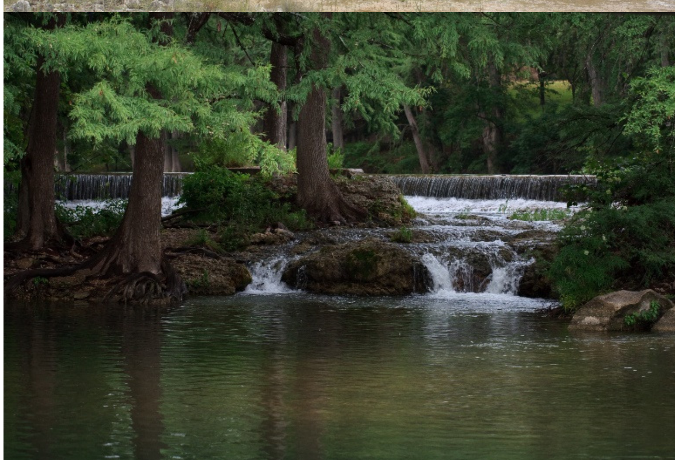

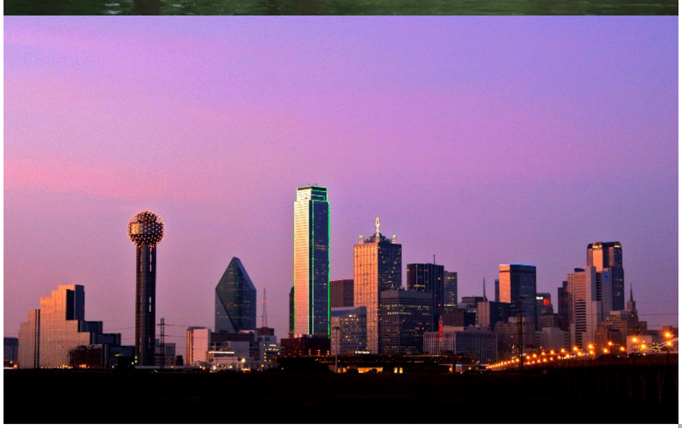

Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects

September 2020

HDR

With support by

Bureau of Economic Geology

Collier Geophysics
Surface • Marine • Borehole

Cooper Consulting

INTERA
Geoscience & Engineering Solutions

GSA GeoSystems Analysis, Inc.
Innovations in Hydrology

Floodace

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Errata – January 22, 2021

The contractor provided updated versions of the following pages for this report:

- 67
- 73
- 82
- 85
- 90

On pages 67, 73, 85, and 90, updates correct the threshold values used for excess water and water supply needs classified as "low," "medium," and "high" suitability as follows:

Replace:

- Low– Water Supply Needs Score < 0.5
- Medium– Water Supply Needs Score 0.5 to 0.7
- High– Water Supply Needs Score > 0.7

With:

- Low– Water Supply Needs Score < 0.34
- Medium– Water Supply Needs Score 0.34 to 0.67
- High– Water Supply Needs Score > 0.67

The update to page 82 is as follows:

Replace:

"Scores and weights to be assigned and verified in TWDB workshop"

With:

"Scores and weights were assigned and verified in TWDB workshop"

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Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects

Final Report

TWDB Contract No. 2000012405

Kristi Shaw, P.E., HDR

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September 30, 2020

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Final Report
TWDB Contract No. 200012405
Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects

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Final Report
TWDB Contract No. 200012405
Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects

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Final Report
TWDB Contract No. 200012405
Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects

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Prepared scripts for processing output of TCEQ Water Availability Models and EPA ECHO databases to calculate scoring parameters for excess water screening. Contributor to literature review and report section comparing study results with previous findings from Yang and Scanlon's 2019 case study on flood flows along coastal basins.

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We are grateful to the Texas Water Development Board (TWDB) for providing constructive and timely feedback during this quick-paced survey, especially during unusual pandemic conditions. To the TWDB staff who participated in any of the six virtual workshops, your feedback and perspectives were very helpful in developing the survey approach. Thank you, Erika Mancha, for providing reuse information; John Dupnik, for legislative considerations; Yun Cho, for providing regional water planning and historical water use shapefiles and revisiting data gaps; Sabrina Anderson, for providing Draft State Water Planning Database (draft DB22) output; and Sarah Backhouse, for data on current ASR projects and studies identified in the draft 2021 Regional Water Plans. Last but not least, a very special thanks to our project manager, Andrea Croskrey, PG (Innovative Water Technologies Team). Andrea’s organizational skills kept this project focused and on-track. We are tremendously grateful for her thoughtful feedback, internal coordination with TWDB staff, reaching across multiple TWDB departments to respond to data and information technology needs for the public data display, and tirelessly (and enthusiastically) engaging in a dozen meetings over a six-month period. For all her efforts, we are truly grateful.

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List of Acronyms

acft	aquifer foot
AR	aquifer recharge
ASR	aquifer storage and recovery
BFZ	Balcones Fault Zone
BRACS	Brackish Resources Aquifer Characterization System
CCEFN	Consensus Criteria for Environmental Flow Needs
DEM	digital elevation model
DFC	desired future conditions
DO	dissolved oxygen
ECHO	Enforcement and Compliance History Online database
EPA	U.S. Environmental Protection Agency
FWI	Freshwater Inflows
GAM	groundwater available model
GMA	groundwater management area
GCD	groundwater conservation districts
HB 720	House Bill 720
HB 721	House Bill 721
MAG	modeled available groundwater
MANU	manufacturing
MAUT	multi-attribute utility theory
MUN	municipal
RCID	row and column id for grid cells
RWPG	regional water planning group
SE	steam electric
SSURGO	Soil Survey Geographic Database
TCEQ	Texas Commission on Environmental Quality
TDS	total dissolved solids
TIFP	Texas Instream Flow Program
TSS	total suspended solids
TWDB	Texas Water Development Board
draft DB22	TWDB Draft State Water Planning Database
WAM	water availability model
WMS	water management strategy
WUG	water user group

Executive Summary

Background

In 2019, the 86th Texas Legislature passed House Bill 721 (HB 721) directing the Texas Water Development Board (TWDB) to conduct a statewide survey of Texas' major and minor aquifers to determine their relative suitability for use in aquifer storage and recovery (ASR) projects or aquifer recharge projects (AR). Aquifer storage and recovery is defined by Section 27.151 of the Texas Water Code as "the injection of water into a geologic formation for the purpose of subsequent recovery and beneficial use by the project operator." Aquifer recharge, as defined by HB 721 and amended Section 11.155 of the Texas Water Code, "involves the intentional recharge of an aquifer by means of an injection well authorized under Chapter 27 of the Texas Water Code or other means of infiltration, including actions designed to (a) reduce declines in the water level of the aquifer; (b) supplement the quantity of groundwater available; (c) improve water quality in an aquifer; (d) improve spring flows and other interactions between groundwater and surface water; and (e) mitigate subsidence." The legislation requires that the relative suitability consider hydrogeological characteristics, the availability of excess water for potential storage, and the current and future water supply needs as documented in the state water plan. To accomplish this, three stand-alone screening were developed.

- The first screening focused on hydrogeological characteristics, such as storage potential, transmissivity, infiltration characteristics, storativity, recoverability, and water quality
- The second screening focused on excess water that could be available for storage and recharge from surface and stormwater, reclaimed water, or groundwater sources based on frequency, volume and other factors affecting reliability.
- The third screening focused on identifying the current and future water supply needs. To use the most current information available, the water supply needs were based on the Draft State Water Planning Database (draft DB22) (submitted March 2020).

Together these three screenings are combined into a Final Suitability Rating to help identify areas where suitable hydrogeology, excess water, and water needs exist for further consideration for ASR or AR project potential. This report documents the approach, methodology, analysis, results completed at each screening level, and summary-level findings to determine the relative hydrogeological suitability of the major and minor aquifers to support ASR or AR.

Results

Texas has numerous areas suitable for ASR or AR. Hydrogeological Parameter Screening results for ASR or AR are categorized as low, medium, or high suitability according to methods described in this report. However, a low suitability score does not necessarily mean that the aquifer is undesirable for ASR or AR rather that it is less preferred relative to other areas that may score as medium or high. Similarly, the Excess Water and Water Supply Needs Screenings categorize results as low, medium, or high, according to parameters and methods described in the report. The Final Suitability Rating, which integrates the three screenings, presents relative suitability by grid cell as less, moderately, and most suitable.

The results of Hydrogeological Parameter Screening for ASR indicate eight of the nine major aquifers have at least some grid cells that are rated “high,” with the Seymour being the only major aquifer with a highest rated cell in the “moderate” suitability category. This indicates that nearly all of the major aquifers have some portions that may be highly suitable for an ASR application. Four of the nine major aquifers have a median score that is in the “high” category (the Trinity Aquifer just misses with a median score of 0.69), indicating that the majority of cells are rated high. These aquifers are the Carrizo-Wilcox, Edwards (Balcones Fault Zone [BFZ]), Gulf Coast, and Trinity aquifers. These aquifers all have either operating ASR wells or pilot studies in Texas in San Antonio, New Braunfels, Victoria, and Kerrville, respectively. In addition, the Hueco-Mesilla Bolsons Aquifer, where El Paso has an indirect ASR system, scores a median of 0.7, which also meets the “high” threshold category.

Seven of the 22 minor aquifers have at least some grid cells that are rated “high” in terms of hydrogeological suitability for ASR, while only 1 of the 22 minor aquifers have a median hydrogeological suitability score that is rated in the “high” category, the Sparta. As expected, while many of the minor aquifers contain portions that are hydrogeologically suitable for ASR, this condition is not nearly as common or pervasive as with the major aquifers.

The results of Hydrogeological Parameter Screening for AR indicate seven of the nine major aquifers have at least some grid cells that are rated “high,” and five of the nine major aquifers have median score rated “high.” One notable exception is the Edwards (BFZ) Aquifer, which just missed a median “high” score at 0.79, but has currently operating recharge features. The Edwards (BFZ) Aquifer is rated slightly lower primarily due to its lower score in storage, as seen in its median storage score of 0.5. This low storage score is due to a low effective porosity, and limited depths to water. In reality, the lack of storage does not affect the current recharge projects in the Edwards Aquifer, because the objective of those projects is not necessarily long-term storage, but general augmentation (i.e., keeping water levels and springflow at desirable levels). So the Edwards (BFZ) Aquifer AR hydrogeologic suitability score should not be considered to be contrary to the reality of current operations.

The Hueco-Mesilla Bolsons Aquifer, where El Paso has performed a type of AR using infiltration ponds, has a median rating of "high."

Four of the 22 minor aquifers have a least some grid cells with a "high" rating, while only one of the 22 aquifers has a median value that qualifies for the "high" rating. Similar to the ASR scores, there will be areas in many of the minor aquifers that may be suitable for AR, but those areas are not as common or pervasive as for the major aquifers.

The Excess Water Screening considered surface water (and stormwater), reclaimed water, and groundwater that could be available for ASR or AR projects. The surface water evaluation considered the following sources:

- Surplus appropriated surface water from run-of-the river and reservoirs as identified in the draft DB22
- Unappropriated streamflow from the Texas Commission on Environmental Quality (TCEQ) Water Availability Model (WAM) analyses; and
- Existing reservoir locations that could be used in conjunction with ASR or AR operations.

Surplus appropriated surface water from run-of-the-river and reservoirs was obtained from draft DB22 and is not widely available throughout the state as most of this surface water source is already dedicated to meet existing water use demands or for future water management strategies. However, where available, the surplus appropriated surface water received higher scores due to the higher frequency and duration scores attributed to reliability during drought, which is a requirement for supply evaluations for regional water planning.

Unappropriated streamflow considers historical flows representative of all climatological conditions included in WAM data files including high flows (stormwater), median flows, and low flow conditions. The scoring of unappropriated streamflow generally follows the climate trends across the state with wetter conditions in the eastern portion of the state resulting in higher scores and drier conditions in the western portion of the state resulting in no availability. Unappropriated streamflow is limited in many urban areas because much of the surface water is already appropriated for impoundment and use from existing reservoirs.

Excess reclaimed water was evaluated using recently reported effluent discharge volumes recorded in the U.S. Environmental Protection Agency (EPA) Enforcement and Compliance History Online (ECHO) database for TCEQ Texas Pollutant Discharge Elimination System (TPDES) program discharge locations. Higher scores are focused near the larger metropolitan areas where larger wastewater effluent discharges are present. The scores also reflect the high reliability of the excess reclaimed water source by receiving a generally high score if wastewater discharges are present.

Excess groundwater supplies were based on data from the TWDB Draft State Water Planning Database (draft DB22) that was used to quantify excess groundwater supplies for major and minor aquifers after current use and future water management strategies from the regional water plans were considered. For major aquifers, excess groundwater from the Ogallala and Seymour in the Panhandle area, Hueco-Mesilla Bolsons and Edwards Trinity-Plateau in West Texas, and the Gulf Coast in East Texas received the highest scores after evaluating the frequency, volume, duration, and estimated water quality. For minor aquifers, the highest scoring aquifers and areas for excess groundwater supplies include the Rita Blanca and Dockum aquifers in the Panhandle, Queen City in East Texas, and Yegua Jackson in South Texas. When excess water supplies from major and minor aquifers are combined to identify opportunities in areas with coincident aquifers, the greatest opportunities for excess groundwater occurs in the Panhandle, West Texas, and East Texas area north of Houston.

Water supply needs scores were prepared for municipal, manufacturing, and steam electric needs identified in draft DB22 that had defined service areas or historical water use data (manufacturing and steam electric) recorded with TWDB. Water needs that exceeded 500 acre-feet/year were scored. The screening does not score county-wide needs for irrigation, mining, or Municipal County-other where spatial data is unavailable at a higher resolution than at a county level.

The results of the water needs supply screening showed municipal needs throughout Texas, however the highest scoring needs generally are along the Interstate Highway 35 (IH 35) corridor from Dallas- Fort Worth Metroplex down towards San Antonio and affect water supply utilities serving those areas. Municipal needs also score highly in South Texas, including Hidalgo, Willacy, and Cameron counties.

Manufacturing needs were identified for about 200 grid cells across Texas. Of these, roughly one-quarter received scores because their needs exceeded 500 acre-feet/year (acft/yr). About 60 percent of these areas had needs scores exceeding 0.75 scattered throughout Texas with no discernible trend observed. A few clustered areas are located in the Beaumont/Port Arthur and Corpus Christi areas. Several manufacturing needs exceeding 10,000 acft/yr were located along the Gulf of Mexico coastline.

Steam electric needs were identified for about 50 grid cells across Texas. Of these, about 72 percent received scores based on needs exceeding 500 acft/yr. About half of the areas with steam electric needs that qualified for scoring had needs scores exceeding 0.75. Similar to the manufacturing needs, these are scattered throughout Texas with no discernible trend observed.

The Final Suitability Rating screen integrates results from the three individual, suitability screens related to hydrogeological parameters, excess water, and water supply needs to identify potential projects based on the relative suitability of Texas' aquifers for ASR or AR.

Final Suitability Ratings were evaluated and assigned for grid cells that previously received an ASR or AR hydrogeological parameter screening score coincident and up to two grid spaces from excess water and water need grids. This "buffer" was assigned to recognize that supplies and needs located within 20 miles of a suitable ASR or AR aquifer area is likely feasible for an ASR or AR project.

The Final Suitability Rating screen includes conjunctive use opportunities by identifying multiple supplies that could be combined to achieve operational, reliability, and redundancy benefits for ASR or AR. The screening takes into account individual water needs, as well as identifying potential opportunities for regional partnership in ASR or AR projects in areas where multiple water needs are in close proximity.

For the ASR Final Suitability Rating, nearly 65 percent of the total statewide grid cells identified in the ASR Hydrogeological Parameter Screening were in close proximity (approximately 20 miles) to excess water and water need grids and received a final suitability rating as shown in **Figure ES1**. Of the cells that were scored, 19 percent reported highly suitable scores for ASR (>0.7) and 51 percent reported moderately suitable ASR scores of 0.5-0.7.

Final ASR suitability scores were assigned to all 9 major aquifers and 15 minor aquifers. Six minor aquifers did not receive a score either because the location was coincident with another aquifer that scored more favorably, or because they occurred in areas without excess water and/or needs. The four aquifers with the most widespread coverage included the Carrizo-Wilcox, Gulf Coast, Ogallala, and Trinity aquifers which combined accounted for nearly 70 percent of the scored cells. The highest ASR final suitability ratings (>0.85) were found in the Carrizo- Wilcox, Trinity, Gulf Coast, and Sparta aquifers.

For the AR Final Suitability Rating, nearly 67 percent of the total statewide grid cells identified in the AR Hydrogeological Parameter Screening were in close proximity to excess water and water need grids and received a final suitability rating as shown in **Figure ES2**. Of the cells that were scored, 22 percent reported highly suitable scores for AR (>0.7) and 53 percent reported moderately suitable AR scores of 0.5-0.7.

Final AR suitability scores were assigned to all 9 major aquifers and 15 minor aquifers. The four aquifers with the most widespread coverage included the Gulf Coast, Ogallala, Cross Timbers and Carrizo-Wilcox aquifers which combined accounted for 57 percent of the scored cells. The highest AR final suitability ratings (>0.85) were found in the Brazos Valley Alluvium, Gulf Coast, Ogallala, Carrizo-Wilcox and Hueco-Mesilla Bolsons Aquifer outcrops.

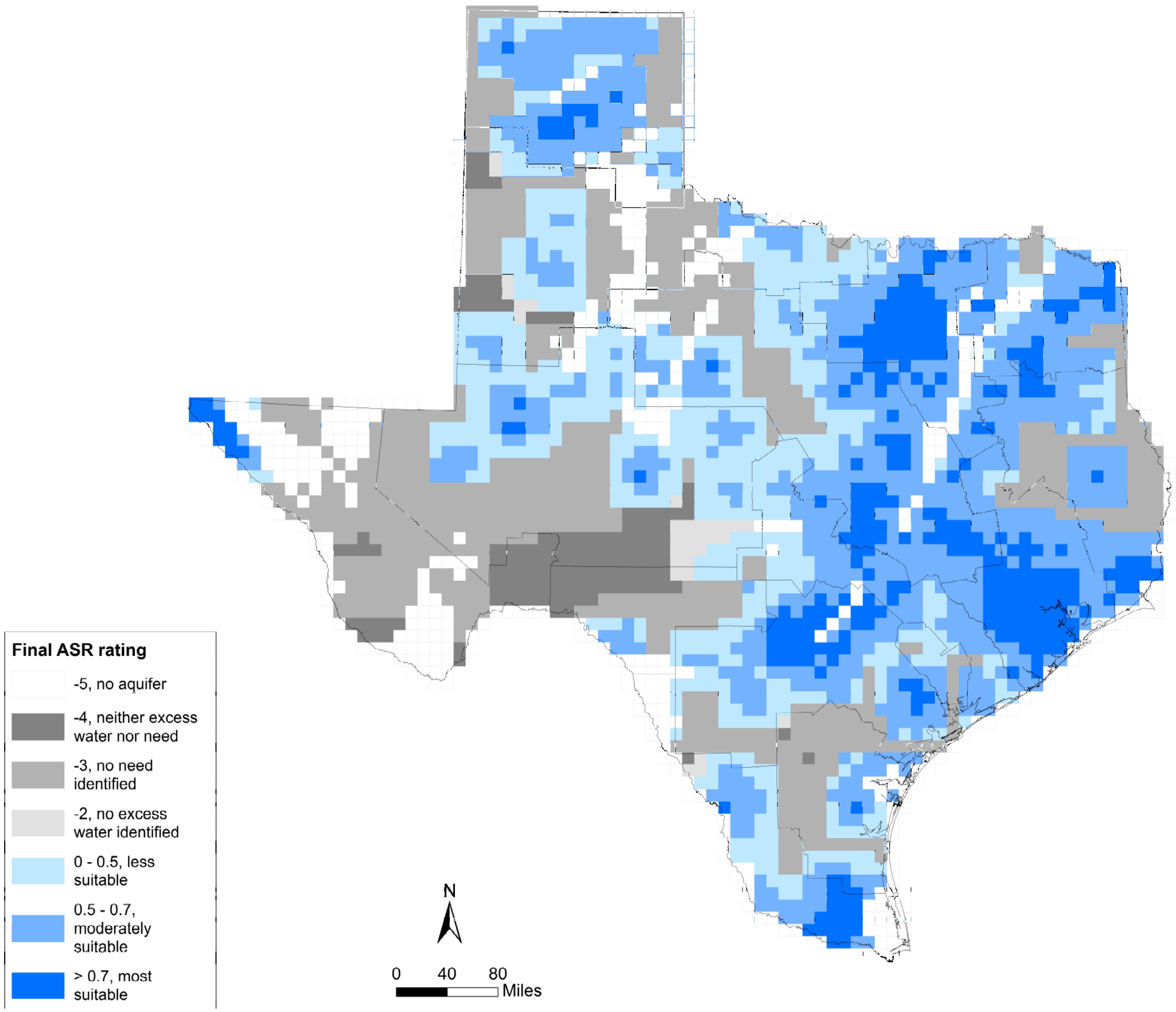

Figure ES1. Final Suitability Rating for ASR

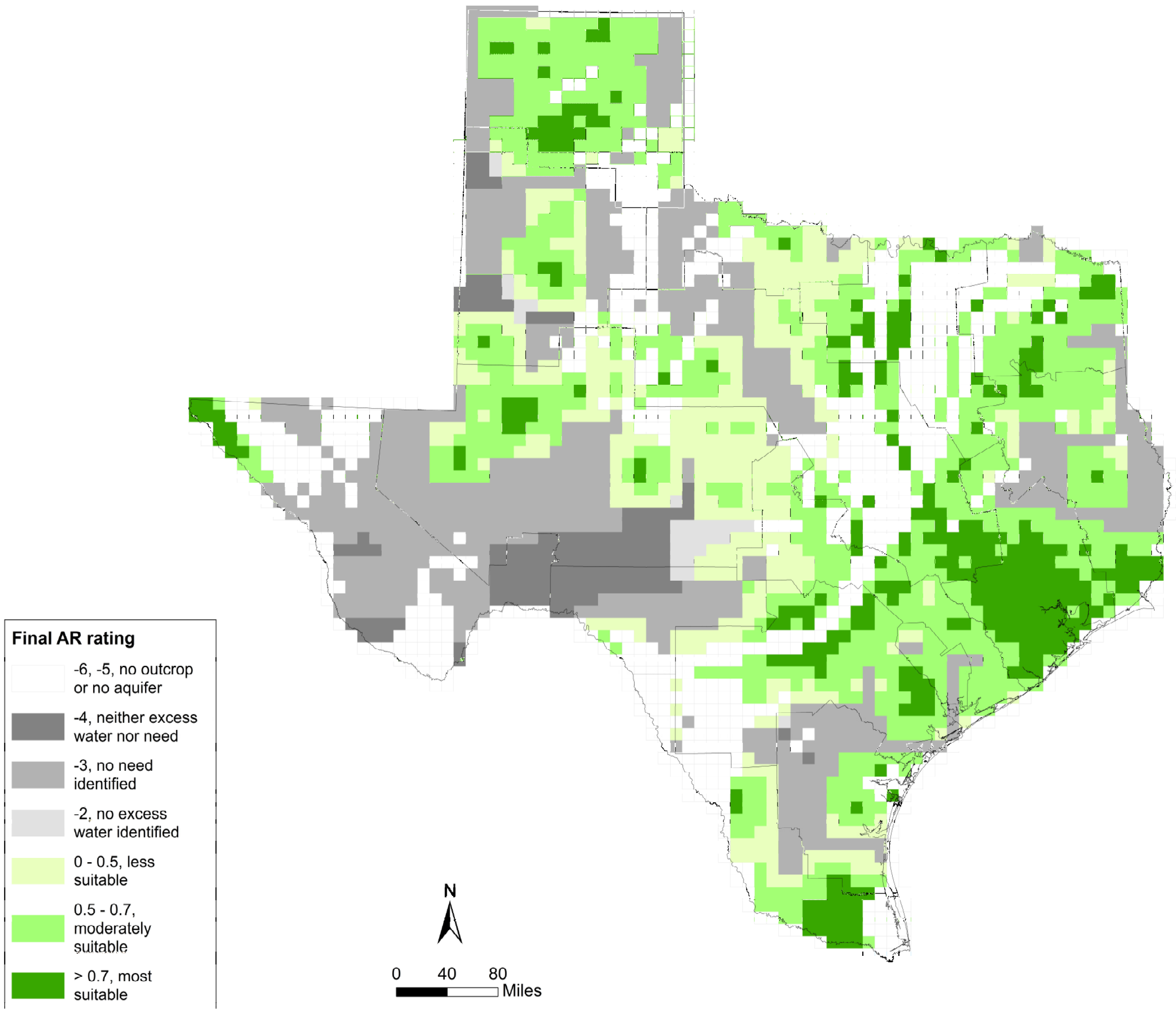

Figure ES2. Final Suitability Rating for AR

The screenings developed in this survey provide support to stakeholders such as water utilities, water planners, and government officials. The screenings are meant to provide regional guidance on ASR or AR development, while at the same time addressing HB 721 legislative requirements by identifying hydrogeological parameters important for assessing ASR and AR on a statewide level. The purpose of these screenings is not to replace the need for field and site-specific studies, but instead to serve as a guide and preliminary screenings for stakeholders.

A grid size at a resolution of 50,000 feet x 50,000 feet (or 89.5 square miles) is considered appropriate for the scale at which data is available while providing sufficient detail to achieve TWDB goal for regional use. Although this survey seeks to identify preferable areas based on hydrogeological parameters, excess water, and water supply needs as key components that shape the feasibility of ASR and AR projects and scores according to relative suitability (low, medium, high) for individual screenings and less, moderately, and most suitable for the Final Suitability Rating, it is recognized that a high suitability score is not required in order for a given area to have a successful ASR or AR project. There are aquifers other than the major and minor aquifers that could host good projects. For example, local and seasonal surplus water supplies could not be mapped at this statewide scale, and countywide water user groups (like mining and irrigation) lack specific location information to map where water supply needs exist.

This statewide survey has many strengths, including giving stakeholders the versatility to use the source data as needed to customize scoring according to parameters they deem most relevant. The Final Suitability Rating includes conjunctive use opportunities by identifying multiple supplies that could be combined in a synergistic way to achieve operational, reliability, and redundancy benefits for ASR or AR. The screening takes into account individual water needs, as well as identifying potential opportunities for regional partnership in ASR or AR projects in areas where multiple water needs are in close proximity. All four screenings provide a strong foundation that future data sets can be added to for update, or as new data becomes available.

The primary limitation for the Statewide Survey of Aquifer Suitability for ASR or AR is the natural tension between evaluation of ASR and AR on a statewide basis and the site-specific nature of ASR and AR projects. The results of the screening can be used as an indicator of the probability of finding suitable sites, and should not be considered absolute with respect to the potential success of a project.

Introduction

Aquifer storage and recovery (ASR) and aquifer recharge (AR) involves the local storage of water within an aquifer for later beneficial use, including water supply purposes. Currently, there are three operational ASR facilities in Texas: City of Kerrville, San Antonio Water System (SAWS), and El Paso Water Utilities (EPWU)[1]. There are many planning projects in Texas that are currently being evaluated for ASR feasibility, including but not limited to: City of Bryan, College Station, New Braunfels, Buda, Victoria, Corpus Christi, Austin, Kerrville, the Tarrant Regional Water District, and Barton Spring Edwards Aquifer Conservation District. El Paso Water Utilities (EPWU) uses spreading basins for recharge[2] and is the only operational AR facility in Texas.

In 2015, the 84th Texas Legislature directed TWDB through House Bill 1, Rider 25 to provide grant support for demonstration projects or feasibility studies that would create new water supplies or increase water availability through innovative storage approaches. This grant funding supported three recently completed ASR demonstration projects for Corpus Christi, New Braunfels Utilities, and Victoria.

In 2019, the 86th Texas Legislature through House Bill 721 tasked the TWDB with determining the feasibility of Texas aquifers for ASR and aquifer recharge. The legislation outlined specific analyses to be included in the statewide survey of relative suitability including considerations for hydrogeological characteristics, the availability of excess water for potential storage, and the current and future water supply needs as documented in the state water plan. This report summarizes the results from the survey, including three stand-alone screenings and a combined screening that were developed to address relative ASR or AR suitability.

During the early stages of survey development, a literature review was conducted to identify recent demonstration projects related to ASR nationally and within Texas, evaluate methodologies from these studies and its application to Texas aquifers, and summarize how existing work could inform the evaluation of relative suitability of ASR and aquifer recharge. The literature review, including an overall summary of Texas aquifer characteristic and identification of recent ASR studies nationally and in Texas is provided in **Appendix A**. It is noteworthy to mention that the literature review included a draft outline of methodology for development of the screenings, however the information presented below supersedes preliminary information included in **Appendix A**.

---

[1] El Paso Water Utilities has a hybrid indirect ASR facility whereby water is added to the aquifer using wells and spreading basins and the stored water is recovered from wells that are not the same as the ones used for injection.
[2] In conjunction with recharge through wells. Recovery is indirect, using different wells than the recharge wells.

This report documents the approach, methodology, analysis, results completed at each screening level, and summary-level findings to determine the relative hydrogeological parameter screening of the major and minor aquifers to support ASR or AR. **Appendix B** includes a description of GIS files developed for this survey.

Hydrogeological Parameter Screening

Objective

The objective of Hydrogeological Parameter Screening is to identify the relative suitability of Texas' aquifers for aquifer storage and recovery (ASR) projects and aquifer recharge (AR) projects based on hydrogeological characteristics with a focus on storage potential, transmissivity, infiltration characteristics, storativity, recoverability, and water quality.

Approach

The general approach to estimating hydrogeological parameter screening for ASR or AR was as follows.

1. Consider hydrogeological parameters that are important to the probable success of an ASR or AR project, including those identified in House Bill 721 (HB 721).
2. Estimate those hydrogeological parameters for each of the major and minor aquifers in Texas. When possible, consider how these parameters vary spatially for a given aquifer.
3. Develop separate strategies for ASR and AR in scoring these parameters on their relative potential impact on the viability of a project.
4. Combine the parameter scores to create a final hydrogeological parameter screening score for ASR and AR.
5. Use the magnitude of the hydrogeological parameter screening score to rank regions of each aquifer according to ASR or AR suitability according to three general categories of relative suitability to identify those that are more suitable than others. The three categories are "low," "medium," or "high" suitability.

This approach is described in more detail in the following sections, starting with the selection of hydrogeological parameters.

Hydrogeological Parameter Methodology

The design and overall suitability of an ASR or AR project is dependent upon many factors. These can generally be divided into operational considerations and factors associated with the hydrogeological characteristics at the location where the project will be developed. This section of the report only focuses on the suitability as can be determined from hydrogeological characteristics.

To assess hydrogeological parameter screening, a series of metrics were calculated spatially. These metrics are based upon aquifer parameters or other characteristics that are considered important to the suitability of ASR or AR. The reality is that local suitability of ASR and AR are very site-specific. However, both a regional analysis documented here, and a site-specific analysis do share many similar aquifer characteristics that would describe suitability. This survey focuses on regional hydrogeological characteristics that are either quantitative or qualitative and are expected to inform overall suitability. Following is a description of the hydrogeological parameter screening parameters chosen for this analysis.

Methodology for parameter selection

Several fundamental hydrogeological properties or characteristics form the basis for scoring the relative suitability of Texas' aquifers for ASR or AR. Parameters are classified into three suitability categories for ASR: recharge, storage, and recoverability. Similarly for AR, suitability parameters are classified into two categories: suitability for recharge and suitability for storage. Recoverability was not considered for AR because while there is an established framework in Texas for how ASR recoverability affects permitting and operations, no such framework exists for AR; thus, it has no demonstrated importance for the success of an AR project. Furthermore, the objective of an AR project is commonly for purposes other than water supply, such as improving local groundwater conditions, improving spring flow and other groundwater-surface water interactions, mitigating subsidence, and others.

HB 721 specified storage potential, transmissivity, infiltration characteristics, storativity, recoverability, and water quality, which are all considered in the screening process either as individual suitability parameters or as scoring categories that are dependent on multiple suitability parameters. **Table 1** shows how each HB 721 focus area is incorporated into the approach.

Table 1. House Bill 721 focus for hydrogeological characterization and how they are addressed in this survey

HB-721 focus area	Description
Storage potential	AR and ASR primary category- *Storage*
Transmissivity	AR and ASR primary category- *Recharge*
Infiltration characteristics	AR primary category- *Recharge*
Storativity	AR and ASR primary category- *Storage*
Recoverability	ASR primary category- *Recoverability*
Water quality	ASR primary category- *Recoverability*

AR = aquifer recharge; ASR = aquifer storage and recovery

Some suitability parameters may have relevance in more than one category. Categorical assignments simplify the task of understanding input/output relationships, because they reduce the number of input variables being considered in a category. The relationship between the weights and scores of the categories can then be analyzed as a separate step before combining into the ASR or AR hydrogeological parameter screening score.

Table 2 includes a list of parameters that are included in the Hydrogeological Parameter Screening for ASR, along with descriptions of the parameter and its scoring category assignment(s). For those parameters that are applicable to more than one category, the primary category is listed first in bold. **Table 3** includes a similar list for AR. Each parameter is described in more detail in the Scoring section.

Table 2. Hydrogeological parameter screening for ASR

Parameter name	Category	Notes
Storage zone depth	Recharge	Depth to top of aquifer in a confined system. In an unconfined system, storage zone depth is estimated to be 100 feet below the top of the saturated zone
Horizontal hydraulic conductivity	**Recharge**, Recoverability	Primary factor for rate of recharge or production
Drawup available	Recharge	Distance between hydraulic head and ground surface
Dominant lithology	**Recharge**, Recoverability	Aquifer texture/porosity. Parameter scoring also includes secondary porosity features associated with fractured rock and limestone or karst formations.
Aquifer thickness	**Storage**, Recharge	For unconfined aquifers, this is based on saturated thickness
Aquifer storativity	Storage	Relevant in confined aquifers
Specific yield	Storage	Relevant in unconfined aquifers
Sediment age	Storage	A qualitative indication of aquifer induration.
Confinement	Recoverability	Important for control of recharge water
Groundwater quality	Recoverability	Total dissolved solids (TDS)
Drift velocity	Recoverability	Natural drift of recharged water
Drawdown available	Recoverability	Amount of head available above the top of aquifer

Note: Where multiple categories exist, the category for which the parameter contributes to scoring is bolded.

Table 3. Hydrogeological parameter screening for AR

Parameter name	Category	Notes
Vertical hydraulic conductivity	Recharge	Proxy for infiltration rate
Horizontal hydraulic conductivity	Recharge	Primary factor for rate of recharge or production
Topographic slope	Recharge	High slope areas limit above ground ponding potential
Sediment age	Recharge	Accounts for induration with sediment age
Aquifer dominant lithology	Recharge	Accounts for aquifer texture/porosity. Parameter scoring also includes secondary porosity features associated with fractured rock and limestone or karst formations.
Specific yield	Storage	Relevant in unconfined portion of the aquifer
Depth to water table	**Storage**, Recharge	Defines potential storage volume and recharge delay

Note: Where multiple categories exist, the category for which the parameter contributes to scoring is bolded.

Assumptions, challenges, and limitations

Several assumptions had to be made to make the analysis reproducible. The following key assumptions were used in the development of the Hydrogeological Parameter Screening.

- To address the challenge of regionally estimating continuous distributions of hydrogeological properties, this survey relied heavily upon the Texas Water Development Board (TWDB) groundwater availability models (GAMs). Parameter values from the published numerical GAMs are currently the best and most readily available estimates. The values in a numerical model may differ from those values proposed in the conceptual model. However, because the numerical model has been calibrated, the additional constraint imposed by calibration should improve the parameter estimates.
- When a major or minor aquifer had multiple hydrogeologic units with varying parameter values, the parameters were averaged to one value to represent the aquifer for that grid cell.
- To address upscaling of hydrogeological parameters, the following assumptions were made:
    - A reasonable scaling approach to move from a finer resolution spatial coverage to the coarser resolution statewide grid used the arithmetic average of cells or pixels that intersect each coarse grid cell.
    - For asymmetrically distributed values, the arithmetic mean tended to emphasize higher values over lower ones. Considering alternate summary statistics, given how the values are eventually converted to suitability scores, provided limited value. As long as a consistent approach is applied to all of the aquifers, the relative suitability scores should not be affected.

Following are some of the key challenges in developing the Hydrogeological Parameter Screening.

- Texas is a large state with aquifers that cover very large areas. A key challenge for this analysis was the efficient estimation of hydrogeological parameters and other aquifer characteristics continuously across entire aquifers.
- Many areas of the state have multiple aquifers potentially available at one geographic location.
- In this analysis, suitability is estimated on a discrete spatial grid. A challenge associated with any spatial analysis performed at a fixed spatial resolution is the issue of upscaling

parameters that may be at a smaller spatial scale than the suitability assessment grid scale.

The primary limitation for the Hydrogeological Parameter Screening is the natural tension between evaluating ASR and AR on a statewide basis and the site-specific nature of ASR and AR projects. While the screening can act as a high-level indicator of suitability, a given statewide grid cell with a "high" suitability rating may not actually be suitable throughout. Similarly, if a statewide grid cell is given a "low" suitability rating, that does not necessarily preclude the chance of a successful project being developed in that area encompassed by that cell, depending on the project need. The screening can be used as an indicator of the probability of finding suitable sites in a county or portion of a county, but cannot be considered the "final answer" with respect to the potential success of a project. This type of limitation exists to some extent for any screening-level approach that is developed over a large area. Since hydrogeological parameters can vary dramatically at local scales and site-specific field testing is essential for successful design and implementation of ASR and AR, this limitation is an especially important consideration with respect to this survey.

Another limitation is the extent of the official TWDB aquifer boundaries which serves as the basis for this survey. Generally they do not include the brackish and saline portions of aquifers which could host viable ASR projects.

Data sources

Primary data sources

The following primary data sources were used to estimate the Hydrogeological Parameter Screening parameters.

The parameters listed in **Table 2** and **Table 3** were estimated for each of the 9 major and 22 minor aquifers in Texas (31 total) based on available data. The TWDB GAM and Brackish Resources Aquifer Characterization System (BRACS) programs have created the most comprehensive quantitative datasets for the aquifers in the state. The GAM program, which assigns hydrogeological parameters spatially in a common modeling platform, offers a relatively efficient repository for spatially varying hydrogeological parameters. Similarly, the BRACS program has produced many aquifer studies that offer a variety of spatially varying, quantitative aquifer assessments. Datasets from these two programs form most of the hydrogeological data sources used in this assessment. When spatially varying data is available and upscaling was relevant, this data was used directly for clipping to the grid cell. When spatially varying data is not available, the aquifer is assigned a single value which may occur over multiple grid cells.

Additional details on the data sources used to develop suitability parameters for all 31 major and minor aquifers is included in **Appendix C.**

Other sources

Several of the suitability parameters, especially those related to AR, could not be derived from GAMs or BRACS studies; therefore, the following sources were used.

<u>Vertical Hydraulic Conductivity</u> - Vertical hydraulic conductivity was derived from the U.S. Department of Agriculture (USDA) Soil Survey Geographic Database (SSURGO) dataset. The SSURGO dataset estimates soil types for the first several soil horizons classified spatially throughout Texas and much of the rest of the country. Each soil type has an estimated saturated vertical hydraulic conductivity. The data is assigned to polygons that bound small areas with a consistent soil type. For each of these polygons, a weighted harmonic mean (weighted by the thickness of the soil horizon) was calculated using the hydraulic conductivities for each of the soil horizons. The harmonic mean was used because the direction of flow is orthogonal to the bedding planes of the soil horizons.

<u>Topographic Slope</u> - Topographic slope is an important consideration for surface AR in the construction of impoundments. Infiltration ponds should be constructed in areas sloping less than 5 percent (Pedrero et al., 2011; Ahmadi et al., 2017). Topographic slope was calculated using the U.S. Geological Survey (USGS) statewide 30-meter digital elevation model (DEM). Because the slope is eventually upscaled to a much coarser grid, the 30-meter DEM was deemed of sufficient resolution for the slope calculation. Topographic slope is a spatially varying coverage and the gradient intervals presented in **Table 5** are based on analysis of statewide topography.

<u>Aquifer Age</u> – Aquifer age was determined as a companion parameter to aquifer dominant lithology (described below), from the 2016 TWDB report, *Aquifers of Texas*. Aquifer age is assigned a single value for the unconfined and confined portions of the aquifer. Many of the aquifers had a range of ages. For AR which only considers the unconfined portion of an aquifer which occurs at surface, two possible ages were assigned. If the aquifer is dipping, it was assigned the midpoint of the age range (since the outcrop likely represents the entire span of age ranges). For non-dipping aquifers, the youngest age was used, since the aquifer material at the surface would trend younger. For ASR, both the unconfined and confined portions were assigned the midpoint of the age range, since the ASR well depth (and thus the age of the sediments it might be completed in) is unknown.

<u>Aquifer Dominant Lithology</u> – Aquifer dominant lithology was derived from a variety of literature sources, such as the *Aquifers of Texas* (TWDB, 2016), smaller reports focused on one or two

aquifers, and other studies. A separate list of references for this work is included at the end of **Appendix C**. Dominant lithology is assigned as a single value for each aquifer.

