 30 TAC §213.6 does make reference to areas that are zero to five and more than five miles upstream from the recharge zone. In some or many cases, these areas will coincide with the regulated contributing zone.

previous rule, requiring a wastewater treatment plant to set land aside for land application of all effluent generated, is too restrictive and disincentivizes development of alternative reuse strategies. This is especially true for utilities in areas where rapid development has left few contiguous tracts of land available for utilities land apply TWW effluent (TCEQ 2019).

As the result of a 1993 lawsuit (*Sierra Club v. United States Fish and Wildlife Service*), the Edwards Aquifer has become one of the most heavily regulated aquifers in Texas (Patoski 2012). The Edwards Aquifer Authority (EAA) was chartered in 1993 by the 73rd Texas Legislature (SB 1477) to study and protect the Edwards Aquifer by establishing pumping limits to maintain base spring flows required to support the aquifer's 11 endemic endangered or threatened species (Blanton & Associates 2016). The EAA works together with stakeholders in the region in an attempt to protect these species from threats that include: over-pumping and water level drawdown of the aquifer, increased pollution from rapid urbanization, and climate change that could lead to their functional extinction in the next century (Devitt et al. 2019).

The Texas Hill Country, positioned along and west of the I-35 Corridor between Austin and San Antonio, is one of the fastest-growing regions in the United States (US Census Bureau 2019). Texas Water Development Board projections show municipal water demand in the three study cities increasing by 35 percent in Blanco, 154 percent in Boerne, and 562 percent in Leander in the years from 2020 to 2070 (TWDB 2016). This increase in water demand will continue to stress the region's already scarce water resources while leading to a proportional increase in production of wastewater effluent. Furthermore, these cities are upstream of the Edwards Aquifer regulated recharge zone and will need to expand their wastewater treatment plants in the near future.

Literature Review

Every year, approximately 1.2 billion acre-feet of wastewater is produced globally (Nath and Sengupta 2016). In Texas, when wastewater is produced, it is generally sent to a wastewater treatment plant (WWTP). At the WTTP, the influent will go through various processes intended to remove organic solids (i.e., primary treatment) and more (e.g., biological oxygen demand or BOD with secondary treatment) and eliminate pathogens per 30 TAC §309.3 (g). After the treatment process has concluded, most plants will discharge the treated effluent into a nearby watercourse according to limits defined by a permit issued by a state regulatory agency (e.g., Texas Commission on Environmental Quality (TCEQ)) under the federal National Pollutant Discharge Elimination System Program created in 1972 by the Clean Water Act (P.L. 92-500; USEPA 2019).

Despite often being properly treated to higher standards than drinking water from natural sources (Asano and Cotruvo 2004), relatively high nutrient concentrations in treated effluent can negatively impact water quality (Liu et al. 2011; Harry et al. 2016), making it one of the most common forms of water pollution in the US (Grantham et al. 2012). When considering only direct financial inputs and minimum safety standards, the model of primary treatment and stream discharge is the least-cost solution for disposing of wastewater (Hardsity, Sivapalan, and Humphries 2013). When factoring in ecosystem health and services, however, advanced secondary treatment (which includes nutrient removal) and disposal can lead to improved stream health and more overall benefits when properly implemented (Plumlee, Gurd, and Reinhard 2012; Hardisty, Sivapalan, and Humphries 2013). But secondary treated effluent will still have higher nutrient concentrations than effluent that receives tertiary treatment.

Municipal wastewater in the US can be thought of as having gone through either primary, secondary, or tertiary (sometimes referred to as advanced treatment) treatment (USEPA 2019). As of the 1972 Clean Water Act, the United States Environmental Protection Agency (USEPA) only sets minimum standards of secondary treatment of wastewater quality in the US. Individual plants or states can decide to pursue tertiary treatment at their discretion (USEPA 2019). Primary treatment of wastewater is the first step in treating wastewater. Primary Treatment consists of removing unprocessable solids from incoming wastewater either by skimming floating solids from the top or by letting the solids settle out of suspension. Once these solids have been removed the wastewater is then sent to secondary treatment, which is designed to remove organic material from the water via organic decomposers (i.e., bacteria, algae, and fungus). Secondary treatment systems generally attempt to create an environment in which wastewater mixes with oxygen to allow the growth of a biofilm that will process out organic materials. The discharge of secondary TWW can still degrade water quality and inhibit aquatic life in the receiving water body since secondary treatment does not typically remove nutrients or pathogens (USEPA 2019).[4]

Any process beyond primary or secondary treatment is considered advanced wastewater treatment that can be segmented in three categories: tertiary treatment, physical-chemical treatment, and combined biological-physical treatment (Brillyant 2009). Another way to classify advanced wastewater treatment types is to differentiate based on treatment goals. Tertiary treatment can be defined as any treatment process in which unit operations are added

---

[4] Disinfection of domestic wastewater which discharges into waters of the State of Texas is required per 30 TAC §309.3 (g).

to the flow scheme following secondary treatment (Brillyant 2009). Tertiary treatment can include microbial disinfection, constructed wetlands (aka, polishing wetlands), or nutrient removal (see also, Mareddy 2017, chapter 12). For the purposes of this study, however, tertiary treatment will be used in reference to nutrient removal. Secondary treatment does not typically remove nutrients (phosphorus and nitrogen) below levels that cause eutrophication (USEPA 2019).

Tertiary treatment for the removal of nitrogen compounds is very similar to secondary treatment in that it relies on bacteria to extract nitrogen from the water. The difference between tertiary and secondary treatments is that the latter purposely adds oxygen, while tertiary treatment purposely creates an anoxic environment so that the bacteria process the nitrate (NO_3) into oxygen (O_2) and inert nitrogen gas (N_2) via a technique called biological nitrogen removal. The Biological Nitrogen Removal process can also be combined with phosphorus removal to save time, space, and money (USEPA 2019). Organic phosphorus in wastewater is a dissolved solid that is not captured by filters. The Organic Phosphorus Coagulation-Sedimentation processes relies on the fact that objects heavier than water sink to the bottom via gravity, and that certain chemicals (Alum, Lime, Iron Salts) can make suspended solids heavier than water or cause dissolved solids to precipitate out of solution. The phosphorus clumps together and is then strained out to be processed into fertilizer or otherwise disposed of. Adding alum, lime, or iron salts to the biological nitrogen removal tank allows both nitrate and organic phosphorus to be extracted without compromising the effectiveness of either process (USEPA 2019). Tertiary treatment of wastewater effluent may be required for land application in the study area depending on site characteristics and location relative to the Edwards Aquifer contributing zone.

Even at contributions of just five percent treated wastewater effluent of total stream flow, there is a measurable effect on macroinvertebrate diversity and populations (Grantham et al. 2012). Treated effluent discharge can also change the types and amount of plankton and bacteria in a receiving water body (Masserat et al. 2000). Streams are especially vulnerable to nutrient pollution during times of low flow since there is a lack of water to dilute TWW effluent (Rice and Westerhoff 2017). Discharge into ephemeral streams (streams that only flow during and immediately after a significant rain event), has been shown to greatly alter their plant populations, stream width, sedimentation patterns, and overall channel morphology (Hassan and Egozi 2001).

Improperly treated wastewater also has the potential to pollute groundwater resources (Tang et al. 2004; Karnjanapiboonwong et al. 2010; Ackerman et al. 2015) and can travel quickly given the right conditions (Donahue et al. 2015; Hubbard et al. 2016). The rapid infiltration of water into a karstic aquifer makes such systems extremely vulnerable to pollution (Katz, Griffin, and Davis 2009: Kelly et al. 2009; Einsiedl, Redke, and Maloszewski 2010), especially those found in semi-arid environments like the Texas Hill Country (Schmidt et al. 2013). This situation makes for a potential challenge to manage when seeking sites for land application in the study area.

Sewer and septic system seepage can raise aquifer levels while lowering water quality (Chamtouri et al. 2007), as can irrigation using TWW effluent with high nutrient concentrations, but TWW Irrigation has the potential to offset future groundwater withdrawals (Yin et al. 2017) and can be less threatening to groundwater if the effluent has undergone tertiary treatment. One study on an aquifer in Jordan, similar to the Edwards Aquifer, found that up to 20 percent of springflow in dry periods could be traced back to wastewater, treated or otherwise (Schmidt et al. 2013).

It is important to note that contaminant transport through karst systems is largely the result of antecedent conditions. Hydraulic connectivity in karst is a factor of existing meteorological and soil conditions of a site as well as plants ability to remediate contaminants in soils (Schwartz et al. 2013; Lerch et al. 2018). For example, a site that features high moisture content through its entire soil column and lacks plants with the ability to uptake high nutrient concentrations will be more likely to see nutrients make it into the aquifer. An optimal site would therefore feature plants with extensive root systems that would uptake large amounts of nutrients. Any land application site will need an individual study to ensure best management practices are followed to minimize or prevent contamination of the Edwards Aquifer.

The relatively high nutrient loads of TWW that has only undergone secondary treatment generally make it useful for agriculture by helping to mitigate the need for fertilizers and acting as a water source for crops (Huertas, Folch, and Salgot 2007; Mahesh, Amerasinghe, and Pavelic 2015; Morretti et al. 2019). Treated wastewater irrigation, however, can increase the amount of salts and metals in soils over time (Tang et al. 2004; Campi et al. 2016; Kaboosi 2016; Li et al. 2019) unless appropriate measures are taken to mitigate long-term soil degradation (Licata et al. 2017; Ganjegunte et al. 2018).

Irrigation with TWW in Texas has been studied since at least the 1970's (Day et al. 1974). Several studies of TWW irrigation in arid and semi-arid environments show that cotton (Day et al. 1981), haylage (Day et al. 1974; Day and Tucker 1977; Day et al. 1982), and forage (Alkhamisi et al. 2011) provide better yields compared to the same crops and conditions using traditional fertilizer and well water. Sorghum seems to be an ideal candidate for TWW irrigation in the study area since it has a high salt tolerance and is drought resistant (Campi et al. 2016; Ganjegunte et al. 2018).

Determining the best reuse of treated wastewater involves a number of different complex factors such as cost, water quality, technology, infrastructure, and existing conditions (Chen et al 2014; Kunz et al 2015; Nath and Sengupta 2016; Cossio et al 2017; Akhoundi and Nazif 2018; Wongburi and Park 2018). But whenever there is limited access to water, TWW irrigation becomes an attractive option (Mahesh, Amerasinghe, and Pavelic 2015). As climate change and population growth increase the potential for water scarcity, wastewater reuse will become a necessity in arid and semi-arid environments (Akhoundi and Nazif 2018; Moretti et al 2019), and efficient wastewater treatment and agricultural practices will become vital to protecting stream ecosystem health (Gücker, Brauns, and Pusch 2006; Banner, Stahl, and Dodds 2009; Grantham et al. 2012).

