Journal of Hydrology: Regional Studies 14 (2017) 92–108

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Assessing aquifer storage and recovery feasibility in the Gulf Coastal Plains of Texas

W. Benjamin Smith[a], Gretchen R. Miller[a,*], Zhuping Sheng[b]

[a] Zachry Department of Civil Engineering, Texas A&M University, 3136 TAMU, College Station, TX, 77845, USA
[b] Texas A&M AgriLife Research and Extension Center at El Paso, 1380 A&M Circle, El Paso, TX, 79927, USA

ARTICLE INFO

Keywords:
Aquifer storage and recovery (ASR)
GIS
Gulf coast
Carrizo-Wilcox
Managed aquifer recharge (MAR)

ABSTRACT

Study region: The Gulf Coast and Carrizo-Wilcox aquifer systems in the Gulf Coastal Plains of Texas.

Study focus: Aquifer storage and recovery is a water storage alternative that is underutilized in Texas, a state with both long periods of drought and high intensity storms. Future water storage plans in Texas almost exclusively rely on surface reservoirs, subject to high evaporative losses. This study seeks to identify sites where aquifer storage and recovery (ASR) may be successful, especially in recovery of injected waters, by analyzing publicly-available hydrogeologic data. Transmissivity, hydraulic gradient, well density, depth to aquifer, and depth to groundwater are used in a GIS-based index to determine feasibility of implementing an ASR system in the Gulf Coast and Carrizo-Wilcox aquifer systems.

New hydrological insights for the region: Large regions of the central and northern Gulf Coast and the central and southern Carrizo-Wilcox aquifer systems are expected to be hydrologically feasible regions for ASR. Corpus Christi, Victoria, San Antonio, Bryan, and College Station are identified as possible cities where ASR would be a useful water storage strategy.

1. Introduction

Aquifer storage and recovery (ASR) is a water storage alternative applicable to a wide range of hydrogeologic conditions and climates. ASR is a subset of managed aquifer recharge (MAR), which sometimes is also termed artificial recharge, artificial aquifer recharge, or artificial recharge and recovery (Dillon, 2005; Sheng and Zhao, 2015). For most purposes, aquifer storage and recovery systems consist of four main subsystems: storage space (aquifer), injection or recharge facilities (wells, infiltration basins, etc.), extraction or recovery facilities (wells), and source water. All four of these subsystems must work in coordination with each other for an ASR system to successfully store water for later use (Sheng, 2005).

ASR has many advantages over surface reservoirs: little to no evaporative losses, minimized environmental disturbances and land consumption, and lower costs (Bouwer, 2002; Khan et al., 2008; Maliva et al., 2006; Maliva and Missimer, 2010; National Research Council, 2008). ASR is highly adaptable and can be used in a variety of aquifer types (e.g., shallow or deep, fresh or saline, thick or thin, sandstone or limestone (Maliva and Missimer, 2010)), in a wide range of climates (e.g., arid deserts (Maliva et al., 2011), temperate grasslands and wetlands (Antoniou et al., 2012), and subtropical wetlands (Jones and Pichler, 2007)), and to provide storage for a range of applications (e.g., drinking water supplies for municipalities, minimum environmental stream flows, and protection against seawater intrusion in freshwater aquifers among other uses (Pyne, 2005)). Two primary methods for determining

* Corresponding author.
E-mail addresses: smithwbtx@tamu.edu (W.B. Smith), gretchen.r.miller@tamu.edu (G.R. Miller), zsheng@ag.tamu.edu (Z. Sheng).

https://doi.org/10.1016/j.ejrh.2017.10.007
Received 17 July 2017; Received in revised form 29 September 2017; Accepted 20 October 2017
Available online 09 November 2017

ASR site suitability have been used in recent years. The more common practice is to develop a qualitative suitability index that involves classifying and weighting various factors and evaluating those factors over a spatial area. For instance, CH2MHILL, an engineering consulting firm, created a tool to assess feasibility of ASR in South Florida for the St. John's River Water Management District (CH2MHILL, 1997). The Comprehensive Everglades Restoration Project (CERP) created a site selection suitability index to evaluate feasibility of potential ASR sites to be used in the restoration of the Everglades and implemented the suitability index in GIS (Brown et al., 2005). Eastwood and Stanfield (2001) also employed a qualitative approach when stressing the importance of environmental acceptability as the more important success factor compared to water quality considerations. They argued water quality can be "engineered out" so as to not be an absolute hindrance to ASR like potential environmental damage, noting the economics of water quality mitigation may still eventually render specific ASR projects unfeasible (Eastwood and Stanfield, 2001). Most other published research focuses on estimating suitability for managed aquifer recharge projects, especially those involving surficial infiltration, as opposed to the injection and extraction via wells of aquifer storage and recovery (Fernandez Escalante et al., 2014; Ghayoumian et al., 2007; Malekmohammadi et al., 2012; Pedrero et al., 2011; Rahman et al., 2012; Rahman et al., 2013). Smith and Pollock's (2012) approach is interesting to note, as they applied an analytical model for managed aquifer recharge via infiltration over an area to identify feasible MAR locations in a more quantitative manner than the other multi-criteria decision methods. Bridging the gap between subsurface ASR systems and MAR surficial systems, Russo et al. (2015) estimated the feasibility of managed aquifer recharge sites in California by weighted sum of classified values, accounting for both potential surface infiltration and subsurface injection systems.

More quantitative methods for estimating the feasibility of locations for ASR-specific systems have been developed as well. These methods involve deriving dimensionless parameters that describe a physical process governing the recovery efficiency of an ASR system. Bakker (2010) created a dimensionless parameter based on well discharge, hydraulic conductivity, aquifer thickness, and dimensionless density difference, and used it along with the relative lengths of injection, storage and recovery periods to evaluate potential feasibility of ASR in saltwater aquifers. Ward et al. (2009) developed four additional dimensionless parameters to describe three major governing factors of ASR recovery efficiency: lateral flow, density-driven flow, and dispersive mixing. They proposed that these parameters could be used to help identify suitable ASR sites if sufficient data were available. The dimensionless parameters of Bakker (2010) and Ward et al. (2009) were evaluated separately to assess their effectiveness at predicting ASR site suitability in a coastal area of the Netherlands using GIS, and both were shown to be effective at predicting successful ASR sites (Zuurbier et al., 2013). Characterization of suitable regions by parameters with real physical significance, instead of simple qualitative characterizations like 'very suitable,' 'suitable,' or 'unsuitable' can provide valuable information to water resource managers.

Historically, Texas water utilities have primarily used surface reservoirs to manage temporal differences in water supply and demand, despite significant evaporative losses. The 2012 Texas State Water Plan, published by the Texas Water Development Board (TWDB), primarily prescribes increasing water storage capacity via the construction of additional surface reservoirs throughout the state. Despite the fact that ASR provides additional benefits beyond water storage, including minimized environmental damage and replenished aquifers, it is currently underutilized in Texas, and based on the 2012 water plan, is projected to be in the future as well (Malcolm Pirnie et al., 2011; TWDB, 2012). ASR can never completely replace surface storage, as it cannot match some benefits of surface storage, especially in regards to storm water management. Surface and subsurface storage of freshwater provide complementary benefits to water providers, and both should be considered for future storage needs.

ASR, when implemented as part of a water storage portfolio, can help Texas achieve water security and replenish aquifers that have been depleted and overstressed for more than 100 years. Natural aquifer recharge rates are typically much lower than anthropogenic extraction rates, and without artificial recharge, groundwater as a natural resource in Texas could easily disappear on a relatively short timescale. A 2011 TWDB report on ASR use in Texas found that the biggest concerns of municipalities in regards to ASR were the ability to physically recover stored water and degradation of water quality during storage, both of which highlight the need for additional information on aquifer storage spaces across the state (Malcolm Pirnie et al., 2011).

This work focuses on the potential feasibility of systems that both inject and extract water from an aquifer via wells. Previous ASR feasibility indices have required significant amounts of site-specific data to assess feasibility at specific locations, which make large, regional scale analyses difficult. The objectives of this study are three-fold: 1) to develop a method for rating the feasibility of aquifer storage and recovery at a regional aquifer scales using commonly available data; 2) to compile a geospatial information system (GIS) database for the Gulf Coast and Carrizo-Wilcox aquifer systems of Texas; and 3) use the database to create feasibility maps suitable for use by regional water planners and other government entities. Specifically, we define ASR as both injection into and extraction from the aquifer occurring via wells. We also view ASR feasibility through the lens of a municipality seeking seasonal or long term water storage in an aquifer, such that locations which minimize injected water losses, operational costs, and constructions costs are given the highest ratings. Mapping scales are appropriate for use in selection of sites where pilot studies or more detailed engineering studies will be conducted, rather for the placement of specific facilities.

2. Materials and methods

2.1. Study areas

Both the Gulf Coast and Carrizo-Wilcox aquifer systems in Texas' Gulf Coastal Plains were evaluated for their feasibility of implementing ASR systems. The primary aquifers within the Gulf Coast system are the Chicot, Evangeline, and Jasper aquifers. The primary aquifers in the Carrizo-Wilcox system are the Carrizo, Middle Wilcox, and Simsboro aquifers. The Simsboro aquifer represents the middle unit of the Wilcox group in the central portion of the Carrizo-Wilcox, and is therefore treated as one "Wilcox"

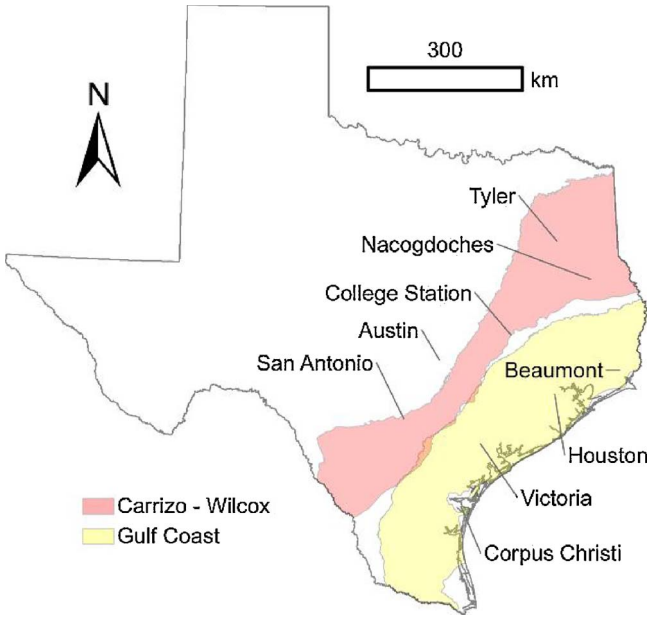

Fig. 1. Aquifer systems in the region of interest with selected cities shown.

aquifer along with the Middle Wilcox unit from the northern and southern portions of the study area (Deeds et al., 2003; Dutton et al., 2003). While the TWDB readily provides each aquifer system's boundaries, as shown in Fig. 1, each constituent aquifer's boundaries are less clear. In this study, aquifer boundaries were defined by the maximum geographic extent of the wells screened into each aquifer, based on the TWDB's Groundwater Database (GWDB) (TWDB, 2015). The GWDB primarily encompasses only the freshwater regions of these aquifers above their "brackish water lines," typically defined in Texas where the total dissolved solids concentration is equal to 3000 mg/L. Therefore, this study implicitly considers only freshwater aquifers when determining feasible locations for ASR.