Groundwater Quality – Groundwater quality for 30 of the 31 aquifers was derived from *Aquifers of Texas* (TWDB, 2016), which includes maps of total dissolved solids (TDS) for all but the Cross Timbers Aquifer, which the TWDB recognized as a minor aquifer of Texas after publication of the 2016 report. These are spatially varying coverages. The water quality of the Cross Timbers Aquifer was estimated from measurements in the TWDB groundwater database.

Integration scale

A statewide grid consisting of cells 50,000 feet by 50,000 feet (or 89.5 square miles) was created to allow a spatially consistent evaluation network for the survey. Given the input datasets, statewide perspective, and timeline of this survey, it was both suitable and relevant. This grid size and extent was used as a template for all screenings and the final suitability rating developed during this survey. This created coincident datasets for consistency and ease of integration.

Aquifer assignments

For each major and minor aquifer, the aquifer extent was intersected with the 50,000 by 50,000 statewide grid. If the centroid of a grid cell occurred in an aquifer polygon, the aquifer was assigned to that grid cell. Grid cell centroids that did not occur in an aquifer did not receive an aquifer assignment. A manual evaluation was made along the edges of the state, and for those aquifers with small, disconnected regions that made representation with a coarse grid challenging. These grid assignments are shown in **Figure 1** and **Figure 2**, for major and minor aquifers, respectively. In general, an inclusive strategy was used to support representation of large portions of even the smaller aquifers in the grid. Each aquifer has a grid representation, so that overlapping aquifers can share grid locations, but have unique suitability parameters at the shared location. Each grid cell for a given aquifer is assigned either an "unconfined" or "confined" attribute, based on the initial intersection and the manual definition of the grid assignments.

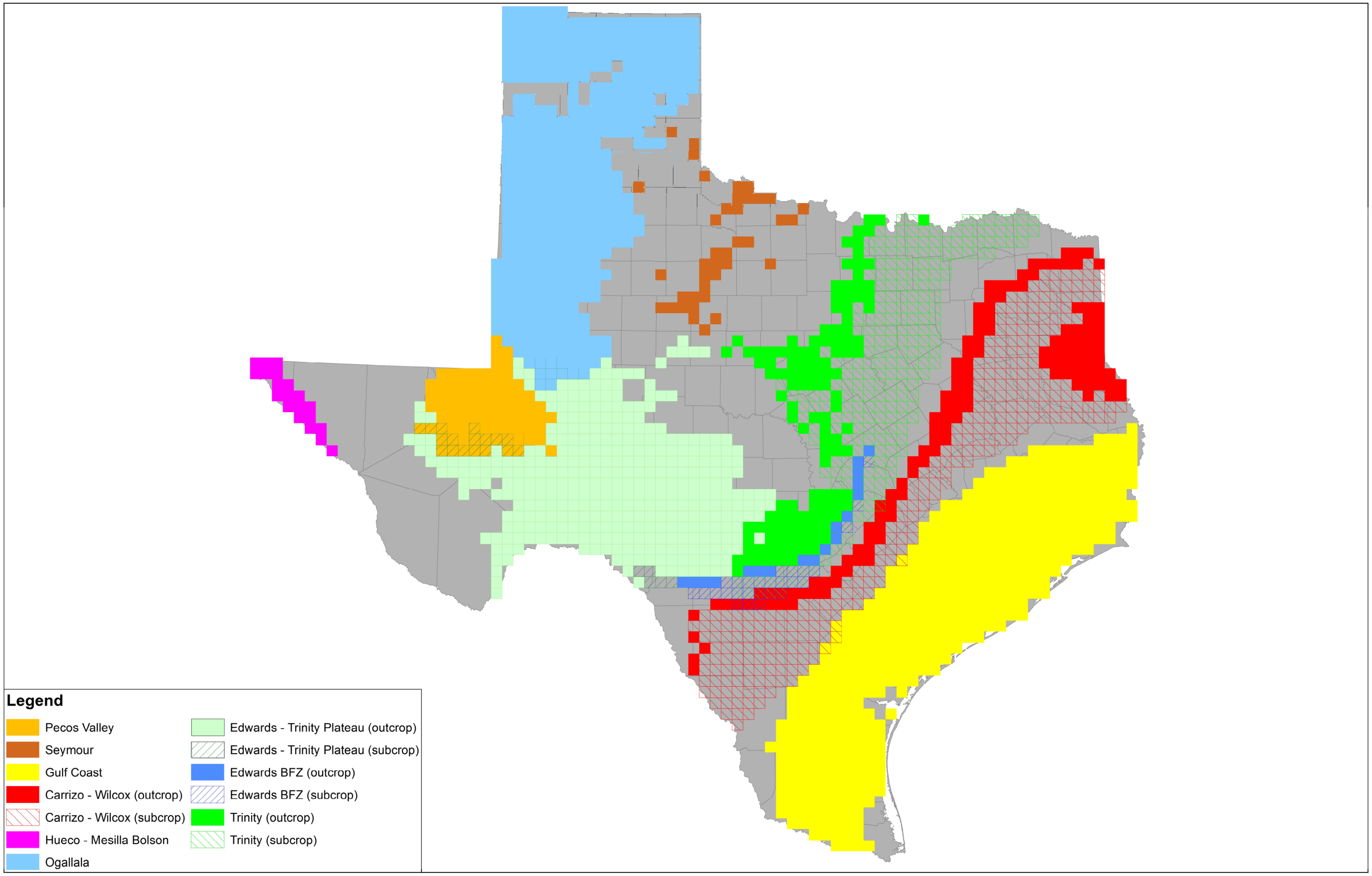

Figure 1. Grid cells for major aquifers

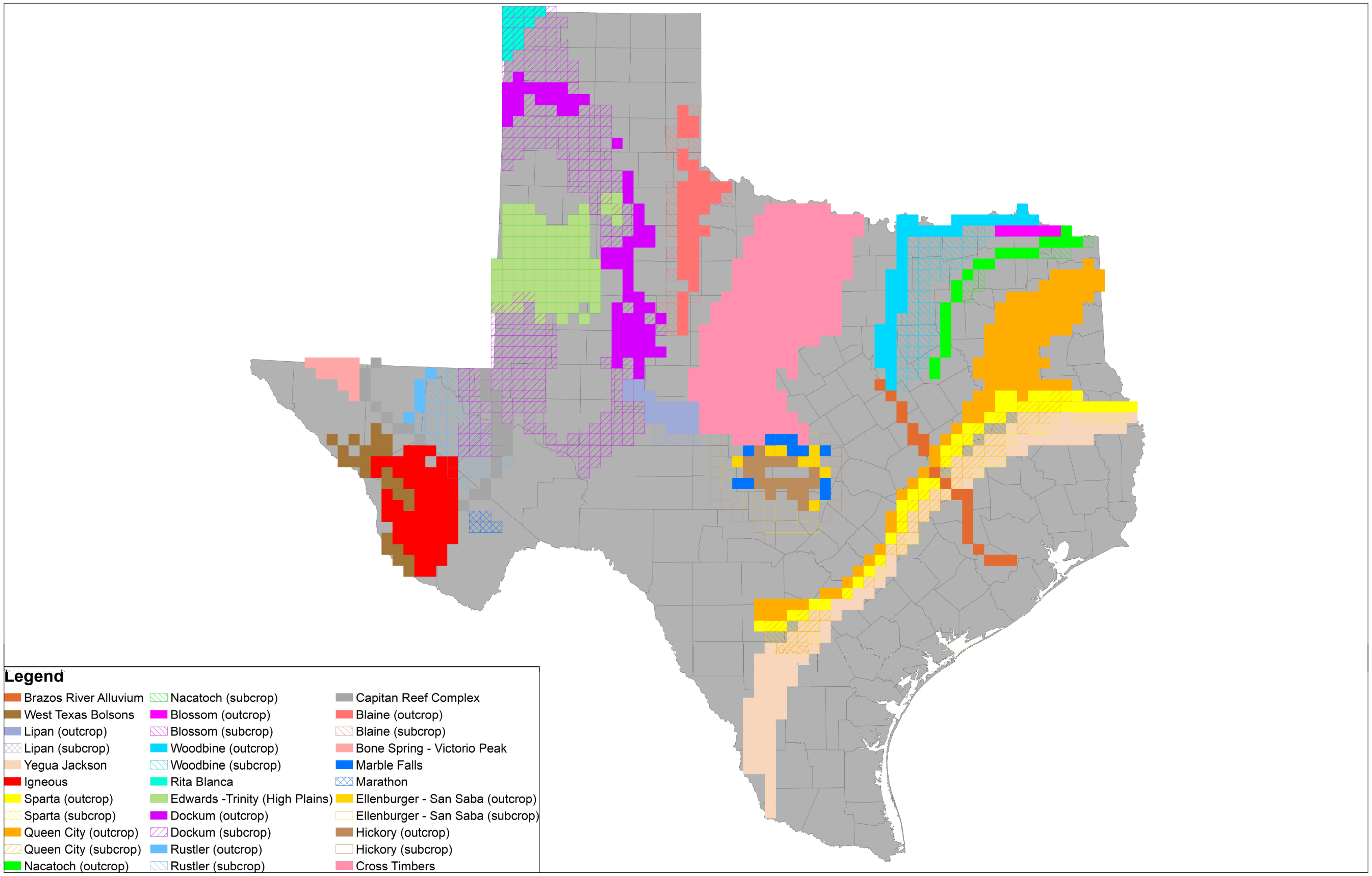

Figure 2. Grid cells for minor aquifers

Scaling source data to the statewide grid

The spatially varying source data, whether it be at a numerical groundwater model grid scale or a raster dataset, exists at a finer resolution than the statewide grid. To scale the parameters to the statewide grid, each input dataset was intersected with the statewide grid, such that the model grid polygons, raster pixels, or other small features were associated on a many-to-one basis with each statewide grid cell, based on the centroid location of the higher resolution dataset falling inside a statewide grid cell. The arithmetic average of the values for the finer cells was then calculated and assigned to the statewide grid cell.

The result of this step was a feature class containing the quantitative values of each of the suitability parameters for each aquifer. The suitability parameters shown in **Table 2** and **Table 3** were identified for all 31 major and minor aquifers to evaluate ASR or AR feasibility.

Data gaps

The following are the key data gaps identified during the development of the Hydrogeological Parameter Screening.

- The Cross Timbers Aquifer does not have a conceptual model or numerical model associated with it, as it is currently under development by TWDB. A numerical model of the Cross Timbers Aquifer described in Oliver and Kelley (2014) was the primary data source. However, the model footprint did not extend as far south or west as the TWDB definition of the aquifer. The parameter values in this southern area were extrapolated along strike, and parameter values in the western area were extrapolated along dip to fill these gaps.
- The Hueco Bolson model, part of the Hueco-Mesilla Bolsons GAM, does not cover the entire area of the Hueco-Mesilla Bolsons Aquifer. Parameter values from adjacent cells were used to fill gaps where coverage was not available.
- Many of the GAMs do not contain estimates of specific yield, because the numerical models were constructed as “confined” models, where transmissivity does not vary with water level. For these cases, the specific yield was estimated from published literature values.

Scoring

In this section, the method of scoring is described for hydrogeological parameters considered most relevant for the relative suitability for ASR and AR projects along with a discussion of the normalized scoring approach for each parameter.

Method

The proposed scoring methodology is based on multi-attribute utility theory (MAUT), which forms a structure for making decisions when many different variables exist. The suitability parameters discussed in the previous section are integrated into a single hydrogeological parameter screening score for ASR or AR using this approach, with suitability scores and weights for each contributing to the overall score. Using this approach, some uncertainty in assigning weights to the various factors exists. A sensitivity analysis provides a method to evaluate weights, and this type of analysis was performed in cooperation with the TWDB to review weights and their impacts on the total analysis.

The weighting and scoring process was completed independently for ASR and for AR. While the two strategies share some of the suitability parameters, the scoring and weighting between ASR and AR are not the same, because they are two fundamentally different strategies with different controlling physics.

In accordance with the MAUT approach, each chosen suitability parameter was mapped onto a utility curve such that the highest suitability has a parameter score equal to one and the lowest suitability has a parameter score equal to zero. This process requires normalizing each suitability parameter to a range from zero to one. The benefit of this process of normalization is the ability to combine quantitatively different, and even qualitative and quantitative suitability parameters, into a decision process. Once a suitability parameter is normalized, it is referred to as a suitability parameter Normalized Score (NS).

For many of the suitability parameters, the NS may be assigned categorically (score constant within ranges) or may be linear within a certain range, with a "ceiling" where the score no longer increases with parameter magnitude. A good example of this is aquifer hydraulic conductivity. For aquifer hydraulic conductivities below a certain threshold, ASR is impractical because of low well productivity. Once hydraulic conductivity reaches a certain threshold where good productivity is possible, the NS reaches a maximum, and increasing hydraulic conductivity no longer affects the score. Note that low well productivity may still meet specific project needs even if the corresponding hydraulic conductivity scores low in this analysis. This is an example of the need to further refine suitability of a specific project beyond the regional analysis approach from this statewide survey.

The objective in this analysis was not to preclude aquifers that may be adequate under certain project constraints and objectives, but rather to provide guidance that the given aquifer is suitable for site/project specific analyses.

Once scores had been developed, the analysis methodology combined the scores for each category into one measure of categorical suitability termed the Categorical Score (CS). The process used is a simple summation allowing the decision maker to weight each performance parameter NS according to the decision maker's knowledge about the decision problem. The equation for the CS is as follows:

$$Categorical\ Score\ (CS) = \frac{\sum_{i=1}^{n} weight_{NS,i}\, NS_i}{\sum_{i=1}^{n} weight_{NS,i}} \qquad \text{(Equation 1)}$$

The categorical scores (suitability for recharge, suitability for storage, and suitability for recoverability) are then combined to create final hydrogeologic suitability score. The final hydrogeologic suitability score is termed the ASR Score (or AR Score) and is calculated as follows:

$$Final\ Score = \frac{\sum_{i=1}^{n} weight_{CS,i}\, CS_i}{\sum_{i=1}^{n} weight_{CS,i}} \qquad \text{(Equation 2)}$$

In Equation 2, *Final Score* is the hydrogeologic ASR or AR suitability score (ASR Score and AR Score will be different for each statewide grid cell). The final hydrogeologic ASR or AR score varies from a minimum of zero to a maximum of one. The ASR Score is comparable across aquifers. Similarly, the AR score is comparable across aquifers. However, the ASR and AR scores are not directly comparable, since the weighting approach is applicable only to the strategy (ASR or AR) being considered.

Appendix C includes additional details on the scoring method process used to calculate a categorical score and combine to create a hydrogeological parameter suitability score.

To simplify the display of the ASR or AR score for an end-user, two threshold values were used for ASR and two threshold values for AR, which divide suitability into classes of “low”, “medium”, and “high”. The ASR scores were categorized as follows:

- Low– ASR Score < 0.5
- Medium– ASR Score 0.5 to 0.7
- High– ASR Score > 0.7

These thresholds were primarily based on inspection of the scoring distributions, and consideration of where current ASR projects and pilot studies have been successful in Texas.

Threshold values were also considered for AR. The thresholds are not consistent between ASR and AR, again because of the unique weighting scheme for each strategy. The AR scores were categorized as follows:

- Low– AR Score < 0.7
- Medium– AR Score 0.7 to 0.8
- High– AR Score > 0.8

These thresholds are proposed to allow high-level categorization of hydrogeological scores, but the “low,” “medium,” and “high” hydrogeological parameter screening categories themselves are not carried through to the Final Suitability Rating. Rather, the actual hydrogeological parameter screening score value (ranging between 0 and 1) is carried through to the Final Suitability Rating calculation to keep calculations intact through the entire scoring process.

ASR hydrogeological parameter scores

Table 4 lists the proposed hydrogeological parameters for ASR, the related numerical or categorical values, and the associated scoring. Scores are normalized from zero to one, with one being the highest suitability and zero being the least suitable. A brief description of these parameters is provided in **Appendix C**.

AR hydrogeological parameter scores

Table 5 lists the proposed hydrogeological parameters for AR, the related numerical or categorical values, and the associated scoring. Scores range from zero to one with zero having low suitability and one having high suitability. A brief description of these parameters is provided in **Appendix C.**

Table 4. Hydrogeological parameter scoring for ASR screening

Storage zone depth	**Depth (ft bgs)**	<200	200-1000	1000-2000	2000-2500	> 2500	
	Score	*0.1*	*1*	*0.75*	*0.5*	*0.1*	
Horizontal hydraulic conductivity	**K (ft/d)**	< 1	1 to 3	3 to 10	10 to 30	> 30	
	Score	*0.2*	*0.3*	*0.5*	*0.8*	*1*	
Drawup available	**Drawup (ft)**	<50	50-100	100-400	> 400		
	Score	*0.1*	*0.2*	*0.2 – 0.9*	*1*		
Dominant lithology	**Dominant Lithology**	clay / silt	Rock[1]	limestone	sandstone	sand	gravel
	Score	*0.1*	*0.2*	*0.5*	*0.5*	*1*	*1*
	Lithology Modifier		Fractured	Karst			
	Added Score		*0.4*	*0.5*			
Aquifer thickness	**Thickness (ft)**	<100	100-300	> 300			
	Score	*0.1*	*0.5*	*1*			
Aquifer storativity	**S (dimensionless)**	< 1e-5	1e-5 to 1e-4	1e-4 to 1e-3	1e-3 to 1e-2	> 1e-2	
	Score	*0.2*	*0.4*	*0.6*	*0.8*	*1*	
Specific yield	**S (dimensionless)**	< 0.01	0.01 to 0.05	0.05 to 0.1	0.1 to 0.15	0.15 to 0.2	> 0.2
	Score	*0.1*	*0.25*	*0.5*	*0.8*	*0.9*	*1*
Sediment age	**Aquifer Age (mya)**	< 56	56 - 541	> 541			
	Score	1	1 - 0.1	0.1			
Groundwater quality	**TDS (mg/L)**	< 300	300 - 1000	1000-1500	1500 - 3000	> 3000	
	Score	*1*	*0.9*	*0.8*	*0.6*	*0.5*	
Confinement	**Unc/Conf (-)**	*unconfined*	*confined*				
	Score	0.1	1.0				
Drift velocity	**Drift Velocity (ft/y)**	< 20	20 - 100	100 - 1000	>1,000		
	Score	*1*	*0.75*	*0.5*	*0.1*		
Drawdown available	**Drawup (ft)**	<50	50-100	100-400	> 400		
	Score	*0.1*	*0.2*	*0.2 – 0.9*	*1*		

[1]Assumed to be indurated.

K= hydraulic conductivity; ft bgs= feet below ground surface; S = storativity; ft = feet; ft/d = feet per day; mya = million years ago; ft/y = feet per year; mg/L = milligrams per liter; TDS = total dissolved solids; unc = unconfined; conf = confined

Table 5. Hydrogeological parameter scoring for AR screening

Vertical hydraulic conductivity	**K (ft/d)**	<5	5 to 20	> 20			
	Score	*0.1*	*0.5*	*1*			
Horizontal hydraulic conductivity	**K (ft/d)**	< 1	1 to 3	3 to 10	10 to 30	> 30	
	Score	*0.2*	*0.3*	*0.5*	*0.8*	*1*	
Topographic slope	**Gradient (degrees)**	< 2	2 to 5	> 5			
	Score	*1*	*0.5*	*0.01*			
Sediment age	**Aquifer Age (mya)**	< 2.5	2.5 – 50	50 - 500	>500		
	Score	1	1 - 0.5	0.5 – 0.1	0.1		
Lithology type	**Dominant Lithology**	clay / silt	rock[1]	limestone	sandstone	sand	gravel
	Score	*0.1*	*0.2*	*0.5*	*0.5*	*1*	*1*
			Fractured	Karst			
			0.3	*0.3*			
Sediment age	**Aquifer Age (mya)**	< 56	56 - 541	> 541			
	Score	1	1 - 0.1	0.1			
Specific yield	**Sy (-)**	< 0.01	0.01 to 0.05	0.05 to 0.1	0.1 to 0.15	0.15 to 0.2	> 0.2
	Score	*0.1*	*0.25*	*0.5*	*0.8*	*0.9*	*1*
Depth to water table	**Depth (ft)**	0	1 - 10	10-30	30-300	> 300	
	Score	*0.01*	*0.2*	*0.5*	*1*	*0.5*	

[1]Assumed to be indurated.

K= hydraulic conductivity; ft/d = feet per day; mya = million years ago; Sy = specific yield; ft = feet;

Weighting

Two sets of weights are needed to complete the scoring, as shown in Equations 1 and 2. In Equation 1, weights are applied to each of the normalized scores of the hydrogeological parameters, resulting in categorical scores for recharge, storage, and recoverability. In Equation 2, weights are applied to each of the categories to calculate a final hydrogeological parameter screening score.

Weights were determined using both a qualitative and qualitative/quantitative hybrid assessment of the parameters and the scoring results. A qualitative assessment is one where, based on experience and input from the team, one parameter is generally considered more important than another. For example, horizontal hydraulic conductivity is generally considered critical to an effective ASR implementation, so that parameter is weighted with a 1.0. Also, parameters that are considered to be broad discriminators, like lithology, were weighted relatively high. A qualitative/quantitative hybrid assessment was performed in which the team reviewed the final hydrogeological parameter screening scores, and compared the scores among aquifers against the expectations based on existing ASR operations and pilot studies.

A sensitivity analysis was performed where weights were set for each parameter at low (0.0), medium (0.5), and high (1.0). In general, a single parameter weight did not have a large effect on the final hydrogeological parameter screening score for a given aquifer. The results of the sensitivity analysis for ASR and AR hydrogeological parameter screening scoring is shown in **Appendix C.** These sensitivities were considered when setting the final weights, but most weights were not changed more than 0.25 from their original estimates.

Table 6 provides the weighting scheme for ASR, along with short descriptor notes. When setting weights, care must be taken to balance “conventional wisdom” (i.e., the collective expectations and experience of the team for how the aquifers should be ranked for hydrogeological parameter screening) versus unexpected insights that might appear in the scoring results. All attempts were made to achieve this balance by holding fairly close to the original weighting scheme, and only changing the weight if there was consensus that the original justification was flawed. **Table 7** provides the weighting scheme for AR, again with short notes describing the weighting approach.

The categorical weights were estimated using the number of parameters contributing to each of the categories. For ASR, this means that each of the categories (recharge, storage, recoverability) was weighted at approximately 0.33, since each category had four contributing suitability parameters. For AR, recharge had a weight of 5/7 or 0.71, while storage had a weight of 2/7 or 0.29. The higher relative weight on recharge is appropriate for environmental flow applications (such as are performed in the Edwards Aquifer), but would not be as appropriate if the AR application were for long-term storage. Long-term storage AR operations are not currently common in Texas, or in the state water plan.

Table 6. Hydrogeological parameter weights for ASR suitability

Parameter name	Weight	Notes
Storage zone depth	0.25	Lower weight because depth generally drives challenges that can be overcome with careful design
Horizontal hydraulic conductivity	1	Key parameter for overall well recharge/production rates
Available drawup	0.5	Can limit recharge rate, but wellheads can be designed to withstand ~70 psi pressure above ground surface, so weighted medium
Aquifer dominant lithology	1	Broad factor separating more suitable from less suitable aquifers, so weighted high
Aquifer thickness	0.5	Very site specific, so weighted medium
Aquifer storativity	0.5	Drives shorter term hydraulic response, but does not typically effect longer term performance, so weighted medium.
Specific yield	0.5	Similar to storativity but for unconfined aquifers
Aquifer age	1	Broad factor separating more suitable from less suitable aquifers, so weighted high
Confinement	1	Broad factor governing hydraulic control challenges, so weighted high
Groundwater quality	0.75	Can be a critical factor for recoverability, but also can be overcome by large buffer zones. Because it is not much of a discriminator among "official" aquifers (which are defined partially by their good water quality), given a medium-high weight.
Drift velocity	0.75	Similar to groundwater quality in terms of recoverability
Drawdown available	0.5	Very site specific, so weighted medium. Can be overcome by increasing local heads through recharge, but this strategy is not possible at all sites.

psi = pounds per square inch

Table 7. Hydrogeological parameter weights for AR suitability

Parameter name	Weight	Notes
Vertical hydraulic conductivity	0.25	While vertical hydraulic conductivity is very important for AR infiltration rates, estimates were limited by a very shallow SSURGO dataset. Because overcoming limited conductivity using excavation or vadose zone wells is very site-specific, this factor was weighted low to offset the overall uncertainty.
Horizontal hydraulic conductivity	1	Key parameter for moving infiltrating water into the deeper aquifer system.
Slope	0.5	Can often be overcome through engineering, so weighted medium.
Aquifer dominant lithology	1	Broad factor separating more suitable from less suitable aquifers, so weighted high
Aquifer age	1	Broad factor separating more suitable from less suitable aquifers, so parameter weighted high.
Specific yield	1	Because the unconfined portion of the aquifer is key to AR, parameter weighted high.
Depth to water table	1	Critical for viability of AR and fairly well-known, so weighted high.

SSURGO = U.S. Department of Agriculture (USDA) Soil Survey Geographic Database

Results

In this section, we discuss the results for ASR and AR hydrogeological parameter scores. About 85% of the cells had an ASR score (meaning that a major or minor aquifer was present), so about 15% of the cells do not have an ASR score. An additional 9% of cells do not have an AR score, because AR was not scored where only a confined aquifer was present.

The highest scoring aquifer was assigned to final ASR and AR grids for areas where more than one aquifer was present. When preparing the final score selection for grid cells, multiple input layers and features were assimilated into a single score per grid cell and categories (low, medium, and high) for ASR and AR potential as described previously. These final Hydrogeological Parameter Screening scores are presented in **Figures 3 and 4** for ASR and AR, respectively.

ASR scores

Summary statistics for the final hydrogeological parameter screening scores for ASR are shown (in **Figure 3**) for the major and minor aquifers in **Table 8** and **Table 9**, respectively. The statistics are calculated using the individual grid cell scores for each aquifer. Recall that scores above 0.7 are considered to be “high” in terms of suitability, while scores less than 0.7 but greater than 0.5

are considered to be “medium” suitability. Scores below 0.5 are considered to be “low” suitability. About 5% of the grid cells (or 158) scored low suitability, 43% (or 1,358 cells) scored medium suitability, and 37% (or 1,172 cells) scored high suitability for ASR. As mentioned previously, 15% of the cells do not have an ASR score.

Eight of the nine major aquifers have at least some grid cells that are rated “high,” with the Seymour being the only major aquifer with a highest rated cell in the “moderate” suitability category. This indicates that nearly all of the major aquifers have some portions that may be highly suitable for an ASR application. Four of the nine major aquifers have a median score that is in the “high” category (the Trinity Aquifer just misses with a median score of 0.69), indicating that the majority of cells are rated high. These aquifers are the Carrizo-Wilcox, Edwards (Balcones Fault Zone [BFZ]), Gulf Coast, and Trinity aquifers. These aquifers all have either operating ASR wells or pilot studies in Texas in San Antonio, New Braunfels, Victoria, and Kerrville, respectively. In addition, the Hueco-Mesilla Bolsons Aquifer, where El Paso has an indirect ASR system, scores a median of 0.7, which also meets the “high” threshold category.

Seven of the 22 minor aquifers have at least some grid cells that are rated “high” in terms of hydrogeological suitability for ASR, while only 1 of the 22 minor aquifers have a median hydrogeological suitability score that is rated in the “high” category, the Sparta. As expected, while many of the minor aquifers contain portions that are hydrogeologically suitable for ASR, this condition is not nearly as common or pervasive as with the major aquifers.

As was discussed previously, a “low” or “moderate” hydrogeological suitability score at a particular location in an aquifer is not an indication that a successfully ASR project cannot be constructed there, since local conditions are key. These regional scores do provide a good indication of areas in aquifers in the state, that are more likely to be suitable than others.

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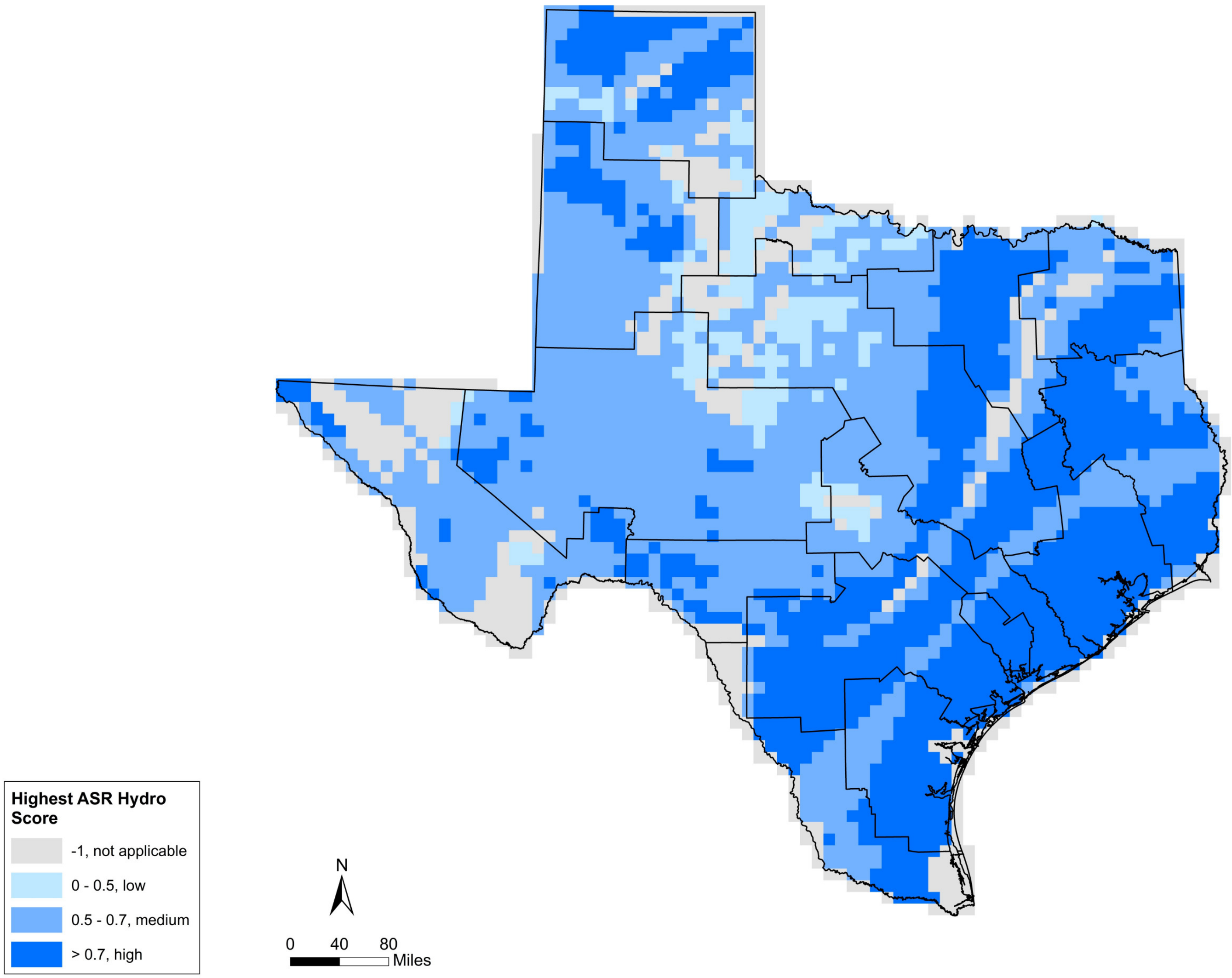

Figure 3. Hydrogeological Parameter Screening Scores for ASR for Major and Minor Aquifers (maximum score)

Table 8. Hydrogeological parameter screening results from ASR screening: Major aquifers

	Final score				Recharge				Storage				Recoverability			
Aquifer*	min	max	med	mean	min	max	med	mean	min	max	med	mean	min	max	med	mean
CZWX	0.54	0.86	0.77	0.74	0.50	0.94	0.70	0.70	0.57	0.79	0.75	0.71	0.30	1.00	0.91	0.81
EBFZ	0.51	0.78	0.71	0.67	0.66	0.90	0.82	0.82	0.47	0.75	0.67	0.63	0.30	0.78	0.62	0.57
ETPT	0.52	0.73	0.63	0.62	0.40	0.82	0.67	0.66	0.57	0.73	0.73	0.70	0.26	0.88	0.50	0.51
GLFC	0.52	0.78	0.72	0.71	0.46	0.93	0.76	0.72	0.62	0.80	0.80	0.79	0.43	0.70	0.61	0.61
HMBL	0.68	0.76	0.71	0.71	0.65	0.88	0.76	0.74	0.78	0.78	0.78	0.78	0.54	0.65	0.60	0.60
OGLL	0.50	0.75	0.63	0.64	0.50	1.00	0.79	0.78	0.58	0.80	0.68	0.70	0.30	0.51	0.40	0.42
PECS	0.53	0.76	0.58	0.61	0.59	0.85	0.74	0.74	0.58	0.78	0.68	0.68	0.30	0.65	0.39	0.42
SYMR	0.53	0.58	0.56	0.56	0.68	0.77	0.75	0.74	0.60	0.60	0.60	0.60	0.28	0.40	0.32	0.34
TRNT	0.50	0.80	0.69	0.67	0.50	0.88	0.68	0.67	0.45	0.73	0.55	0.58	0.36	0.98	0.83	0.75

*Note: The aquifer codes are included in Appendix C.

Table 9. Hydrogeological parameter screening results from ASR screening: Minor aquifers

	Final score				Recharge				Storage				Recoverability			
Aquifer*	min	max	med	mean	min	max	med	mean	min	max	med	mean	min	max	med	mean
BLIN	0.38	0.50	0.47	0.46	0.17	0.35	0.27	0.28	0.51	0.61	0.55	0.57	0.38	0.75	0.49	0.54
BLSM	0.56	0.69	0.58	0.60	0.57	0.69	0.58	0.61	0.65	0.75	0.65	0.67	0.45	0.68	0.48	0.51
BSVP	0.53	0.64	0.59	0.59	0.67	0.82	0.76	0.76	0.60	0.60	0.60	0.60	0.24	0.54	0.43	0.41
BSRV	0.54	0.61	0.58	0.58	0.68	0.75	0.75	0.74	0.60	0.60	0.60	0.60	0.28	0.46	0.40	0.39
CRCX	0.56	0.65	0.60	0.60	0.52	0.87	0.70	0.68	0.61	0.61	0.61	0.61	0.40	0.68	0.51	0.52
CSTB	0.44	0.58	0.52	0.51	0.45	0.56	0.53	0.53	0.40	0.50	0.40	0.42	0.41	0.68	0.59	0.59
DCKM	0.41	0.65	0.58	0.56	0.28	0.56	0.41	0.41	0.41	0.65	0.49	0.53	0.36	0.98	0.82	0.75
ETHP	0.42	0.54	0.48	0.48	0.37	0.61	0.50	0.49	0.47	0.61	0.55	0.53	0.30	0.48	0.42	0.42
EBSS	0.44	0.68	0.62	0.61	0.55	0.79	0.66	0.67	0.19	0.43	0.37	0.35	0.40	1.00	0.85	0.80
HCKR	0.35	0.67	0.57	0.55	0.39	0.66	0.49	0.49	0.18	0.42	0.36	0.32	0.40	0.98	0.91	0.85
IGBL	0.54	0.61	0.58	0.58	0.38	0.74	0.52	0.50	0.62	0.62	0.62	0.62	0.45	0.70	0.61	0.62
LIPN	0.54	0.73	0.59	0.61	0.57	0.79	0.67	0.70	0.62	0.76	0.65	0.66	0.32	0.70	0.42	0.46
MRTN	0.42	0.42	0.42	0.42	0.49	0.49	0.49	0.49	0.35	0.35	0.35	0.35	0.43	0.43	0.43	0.43
MBLF	0.42	0.49	0.45	0.45	0.41	0.53	0.46	0.46	0.39	0.47	0.39	0.42	0.40	0.54	0.46	0.47
NCTC	0.47	0.74	0.54	0.57	0.50	0.67	0.58	0.60	0.43	0.71	0.51	0.55	0.38	0.91	0.51	0.56
QNCT	0.52	0.80	0.65	0.66	0.50	0.68	0.58	0.57	0.58	0.80	0.76	0.72	0.39	1.00	0.59	0.69
RTBC	0.52	0.61	0.55	0.55	0.48	0.57	0.53	0.53	0.54	0.62	0.58	0.58	0.52	0.63	0.55	0.55
RSLR	0.43	0.65	0.61	0.60	0.28	0.61	0.41	0.42	0.42	0.62	0.56	0.53	0.45	0.90	0.88	0.83
SPRT	0.51	0.79	0.70	0.66	0.48	0.68	0.58	0.59	0.58	0.80	0.66	0.66	0.39	1.00	0.80	0.74
WXBL	0.58	0.70	0.65	0.66	0.52	0.84	0.71	0.68	0.60	0.70	0.70	0.70	0.32	0.70	0.68	0.61
WDBN	0.44	0.72	0.63	0.60	0.28	0.53	0.41	0.40	0.46	0.74	0.68	0.64	0.45	0.98	0.84	0.76
YGJK	0.49	0.71	0.64	0.63	0.55	0.80	0.68	0.68	0.47	0.78	0.68	0.67	0.33	0.68	0.53	0.53

*Note: The aquifer codes are included in Appendix C.

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AR scores

Summary statistics for the final hydrogeologic suitability scores for AR are shown (in **Figure 4**) for the major and minor aquifers in **Table 10** and **Table 11**, respectively. The statistics are calculated using the individual grid cell scores for each aquifer. Recall that scores above 0.8 are considered to be "high" in terms of suitability, while scores less than 0.8 but greater than 0.7 are considered to be "medium" suitability. Scores below 0.7 are considered to be "low" suitability. About 27% of the grid cells (or 863) scored low suitability, 20% (or 623 cells) scored medium suitability, and 29% (or 917 cells) scored high suitability for AR. As mentioned previously, 15% of the cells are not over major or minor aquifers and therefore do not have a score. An additional 9% of cells do not have an AR score were no outcrop was present.

Seven of the nine major aquifers have at least some grid cells that are rated "high," and five of the nine major aquifers have median score rated "high." One notable exception is the Edwards (BFZ) Aquifer, which just missed a median "high" score at 0.79 but has currently operating recharge features. The Edwards (BFZ) Aquifer is rated slightly lower primarily due to its lower score in storage, as seen in its median storage score of 0.5. This low storage score is due to a low effective porosity, and limited depths to water. In reality, the lack of storage does not affect the current recharge projects in the Edwards Aquifer, because the objective of those projects is not necessarily long-term storage, but general augmentation (i.e., keeping water levels and springflow at desirable levels). So the Edwards (BFZ) Aquifer AR hydrogeologic suitability score should not be considered to be contrary to the reality of current operations.

The Hueco-Mesilla Bolsons Aquifer, where El Paso has performed a type of AR using infiltration ponds, has a median rating of "high."

Four of the 22 minor aquifers have a least some grid cells with a "high" rating, while only one of the 22 aquifers has a median value that qualifies for the "high" rating. Similar to the ASR scores, there will be areas in many of the minor aquifers that may be suitable for AR, but those areas will not be as common or pervasive as for the major aquifers.