Besides the potential benefits of land application and as suggested above, there are legitimate concerns with land application of TWW in the Texas Hill Country. They include level of wastewater treatment applied and resultant nutrient concentrations vis-à-vis application-site characteristics, use of an application rate that doesn't oversaturate soils, and vegetation management that ensures proper harvest of nutrients taken up by plants (*personal communication,* Kelly Davis, Staff Attorney, Save our Springs Alliance, November 5, 2019, conversation). Other challenges have to do with the current regulatory environment with regards to inadequate or lack of soil and downgradient water-quality monitoring requirements and other related concerns (Ross 2011; Ross 2019; Porras et al. 2016). Richter and Hiers (2017) have documented elevated concentrations of chloride, nitrate/nitrite, sodium, and strontium isotopes at springs and downgradient streams adjacent to two Texas Land Application Permit (TLAP) facilities. There is room for improvement, therefore, to safeguard local and regional water quality while taking advantage of TWW as a useful source of water.

Methods

This research project utilizes a geographic information system (GIS) in order to identify the best cities and sites for land application of TWW. A GIS is an important tool in solving spatial problems and has been used before to answer questions related to TWW reuse (Barbagello et al. 2012; Ahmadi and Merkley 2017). A GIS has the ability to analyze disparate pieces of data to identify sites that meet a user's selection criteria (Pedrero et al. 2011; Barbagallo et al. 2012; Ahmadi and Merkley 2017; Viccaro 2017). This research is most similar to Ahmadi and Merkley in theme, and Pedrero et al. (2011) in execution. Ahmadi and Merkley (2017) chose to calculate reuse potential for a single a city in Utah using a water budget, but not to identify individual sites suited to reuse. This research project utilizes a GIS in order to identify the best cities and sites for TWW reuse. Methodologically, this work is similar to Pedrero et al. (2011) where map algebra and Boolean algorithms were used to identify individual sites that would be ideal for aquifer recharge with treated wastewater. Pedrero et al. (2011) chose to conduct their analysis by combining multiple layers into a Boolean grid with simple yes/no criteria then chose the sites that had “yes” where map algebra and Boolean algorithms were used to identify individual sites that would be ideal for aquifer recharge with treated wastewater.

The data used in this study include water use and population from 2010 (TxDOT 2018) and projections out to 2070 (TWDB 2016). This study looked at the areas within one-, two-, and three-mile radii of the WWTPs of three target cities in order to identify sites that meet the selection criteria and could benefit from land application to prevent increased wastewater discharges into Hill Country streams.

The first phase of analysis began with identifying 27 Hill Country cities based on their location relative to the Edwards Aquifer. This phase focused on gathering publicly available data from the TWDB, TCEQ, and the Texas Natural Resource Inventory System (TNRIS) and then analyzing it to winnow down the list to a smaller subset of the best candidate cities. This study used shapefiles available through TNRIS to select cities that were situated in either the contributing zone or the recharge zone of the Edwards Aquifer. It was assumed that increases in these cities stream discharge of treated effluent could potentially degrade the water quality in the aquifer. While the Edwards Natural Boundaries were used for city selection, the Edwards Regulatory Boundaries were chosen for second phase analysis since they are more pertinent to the permits issued by the TCEQ for WWTPs. Just because a part of the Edwards Contributing zone is unregulated, however, does not mean that it is not hydraulically connected to the aquifer and that effluent disposal methods there can't affect the aquifer’s water quality.

Raster data sets were then either found or generated from the available data for projected population growth from 2020 to 2070, land cover data from the National Landcover Database (NLCD), and Euclidean distance of sites from the cities’ WWTP. The raster data were then all reclassified to a standardized 1 to 10 scale so that they could be run through a weighted average tool. The selection criteria and weighting scale is shown (Table 1).

Table 1. Phase 1 selection criteria and weighting scale applied to initial set of 27 Hill Country cities.

Selection Criteria	Assigned Weight
Population Growth Rate	40%
Distance from WWTP	30%
Land Use (NLCD)	30%

Population growth out to 2070 was given priority in the first-phase analysis since it was used as a proxy to represent a given municipalities need to expand the WWTP and this study wanted to prioritize finding solutions for cities that were expanding the fastest. Land use and Distance from the WWTP were considered equally important in the first-phase selection, but only a little less important than population growth. A 40:30:30 ratio was chosen for weighting these three criteria.

The USGS's National Landcover Database (2016) was also used in the first-phase analysis since it required less resolution and its categories of Hay and Cultivated Crops were considered sufficient for identifying suitable agricultural land for potential land application. The United States Department of Agriculture CropScape (2016) data set was used in the second-phase analysis since it explicitly listed different crop types in a given location but is still derived from the NLCD 2016 LIDAR data.

Scores of 1 in any given category represented the scenarios that were least ideal for each category such as; slowest rates of population growth, land-use designations where reuse was not an option, and sites furthest from WWTPs. Scores of 10 represented the factors that made a site an ideal candidate; fastest rates of population growth, land-use designations traditionally associated with reuse, and sites located nearest to WWTPs. Different raster data values were manually assigned scores within the weighted overlay modelling tool itself. Scores between 1 and 10 represented varying degrees of usefulness for beneficial reuse. A 1 to 10 scale was used because it was something that a casual observer should be generally familiar with and allowed for finer resolution than a scale with fewer designated categories. After the reclassification process the raster data were put through a weighted overlay model. The model calculated a weighted average for each pixel in the study area based on the reclassified 1 to 10 scale raster-data layer generated for population growth, Euclidean distance from WWTPs, and Land Use Designation. The cities in the region that had the most high-scoring pixels within a 3-mile radius were then compiled into a list of the nine top candidates out of the original 27 cities considered.

The top nine cities had their WWTP's most recent average daily discharges compared to their permitted maximum daily discharge to see if they had hit the legally required threshold (75 percent of permitted maximum discharge) for plant expansion. From this group of nine cities, the final three target cities were chosen for study based on meeting the following criteria:

1. The target city's WWTP is located within or upstream of either the contributing or recharge zones of the Edwards Aquifer regulatory boundary,
2. Have a current or near future need to expand their WWTP based on reported average daily discharge being 75 percent or more of permitted maximum daily discharge,

3. Be early enough in their planning development cycle, either hypothetically or in actual practice, that reuse infrastructure could be carefully examined and planned for at the most efficient time, and
4. Have land-use scenarios suitable for land application that were within a 3-mile (maximum) radius of the WWTP.

The three cities that met these criteria are Blanco (Figure 3), Boerne (Figure 4), and Leander (Figure 5). These cities were then given a second and more in-depth analysis. Population projections for these three cities are featured in Table 2.

Table 2. Population and projections for three study cities in Texas.

City	Population 2010	Population Projections			
		2020	2030	2050	2070
Blanco	1,739	2,156	2,563	2,927	3,060
Boerne	10,471	14,367	18,820	28,187	37,619
Leander	26,521	50,562	94,378	235,142	344,240

Both Boerne and Leander had two different WWTPs available for analysis. For practical reasons related to project length and budget, this study focuses on one WWTP from each city. Boerne's newer WWTP was chosen since it was closer to reaching its permitted maximum discharge. While Leander's older WWTP was chosen because it was nearing the 75 percent of maximum discharge threshold. The second WWTP serving Leander, the Brushy Creek WWTP, is a regional plant that also serves parts of the City of Round Rock and City of Austin's northern residential districts (K Friese & Associates, Inc. 2008).

Figure 3. City of Blanco, Texas and relevant spatial features.