The Gulf Coast aquifer system's major units, as seen in Fig. 2, are the Chicot aquifer, Evangeline aquifer, Burkeville confining unit, Jasper aquifer, and Catahoula confining unit (only in the northern portion of the aquifer system) (Kasmarek, 2013). Changes in ancient sea levels and in depositional amounts and sources led to the discontinuous beds of sand, gravel, silt, and clay that comprise the three aquifer units. Subsidence of the depositional basin and rising land surfaces caused many of the units of the Gulf Coast aquifer to thicken downdip. These changes, along with growth faults in the area, all factored in to the heterogeneity seen today in the strata of the Gulf Coast aquifer (Baker, 1979).

The Carrizo-Wilcox aquifer system is comprised of the Carrizo aquifer and the Wilcox group beneath it, both of which were deposited along the Gulf of Mexico between 50 and 60 million years ago, when the coastline was 240–320 kilometers inland relative to its current location (Mace et al., 2000). The Carrizo unit is overlain by the confining Reklaw, which itself is overlain by other layers including the Queen City and Sparta aquifers as shown in Fig. 3. There are also some incomplete hydraulic barriers in the lower Carrizo and middle and upper Wilcox units (Mace et al., 2000). The aquifer is primarily sand or sandstone, but is locally interbedded with gravel, silt, clay, and lignite (George et al., 2011).

2.2. Determining ASR feasibility scores

Public data for Texas aquifers do not exist at the required resolution or scale to evaluate the more physically based factors of Bakker (2010) and Ward et al. (2009). Therefore, the classified and weighted factor analysis was used on factors that could be determined at useful scales and resolutions. In this study the relative feasibility of ASR across each of the five aquifers was estimated based on the following five hydrogeologic factors: transmissivity, hydraulic gradient, density of existing wells, depth to the potentiometric surface, and depth to the top of the aquifer formation. These factors were chosen based on both their potential to affect ASR feasibility and the existence of large scale datasets across each aquifer. The data used to map these factors came from several sources, including the TWDB Groundwater Database, TWDB Groundwater Availability Models data, and historical reports (Chowdhury and Mace, 2007; Deeds et al., 2003; Dutton et al., 2003; Fryar et al., 2003; Kasmarek, 2013; TWDB, 2015; Waterstone Inc. and Parsons Inc., 2003; Young et al., 2012). Based on the smallest scale of the datasets used in this study, a spatial resolution of 1.6 kilometers was used.

In order to standardize comparisons between the factors, data were reclassified based on a relative ranking system, with higher numbers indicating areas expected to be more feasible for ASR systems and zeros indicating that no data were available. The factors were then combined via weighted sum to determine an overall expected feasibility rating from 0 to 100 (Fig. 4). The rationale for determining the weights and rankings for each hydrogeologic variable is described below and summarized in Fig. 5.

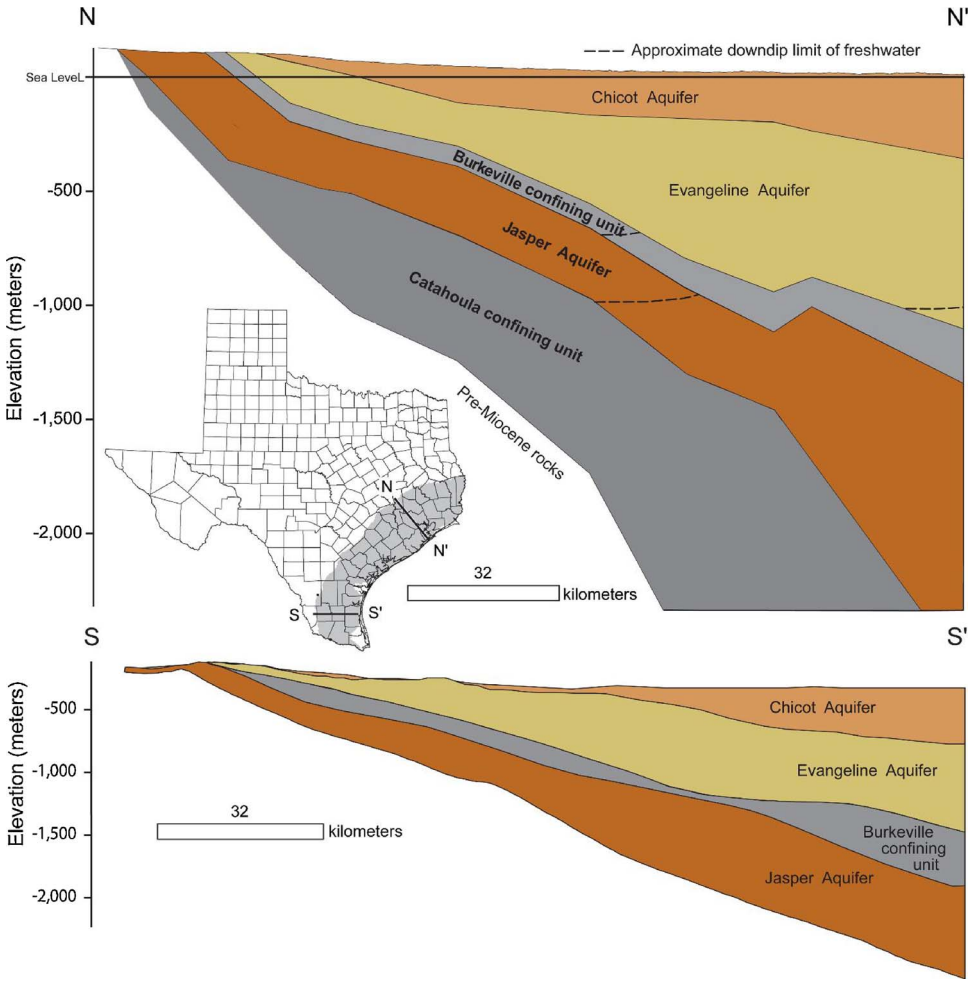

Fig. 2. Structural cross sections of the Gulf Coast aquifer system (modified from George et al., 2011).

2.2.1. Transmissivity

Transmissivity is an important factor in the feasibility analysis of ASR systems, as it affects both injection rates and retention of injected waters near recovery wells (Maliva and Missimer, 2010). Aquifers with low transmissivities may not be able to inject, and thus store, water at usable rates, while aquifers with high transmissivities may allow too much migration of injected water out of the recoverable radius of wells, especially when paired with high regional hydraulic gradients. Transmissivity values were reclassified from 1 to 4 as shown in Fig. 5, with both low and high values of transmissivity receiving the lowest possible score for the reasons described above. These classifications are based on previous ASR site suitability indices (Brown et al., 2005; CH2MHILL, 1997). Transmissivity data were primarily sourced from the data used to develop Groundwater Availability Models (GAMs) for each aquifer, commissioned by the TWDB (Chowdhury and Mace, 2007; Deeds et al., 2003; Dutton et al., 2003; Fryar et al., 2003; Kasmarek, 2013; Waterstone Inc. and Parsons Inc., 2003). When available in sufficient coverage and resolution, transmissivity data were used, otherwise the product of hydraulic conductivity and aquifer thickness were used. Aquifer thickness was derived from GAM source data first, and if not present or available, was digitized and interpolated from historical aquifer maps (Baker, 1979). For both the Gulf Coast and Carrizo-Wilcox, three GAMs each were done, representing the Northern, Central, and Southern portions of each aquifer system. As the GAMs were completed by various consulting firms and agencies, the transmissivity datasets varied based on available sources and issues encountered during modeling. For instance, the central Gulf Coast GAM calculated layer transmissivities as the product of its estimated sand thicknesses and geometric mean hydraulic conductivity (Waterstone Inc. and Parsons Inc., 2003), while the northern Gulf Coast GAM used digitized transmissivity estimates from the literature (Baker, 1986; Carr et al., 1985; Kasmarek, 2013). Transmissivity data were preferentially used in the following order: historic values from the literature, values estimated in the GAM process, values calibrated in the GAM process, and finally values that were derived from GAM hydraulic conductivity estimates and thicknesses of the aquifer from other historical reports.