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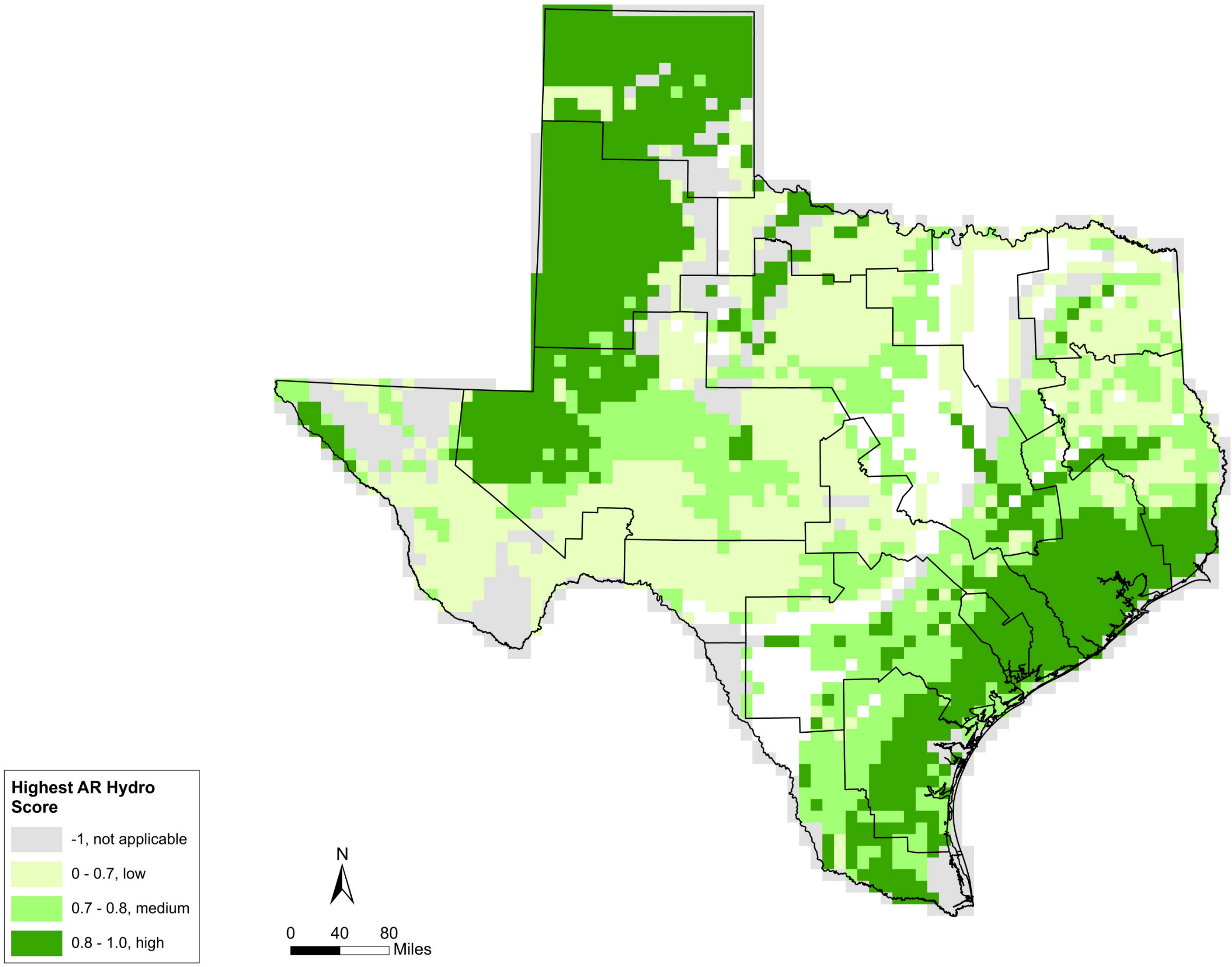

Figure 4. Hydrogeological Parameter Screening Scores for AR for Major and Minor Aquifers (maximum score)

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Table 10. Hydrogeological parameter screening results from AR screening: Major aquifers

	Final score				Recharge				Storage			
Aquifer*	min	max	med	mean	min	max	med	mean	min	max	med	mean
CZWX	0.60	0.83	0.74	0.75	0.55	0.81	0.68	0.69	0.50	1.00	0.88	0.88
EBFZ	0.50	0.79	0.64	0.65	0.63	0.71	0.70	0.68	0.01	1.00	0.50	0.56
ETPT	0.44	0.78	0.66	0.65	0.31	0.70	0.56	0.55	0.75	1.00	1.00	0.90
GLFC	0.62	0.98	0.84	0.83	0.63	0.97	0.86	0.83	0.50	1.00	1.00	0.84
HMBL	0.77	0.89	0.81	0.82	0.67	0.85	0.81	0.80	0.75	1.00	0.88	0.88
OGLL	0.72	1.00	0.92	0.91	0.75	1.00	0.88	0.89	0.50	1.00	1.00	0.95
PECS	0.78	1.00	0.92	0.92	0.82	1.00	0.89	0.91	0.50	1.00	1.00	0.95
SYMR	0.77	0.96	0.84	0.86	0.87	1.00	0.94	0.94	0.50	1.00	0.60	0.66
TRNT	0.57	0.80	0.71	0.71	0.53	0.72	0.59	0.60	0.50	1.00	1.00	0.99

*Note: The aquifer codes are included in Appendix C.

Table 11. Hydrogeological parameter screening results from AR screening: Minor aquifers

	Final score				Recharge				Storage			
Aquifer*	min	max	med	mean	min	max	med	mean	min	max	med	mean
BLIN	0.45	0.56	0.51	0.52	0.26	0.38	0.32	0.33	0.75	1.00	1.00	0.98
BLSM	0.65	0.76	0.69	0.71	0.67	0.67	0.67	0.67	0.60	1.00	0.75	0.81
BSVP	0.57	0.77	0.64	0.65	0.50	0.68	0.60	0.59	0.75	1.00	0.75	0.81
BSRV	0.76	0.89	0.89	0.87	0.82	0.97	0.94	0.93	0.60	0.75	0.75	0.70
CRCX	0.57	0.77	0.67	0.66	0.53	0.74	0.60	0.60	0.50	1.00	1.00	0.80
CSTB	0.35	0.48	0.43	0.42	0.30	0.47	0.40	0.39	0.50	0.50	0.50	0.50
DCKM	0.49	0.68	0.59	0.58	0.32	0.58	0.44	0.42	0.75	1.00	1.00	0.98
ETHP	0.57	0.68	0.65	0.63	0.47	0.63	0.61	0.57	0.48	0.88	0.75	0.78
EBSS	0.58	0.68	0.68	0.66	0.41	0.56	0.56	0.52	1.00	1.00	1.00	1.00
HCKR	0.46	0.60	0.55	0.56	0.30	0.45	0.37	0.40	0.50	1.00	1.00	0.96
IGBL	0.37	0.64	0.41	0.44	0.42	0.70	0.46	0.48	0.26	0.50	0.26	0.33
LIPN	0.67	0.81	0.73	0.74	0.74	0.89	0.82	0.82	0.50	0.62	0.50	0.55
MRTN	0.34	0.39	0.39	0.37	0.27	0.34	0.34	0.31	0.50	0.50	0.50	0.50
MBLF	0.53	0.64	0.58	0.60	0.35	0.49	0.41	0.44	1.00	1.00	1.00	1.00
NCTC	0.47	0.66	0.55	0.56	0.59	0.72	0.67	0.66	0.01	0.62	0.26	0.30
QNCT	0.55	0.78	0.69	0.68	0.55	0.69	0.57	0.60	0.50	1.00	1.00	0.87
RTBC	0.70	0.73	0.70	0.71	0.58	0.62	0.58	0.59	1.00	1.00	1.00	1.00
RSLR	0.39	0.58	0.53	0.49	0.35	0.41	0.35	0.37	0.50	1.00	1.00	0.80
SPRT	0.62	0.82	0.76	0.74	0.63	0.75	0.69	0.67	0.60	1.00	1.00	0.92
WXBL	0.53	0.76	0.68	0.66	0.59	0.98	0.86	0.80	0.13	0.62	0.22	0.30
WDBN	0.46	0.63	0.61	0.58	0.38	0.50	0.45	0.44	0.50	1.00	1.00	0.91
YGJK	0.54	0.84	0.77	0.77	0.55	0.83	0.78	0.74	0.38	1.00	0.88	0.85

*Note: The aquifer codes are included in Appendix C.

Future Work

This survey provides a statewide evaluation of hydrogeological parameter screening of the major and minor aquifers for ASR and AR. A natural progression of the analysis is to increase the resolution of the survey, by focusing in particular areas of high interest, or to increase the spatial extent of the survey in key areas. For example:

1. The current major and minor aquifer boundaries generally do not include brackish portions of the aquifer, and this survey was limited to the TWDB official boundaries. There are aquifers, such as the Edwards (BFZ) Aquifer and the Carrizo-Wilcox Aquifer, where ASR would clearly be feasible.

2. Many of the minor aquifers have dated or sparse underlying datasets. For example, the Cross Timbers Aquifer conceptual model is currently in development for the TWDB, but was not available for this current survey. As conceptual or numerical models are updated, they could be easily integrated into the existing workflow to update and improve the hydrogeological parameter screening scoring.

3. Some aquifers have multiple formations that can be used independently at nearby locations. The Carrizo-Wilcox Aquifer is a good example of this, where the Carrizo and Simsboro formations may be productive and suitable for ASR at the same location. A future survey could assess these formations independently, rather than as a single aquifer.

Excess Water Screening

Objective

For an ASR or AR project to be considered a viable water management strategy, excess water supplies must be available for recharge and storage. The objective of the Excess Water Screening is to identify and score the potential availability of excess water sources based on frequency, volume, and duration through development of an Excess Water Screening and associated geodatabase.

The Excess Water Screening, designed in accordance with scope and legislation, is a statewide screen with the goal of presenting information for regional water planning and stakeholder consideration and discussion. The Excess Water Screening identifies excess water that could be developed for ASR or AR projects that can be leveraged by water users or stakeholders desiring to pursue advancement of more detailed studies. The screening is not intended to replace or be a substitute for site- and project-specific detailed analyses that are required for permitting, financing, and design of actual projects prior to implementation.

Approach

The general approach to estimating excess water for ASR or AR was as follows.

1. Compile data on excess water sources including surface water, groundwater, reclaimed water, and stormwater deemed available for potential storage for ASR or AR.
2. Estimate parameters that are important to the probable success of an ASR or AR project consistent with HB 721 provisions. In accordance with HB 721, excess water parameters that were evaluated, including frequency, volume, duration and distance of excess water to relatively suitable aquifer storage areas identified in the Hydrogeological Parameter Screening described previously. The distance parameter was included in the Final Suitability screening and is discussed in the Final Suitability Rating section later in the report.
3. Estimate those parameters for excess water sources identified for screening at resolution consistent with native data.
4. Develop strategy for scoring of parameters and their relative potential impact (or weighting) on their relative potential impact on the viability of a project, including how these parameters scale up on the grid cell level for consistency amongst screenings.
5. Calculate a composite score for each supply source on a 50,000-foot by 50,000-foot (or 89.5 square miles) grid cell basis, coincident with the Hydrogeological Parameter Screening.
6. Use the magnitude of the Excess Water Screening scores to rank grid cells into three general categories of relative suitability, “low,” “medium,” or “high.”
7. Aggregate overlapping scores into a single scored layer for the screening.

It is generally assumed that water is stored in ASR or AR during times of plenty and used in times of need. For some supplies, such as groundwater and surface water supplies identified through the TWDB Draft State Water Planning Database (draft DB22), drought conditions were used to be consistent with regional water planning efforts. Where practicable, excess supplies have been identified during non-drought times. Due to data constraints, it is not feasible to address non-drought-of-record excess supplies for all potential excess water sources. The following sections detail the excess supply sources that were included in the Excess Water

Screening evaluation, including methodology, assumptions, data sources, results, and other information.

Excess Water Methodology

Parameters related to excess water and relevant to the probable success of an ASR or AR project were identified by source water category (surface water, reclaimed water, and groundwater). Stormwater was included in the surface water evaluation for consistency with how water rights are administered in the state, as discussed further below. Groundwater produced from oil and gas exploration is not explicitly addressed in this screen and attempts to parse and segregate produced groundwater from individual sources is exceedingly labor intensive. Additionally, challenges associated with water quality and limited volume, frequency, and duration of available excess supplies from these sources make produced groundwater an unlikely feasible supply source for ASR and AR projects at this time. The screening is readily adaptable and capable of receiving additional excess water sources in the future that are deemed practicable and for which data is available.

Table 12 through **Table 14** list the parameters included in the Excess Water Screening by source water category, along with descriptions of the attribute table fields, weighting and data source.

The excess surface water source is comprised of three components: surplus appropriated surface water, unappropriated streamflow supply, and existing reservoir storage. Surplus appropriated surface water and reservoir storage volumes at point locations are summed within a grid cell and scoring is completed at the component grid level at a value between 0 and 1. This approach reflects the ability of an ASR or AR project to use multiple reservoirs or surplus appropriated surface water sources within a grid cell.

Scoring for the unappropriated supply component is completed at the point level and the maximum score of individual points is taken as the score at the component grid level at a value between 0 and 1. The highest point score is used as opposed to combining the scores of all points within a grid cell because available unappropriated streamflow is not independent amongst point locations. For example, if unappropriated streamflow is diverted and used for ASR or AR at an upstream point, the amount of unappropriated streamflow at a downstream point would be reduced.

The three surface water component scores are then added together and capped at a value of one and reported at the excess surface water source grid level. This approach reflects the ability of an ASR or AR project to use the three surface water components within a grid cell.

For reclaimed water, the 10-mile grid cells report a score based on the frequency, duration, volume, and water quality of the combined reclaimed water points within a grid cell. This approach recognizes that sources of reclaimed water are independent of each other and can be combined to increase the excess reclaimed water supply.

For groundwater, excess water volume is calculated at the county and river basin polygon-level after subtracting current and recommended water strategies from the modeled available groundwater (MAG), consistent with the draft DB22 database availability. This excess water volume was divided and distributed equally to all 10-mile grid cells with centroids located within county and river basin polygons. Scoring for the groundwater source was then completed at the grid level.

Table 12. Surface water parameters for Excess Water Screening

Field name ID	Weight	Alias	Notes	Data source
Surface_Frequency	0.3	Excess Surface Water Availability Frequency	Score of 0-1 (unappropriated streamflow and unutilized appropriated streamflow & reservoir volume. *See text below for details.*)	WAM/draft DB22/TWDB Water Data for Texas Website
Surface_Duration	0.3	Excess Surface Water Availability Duration	Score of 0-1 (unappropriated streamflow and unutilized appropriated streamflow & reservoir volume) *See text below for details.*	WAM/draft DB22/ TWDB Water Data for Texas Website
Surface_Volume	0.3	Excess Surface Water Availability Volume	Score of 0-1 (unappropriated streamflow and unutilized appropriated streamflow & reservoir volume) *See text below for details.*	WAM/draft DB22/ TWDB Water Data for Texas Website
Surface_WQ	0.1	Water Quality	Score of 0.5 (assumes conventional treatment required for surface water)	
Surface_Score	---	Excess Surface Water Supply Composite Score	Score of 0-1	**See Table 17**

WAM = water availability model; draft DB22 = TWDB Draft State Water Planning Database;
TWDB = Texas Water Development Board

Table 13. Reclaimed water parameters for Excess Water Screening

Field name ID	Weight	Alias	Notes	Data source
Reclaimed_Frequency	0.3	Excess Reclaimed Water Availability Frequency	Score of 0-1 No excess supply amount – 0; Supply amount available – 1	EPA ECHO
Reclaimed_Duration	0.3	Excess Reclaimed Water Availability Duration	Score of 0-1 No excess supply amount – 0; Supply amount available – 1	EPA ECHO
Reclaimed_Volume	0.3	Excess Reclaimed Water Availability Volume	Score of 0-1 For projected treated effluent in 2040 Available supply > 35,000 acft/yr – 1 Available supply between 15,000 and 35,000 acft/yr – 0.75 Available supply between 2,500 and 15,000 acft/yr – 0.5 Available supply between 500 and 2,500 acft/yr – 0.25 Available supply < 500 acft/yr – 0	EPA ECHO/draft DB22
Reclaimed_WQ	0.1	Water Quality	Score of 0 (assumes high level of treatment required for reclaimed water)	
Reclaimed_Score	---	Excess Reclaimed Water Supply Composite Score	Score of 0-1	

EPA ECHO = U.S. Environmental Protection Agency Enforcement and Compliance History Online database; draft DB22 = TWDB Draft State Water Planning Database; acft/yr = acre-feet per year

Table 14. Groundwater (GW) parameters for Excess Water Screening

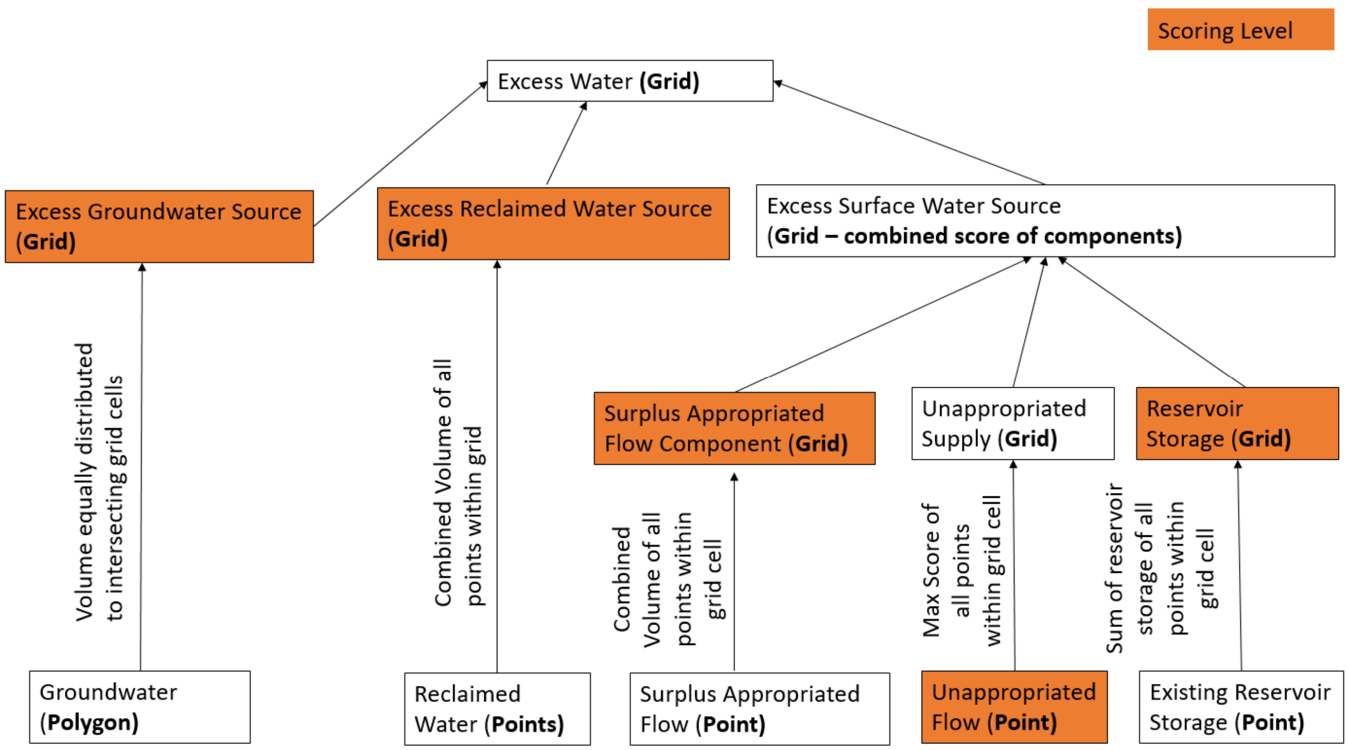
Field name ID	Weight	Alias	Notes	Data source
Ground_Frequency	0.3	Excess GW Availability Frequency	Score of 0-1 Surplus amount in all 6 decades – 1; Surplus amount in 4 or 5 decades - 0.75; Surplus amount in 2 or 3 decades - 0.50; Surplus amount in 1 decade - 0.25; No surplus amount - 0	Draft DB22
Ground_Duration	0.3	Excess GW Availability Duration	Score of 0-1 MAG available (after WMS) 2020-2070 period. 5-6 consecutive decades - 1 4 consecutive decades – 0.75 3 consecutive decades – 0.5 2 consecutive decades – 0.25 No consecutive decades – 0	Draft DB22
Ground_Volume	0.3	Excess GW Availability Volume	Score of 0-1 Minimum MAG (after WMS) over 2020-2070. Available supply > 35,000 acft/yr – 1 Available supply between 15,000 and 35,000 acft/yr – 0.75 Available supply between 2,500 and 15,000 acft/yr – 0.5 Available supply between 500 and 2,500 acft/yr – 0.25 Available supply < 500 acft/yr – 0	Draft DB22
Ground_WQ	0.1	GW_WQ	Score of 1 (assumes low level of treatment required for groundwater)	Draft DB22
Ground_Score	---	Excess GW Supply Composite Score	Score of 0-1	

Draft DB22 = TWDB Draft State Water Planning Database; MAG = modeled available groundwater; WMS = water management strategy; acft/yr = acre-feet per year

Three feature classes (one for each excess water source) were compiled into a geodatabase at grid-level resolution coincident with the Hydrogeological Parameter Screening. For the surface water and reclaimed water sources, point data were used to calculate the availability composite score within a grid cell based on the volume, frequency, and duration parameters of the excess water source. For groundwater sources, polygon data for each major and minor aquifer supply were clipped to grid to calculate grid cell scores. **Note:** The orange highlights indicate the level at which availability of excess water sources is scored.

Figure 5 provides the general framework of the Excess Water Screening and the level in which availability of excess water sources is scored.

The detailed methodology used to identify and score each excess water source is included in **Appendix D**.



Note: The orange highlights indicate the level at which availability of excess water sources is scored.

Figure 5. Framework of Excess Water Screening

Excess Surface Water and Stormwater

Methodology

Surface water in Texas is owned by the state and is defined by the Texas Water Code, Section 11.021, to be the ordinary flow, underflow, and tides of every flowing river, natural stream, and lake, and of every bay or arm of the Gulf of Mexico, and the stormwater, floodwater, and rainwater of every river, natural stream, canyon, ravine, depression, and watershed. The Texas Commission on Environmental Quality (TCEQ) administers water rights and regulates the use of surface water in Texas. House Bill 720 (HB 720) of the 86th Texas Legislature recognizes aquifer recharge as a beneficial use of state water and further authorizes the TCEQ to appropriate state water, including stormwater and floodwater, for aquifer recharge. The methodology used to identify and score the availability of excess surface water, including stormwater and floodwater, was developed to be consistent with State law (including HB 720) and with current practice for appropriation of state water in Texas.

The Excess Water Screening considers surface water available for ASR or AR from surplus surface water that is already appropriated to water users under existing water rights and from unappropriated streamflow (excess streamflow, including stormwater and flood water, available after all surface water that is appropriated to existing water rights and after downstream TCEQ-adopted environmental flow standards have been satisfied). Additionally, the screening identifies locations of existing reservoir storage that could be used to create excess surface water through reservoir operations, such as by overdrafting a portion of the stored water from conservation or flood storage for aquifer recharge. Although reservoir operations have the potential to create excess surface water supply, explicit accounting of such supply was beyond the scope of the survey.

Surplus appropriated surface water available from reservoir and run-of-river sources is the amount of supply (yield) remaining after accounting for current demands and recommended WMS from the Draft State Water Planning Database (draft DB22). Since these supplies are currently appropriated, it is a challenge to predict how the legal water right user would operate during non-drought-of-record conditions. A one-size-fits-all assumption for non-drought conditions is not appropriate and prone to error at a statewide screening scale by overestimating supplies that may not be available, especially when supplies are operated as part of a multi-source system. In an absence of this information, drought-of-record conditions were considered the most appropriate for this excess supply opportunity consistent with regional water planning and draft DB22 database. Data from the draft DB22 database are available on an annual volume basis and only at the county level. As a result, the county level data was converted to point locations at the centroid of reservoirs or the centroid of the longest stream reach within a county for run-of-river sources.

The TCEQ evaluates the availability of unappropriated streamflow for water right permit applications using the TCEQ water availability models (WAMs). To be consistent with current practice for appropriation of state water in Texas, the TCEQ WAMs were applied to estimate the monthly availability of unappropriated streamflow, including stormwater and floodwater. This approach considers the availability of excess unappropriated streamflow during non-drought and drought conditions at point locations throughout the state. The method for evaluating unappropriated streamflow is the most complex analysis for excess water in this survey due to the need to analyze water rights and environmental flows at multiple locations within a basin using approved TCEQ WAMs for consistency with how water rights are administered in Texas. In cases where WAMs have not been updated to reflect adopted instream and freshwater flow standards, a method was developed for this survey to account for environmental flows to avoid overestimating water availability for ASR or AR. Additional detail on method is included in **Appendix D**.

Previous excess surface water availability analyses quantified the daily floodwater (≥95th percentile of daily discharge) volume at the outlet of 10 major river basins in Texas and evaluated the availability of streamflow based on the volume, frequency, and duration of the occurrence of flood flows (Yang and Scanlon, 2019). The evaluation of available unappropriated streamflow in this survey builds upon the previous analysis by also considering the availability of unappropriated streamflow outside of flood events and at locations throughout the major river and coastal basins of Texas. In comparing Yang and Scanlon's study with this survey, the following observations were noted:

- The annual floodwater volume aggregated from daily volumes in Yang and Scanlon's study is less than unappropriated streamflow volume simulated during this survey based on TCEQ WAM analyses at 8 out of 10 outlet gages, meaning that most of those floodwaters were not appropriated over the period 1940 to 1988 (WAM simulation period).

- At the outlets of Nueces, San Antonio, Lavaca, Colorado, and San Jacinto river basins, the annual floodwater volume is close to the annual unappropriated flow volume from WAM simulations and the total floodwater volume is at least 50 percent of the total unappropriated flow volume, suggesting that the annual volume of unappropriated flow used in this survey is a good proxy for the annual volume of stormwater and floodwater in these basins.

- At the outlets of other basins, floodwater only represented a small portion of the unappropriated flow. For areas of greater stakeholder interest, a quantification of surface water availability during storms, especially regarding duration and frequency, would require a daily time step WAM, which is beyond the scale of this survey.

The Excess Water Screening identifies existing reservoir storage locations; however, the ability to overdraft the conservation pool and use the flood pool of a reservoir was not explicitly included in the model. Such analysis would need to consider each reservoir individually and the limitations of the existing water rights associated with the reservoir and the current demand on the reservoir which may result in excess water that is different than what was calculated as the reservoir supply.

Assumptions, challenges, and limitations

Key assumptions and challenges for the surface water component included in the Excess Water Screening include the following.

- Monthly Availability Timestep – TCEQ WAM analyses used for permitting are typically performed on a monthly timestep. Analyses could be performed to evaluate excess water availability on a daily timestep; however, such analyses would need to be done at numerous locations within each basin and would require a substantial effort to consider existing water rights and environmental flow standards. Thus, evaluating excess water availability on a daily timestep is impractical on a statewide basis. An example daily streamflow availability assessment could be conducted to provide a framework for water user groups and project sponsors to consider when determining excess water availability for a deeper, site-specific analysis of ASR/AR feasibility. Such daily timestep would also identify non-drought times where more water could be available. Native data compiled on a monthly basis is aggregated on an annual basis (acre-feet per year [acft/yr]) for volume and duration parameters for the screening to be consistent with surplus appropriated surface water and excess groundwater units. This method provides uniformity in evaluating excess supplies.

- Consideration of TCEQ Instream Flow Standards - Most of the WAMs include the TCEQ instream flow standards in the river basins in which they have been adopted. However, a few of the WAMs do not include some or all of the adopted instream flow standards as shown in **Table 15.** For these locations, the adopted base flow requirements were added to the WAMs at gage points in the Colorado, Guadalupe- San Antonio, Nueces, Rio Grande and a few coastal basins as shown in **Appendix D**. Adding pulse flow requirements would be a substantial effort and is impractical for this application. For river basins where TCEQ standards have not been adopted, the TCEQ determines the instream flow requirements for a new permit on a case-by-case basis and the default method used by the TCEQ is the Lyons Method (Bounds, R. and Lyons, B, 1979). For consistency with current TCEQ permitting procedures, the Lyons Method was selected for considering instream flow requirements in river basins without adopted instream flow standards as opposed to the Consensus Criteria for Environmental Flow Needs (CCEFN) method used by the TWDB for regional and state water planning. A summary of the 11 locations where Lyons Method instream flow criteria was added to the WAMs is included in **Appendix D**. An additional parameter is included in the unappropriated streamflow point feature as a placeholder to calculate scores in future work considering CCEFN. In all basins, including those with adopted TCEQ standards, instream flow requirements that are included as special conditions in water right certificates of adjudication or permits are in most cases already included in the WAMs.

- Consideration of TCEQ Freshwater Inflows (FWI) Standards - TCEQ FWI standards are long term statistics (as opposed to instream flow standards that are daily average flow criteria). Compliance with FWI standards is determined by simulating a project in the WAM with specific storage, diversion capacity and volume, etc., and then determining whether the long-term FWI statistics were reduced below the criteria, or in some cases, significantly reduced from the baseline simulation without the project. As a result, FWI criteria cannot be modeled in the WAM similar to TCEQ-adopted instream flow standards and must be done through post processing of WAM output for each specific project. It is impractical to simulate every potential project to consider the effect of FWI standards on surface water availability. To account for FWIs, a parameter was included in the scoring screen based on distance of available unappropriated streamflow from the coast with the understanding that streamflow locations closer to the coast would most likely be subject to FWI standards when water rights applications are filed.

- The operation of water treatment facilities to treat available excess surface water for ASR using seasonal excess treatment capacity was considered for the screening, but will not be included due to the absence of a publicly-available database containing such information related to water treatment facility operations throughout the state.

- Water generated as runoff from impervious cover, temporarily impounded in stormwater detention facilities, and/or permanently impounded in water quality ponds on a site-specific basis is not explicitly addressed in this screening intended to be applicable on a statewide basis. Attempts to parse and segregate components of runoff based on impervious cover or theoretical interpretations of diffused water definitions is exceedingly labor intensive and does not serve a clear purpose in terms of quantifying excess state water potentially available for appropriation by the TCEQ for aquifer recharge pursuant to HB 720.

- The analyses required to quantify the ability to overdraft and use the flood pool of each reservoir location is not practical for this screening process. Therefore, existing reservoir point locations and storage volume are used to estimate the availability of this potential supply source rather that quantify excess supply opportunities.

- Permits will need to be obtained from TCEQ for surface water supplies identified to be eligible for project use.

Table 15. Summary of basins with TCEQ environmental flow standards

River or coastal basin	Instream flow standards		Freshwater inflow standards	
	Adopted in basin	Included in WAM	Adopted in basin	Included in WAM
River basins				
Brazos	Yes	Yes	Yes	No
Canadian	No	---	No	---
Colorado	Yes	Partial	Yes	No
Cypress	No	---	No	---
Guadalupe-San Antonio	Yes	Partial	Yes	No
Lavaca	Yes	Yes	Yes	No
Neches	Yes	Yes	Yes	No
Nueces	Yes	No	Yes	No
Red	No	---	No	---
Rio Grande	Yes	Partial	Yes	No
Sabine	Yes	Yes	Yes	No
San Jacinto	Yes	Yes	Yes	No
Sulphur	No	---	No	---
Trinity	Yes	Yes	Yes	No
Coastal basins				
Brazos-Colorado	Yes	No	No	---
Colorado-Lavaca	Yes	No	Yes	No
Lavaca-Guadalupe	Yes	Yes	Yes	No
Neches-Trinity	No	---	No	---
Nueces-Rio Grande	Yes	No	No	---
San Antonio-Nueces	Yes	No	Yes	No
San Jacinto-Brazos	No	---	No	---
Trinity-San Jacinto	No	---	No	---

NOTE: TCEQ rules state that the Sabine-Neches, Brazos, and Rio Grande estuaries are sound ecological environments that can best be maintained by a set of flow standards that implement a schedule of flow quantities that contain subsistence flow, base flow, and high flow pulses at defined measurement points. Defined measurement points in the rules for these basins do not include the associated estuaries.

TCEQ = Texas Commission on Environmental Quality; WAM = water availability model

Data sources

The data sources that were used to estimate excess surface water include the following.

- TCEQ WAM Run 3 (full authorization and no return flows).
- TCEQ WAM Control Point Geodatabase,
- Draft DB22; and
- TWDB Water Data for Texas.

Data gaps

The data gaps identified during the excess surface water analysis include the following.

- For Surplus Appropriated Surface Water (Reservoirs), 55 reservoirs with draft DB22 records did not have a corresponding match in the TWDB Reservoir shapefile (online). Of these reservoirs, 15 of the 55 records showed excess water available during the 2020-2070 period. The 15 points were geo-spatially referenced on Google Earth and points added to the geodatabase.

- For Surplus Appropriated Surface Water (Run-of-River), draft DB22 records were provided for basin and county only. The longest stream in the respective basin and county was identified and a point was placed at the centroid of the reach. The locations for surface appropriated surface water (run-of-river) could be refined in the future with additional details beyond the county and river basin level.

Excess Reclaimed Water

Reclaimed water in the form of treated wastewater effluent discharges is included separately as a potential surface water excess supply source in the screening evaluation, as these return flows are not included in the unappropriated streamflow analysis[3]. Treated wastewater effluent is owned by the entity producing the effluent until the effluent is returned to a state watercourse. Once the treated effluent enters a state watercourse, the effluent becomes state water, is available to existing water rights, and subject to TCEQ-adopted environmental flow standards, unless the entity discharging the treated effluent owns a water use permit to convey the treated effluent using the bed and banks of a state watercourse. A comprehensive database of water use permits for the conveyance of treated effluent does not exist, nor do the TCEQ WAMs calculate excess treated effluent in a state watercourse. As a result, site-specific analyses would need to be performed to account for existing water rights and planned reuse projects, and the level of effort to perform such analyses at every reservoir location throughout the state is not practical for this screening process.

Methodology

Historical treated effluent discharge data at point locations from the U.S. Environmental Protection Agency (EPA) Enforcement and Compliance History Online (ECHO) database was used to estimate the availability of the reclaimed water source. Discharge data included in the ECHO database is the amount of treated discharge that is returned to a watercourse, after other existing uses, including direct reuse programs. The average annual discharge data[4] reported

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[3] The unappropriated streamflow analysis was based on TCEQ WAM Run 3 (full authorization and no return flows).
[4] Average annual ECHO discharge data over five year period (2015 to 2019) ranged from 0 in Cass County to 700,770,000 acft/yr in Harris County.

from 2015 to 2019 is considered representative of the current availability of the reclaimed water source. Future increases in treated discharge are projected to 2070 using approved county population estimates from draft DB22. ECHO discharge data for municipal users does not show significant variability throughout the year, as municipal discharges are generally the result of indoor water use. Outdoor irrigation, which results in higher summer water use, is not collected and treated and does not influence municipal discharges. As a result, the excess supply identified for reclaimed water is considered available during drought and non-drought conditions.

Data from the draft DB22 was initially considered for estimating excess reclaimed water used throughout the state. However, after reviewing additional information provided by TWDB[5], it was determined planning data would not be used in the screening due to data discrepancies in self-reported water user survey information.

Assumptions, challenges, and limitations

Key assumptions and challenges for the excess reclaimed water component included in the Excess Water Screening include the following.

- Available unappropriated streamflow calculations to estimate excess surface water use TCEQ Run 3 WAMs (no return flows). For this reason, ECHO discharge volumes can be considered available for reclaimed supply and excess water is not double counted.
- All ECHO discharge data from 2015 to 2019 was considered. Discharges associated with power generation and other industrial uses were not included in estimating excess reclaimed water. These discharges were excluded because, in most cases, the source water used for power generation and other industrial applications is surface water that is diverted from a stream or reservoir, used for power generation cooling or mining activities, and then returned to the surface water source. These water management activities are typically simulated in a simplified manner in the WAMs. Considering these discharges in the excess reclaimed water availability category would effectively be double-counting available excess supply for ASR and AR. Additionally, industrial discharge often has lower water quality than desirable for ASR or AR purposes.
- Planning data was ultimately not used as the basis for evaluating excess reclaimed water availability; however, it is recognized that some planning groups have included reclaimed water "reuse" as a future, recommended WMS.

[5] TWDB presentation by Simon Schmitz, Mickey Leland Intern, entitled "2016/2017 Reuse Data Patterns and Discrepancies, An Analysis of Data Reporting between TCEQ's Monthly Effluent Reports the TWDB Water Use Survey, and Annual Report".

- Reclaimed water quality is assumed to require more treatment than surface water and groundwater, except for sources noted as brackish in the draft DB22. High total suspended solids (TSS) in reclaimed water is often an indication of the presence of bacteria, which could require advanced treatment for quality to be suitable for ASR. Additional water quality discussion is provided in the Scoring section below.

Data sources

The data sources that were used to estimate excess reclaimed water include the following.

- TCEQ Texas Pollutant Discharge Elimination System (TPDES) Geodatabase
- EPA ECHO database
- TWDB county population projections

Data gaps

The data gaps identified during the excess reclaimed water analysis include the following.

- Basin and/or statewide reclaimed WAMs.
- EPA ECHO database included 108 records that could not be matched to TPDES discharge locations from the TCEQ. These points were excluded from the excess water screen because they could not be readily spatially located.

Excess Groundwater Parameters

There are 31 major and minor aquifers in Texas. Local groundwater conservation districts (GCDs) and groundwater management areas (GMA) have been created over much of Texas to manage and protect these major and minor aquifer systems. The GCDs have authority to issue permits to achieve desired future conditions (DFCs), such as maximum drawdown conditions or maintaining springflow, that are established within GMAs. These DFCs are adopted by the local GCD and GMAs and provided to the TWDB, which in turn simulates DFC conditions in the respective GAM to develop MAG estimates.

MAGs are used as a proxy for groundwater availability and regional water planning groups (RWPGs) are required to constrain groundwater availability according to MAGs. For areas where MAGs have not been developed, RWPGs have the discretion to prepare non-MAG groundwater availability estimates. These are often determined by simulating pumping in TWDB-adopted GAMs and identifying an amount that can be pumped such that drawdown criteria identified by the RWPG or local stakeholders is met and not exceeded.

The draft DB22 identifies surplus MAG, non-MAG, and partial MAG volumes that are considered available from 2020 to 2070 after accounting for current use and future recommended WMSs.

This information is presented on the county, river basin level for each aquifer for which MAG was developed or supply determined by RWPG methods.

Methodology

The draft DB22 database identifies groundwater availability (note this term includes MAGs and region-determined availability) surplus from 2020 to 2070 after accounting for current groundwater use, and future recommended WMSs. To support the regional water planning process and avoid double-counting, excess groundwater for potential ASR and AR projects is estimated to be the amount remaining from MAG, non-MAG, and partial MAG values *after* accounting for recommended WMSs identified in the draft DB22. A draft DB22 spreadsheet with this data was provided by the TWDB for use in the screening.

Each excess groundwater supply and aquifer, county, river basin combination was clipped to the grid level coincident with the Hydrogeological Parameter Screening grid for the 31 major and minor aquifers. Several RWPGs classified groundwater from non-major or minor aquifers considered "Other Aquifers". However, supplies from Other Aquifers, which amounted to 3 percent of the total excess groundwater identified in draft DB22, were not included in the screening for two reasons: (1) the TWDB screening focuses on major and minor aquifers, and (2) lack of geographical data regarding the location of these other aquifer units needed to clip to grid cells with accuracy.

Because groundwater supplies are currently limited by GCDs according to MAG values, it is challenging to predict how groundwater users would operate during non-drought-of-record conditions, including seasonal use patterns that may offer excess water opportunities when water use pumping is low. A one-size-fits-all assumption for non-drought conditions is not appropriate and may conflict with GCD management in addition to being prone to error at a statewide screening scale by overestimating supplies that may not be available, especially when supplies are operated as part of a managed system. In the absence of this information, only drought-of-record conditions are considered in evaluating this excess supply opportunity consistent with regional water planning and draft DB22.

Assumptions, challenges, and limitations

The key assumptions and challenges for the excess groundwater component included in the Excess Water Screening include the following.

- Groundwater surplus identified in the draft DB22 is considered excess water available for ASR or AR. Furthermore, the draft DB22 database categorizes general water quality according to Fresh, Brackish (some), or Saline which was used by the scoring screen to assess treatment level. This water quality designation is general at the county and river basin level and may vary considerably based on site specific conditions encountered.

- There may be additional groundwater supply opportunities for ASR beyond those included in MAG projections and other groundwater supplies considered during the regional water planning process. Due to timeline and data gaps in this information being readily available across the entire state, these additional groundwater supplies are not included in the screening. When data becomes available, future versions of the screening can be adapted to include such information.

Data sources

The data source used to estimate excess groundwater includes the following.

- Draft DB22 database

Data gaps

The data gaps identified during the excess groundwater analysis include the following.

- Groundwater availability in areas where no MAG was identified during the GCD process nor estimated by RWPGs as non-MAG availability.

- Water supplies from "Other Aquifer" systems identified in draft DB22 were not included in the excess water evaluation due to the lack of more detailed information at a more refined level than county and river basin.

- Spatial information on "Other" aquifers by which groundwater supplies have been quantified on a county/basin level through the regional water planning process.

Scoring

Table 16 lists the parameters, weighting, and scale included in the Excess Water Screening for surface water, reclaimed water, and groundwater as discussed previously in **Table 12** through **Table 14**. Additional details regarding the scoring of parameters for surface water sources is presented in **Table 17**. The frequency, volume and duration parameters each carry an equal weight of 30 percent with the water quality parameter contributing the remaining 10 percent of the composite score for each surface water source. Each parameter receives a score ranging from 0 to 1 in the screening and is then weighted accordingly. A detailed methodology used for calculating and scoring the availability of excess water for each of the identified surface water sources, reclaimed water, and groundwater is detailed in **Appendix D**. The data used in calculating the excess water scores was compiled in a separate geodatabase, and used as a precursor for developing the grid-level geodatabase to preserve data integrity for future updates. At the grid-level, the excess water scores are compiled and normalized to calculate the Final Suitability Rating described later in this report.

Table 16. Weighting of availability parameters

	Frequency	Volume	Duration	Water quality
Weight	0.30	0.30	0.30	0.10
Scale	0 (low) 1 (high)	0 (low) 1 (high)	0 (low) 1 (high)	0 (high TDS, high TSS) 1 (low treatment)

TDS = total dissolved solids; TSS = total suspended solids

The excess water volume parameter was scored consistently amongst all supply categories, with scoring breaks to capture a range of sizes for potential AR and ASR projects. Based on industry experience, water supplies that provide less than 500 acre-feet per year (acft/yr) are unlikely to be cost-effective for ASR and AR projects. As a result, if an excess water supply volume did not exceed 500 acft/yr, the volume, frequency and duration parameters received a score of zero.