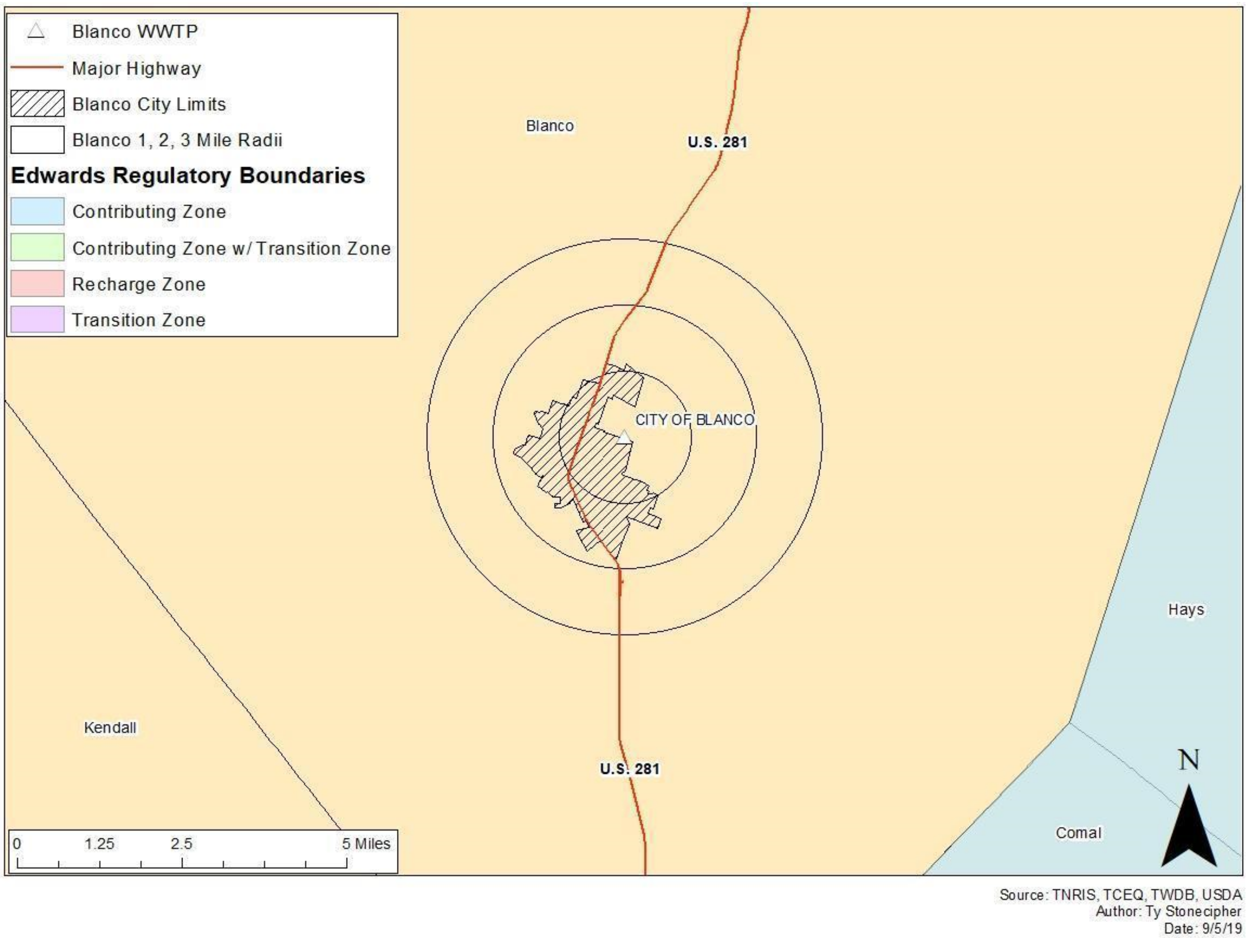
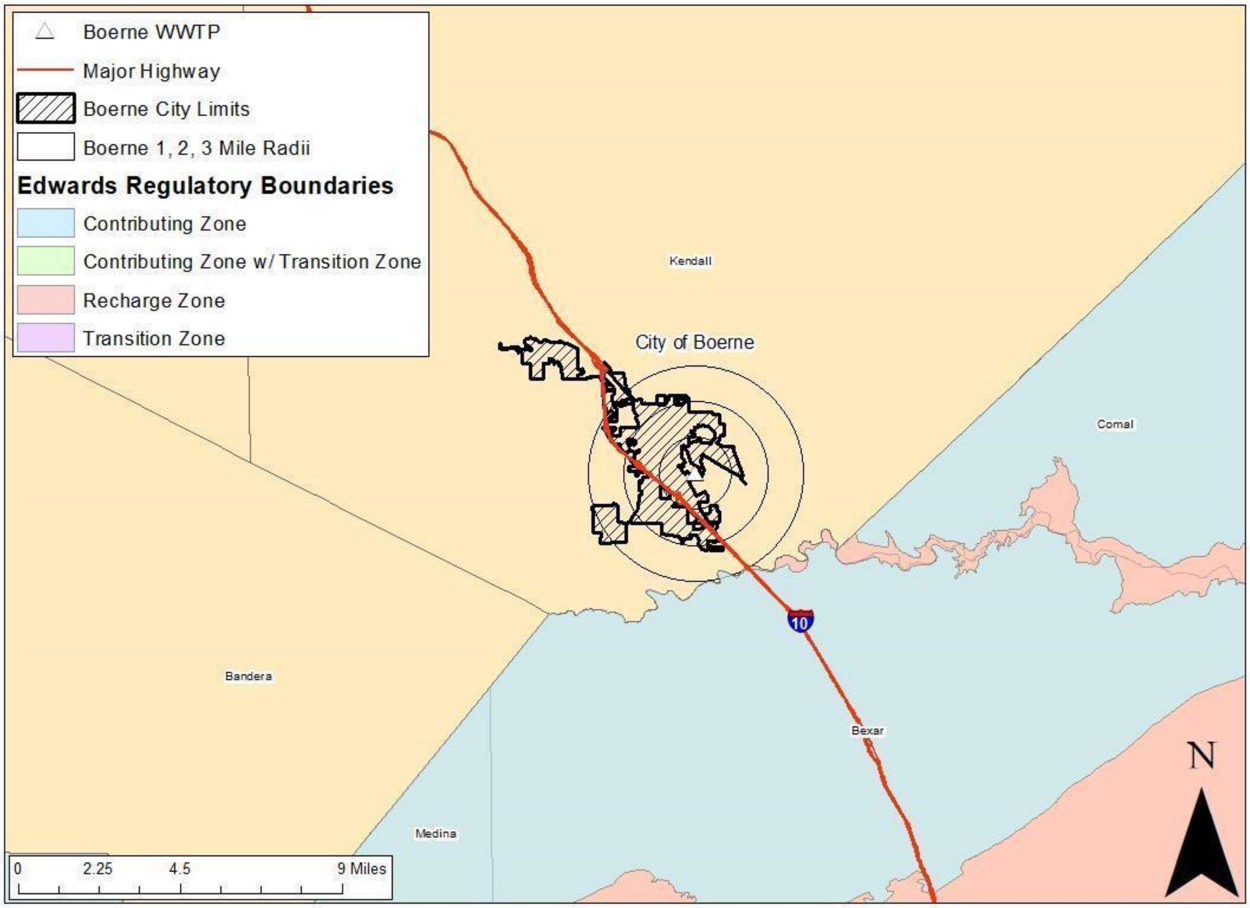
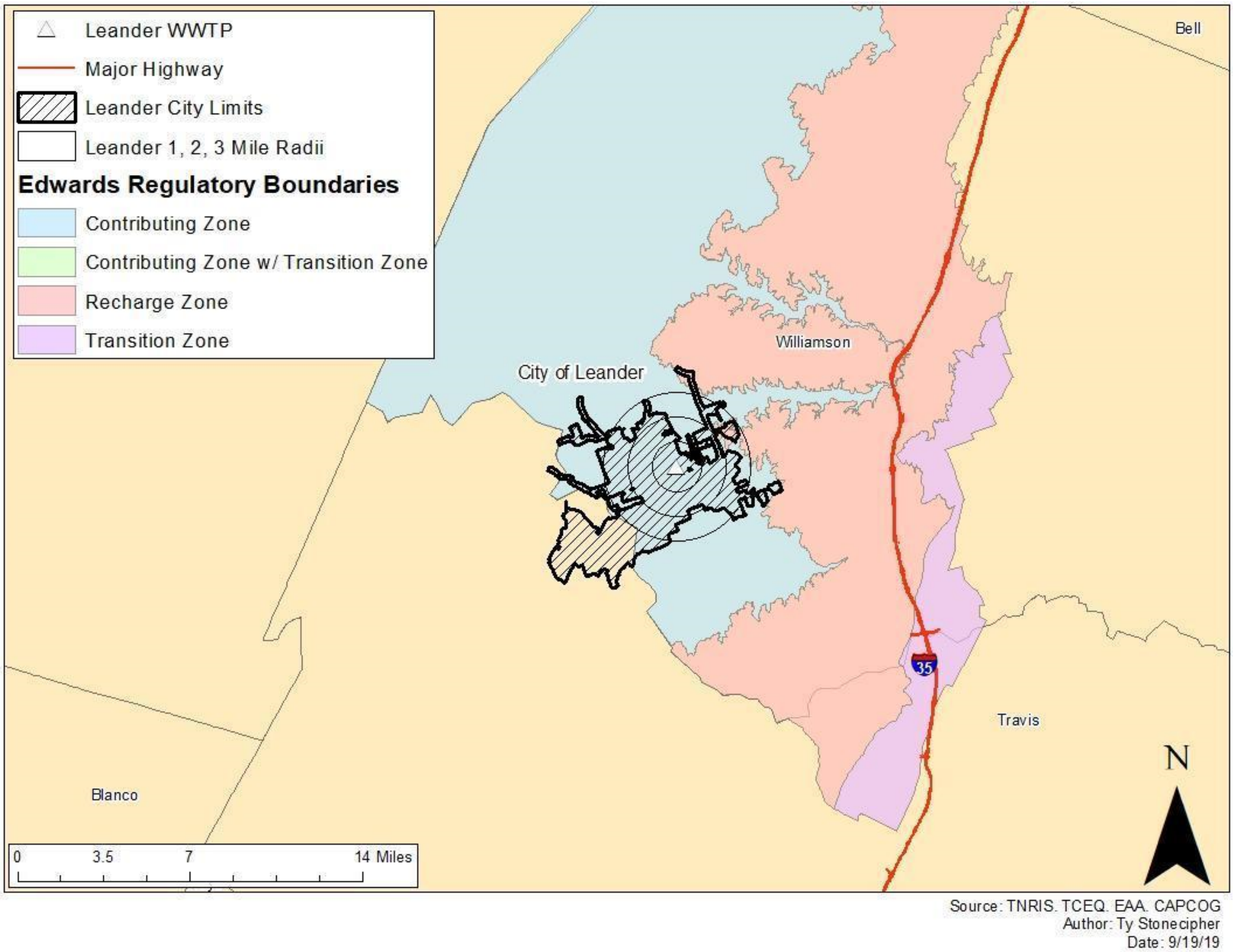


Figure 4. City of Boerne, Texas and relevant spatial features.



Author: Ty Stonecipher
Data Source: TNRIS, TCEQ, Kendall County GIS Department
Date: 9/5/2019

Figure 5. City of Leander, Texas and relevant spatial features.



The second phase of this study features a more in-depth investigation into specific sites around each of the target cities that would be ideal for TWW reuse. All three cities were analyzed individually. The analysis began by calculating the number of acres required to meet present outflows and future effluent land application needs. Current needs for total land application of effluent were calculated by dividing the most recent average daily discharge as of June 2019 by an application rate based on land application permits issued by the TCEQ to several nearby cities with similar environmental conditions; Kerrville, Marble Falls, and Wimberly. Wimberly's permitted application rate of 4,195 gallons per acre per day was chosen for calculating the required acreage for meeting all effluent allocation needs via land application since it was the most conservative of the three relevant permits. Note that full implementation of land application will require its own unique land application rate based on site specifics including soil type(s), plant cover, and evapotranspiration rates. Use of an application rate from another permit was used in this study as a proxy since calculating individual application rates for each site was both beyond the scope of this research and would be done as part of the permitting process for any new or (amendments to) existing permits.

Future acreage required was calculated by using an estimate of residential indoor water use, expressed as gallons per capita per day (GPCD), of 62 (Loftus and Smith 2018; Hermitte and Mace 2012), then multiplying that number by future population estimates to determine the amount of water that would become treated effluent and thus, potentially discharged to a local stream in the future (Table 3). That number was then divided by the aforementioned application rate to determine the area required to achieve 100 percent land application in the future (Table 4).

Table 3. WWTP discharge data by city

City	Average Daily Discharge Gallons/Day (6/6/19)	Projected Future Effluent Gallons/Day (2070)
Blanco	135,000	189,720
Boerne	1,023,500	2,332,378
Leander	1,196,000	21,342,880

Table 4. Acreage requirements for full reuse via land application by city.

City	Current Land Application Area Needed for Full Reuse	Future Land Application Area Needed for Full Reuse
Blanco	32 acres	45 acres
Boerne	244 acres	556 acres
Leander	286 acres	5,088 acres

A weighted overlay model was again used to determine sites in proximity to the WWTPs that could benefit from land application of treated effluent. The criteria for this weighted overlay were determined by a combination of the Texas Administrative Code's Title 30, Part 1, Chapter 213 rules for the Edwards Aquifer (specifically §213.6 having to do with wastewater treatment and disposal systems) and a synthesis of information gained from reading relevant literature. The selection criteria weighting scale for the phase 2 analysis is shown in Table 5. Note that the Edwards Aquifer regulatory boundary criterion did not use all scores between 1 and 10.