2.2.2. Hydraulic gradient

Hydraulic gradient is another important factor in the design of ASR systems as it affects the ability to keep injected water on site

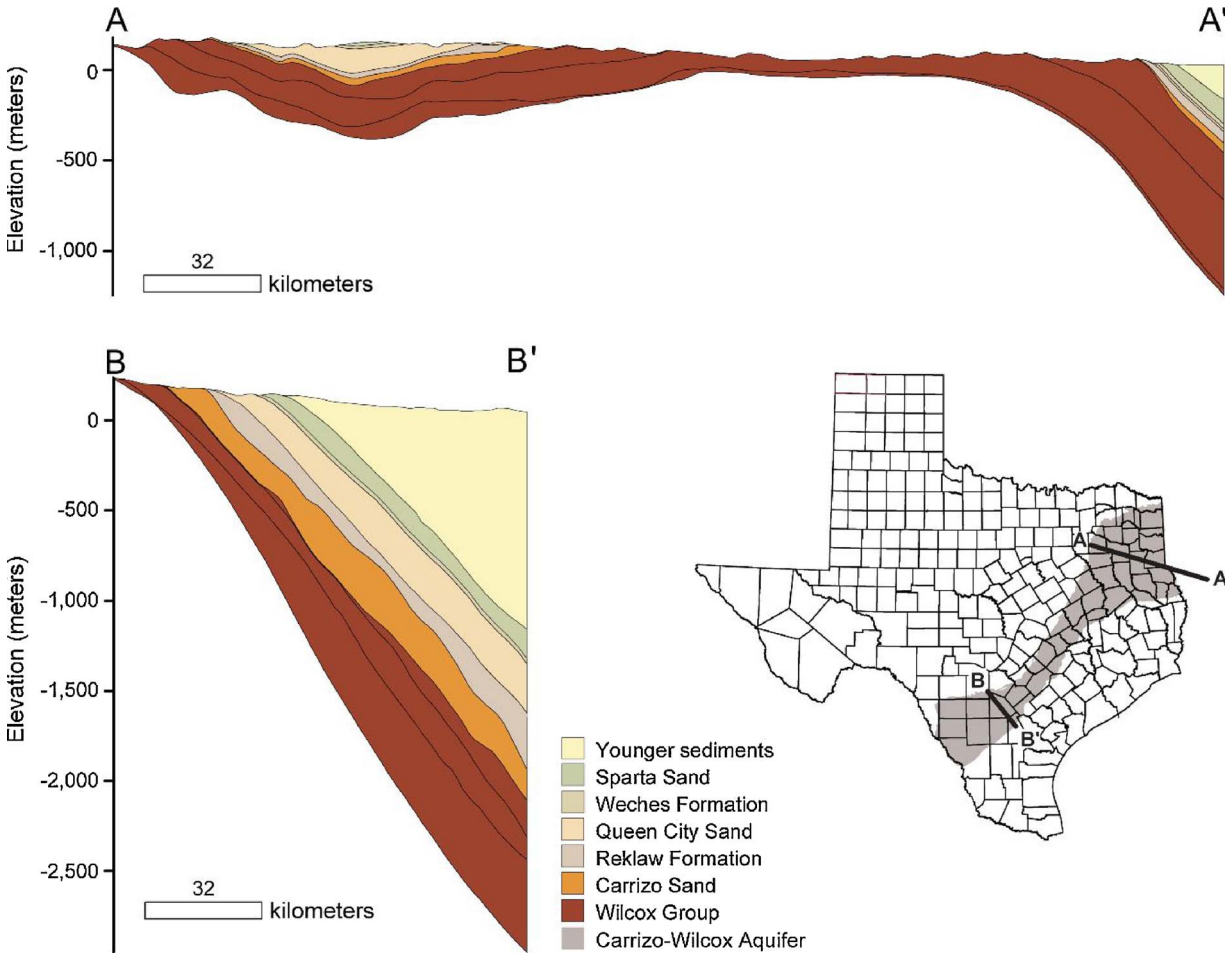

Fig. 3. Structural cross sections of the Carrizo-Wilcox aquifer system (modified from George et al., 2011).

(Maliva and Missimer, 2010). Steep regional gradients may move injected water out of recoverable zones, especially if storage times are long or transmissivities are high. Therefore, lower regional hydraulic gradients are seen as much more feasible for implementing an ASR system. Hydraulic gradient was reclassified from 1 to 4, as described in Fig. 5, in part based on results from a simulated modeling study by Lowry and Anderson where recovery efficiency was related to regional hydraulic gradient (2006). The slope of each aquifer's estimated potentiometric surface was used to represent the regional hydraulic gradient. The elevation of the potentiometric surface was generated by kriging 15-year-average water levels. Only wells with sufficient water level data in the TWDB's Groundwater Database were used to calculate these 15-year-average water levels (TWDB, 2015). Sufficient water level data were defined as having one or more publishable, representative measurements (i.e. not during pumping or other disturbance) from 2000 to 2015, with the standard deviation of all such water levels in each well not exceeding 4.5 m.

2.2.3. Depth to potentiometric surface

Depth to the potentiometric surface, simplified elsewhere in this text as depth to groundwater, is used as a proxy for energy usage required to extract water during recovery phases, with greater depths being deemed less feasible since more energy would be required to recover water. Depth to groundwater was reclassified from 1 to 3 based on the terciles of the depth to groundwater values for the GWDB wells in each aquifer system (TWDB, 2015). Depth was calculated as the difference between the digital elevation model (DEM) of the land surface and the potentiometric surface elevation, described in 2.2.2.

2.2.4. Depth to aquifer

Depth to aquifer is kriged from well depths in each aquifer. This factor is a proxy for construction ease and costs, where deeper wells would be more expensive or less feasible for an ASR system. Similar to depth to groundwater, depth to aquifer was reclassified from 1 to 3 based on the terciles of well depths within each aquifer system (Fig. 5). The well depths are those given for the wells in the GWDB (TWDB, 2015). Thus, this factor attempts to indicate the typical depth at which each aquifer is being used in given area, instead of the depth to the top or middle of the aquifer.

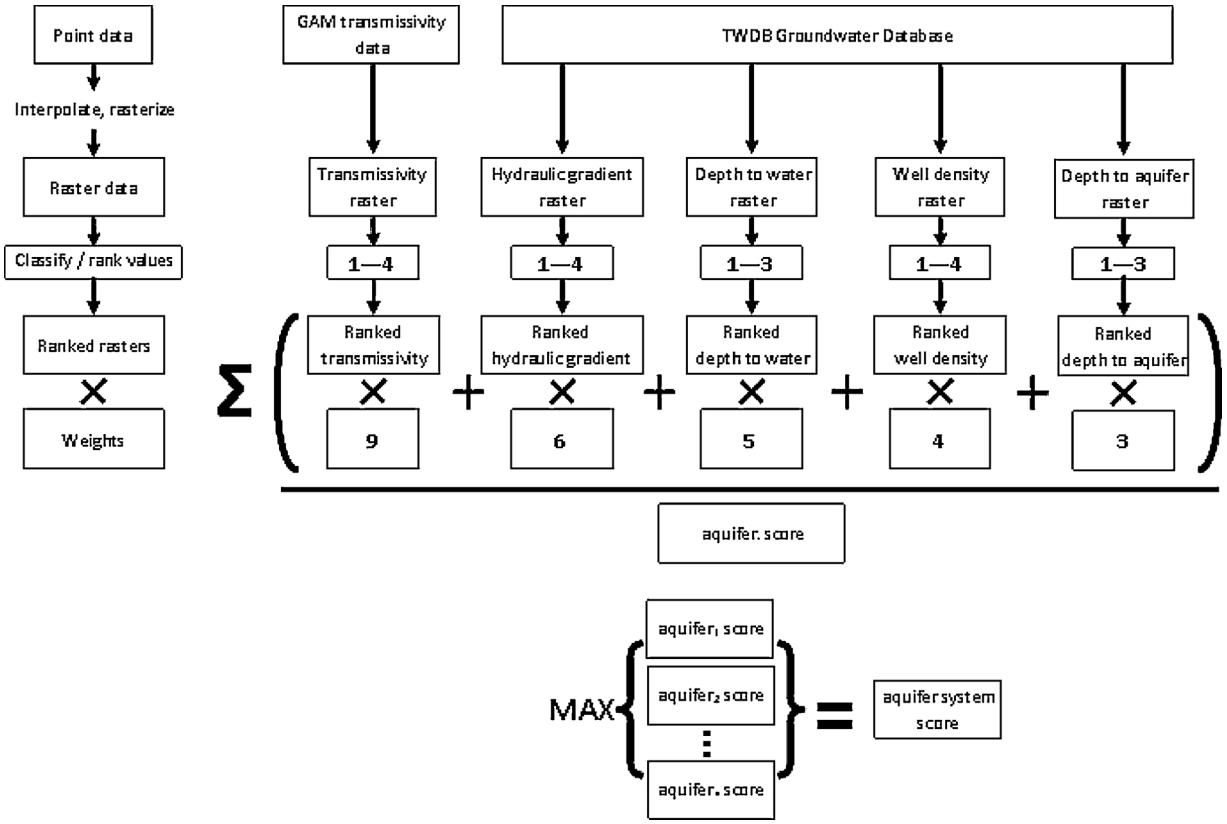

Fig. 4. Process flow chart with relative weights and reclassification rankings for the five selected hydrogeologic factors.

2.2.5. Density of existing wells

Well density determines the potential for nearby wells to extract stored water or otherwise interfere with an ASR system's performance (i.e. by increasing the regional hydraulic gradient or potentially polluting the aquifer). Wells were counted in each 2.6 square kilometer cell and reclassified from 1 to 4 according to Fig. 5. Well density is based on the locations of all the wells defined in the GWDB for each aquifer (TWDB, 2015). The wells used to calculate this well density clearly do not include all wells screened in each aquifer, however, we assume that they are representative of the overall trend.

2.3. Limitations

Assumptions made in this analysis may not apply to every city in the region, so it is possible that the cities identified in the results are not the only locations where ASR is viable in the Gulf Coastal Plain. Other cities may expand their search radius for locations with high ASR feasibility scores or may have water sources or needs beyond what was considered in this study. This analysis is meant to serve as a starting point for identifying areas where ASR may be well suited. Clearly, more factors than the five identified here, such as storage capacity and compatibility of source and native waters, are important to the success of an ASR system. Factors were omitted from this study for one of two main reasons. First, many factors lacked adequate regional scale data. Second, other factors like compatibility of source and native waters, are highly complex, site-specific, and often dependent on design choices. Other non-physical factors also affect the feasibility of ASR systems. For example, laws and boundaries may sometime supersede physical factors when selecting ASR sites. These sociopolitical factors are not static; since this study began, Texas passed HB 655 in 2015 in order to make the permitting process easier for implementing ASR systems. GCDs, which have the power to regulate ASR systems, are still being created, with two new GCDs beginning in 2015 and another GCD yet to be confirmed via election.