Excess water supplies that ranged between 500 and 2,500 acft/yr were assigned a volume score of 0.25; between 2,500 acft/yr and 15,000 acft/yr a score of 0.5; between 15,000 and 35,000 acft/yr a score of 0.75; and supplies exceeding 35,000 acft/yr a score of 1. While this screening does not take the place of site-specific evaluations, the above ranges were identified with the small- to mid-sized utilities in mind and provides flexibility according to system needs. The above intervals also recognize that if excess supplies are available for multiple years in a row, that storage capacity could increase (subject to hydrogeological favorability) to provide prolonged supplies during extreme, multi-year drought conditions. The upper end (35,000 acft/yr) is scaled for larger-utility projects. For instance, if a utility is primarily considering ASR for drought protection and excess supplies of 35,000 acft/yr are available for multiple years during an average or rainy condition, then after 5 years the storage capacity could be nearly 200,000 acft/yr. The same scoring intervals are used for evaluating water supply needs in the Water Supply Needs Screening.

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Table 17. Scoring matrix for excess surface water

<table>
<tr><th>Weight</th><th colspan="2">---</th><th>0.30</th><th>0.30</th><th>0.30</th><th>0.1</th></tr>
<tr><th>---</th><th colspan="2">Category</th><th>Frequency</th><th>Volume</th><th>Duration</th><th>Water quality indicator</th></tr>
<tr><td>1.00</td><td colspan="2">Surplus appropriated surface water (reservoirs and run-of-river)</td><td>• No surplus amount - 0
• Surplus amount in 1 decade - 0.25
• Surplus amount in 2 or 3 decades - 0.50
• Surplus amount in 4 or 5 decades - 0.75
• Surplus amount in all 6 decades - 1</td><td>• Average decade surplus amount (2020-2070) < 500 acft/yr - 0
• Average decade surplus amount (2020-2070) between 500 and 2,500 acft/yr - 0.25
• Average decade surplus amount (2020-2070) between 2,500 and 15,000 acft/yr - 0.50
• Average decade surplus amount (2020-2070) between 15,000 and 35,000 acft/yr - 0.75
• Average decade surplus amount (2020-2070) > 35,000 acft/yr – 1</td><td>• No consecutive decades – 0
• 2 consecutive decades – 0.25
• 3 consecutive decades – 0.5
• 4 consecutive decades – 0.75
• 5-6 consecutive decades – 1.0</td><td>• High treatment level (bact, high TDS, cl, TSS, low DO) – 0
• Conventional treatment (SW) – 0.5 <most likely>
• Low treatment level (low TDS, fresh GW) – 1</td></tr>
<tr><td rowspan="3">1.00</td><td rowspan="3">Available unappropriated streamflow</td><td rowspan="2">WAM unappropriated streamflow weight (0.90)</td><td rowspan="2">Percentage of months with available flow:
*The actual percentage is the score i.e. if a point has available flow in 36% of the months then the score is 0.36</td><td rowspan="2">• Median Annual Volume is < 500 acft/yr (30th percentile) - 0
• Median Annual Volume is between 30th (500 acft/yr) and 45th (2,500 acft/yr) percentile - 0.25
• Median Annual Volume is between 45th (2,500 acft/yr) and 60th percentile (15,000 acft/yr) - 0.5
• Median Annual Volume is between 60th (15,000 acft/yr) and 75th percentile (35,000 acft/yr) - 0.75
• Median Annual Volume is greater than 75th percentile (35,000 acft/yr) - 1</td><td>Max consecutive years with available flow greater than the median
* Less than 5 years - 0
* 5 years or more - 0.5</td><td rowspan="3">• High treatment level (bact, high TDS, cl, TSS, low DO) – 0
• Conventional treatment (SW) – 0.5 <most likely>
• Low treatment level (low TDS, fresh GW) – 1</td></tr>
<tr><td>Max consecutive years with available flow less than the median
* More than 8 years - 0
* 8 years or less - 0.5</td></tr>
<tr><td>FWI consideration weight (0.10)</td><td>Straight line distance from coast x2
*Less than 50 miles - 0
*50 miles to 100 miles - 0.25
*100 miles - 150 miles - 0.5
*150 miles - 200 miles - 0.75
*greater than 200 miles - 1</td><td>Straight Line Distance from Coast x2
*Less than 50 miles - 0
*50 miles to 100 miles - 0.25
*100 miles - 150 miles - 0.5
*150 miles - 200 miles - 0.75
*greater than 200 miles - 1</td><td>Straight Line Distance from Coast x2
*Less than 50 miles - 0
*50 miles to 100 miles - 0.25
*100 miles - 150 miles - 0.5
*150 miles - 200 miles - 0.75
*greater than 200 miles - 1</td></tr>
<tr><td>1.00</td><td colspan="2">Existing reservoir storage</td><td>* No storage or storage less than 5000 acft - 0
*Storage greater than 5000 acft - 1</td><td>*0-5,000 acft - 0
*5,000-100,000 acft - 0.5
Greater than 100,000 acft - 1</td><td> No storage or storage less than 5000 acft - 0
*Storage greater than 5000 acft - 1</td><td>• High treatment level (bact, high TDS, cl, TSS, low DO) – 0
• Conventional treatment (SW) – 0.5 <most likely>
• Low treatment level (low TDS, fresh GW) – 1</td></tr>
</table>

WAM = water availability model; FWI = Freshwater Inflows; acft/yr = acre-feet per year; SW = surface water; GW = groundwater; TDS = total dissolved solids; TSS = total suspended solids; DO = dissolved oxygen

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The frequency and duration parameters were evaluated using specific criteria for each excess supply source to accommodate the varying timestep of source data. For instance, the TCEQ WAMs were applied to calculate the availability of unappropriated surface water on a monthly timestep, while the availability of groundwater is evaluated on an annual timestep. An exception to this is for existing reservoir storage sources, which used frequency and duration parameters to identify reservoirs exceeding 5000 acft in size. Scoring criteria for the frequency and duration parameters for each excess water category is described in **Table 12** through **Table 14**.

A water quality score is also included in the Excess Water Screening to generally recognize different treatment levels that may be needed to use excess water sources. Water quality was categorized according to three levels of treatment: high treatment level (bacteria, high TDS, chloride, total suspended solids [TSS], low dissolved oxygen [DO]), conventional treatment (most likely treatment for surface water), or low treatment level (low TDS). Reclaimed water typically requires high treatment level, whereas fresh groundwater likely requires much less treatment. The statewide screening presents water quality at a very cursory level as this survey not intended to replace site- and system-specific water quality evaluations that are needed to understand source water compatibility, blending, and/or specific water quality parameter interaction before combining with existing supplies or systems. As a result, scoring the water quality parameter is based on the source of the excess supply with groundwater sources receiving a score of 1, surface water sources receiving a score of 0.5, and reclaimed water sources receiving a score of 0. A site and project specific feasibility study will incorporate fatal-flaw considerations, like water compatibility, that this survey cannot provide at the statewide level.

A full list of parameters that were considered in the Excess Water Screening, including unappropriated available flow statistics compiled from WAM output, but not included in the scoring are included in tables in **Appendix D**, for use in a future phase of screening.

Results

Results of the Excess Water Screening scores are presented in **Figure 6** through **Figure 10** for each of the three excess water categories (surface water, reclaimed water, and groundwater). These total scores were calculated from parameters scores and weights identified in **Table 12** through **Table 14** according to criteria described above and in **Appendix D**. In general, results of the evaluation indicate excess surface water is the most widely available source for potential use in ASR and AR projects. However, if excess reclaimed water and groundwater sources are available, they generally receive a higher score compared to the excess surface water sources.

Excess surface water and stormwater

Figure 6 shows the scoring results for the three excess surface water components (surplus appropriated surface water, unappropriated surface water and existing reservoir storage).

Results of the component scores show that surplus appropriated surplus surface water is not widely available throughout the state as most of this surface water component is already dedicated to meet existing water use demands or for future WMSs. However, where available, the surplus appropriated surface water received higher scores due to the higher frequency and duration scores. Similar to the scoring results of the surplus appropriated surface water component, the availability of existing reservoir storage receives high scores where available due to high frequency and duration scores.

The scoring of the available unappropriated streamflow component generally follows the climate trends across the state with wetter conditions in the eastern portion of the state resulting in higher scores, and drier conditions in the western portion of the state resulting in no availability. Limited availability is present in the Colorado Basin due to high levels of water management and existing appropriations resulting in limited available unappropriated water. The TCEQ Colorado and Sulphur WAMs contain an extended hydrologic period of 1940-2016 and 1940-2017 and include the recent drought conditions experienced across most of the state. Hydrologic periods included in the TCEQ WAMs for other basins do not extend past 1997 and do not include the recent drought. As a result, the extended period of record in the Colorado and Sulphur basins could have lower availability statistics compared to the other basins.

Lower scores are also present in the Upper Trinity River Basin upstream of the reservoirs in the vicinity of the Dallas-Fort Worth Metroplex. Unappropriated streamflow is limited in these areas because most of the surface water is already appropriated for impoundment and use from the reservoirs. The component scores shown in **Figure 6** are summed and capped at one to calculate the final excess surface water score that considers all three sources, shown in **Figure 7.**

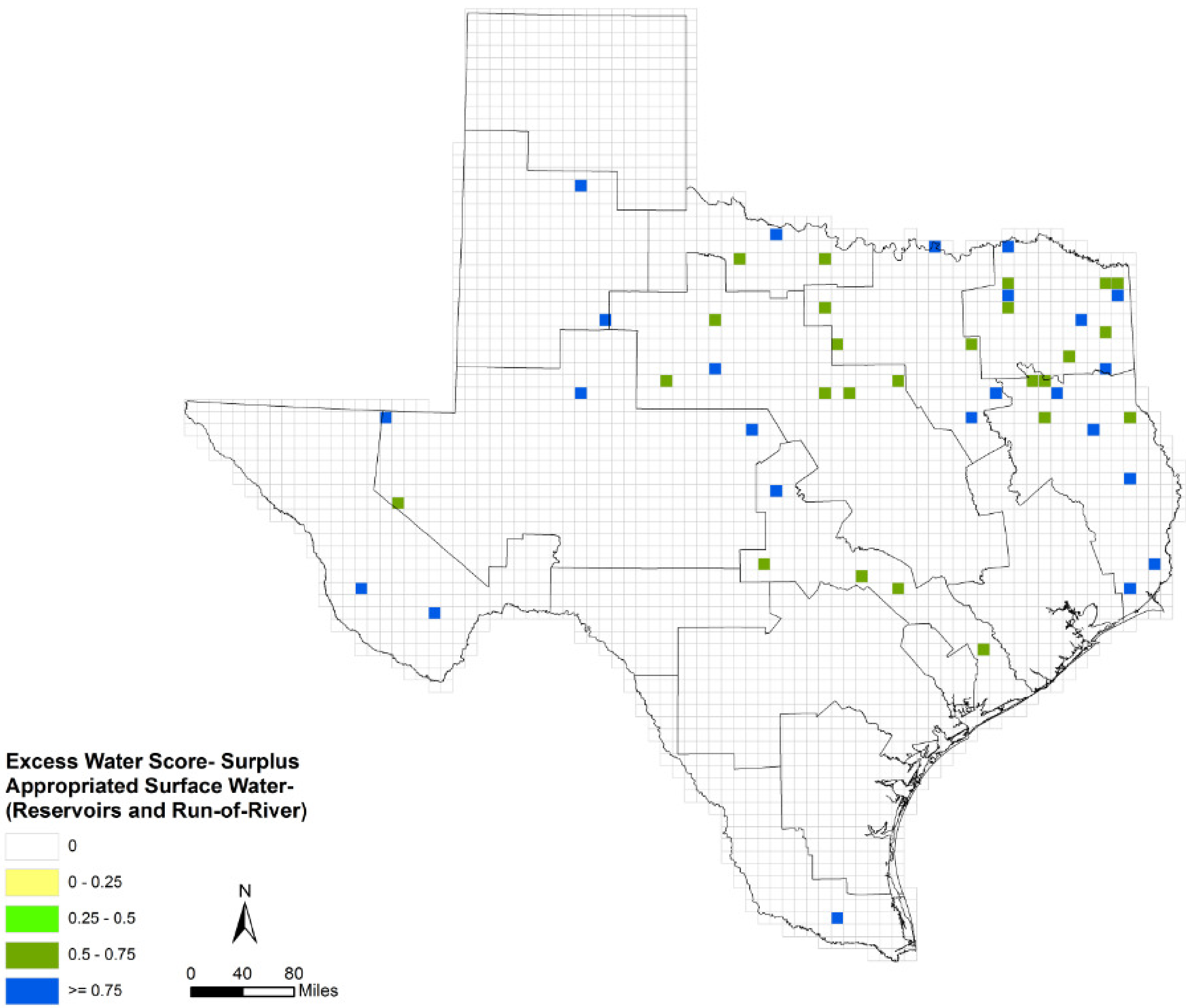

Figure 6a. Excess surface water component scoring results

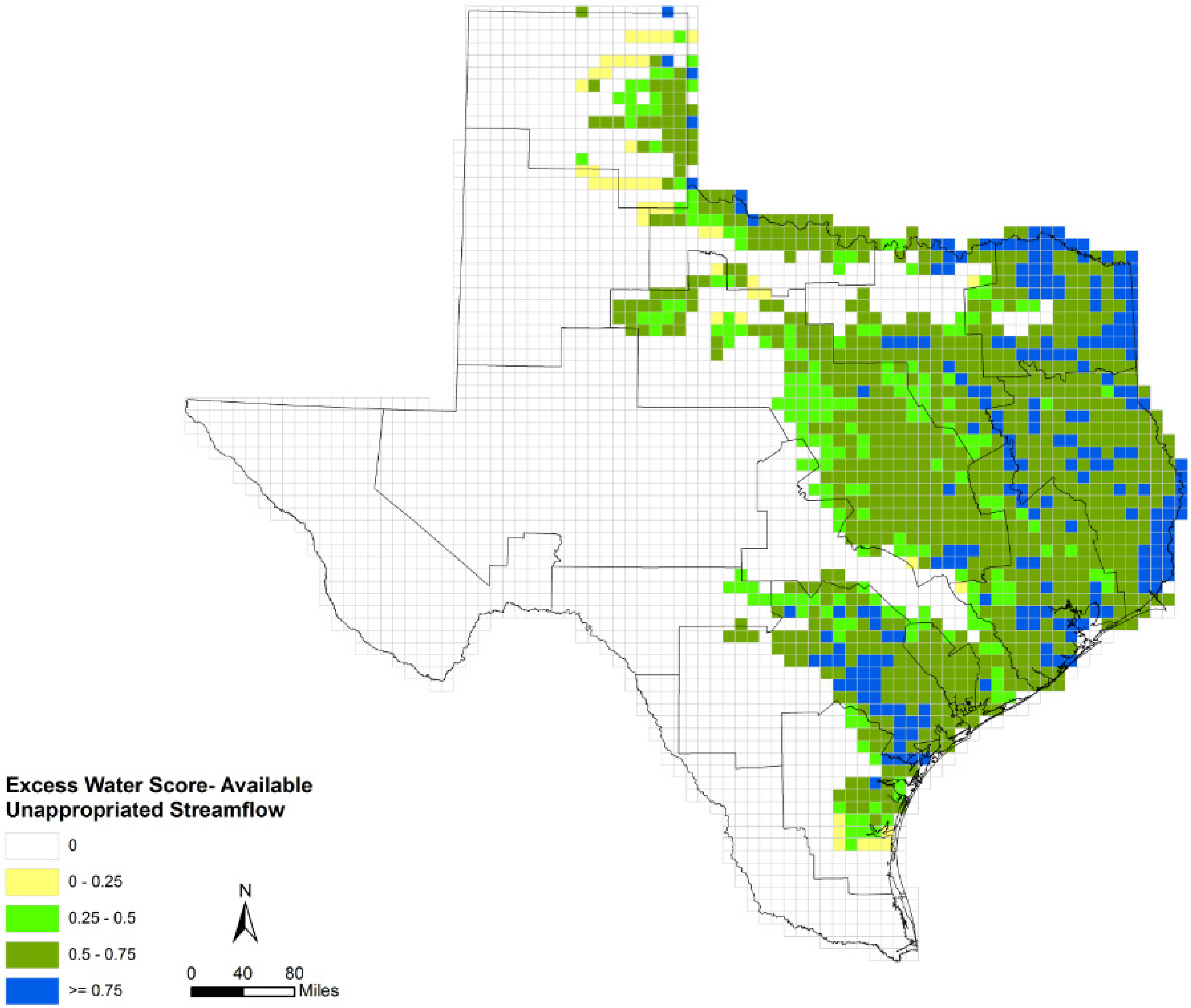

Figure 6b. Excess surface water component scoring results (continued)

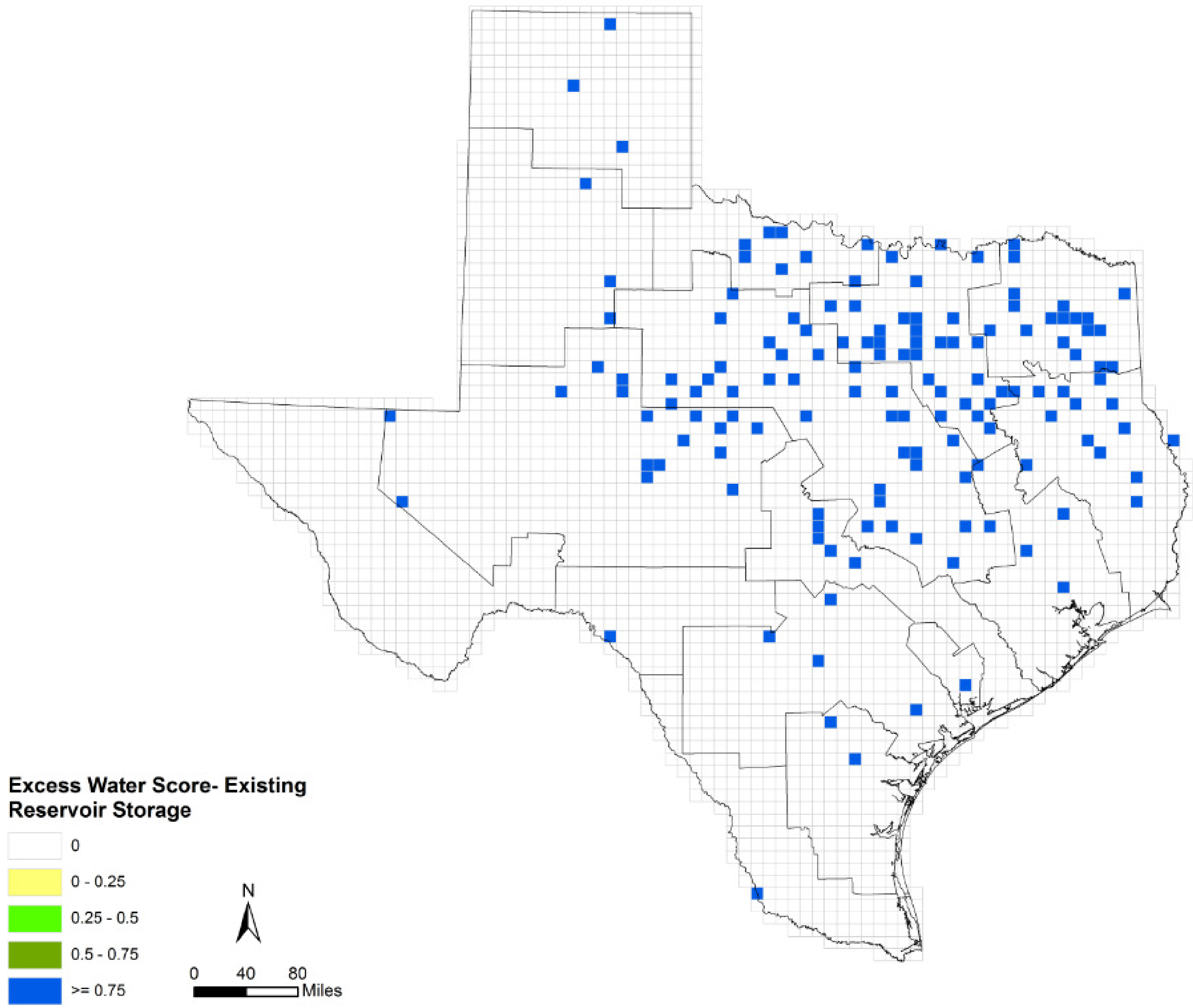

Figure 6c. Excess surface water component scoring results (completed)

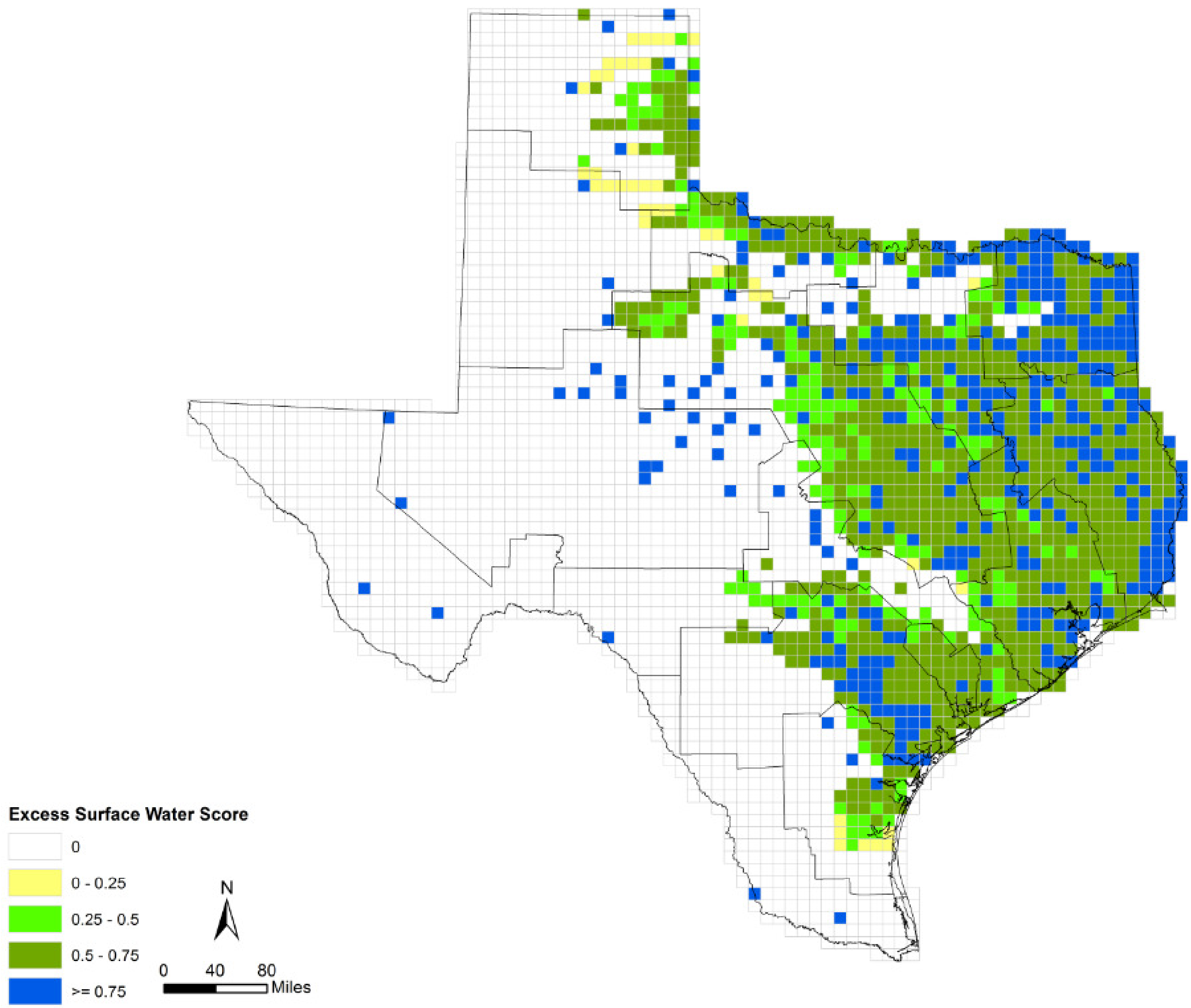

Figure 7. Excess surface water scoring results

Excess reclaimed water

Figure 8 shows the scoring results for excess reclaimed water throughout the state. Higher scores are focused near the larger metropolitan areas where larger wastewater effluent discharges are present. The scores also reflect the high reliability of the excess reclaimed water source by receiving a generally high score if wastewater discharges are present.

Excess groundwater

Figure 9 shows the scoring results for excess groundwater available from major and minor aquifers throughout the state. The highest scoring excess supplies from major aquifers include the Ogallala and Seymour in the Panhandle area, Hueco-Mesilla Bolsons and Edwards Trinity-Plateau in West Texas, and the Gulf Coast in East Texas. For minor aquifers, the areas showing highest scoring excess supplies include the Rita Blanca and Dockum in the Panhandle, Queen City in East Texas, and Yegua Jackson in South Texas. When excess water supplies from major and minor aquifers are combined to identify opportunities in areas with coincident aquifers, high scoring areas are shown in the Panhandle, West Texas, and East Texas area north of Houston. **Figure 10** shows the maximum excess groundwater score by grid cell.

Summary of Excess Water

The excess water scores for the three source categories were combined in a final excess water grid in areas where multiple excess water supplies were present.

The Excess Water Screening scores were categorized for each grid cell with excess supplies identified (in **Figure 11**). Threshold values used for excess water divided suitability into classes of “low”, “medium”, and “high” as follows:

- Low− Excess Water Score < 0.5
- Medium− Excess Water Score 0.5 to 0.7
- High− Excess Water Score > 0.7

About 14% of the grid cells (or 448) scored low suitability, 35% (or 1,115 cells) scored medium suitability, and 21% (or 677 cells) scored high suitability for excess water. The remaining 29% (or 920 cells) did not have excess water supplies.

This actual values were used in the Final Suitability Rating, discussed later, to evaluate ASR or AR project suitability.

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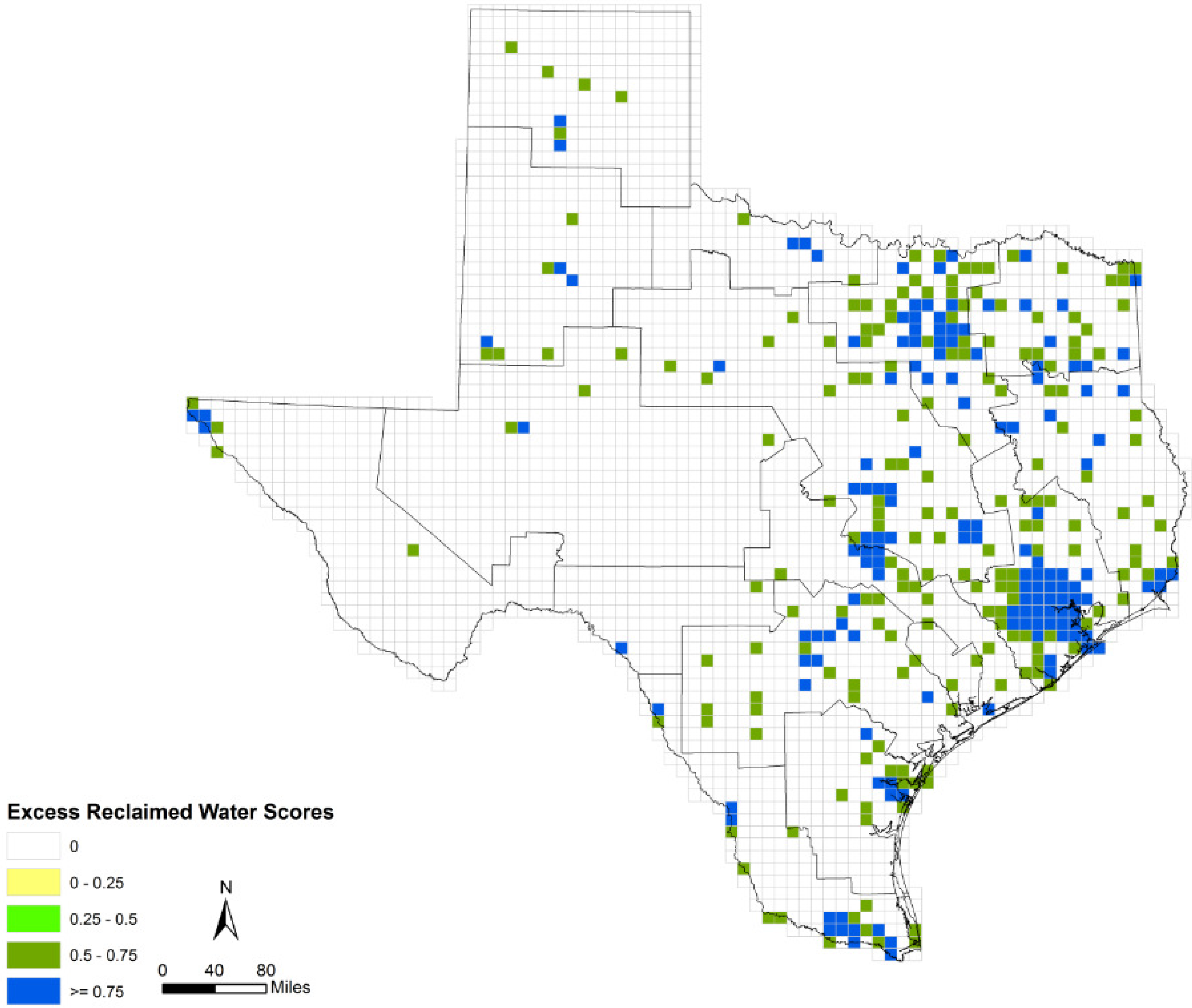

Figure 8. Excess reclaimed water scoring results

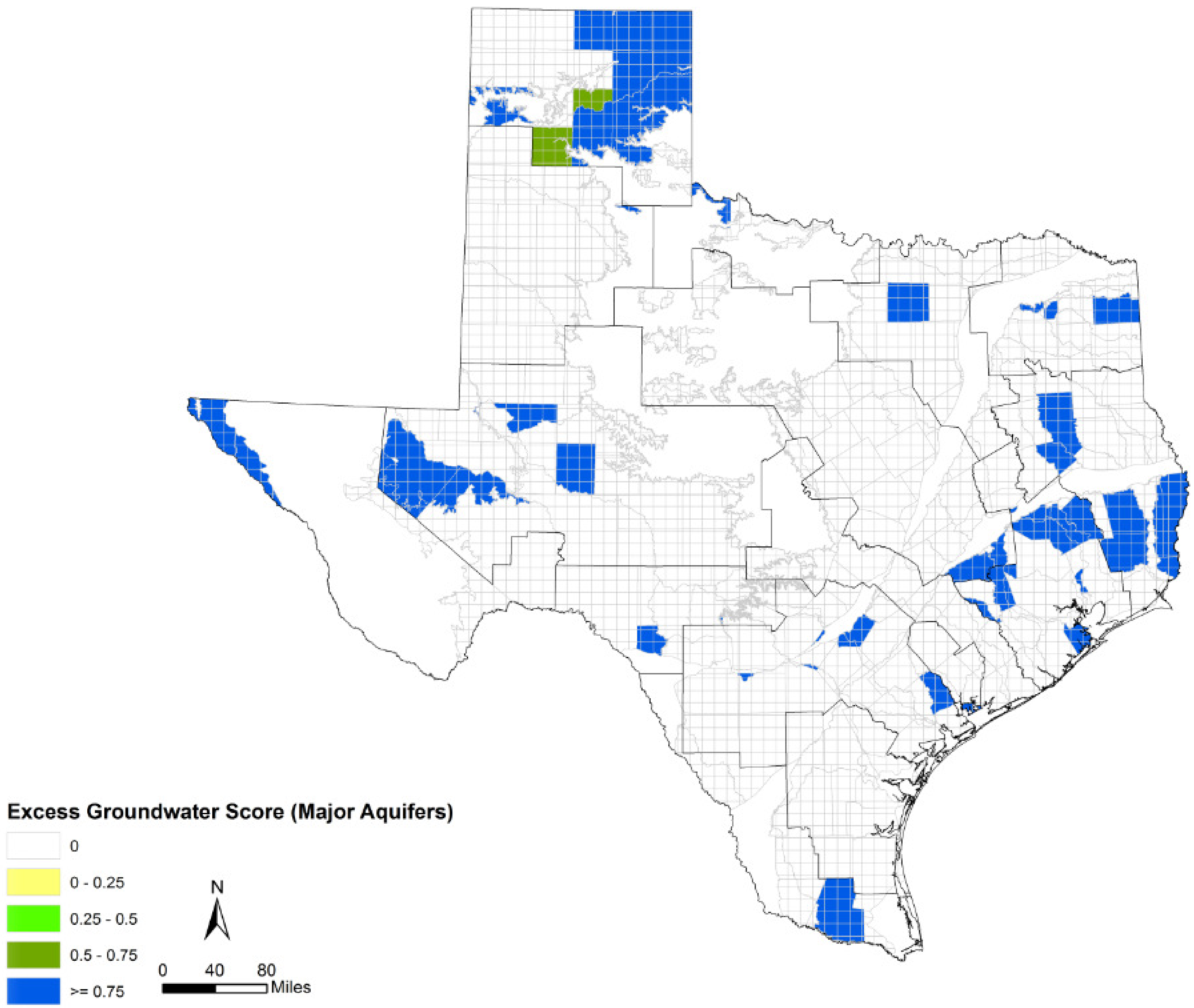

Figure 9a. Excess groundwater scoring results for major and minor aquifers

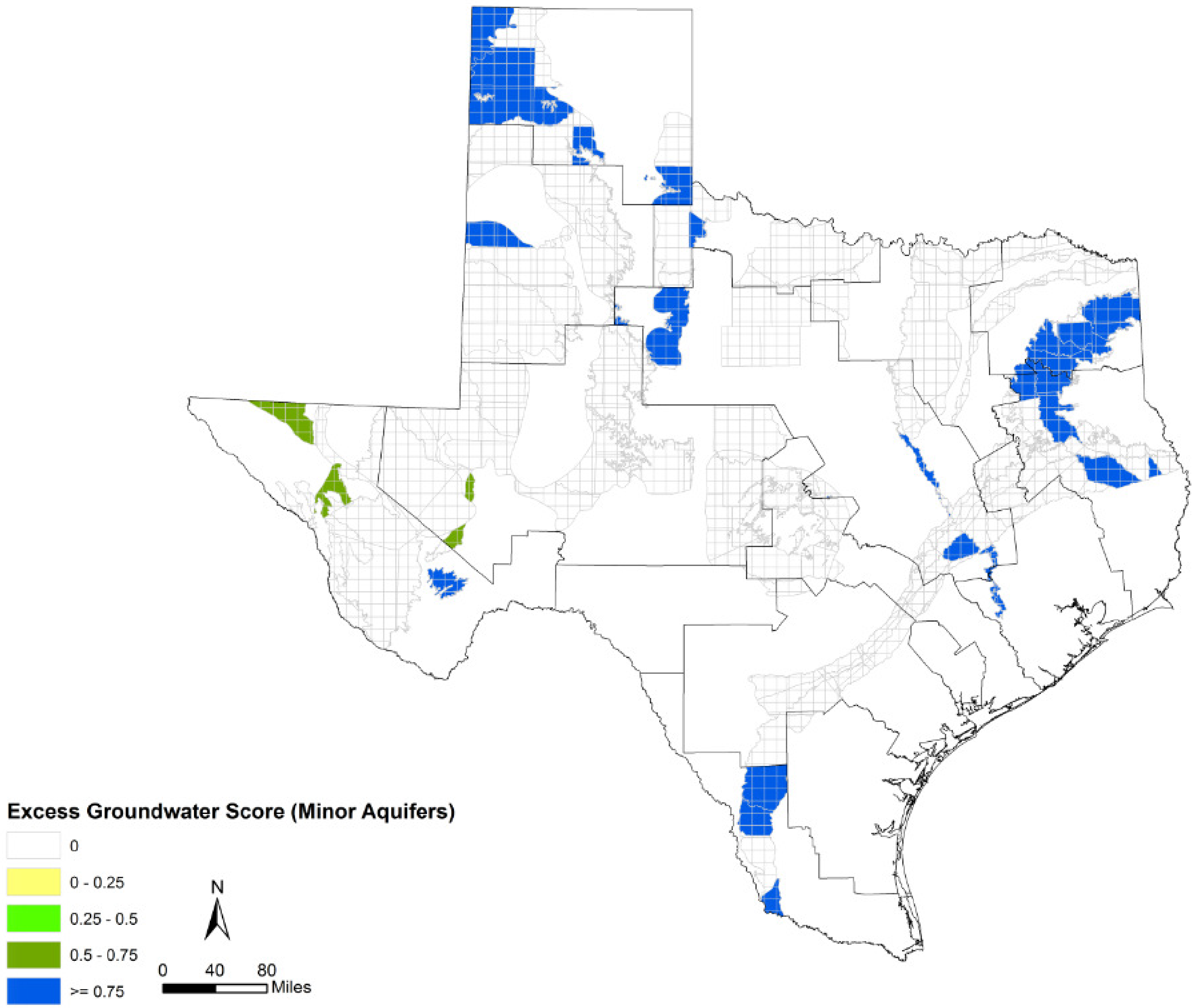

Figure 9b. Excess groundwater scoring results for major and minor aquifers (completed)

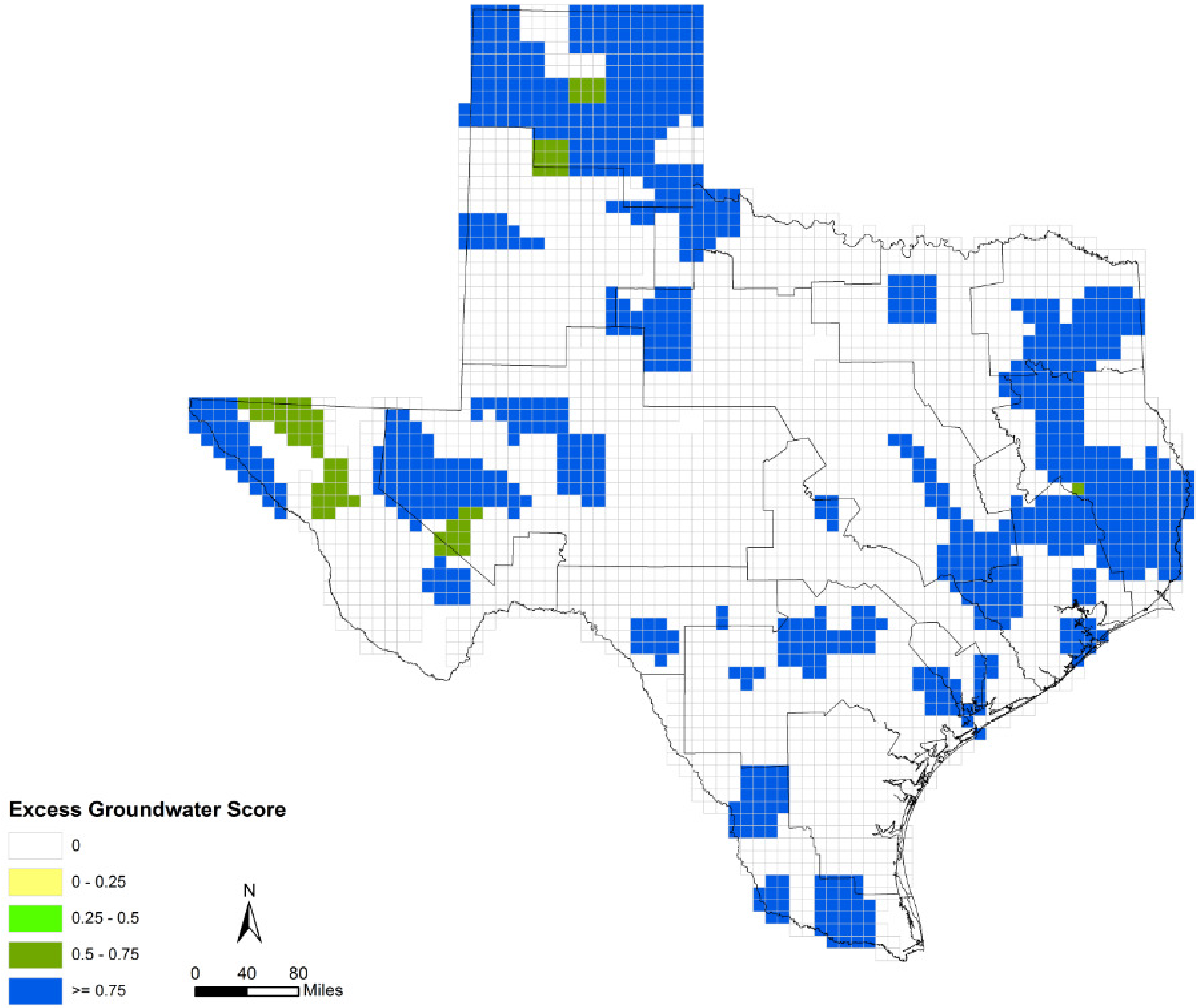

Figure 10. Excess groundwater scoring results (maximum of Texas' 31 major and minor aquifers)

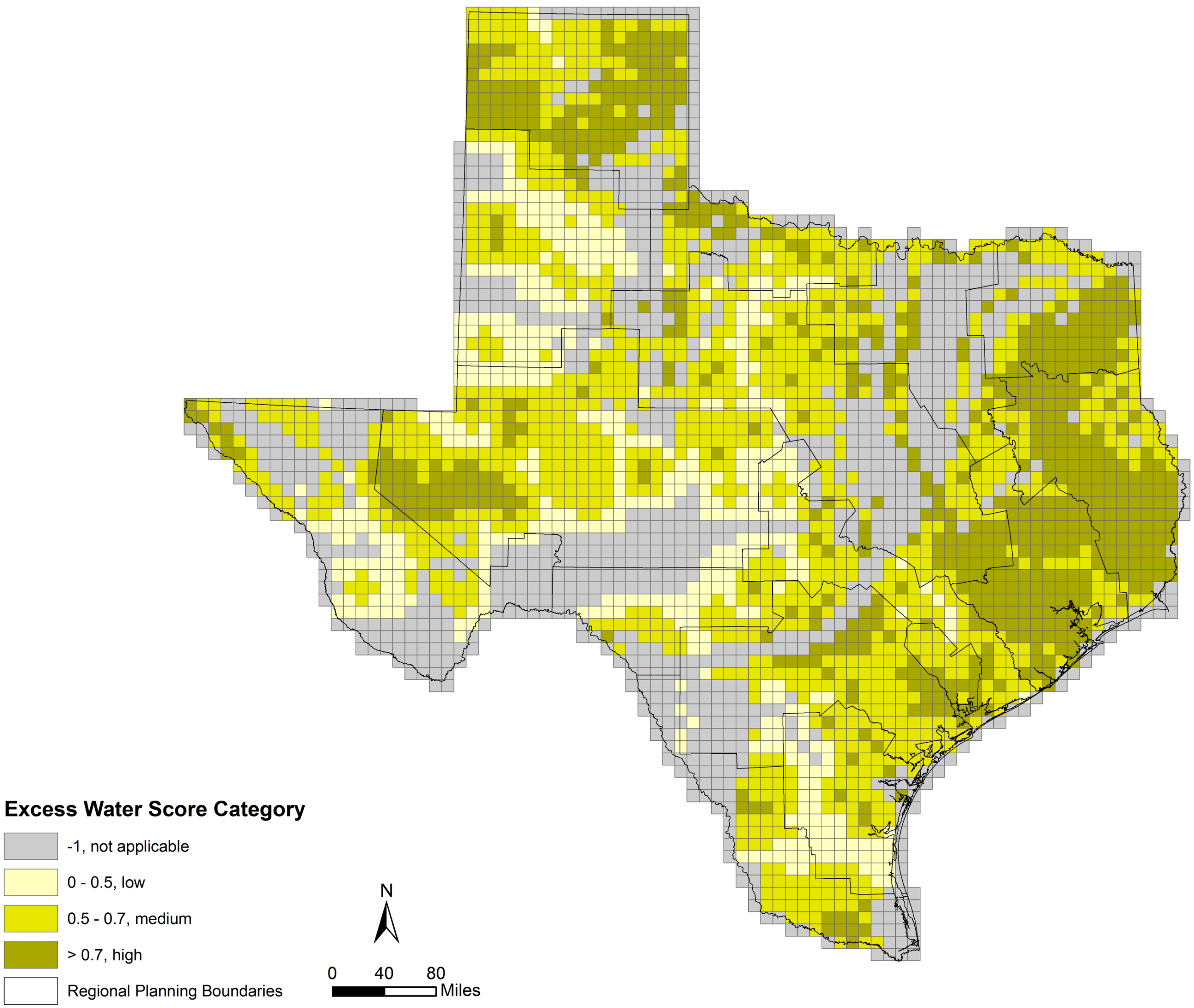

Figure 11. Excess Water Screening Scores by Category

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Future Work

This survey has provided a good statewide look at excess water that could be available for ASR or AR storage. The following items were identified throughout the development of the Excess Water Screening and by the TWDB to update and refine the screening in future work efforts to focus in particular areas of high interest.