Table 5. Phase 2 selection criteria and weighting scale.

Site Selection Criteria	Assigned Weight
Land Use (CropScape)	50%
Edwards Aquifer Regulatory Boundary	25%
Distance From WWTP	15%
Percent Slope	10%

This analysis prioritized:

1. sites with traditional land use scenarios like parks, school related recreational fields, cemeteries, golf courses, and nonfood crops,
2. sites outside Edwards Aquifer regulatory boundary,
3. sites closer to the WWTP within the radius of interest, and
4. sites with slopes of less than 8 percent.

Some criteria in the Texas Administrative Code that are related to land application not considered as part of this initial study of potential: soil properties, site specific evapotranspiration rates, public and private well locations, and well water quality near application sites. These criteria will be considered by the TCEQ on a case by case basis during the permit application process. Here, land use was considered to be an acceptable proxy for soils, and the area's average net lake evaporation of 60" per year (TWDB 2012) should generally support land application. While well data may be available from local groundwater conservation districts (GCD), not all private wells are known to be registered with the local GCD. Thus, ground truthing and additional data collection may ultimately be necessary to determine the presence of or distance from a well. It should be noted, however, the presence of water wells doesn't automatically disqualify a site from being used for land application and must be reviewed based on the permitting requirements found in 30 TAC Chapter 210 and 30 TAC §309.13, rules defining unsuitable site characteristics for irrigation using wastewater effluent.

Much like in phase 1, a 1 to 10 scale raster data layer was generated for each of the four criteria identified in Table 5. Much like in the first phase analysis, higher scores represented sites with more ideal conditions per the selection criteria while lower scores denoted sites that were less ideal. A few conditions automatically excluded a site from beneficial reuse: sites that had slopes greater than eight percent, sites that were located within the floodway, or were within the Edwards Aquifer recharge zone. Anytime a site met one or more of these three conditions, that cell's score was automatically set to a value of zero, regardless of how well it scored in any other category since it would automatically fail the permitting process

The second weighted-overlay model automatically generated a results raster data layer based on the weighted average of the four new 1 to 10 scale raster data. The results raster data layer was also a 1 to 10 scale raster where pixels with a higher score represent sites that are theoretically more ideal for beneficial reuse. A site with a score of 10, for example, may represent a flat field exceptionally close to the WWTP that is growing a growing a crop that meets the rules outlined in 30 TAC §210.24 (Irrigation Using Reclaimed Water) and §210.32 (Specific Uses of Reclaimed Water.) A site with a score of 8 might be that same agriculture field but further away from the WWTP or be a ballpark that has more restrictions on how to use land application.

Lastly, water quality protection buffers were added for both the Blanco and Boerne analyses. These buffer zones are required for subsurface area drip dispersal systems per 30 TAC §222.81. Buffers were set for a radius of 500 ft from a public water supply well, 150 ft from all privately owned wells, and 100 ft from all delineated waters of the state. No subsurface drip-disposal systems are allowed within those buffers, and since this research does not differentiate between types of land application systems, any sites within those buffers were noted and removed from consideration for implementing land application effluent.

Results

The results section for each city first quantifies the amount of high scoring sites that are available to meet current and future land application needs. Secondly, the results quantify the percentage of sites required to meet future land application needs that are within the current regulatory boundary of the Edwards Aquifer (other than recharge). Finally, additional analysis indicates slight reductions in high-scoring land application sites due to losses to the buffer zones that have been placed around water supply features for Blanco and Boerne. Since Leander appears unable to implement land application of TWW on a scale large enough to meet its future needs, this additional analysis was not performed there.

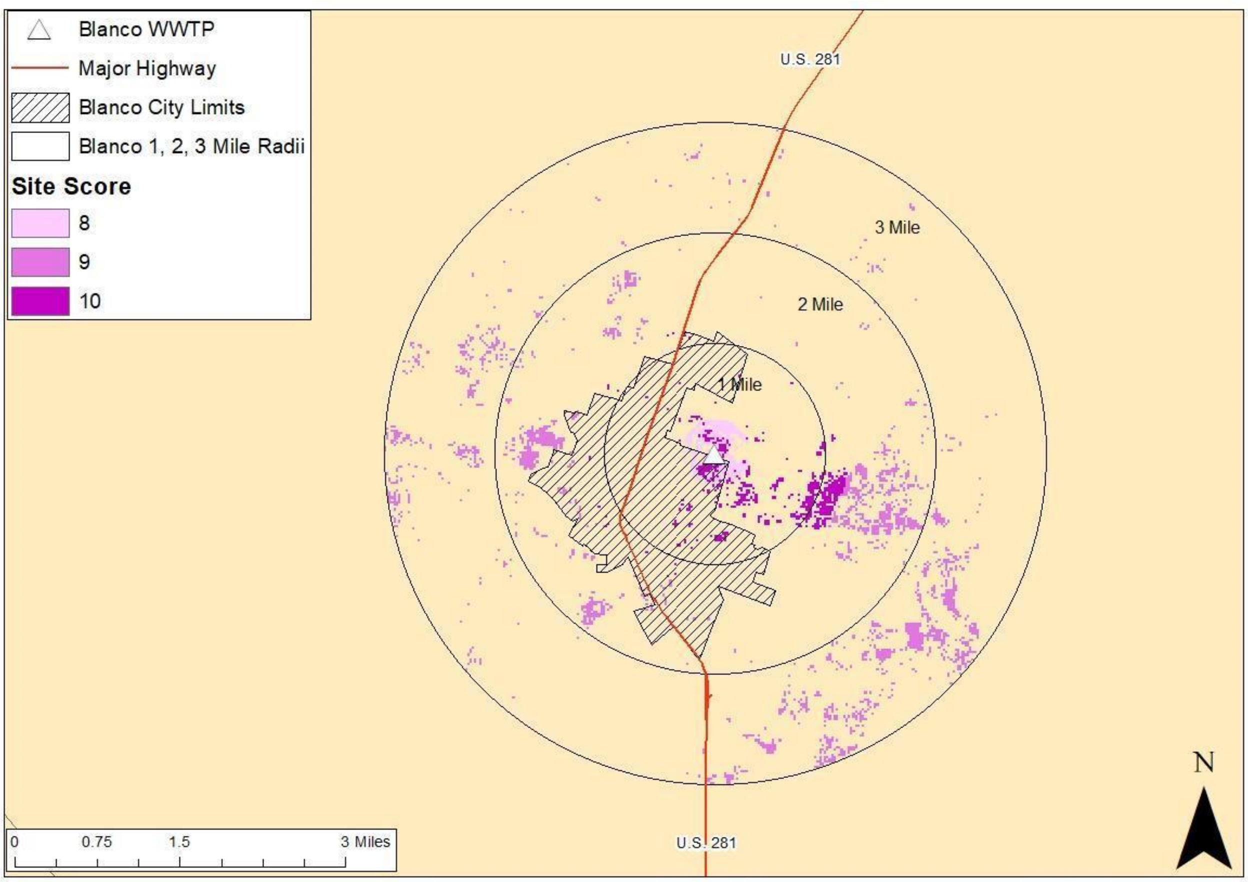
Blanco, Texas

The City of Blanco (Figure 6) can meet 100 percent of its current (32 acres) and future (45 acres) needs for land application sites within a one-mile radius using only sites with a score of 10 (Table 6). One hundred percent of the highest quality sites identified for Blanco are outside of the regulatory boundary of the Edwards Aquifer. The buffer for wells and waters of the state (Figure 7) as per state regulations showed no appreciable loss of usable land-application area. Less than five acres out of the 192 acres identified as reuse sites fell within water quality protection buffers. Thus, Blanco can still meet 100% of its future land disposal needs within one mile of the WWTP and with the most suitable acreage.

Table 6. Breakdown by site scores of acreage needs met within one mile of WWTP for City of Blanco, Texas.

Site Scores Within 1-Mile Radius of WWTP	Current Acreage Need Met (%)	Current Area in Acres	Future Acreage Need Met (%)	Future Area in Acres
Score of 10	100	33	100	46
Score of 9	N/A	N/A	N/A	N/A
Score of 8	N/A	N/A	N/A	N/A

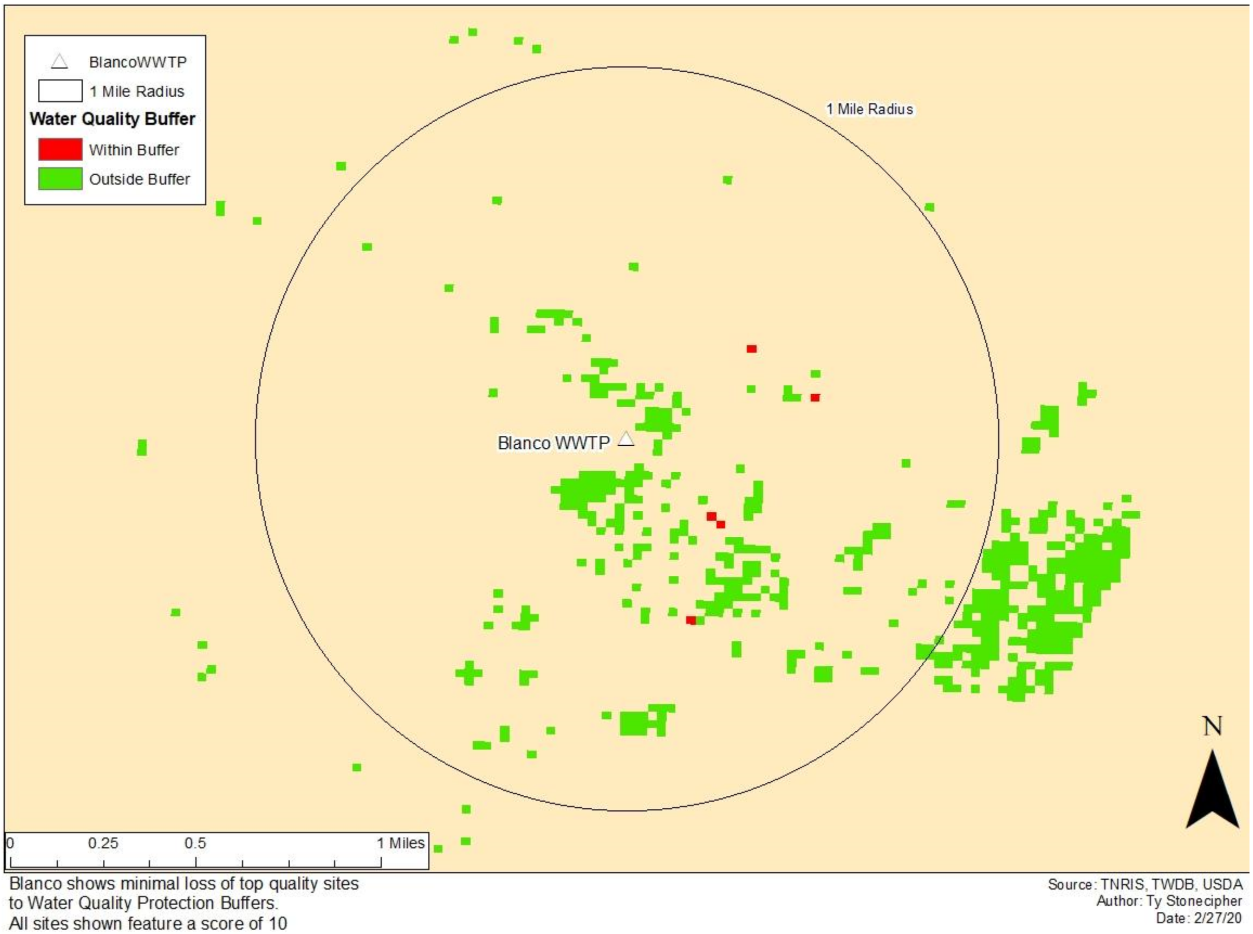
Figure 6. Distribution of weighted-site scores for City of Blanco, Texas.