3. Results and discussion

3.1. ASR feasibility scores

3.1.1. Scores for the Gulf Coast aquifer system

The estimated and reclassified, or ranked, values of each of the five factors are shown in Fig. 6 for the three aquifers that comprise the Gulf Coast aquifer system. The influence of the greater Houston area on the Chicot and Evangeline aquifers can be seen in each of the three human-induced factors of hydraulic gradient, well density, and depth to groundwater in Fig. 6. Significant numbers of wells

All aquifers

Transmissivity (m^2/d)	
Class	Score
0 - 230	1
230 - 700	2
700 - 1160	3
1160 - 1630	4
1630 - 2550	3
2550 - 3950	2
> 3950	1

Well Density (wells/km^2)	
Class	Score
0	4
0.39	3
0.77	2
> 0.77	1

Hydraulic Gradient	
Class	Score
0 – 0.1	4
0.1 – 0.2	3
0.2 – 0.3	2
> 0.3	1

Gulf Coast aquifer system

Depth to Aquifer (m)	
Class	Score
< 57	3
57 - 138	2
> 138	1

Depth to Groundwater (m)	
Class	Score
< 12	3
12 - 26	2
> 26	1

Carrizo-Wilcox aquifer system

Depth to Aquifer (m)	
Class	Score
< 88	3
88 - 198	2
> 198	1

Depth to Groundwater (m)	
Class	Score
< 23	3
23 - 50	2
> 50	1

Fig. 5. Reclassification ranges for each of the five selected hydrogeologic factors, with the respective ranges of the Gulf Coast aquifer system (GC) and Carrizo-Wilcox aquifer system (CW) for the depth to aquifer and depth to groundwater factors.

in the area appears to have contributed to regional groundwater depressions, resulting in lower ranked scores for all three human-induced factors.

Fig. 7 represents the weighted-sum ASR feasibility score for each Gulf Coast aquifer, using the weights from Fig. 4 and the ranked value datasets from Fig. 6. The influence of the greater Houston area, seen in the human-induced factors in Fig. 6, is also apparent in these ASR feasibility scores for the Chicot and Evangeline aquifers. ASR feasibility scores in the greater Houston area are among the lowest in the areas with full data coverage for each factor. Lower scores do exist in some aquifer regions, but generally only on the edges of aquifers where some datasets do not exist.

The maximum ASR feasibility score from the set of the Chicot, Evangeline, and Jasper aquifers was determined for each location (Fig. 8). Generally, it appears that the central and northern regions of the Gulf Coast aquifer system are the most feasible for ASR systems, especially around cities like Victoria and Beaumont. Areas south of Corpus Christi appear to be generally less feasible. These lower scores are partially due to a lack of water level data in the Chicot and Jasper aquifers in the southern region, but also because the primary aquifer in the region, the Evangeline, is characterized by lower groundwater levels, steeper regional hydraulic gradients, and small transmissivities.

3.1.2. Scores for the Carrizo-Wilcox aquifer system

The estimated and reclassified, or ranked, values of each of the five factors are shown in Fig. 9 for the Carrizo and Wilcox aquifers. Similarly to Houston, the effects of groundwater usage around the cities of Nacogdoches and Tyler in the Carrizo aquifer are evident in the human-induced factors of hydraulic gradient and depth to groundwater. However, the areas around both of these cities also have low ranked values for transmissivity and depth to aquifer, which contribute to the significantly lower ASR feasibility scores (Fig. 10) compared to most of the rest of the Carrizo aquifer. The wellfield for the Bryan/College Station metro area is slightly to its northwest in the Carrizo aquifer, but appears to show little human influence on the groundwater table or hydraulic gradient (Fig. 9). This is most likely due to low density in this area of water level data from the TWDB's Groundwater Database deemed suitable as described in Section 2.2.2. Previous studies (George et al., 2011) have indicated a significant drawdown cone near this area, which would decrease the ranked values for these two factors from those shown here. The high ranked values for transmissivity near Bryan/College Station and the rest of the Central Carrizo region (Fig. 9) suggests the possibility of feasible ASR locations there (Fig. 10).

The central and southern regions of the Carrizo-Wilcox appear to be the most feasible areas in either aquifer system (Fig. 11),

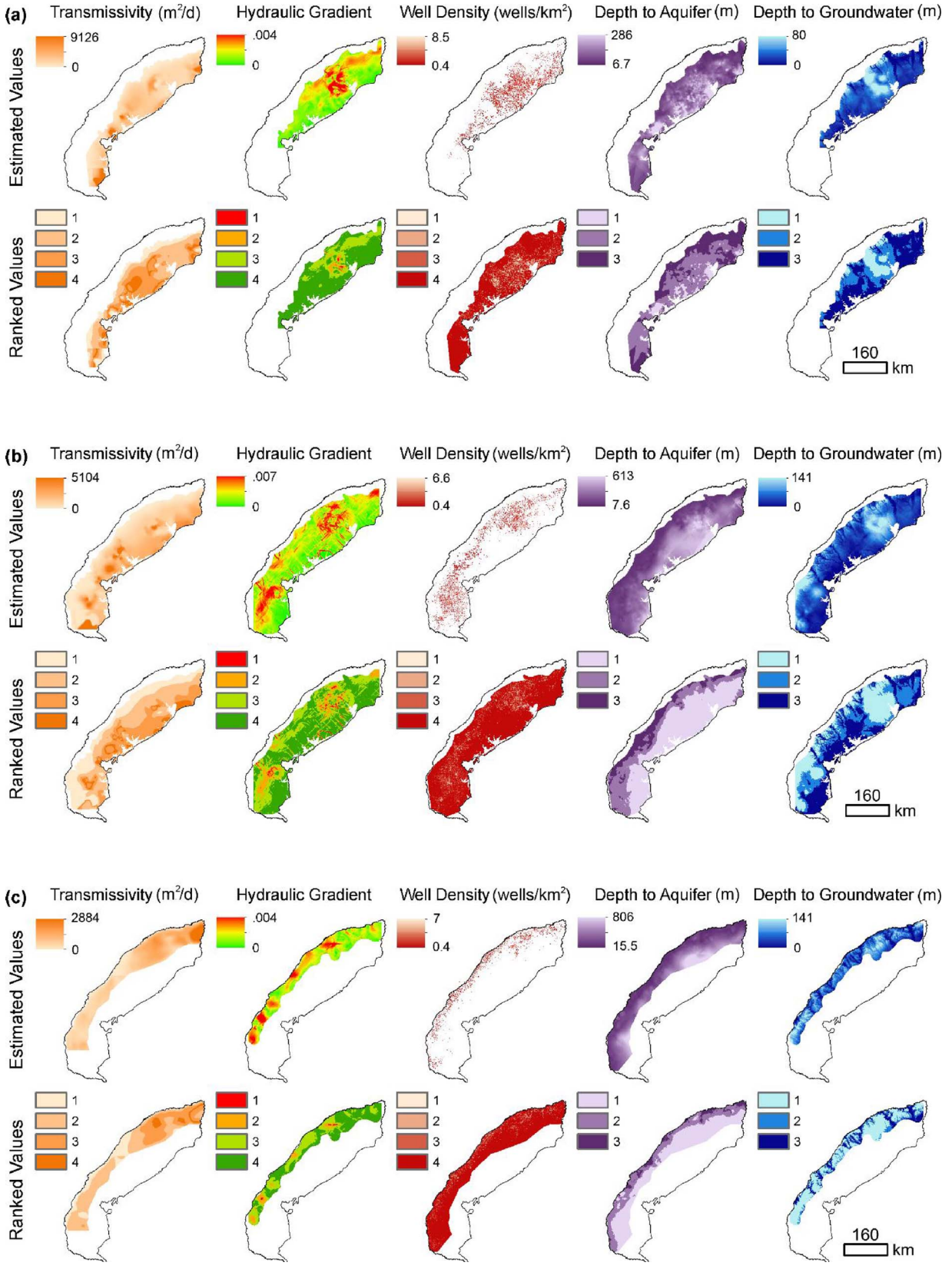

Fig. 6. (a–c): Maps of estimated and ranked values for transmissivity, hydraulic gradient, well density, depth to aquifer, and depth to groundwater for the Chicot (a), Evangeline (b), and Jasper (c) aquifers in the Gulf Coast aquifer system.

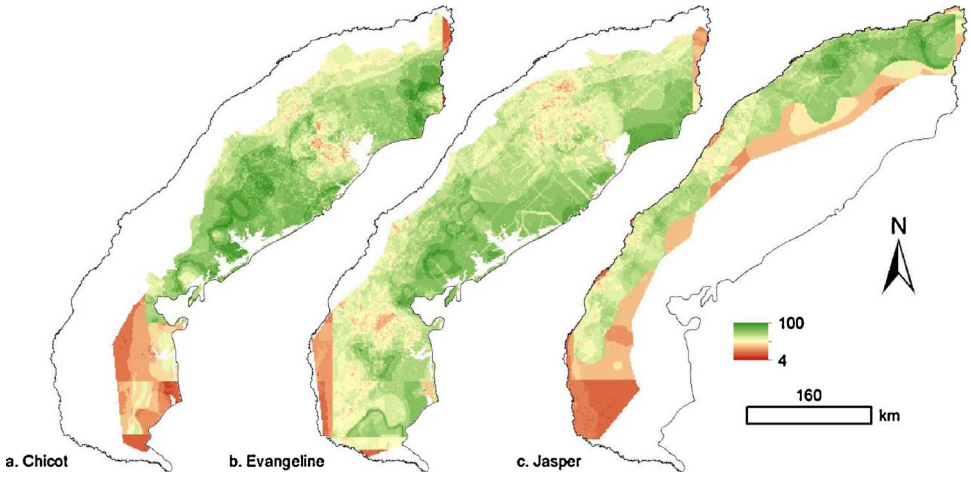

Fig. 7. (a–c): ASR feasibility ratings for the Chicot, Evangeline, and Jasper aquifers in the Gulf Coast aquifer system.