- The accuracy of the excess surface water evaluation could be potentially improved by incorporating the following elements into the identification and scoring of the excess water source.
    - Texas Instream Flow Program (TIFP) studies are currently limited to a small portion of the state: lower San Antonio, middle and lower Brazos, middle Trinity and lower Guadalupe river basins. However, as TIFP studies are completed in more portions of the state, recommendations from these studies could be incorporated into the screening to refine estimates of available surface water after consideration of environmental needs.
    - TIFP studies consider pulse flows and overbank flows, and flows required to transport sediment and maintain channel geometry (TCEQ, TWDB, TWPD, 2017; TCEQ, TWDB, TWPD, 2018) could further reduce the amount of excess surface water. Future studies could be required to quantify what percent of excess surface water would be available in specific areas for ASR/AR projects without impacting high pulse flows and overbank flows or substantially altering sediment transportation.
    - CCEFN instream environmental flow requirements for river basins without adopted TCEQ environmental flow standards.
    - Calculation of river miles from the Bay and Estuary to unappropriated streamflow control points for consideration of freshwater inflow requirements.
    - Inclusion of TCEQ-adopted high-flow pulse requirements at locations not already included in the current TCEQ WAMs.
    - Evaluate discharge points related to geographic proximity to water user groups that have identified existing and/or future reclaimed projects greater than 1,000 acft/yr.
    - A source of surface water identified by this survey is use of reservoirs for conjunctive use with AR or ASR, which could be operated within conservation and flood storage for beneficial outcome. However, the timeframe, statewide scale,

data availability, and uncertain permitting options did not allow for mapping these potential sources in this survey.

- The Rio Grande is subject to international treaty agreements with Mexico for use, and a detailed evaluation of these operations are beyond the scope of the statewide survey. For this reason, a conservative approach was taken to omit unappropriated streamflow opportunities to avoid overestimation of availability.

Water Supply Needs Screening

Objective

The objective of the Water Supply Needs Screening is to identify the relative suitability of Texas' aquifers for ASR or AR projects based on current and future water supply needs. This section describes the approach, methodology, scoring, and results of the Water Supply Needs Screening.

This screening is intended to serve as a guide for regional water planning stakeholders; however, it is not the intention of this screening to substitute for local, field studies that are required to "prove-up" ASR or AR suitability or to prioritize ASR or AR projects. This survey does not include economic, infrastructure, water compatibility, seasonal or supply system operations for integration, or other topics that are important considerations to determine site and project specific ASR or AR feasbility.

Approach

The general approach to evaluating water supply needs for ASR or AR relative project suitability was as follows.

1. Obtain current and future water supply needs in the draft DB22 database by category. Water supply needs in draft DB22 are input by regional water planning groups, and represent projected water demand minus existing supplies (prior to consideration of future water management strategies). Identify water user group categories to include in the screening, based on available data.

2. Consider water supply needs parameters that are important to the probable success of an ASR or AR project pursuant to HB 721.

3. Develop strategies for scoring needs related parameters.

4. Combine the parameter scores to create a final water supply needs score on a grid cell basis, spatially coincident with the Hydrogeological Parameter and Excess Water Screenings.

5. Use the magnitude of the Water Supply Needs Screening scores to rank grid cells into three general categories of relative suitability, “low,” “medium,” or “high.”

6. Aggregate overlapping scores into a single scored layer for the screening.

The Water Supply Needs Screening attributes from DB22 is transferred to grid cells with feature classes organized by water user group category consistent with draft DB22. This multiple layers system nested within the geodatabase provides user flexibility to view current and future water needs for different water user categories that are spatially coincident. This information could then be considered by potential project sponsors to evaluate regional opportunities. There are numerous aspects of water supply planning that affect the feasibility of an ASR or AR project, including the project objectives based on utility or project sponsor needs. This screening is focused on available data, which is better equipped to address long-term water supply needs rather than identifying peaking or seasonal water opportunities. Future versions of the screening may be to incorporate water treatment plant capacity and water demand patterns to develop a score that considers these and other important parameters affecting system operations.

Water Supply Needs

Methodology

The following method was used to identify parameters associated with water supply needs for scoring and weighting.

1. Obtain current and future water supply needs from the draft DB22 from TWDB. Water supply needs identified in draft DB22 are presented on a decadal basis from 2020 to 2070 for each water user group (WUG) category: municipal, manufacturing, irrigation, mining, livestock[6], and steam electric power.

2. Water supply needs were considered for all water user group categories included in draft DB22 in accordance with HB 721 and TWDB scope. The volume of needs for all user categories, related information, and spatial coverages for DB22 information provided by the TWDB was compiled and assessed.

[6] Note: Livestock water users were not included in House Bill 721 or TWDB scope, but considered since it is a water user category included in draft DB22.

3. Based on data availability and discussions with TWDB, it was determined that three WUG categories with spatially-referenced information would be prepared for the Water Supply Needs Screening: municipal (discrete WUGs only), steam electric, and manufacturing WUGs.

4. The municipal layer was developed by assigning municipal WUG water supply need attributes from the draft DB22 to the appropriate DB22 boundaries (see example **Figure 12** for DB22 boundaries extent). Municipal water supply needs are presented in DB22 for both individual (discrete) WUGs and on a county-wide level for municipal WUGs (County-Other) that have a smaller service area capacity. For individual municipal WUGs, parameter information is assigned for all grid cells located within the draft DB22 municipal WUG boundary coverage. Since Municipal County-Other water supply needs are presented county-wide, it's not possible to practically and accurately identify the location of these needs with certainty. After confirming with the TWDB, the County-Other needs were removed from further evaluation in this screening. The scoring/ranking of municipal County-Other WUGs cannot be meaningfully assessed since location information is not readily available other than on a county-level basis and project sponsor information to build such an ASR or AR project is unknown. If in the future, county-other interests desire to pursue ASR or AR with TWDB financing, the datasets could be revisited and customized accordingly.

5. The non-municipal water supply needs layer was developed as follows.

    a. In draft DB22, the water supply needs for manufacturing, irrigation, mining, livestock, and steam electric are only listed on a county-wide level. This makes determining the distance to suitable ASR and AR projects challenging, since the location of these needs within a county are unknown.

    b. For manufacturing and steam electric water supply needs, the TWDB provided point location information based on 2017 Historical Water Use information. The TWDB shapefile was used as a proxy for assigning manufacturing and steam electric water supply needs within a county. Future manufacturing and steam electric growth areas were unavailable; therefore, new industrial locations are not accounted for in the screening. After plotting the point location data, it was determined that 393 out of 1,453 manufacturing points had incorrect latitude/longitude coordinates that either plotted outside of Texas or in a different county or region than specified in the dataset. In an attempt to focus on resolving spatial issues with higher use entities, the TWDB provided corrected location information for those points that showed water use over 500 acft/yr (48 locations). All other points that plotted incorrectly were removed, representing less than 5% of the total statewide manufacturing demand. The SE locations did not appear to have any location discrepancies. The updated point file with reconciled locations was used to distribute county-wide manufacturing and steam electric needs to individual points by assigning its pro rata share of 2017 water use as compared to 2017 water use of all manufacturing (or steam electric) points within a county. For multiple points located within the grid cell, the prorated needs were aggregated (summed) together and snapped to the grid level.

c. After researching available data for mining, irrigation, and livestock needs, it became apparent that it is not practical to accurately identify the location of these needs beyond the county scale. Better location information is necessary to meaningfully assess the mining, irrigation, and livestock water supply needs for ASR or AR suitability scoring. Therefore, these county-wide needs will not be addressed by this survey. If sponsors with mining, irrigation, and livestock needs desire to evaluate their ASR or AR suitability on a statewide level, they could individually compare the location of their need with the hydrogeological and excess water supply layers created by this survey.

6. The following process was used to merge municipal, manufacturing, and steam electric needs information into grid cells.

   a. Municipal scores were distributed to grid cells that are located (even partially) within the draft DB22 municipal WUG boundary coverage. For grid cells where multiple WUGs exist, each WUG receives a record and score.

   b. Manufacturing and steam electric needs were assigned to coincident grid cells. For grid cells where multiple points exist, the water needs data are summed on a grid cell level (for manufacturing and steam electric layers, respectively) prior to ranking.

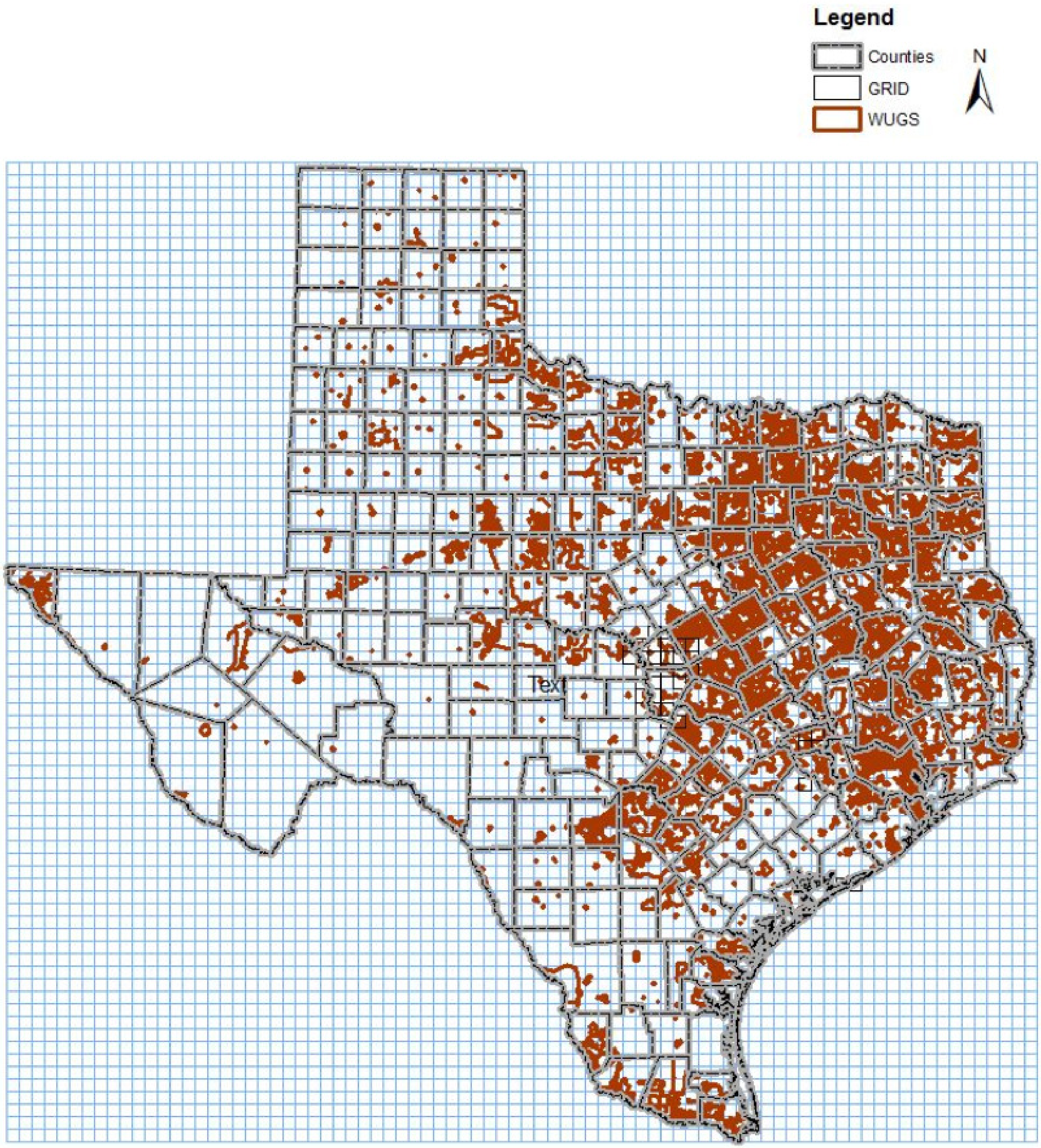

Figure 12. Example of grid, counties, and draft DB22 municipal WUG boundaries (Source: TWDB)

Table 18 includes a list of parameters included in the Water Supply Needs Screening, along with brief descriptions of the attribute table fields. The data source for all parameters is draft DB22 and associated geospatial WUG boundary and/or historical use point files. Proposed rankings are indicated, and bolded parameters are used explicitly in the screening to calculate the water needs score. A detailed description of each parameter is included in **Appendix E**. The parameter values are normalized to a scale from 0 to 1 after weighting is applied. This approach is a consistent technique used for the Hydrogeological Parameter and Excess Water Screenings previously discussed.

A step wise user's manual was prepared to list procedures needed so that the TWDB can update the screening to adapt and readily accept data from future planning cycles. This excel-based spreadsheet is delivered alongside this report.

Table 18. Parameters for Water Supply Needs Screening

Field name ID	Alias grid ID	Notes
WUG_Name	WUG Name 1	Feature datasets will be provided for discrete Municipal (MUN), Steam Electric (SE), and Manufacturing (MANU) WUG entities
WUG Entity ID	Draft DB22 WUG Entity ID	WUG Names and Entity_ID have one-to-one relationship
Active_WUG	Grid cells coincident with active WUG	Grid contains WUG – 1; Grid does not contain WUG- 0. This field is to ease integration for Final Suitability Rating
Use_Type	Use Type (WUG category in State Water Plan)	MUN, SE, MANU
Water_Needs_Max (and associated Water_Needs_Max_S)	Water Needs (Maximum 2020-2070 period)	Ranking of 0 to 1 as follows: Needs ≥ 35,000 acft/yr – 1 Needs ≥ 15,000 and < 35,000 acft/yr – 0.75 Needs ≥ 2,500 and < 15,000 acft/yr – 0.5 Needs ≥ 500 and < 2,500 acft/yr – 0.25 Needs < 500 acft/yr – 0
First_Needs_Decade (and associated First_Needs_Decade_S)	First Decade of Need	Ranking of 0 to 1 as follows: 2020-2030 – 1, 2040 – 0.75, 2050 – 0.5, and 2060-2070 – 0.25
Unmet_Needs	WUG has unmet needs[1] identified in RWP	Yes – 1, No – 0
Per_Volume (and associated Per_Volume_S)	Needs as Percent Volume of Demand (Maximum 2020-2070 period)	Ranking of 0 to 1 as follows: <10% – 0.25 ≥10 and ≤25% – 0.5 >25 and ≤ 40% – 0.75 >40% – 1
Existing_Supply	Existing Supply	GW – 1, SW – 0.25, both – 0.5
Sole_Supply	Sole Supply	Yes – 1, No – 0
Length_of_Need	Length of a Need	< 20 Yrs – 0, ≥ 20 Yrs – 1
Recommended_ WMS_ASR	ASR Recommended as WMS in Plan	Yes – 1, No – 0
Existing_ASR	Existing ASR Present	Yes – 1, No – 0

Field name ID	Alias grid ID	Notes
Recommended _WMS_AR	AR Recommended as WMS in Plan	Yes – 1, No – 0
Existing_AR	Existing AR Present	Yes – 1, No – 0
Water_Needs_Score	Water Supply Needs Score	Based on attributes above and solely related to needs. Scores and weights to be assigned and verified in TWDB workshop.

[1] Unmet needs are water supply needs identified in draft DB22 that do not have enough supplies identified through recommended water management strategies to fully address the need or shortage.

Note: The data source for all parameters shown above as draft DB22 is associated with the Draft State Water Planning Database. The TWDB draft DB22 municipal WUG coverage was used for municipal users. For manufacturing and steam-electric users, historical water use point files provided by the TWDB were used.

Parameters shown above in **Bold** text are used to calculate the Water_Needs_Score, as discussed in the Scoring section.

WUG = water user group; WMS = water management strategy; acft/yr = acre-feet per year; RWP = regional water plan; draft DB22 = TWDB Draft State Water Planning Database

Assumptions, challenges, and limitations

The following are some of the key assumptions identified during development of the Water Supply Needs Screening.

- The draft DB22, associated WUG boundaries, and historical use files for manufacturing and steam electric users were used as a basis for evaluating water supply needs for the Water Supply Needs Screening. It is anticipated that minimal changes in draft DB22 data will occur for final DB22 data used to develop the 2022 State Water Plan.
- Excluded manufacturing and steam electric points described previously are not anticipated to have a relevant impact on the statewide survey.

One challenge for the use of grid cells is spatially distributing the needs and demands for the WUGs developed from the draft DB22 data and applying the distributed data to the grids across the State. The draft DB22 database was created for a purpose different than for use in this survey. For this reason, some county-wide demands such as livestock, irrigation, mining, and municipal county-other, were not included because there is no locational information to distribute them. As currently formulated, the screening should not seek to provide a level of refinement beyond that which is available on the regional water planning level.

ASR or AR projects are regularly used to augment supplies during peak or high seasonal water use conditions when needed to boost overall supply capacity. The length of need, based on draft DB22 drought of record future conditions presented on a decadal basis, does not account for this operational strategy, which reduces costs over long term by providing system flexibility and demand management. Seasonal needs are system-specific and beyond the scope of this project. Data are unavailable from TWDB or other publicly-available sources to assess peaking potential consistently across the state, and for this reason, are not included in this survey.

The water needs from draft DB22 include needs for steam electric that might be closing, are now closed, or for future projects that are no longer actively being considered. It was decided to leave these needs in the screening for consistency with draft DB22.

It is important to balance the statewide screening needs at a level appropriate to provide guidance to regional water planning groups and other entities in evaluating ASR or AR suitability.

Data sources

The data sources that were used to evaluate water supply needs include the following.

- Draft DB22;
- TWDB-provided shapefile (2022WUGs) associated with regional water planning
- TWDB-provided manufacturing shapefile associated with Water Use Survey responses received by manufacturing water users in 2017
- TWDB-provided Steam_Electric_Power_Plants_2017 shapefile associated with Water Use Survey submitted by Steam Electric water users in 2017

Data gaps

The following are the key data gaps identified during the development of the Water Supply Needs Screening.

- County-other municipal and non-municipal WUG needs (Irrigation, Livestock, and Mining) are not included in the Water Supply Needs Screening.
    - Water supply needs for these WUGs are presented in the draft DB22 on a county-wide level. The scoring of these county-wide needs cannot be meaningfully assessed for inclusion in the screening since location information is not readily available other than on a county-level basis and project sponsor information to build such an ASR or AR project is challenging to assess.
    - If in the future, irrigation, mining, or livestock interests desire to pursue ASR or AR with TWDB financing, the screening datasets could be revisited and customized accordingly.

Scoring

The scoring of parameters at the grid-level was considered to approximate the level of data available for the screening. After consulting with the TWDB, three parameters were selected for scoring (bolded in **Table 18**) to align with HB 721: maximum water supply need (from 2020-2070), first decade of need, and needs as a percent of total volume of demand. Additional draft DB22 parameters considered useful for evaluating ASR or AR project feasibility and helpful in a future phase of this screening, were included in the screening although they were not used as parameters for scoring or weighting.

The parameters and weights used to calculate a needs score is shown in **Table 19**. A needs score was calculated for each grid cell with municipal, manufacturing, or steam electric needs greater than 500 acft/yr. Some parameters that did not factor in the water needs score may be important for stakeholders and regional water planning consideration. These parameters are included in **Table 20** and will be included in the screening to allow reviewers to add subjective factors or parameters most relevant to the region to the scoring of water supply needs. Furthermore, the accompanying geodatabase has a blank field to allow regional planning groups to calculate parameters that they deem most relevant to the region related to needs and relative suitability for ASR or AR.

Table 19. Parameters recommended for use in calculating a Wate Needs Score

	WUG entity ID	Active WUG	Water_Needs _Max	First_Needs _Decade	Per_ Volume	Water_Needs _Score
Preliminary Weighting[1]			0.33	0.34	0.33	
Score			0 (low) 1 (high)	0.25 (low) 1 (high)	0.25 (low) 1 (high)	Calculated (0-1)

[1]Final weightings to be confirmed during workshop.
WUG = water user group

Table 20. Additional parameters that could be used by stakeholders as a polishing step in evaluating Water Needs Score

	WUG entity ID	Active WUG	Unmet Needs	Length of Need	Sole Supply	ASR_Rec WMS	Existing ASR	AR_Rec WMS	Existing AR
Score			0 (no) 1 (yes)	0 (<20 yrs) 1 (>20 yrs)	0 (no) 1 (yes)	0 (no) 1 (yes)	0 (no) 1 (yes)	0 (no) 1 (yes)	0 (no) 1 (yes)

WUG = water user group; WMS = water management strategy; yrs = years

Results

The results of the Water Supply Needs Screening serve as a guide for regional water planning stakeholders. **Figure 13** shows the scoring results for municipal needs. There were 624 grid cells that showed municipal water needs, some of which reported needs for multiple municipal users were service areas overlapped. There are municipal needs identified throughout Texas; however, the highest scoring needs generally are along the Interstate Highway 35 (IH 35) corridor from Dallas-Fort Worth Metroplex down towards San Antonio, near Houston, and affect water supply utilities serving those areas. Municipal needs also score highly in South Texas, including Hidalgo, Willacy, and Cameron counties.

Figure 14 shows manufacturing needs scores throughout Texas. There were 203 grid cells that showed manufacturing water needs. Of these, 55 cells received scores based on needs exceeding 500 acft/yr. All 7 cells that reported manufacturing needs exceeding 10,000 acft/yr were located along the Gulf of Mexico coastline. There are 32 grid cells that show needs scores exceeding 0.75, and these are scattered throughout Texas and with no discernible trend observed. A few clustered areas are located in the Beaumont/Port Arthur and Corpus Christi areas.

Figure 15 shows steam-electric needs scores throughout Texas. Fifty grid cells showed steam-electric water needs. Of these, only 36 received scores based on needs exceeding 500 acft/yr. There are 20 grid cells that show need scores that exceed 0.75, and similar to the manufacturing needs these are scattered throughout Texas and with no discernible trend observed.

Summary of Water Supply Needs

The water supply needs for the three user categories were combined in a final excess water grid in areas where multiple excess water supplies were present.

The Water Supply Needs Screening scores were categorized for each grid cell with water needs identified (in **Figure 16**). Threshold values used for water supply needs divided suitability into classes of “low”, “medium”, and “high” as follows:

- Low– Excess Water Score < 0.5
- Medium– Excess Water Score 0.5 to 0.7
- High– Excess Water Score > 0.7

About 20% of the grid cells (or 645) scored low suitability, 17% (or 527 cells) scored medium suitability, and 12% (or 365 cells) scored high suitability for water supply needs. The remaining 51% (or 1,623 cells) did not have water supply needs identified for the water user categories evaluated.

This actual values were used in the Final Suitability Rating, discussed later, to evaluate ASR or AR project suitability.

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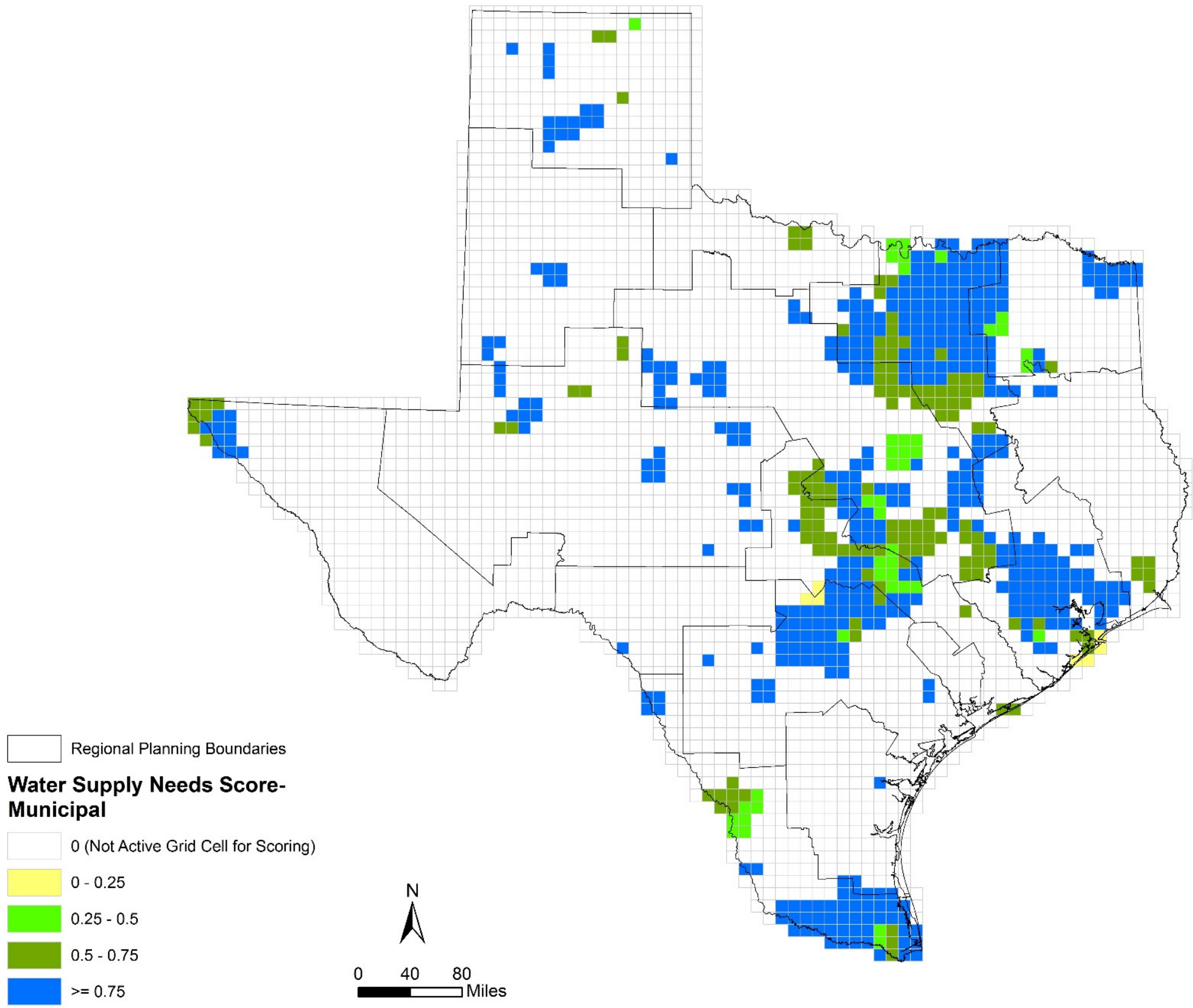
Regional Planning Boundaries
Water Supply Needs Score-Municipal
0 (Not Active Grid Cell for Scoring)
0 - 0.25
0.25 - 0.5
0.5 - 0.75
>= 0.75
N
0 40 80
Miles

Figure 13. Municipal water needs scoring results

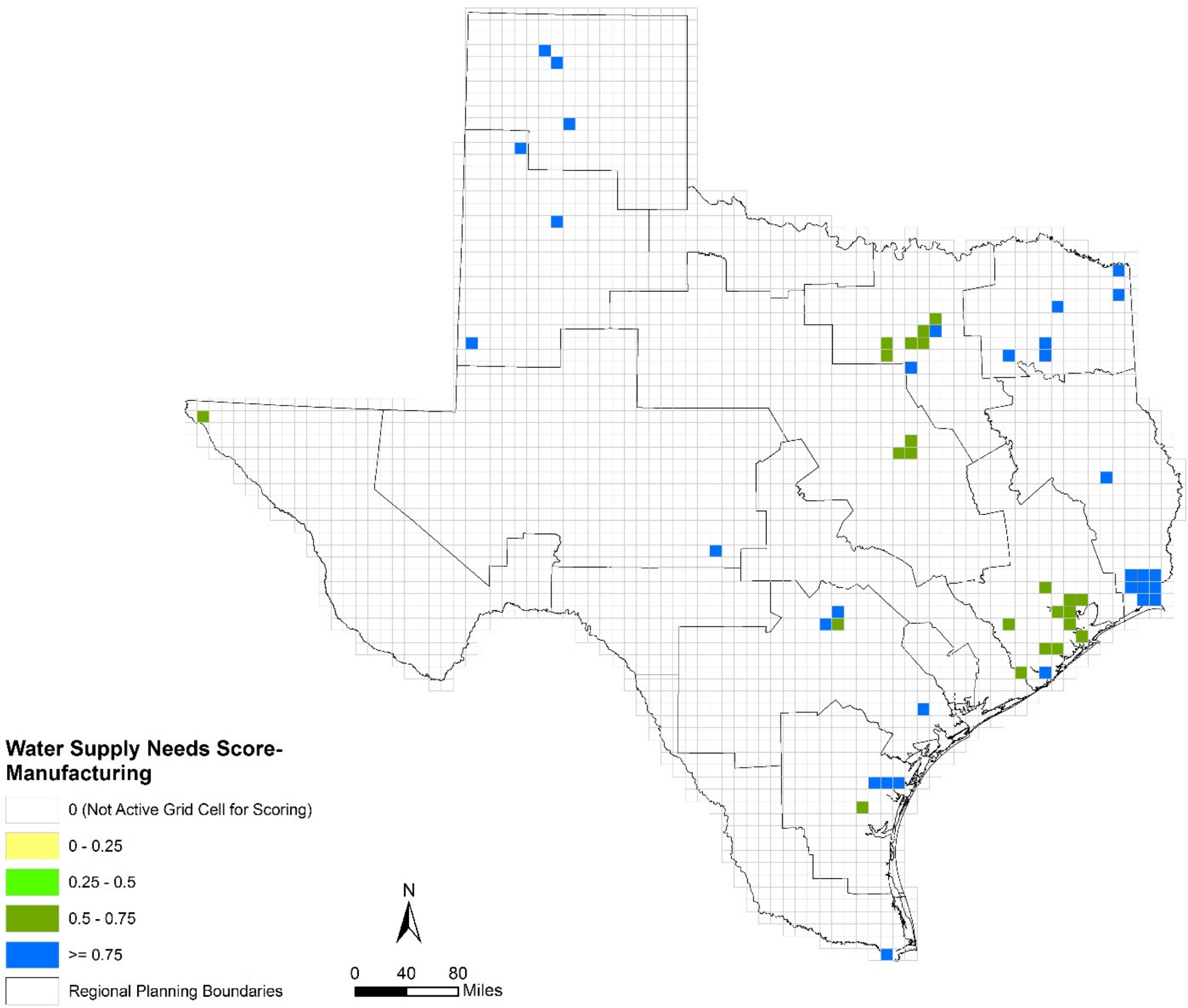

Figure 14. Manufacturing water needs scoring results

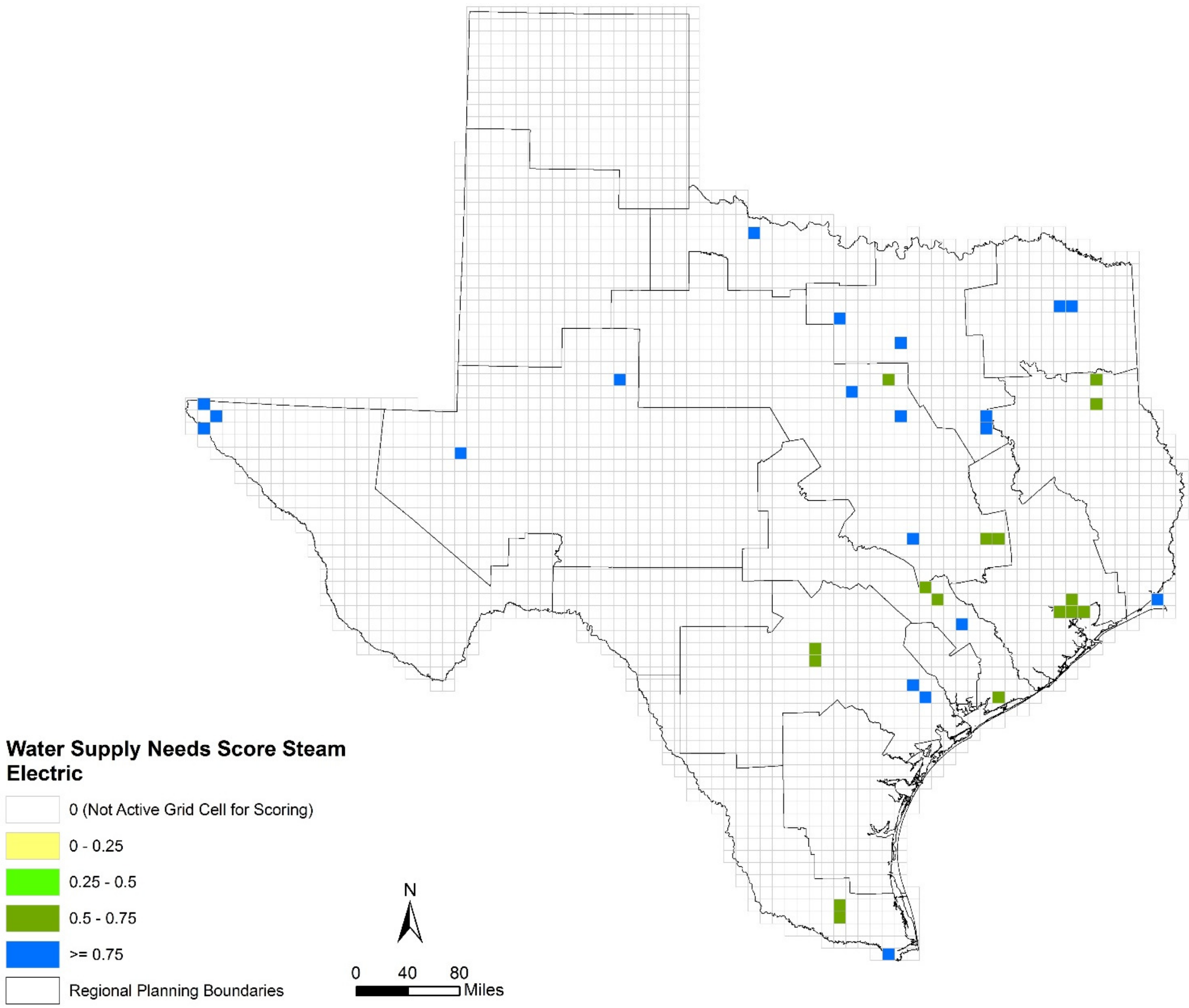

Figure 15. Steam electric water needs scoring results

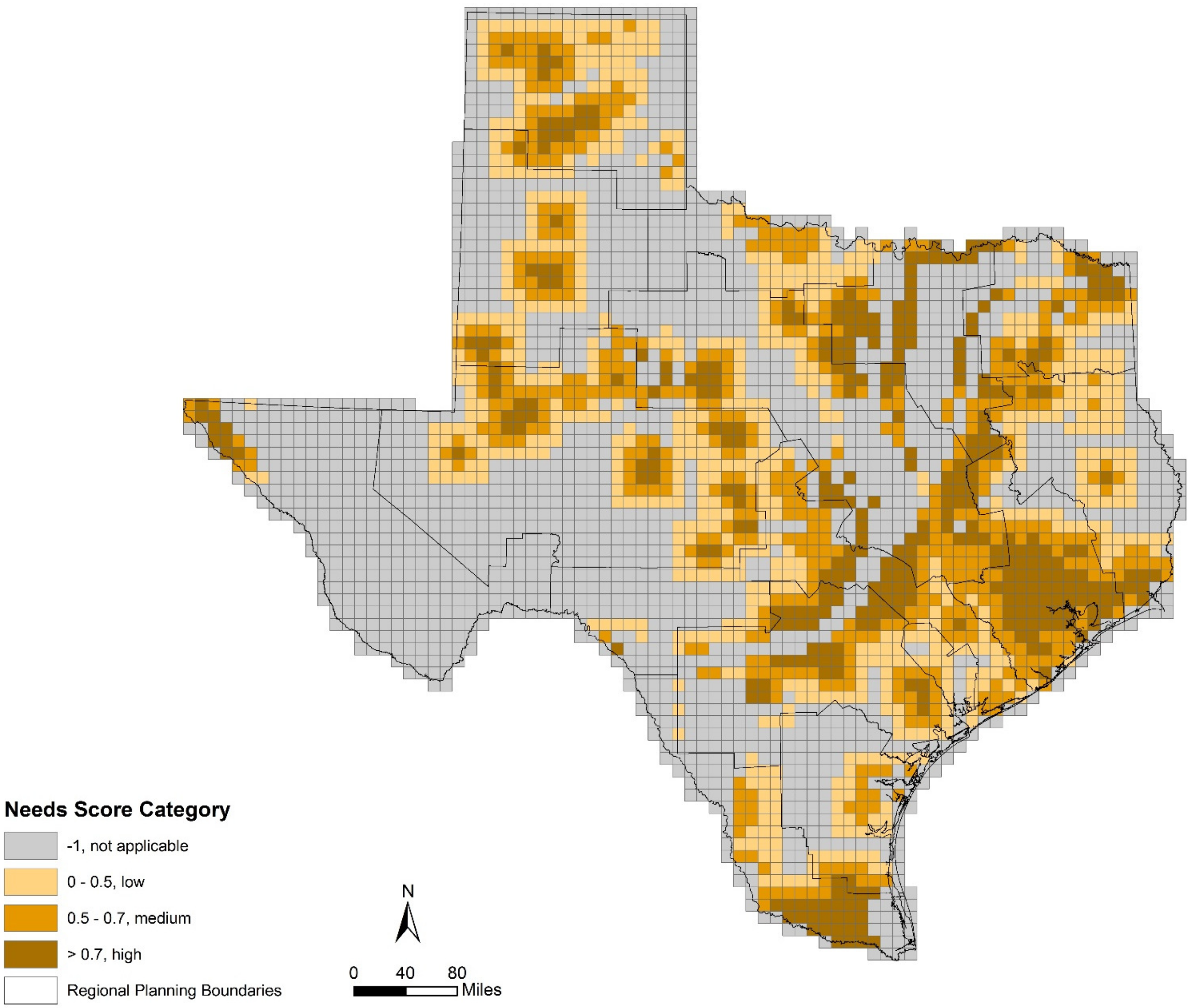

Figure 16. Water Supply Needs Screening Score Categories

Future Work

This survey provided a statewide evaluation of water supply needs. The following items were identified throughout the development of the Water Supply Needs Screening and the TWDB to update and refine the screening in future work efforts to focus in particular areas of high interest.