Blanco can satisfy its current and future need by using only sites with a score of 10 with in 1 mile.

Source: TNRIS, TCEQ, TWDB, USDA
Author: Ty Stonecipher
Date: 9/27/19

Figure 7. Comparison of Reuse sites inside and outside of Water Quality Buffers for Blanco, Texas



Boerne, Texas

The City of Boerne (Figure 8) can meet current needs (244 acres) with sites featuring scores of 9 or 10 within a one-mile radius of the WWTP. Ninety-two percent of the sites needed to meet current needs within one mile of the WWTP feature a score of 9 (Table 7). Meeting all of Boerne's future needs (556 acres) within one mile would require that twenty-one percent of future effluent would be applied to sites with a score of 8. Given the weighting scale, a lower site score most likely represents a land use category that is less ideal for land application, but could potentially represent a site that is further away (within the radius under study: here, one mile) or within a regulatory boundary (i.e., contributing zone) of the Edwards Aquifer. Table 7 shows how acreage needs are met within the 1-mile radius of the WWTP. Zero percent of sites required to meet either current or future land application needs fall within the Edwards Regulatory Boundary. Extending the radius out to two miles will allow Boerne to meet its future needs entirely with sites featuring a score of 9 or 10 should sites scores of 8 be deemed less feasible. The buffer analysis for Boerne (Figure 9) also showed minimal loss of identified reuse sites to water quality buffers. Of the 874 acres of usable land within one mile of the WWTP, 82 acres were found to be within the water quality buffer around water supply features. Ultimately, Boerne will be able to meet future reuse needs within one mile via land application.

Table 7. Breakdown by site scores of acreage needs met within one mile of WWTP for City of Boerne, Texas.

Site Scores Within 1-Mile Radius of WWTP	Current Acreage Need Met (%)	Current Area in Acres	Future Acreage Need Met (%)	Future Area in Acres
Score of 10	8	18	4	18
Score of 9	92	224	75	420
Score of 8	N/A	N/A	21	117

Figure 8. Distribution of weighted-site scores for City of Boerne, Texas.

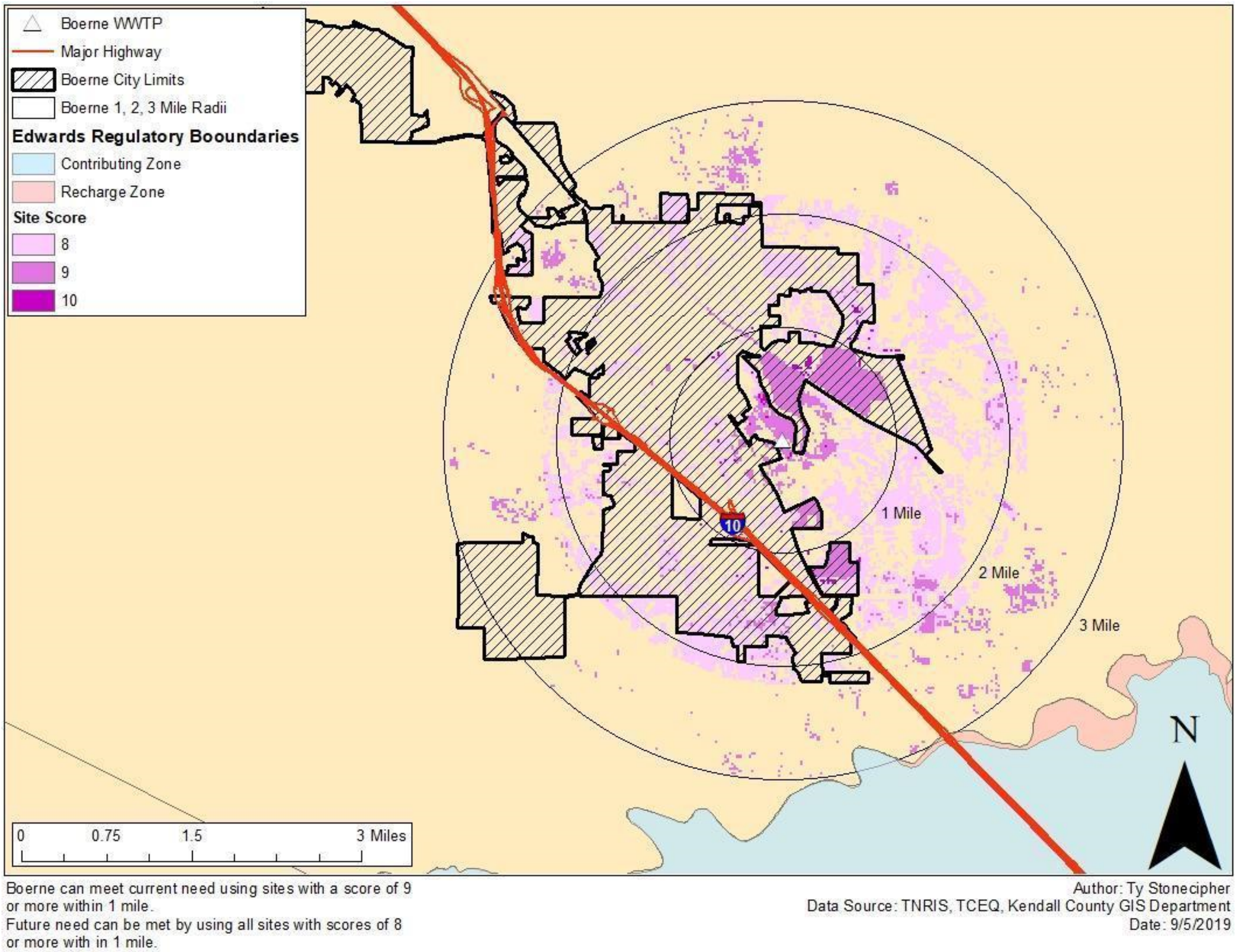
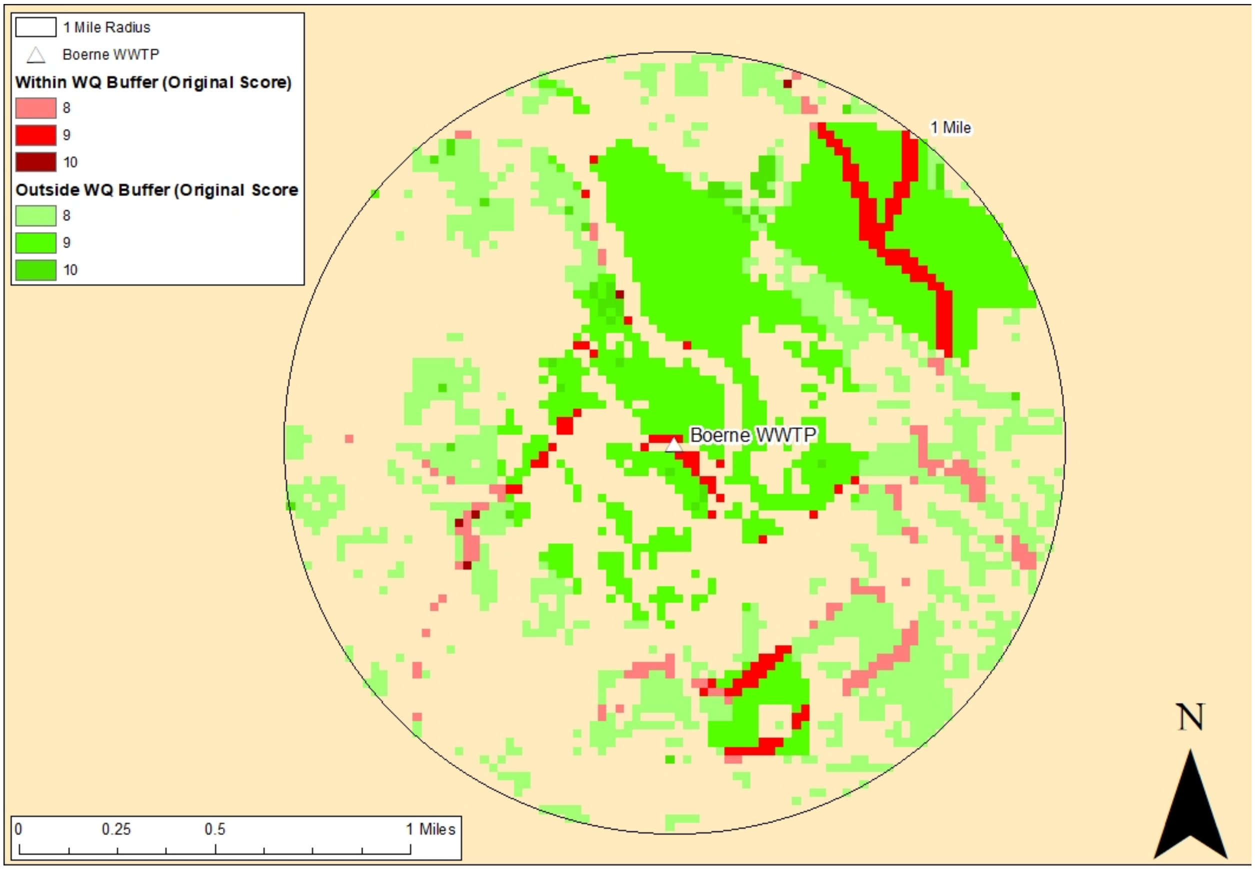


Figure 9. Comparison of Reuse sites inside and outside of Water Quality Buffers for Boerne, Texas.