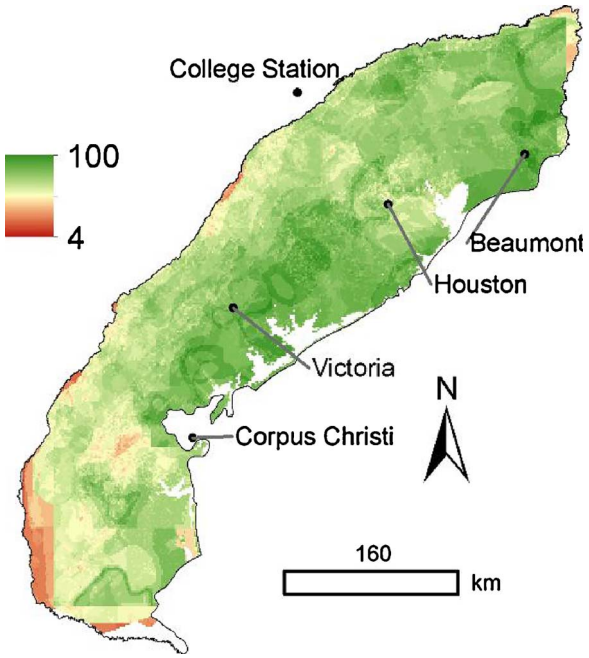

Fig. 8. Maximum ASR feasibility ratings for the Gulf Coast aquifer system, as defined by the highest feasibility rating of the constituent aquifers (Chicot, Evangeline, or Jasper) in each location, with selected cities shown.

including near Bryan/College Station and San Antonio. We note that both Bryan and College Station are currently conducting ASR feasibility studies, while San Antonio is one of only three cities in Texas currently operating an ASR system.

3.2. Current ASR facilities in study area

San Antonio Water System (SAWS) opened the Twin Oaks ASR facility, a multi-well ASR system south of the city in the Carrizo aquifer, in 2004 (CH2MHILL, 2006). This 230 ML/d facility, with 29 dual purpose ASR wells, was developed to store Edwards aquifer water in order to fully utilize SAWS' annual Edwards aquifer water permit. The Edwards aquifer, governed by the Edwards Aquifer Authority, legally functions similarly to surface reservoirs in Texas. However, the Carrizo-Wilcox aquifer, which legally functions similarly to all other Texas aquifers, is still primarily governed by the Rule of Capture, allowing users to pump groundwater nearly unchecked, especially in areas without groundwater conservation districts (GCDs). Moving water from the Edwards to the Carrizo effectively allows SAWS long-term storage of their current valuable Edwards allotment for potential future needs, as long as it can prevent its injected waters from moving out of the recoverable range of its dual-purpose wells (Malcolm Pirnie et al., 2011). Fig. 12 shows an inset of the Carrizo aquifer's ASR feasibility scores near the ASR wellfield.

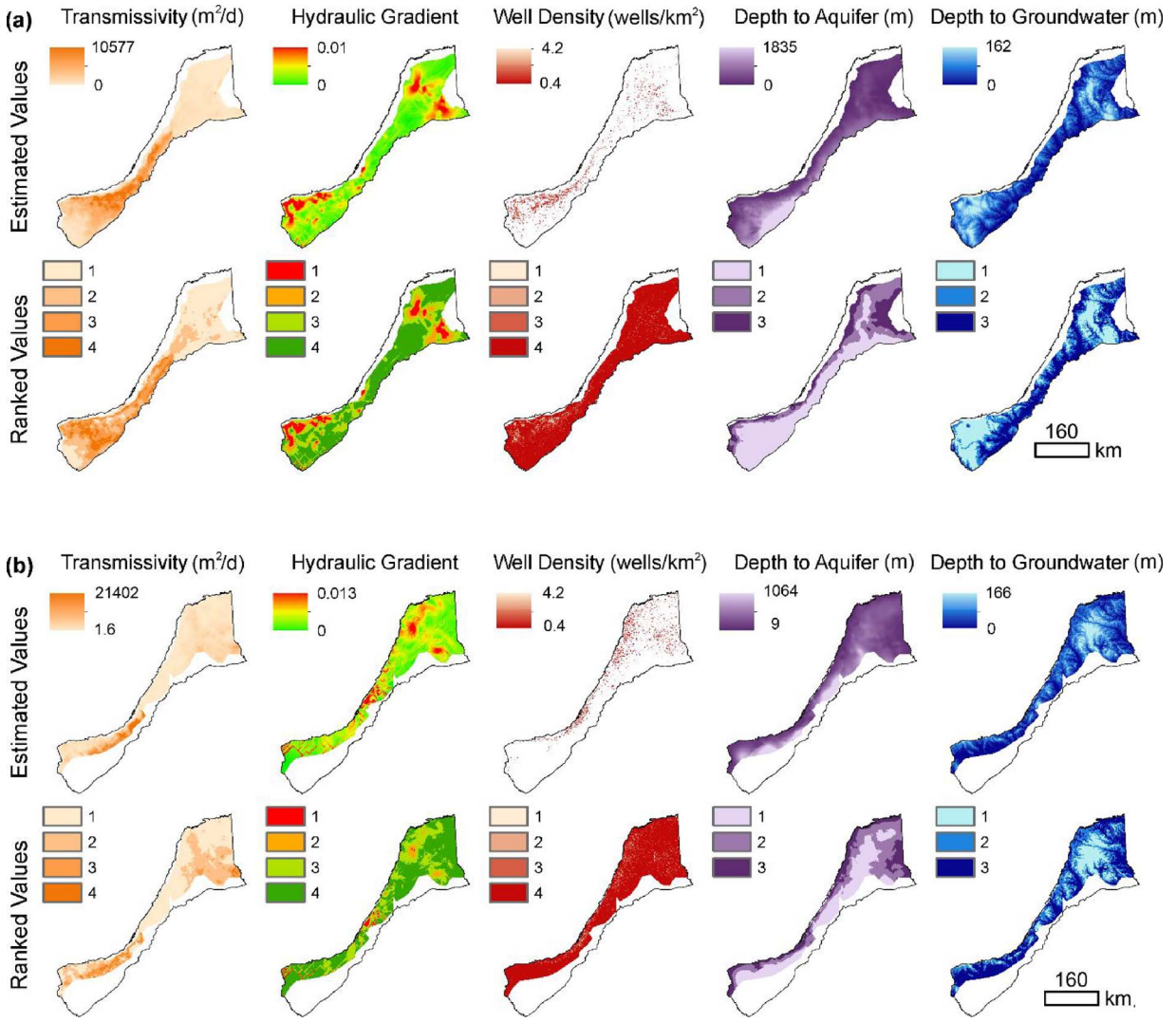

Fig. 9. (a, b): Maps of estimated and ranked values for transmissivity, hydraulic gradient, well density, depth to aquifer, and depth to groundwater for the Carrizo (a) and Wilcox (b) aquifers in the Carrizo-Wilcox aquifer system.

Fig. 12 represents the Carrizo score when the SAWS ASR wells are omitted from the GWDB, so as not to artificially lower the well density ranking. The mean score of the ASR wells is 53. An adjacent area in the Carrizo aquifer to the northeast appears to have a higher potential feasibility rating, but the influence of groundwater conservation districts (GCDs) in the area is apparent, as all of the ASR wells are clustered in the southern portion of Bexar County, where no GCD limits pumping or ASR activities in the Carrizo aquifer at this location. The Twin Oaks ASR facility is surrounded to the south, east, and west by the Evergreen Underground Water Conservation District which does have regulations concerning groundwater withdrawals from ASR systems. This map illustrates the fact that placement of groundwater facilities such as ASR systems are influenced by more than just natural and anthropogenic hydrogeologic conditions. Existing infrastructure, available surface water rights, and sociopolitical considerations like regulatory boundaries and public support are just a few of the myriad considerations that go into selecting such a site. Those considerations are clearly pertinent and valid, but too innumerable and location-specific to consider in this study, which is meant to serve as a starting point for more in-depth feasibility assessments of ASR by municipalities and other water users in Texas.

3.3. Potential locations for future ASR development

3.3.1. Aquifers beneath the selected cities

ASR feasibility score statistics were calculated within the boundaries of city polygons for cities with populations greater than 20,000 in the 2010 census. Populations of 20,000 or greater were chosen, as Kerrville, a city of about 22,000, currently operates one of the three ASR facilities in Texas. The 5 cities from each aquifer with the highest mean feasibility scores are shown in Table 1. The "count" column indicates how many of the feasibility score raster cells fall within a city's boundaries, while the "variety" column

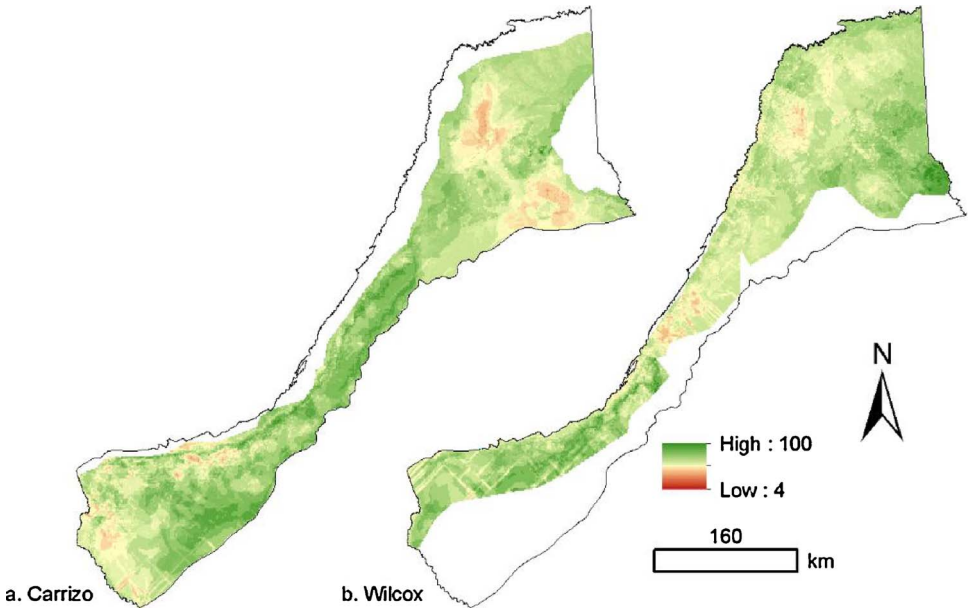

Fig. 10. (a, b) Overall ASR feasibility ratings for the Carrizo and Wilcox aquifers in the Carrizo-Wilcox aquifer system.