- There are large gaps in coverage for West Texas and the Panhandle needs due to a lack of specific information on location of current and future use for county-wide municipal, irrigation, and mining users at a level of detail that could be accurately applied on the grid cell level.
- Additional data and tools may be useful for future ASR or AR evaluation, particularly in areas relying on a single supply and for which water management strategies have not been identified in draft DB22 to fully meet needs.
- In many cases, developing an ASR or AR project may be challenging and impractical especially in widespread areas of need in the absence of project sponsors.

Final Suitability Rating

Objective

The objective of the Final Suitability Rating is to integrate results from the three screening geodatabases related to hydrogeological parameters, excess water, and water supply needs into a final suitability rating. This rating will serve as a statewide survey to identify the relative suitability of various major and minor aquifers for use in ASR or AR projects.

Approach

The Final Suitability Rating draws upon scores determined in the previous hydrogeological parameter, excess water, and water supply needs geodatabase datasets and calculates an overall relative suitability score for each grid cell identified for ASR or AR potential in the Hydrogeological Parameter Screening based on its proximity (distance) to excess water and water supply needs.

The general approach used to estimating Final Suitability Rating for ASR or AR was as follows.

1. Consider hydrogeological parameter scores identified in the Hydrogeological Parameter Screening and select the highest scoring aquifer by cell for final suitability scoring.

2. Combine scores from the Excess Water and Water Supply Needs Screenings and develop an approach to score the distance of these features relative to suitable ASR or AR locations identified in the Hydrogeological Parameter Screening.

3. Combine the parameter scores to create a Final Suitability Rating for ASR and AR. Each grid cell has a single score layer for the screening.

4. Use the magnitude of the final suitability rating to rank regions according to three general categories of relative suitability to identify those that are more suitable than others. The three categories are "less," "moderately," or "most" suitable.

Combining Parameters

Methodology

The Final Suitability Rating was developed to evaluate excess water and locations of needs *from* potential ASR or AR locations identified in the Hydrogeological Parameter Screening, in an effort to align with HB 721 and survey objectives to identify the relative suitability of aquifers for ASR or AR projects. The scores from the three previous screenings were consistently normalized to 1 to support ease of integration and avoid bias in the Final Suitability Rating. For locations where multiple major or minor aquifers exist, the highest scoring aquifer from the Hydrogeological Parameter Screening (for ASR or AR respectively) was identified by row- column grid cell (RCID) with the aquifer noted in the Final Suitability Rating. Although the highest aquifer value is used for the Final Suitability Rating, the Hydrogeological Parameter Screening includes results for all major and minor aquifers coincident with the grid cell.

Table 21 lists the parameters that are included in the Final Suitability Rating, along with descriptions of the attribute table fields and data source(s). The Final Suitability Rating calculates a relative suitability score for cells where major and/or minor aquifers are present, according to the approved grid. Two feature classes (one for ASR and the other for AR) are compiled in a geodatabase at grid-level resolution consistent and coincident with other screenings in cell size and extent. The four-digit aquifer classification code used is consistent to the identifier used in the Hydrogeological Parameter Screening.

Multiple combinations exist for excess water and water needs coincident or in close proximity to ASR or AR grid cells. For this reason, a distance approach was used to pre-select the most preferable excess water or water needs score as follows.

1. Excess water or needs scores from cells coincident and up to two cells away from a given ASR or AR grid cell (identified in the Hydrogeological Parameter screen) are considered.

Weights are applied to excess water or needs scores moving directly north-south, or east-west, as follows.

a. 1 = excess water or needs cell coincident with ASR or AR cell;

b. 0.64 = excess water or needs cell is one cell away from ASR or AR cell;

c. 0.29 = excess water or needs cell is two cells away from ASR or AR cells;

d. For diagonal (corner) cells, the weights are slightly less than the adjoining cells in vertical and horizontal plane, with a minimum weight of 0.25.

A graphical depiction of the distance weights is shown in **Figure 17,** which affects the given ASR or AR grid cell and surrounding 24 cells within an approximate 20-mile buffer zone. The grid cells are precisely 50,000 feet by 50,000 feet, resulting in a centroid distance of 9.5 rather than 10 miles for adjoining cells, which affects the weighting.

2. Recall from Excess Water Screening, that excess water scores were estimated for surface water, reclaimed water, and/or groundwater at each cell. If more than one excess water score was present in a cell, the scores were summed, in order to capture the potential added benefit of having multiple scores. So this excess water sum could theoretically be as high as 3, although in practice the maximum sum was 2.75. In order to normalize this sum to a 0 to 1 scale, an approach was taken that attempted to achieve two objectives:

   a. Reward scores of greater than 1.0, which mark a potential benefit of having multiple source types.

   b. Avoid penalizing individual scores that are close to 1.0, since they may represent a good source, even if only a single type.

   The approach uses a two-part linear normalization curve that gives a normalized score between 0 and 0.75 for sums between 0 and 1.0. So an excess water sum of 1.0 results in a normalized score of 0.75. For sums greater than 1.0, the normalized score is increased linearly up to 1.0.

0	0	0	0	0	0	0
0	0.25	0.25	0.29	0.25	0.25	0
0	0.25	0.50	0.64	0.50	0.25	0
0	0.29	0.64	**1**	0.64	0.29	0
0	0.25	0.50	0.64	0.50	0.25	0
0	0.25	0.25	0.29	0.25	0.25	0
0	0	0	0	0	0	0

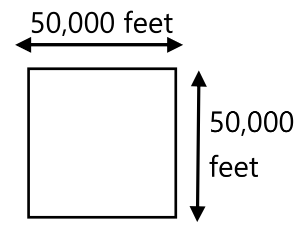

Figure 17. Distance weights applied to excess supply and water needs to select the best excess supply and needs combination by grid cell for final suitability rating

3. The same approach was taken for the normalized needs score, based on the sum of the three contributing need categories. The approach uses a two-part linear normalization curve that gives a normalized score between 0 and 0.9 for sums between 0 and 1.0, and needs sum of 1.0 results in a normalized score of 0.9. For sums greater than 1.0, the normalized score is increased linearly up to 1.0. The difference between the "pivot point" for excess water versus needs was based on an inspection of the distribution of the sums. The needs distribution had many more of the sums clustered at less than 1.0.

4. The maximum Excess_Water_Score and maximum Needs_Score within the buffer area are then selected and assigned to the respective ASR or AR RCID. The cell for selected score is recorded in Excess_Water_ID and Needs_ID, respectively, in addition to the distance of RCID centroid to centroid of the cell with the maximum excess water score and maximum needs score.

5. A Final_ASR(AR)_rating is then calculated based on three parameters: Highest_ASR(AR)_Hydro_Score, Excess_Water_Score, and Needs_Score each receiving equal weights.

   This method achieves two objectives considered important for ASR or AR relative suitability:

   a. It identifies hydrogeological areas suitable for ASR or AR that have multiple excess supply sources and/or multiple water user needs to provide flexibility in project planning and identify potential regional partnership opportunities, while still supporting with a favorable score areas that indicate good hydrogeology, a suitable excess water supply, and need even if they do not have multiple supply sources or water users. Excess supply sources can be used conjunctively (especially in cells where unappropriated water, reservoirs, and available groundwater exist), and this benefit is accounted for in scores that exceed 0.75. For areas with multiple water user groups showing a need, potential regionalization opportunities are accounted for in scores that exceed 0.9.

b. It does not limit excess water supplies or needs to those cells that are coincident with the aquifer cell being considered. However, it does score nearer cells more favorably in a relative sense, thus recognizing the increased difficulty and/or cost in conveying excess water or supplying a water need over a longer distance.

Table 21. Parameters for Final Suitability Rating for aquifer storage and recovery (ASR) and aquifer recharge (AR)

Field name	Description	Notes	Data source
RCID	Row Column ID	Row column unique identifier	
Highest_ASR_Hydro_Score or Highest_AR_Hydro_Score	Maximum ASR (AR) score, for all aquifers coincident with grid cell	Score 0-1 -1: no major/minor aquifer	From Hydrogeological parameter screen
Highest_Scoring_Aquifer_ID	ID of the highest hydro scoring aquifer	Four digit aquifer code-Appendix C	
Excess_Water_ID	Cell ID for Excess Water Source	Cell ID that corresponds with Excess_Water_Score. This is the maximum of 24 cell buffer around the cell of interest (RCID)	From Excess Water screen
Excess_Water_Sum	Excess Water Score, Sum of Sources	Excess Water Score from final grid Excess Water Screening geodatabase	
Excess_Water_Normalized_Score	Excess Water Score (normalized score)	Score 0-1 for best (maximum score) within 24 cell buffer around RCID calculated as: Excess_Water_Score = Excess_Surface_Water_Score + Reclaimed_Score + Excess_GW_Water_Score normalized as described above x respective distance factor (Figure 15)	Calculated in Final Suitability Rating
Excess_Water_Distance	Distance from ASR grid cell to Excess Water	Miles. Score from 0 – 26.8 miles based on centroid, for cell associated with Excess_Water_ID that scored the best.	
Excess_Water_Distance_Weight	Weight to be applied due to distance	Score 0-1 based on distance to Excess Water	
Excess_Water_Score	Distance-Weighted Excess Water Score	Calculated by multiplying Excess_Water_Normalized_Score * Excess_Water_Distance_Weight	
Needs_ID	Cell ID for Water Need	Cell ID that corresponds with Needs _Score. This is the maximum of 24 cell buffer around the cell of interest (RCID)	From Water Supply Needs screen

Field name	Description	Notes	Data source
Needs_Sum	Water Needs Score, Sum of all Needs	Water Needs Score from final grid Water Supply Needs Screening geodatabase	From Water Supply Needs screen
Needs_Normalized_Score	Water Needs Score (normalized score)	Score 0-1 for best (maximum score) within 24 cell buffer around RCID based on the sum of Scores from Municipal, Manufacturing, and Steam Electric feature classes normalize as described above x distance factor (Figure 1)	Calculated in Final Suitability Rating
Needs_Distance	Distance from ASR grid cell to Needs	Miles. Score from 0 – 26.8 miles based on centroid, for cell associated with Needs_ID that scored the best.	
Needs_Distance_Weight	Weight to be applied due to distance	Score 0-1 based on distance to Water Needs	
Needs_Score	Distance-Weighted Needs Score	Calculated by multiplying Excess_Water_Normalized_Score * Excess_Water_Distance_Weight	
Final_ASR_rating or Final_AR_rating	Integrates aquifer, excess water and needs scores, incl. intervening distances.	Score 0-1 (flags: -2, -3, or -4 described below). Final Suitability Rating = Highest_ASR(AR)_Hydro_Score*0.34 + Excess_Water_Score*0.33 + Needs_Score* 0.33	

RCID = row and column id for grid cells

Assumptions, challenges, and limitations

The following assumptions and challenges were identified during development of the Final Suitability Rating:

- Scoring coverage is constrained to only those grid cells corresponding to major or minor aquifers (consistent with the Hydrogeological Parameter Screening);
- Excess supplies or needs located in excess of two cells away from ASR or AR cells do not contribute to a cell's score. This was an assumption developed during this survey, recognizing that aquifer, excess supplies, and needs shouldn't be confined to coincident grid cell only. An estimate of 20 miles (2 grid cells) was determined to be a reasonable estimate for various sized water users, recognizing that some sponsors may consider ASR

or AR projects over larger distances. These larger distances are not included in the Final Suitability Rating.

    - If no excess water sources are identified within a two cell buffer from an ASR or AR cell, a value of "-1" is included in the excess supply fields (Excess_Water_Score; Excess_Water_ID, and Excess_Water_Distance).
    - If no needs are identified within a two cell buffer from an ASR or AR cell, a value of "-1" is included in the needs fields (Needs_Score; Needs_ID, and Needs_Distance).

- This screening assumes that all key parameters (aquifer, excess water, and needs) are present in the vicinity of one another to be scored, since all are considered important for ASR or AR projects to occur except in cases where ASR is considered for seasonal peaking operations or other purposes not addressed by this survey. If a given ASR or AR cell does not have either excess supplies or needs within a distance of two cells (approximately 20 miles) the following flags are placed in the Final_ASR_rating (or Final_AR_rating):
    - -2 no excess water identified
    - -3 no need identified
    - -4 neither excess water or need identified
- The data gaps, challenges, and limitations associated with each of the three screenings are also relevant to the Final Suitability Rating, which used scores developed from those datasets. For instance, the Needs geodatabase does not include projected water needs for Mining, Irrigation, and Municipal County-Other users for which spatial data is not available from the draft DB22 other than at a county-wide level. Some of these categories represent significant regional needs (such as irrigation needs in the Panhandle and West Texas) that are not included in the screening. See data gaps map below.
- The Final Suitability Rating presents the best scoring excess water supplies and needs located within approximately 20 miles from AR or ASR suitable locations based on the Hydrogeological Parameter Screening. The following conditions associated with ASR or AR relative suitability are beyond the scope of the statewide survey and not considered in the screening:
    - Longer distances to excess supplies or needs (>20 miles) may be considered viable by a project sponsor. These opportunities are not included in the screening.

- Site-specific considerations, including water compatibility, geochemical aspects of water storage, and other factors that are essential considerations prior to project implementation.
- Integration, system operations, treatment, and seasonal water use ASR or AR applications. This level of analysis is beyond the scope of the statewide screening.
- Site- and system-specific water quality evaluations are needed to understand source water compatibility, blending, and/or specific water quality parameter interaction before combining with existing supplies or systems. For instance, naturally occurring arsenic in aquifer minerals need to be evaluated and carefully considered as these can be released during introduction on new waters into storage. A study prepared by TCEQ (Reedy, 2018) that assesses arsenic in groundwater and water supply systems in Texas should be considered, in addition to other sources and field testing results as the next phase of study prior to implementing AR or ASR projects.

Data sources

Results from the Hydrogeological Parameter, Excess Water, and Water Supply Needs Screenings of this survey were used for the Final Suitability Rating.

Data gaps

The Final Suitability Rating generally provides good statewide coverage; however, there are locations scattered throughout the state that do not show water needs for specific municipal, manufacturing, and steam-electric water users as seen in **Figure 18**. These areas have county-level needs represented in draft DB22 that are not included in the screening, due to a lack of spatial information on where these needs occur. There are 920 cells (out of 3,160 total grid cells statewide) for which excess supplies do not exist, representing 29 percent of the statewide coverage. There are 1,623 cells (out of 3,160 total grid cells statewide) for which water supply needs do not exist, representing 51 percent of the statewide coverage.

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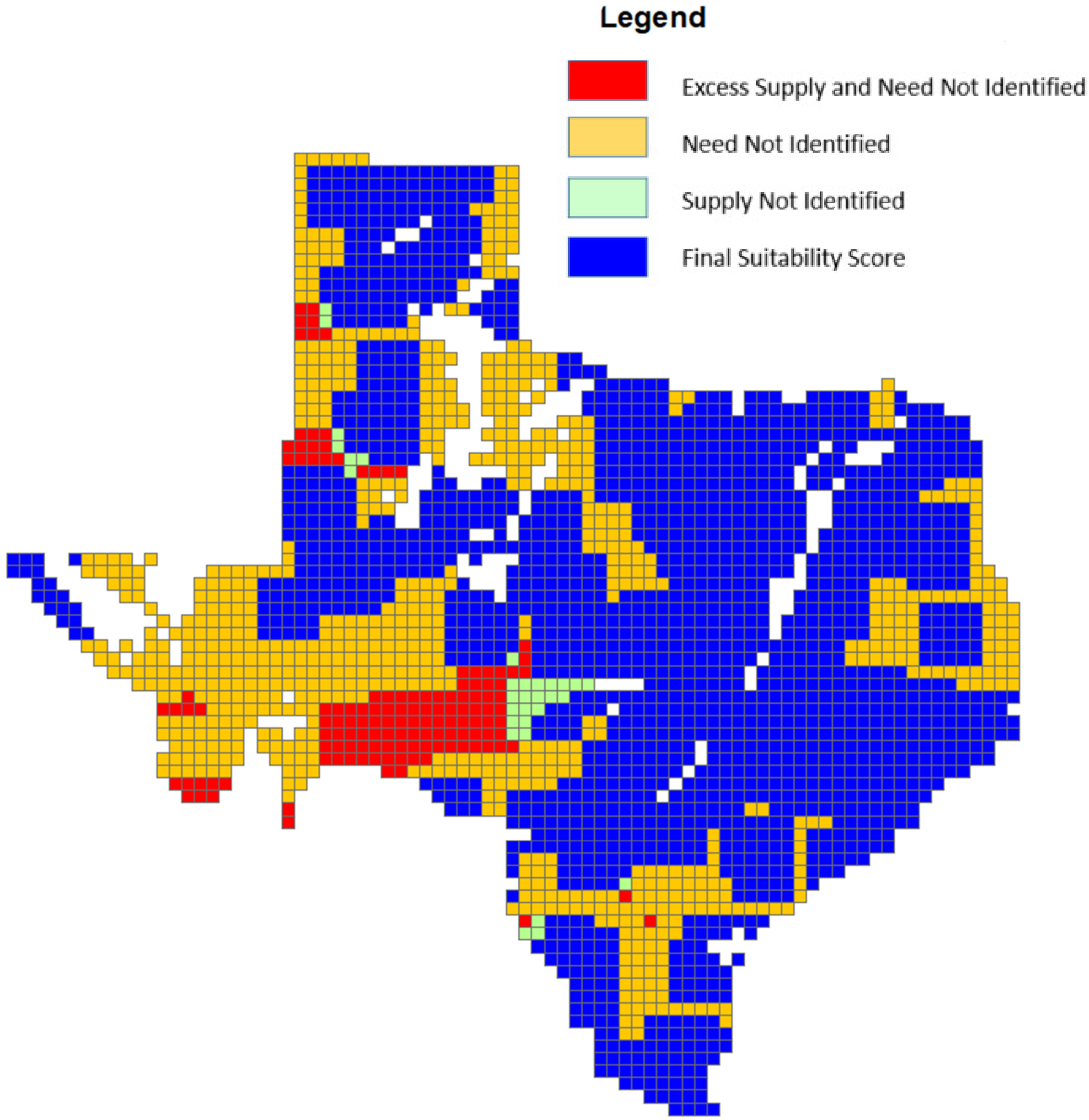

Figure 18. Summary of grid cell details affecting Final Suitability Rating

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Scoring

The final suitability rating is calculated for ASR and AR cells using the following parameters.

- 'Highest_ASR_Hydro_Score' (or Highest_AR_Hydro_Score)
- 'Excess_Water_Score'
- 'Needs_Score'

The scores were almost weighted equally, with 'Aquifer_Score', 'Excess_Water_Score', and 'Needs_score' respectively weighted at 0.34, 0.33, and 0.33'. One weight needed to be 0.34 so the sum could equal 1. The statewide final suitability ratings range from 0 to 1, with 1 being the highest suitability rating based on the parameters of this survey's hydrogeology, excess water, and water needs mapping.

Parameters and weights used to calculate the final suitability ratings for ASR or AR are summarized in **Table 22**.

Table 22. Parameters recommended for use in calculating a Final Suitability Rating for ASR or AR

Field name	Preliminary Weighting	Score
RCID	--	--
Highest_ASR_Hydro_Score or Highest_AR_Hydro_Score	0.34	0 (low) 1 (high)
Highest_Scoring_Aquifer_ID	--	--
Excess_Water_ID	--	--
Excess_Water_Sum	--	--
Excess_Water_Normalized_Score	--	--
Excess_Water_Distance	--	--
Excess_Water_Distance_Weight	--	--
Excess_Water_Score	0.33	0 (low) 1 (high)
Needs_ID	--	--
Needs_Sum	--	--
Needs_Normalized_Score	--	--
Needs_Distance	--	--
Needs_Distance_Weight	--	--
Needs_Score	0.33	0 (low) 1 (high)
Final_ASR_rating or Final_AR_rating	--	--

Overall Findings and Conclusions

Figure 19 shows the final suitability rating for ASR after intersecting hydrogeology, excess water, and water needs. Of the 2,688 grid cells included in the statewide ASR coverage, 934 (or 35 percent) reported no water need and/or excess supply within about 20 miles (2 grid cells) of the hydrogeological parameter grid cell, which received an ASR hydrogeological score in the first screening. For the remaining 1,754 grid cells (65 percent total statewide grid cells) for which hydrogeology, excess water, and needs were combined, 309 grid cells (or 18 percent) reported most suitable ratings for ASR (>0.7) and 876 grid cells (or 50 percent) reported moderately suitable ASR ratings of 0.5 to 0.7. Final ASR suitability ratings were assigned to all 9 major aquifers and 16 minor aquifers. Six minor aquifers did not receive a score either because the location was coincident with another aquifer that scored more favorably, or because they occurred in areas without excess water and/or needs. The four aquifers with the most widespread coverage included the Carrizo-Wilcox, Gulf Coast, Ogallala, and Trinity aquifers, which combined accounted for nearly 70 percent of the scored cells. This widespread coverage reflects the extent and high productivity of these aquifers combined with the presence of excess water and needs. The highest ASR final suitability ratings (>0.85) were found in the Carrizo-

Wilcox, Trinity, Gulf Coast, and Sparta aquifers. Each of these aquifers had median hydrogeological parameter screening scores that rated in the “high” category. This combined with the presence of major population centers nearby, along with available excess supplies, drives their ratings toward this high value.

Figure 20 shows the final suitability rating by grid cell for AR after intersecting hydrogeology, excess water, and water needs. Of the 2,403 grid cells included in the statewide AR coverage, 894 (or 33 percent) reported no water need and/or excess supply within about 20 miles (2 grid cells) of the hydrogeological parameter grid cell which received an AR score in the first screening. For the remaining 1,509 grid cells (67 percent total statewide grid cells) for which hydrogeology, excess water, and needs were combined, 314 grid cells (or 21 percent) reported most suitable ratings for AR (>0.7) and 799 grid cells (or 53 percent) reported moderately suitable AR scores of 0.5-0.7. Final AR suitability scores were assigned to all 9 major aquifers and 15 minor aquifers. Seven minor aquifers did not receive a score either because the location was coincident with another aquifer that scored more favorably, or because they occurred in areas without excess water and/or needs. The four aquifers with the most widespread coverage included the Gulf Coast, Ogallala, Cross Timbers and Carrizo-Wilcox aquifers, which combined accounted for 57 percent of the scored cells, which indicates that AR cells had more aquifer distribution than ASR. The highest AR final suitability ratings (>0.85) were found in the Brazos Valley Alluvium, Gulf Coast, Ogallala, Carrizo-Wilcox and Hueco-Mesilla Bolsons aquifer outcrops.

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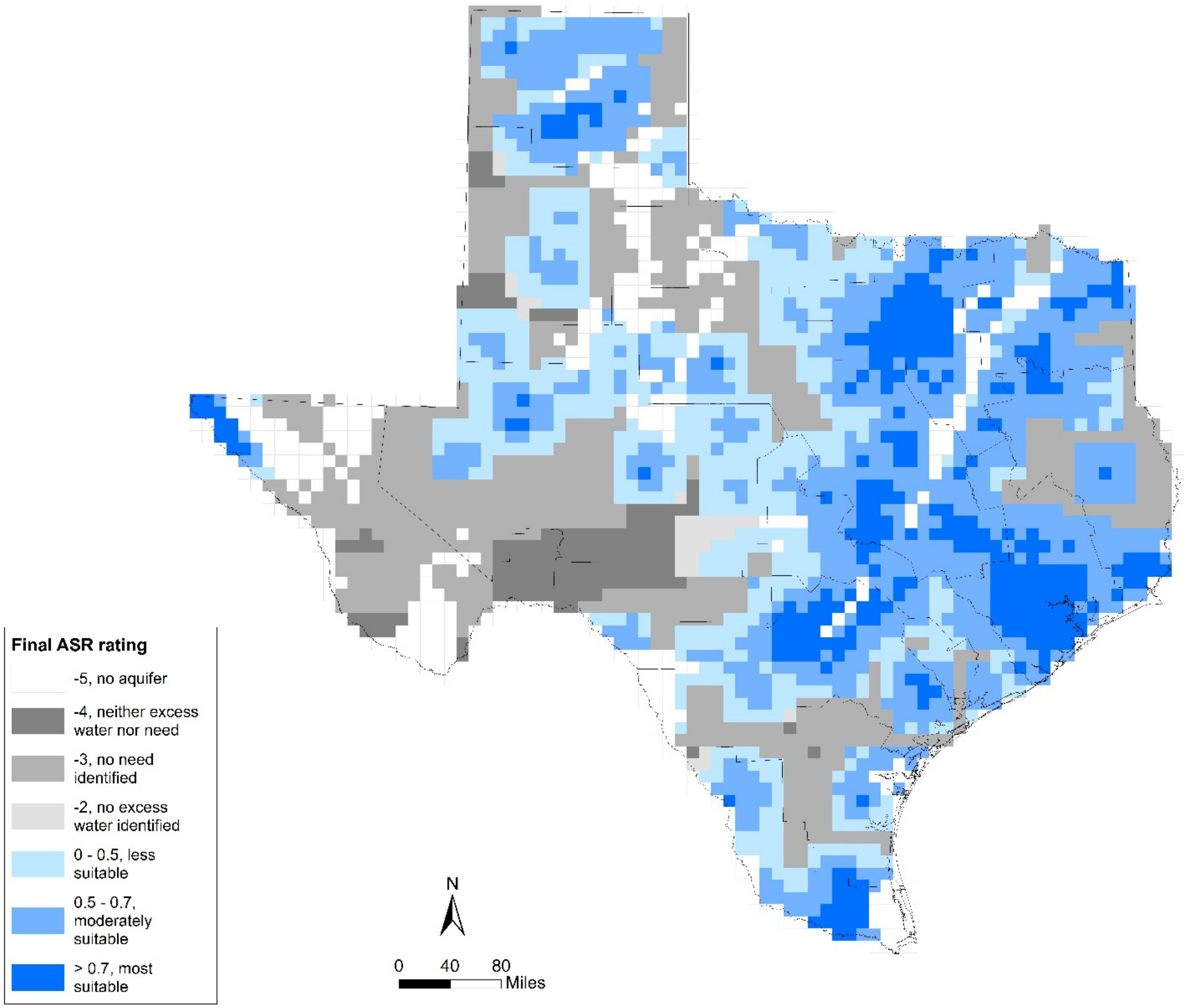

Figure 19. Final Suitability Rating for ASR

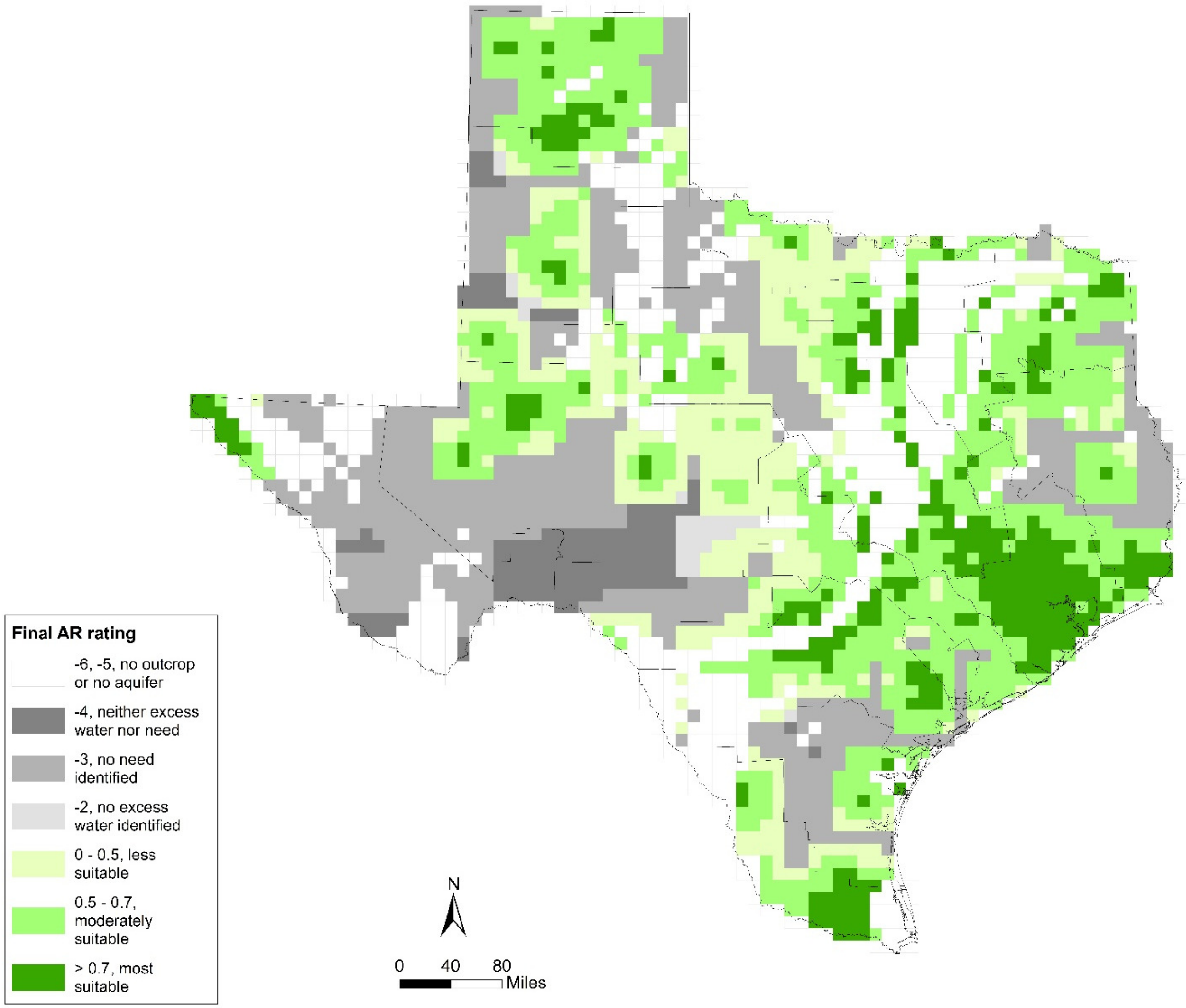

Figure 20. Final Suitability Rating for AR

Future Work

This survey provided a good statewide look at relative aquifers suitability for ASR and AR, including evaluating "project potential" by considering the locations of excess water available storage and water needs to ASR or AR suitable areas based on hydrogeology. In the future, should additional data become available on county-level water needs considered significant, especially is areas where data is absent (grey) in ASR and AR final suitability maps, it may be beneficial to update the screening with such information to have a more complete understanding of ASR or AR suitability across Texas.

Public Data Display

Objective

The objective of this work effort is to allow the public to explore the hydrogeological parameters, excess water, and water supply needs data that went into the Final Suitability Rating without license subscriptions or specialized expertise.

Approach

The results from the four screenings was compiled to develop a final, finished StoryMap to describe the process, method, and results of the statewide ASR and AR survey. A StoryMap is defined as the end result of creating inspiring, immersive stories by combining text, interactive maps, and other multimedia content. StoryMaps allow the organization to publish and share the story within an organization or with everyone in the broader community who might be interested.

The outputs/artifacts from the four screening datasets included map data/layers, graphics, static maps, scoring, and contextual text to go along with each of those artifacts.

Using those artifacts, and map data provided by TWDB, map applications were created to drive the creation of the StoryMap providing interactive map capabilities.

Included are the following ESRI "widgets" in the capabilities of this deliverable.

- Search
- Query
- Bookmarks
- Lat-Long Finder
- Location (requires location services to be turned on)
- Measure
- Pan/zoom
- Administrative Boundaries (Regional Water Planning Groups, Groundwater Conservation Districts, and Legislative Districts)

Viewer

StoryMaps generally uses a visualization template – in this case the Sidecar template was selected. Sidecar blocks are a combination of media and story narrative that fill the display, creating an immersive experience in stories. Sidecars are made up of slides, and each slide has a stationary media panel and scrolling narrative content such as text, media, and maps. As readers scroll through a sidecar, the media panel changes to match the narrative panel content for each slide. With sidecars, one can also highlight map locations and data in the media panel through map choreography and map actions.

Web mapping application is a browser-based map screening for users interested in a more in-depth exploration of the survey data.

Methodology

As noted in the prologue, the methodology includes using existent map layers to create map applications that underlie the StoryMap.

An iterative approach was used with TWDB stakeholders to finalize the functionality and visualization of the elements of the StoryMap. The TWDB was provided a draft of the deliverable and asked to provide feedback and direction to prioritize functionality important for public data display. Multiple sessions to view the versions of the deliverable were conducted in order to get the final product to meet the legislative requirements, meet the needs of the diverse audiences for the information/data, and to be aesthetically pleasing and Section 508 compliant.

Assumptions, challenges, and limitations

The following assumptions were used in the development of the public data display.

- All map layers were provided as needed for the creation of the final deliverable.
- All graphics/colors/logos were to be provided and approved by the TWDB.
- All text was to be approved by the TWDB.

The following are some of the key challenges for the development of the StoryMap and ArcGIS Online content such as the web map application.

- The survey development was constructed under an extremely aggressive schedule in order to meet legislative requirements.

- Agreement was reached early in the survey that the product should be achieved with "out of the box" capabilities and no custom code.

Data sources

The primary data sources that were used include the following.

- Screening geodatabases,

- TWDB provided base maps, including groundwater management districts, regional water planning boundaries, standard map layers for county boundaries, legislative district boundaries.

Data gaps

None

Results

This deliverable was completed and delivered to the TWDB on September 30, 2020.

The deliverable was made public on September 30, 2020.

The StoryMap can be reached at:
https://storymaps.arcgis.com/stories/3f84f43b3b884cfcab7ecfedd979c648

Future Work

The TWDB may want to continue to examine the available ESRI "widgets" to determine whether adding one or some would enhance the usability and/or functionality of the StoryMap.

At this time no additional widgets have been identified and the features included in the StoryMap allow the public to review results and query scores from the screenings developed as part of the statewide ASR and AR survey.

Conclusions

This survey provides support to water planners, engineers, and government officials for consideration of ASR and AR projects in Texas.

The survey results show that Texas has numerous areas suitable for ASR or AR. Final Suitability Rating for ASR or AR is categorized as: less, moderately, and most suitable. A "less" suitability rating does not necessarily preclude the chance of a successful project being developed in the area. The score is rather a relative indicator of statewide favorability.

The framework of source data assembled and analyzed for this survey provides versatility for stakeholders. The hydrogeological parameter, excess water, and water supply needs screenings are standalone products, and each offers value on its own. Source data can be customized as needed according to parameters that are deemed most relevant to each stakeholder. All four screenings provide a strong foundation that future datasets can be added to for update, or as new data becomes available.

References

Ahmadi, M., H. Mahdavirad, and B. Bakhtiari. 2017. Multi-criteria Analysis of Site Selection for Groundwater Recharge with Treated Municipal Wastewater, Water Science Technology 76 (4): 909-919.

Bounds, R. and Lyons, B. (1979). *Existing Reservoir and Stream Management: Statewide Minimum Streamflow Recommendations*. Texas Parks and Wildlife Department, Austin, Texas.

EPA [U.S. Environmental Protection Agency]. ND. Enforcement and Compliance History Online (ECHO). Available online: https://echo.epa.gov/

House Bill 720. 86th Texas Legislature. 2019. Available online: https://legiscan.com/TX/text/HB720/id/2026232/Texas-2019-HB720-Enrolled.html

House Bill 721. 86th Texas Legislature. 2019. Available online: https://capitol.texas.gov/tlodocs/86R/billtext/html/HB00721S.htm

Oliver, W. and V. Kelley. 2014. Modification and Recalibration of the Groundwater Model for Paleozoic Aquifers in the Upper Trinity Groundwater Conservation District- Draft Report: INTERA Inc., prepared for Upper Trinity Groundwater Conservation District, Austin, Texas 130 p.

Pedrero, F. et al. 2011. Application of GIS-based multi-criteria analysis for site selection of aquifer recharge with reclaimed water. Available online: https://www.sciencedirect.com/science/article/abs/pii/S0921344911001649?via%3Dihub

Pyne, David. 2020. Personal communication with Neil Deeds (INTERA) by phone.

Reedy, R. and B. Scanlon. 2018. Assessment of Arsenic in Groundwater and Water Supply Systems in Texas. Prepared for Texas Commission on Environmental Quality.

SURRGO [U.S. Department of Agriculture Soil Survey Geographic Database]. ND. Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627

TCEQ [Texas Commission on Environmental Quality]. ND. *Texas Pollutant Discharge Elimination System (TPDES) Program*. Available online: https://www.tceq.texas.gov/permitting/wastewater

TCEQ. ND. *Water Availability Models (WAM)*. Available online: https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/wam.html

TCEQ, TWDB, and TPWD [Texas Parks and Wildlife Department], Texas Instream Flow Program (TIFP), 2017. Instream Flow study of the Lower San Antonio River and Lower Cibolo Creek. 336 p.

TCEQ, TWDB, and TPWD [Texas Parks and Wildlife Department(], Texas Instream Flow Program (TIFP), 2018. Instream flow study of the Middle and Lower Brazos River. 326 p.

TWDB [Texas Water Development Board]. 2016. *Aquifers of Texas*.

TWDB. ND. *Brackish Resources Aquifer Characterization System (BRACS)* studies. Available online: https://www.twdb.texas.gov/innovativewater/bracs/

TWDB. ND. *Groundwater Availability Models (GAM)*. Available online: https://www.twdb.texas.gov/groundwater/models/gam/index.asp

TWDB. 2021. *2021 Draft Regional Water Plans*. Available online: http://www.twdb.texas.gov/waterplanning/rwp/plans/2021/index.asp

TWDB. ND. *Water Data for Texas*. Available online: https://www.waterdatafortexas.org/reservoirs/statewide

Texas Water Code. Section 27.151, 2015. Available online: https://statutes.capitol.texas.gov/Docs/WA/htm/WA.27.htm

Texas Water Code, Section 11.155, 2019. Available online: https://statutes.capitol.texas.gov/Docs/WA/htm/WA.11.htm

Texas Water Code, Section 11.021, 1977. Available online: https://statutes.capitol.texas.gov/Docs/WA/htm/WA.11.htm

USGS [U.S. Geological Survey]. ND. Digital Elevation Model Program https://www.usgs.gov/core-science-systems/ngp/3dep

Yang, Q. and B.R. Scanlon. 2019. "How much water can be captured from flood flows to store in depleted aquifers for mitigating floods and droughts? A case study from Texas, U.S."," Environmental Research Letters, 14(5).