While Boerne did lose some high quality sites to the WQ Buffer. Boerne should still be able to meet future need within 1 mile.
Scores reflect original value.

Author: Ty Stonecipher
Data Source: TNRIS, TCEQ, Kendall County GIS Department
Date: 3/16/2020

Leander, Texas

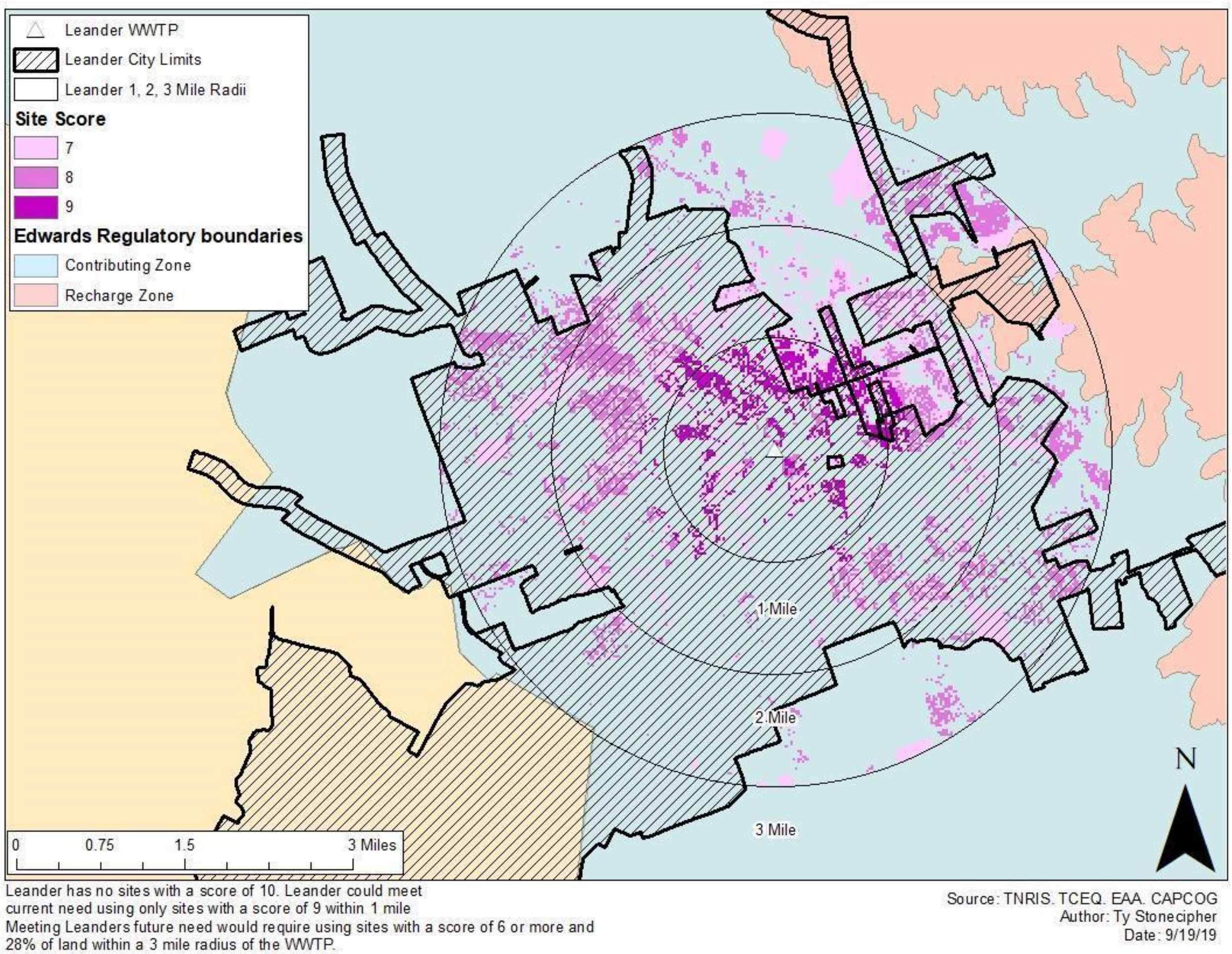
The City of Leander (Figure 10) does not feature any sites with a score of 10 within a three-mile radius of its WWTP. Leander can meet its current need (285 acres) for land application of effluent, however, using sites with a score of 9 within a one-mile radius (Table 8). To meet Leander's future need (5,088 acres), the city will need to irrigate every site with a score of 7 or more and irrigate to meet the last 17 percent of its effluent-allocation needs with sites featuring a score of 6; extending out to a three-mile radius. Meeting Leander's future needs would require using approximately 28 percent of all the land within a three-mile radius of its

WWTP. About three percent of Leander's three-mile radius is within the recharge zone of the Edwards Aquifer regulatory boundary and 97 percent is within the contributing zone. Thus, 100 percent of sites required to meet future land application needs are located in the contributing zone. Given the fact that Leander does not appear able to meet future needs within a 3-mile radius under ideal conditions, a water quality buffer analysis was not done for this rapidly growing city.

Table 8. Breakdown by site scores of acreage needs met within one and three miles of WWTP for City of Leander, Texas.

Site Scores Within 1- and 3-Mile Radius of WWTP	Current Need – 1-mile radius	Current Area in Acres – 1-mile Radius	Future Need – 3-mile radius	Future Area in Acres – 3-mile Radius
Score of 10	0%	0	0%	0
Score of 9	100%	286	10%	488
Score of 8	N/A	N/A	32%	1643
Score of 7	N/A	N/A	41%	2086
Score of 6	N/A	N/A	17%	871

Figure 10. Distribution of weighted-site scores for City of Leander, Texas



Discussion

This study identified over 800 acres of high-quality sites within three miles of Blanco, and almost 4,000 acres of ideal reuse sites within three miles of Boerne. Both Blanco and Boerne currently have 17 and seven times the amount of land required, within three miles of their WWTPs, to meet their respective effluent allocation needs. This abundance of high-quality sites nearby increases the likelihood of these two cities securing enough land to actually implement 100 percent reuse of TWW via land application.

Of the three cities studied, Blanco appears to be an ideal candidate for land application of TWW effluent given the ample supply of high-quality sites also identified within one mile of their WWTP. Blanco is smaller and growing at a slower rate than the other cities studied. For example, the acreage required for Blanco to land apply all of its treated effluent in the future is only eight percent of Boerne's future need and 0.8 percent of Leander's. Blanco is still relatively undeveloped and has plenty of agriculture fields and pastures that would benefit from TWW reuse in close proximity to their WWTP.

Another benefit that Blanco enjoys is that of being a relatively smaller, less populous city that produces commensurably less effluent requiring less area to achieve one hundred percent land application. Blanco does not have neighboring cities encroaching on its boundaries; another potential limit to land availability for reuse of TWW. If the city plans its growth well, then they should be able to acquire, lease, or contract with enough sites for land application of effluent to ensure total reuse while still having room for their expected future development.

The City of Boerne can potentially benefit from TWW reuse but needs to act quickly on making arrangements with enough high-quality sites to meet both present and future demand. Based on population projections, Boerne will need more area for land application from an increasingly shrinking number of nearby-available sites as the city grows. Boerne's land application future lies in utilizing the parks and open spaces that are already near its WWTP and securing an arrangement for/with the large fields of nearby shrubland before they are developed. If Boerne does not act quickly to secure the best reuse sites, then the large open fields required for 100 percent reuse will likely be developed and become mostly unusable for future land application of TWW effluent. If most of the land around the WWTP were to be developed, Boerne's ability to pursue land application will not necessarily end. The city could establish an ordinance or building code for new subdivisions and developments on the north and west sides of the city to start building decentralized WWTPs that would be closer to other suitable land application sites. Examples of developments that are self-contained in this way can be found elsewhere in the country including the Mill Creek subdivision in Geneva, Illinois (Sheaffer [2004?]).[5]

Considering that Leander is a rapidly urbanizing city with 99.97% of the three-mile radius of its WWTP falling within a Edwards Aquifer regulatory boundary, reuse of treated wastewater from this central location may not be a viable way to deal with the increased volumes of effluent that will result from its future growth. Leander lacks sufficient quantities of agricultural land and open fields that are well suited for land application of TWW effluent within a three-mile radius. While the USEPA's "Design Process Manual: Land Treatment of Municipal Wastewater Effluents" indicates that the maximum economic distance to pipe TWW effluent is eight km (approximately 5 miles) (USEPA 2006), Leander is unlikely to find sufficient sites within that radius given the proximity of neighboring cities, competition for space (e.g., extra-territorial jurisdictions), and relative location to the Edwards Aquifer Recharge Zone. Leander does have parks, cemeteries, and ballfields in within proximity to the WWTP, but these do not represent a large enough area to meet Leander's future effluent application needs. A series of decentralized WWTPs nearer to land application sites also does not seem to hold the answer for Leander's future needs because Leander abuts three other rapidly growing suburbs

[5] The Mill Creek Project is designed by Sheaffer and Roland, Inc.

of Austin: Cedar Park, Georgetown, and Round Rock and has another neighbor that has the potential to box them in. Development-specific, on-site treatment and reuse capacity can obviate this constraint.

Considering alternatives, Leander might be better served by other reuse options: direct-potable reuse, dual plumbing in new developments, and industrial reuse that this study did not consider. A future study can quantify the industrial reuse potential in or near the growing suburbs of Austin and San Antonio, study the cost of direct-potable reuse and/or dual plumbing in new construction, or explore the viability of a residential lawn reuse program. Lastly, the authors would be remiss if we didn't stress that the pursuit to maximize water-use conservation and efficiency and thus, reduce the production of wastewater effluent, is a cost-effective and first-order strategy for all communities to implement.

Conclusion

Rapidly growing towns and urbanizing areas face many challenges and achieving efficient water resource management is among them. The Texas Hill Country faces such challenges and is a unique and beautiful landscape where drought is commonplace, scarcity looms large in the face of a growing population, and competition for water is a growing phenomenon. Here, concern for managing water demand and protecting the high-quality streams and the Edwards Aquifer is very high.

This research was conducted because of the opportunity available to anticipate new developments in the region and to help accelerate the transformation of treated wastewater from a pollutant and waste by-product into a resource that protects water quality and extends water supply. Reuse of treated wastewater effluent also has the potential to create new economic opportunities for both city utilities and landowners who receive the resource.