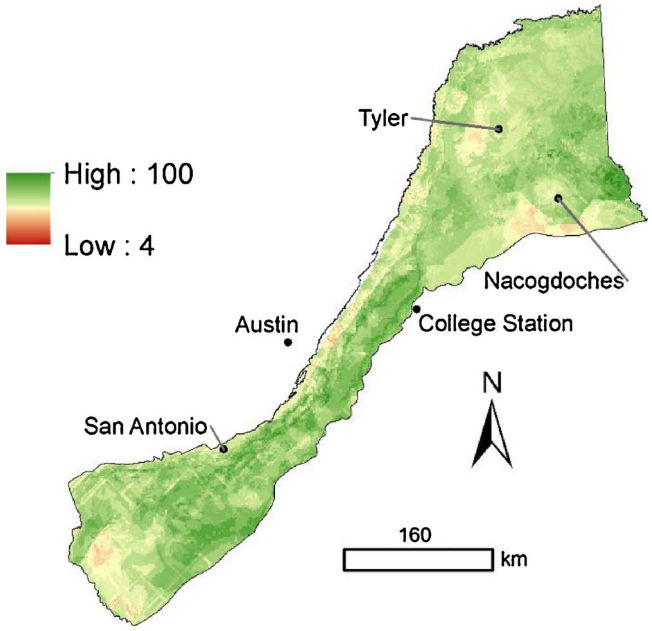

Fig. 11. ASR feasibility ratings for the Carrizo-Wilcox aquifer system, as defined by the maximum feasibility rating of the constituent aquifers (the Carrizo or Wilcox) in each location, with selected cities shown.

indicates how many different score values occur within a city.

Table 1 emphasizes the high feasibility scores predicted for the Gulf Coast aquifer around Beaumont, as both it and nearby Port Arthur have high mean, maximum, and minimum feasibility scores within their boundaries. Lake Jackson, Bryan, and College Station also have high predicted ASR feasibility directly beneath their cities in the Gulf Coast and Carrizo-Wilcox, respectively. Such an ASR system would be similar to the system currently in place in Kerrville, Texas, which has ASR wells screened in the Trinity aquifer throughout its city limits (Malcolm Pirnie et al., 2011). In cities primarily surrounded by other cities, like those around Houston, such an ASR system developed in the aquifer directly below might be the only option, as nearby land acquisition costs are likely to be prohibitively large. Fewer cities have high feasibility scores in the Carrizo-Wilcox partly because only 11 cities overlap the aquifer, whereas 31 cities overlap the Gulf Coast aquifer, as seen in Fig. 13.

Table 1 does not capture the ability of more remote cities to explore larger areas around their boundaries for hydrogeologic

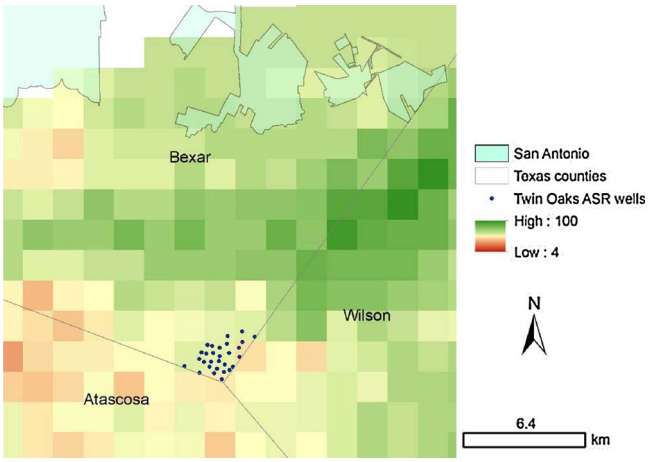

Fig. 12. Carrizo aquifer feasibility, with Twin Oaks ASR well locations and San Antonio depicted. Note how ASR wells are clustered at the bottom of Bexar County, where no GCD governs the Carrizo-Wilcox aquifer system, which the ASR wells are screened in.

Table 1
ASR feasibility score statistics for 5 cities with the highest mean feasibility scores from each aquifer. Table for all cities with populations of 20,000+ can be found in the Supplementary Material.

Aquifer	CITY	MEAN	MAX	MIN	COUNT	STDEV	VARIETY
Gulf Coast	Port Arthur	90.8	100	86	35	5.5	6
Gulf Coast	Beaumont	87.8	100	78	86	5.0	11
Gulf Coast	Lake Jackson	86.6	92	80	20	4.8	7
Gulf Coast	Victoria	79.7	87	73	35	3.2	8
Gulf Coast	Rosenberg	78.1	91	66	24	6.7	14
Carrizo-Wilcox	Bryan	88.3	94	80	32	4.8	3
Carrizo-Wilcox	College Station	81.1	85	76	7	4.5	2
Carrizo-Wilcox	Laredo	62.3	76	50	33	6.0	14
Carrizo-Wilcox	Longview	66.4	74	60	56	3.9	10
Carrizo-Wilcox	Lufkin	53.6	66	51	32	5.1	3

conditions more favorable for implementing ASR. Corpus Christi, despite not appearing in Table 1, is near an area with feasibility scores as high as 95 just northwest of the city that should be explored further, as shown in Fig. 8. Corpus Christi, it should be noted, is also currently conducting its own ASR feasibility study. Victoria and Huntsville are also near regions of high feasibility scores in the Gulf Coast. Almost no cities with populations greater than 20,000 exist in the high feasibility regions of the central and southern Carrizo-Wilcox. Despite this, San Antonio Water Supply purchased land for its ASR system south of its city limits where conditions were the most conducive for implementing ASR, as depicted in Fig. 12. Nine cities from Austin to San Antonio are within 32 kilometers of the outcrop of the Carrizo-Wilcox and could follow San Antonio's example by exploring ASR options in nearby high feasibility regions.

3.3.2. Areas with potential water supplies

In order to develop an ASR system, source water is required. As discussed in the introduction, ASR is an alternative approach for water storage, not a water source itself. An in-depth review of all potential water sources and associated water rights becomes excessively complex and is outside of the scope of this analysis. However, Fig. 14 identifies regions that may have water sources available for ASR development, specifically areas within 32 kilometers of major surface reservoirs or wastewater treatment plants with average daily flow above 38 million liters.

Surface water in reservoirs can serve as a water source for an ASR system to take advantage of ASR's primary benefit - no evaporative water losses. A municipality with water supply rights from a reservoir currently in excess of its demand (to plan for future growth, for instance) could take advantage of its current excess supply by storing it via ASR. The stored water could then be used at some point in the future. Water from a surface reservoir will most likely still need to be treated before injection in order to comply with relevant water quality regulations and avoid degrading the native groundwater quality.

Wastewater effluent from publicly owned wastewater treatment plants, despite the "ick factor" that still exists with some of the public, is another potential water source. Until it enters a stream, wastewater is still owned by the municipality, and has already received a significant level of treatment. Additional treatment may be required to satisfy legal requirements for injection into an aquifer (Sheng, 2005). Additional filtration via the aquifer would also occur during ASR. This filtration by a natural system could potentially ease public concerns over using treated wastewater effluent as a source for ASR. These three attributes (minimal additionally required treatment, current ownership, and a potentially supportive public) make treated wastewater effluents a sensible

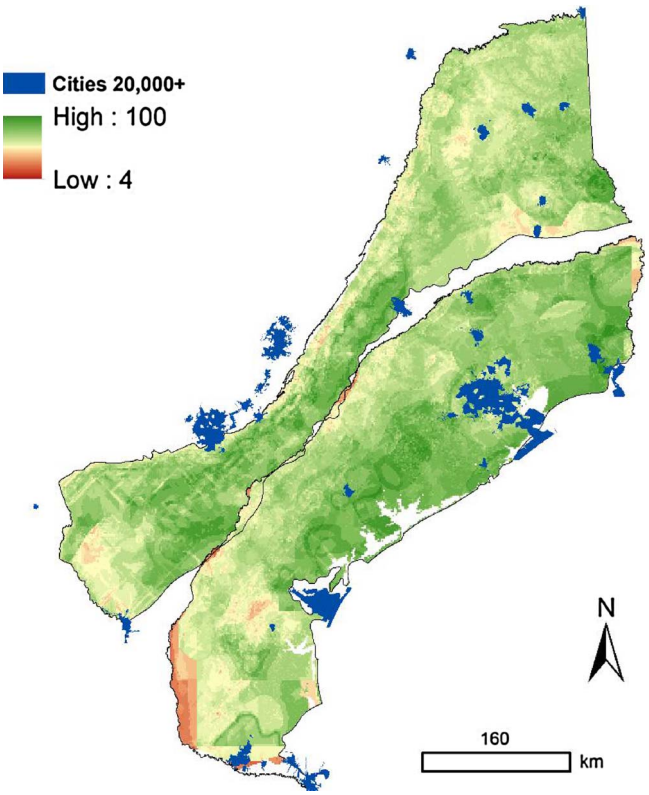

Fig. 13. Gulf Coast and Carrizo-Wilcox ASR feasibility scores with boundaries of cities with populations greater than 20,000. City boundaries within at least 32 kilometers of either aquifer are shown.

potential water source for ASR systems.

Surface reservoirs are primarily responsible for the highlighted areas northeast of the line between Houston and Austin, while the more sporadic highlights in the southwest come primarily, but not exclusively, from wastewater treatment plants. Lake Jackson is the only city with a mean score greater than 80 from Table 1 without a nearby large wastewater plant or reservoir, whereas Beaumont, Port Arthur, Bryan, and College Station all have potential water sources. Of the cities with nearby high feasibility regions, Corpus Christi, Victoria, Huntsville, and San Antonio have potential water sources; however, many of the cities between Austin and San Antonio do not.

3.3.3. Drought-prone regions

ASR can be used either for seasonal storage to ease peak demands, or for long term water storage to help alleviate water shortages during droughts. We determined which counties in the Gulf Coastal Plain have experienced the most Extreme Drought (as defined by the United States Drought Monitor), calculated as the 10-year average of the percent county area in USDM drought category D4. Fig. 15(b) varies the transparency of Fig. 14 based on this calculated 10-year drought-prone index, with the most drought-prone counties being fully transparent and the least drought-prone counties being opaque.