Attachments to be included in Electronic Submittal

Geodatabases and Supporting GIS Files (Hydrogeological Parameter, Excess Water, Water Supply Needs, and Final Suitability Screenings)

Step-Wise User's Manual to Support Future State Water Plan Updates for the Water Supply Needs Screening

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Appendix A- Literature Review

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Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects

Literature Review

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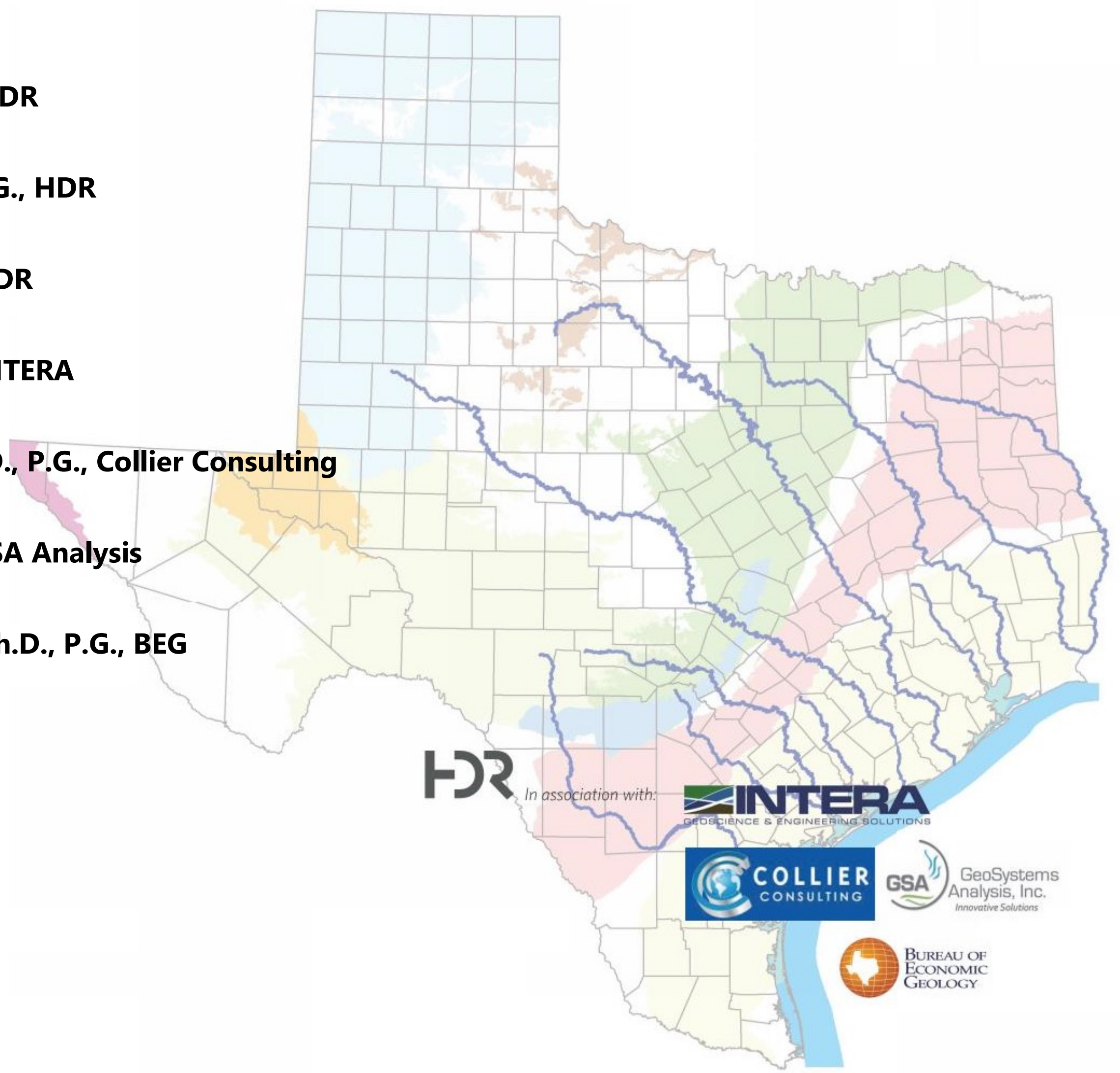

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Background and project objectives

Aquifer storage and recovery (ASR) and aquifer recharge involves the local storage of water within an aquifer for later beneficial use, including water supply purposes. According to the 2017 State Water Plan, ASR projects constitute 1.45 percent of the new water supplies that will be developed in Texas by 2070. In the 2017 State Water Plan there are 43 water management strategies that are recommended or alternative ASR strategies to meet future needs in Regions: E, F, G, J, K, L, and O (see Figure 1; TWDB, 2017). The estimated water supplied from ASR is 46,349 acre-feet/year (ac-ft. /yr) in 2020 and increases to 123,114 ac-ft/yr by 2070, at an average unit cost of $450 per ac-ft (TWDB, 2017). The 2021 Regional Water Plans are currently being developed by the 16 regions, and it is estimated that the cumulative volume of water supplied by ASR water management strategies will be significantly larger in the 2022 State Water Plan.

The 2070 Regional projects are located here with the Red Triangles:

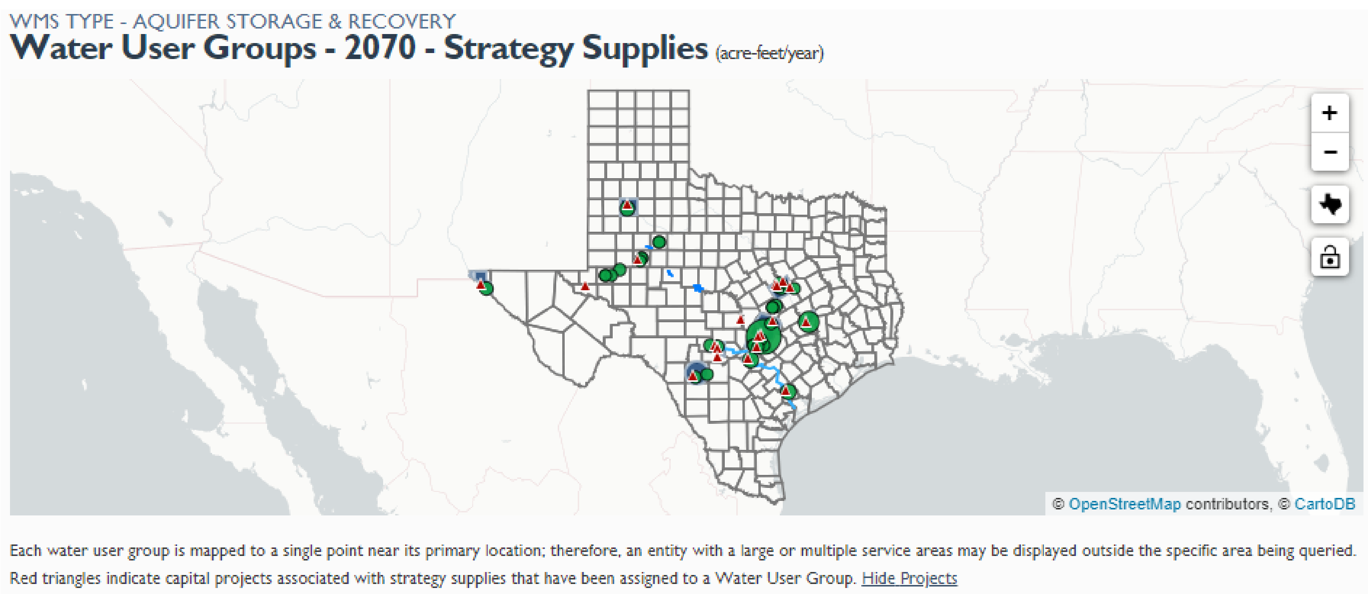

Figure 1. Locations of Water Management Strategies Related to ASR in the 2017 State Water Plan. Projects are noted with the red triangles.

Currently, there are three operational ASR facilities in Texas: El Paso Water Utilities (EPWU), City of Kerrville, and San Antonio Water System (SAWS). There are many planning projects in Texas that are currently being evaluated for ASR feasibility, to include but not limited to: City of Bryan, College Station, New Braunfels, Buda, Victoria, Corpus Christi, Austin, Kerrville, the Tarrant Regional Water District, and Barton Spring Edwards Aquifer Conservation District.

In 2015, the 84th Texas Legislature directed TWDB through House Bill 1, Rider 25 to provide grant support for demonstration projects or feasibility studies that would create new water supplies or increase water availability through innovative storage approaches. This grant funding supported three recently completed ASR demonstration projects for Corpus Christi, New Braunfels Utilities, and Victoria. In 2019, the 86th Texas Legislature through House Bill 721 tasked the TWDB with determining the feasibility of Texas aquifers for ASR and aquifer recharge. In December 2019, HDR was selected to address the legislative mandate through a Statewide Survey of Aquifer Suitability for ASR or Aquifer Recharge Project.

The objective of this report is to identify recent demonstration projects related to ASR nationally and within Texas, evaluate methodologies from these studies and its application to Texas aquifers, and to summarize how existing work could inform the evaluation of relative suitability of ASR and aquifer recharge. This report provides an overall summary of Texas aquifer characteristics, identification of recent ASR studies nationally and in Texas and their methodologies for evaluating ASR feasibility including detailed summaries of the eight recent studies requested for review in the TWDB scope of work. The report closes with an outline of proposed methodology for this study based on reviewed literature and experience. The literature review (Task 1) was conducted by HDR Engineering, the University of Texas at Austin-Bureau of Economic Geology (BEG), INTERA, Collier Consulting, and GeoSystems Analysis Inc.

Overall summary of Texas aquifer characteristics

An overall summary of Texas aquifer characteristics aides in determining the relevance of recent studies as it pertains to evaluating the suitability of Texas aquifers for ASR and aquifer recharge.[1]

Texas aquifer characteristics with respect to ASR

The most important characteristic of an aquifer for ASR feasibility is its general physical characteristics (lithology). For example, those composed of sand and gravel are more suitable than those aquifers that are fractured and faulted. Lithology in terms of rock size and small grains inside the rocks and type of rock or mineral, aside from how closely bound the grains or rock) , determines porosity, and permeability. Other characteristics to consider include structures such as faults/fractures, and regional hydraulic gradient, both affect flow through an

[1] During subsequent project tasks, HDR will survey the relative suitability of Texas' 31 major and minor aquifers for ASR or aquifer recharge projects based on hydrogeological characteristics with a focus on storage potential, transmissivity, infiltration characteristics, storativity, recoverability, and water quality to prepare a detailed hydrogeological parameter screening tool to identify preferable locations for recharge.

aquifer. The quality of the native groundwater, and how it interacts with stored water is also an important factor.

Texas aquifer characteristics with respect to AR

In natural settings, groundwater recharge occurs through: a) soils and the vadose zone in inter-drainage areas; b) streambeds, and c) localized near-surface concentrations of water in the absence of well-defined channels (Lerner et al., 1990). The relative importance of each of these recharge environments correlate strongly with the local and regional geology and geomorphology, and climate and weather patterns. Research in the southwestern United States (including Texas) indicates that natural recharge depends strongly on high-intensity rainfall events, accumulation of rain water in depressions and streams, and the ability of rain water to percolate deeply and rapidly through porous sediments, cracks, fissures, or solution channels (Devries and Simmers, 2002).

Managed aquifer recharge (MAR) is intentional groundwater replenishment, which could be done to improve the quantity or quality of groundwater available or to mitigate subsidence. The successful application of MAR therefore is dependent on identifying natural recharge zones (i.e. high permeability sediments or fracture zones) or using recharge enhancement technologies (i.e. infiltration trenches/galleries and drywells) to access high permeability vadose zone sediments.

The principal aquifers of Texas can be broadly categorized into alluvial sedimentary basins in the west and High Plains (i.e. Hueco-Mesilla Bolsons, Pecos Valley, and Seymour and Ogallala aquifers), the sedimentary Gulf Coast aquifers, and sedimentary rock aquifers (i.e. Edwards-Trinity (Plateau), Trinity, Edwards (Balcones Fault Zone) and Carrizo-Wilcox aquifers). At most locations in the western and High Plains aquifers the depth to water is sufficient (i.e. > 50 feet below ground surface (bgs) to allow aquifer storage, thus MAR using surface methods may be suitable for these aquifers. As an example, surface spreading basins are currently being successfully used by El Paso Water to recharge advanced treated wastewater into the Hueco Bolsons (Sheng, 2005, Moreno Cardenas, 2018).

Depending on local conditions and historic groundwater pumping, sufficient vadose zone may be available in the Gulf Coast aquifers to also allow MAR (i.e. Yang and Scanlon, 2019). However, because of the frequent occurrence of fine-grained lithologic units, the use of vadose zone injection and/or drywells (storm water management wells as per Yang and Scanlon), would most likely be needed for surface MAR methods to be used.

Bedrock aquifers are not typically considered for surface MAR, however, localized areas within the surface expressions of these aquifers act as natural recharge zones (i.e. highly fractured depressions, volcanic sediments) and thus directing surface water to these areas will enhance natural recharge rates. As an example, Amunas and Careos have been used for at least 800 years in Perú and Spain respectively, as surface MAR methods in mountainous regions. Surface water is diverted via canals to fractured, high permeability bedrock zones during wet season river flows, and aquifer recharge occurs via canal leakage and infiltration in small ponds and fields located in fracture zones (Fernández Escalante et al., 2019, Apaza et al., 2006). Recharge water recovery occurs via increased flow rates from downgradient springs and wells during the dry season.

Major aquifers

Sand and gravel compositions

The majority of major aquifers in the state have sand and gravel compositions that are conducive to ASR, but to varying degrees (Table 1). These include the Carrizo-Wilcox, Gulf Coast, Hueco-Mesilla Bolsons, Ogallala, Pecos Valley, Seymour, and Trinity aquifers. The Edwards-Trinity (Plateau) and Trinity aquifers, given its large areal extent, includes both productive sandstones and limestones. Where the aquifers differ in applicability to ASR, in part, concerns their respective locations. Their locations determine the source of water to be stored, as well as proximity to population centers that can use the water. In addition to their geography, structural characteristics of the aquifers can affect their suitability for ASR. These include the presence or absence of faults, fracture systems, and the overall geometry of bedding (Table 1). Bed thickness is also a factor, as is the lateral continuity of sand bodies, but these are a function of depositional environments rather than structural deformation.

Limestone and dolomite compositions

The major aquifers in the state that have limestone and dolomite beds are the Edwards (Balcones Fault Zone) Aquifer and the Edwards-Trinity (Plateau) Aquifer (Table 1). The Trinity Aquifer, in the Glen Rose and Cow Creek formations, also has some production from limestone beds. Aquifer storage in these aquifers would be affected by the geometries of faults and fracture systems. They commonly have karst features that affect storage. The Edwards-Trinity (Plateau) Aquifer is used by the City of Kerrville for ASR, but storage is in the lower Trinity sands and not limestone units. New Braunfels Utilities is currently constructing a pilot well to test ASR in the saline Edwards.

Minor aquifers

Sand and gravel compositions

The minor aquifers in the state that have sand dominated compositions are shown in Table 1. The majority of them are younger than the Cretaceous-age limestones that occur throughout central and West Texas. These younger Tertiary aquifers tend to be less fractured and less cemented. They are good candidates for ASR given their respective lithologies. The older

Hickory Sandstone surrounding the Llano Uplift may not be a good candidate for ASR because of the composition of its native groundwater, which can be high in radionuclides, and opportunities for mixing along the periphery of stored water zone. The Dockum Aquifer in its lower section, locally known as the Santa Rosa Aquifer, could potentially store fresh surface water. Its permeable sands are contained by shaly units and its beds are laterally continuous. The Woodbine Aquifer, although Late Cretaceous in age, could also be suitable for ASR with its relatively shallow and extensive uncemented sand units.

Limestone, dolomitic, and volcanic compositions

The minor aquifers in the state that are composed of fractured limestone, but do not have developed karst could be used for ASR. Examples of these types of aquifers are the Cross Timbers and Bone Springs-Victorio Peak. Aquifers with beds including dolomite, gypsum, and limestone with poorly characterized faults and fracture zones that affect recoverability might not be good candidates for ASR. These include the Blaine, Capitan Reef Complex, Ellenburger-San Saba, Marble Falls, and Rustler aquifers. The Igneous aquifer in Far West Texas has interbedded units capable of accepting stored water. However, fractured volcanic beds above and below may not provide adequate barriers to flow and require detailed hydrogeological analyses.

Table 1. Aquifer characteristics related to ASR

Aquifer	Lithology	Structural Characteristics	Water Quality Notes	Suitability for ASR*
Major Aquifer				
Carrizo-Wilcox	sand, gravel, silt, clay	minor local faulting	some high Fe and Mg levels	yes
Edwards (Balcones Fault Zone)	limestone, dolomite	highly faulted, fractured, karst	increased salinity with depth	in places
Edwards-Trinity (Plateau)	limestone, dolomite, sandstone, shale	some faults, fractures, karst	increased salinity with depth	in places
Gulf Coast	thick sands, clay	some faults, salt domes	increased salinity with depth	yes
Hueco-Mesilla Bolsons	sand, gravel, silt, clay	discontinuous sand bodies	increased salinity with depth	yes
Ogallala	sand, gravel, silt, clay	discontinuous sand bodies	some high NO_3 levels	yes
Pecos Valley	sand, gravel, silt, clay	unconfined alluvium	some high Cl, SO_4^{2-}, As, radionuclides	yes
Seymour	gravel, sand, silty clay	discontinuous sand bodies	some high Cl, NO_3 levels	yes
Trinity	limestone, dolomite, sandstone, shale	some faults, fractures, karst	generally fresh	yes
Minor Aquifer				
Blaine	shale, gypsum, anhydrite, salt, dolomite	karst, solution channels	overall poor quality	not likely
Blossom	alternating sand and clay beds	gently dipping beds	some high Fe, Na, F, HCO_3 levels	yes
Bone Spring–Victorio Peak	limestone	jointed, fractured	slightly saline	yes
Brazos River Alluvium	sand, gravel, silt, and clay	complex sand body geometries	generally fresh	in places
Capitan Reef Complex	cavernous dolomite and limestone	faulted, fractured, karst	generally fresh	not likely
Cross Timbers	limestone, shale, and sandstone	fractures	increased salinity with depth	yes
Dockum	gravel, sandstone, siltstone, shale	discontinuous sand bodies	fresh in Santa Rosa Sand	yes
Edwards-Trinity(High Plains)	limestone, sandstone	gently dipping beds	generally slightly saline	yes
Ellenburger–San Saba	limestone and dolomite	faulted, fractured, karst	some high radium and radon levels	not likely
Hickory	sandstone	faulted, fractured	some high radium and radon levels	not likely
Igneous	pyroclastic rock, lava, volcanoclastic	some faults, fractures	generally fresh	yes
Lipan	gravels and conglomerates, some clay	unconfined alluvium	variable salinity	yes
Marathon	limestone and older Paleozoic rocks	folded, faulted, fractured	generally fresh	not likely
Marble Falls	limestone	fractures, solution channels	susceptible to pollution	not likely
Nacatoch	sandstone, mudstone or clay	faulted, discontinuous sands	generally fresh to slightly saline	yes
Queen City	sands and clay	gently dipping beds	generally fresh	yes
Rita Blanca	sand, gravel, sandstone	wholly confined	generally fresh	yes
Rustler	dolomite, limestone, and gypsum	fractured, karst	slightly to moderately saline	not likely

Aquifer	Lithology	Structural Characteristics	Water Quality Notes	Suitability for ASR
Minor Aquifer (cont.)				
Sparta	sand, silt, clay	gently dipping beds	high Fe, increased salinity with depth	yes
West Texas Bolsons	limestone, volcanic, silt, clay	closed fault bounded basins	salinity varies with basin	yes
Woodbine	interbedded sandstone, clay, shale	gently dipping beds	generally fresh	yes
Yegua-Jackson	interbedded sand, silt, and clay	discontinuous sand bodies	generally fresh	yes
Fe-iron, Mg-magnesium, F-fluoride, Na-sodium, Cl-chloride, HCO_3-bicarbonate, SO_4^{2-}-sulfate, As-arsenic, NO_3-nitrate				
*** Suitability based primarily on lithology and to a lesser degree, water quality , would need to include an analysis of aquifer productivity (current wells), source water and water demand**				

Literature review of recent ASR and aquifer recharge suitability studies

A summary of each of the compiled studies is provided in Table 2, including any methodologies that were applied or developed related to hydrogeology, excess water, and water supply needs screenings. The bold text in Table 2 highlights aspects of prior work that are estimated to be relevant to this statewide survey for Texas.

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Table 2. Summary of Recent ASR and Aquifer Recharge Suitability Studies and Results

Project Name	Methodology Used to Determine Suitability	Results (Top Findings for ASR suitability)	Applicable in Texas (Y/N, Why?)	Lessons Learned (pros (+) and cons (-))	Main Geologic Aquifer Composition		Evaluations Included in Study (checked if applicable)			Weblink to Publications (if available)
					Infiltration	Deep Storage	Hydrogeo Setting	Excess Water for Storage	Proximity to Water Need	
International										
Web-based global inventory of managed aquifer recharge Applications	Synthesis of 1,200 case studies from 62 countries to improve understanding of role of managed aquifer recharge (MAR) in sustainable water management and adaptation	1. Increases awareness of MAR for sustainable groundwater management 2. Regional differences in type of MAR used, water source, and abstraction use	Yes. Web portal can be used to find comparable settings and approaches for planning and data validation purposes	+ Demonstrates that MAR is considered at many locations worldwide - Limited availability of technical documentation on many MAR studies impedes database integration	Variable	Variable	√	√	√	https://link.springer.com/content/pdf/10.1007/s40899-017-0212-6?wt_mc=alerts.TOCjournals&utm_source=toc&utm_medium=email&utm_campaign=toc_40899_4_2 https://inowas.com/tools/t17-global-mar-portal/
National										
LOTT Reclaimed Water Aquifer Recharge Project Aquifer Recharge	Used tracer testing and a groundwater monitoring to evaluate effectiveness of soil aquifer treatment on **infiltrated reclaimed water**, and to evaluate the risks of infiltrating reclaimed water into groundwater. Primary focus is on residual chemicals and nutrients.	1. Tracer test and water quality data support connectivity between the Shallow (unconfined) and Sea-Level (confined) Aquifers. 2. Water quality changes support the occurrence of soil aquifer treatment in both the vadose and saturated zones. 3. Rates of concentration decrease, downgradient of the infiltration basins, vary between chemicals.	Yes. Study pertains to the feasibility of using reclaimed water as recharge supply and the effectiveness of passive infiltration treatment.	+ Soil aquifer treatment is effective in further treating reclaimed water. - Facets requiring further study: vadose zone travel times, the effect of the vadose zone on reclaimed water quality, and the effect of dilution on reclaimed water.	Generally unconfined aquifer composed of sand and gravel glacial deposits.	N/A	√	N/A	√	https://lottcleanwater.org/wp-content/uploads/rwis_tracer2.pdf
Enhancing Drought Resilience with Conjunctive Use and Managed Aquifer Recharge in California and Arizona	Effectiveness of water recharged from the surface using managed aquifer recharge with surface ponds in existing operational managed aquifer recharge sites	1. GW depletion created substantial subsurface storage opportunities. 2. Local river water or transported surface water substituted for GW during wet years shifting to mostly GW pumpage during droughts. 3. Conjunctive use of SW and GW and MAR locally reversed declining GW trends in the Central Valley and in Arizona.	These studies are applicable to outcrop areas of Texas with suitable soils and aquifer materials for high levels of GW recharge. Examples include aquifer outcrops, like Brazos River Alluvial Aquifer.	+ **Conjunctive use of SW and GW can mitigate extreme floods and droughts**. + Inefficient surface water irrigation can recharge aquifers and is similar to managed aquifer recharge. - The soils and aquifers in Texas are not as suitable for surface based recharge as those in CA and AZ.	Coarse soils associated with alluvial deposits in CA and AZ derived from nearby mountains	N/A	√	√	√	https://iopscience.iop.org/article/10.1088/1748-9326/11/3/035013
An Aquifer Storage and Recovery System to Preserve and Rehabilitate Native Groundwater in Hastings, NE	Modeling and pilot studies	1. Confined geologic system 2. Porous and permeable beds 3. Structural geology is simple, no faulting or fracturing	Yes, system would be an analog for areas in the Ogallala where nitrate levels are of concern	+ **Storage system used to removed nitrates and uranium from well water** + Taking high nitrate water from the aquifer, treating it, then returning it down dip	N/A	In shallow glacial till deposits, using wells for injection	√	√	√	http://www.gwpc.org/sites/default/files/event-sessions/ASR%20-%20Jones.pdf

Project Name	Methodology Used to Determine Suitability	Results (Top Findings for ASR suitability)	Applicable in Texas (Y/N, Why?)	Lessons Learned (pros (+) and cons (-))	Main Geologic Aquifer Composition		Evaluations Included in Study (checked if applicable)			Weblink to Publications (if available)
					Infiltration	**Deep Storage**	**Hydrogeo Setting**	**Excess Water for Storage**	**Proximity to Water Need**	
Assessment of Increased Recharge due to Urbanization and Stormwater Detention Chandler, Arizona	GIS assessment of groundwater recharge from over 3,800 drywells and 1,400 acres of stormwater retention basins within City of Chandler	1. Permeable basin fill sediments useful for surface water recharge via drywells. 2. Drywells are successful in **recharging captured floodflow/stormwater over short time periods** 3. Study resulted in enhanced groundwater recharge and groundwater credits	Yes. Dry wells can be used to recharge large quantities of flood/stormwater quickly (Gulf Coast- Houston area).	+ Natural recharge rates enhanced by 10X via stormwater capture and injection via drywells + Estimated recharge rates 2,100 to 3,100 ac-ft. annually through retention basins and dry wells	Fine to coarse grained alluvium, with interbedded layers	Upper and Middle Alluvial Units (Quaternary and Holocene age) and Lower Alluvial Unit	√	√	√	https://www.researchgate.net/publication/299579764_Preliminary_Assessment_of_Increased_Natural_Recharge_Resulting_from_Urbanization_and_Stormwater_Retention_within_the_City_of_Chandler
Scottsdale Water Campus Vadose Zone Well Injection Scottsdale, AZ	The City of Scottsdale **recharges over 5,200 ac-ft. annually of advanced treated wastewater (AWT)** in 63, 180-ft deep vadose zone recharge wells. Vadose zone recharge wells are designed to by-pass 90 feet of low permeability surface sediments.	1. 400 ft. vadose zone, 18-inch diameter injection wells screened from 90 to 170 ft. bgs. 2. Drywells have been successfully used for over 20 years 3. Excess drywell capacity is needed to allow periodic shutdown to control clogging	Yes. **Vadose zone wells can be used to bypass low permeability surface sediments**	+ Vadose zone injection wells provide an intermediate cost solution between surface spreading and ASR injection - Clogging reduced Specific Injection Capacity (SIC) by up to 50% over 10 years; well performance can be increased by periodic shutdown and reducing injection rates	Fine-grained low permeability sediments from 0 to 90 ft., medium to coarse grained sediments deeper	Middle Alluvial Unit (Quaternary) with shallow bedrock	√	√	√	http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.607.6821&rep=rep1&type=pdf https://wrrc.arizona.edu/sites/wrrc.arizona.edu/files/UA-WRRC-BB-1-18-Scottsdale.pdf
Riverbank Filtration to Improve Water Quality for Recharge Orange County, CA	Feasibility study and pilot project to evaluate use of **riverbed filtration to treat surface water for sediment removal prior to groundwater recharge**.	1. Riverbed filtration is an effective method for remove TSS, and reduce dissolved organic carbon (TOC) and nitrogen compounds (N) to minimize clogging of recharge basins. 2. Riverbed clogging is predicted but can be mitigated with surface flushing or treatment (i.e. ripping).	Yes. Similar riverbed filtration treatment could be used in Texas to treat surface water for sediment, TOC and N removal where alluvial sediments and shallow groundwater conditions are present.	+ Treatment using riverbed filtration was superior to conventional active treatment in improving water quality. - Achievable induced recharge rates were 30-44% of the design collection rate due to discrepancies between design and actual field conditions. - Recharge water infiltration and capture rates are dependent on surface water depths and static GW levels.	Recent Holocene alluvial sediments	N/A	√	√	√	http://www.gsanalysis.com/publications/Milczarek_20et_20al_OCWD_20ISMAR7.pdf http://www.gsanalysis.com/publications/Keller_20et_20al_20ISMAR7_10.pdf
GAC and IX Groundwater Treatment Pilot Test Plan Cape Fear Public Utility Authority Cape Fear, NC	The system is well established and has been cycle tested. Stored water is also being tested.	1. Consistent water source from the Cape Fear River 2. Well confined sandy aquifer 3. Large population served by the system	Yes, the system could be used to develop ASR in the Gulf Coast Aquifer	+ **Locate near larger/artery type mains to reduce infrastructure improvements where possible** + Need to have a good inventory of neighboring wells + Recharge rate to reduce impact to wells	N/A	Storage in Upper Peedee, fine to medium grained sand intermittent black clay	√	√	√	https://www.cfpua.org/DocumentCenter/View/11976/ASR-GAC-and-IX-Groundwater-Treatment-Pilot-Test-Plan-FINAL https://pubs.er.usgs.gov/publication/sir20145169

Project Name	Methodology Used to Determine Suitability	Results (Top Findings for ASR suitability)	Applicable in Texas (Y/N, Why?)	Lessons Learned (pros (+) and cons (-))	Main Geologic Aquifer Composition		Evaluations Included in Study (checked if applicable)			Weblink to Publications (if available)
					Infiltration	Deep Storage	Hydrogeo Setting	Excess Water for Storage	Proximity to Water Need	
Colorado Water Aquifer Storage and Recovery Denver Basin ASR, CO	The basin currently hosts six well fields with 45 individual ASR well. They have been successfully operated and tested since 1994. Multiple pilot studies large dataset for evaluation.	1. **Stacked aquifers provide opportunities for multiple ASR projects** 2. High population density with high spring runoff	Yes, large size of Texas aquifers can accommodate multiple ASR projects within the same basin.	+ Multiple projects in a single large basin have synergistic effects	N/A	Denver Basin in bedrock aquifers	√	√	√	http://wsnet2.colostate.edu/cwis31/ColoradoWater/Images/Newsletters/2017/CW_34_4.pdf
Equus Beds Recharge Project, KS	U.S. Geological Survey, in cooperation with the city of Wichita, developed and implemented a hydrobiological monitoring program as part of an **alluvial project** to characterize and quantify the effects of ASR on the Little Arkansas River and Equus Beds aquifer water quality	1. Project was developed to help the city of Wichita meet increasing current (2016) and future water demands. 2. An important source of groundwater because of its water quality and shallow depth to the water table 3. Large saturated thickness available for ASR.	Yes, have similar alluvial aquifers along major river courses, for example the Brazos River	+ Nitrates decreased in the upstream and downstream sites - Arsenic concentrations in surface water were larger after ASR	N/A	Aquifer is about 300 feet thick and consists of alluvial deposits of sand and gravel interbedded with clay/ silt	√	√	√	https://pubs.usgs.gov/sir/2016/5042/sir20165042.pdf https://www.usgs.gov/centers/kswsc/science/equus-beds-recharge-project?qt-science_center_objects=3#qt-science_center_objects
Developing a Sustainable Water Supply in the American West Rio Rancho, NM	Using Recharge Demonstration & Treatment Pilot Sites	1. Thick section of **porous sandstone** of the Santa Fe Group in a **structurally closed basin** 2. Arsenic problems handled with advanced treatment processes 3. Substantial source of water, Rio Grande	Yes, Closed basin of the Rio Grande Rift similar to the Bolsons of West Texas.	+ Rio Rancho is the first injection facility in NM, can learn ways to introduce ASR into areas not familiar with it.	N/A	Santa Fe Group Aquifer, a layer of unconsolidated deposits	√	√	√	https://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=1026&context=subsust
Southern Nevada Water Authority ASR system Las Vegas, NV	**Long term and large scale (78 injection well sites) ASR**	1. Uses a combination of aquifer recharge wells, duel use wells, and production wells 2. Las Vegas claims they maintain the world's largest ASR system. 3. High demand for water in arid region	Yes, the size of the system could provide lessons for other large Texas cities like Dallas and Houston.	+ Size of system can be as many as 78 wells and larger	N/A	semi-consolidated interbedded sands and gravels	N/A	√	√	http://www.groundwatergeek.com/asr-by-state/nevada/las-vegas
Vadose Zone Recharge Wells: Ten Years Later at the City of Scottsdale's Water Campus Facility City of Scottsdale West Campus Facility, AZ	Performance testing of storage and recovery wells	1. For shallow alluvial aquifers it is more economical to use shallow vadose wells 2. High demand from City of Scottsdale 3. Arid conditions	Yes, vadose wells in alluvium could recharge deeper aquifers	+ More economical to **inject into shallow vadose well that ultimately recharges deeper sand units** + River water or recycled water can be used	N/A	A 63 vadose zone well field injects at a depth of 180 ft. down to an aquifer at 500 feet	√	√	√	http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.607.6821&rep=rep1&type=pdf https://wrrc.arizona.edu/sites/wrrc.arizona.edu/files/UA-WRRC-BB-1-18-Scottsdale.pdf

Project Name	Methodology Used to Determine Suitability	Results (Top Findings for ASR suitability)	Applicable in Texas (Y/N, Why?)	Lessons Learned (pros (+) and cons (-))	Main Geologic Aquifer Composition		Evaluations Included in Study (checked if applicable)			Weblink to Publications (if available)
					Infiltration	Deep Storage	Hydrogeo Setting	Excess Water for Storage	Proximity to Water Need	
Monterey Peninsula Water Management District, CA	**Long term feasibility testing program**	1. Functioning successfully over a long period (started in 2006) 2. High demand area 3. Strong legislative support	Yes, taking river water and injecting into a sandstone aquifer is possible at numerous sites in Texas	+ ASR can work in basins that are highly faulted as long as geology is understood	N/A	Santa Margarita Sandstone consists of conglomerates and coarse sandstone	√	√	√	https://www.mpwmd.net/wp-content/uploads/2015/08/Proj_Sum_1.pdf
Estimating Aquifer Storage and Recovery (ASR) Regional and Local Suitability: A Case Study in Washington State, USA	**GIS scoring system to identify potential ASR locations and estimate storage capacity**	1. Regional data useful for assessment 2. GIS analysis and ranking scheme successful for screening large areas 3. 280 locations within 62 watersheds in Washington, determined that over 50% of locations evaluated are suitable for ASR and statewide injection potential equaled 6,400 million liters per day	Yes in terms of methodology for regional screening studies	+ Demonstrated that large areas could be effectively screened for ASR potential. - The analysis is dependent on adequate regional data and local scale testing is needed to verify the results.	N/A	Various alluvial and bedrock	√	√	N/A	https://doi.org/10.3390/hydrology5010007
Texas										
Identification of Geographic Areas in Texas Suitable for Groundwater Banking*	GIS spatial analysis used to screen select candidate county areas for in-depth evaluation. **At the county level, the spatial distributions of soil permeability attributes, surface slope, and proximity to surface water sources were used to identify hypothetical groundwater banking sites.**	1. The state-wide criteria identified 48 counties in Texas that were broadly suitable for groundwater banking. Six were evaluated in greater detail and 9 potential banking sites were identified. 2. Cumulative total infiltration for all of the sites was ~0.5 million ac-ft. for water availability periods ranging from 3 to 57 days. Almost half was associated with one site on the Brazos River in Parker County.	3. Yes	+ GIS analysis is an effective tool in identifying potential groundwater banking sites. - Local conditions that may not be represented in the GIS model may also need to be considered. - Incomplete WAM records. Available hydrographs used in the analyses had relatively short duration record of ~10 yr.	Based only on surface soil layer hydraulic properties to a depth of ~4-6 ft.	N/A	√	√	N/A	http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/IndividualReportPages/2001483388.asp
Aquifer storage and recovery and managed aquifer recharge using wells: Planning, hydrogeology, design and operation*	Comprehensive reference-overview of ASR technologies that use wells to recharge aquifers. Addresses key challenges surrounding ASR systems, such as project planning, aquifer characterization, well design, system operation, and source water quality and pretreatment.	1. ASR does not work everywhere. Many systems have not met expectations or failed. 2. **Proper planning of ASR projects increases the probability of their success and reduces project costs.** 3. Successful implementation of ASR project at a given location is dependent on a number of factors that can be subdivided into infrastructure, regulatory, and hydrogeological components.	Yes. Provides an overview of ASR technologies, gives guidance for unconfined, alluvial, and brackish aquifers, and covers storage of reclaimed water. Also provides an **example of an ASR feasibility ranking tool**.	-ASR systems can cause adverse hydrologic impacts during recovery (demonstrated in SAWS ASR) -Potential recovery efficiencies are often overestimated -Large-scale ASR requires an accommodating regulatory framework -Large-scale ASR may not be feasible in brackish aquifers	N/A	Siliciclastic, carbonate, crystalline, and mixed-lithology aquifers.	√	√	√	https://www.slb.com/resource-library/book/aquifer-storage-and-recovery-and-managed-aquifer-recharge-using-wells

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					Infiltration	**Deep Storage**	**Hydrogeo Setting**	**Excess Water for Storage**	**Proximity to Water Need**	
An Assessment of Aquifer Storage and Recovery in Texas*	Conducts interviews with three Texas utilities utilizing ASR systems in Kerrville, San Antonio, and El Paso, and considers online survey responses from water providers who have previously studied or considered ASR but decided against implementation.	1. The chief concern of utilities who decided against ASR was the **ability to recover stored water and challenges in protecting that water.** 2. For ASR implementation, legal and regulatory matters were more challenging. 3. **Utilities with ASR systems found they reaped additional benefits over their initial objectives and ASR exceeded expectations**.	Yes. The report provides an overview of why ASR implementation has been slow in Texas, and outlines steps to increase ASR system utilization.	- Legal and regulatory obstacles provide the largest challenge to Texas ASR implementation.	N/A	N/A	N/A	N/A	N/A	http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf?d=1567703502249
Assessing aquifer storage and recovery feasibility in the Gulf Coastal Plains of Texas*	Develops a **method for rating ASR feasibility at regional aquifer scale** for the Gulf Coast and Carrizo-Wilcox Aquifer Systems. Complies a GIS database of feasibility factors and uses the database to produce ASR suitability maps.	1. The central and northern regions of the Gulf Coast Aquifer and the central and southern regions of the Carrizo-Wilcox Aquifer are most feasible for ASR. 2. Corpus Christi, Victoria, San Antonio, Bryan, and College Station are identified as candidates for ASR systems within the study area based on high ASR feasibility scores, potential source water availability, and susceptibility to drought (demonstrating need). 3. Most regions with high ASR feasibility are located between, not within, cities. Therefore, future ASR wells will likely require transmission lines to connect well fields to cities.	Yes. The analysis informs on feasibility of ASR within Texas' Gulf Coast and Carrizo-Wilcox aquifer systems. The study also provides an example of a regional ASR suitability rating system.	+ This study focuses on hydrogeological ASR suitability. Other factors not covered in this analysis, such as existing infrastructure, source water availability, and sociopolitical considerations are also important in determining ASR feasibility. Areas deemed suitable should be studied further. - It may not be accurate to count ASR wells towards a region's well density rating.	N/A	Gulf Coast Aquifer System and Carrizo-Wilcox Aquifer Systems	√	N/A	√	https://www.sciencedirect.com/science/article/pii/S2214581817302628
TWDB ASR Demo Project- New Braunfels Utilities Aquifer Storage and Recovery Demonstration Project*	Field program, including test hole and continuous core.	1. Data gathered on geochemistry, geology, and hydraulics can be utilized for TCEQ permit 2. **Brackish Edwards aquifer can be used as a storage zone for ASR**. Confinement above and below. 3. Collecting core and water quality samples is an essential step in evaluating ASR storage zone.	Yes, project is in Texas.	+ Brackish Edwards may be productive, in spite of reduced dissolution. + Regional dense member exists in this location in brackish zone. - CO_2 may be an issue due to low pH of the Edwards Aquifer.	N/A	Karst Limestone, Edwards Aquifer	√	√	√	https://www.twdb.texas.gov/innovativewater/asr/projects/EAA/index.asp

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					Infiltration	Deep Storage	Hydrogeo Setting	Excess Water for Storage	Proximity to Water Need	
TWDB ASR Demo Project- Victoria Aquifer Storage and Recovery Demonstration Project*	Retrofit existing well, perform cycle testing.	1. Retrofit well may perform as ASR well 2. Mobile arsenic clears below MCL after one cycle 3. **Gulf Coast Aquifer productive for ASR**	Yes, project in Texas	+ Existing production well may be retrofit for ASR - Existing wells may be problematic if old or in poor condition.	N/A	Unconsolidated sands and clays of the Gulf Coast Aquifer.	√	√	√	https://www.twdb.texas.gov/innovativewater/asr/projects/Victoria/index.asp
TWDB ASR Demo Project- Corpus Christi Aquifer Storage and Recovery Feasibility*	Exploratory test program including aquifer core, pump tests, and water quality. Modeled geochemistry of aquifer and source water. Groundwater model to simulate short/long term ASR operations. Identified storage zones, ASR capacity, operations, and costs.	1. Collecting core and water quality samples is an essential step in evaluating ASR storage zone. 2. Brackish Gulf Coast down to 800 ft yields 10-18 million gallons per day (MGD) supply with phasing. Volumetric recovery >61 %. ASR focus for industrial non-potable needs ASR over time freshens native brackish aquifer.	Yes. **The Gulf Coast Aquifer system** is similar to other sand and clay aquifers of Texas. Highly stratified with discontinuous layers of sand and clay alluvium.	+ Core tool adapted to get good recovery of fine sands for testing. + **Although soils were generally fine-grained, interbedded coarse-grained sediments provide preferential flow paths which increased recovery rates** - Pre-treat source water to reduce TSS, TOC, Mn, bacteria, NO3. Piloting needed to prove up best non-RO method.	N/A	Yes in sand lenses in between the clay.	√	√	√	https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011956_Corpus_Christi_ASR.pdf?d=3996.0699998773634
How much Water Can Be Captured from Flood Flows to Store in Depleted Aquifers for Mitigating Floods and Droughts?*	The volume of high magnitude flows (HMFs) (≥95th percentile) were quantified in Texas's 10 major rivers discharging to the Gulf of Mexico. Assess the availability of HMFs at the outlet gages considering water rights, instream flow requirements. Used three metrics, namely duration, intra-annual frequency, and inter-annual frequency, to describe the HMFs at each gage.	1. Unappropriated HMFs in Texas's 10 major rivers, totaling 30 million acre feet (MAF) in 2015–2017, are co-located with depleted major aquifers in Texas, including the **Texas Gulf Coast and Trinity aquifers** which provides space that could store ~80% (~20 MAF) of the recent HMFs. 2. Limited analysis in the San Antonio and Brazos river basins shows that capturing ~65% of HMFs may not negatively impact the instream flow requirements. 3. **About 80% of HMF volumes is contributed by events lasting for at least one week**, HMFs intensity is greater than aquifer injectivity. **More interim storage is needed to temporarily store those HMFs before slowly injecting them into the subsurface.**	Yes	+ Large volume (~30 MAF) of unappropriated HMFs in Texas's 10 major rivers discharged to the Gulf of Mexico in 2015 – 2017. - Current surface reservoirs cannot provide sufficient storage capacity for storing HMFs. Therefore, more interim storage space would be needed. - Instream flow requirements limit the potential to capture HMFs at the San Antonio and Brazos river basins. - In addition, Texas Instream Flow Program suggests capturing 5% of lower flows to maintain sediment transport, which is however infeasible with Texas water right appropriations.	N/A	N/A	N/A	√	N/A	https://iopscience.iop.org/article/10.1088/1748-9326/ab148e/meta