This study applies a replicable methodology that makes use of publicly available data for identifying candidate cities and specific sites that could potentially benefit from land application (i.e., reuse) of TWW. The attributes of readily available technology, social and environmental benefits related to protecting the health of local streams and rivers, and increasing need for water conservation, make land application an ideal best management practice for a city and utility to implement. That said, it is acknowledged that tertiary treatment of wastewater may be necessary in certain situations for achieving both land application goals and simultaneously protecting the quality of groundwater and local streams that are closely connected with the Edwards Aquifer.

The results of this study are mixed across the three cities considered, owing to the many factors that constrain decision-making that is centered on land application of TWW. A follow-up feasibility analysis that considers, for example, cost and willingness of neighboring landowners to collaborate as partners is warranted for both Blanco and Boerne. The City of Leander poses additional challenges and warrants discussion among residents and elected officials alike about how and where they plan to treat greatly increasing volumes of wastewater and what they plan to do with the resulting effluent.

In the case of all three cities studied here along with others in the Texas Hill Country, leaders and residents must work together to build a shared vision for their community's water future. A shared vision need not be bound by the predominant 20th Century model for development including the more traditional ways of thinking about wastewater disposal. In the

Texas Hill Country, treated effluent is growing in volume in lockstep with population and increasing demand for more water. Here in the Texas Hill Country and elsewhere, development provides an opportunity to manage water in a holistic and integrated fashion; as "One Water" on a watershed basis rather than different kinds of water that each require separate and independent planning and management scenarios.

As noted above, TWW reuse is not without challenges to overcome and costs to be considered. In any event, there is ample reason to pursue alternatives to stream discharge of treated wastewater including land application where possible. Cities that wish to pursue reuse of TWW such as the land application potential explored here, will need to begin discussions and planning now in order to get ahead of inevitable development and reap the full benefits potentially available.

References

Ackerman, J. R., E. W. Peterson, S. V. D. Hoven, and W. L. Perry. 2015. Quantifying nutrient removal from groundwater seepage out of constructed wetlands receiving treated wastewater effluent. *Environmental Earth Sciences* 74 (2):1633–1645.

Ahmadi, L., and G. P. Merkley. 2017. Wastewater reuse potential for irrigated agriculture. *Irrigation Science* 35:275–285.

Akhoundi, A., and S. Nazif. 2018. Sustainability assessment of wastewater reuse alternatives using the evidential reasoning approach. *Journal of Cleaner Production* 195:1350–1376.

Alkhamisi, S. A., H. A. Abdelrahman, M. Ahmed, and M. F. A. Goosen. 2011. Assessment of reclaimed water irrigation on growth, yield, and water-use efficiency of forage crops. *Applied Water Science* 1 (1-2):57–65.

Asano, T., and J. A. Cotruvo. 2004. Groundwater recharge with reclaimed municipal wastewater: health and regulatory considerations. *Water Research* 38 (8):1941–1951.

Banner, E. B. K., A. J. Stahl, and W. K. Dodds. 2009. Stream Discharge and Riparian Land Use Influence In-Stream Concentrations and Loads of Phosphorus from Central Plains Watersheds. *Environmental Management* 44 (3):552–565.

Barbagallo, S., G. L. Cirelli, S. Consoli, F. Licciardello, A. Marzo, and A. Toscano. 2012. Analysis of treated wastewater reuse potential for irrigation in Sicily. *Water Science and Technology* 65 (11):2024–2033.

Baresel, C., L. Dahlgren, M. Almemark, and A. Lazic. 2015. Municipal wastewater reclamation for non-potable reuse – environmental assessments based on pilot-plant studies and system modelling. *Water Science and Technology* 72 (9):1635–1643.

Blanton & Associates, Inc. 2017. Edwards Aquifer Habitat Conservation Program, 2016 Annual Report. https://www.edwardsaquifer.org/doc_publications/2016-eahcp-annual-report/ (accessed August 25, 2019).

Brillyant. 2009. What is advanced wastewater treatment? http://www.brillyantinc.com/index.php?option=com_content&view=article&id=69:what-is-advanced-wastewater-treatment&catid=56:wastewater-treatment&Itemid=41 (accessed November 13, 2019).

Campi, P., A. Navarro, A. D. Palumbo, F. Modugno, C. Vitti, and M. Mastrorilli. 2016. Energy of biomass sorghum irrigated with reclaimed wastewaters. *European Journal of Agronomy* 76:176–185.

Chamtouri, I., H. Abida, H. Khanfir, and S. Bouri. 2007. Impacts of at-site wastewater disposal systems on the groundwater aquifer in arid regions: case of Sfax City, Southern Tunisia. *Environmental Geology* 55 (5):1123–1133.

Chen, S.-M., Y.-M. Wu, and L. Yang. 2014. Application of the Analytic Hierarchy Process for the selection of wastewater reuse targets. *Management Decision* 52 (7):1222–1235.

Chrislock, M., E. Doster, R. Zitomer, and A. Wilson. 2013. Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. *Nature News*. https://www.nature.com/scitable/knowledge/library/eutrophication-causes-consequences-and-controls-in-aquatic-102364466 (last accessed 23 July 2019).

Corominas, L., V. Acuña, A. Ginebreda, and M. Poch. 2013. Integration of freshwater environmental policies and wastewater treatment plant management. *Science of The Total Environment* 445-446:185–191.

Day, A. D., A. Rahman, F. R. H. Katterman, and V. Jensen. 1974. Effects of Treated Municipal Wastewater and Commercial Fertilizer on Growth, Fiber, Acid-Soluble Nucleotides, Protein, and Amino Acid Content in Wheat Hay. *Journal of Environment Quality* 3 (1):17.

Day, A. D., and T. C. Tucker. 1977. Effects of Treated Municipal Waste Water on Growth, Fiber, Protein, and Amino Acid Content of Sorghum Grain. *Journal of Environment Quality* 6 (3):325.

Day, A. D., J. A. M. Fadyen, T. C. Tucker, and C. B. Cluff. 1981. Effects of Municipal Waste Water on the Yield and Quality of Cotton. *Journal of Environment Quality* 10 (1):47.

Day, A. D., R. S. Swingle, T. C. Tucker, and C. B. Cluff. 1982. Alfalfa Hay Grown with Municipal Waste Water and Pump Water. *Journal of Environment Quality* 11 (1):23.

Devitt, T. J., A. M. Wright, D. C. Cannatella, and D. M. Hillis. 2019. Species delimitation in endangered groundwater salamanders: Implications for aquifer management and biodiversity conservation. *Proceedings of the National Academy of Sciences* 116 (7):2624–2633.

Donohue, S., V. Mccarthy, P. Rafferty, A. Orr, and R. Flynn. 2015. Geophysical and hydrogeological characterisation of the impacts of on-site wastewater treatment discharge to groundwater in a poorly productive bedrock aquifer. *Science of The Total Environment* 523:109–119.

Dyer, S. D., and X. Wang. 2002. A Comparison Of Stream Biological Responses To Discharge From Wastewater Treatment Plants In High And Low Population Density Areas. *Environmental Toxicology and Chemistry* 21 (5):1065.

Earl, Richard A., Richard W. Dixon, and C. Andrew Day. 2006. "Long Term Precipitation and Water Supply Variability in South-Central Texas." *Proceedings and Papers of the Applied Geography Conferences* 29: 11-22.

Edwards Aquifer Authority. 2019a. Edwards Aquifer Authority, About the Edwards Aquifer. https://www.edwardsaquifer.org/science-and-maps/about-the-edwards-aquifer (accessed July 23, 2019).

_____. 2019b. Edwards Aquifer Authority, Jurisdiction. https://www.edwardsaquifer.org/eaa/history/jurisdiction/ (accessed November 14, 2019).

Einsiedl, F., M. Radke, and P. Maloszewski. 2010. Occurrence and transport of pharmaceuticals in a karst groundwater system affected by domestic wastewater treatment plants. *Journal of Contaminant Hydrology* 117 (1-4):26–36.

Fujita, Y., W.-H. Ding, and M. Reinhard. 1996. Identification of wastewater dissolved organic carbon characteristics in reclaimed wastewater and recharged groundwater. *Water Environment Research* 68 (5):867–876.

Ganjegunte, G., A. Ulery, G. Niu, and Y. Wu. 2018. Treated urban wastewater irrigation effects on bioenergy sorghum biomass, quality, and soil salinity in an arid environment. *Land Degradation & Development* 29 (3):534–542.

Grantham, T. E., M. Cañedo-Argüelles, I. Perrée, M. Rieradevall, and N. Prat. 2012. A mesocosm approach for detecting stream invertebrate community responses to treated wastewater effluent. *Environmental Pollution* 160:95–102.

Gücker, B., M. Brauns, and M. T. Pusch. 2006. Effects of wastewater treatment plant discharge on ecosystem structure and function of lowland streams. *Journal of the North American Benthological Society* 25 (2):313–329.

Hardisty, P. E., M. Sivapalan, and R. Humphries. 2013. Determining a sustainable and economically optimal wastewater treatment and discharge strategy. *Journal of Environmental Management* 114:285–292.

Harry, I. S. K., E. Ameh, F. Coulon, and A. Nocker. 2016. Impact of Treated Sewage Effluent on the Microbiology of a Small Brook Using Flow Cytometry as a Diagnostic Tool. *Water, Air, & Soil Pollution* 227 (2).

Hassan, M. A., and R. Egozi. 2001. Impact of wastewater discharge on the channel morphology of ephemeral streams. *Earth Surface Processes and Landforms* 26 (12):1285–1302.

Hermitte, S., and Mace, R.E. 2012. The grass is always greener…Outdoor residential water use in Texas. Texas Water Development Board Technical Note 12-01

Horne, A. J., and C. R. Goldman. 1994. *Limnology, Second Edition.* New York, NY: McGraw-Hill, Inc.

Huertas, E., M. Folch, and M. Salgot. 2007. Wastewater reclamation through a combination of natural systems (infiltration-percolation and constructed wetlands): a solution for small communities. *Water Science and Technology* 55 (7):143–148.

Humphrey, C., M. Odriscoll, and J. Harris. 2014. Spatial Distribution of Fecal Indicator Bacteria in Groundwater beneath Two Large On-Site Wastewater Treatment Systems. *Water* 6 (3):602–619.

K Friese & Associates, Inc. 2008. City of Leander, Texas Wastewater Master Plan. https://www.leandertx.gov/planning/page/comprehensive-plan-update-destination-leander-0 (Accessed May 20, 2019).

Kaboosi, K. 2016. The assessment of treated wastewater quality and the effects of mid-term irrigation on soil physical and chemical properties (case study: Bandargaz-treated wastewater). *Applied Water Science* 7 (5):2385–2396.