This drought-prone index attempts to identify which counties have been most affected by extreme drought, and thus, could have been well-served with a drought-resistant water storage option like ASR in their water portfolio. This highlights the high feasibility region southeast of Austin in the central Carrizo-Wilcox, the high feasibility area northwest of Corpus Christi, which was also noted in both 3.3.1 and 3.3.2, and to a lesser extent, the high feasibility region around Victoria. Fig. 16 overlays the varying-transparency drought layer on Fig. 14, highlighting the cities with nearby ASR feasible regions, potential water sources, and significant experience with drought in recent history: Corpus Christi, San Antonio, Victoria, Bryan, and College Station.

4. Conclusions

The classified and weighted factor analysis was used to assess ASR feasibility based on five hydrogeologic factors: transmissivity, hydraulic gradient, density of existing wells, depth to the potentiometric surface, and depth to aquifer (well depth). These factors were selected based on both their potential to affect ASR feasibility and the availability of large scale datasets across each aquifer. Some assumptions may limit the applicability of the method. Further study is recommended to enhance the score system by considering other factors.

Several cities of the northern Gulf Coast are in or near high feasibility regions with potential ASR-compatible water sources

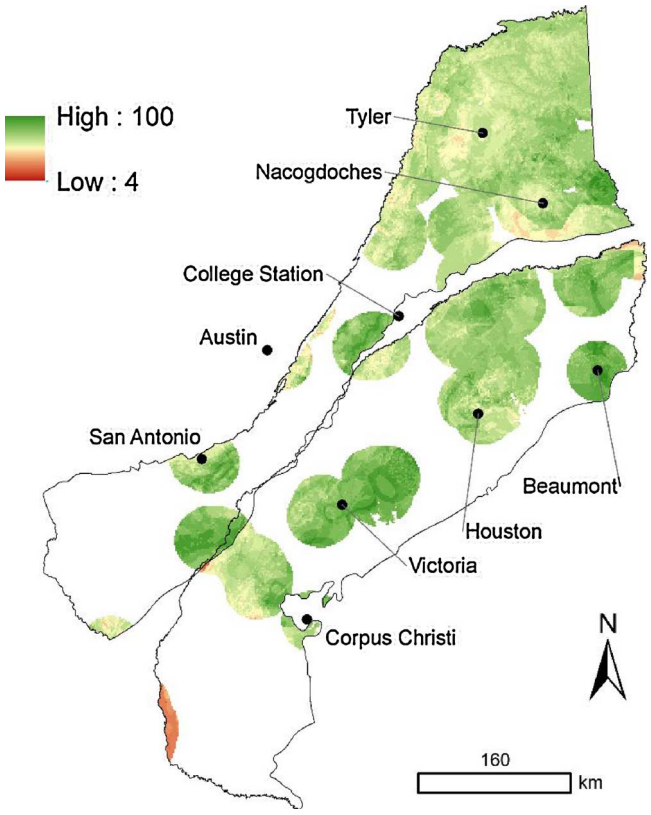

Fig. 14. ASR feasibility scores highlighted in areas within 32 kilometers of potential water sources, specifically major surface reservoirs and publicly-owned wastewater treatment plants with average daily flow greater than 38 ML/d. In minor areas of overlap, Carrizo-Wilcox ASR feasibility scores are shown.

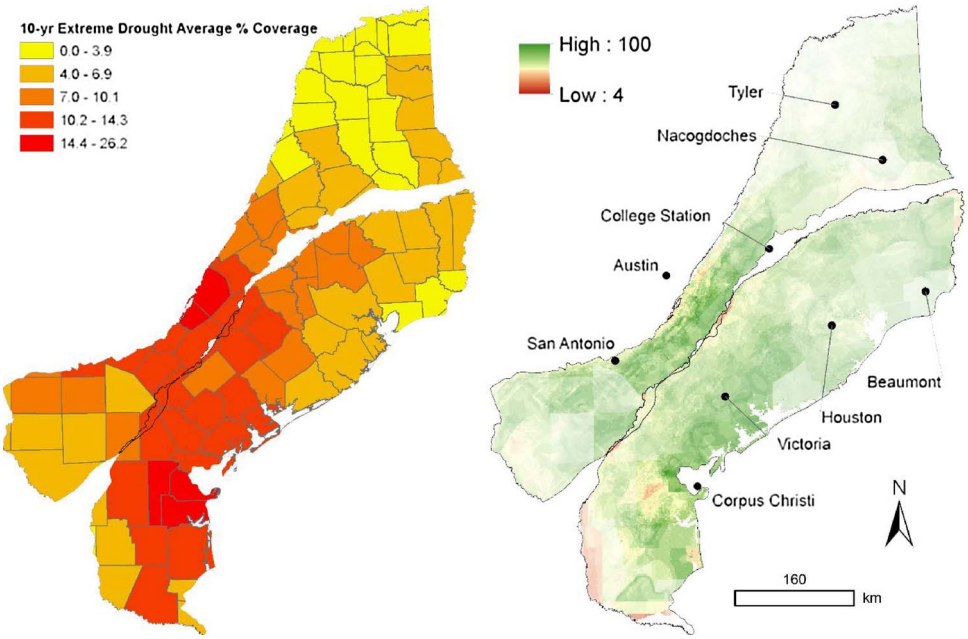

Fig. 15. (a) The 10-year average of the U.S. Drought Monitor's% areal coverage in Extreme Drought, category D4. (b) ASR feasibility scores are progressively highlighted in areas more prone to drought by using the layer from (a) to vary transparency.

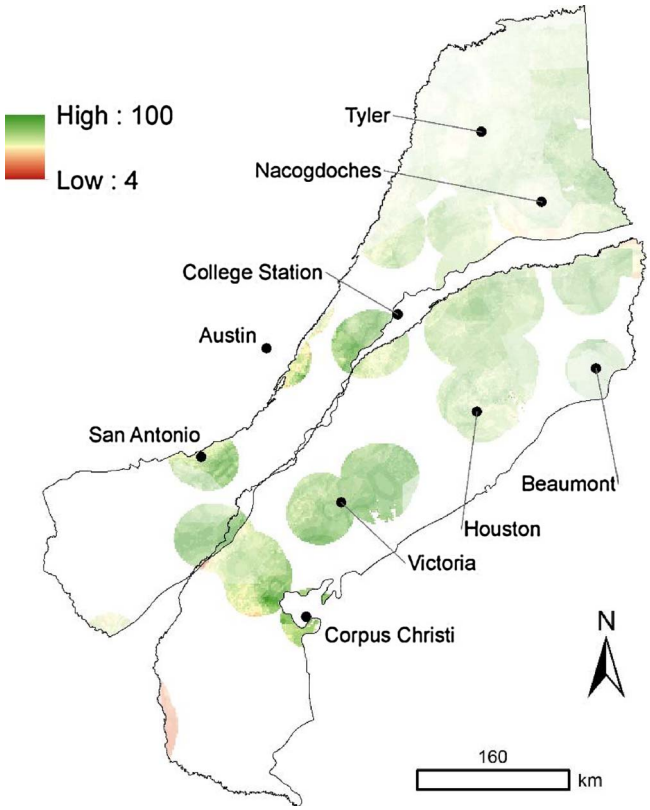

Fig. 16. ASR feasibility scores in areas with potential ASR-compatible water sources, highlighted in the most drought-prone regions.

nearby, while cities between Austin and San Antonio are near high ASR feasibility regions in the Carrizo and have a need for drought-resistant water storage. But Corpus Christi, and to a lesser extent Victoria, San Antonio, Bryan, and College Station stand apart as areas that could be served well by implementing ASR. All these cities have nearby areas of high ASR feasibility, potential ASR-compatible water sources, and a need for drought-resistant water storage, as they have all been exposed to a higher frequency of extreme drought over the last decade relative to nearby areas. In fact, San Antonio operates one of the largest ASR facilities in the United States, and all of the other four cities currently have ongoing ASR studies.

Only a few cities sit directly in regions of high predicted ASR feasibility; most of the feasible regions exist between cities. In order to take advantage of these feasible regions, future ASR wells would most likely be installed away from cities and connected to them via transmission lines, similar to SAWS' Twin Oaks system.

Regardless, ASR systems will be much more successful in areas with proper hydrogeologic conditions. This study identifies areas where ASR systems should be expected to perform well, and those areas should be studied further by local municipalities and water resources managers before implementation of ASR systems.

Conflicts of interest

The authors have no competing interests to declare.

Acknowledgements

This project was supported by Texas A&M AgriLife Research, Texas A&M AgriLife Extension, and the Texas A&M Engineering Experiment Station through a grant from the program "Research, Engineering, and Extension: Creation and Deployment of Water-Use Efficient Technology Platforms."

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2017.10.007.

References

Antoniou, E.A., van Breukelen, B.M., Putters, B., Stuyfzand, P.J., 2012. Hydrogeochemical patterns, processes and mass transfers during aquifer storage and recovery (ASR) in an anoxic sandy aquifer. Appl. Geochem. 27, 2435–2452. http://dx.doi.org/10.1016/j.apgeochem.2012.09.006.

Baker Jr., E.T., 1979. Stratigraphic and Hydrogeologic Framework of Part of The Coastal Plain of Texas. U.S.G.S. Report 236. Texas Department of Water Resources, Austin, TX. http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R236/Report236.asp.

Baker Jr., E.T., 1986. Hydrology of The Jasper Aquifer in the Southeast Texas Coastal Plain. U.S.G.S. Report 295. Texas Water Development Board, Austin, TX. http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R295/Report295.asp.

Bakker, M., 2010. Radial Dupuit interface flow to assess the aquifer storage and recovery potential of saltwater aquifers. Hydrogeol. J. 18, 107–115. http://dx.doi.org/10.1007/s10040-009-0508-1.

Bouwer, H., 2002. Artificial recharge of groundwater: hydrogeology and engineering. Hydrogeol. J. 10, 121–142. http://dx.doi.org/10.1007/s10040-001-0182-4.

Brown, C.J., Weiss, R., Sutterfield, S., Verrastro, R., Kwiatkowski, P., Schubert, S., et al., 2005. Development of an aquifer, storage and recovery (ASR) site selection suitability index in support of the comprehensive everglades restoration project. J. Environ. Hydrol. 13. www.hydroweb.com/journal-hydrology-2005-paper-20.html.

CH2MHILL, 1997. Water Supply Needs and Sources Assessment; Alternative Water Supply Strategies Investigation; A Tool For Assessing the Feasibility of Aquifer Storage Recovery. Report SJ97-SP4. St. Johns River Water Management District, Palatka, FL. http://www.sjrwmd.com/technicalreports/pdfs/SP/SJ96-SP7.pdf.

CH2MHILL, 2006. Final Report South Bexar County Aquifer Storage and Recovery Phase II Well Construction and Testing. San Antonio Water System, San Antonio, TX.

Carr, J.E., Meyer, W.R., Sandeen, W.M., McLane, I.R., 1985. Digital Models for Simulation of Ground-Water Hydrology of The Chicot and Evangeline Aquifers Along The Gulf Coast of Texas. U.S.G.S. Report 289. Texas Department of Water Resources, Austin, TX. http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R289/report289.asp.

Chowdhury, A., Mace, R.E., 2007. Groundwater Resource Evaluation and Availability Model of The Gulf Coast Aquifer in The Lower Rio Grande Valley of Texas. Report 368. Texas Water Development Board, Austin, TX. http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R368/report368. asp.

Deeds, N., Kelley, V., Fryar, D., Jones, T., Whallon, A.J., Dean, K.E., 2003. Final Report: Groundwater Availability Model for The Southern-Carrizo Wilcox Aquifer. Intera Inc., Parsons Inc., Texas Water Development Board, Austin, TX. https://www.twdb.texas.gov/groundwater/models/gam/czwx_s/CZWX_S_Full_Report.pdf.

Dillon, P., 2005. Future management of aquifer recharge. Hydrogeol. J. 13, 313–316. http://dx.doi.org/10.1007/s10040-004-0413-6.

Dutton, A.R., Harden, B., Nicot, J., O'Rourke, D., 2003. Groundwater Availability Model for The Central Part of The Carrizo-Wilcox Aquifer in Texas. Bureau of Economic Geology. The University of Texas at Austin. Texas Water Development Board, Austin, TX. https://www.twdb.texas.gov/groundwater/models/gam/czwx_c/CZWX_C_Full_Report.pdf.

Eastwood, J.C., Stanfield, P.J., 2001. Key success factors in an ASR scheme. Q. J. Eng. Geol. Hydrogeol. 34, 399–409. http://dx.doi.org/10.1144/qjegh.34.4.399.

Fernandez Escalante, E., Calero Gil, R., San Miguel Fraile, Maria A., Sanchez Serrano, F., 2014. Economic assessment of opportunities for managed aquifer recharge techniques in Spain using an advanced geographic information system (GIS). Water 6, 2021–2040. http://dx.doi.org/10.3390/w6072021.

Fryar, D., Senger, R., Deeds, N., Pickens, J., Jones, T., Whallon, A.J., et al., 2003. Final Report: Groundwater Availability Model for The Northern Carrizo-Wilcox Aquifer. Intera Inc., Parsons Inc., Texas Water Development Board, Austin, TX. https://www.twdb.texas.gov/groundwater/models/gam/czwx_n/CZWX_N_Full_Report.pdf.

George, P.G., Mace, R.E., Petrossian, R., 2011. Aquifers of Texas. Report 380. Texas Water Development Board, Austin, TX. http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R380_AquifersofTexas.pdf.

Ghayoumian, J., Mohseni Saravi, M., Feiznia, S., Nouri, B., Malekian, A., 2007. Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran. J. Asian Earth Sci. 30, 364–374. http://dx.doi.org/10.1016/j.jseaes.2006.11.002.

Jones, G.W., Pichler, T., 2007. Relationship between pyrite stability and arsenic mobility during aquifer storage and recovery in southwest central Florida. Environ. Sci. Technol. 41, 723–730. http://dx.doi.org/10.1021/es061901w.

Kasmarek, M.C., 2013. Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in The Northern Part of The Gulf Coast Aquifer System, Texas 1891–2009. U.S.G.S. Texas Water Development Board, Austin, TX. https://www.twdb.texas.gov/groundwater/models/gam/glfc_n/GLFC_N_Full_Report.pdf.

Khan, S., Mushtaq, S., Hanjra, M.A., Schaeffer, J., 2008. Estimating potential costs and gains from an aquifer storage and recovery program in Australia. Agric. Water Manage. 95, 477–488. http://dx.doi.org/10.1016/j.agwat.2007.12.002.

Lowry, C.S., Anderson, M.P., 2006. An assessment of aquifer storage recovery using ground water flow models. Groundwater 44, 661–667. http://dx.doi.org/10.1111/j.1745-6584.2006.00237.x.

Mace, R.E., Smyth, R.C., Xu, L., Liang, J., 2000. Transmissivity, Hydraulic Conductivity, and Storativity of The Carrizo-Wilcox Aquifer in Texas. Bureau of Economic Geology, The University of Texas at Austin. Texas Water Development Board, Austin, TX. http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/99483279.pdf.

Malcolm Pirnie Inc, ASR Systems LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, 2011. An Assessment of Aquifer Storage and Recovery in Texas. Report 0904830940. Texas Water Development Board, Austin, TX. http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf.

Malekmohammadi, B., Ramezani Mehrian, M., Jafari, H., 2012. Site selection for managed aquifer recharge using fuzzy rules: integrating geographical information system (GIS) tools and multi-criteria decision making. Hydrogeol. J. 20, 1393–1405. http://dx.doi.org/10.1007/s10040-012-0869-8.

Maliva, R.G., Missimer, T.M., 2010. Aquifer Storage and Recovery and Managed Aquifer Recharge Using Wells: Planning, Hydrogeology, Design, and Operation. Schlumberger, Sugar Land, Texas.

Maliva, R.G., Guo, W., Missimer, T.M., 2006. Aquifer storage and recovery: recent hydrogeological advances and system performance. Water Environ. Res. 78, 2428–2435. http://dx.doi.org/10.2175/106143006X123102.

Maliva, R.G., Missimer, T.M., Winslow, F.P., Herrmann, R., 2011. Aquifer storage and recovery of treated sewage effluent in the middle east. Arabian J. Sci. Eng. 36, 63–74. http://dx.doi.org/10.1007/s13369-010-0011-y.

National Research Council, 2008. Prospects for Managed Underground Storage of Recoverable Water. National Academies Press, Washington, D.C.

Pedrero, F., Albuquerque, A., Marecos do Monte, H., Cavaleiro, V., Alarcón, J.J., 2011. Application of GIS-based multi-criteria analysis for site selection of aquifer recharge with reclaimed water. Resour. Conserv. Recycl. 56, 105–116. http://dx.doi.org/10.1016/j.resconrec.2011.08.003.

Pyne, R.D.G., 2005. Aquifer Storage Recovery: A Guide to Groundwater Recharge Through Wells. ASR Systems, Gainesville, FL.

Rahman, M.A., Rusteberg, B., Gogu, R.C., Lobo Ferreira, J.P., Sauter, M., 2012. A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. J. Environ. Manage. 99, 61–75. http://dx.doi.org/10.1016/j.jenvman.2012.01.003.

Rahman, M.A., Rusteberg, B., Uddin, M.S., Lutz, A., Abu Saada, M., Sauter, M., 2013. An integrated study of spatial multicriteria analysis and mathematical modelling for managed aquifer recharge site suitability mapping and site ranking at Northern Gaza coastal aquifer. J. Environ. Manage. 124, 25–39. http://dx.doi.org/10.1016/j.jenvman.2013.03.023.

Russo, T.A., Fisher, A.T., Lockwood, B.S., 2015. Assessment of managed aquifer recharge site suitability using a GIS and modeling. Groundwater 53, 389–400. http://dx.doi.org/10.1111/gwat.12213.

Sheng, Z., Zhao, X., 2015. Special issue on managed aquifer recharge: powerful management tool for meeting water resources challenges. J. Hydrol. Eng. 20. http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0001139.

Sheng, Z.P., 2005. An aquifer storage and recovery system with reclaimed wastewater to preserve native groundwater resources in El Paso, Texas. J. Environ. Manage. 75, 367–377. http://dx.doi.org/10.1016/j.jenvman.2004.10.007.

Smith, A.J., Pollock, D.W., 2012. Assessment of managed aquifer recharge potential using ensembles of local models. Groundwater 50, 133–143. http://dx.doi.org/10.1111/j.1745-6584.2011.00808.x.

TWDB, 2012. Water for Texas 2012 State Water Plan. Texas Water Development Board, Austin, TX. http://www.twdb.texas.gov/publications/state_water_plan/2012/2012_SWP.pdf.

TWDB, 2015. Groundwater Database Reports. Texas Water Development Board, Austin, TX. http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp.

Ward, J.D., Simmons, C.T., Dillon, P.J., Pavelic, P., 2009. Integrated assessment of lateral flow, density effects and dispersion in aquifer storage and recovery. J. Hydrol. 370, 83–99. http://dx.doi.org/10.1016/j.jhydrol.2009.02.055.

Waterstone Inc, Parsons Inc, 2003. Groundwater Availability of The Central Gulf Coast Aquifer: Numerical Simulations to 2050, Central Gulf Coast, Texas. Texas Water Development Board, Austin, Texas. https://www.twdb.texas.gov/groundwater/models/gam/glfc_c/Waterstone_Conceptual_Report.pdf.

Young, S.C., Ewing, T., Hamlin, S., Baker, E., Lupton, D., 2012. Updating The Hydrogeologic Framework for The Northern Portion of the Gulf Coast Aquifer. Report CR-1004831113. Texas Water Development Board, Austin, Texas. http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1004831113_GulfCoast.pdf.

Zuurbier, K.G., Bakker, M., Zaadnoordijk, W.J., Stuyfzand, P.J., 2013. Identification of potential sites for aquifer storage and recovery (ASR) in coastal areas using ASR performance estimation methods. Hydrogeol. J. 21, 1373–1383. http://dx.doi.org/10.1007/s10040-013-1003-2.