Karnjanapiboonwong, A., J. G. Suski, A. A. Shah, Q. Cai, A. N. Morse, and T. A. Anderson. 2010. Occurrence of PPCPs at a Wastewater Treatment Plant and in Soil and Groundwater at a Land Application Site. *Water, Air, & Soil Pollution* 216 (1-4):257–273

Katz, B. G., D. W. Griffin, and J. H. Davis. 2009. Groundwater quality impacts from the land application of treated municipal wastewater in a large karstic spring basin: Chemical and microbiological indicators. *Science of The Total Environment* 407 (8):2872–2886.

Kelly, W. R., S. V. Panno, K. C. Hackley, A. T. Martinsek, I. G. Krapac, C. P. Weibel, and E. C. Storment. 2009. Bacteria Contamination of Groundwater in a Mixed Land-Use Karst Region. *Water Quality, Exposure and Health* 1 (2):69–78.

Kunz, N. C., M. Fischer, K. Ingold, and J. G. Hering. 2015. Drivers for and against municipal wastewater recycling: a review. *Water Science and Technology* 73 (2):251–259.

Larkin, T.J. and G.W. Bomar. 1983. *Climatic Atlas of Texas. Report LP-192*. Austin: TX: Department of Water Resources.

Lerch, R. N., C. G. Groves, J. S. Polk, B. V. Miller, and J. Shelley. 2018. Atrazine Transport through a Soil–Epikarst System. Journal of Environment Quality 47 (5):1205.Li, B., Y. Cao, X. Guan, Y. Li, Z. Hao, W. Hu, and L. Chen. 2019. Microbial assessments of soil with a 40-year history of reclaimed wastewater irrigation. *Science of The Total Environment* 651:696–705.

Licata, M., T. Tuttolomondo, C. Leto, S. L. Bella, and G. Virga. 2017. The use of constructed wetlands for the treatment and reuse of urban wastewater for the irrigation of two warm-season turfgrass species under Mediterranean climatic conditions. *Water Science and Technology* 76 (2):459–470

Liu, H., J. Jeong, H. Gray, S. Smith, and D. L. Sedlak. 2011. Algal Uptake of Hydrophobic and Hydrophilic Dissolved Organic Nitrogen in Effluent from Biological Nutrient Removal Municipal Wastewater Treatment Systems. *Environmental Science & Technology* 46 (2):713–721.

Loftus, T., and L. Smith. 2018. Estimating the Potential of Urban Water-Use Conservation in Texas: A Pilot Study of Two Planning Regions. *Meadows Center for Water and the Environment, Texas State University*. https://gato-docs.its.txstate.edu/jcr:a5aaeff7-3822-4c54-a5f6-fb1b6ff0e138 (accessed August 15, 2019).

Mahesh, J., P. Amerasinghe, and P. Pavelic. 2015. An integrated approach to assess the dynamics of a peri-urban watershed influenced by wastewater irrigation. *Journal of Hydrology* 523:427–440.

Mareddy, A. R. 2017. *Environmental Impact Assessment: Theory and Practice.* Oxford, UK: Elsevier. https://doi.org/10.1016/C2015-0-06055-5 (accessed November 13, 2019).

Masseret, E., C. Amblard, G. Bourdier, and D. Sargos. 2000. Effects of a Waste Stabilization Lagoon Discharge on Bacterial and Phytoplanktonic Communities of a Stream. *Water Environment Research* 72 (3):285–294.

Mohamed, D., B.-K. Houria, K. Nacer, and N. Imed-Eddin. 2008. Alteration of the Aquifer Water in Hyperarid Climate, by Wastewater: Cases of Groundwater from Ouargla (Northern Sahara, Algeria). *American Journal of Environmental Sciences* 4 (6):569–575.

Moretti, M., S. V. Passel, S. Camposeo, F. Pedrero, T. Dogot, P. Lebailly, and G. Vivaldi. 2019. Modelling environmental impacts of treated municipal wastewater reuse for tree crops irrigation in the Mediterranean coastal region. *Science of The Total Environment* 660:1513–1521.

Nath, K. J., and A. K. Sengupta. 2016. An alternative approach for municipal wastewater management: Technology options for small and medium towns. *Water Practice and Technology* 11 (1):157–165.

Patoski, J. Edwards Aquifer Authority › History. *Edwards Aquifer Authority › History*. https://www.edwardsaquifer.org/eaa/history (accessed July 30, 2019).

Pedrero, F., A. Albuquerque, H. M. D. Monte, V. Cavaleiro, and J. J. Alarcón. 2011. Application of GIS-based multi-criteria analysis for site selection of aquifer recharge with reclaimed water. *Resources, Conservation and Recycling* 56 (1):105–116.

Pi, Y.-Z., and J.-L. Wang. 2006. A field study of advanced municipal wastewater treatment technology for artificial groundwater recharge. *Journal of Environmental Sciences* 18 (6):1056–1060.

Plumlee, M. H., C. J. Gurr, and M. Reinhard. 2012. Recycled water for stream flow augmentation: Benefits, challenges, and the presence of wastewater-derived organic compounds. *Science of The Total Environment* 438:541–548.

Porras A., A. Richter, S. Hiers, A. Clamann, M. Scoggins, C. Herrington, W. Burdick, and S. Sudduth. 2016. Reclaimed water irrigation water quality impact assessment. SR-16-06. City of Austin, Watershed Protection Department.

Rice, J., and P. Westerhoff. 2017. High levels of endocrine pollutants in US streams during low flow due to insufficient wastewater dilution. *Nature Geoscience* 10 (8):587–591.

Richter, A., and S. Hiers. 2017. Comparison of water quality at locations currently receiving wastewater effluent irrigation to locations planned for future wastewater effluent irrigation. DR-18-01. City of Austin, Watershed Protection Department.

Ross, D. L. 2011. Land-Applied Wastewater Effluent Impacts on the Edwards Aquifer. Prepared for: Greater Edwards Aquifer Alliance and Save Our Springs Alliance.

Schmidt, S., T. Geyer, A. Marei, J. Guttman, and M. Sauter. 2013. Quantification of long-term wastewater impacts on karst groundwater resources in a semi-arid environment by chloride mass balance methods. *Journal of Hydrology* 502:177–190.

Schwartz, B. F., S. Schwinning, B. Gerrard, K. R. Kukowski, C. L. Stinson, and H. C. Dammeyer. 2013. Using hydrogeochemical and ecohydrologic responses to understand epikarst process in semi-arid systems, Edwards plateau, Texas, USA. Acta Carsologica 42 (2-3).Sheaffer, J. [2004?]. The Shining City on the Hill Report. http://sheafferandroland.com/projects/REP24NOV2004millcreekreportRJPdraft4.pdf (accessed November 14, 2019).

Spongberg, A. L., and J. D. Witter. 2008. Pharmaceutical compounds in the wastewater process stream in Northwest Ohio. *Science of The Total Environment* 397 (1-3):148–157.

Tang, C., J. Chen, S. Shindo, Y. Sakura, W. Zhang, and Y. Shen. 2004. Assessment of groundwater contamination by nitrates associated with wastewater irrigation: A case study in Shijiazhuang region, China. Hydrological Processes 18 (12):2303–2312.

Texas Department of Transportation (TxDOT). 2019. Political Boundary Shapefiles (Population Data).

Texas Commission on Environmental Quality. June, 2019. Beneficial Reuse of Treated Wastewater: Rulemaking Comment Period and Public Meeting. https://www.tceq.texas.gov/assistance/resources/the-advocate-1/beneficial-reuse-of-treated-wastewater-rulemaking-comment-period-and-public-meeting (last accessed 13 February 2020).

_____. 2019. Subject: Rule Project Number 2016-042-309-OW: Proposed rule-making to allow beneficial reuse to partially substitute for TLAP wastewater disposal area. Public comment submitted to the Texas Commission on Environmental Quality.

Texas Water Development Board. 2012. 2012 State Water Plan. http://www.twdb.texas.gov/publications/state_water_plan/2012/2012_SWP.pdf (accessed July 23, 2019).

_____. 2016. Interactive 2017 Texas State Water Plan Website. https://2017.texasstatewaterplan.org/statewide (accessed October 22, 2019).

US Census Bureau. 2010. American Fact Finder. Decennial Census, 2010 Demographic Profile Data. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF (accessed October 22, 2019).

_____. 2019. Fastest-Growing Cities Primarily in the South and West. *The United States Census Bureau*. https://www.census.gov/newsroom/press-releases/2019/subcounty-population-estimates.html (accessed July 23, 2019).

US Department of Agriculture, 2016. Cropscape (2016) https://nassgeodata.gmu.edu/CropScape/ (accessed July 23, 2019)

US Environmental Protection Agency, 2006. Process Design Manual: Land Treatment of Municipal Wastewater Effluents. https://nepis.epa.gov/Exe/tiff2png.cgi/2000ZYD5.PNG?-r+75+-g+7+D%3A%5CZYFILES%5CINDEX%20DATA%5C06THRU10%5CTIFF%5C00000009%5C2000ZYD5.TIF (accessed February 29, 2020).

_____. 2019 Nutrient Pollution: The Issue. https://www.epa.gov/nutrientpollution/issue (accessed July 23, 2019).

_____. 2019 NPDES Permit Basics. https://www.epa.gov/npdes/npdes-permit-basics (accessed October 1, 2019).

_____. 2019 Primer for Municipal Wastewater Treatment systems. https://www3.epa.gov/npdes/pubs/primer.pdf (accessed October 28, 2019).

US Geological Survey, 2016. National Land Cover Database 2016

Viccaro, M., M. Cozzi, D. Caniani, S. Masi, I. Mancini, M. Caivano, and S. Romano. 2017. Wastewater Reuse: An Economic Perspective to Identify Suitable Areas for Poplar Vegetation Filter Systems for Energy Production. *Sustainability* 9 (12):2161.

Wang, S., W. Wu, F. Liu, S. Yin, Z. Bao, and H. Liu. 2015. Spatial distribution and migration of nonylphenol in groundwater following long-term wastewater irrigation. *Journal of Contaminant Hydrology* 177-178:85–92.

Wongburi, P., and J. K. Park. 2018. Decision making tools for selecting sustainable wastewater treatment technologies in Thailand. *IOP Conference Series: Earth and Environmental Science* 150:012013.

Yin, S., X. Gu, Y. Xiao, W. Wu, X. Pan, J. Shao, and Q. Zhang. 2017. Geostatistics-based spatial variation characteristics of groundwater levels in a wastewater irrigation area, northern China. *Water Science and Technology: Water Supply* 17 (5):1479–1489.