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					Infiltration	Deep Storage	Hydrogeo Setting	Excess Water for Storage	Proximity to Water Need	
El Paso Aquifer Recharge Program	Long term (30+ yr) aquifer recharge project utilizing ASR, spreading basins, and infiltration galleries resulting in over 60,000 acre-feet of reclaimed wastewater recharge.	1. Initial recharge of advanced treated wastewater effluent was via ASR wells. 2. Subsequent studies evaluated surface spreading which is current primary recharge method. 3. Expansion via discharge into basins constructed in ephemeral stream channel is planned.	Yes. Project is being conducted in West Texas and is a useful example for comparison of surface spreading infiltration with ASR wells.	+ Surface spreading far more effective than ASR injection. Lower maintenance and operations costs with surface spreading vs ASR wells - Caliche layer needs to be treated.	Moderately deep clay loam subsoils with soft caliche and/or gypsum sublayer	Quaternary and Tertiary basin-fill deposits.	√	√	√	https://www.sciencedirect.com/science/article/pii/S0301479705000216
City of Lubbock ASR Feasibility Study	This report evaluated ASR in the Ogallala, Edwards Trinity (High Plains), and Dockum Aquifers. These were investigated based on groundwater pumping, assessment of permitting, water availability and hydrogeoloic characterization. They **scored water supply based on confidence, reliability, sustainability, permit ability, quantity, quality, schedule, unit costs, project and annual cost.**	1. Based on **scoring of alternative strategies** there are three sites that are feasible for ASR, but need further investigation. 2. The ASR project could aid in seasonal peaking to meet summer demands. 3. They recommend conducting a location specific program to determine ASR feasibility.	Yes. They investigated the Ogallala, Edwards Trinity (High Plains), and Dockum Aquifers near Lubbock.	+ Existing water supply data and location data can be used to rank and evaluate sites + Test drilling location specific would provide valuable data in site selection. + An ASR simulation model could further refine water supply, demands, quality, storage volumes, and recharge and recovery rates.	N/A	Yes in the Ogallala, Edwards Trinity (High Plains), and Dockum Aquifers.	√	√	√	https://www.twdb.texas.gov/waterplanning/rwp/plans/2016/O/Region_O_2016_RWP.pdf?d=1764.870000013616
Preliminary Investigation and Feasibility Analysis: San Antonio ASR System	Evaluated **storage zone based on: potential well yield, native water quality, surface contamination potential, existing well density, average daily demand and total depth**. Other factors pertinent to site selection: water source, future permit limitations, existing well development data, and the characterization of geologic formations in Bexar County.	1. There are many potential groundwater storage zones underlying Bexar County. 2. Phase ASR System in 3 Phases: Phase 1 Test wells, Phase 2 laboratory analysis and geochemistry investigation, Phase 3 develop a prototypic ASR wells to confirm full scale compatibility	Yes. They investigated the Middle/Lower Trinity, Brackish Edwards, Wilcox and Carrizo in Bexar county.	+ There are potential groundwater storage zones in Bexar county + Attention to detail for well construction and gravel pack installation. + Match volume calculation from caliper log. - Be cautious of sand production, turbidity, and silt density index.	N/A	Yes in sand lenses in the Lower Wilcox.	√	√	√	http://www.twdb.texas.gov/innovativewater/asr/doc/SAWS_ASR_Step%201_OCR.pdf https://www.texasdesal.com/wp-content/uploads/2017/09/CrossBrad.pdf

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					Infiltration	Deep Storage	Hydrogeo Setting	Excess Water for Storage	Proximity to Water Need	
Kerrville Aquifer Storage and Recovery Investigation	Evaluated the aquifer based on: geologic logs, water demands, potential for storage, and field scale studies. This was done in multiple phases before a full-scale ASR operation system was put into place	1. The treated water is compatible with the aquifer minerals and water, therefore geochemical and biologically plugging of the aquifer is not expected. 2. **The Trinity Aquifer (Hosston-Sligo formations) was almost twice as thick as originally estimated increasing the storage potential.** 3. Suitable subsurface storage using screening in the production zone.	Yes. They investigated the Lower Trinity Aquifer, specifically the Hosston-Sligo sands	+ Drilling test wells is important as site hydrogeology can change - Open boreholes in the aquifer may be unstable, therefore screening the production zones is recommended. + Special design should be considering how water will be recovered at the surface	N/A	Yes in the Lower Trinity	√	√	√	http://www.twdb.texas.gov/innovativewater/asr/doc/UGRA_PhaseIIB_1992_Kerrville_OCR.pdf http://www.twdb.texas.gov/innovativewater/asr/doc/UGRA_PhaseIIA_1989_Kerrville_OCR.pdf http://www.twdb.texas.gov/innovativewater/asr/doc/UGRA_PhaseI_1988_Kerrville_OCR.pdf
Brownsville Public Utility Board ASR Feasibility Study: Step 1 and 2	They recommend conducting three phases, which include: feasibility investigation, test drilling program, and ASR prototype facility construction and testing. Investigated 3 suitable geologic zones using field analysis, pump test, water quality sampling, and geophysical logging. The study also investigated the most feasible area to conduct ASR.	1. The Gravel Zone is the best area for ASR based on transmissivity and aquifer properties. 2. There are multiple locations where ASR would be feasible on PUB land. 3. A 10 MGD ASR facility could be built in phases to manage water supply.	Yes. They investigated the **alluvial materials of the Gulf Coast System (Beaumont and Lissie formations, Uvalde Gravel, and the Goliad Formation)**.	+ **Having multiple sites for future ASR growth is important.** + Phasing the ASR system can be helpful in developing wells and the ASR system.	N/A	Yes in the Chicot and Evangeline part of the Gulf Coast Aquifer	√	√	√	http://www.twdb.texas.gov/innovativewater/asr/doc/Brownsville_ASR_Step2_OCR.pdf http://www.twdb.texas.gov/innovativewater/asr/doc/Brownsville%20ASR%20Step%201_OCR.pdf
Laredo ASR Feasibility Study: Step 1	Investigated existing hydrogeological data of shallow and deep aquifer and water availability/demand data.	1. The **Laredo Formation has the greatest potential for ASR**. The deeper aquifers could have issues with plugging due to the fine grain sediments. 2. Mixing between the native and injected waters needs to be investigated. 3. It is important to understand the lateral continuity of sands and sandstones and the relative hydraulic connection between these layers and lower permeability silts and clay.	Yes. They investigated the Laredo Formation. The Larado Aquifer is not classified as a Major or Minor Aquifer by TWDB.	- Geochemical issues need to be evaluated carefully especially iron and aluminum. - Calcium carbonate precipitate in the well can lead to plugging problems. + A small percentage of stored water needs to be left as a buffer zone.	N/A	Semi-consolidated sands and sandstones interbedded with silts and clays.	√	√	√	http://www.twdb.texas.gov/innovativewater/asr/doc/Laredo_ASR_Step1_OCR.pdf

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					Infiltration	Deep Storage	Hydrogeo Setting	Excess Water for Storage	Proximity to Water Need	
TWDB 2017 State Water Plan	This report summarizes all of the Regional Plans and those that have included ASR as a strategy and it recommended a 1.8% water management strategy of the total water supply that ranges from 53,000 to 152,000 ac-ft. There are 43 strategies in Texas in Regions: E, F, G, J, K, L, and O. The average unit cost is $450 per ac-ft.	1. The ASR strategies are in many regions in the State Water Plan. 2. There is 152,000 ac-ft. predicted by 2070 that will come from ASR supplies. 3. Multiple areas in the state have feasibility for ASR.	Yes.	N/A	N/A	Yes	√	√	√	https://www.twdb.texas.gov/waterplanning/swp/2017/doc/SWP17-Water-for-Texas.pdf?d=1578931562091
City of Buda ASR Feasibility Study	This assessment investigated storage zones by characterizing the geology, hydrogeological setting, hydraulic properties, groundwater quality, and the distribution of existing wells to be considered in the subsequent feasibility analyses. They also investigated: source water, permitting and regulations, and ASR application/feasibility.	1. Geochemical modeling of a range of mixes of source and storage zone waters suggests there is little potential for significant precipitation and associated loss of well yield. 2. There is **isolation between the Edwards and lower Trinity Aquifers.** 3. Based on the findings of this study, meaningful volumes of untreated Edwards water could potentially be stored in middle and lower Trinity storage zones for recovery during drought or peak demands.	Yes. They investigated the Edwards and Trinity Aquifer near Buda, TX.	- Geochemical issues need to be evaluated carefully especially because the Edwards has pyrite deposits. - Dissolved metals should be monitored during pilot testing of ASR. + **The middle or lower trinity are both suitable for ASR.**	N/A	Yes in Middle or Lower Trinity.	√	√	√	https://legistarweb-production.s3.amazonaws.com/uploads/attachment/pdf/122929/ASR_TM_Final.pdf
Aquifers of Texas	Provides **summaries of all major and minor aquifers in Texas**, including their geology, hydrology, and water use. Includes a review of Texas groundwater management, TWDB modeling and monitoring programs, and statewide groundwater issues.	1. Aquifers with significant water level decline: the Trinity, particularly in the Dallas-Fort Worth and Waco areas; Carrizo-Wilcox in the Winter Garden irrigation area; and the Gulf Coast Aquifer around the Houston area. 2. Major water quality constituents of concern within Texas: TDS, arsenic, radionuclides, and nitrates. 3. Projected decrease in statewide groundwater availability (12.7 mil ac-ft/yr in 2010 to 9.9 mil ac-ft/yr in 2060).	Yes, understanding Texas aquifer characteristics and use is essential in evaluating ASR feasibility.	N/A	N/A	N/A	√	N/A	N/A	http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R380_AquifersofTexas.pdf?d=6819.2800000542775

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					Infiltration	Deep Storage	Hydrogeo Setting	Excess Water for Storage	Proximity to Water Need	
Barton Springs Edwards Aquifer Conservation District Regional Plan for Desalination and Aquifer Storage Recovery Report 1 Desalination and ASR Feasibility Assessment	In this study they investigated the phasing and well field development using existing hydrogeological data collected with a multi-port well at the Texas Disposal System site.	1. The **Brackish Edwards could be used for ASR**. 2. The brackish groundwater could be run through a desalination plant and then stored using ASR. 3. ASR could provide water supplies to meet peak demands and enhance the reality during drought.	Yes. They investigated the Brackish Edwards in Travis County near Creedmoor.	- Boron may be an issue for plant life, so to reduce that a two stage RO system would be needed to be used for irrigation and human consumption. + Power generated from the landfill can be used for the desalination and possibly for the ASR wells.	N/A	Yes in the Brackish Edwards	√	√	√	https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1548321870.pdf

Note: * Designates Tier 1- One of the Eight (8) Reports specified by TWDB in RFQ. The bold text in the document signifies useful methodology and/or study results that may be applicable in developing methodologies to assess AR and ASR in Texas.

Proposed methodology for survey

A proposed methodology to achieve TWDB objectives and goals in accordance with House Bill 721 (HB 721) were developed based on the literature review summarized in Table 2, project experience, and the understanding of key parameters affecting the suitability of aquifers for ASR or aquifer recharge (AR). Each of the 31 Texas aquifers will be evaluated using a multi-attribute theory method, with scores and weights for each parameter to provide an overall score. Lumped parameters will be considered for attributes that can be combined to simplify screening and these will be identified early in the screening process for TWDB consideration. HDR will meet with TWDB staff in a workshop to consider parameters, scores, and weights and a sensitivity analysis will be performed to determine how assigned weighting affects the screening result.

Three screening tools will be developed to survey the relative suitability of Texas' 31 major and minor aquifers for ASR or AR potential based on Hydrogeological Parameters, Excess Water Availability, and Water Supply Needs. A proposed methodology for developing these screening tools is presented below. Figure 2 shows a preliminary hydrogeological parameter screening process. Figure 3 shows a preliminary excess water screening process. Figure 4 shows a prelimnary water demand screening process. Further details and refinement of these screening tool methodologies will be developed during subsequent tasks that focus on each screening tool. The results from these three screening tools will be aggregated to create a final suitability rating for each aquifer (Figure 5) with results presented in a GIS StoryMap type-format Public Data Display for viewing and discussion. The feature classes or rasters for each parameter and screening rating will feed into a StoryMap or similarly low maintance public data display. The public display will deliver understandable, concise messaging in a non-technical, graphic-rich way to provide clarity on technical issues and support transparency. An example of a public-facing non-technical format is shown in Figure 6.

Proposed methodology for hydrogeological parameter screening

- The first step of the hydrogeological assessment is gathering all the hydrogeological data from sources such as TWDB, USGS, and groundwater conservation districts (GCDs) and the Bureau of Economic Geology (BEG) on all Texas Aquifers.
- After data is gathered each aquifer parameter will be ranked based on a criteria that has numerical value for ASR feasibility or AR feasibility. Then each parameter will receive a weight, which will determine a final score for each aquifer. A ranking and weighting of key parameters related to the hydrogeological parameter screening will be developed and presented to the TWDB with discussion to confirm parameters to include in the screening tool.

- The assessment of hydrogeological suitability is divided into three categories for ASR: suitability for recharge, suitability for storage, and suitability for recovery. For AR, the hydrogeological suitability assessment is on recharge and suitability for storage to reduce water level declines, supplement groundwater volume, improve water quality, improve spring flow and groundwater/surface water interactions, and/or mitigate subsidence according to HB 721 objectives.
- The suitability for aquifer recharge is assessed for three types of applications infiltration/spreading basins, vadose zone wells, and saturated zone (deep) wells.
- Parameters for aquifer structure favorability will be assessed to include: permeability, aerial extent, thickness, hydraulic gradient, geology/structure, mineralogy, native water quality, and others.
- Infiltration basins are most commonly implemented in highly transmissive aquifers with clean, shallow sands, and they work best when there is good vertical permeability and limited heterogeneity in surface and shallow systems. Vertical permeability will be analyzed by estimating a vertical conductivity for various soil horizons documented by Soil Survey Geographic (SSURGO) database. Hydrogeological parameters used to screen for infiltration basin and vadose zone potential include: hydraulic conductivity, thickness, degree of lamination, depth to static level, and proximity to known contamination sources. Recharge into saturated zone wells, or ASR wells, is dependent on saturated hydraulic conductivity, and the amount of unsaturated capacity in the aquifer storage zone.
- Recovery rate and recoverable volume are important factors affecting cost. Additional hydrogeological parameters affecting potential recovery rate and recoverable volume include the following implementation-related parameters: depth to top of storage zone, depth to static level, proximity to existing water wells, duration of storage, and proximity to known contamination sources.
- The screening tool will consist of a geodatabase with a feature class or raster containing raw values for each of the parameters and suitability rating results related to ASR or AR Hydrogeological Parameter Screenings.

Proposed methodology for excess water screening

- Information will be gathered on factors that affect excess water screening tool such as: water availability, water quality, proximity of available water (stormwater, instream flow, WTP/WWTP) to reservoirs/storage or ability /ease in being able to develop storage readily, groundwater availability limited by modeled available groundwater and local groundwater management goals, proximity of stored or collected water to aquifers suitable for ASR, and other factors.
- For stormwater and instream flow availability:

- A threshold value or percentile will be developed for instream flow opportunities to capture excess surface water.
  - Assessing four metrics (volume, duration, intra-annual frequency, and inter-annual frequency) similar to those developed by Yang and Scanlon (2019).
  - Perform water availability analysis using Water Right Models (WAMs). Compare the volume of unappropriated flows with high magnitude flows (HMFs) at each gage to assess the availability of surface water volumes for ASR considering water rights and environmental flow needs.
  - Compare HMFs with instream flow requirements recommended by TIFP at other gages of the San Antonio and Brazos river basins (TIFP, 2017; 2018). The instream flow and freshwater inflow standards adopted by TCEQ and described in Title 30, Texas Administrative Code, Chapter 298 (A – H) will be considered.
- For reuse availability:
  - Identify WTP and WWTP with low average day to rated capacity ratios and corresponding treatment process.
  - Evaluate proximity of WTP/WWTP to ASR.
- For groundwater availability:
  - Excess groundwater could be available from some aquifers for pumping and storage in aquifers adjacent to future water supply needs.
  - Groundwater is often pumped at less than Modeled Available Groundwater (MAG) rates during average or above average rainfall conditions or times of reduced water demands. MAGs are an estimated total groundwater production volume from the aquifer that when pumped on an average annual basis, achieves a desired future conditions (DFC) adopted by Groundwater Management Area. MAGs define groundwater availability for regional water plan purposes, however MAG peaking factors are permissible by some planning group areas and could allow additional groundwater to be developed while not exceeding the MAG, on average.
  - Excess groundwater that is available for recharge through MAG peak factors or other means will be considered during the study.
- Other factors to consider for the excess water screening analysis will include: identified strategies in the State Water Plan to utilize excess water identified, and recommended water management strategies that might impact excess water.
- A ranking and weighting of key parameters related to excess water parameter screening will be developed and presented to the TWDB with discussion to confirm parameters to include in the screening tool.

- The screening tool will consist of a geodatabase with a feature class or raster containing raw values for each of the parameters and suitability rating results related to Excess Water Screening.

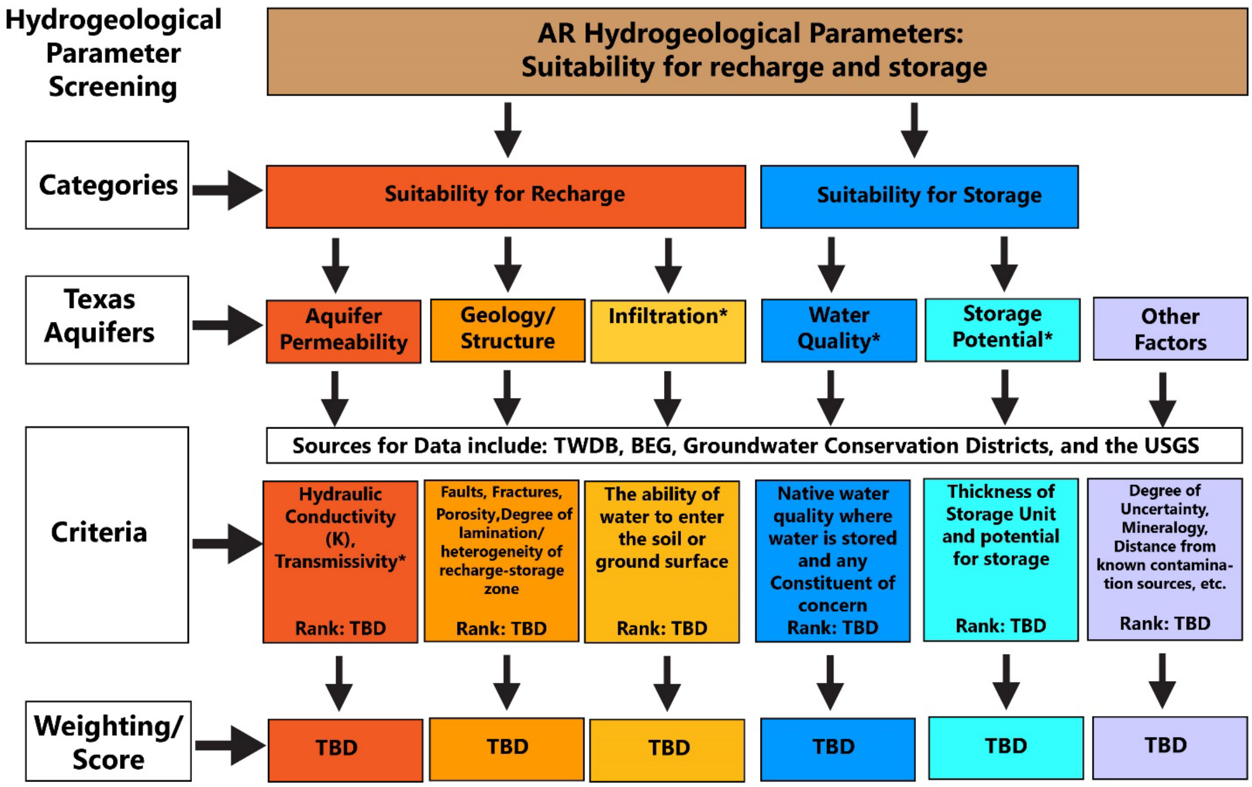
Proposed methodology for water supply needs screening

- The 2017 State Water Plan water supply needs will be compiled by major water use area, including consideration of other Texas areas with growing population or single supply users prone to drought.
- The water supply needs assessment will include evaluation of both raw water and treated water needs.
- A ranking and weighting of key parameters related to water supply needs screening will be developed and presented to the TWDB with discussion to confirm parameters to include in the screening tool.
- The screening tool will consist of a geodatabase with a feature class or raster containing raw values for each of the parameters and suitability rating results related to Water Supply Needs Screening. This format will allow for flexibility in updating data for the 2022 State Water Plan information, when available. Guidance will be provided on how to adapt and update based on future State Water Plan information.

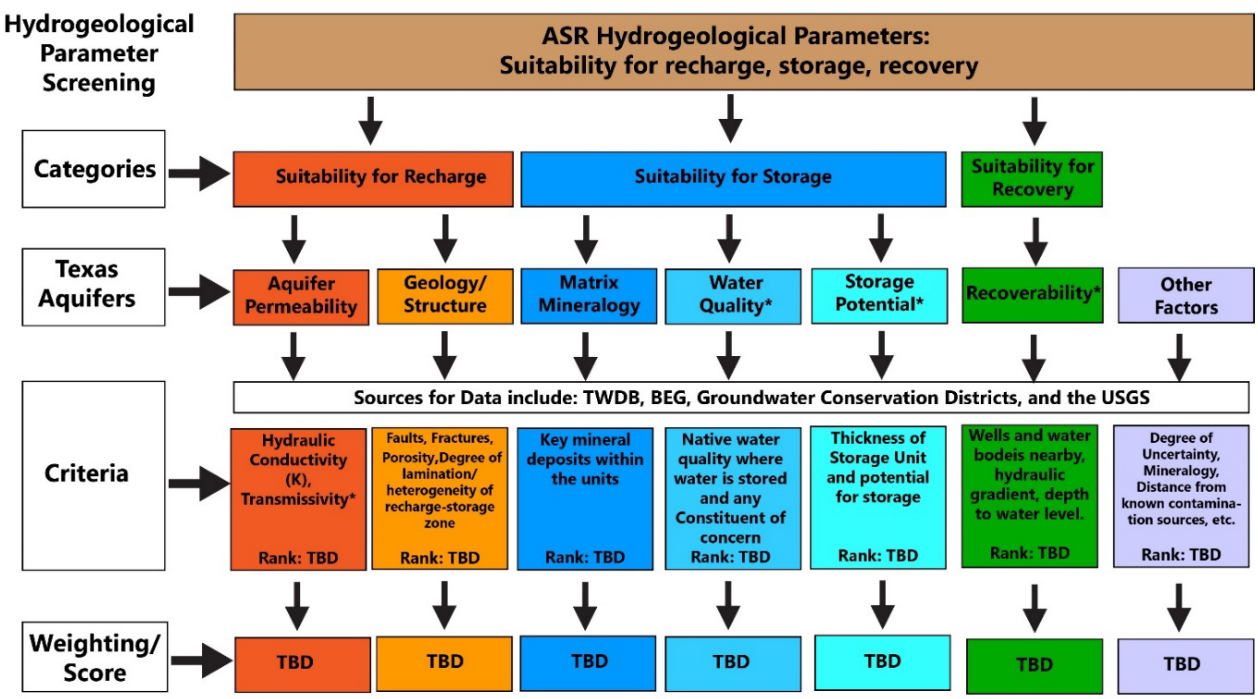
Final suitability rating

- The final suitability rating will assimilate the screening tools described above and consider the decade of water supply need, volume, and usage type. The weighting factors for the individual screenings associated with hydrogeological parameter, excess water, and water supply needs heavily influence the final screening criteria, which may be revisited during the final suitability rating in coordination with the TWDB (as needed).
- This screening criteria will consider the cumulative effects on ASR or AR project suitability.
- A range of weighted scores for each attribute are identified so as to not exclude or eliminate from consideration any Texas aquifers, excess water available, or water supply need entries.
- A higher score is assigned for most favorable combinations of aquifers for ASR or aquifer recharge and proximity to excess water available and water needs. With this approach, the TWDB will have a complete tool that can be adapted to future conditions (i.e. large water supplies are brought on to address water demands, water treatment plant expansions result in excess water supplies being made available for storage, surface WAMs are updated for new period of record, etc.) and re-prioritization if necessary.

- The screening tool will consist of a geodatabase with a feature class or raster containing raw values for each of the parameters and suitability rating results related to the final suitability rating.
- The final project suitability rating will be adaptable to include future modifications to the Water Supply Needs Screening Tool (Figure 6).



* Indicates it is a parameter screening HB 721



* Indicates it is a parameter screening HB 721

Key, Rank, and Weight- Determined during future phases of study (as of Feb 2020)

Figure 2. Preliminary Hydrogeological Parameter Screening Process for AR and ASR

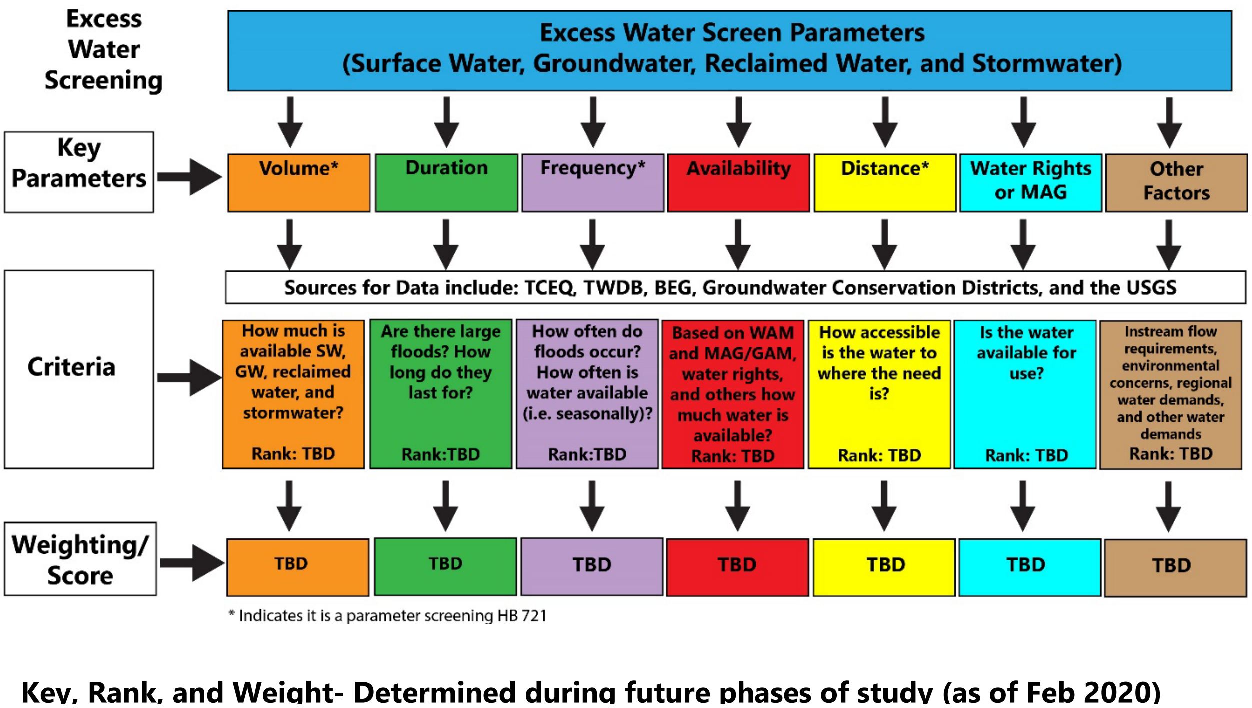
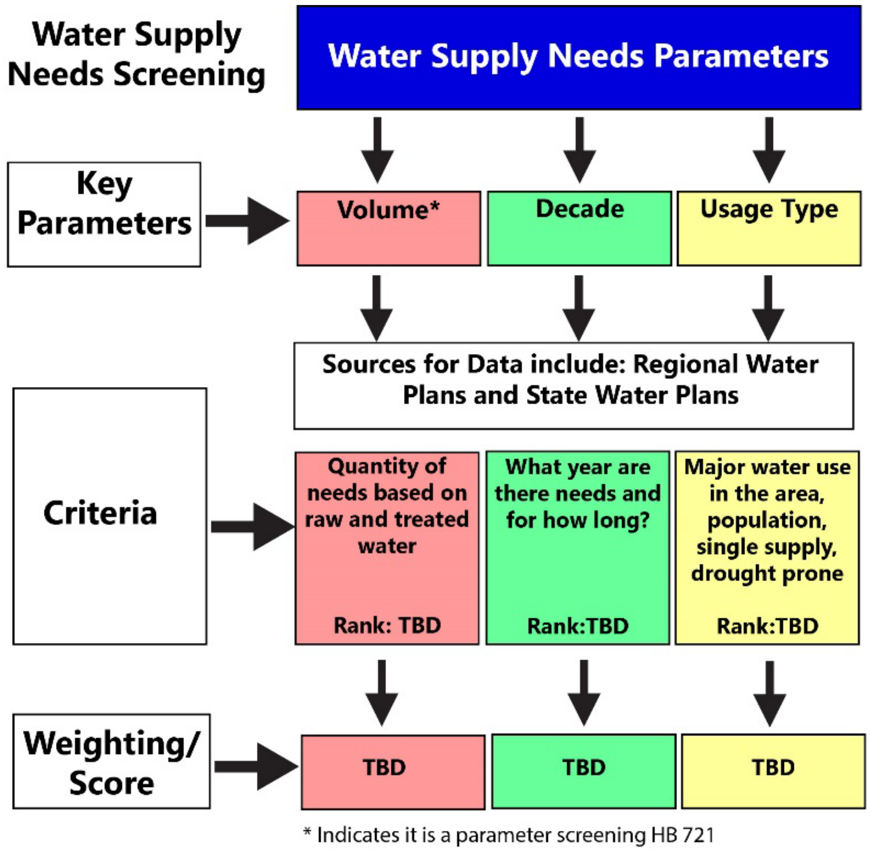


Figure 3. Preliminary Excess Water Parameter Screening Process



Key, Rank, and Weight- Determined during future phases of study (as of Feb 2020)

Figure 4. Preliminary Water Supply Needs Parameters Screening Process

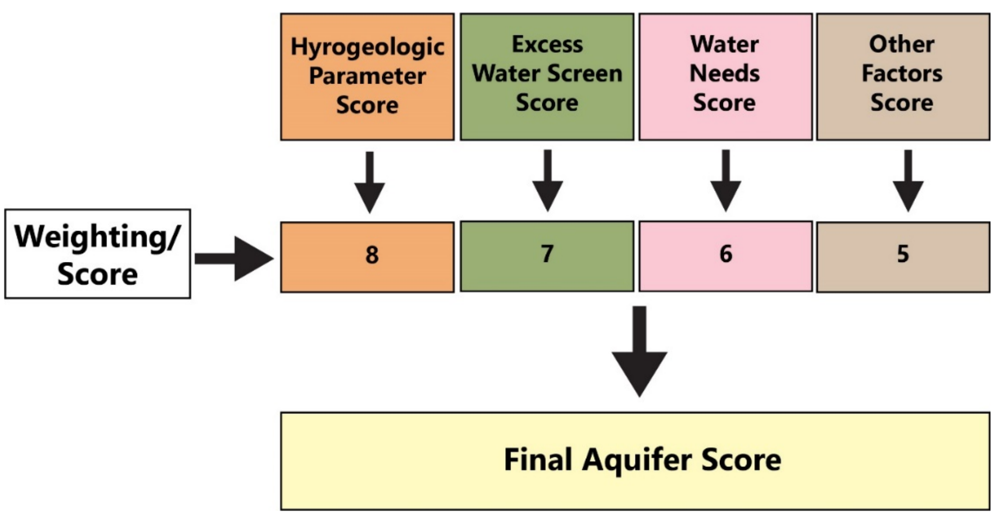


Figure 5. Preliminary Scoring for Aquifers

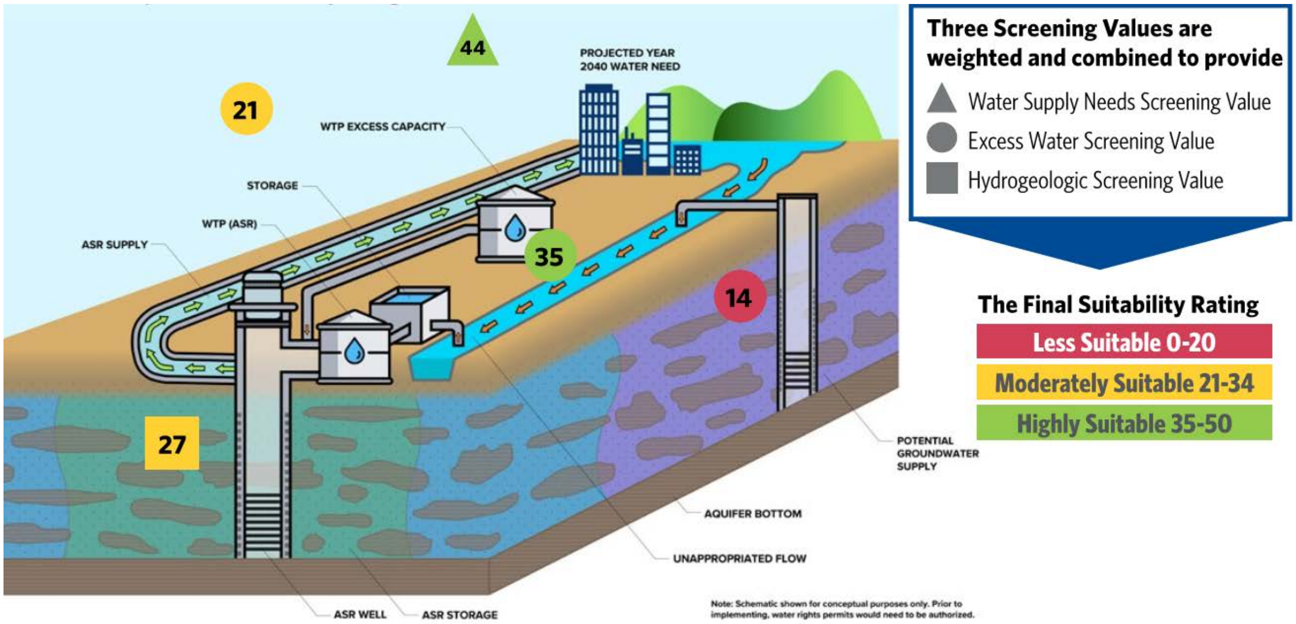


Figure 6. Example of Final Suitability Rating Tool Results

References

Apaza, D; Arroyo, R y Alencastre, A. (2006). Las amunas de Huarochirí. Recarga de acuíferos en Los Andes. Gestión social del agua y ambiente en cuencas. GSAAC, Lima, Junio de 2006.

Arcadis and others, 2019. TWDB ASR Demonstration Project- New Braunfels Utilities: Aquifer Storage and Recovery Demonstration Project. https://www.twdb.texas.gov/innovativewater/asr/projects/EAA/index.asp

Arcadis and ASR Systems, 2019. TWDB ASR Demonstration Project- Victoria Aquifer Storage and Recovery Demonstration Project. https://www.twdb.texas.gov/innovativewater/asr/projects/Victoria/index.asp

Arcadis, 2017. Aquifer Storage and Recovery in Texas. http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf?d=1567703502249

Carollo, 2018. Barton Springs Edwards Aquifer Conservation District Regional Plan for Desalination and Aquifer Storage Recovery Report 1 Desalination and ASR Feasibility Assessment. https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1548321870.pdf

Cardenas, M Inc. 2018. El Paso Aquifer Storage and Recovery Using Reclaimed Water Project – Title XVI Feasibility Study. Prepared for El Paso Water and U.S. BOR.

CH2M, 2017. City of Buda ASR Feasibility Study. https://legistarweb-production.s3.amazonaws.com/uploads/attachment/pdf/122929/ASR_TM_Final.pdf

CH2MHill, 1998. Preliminary Investigation and Feasibility Analysis Step 1 Report. http://www.twdb.texas.gov/innovativewater/asr/doc/SAWS_ASR_Step%201_OCR.pdf

CH2MHill, 1997. Aquifer Storage Recovery Feasibility Investigation Brownsville. http://www.twdb.texas.gov/innovativewater/asr/doc/Brownsville_ASR_Step2_OCR.pdf

CH2MHill, 1996. Aquifer Storage Recovery Feasibility Investigation Laredo. http://www.twdb.texas.gov/innovativewater/asr/doc/Laredo_ASR_Step1_OCR.pdf

CH2MHill, 1992. Aquifer Storage Recovery Feasibility Investigation Kerrville. http://www.twdb.texas.gov/innovativewater/asr/doc/UGRA_PhaseIIB_1992_Kerrville_OCR.pdf

Daniel B Stephens and Associates and Bureau of Economic Geology, 2002. Identification of Geographic Areas in Texas Suitable for Groundwater Banking. https://www.beg.utexas.edu/files/publications/cr/CR2002-Scanlon-2_QAe6971.pdf

Daniel B Stephens & Associates, RSP Espey, Parkhill, Smith & Cooper, 2015. Llano Estacado (Region O) 2016 Regional Water Plan.

https://www.twdb.texas.gov/waterplanning/rwp/plans/2016/O/Region_O_2016_RWP.pdf?d=1764.870000013616

DeVries, J.J. and 1. Simmers, 2002. Groundwater Recharge: an Overview of Processes and Challenges, Hydrol. J. 10:5-17.

Drager, D., 2016. Aquifer Storage Recovery ASR at New Braunfels Airport. http://www.nbutexas.com/Portals/11/NBU%20ASR%20Slides%20Presentation%20to%20NB%20City%20Council%206-27%20Draft%206-16%20(3).pdf?ver=2018-11-30-155304-250

Fernández Escalante, E., J.M. García Asensio, F. Ayuga, C. Rojas Vega, P. Guerrero Salazar, and J. San Sebastián Sauto, 2019. Ancient techniques of Managed Aquifer Recharge: Spanish Careos and Peruvian Amunas as an Adaptive Complex System. Breakdown, Anthropology and comparative analysis. 10th International Symposium on Managed Aquifer Recharge, Madrid, Spain, May 20-24, 2019. pp 389-401.

Gastélum, J., Lluria, M., and Small, G., 2018. Vadose Zone Recharge Wells: Ten Years Later at the City of Scottsdale's Water Campus Facility. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.607.6821&rep=rep1&type=pdf

George, P., Mace, R., and Petrossian, R. 2011. TWDB: Aquifers of Texas. http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R380_AquifersofTexas.pdf

Gibson M.T., Campana, M.E., Nazy, D., 2018. Estimating Aquifer Storage and Recovery (ASR) Regional and Location Suitability: A Case Study in Washington State, USA. Hydrology, 5, 7. https://doi.org/10.3390/hydrology5010007

House Bill 1, General Appropriations Act, 2015 Legislature, Regular Session, page VI-60, Rider 25:

HDR, 2019. TWDB ASR Demonstration Project: Corpus Christi Aquifer Storage and Recovery (ASR) Feasibility Study. https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011956_Corpus_Christi_ASR.pdf?d=3996.0699998773634

HDR, 2019. Tracer Test and Water Quality Monitoring: LOTT Clean Water Alliance Reclaimed Water Infiltration Study. https://lottcleanwater.org/wp-content/uploads/rwis_tracer2.pdf

HDR, 2019. GAC and IX Groundwater Treatment Pilot Test Plan Cape Fear Public Utility Authority. https://www.cfpua.org/DocumentCenter/View/11976/ASR-GAC-and-IX-Groundwater-Treatment-Pilot-Test-Plan-FINAL

Jones, A., 2019. An Aquifer Storage and Recovery System to Preserve and Rehabilitate Native Groundwater in Hastings, NE. http://www.gwpc.org/sites/default/files/event-sessions/ASR%20-%20Jones.pdf

Konikow, L. F., 2015. Long-Term Groundwater Depletion in the United States, Groundwater. https://ngwa.onlinelibrary.wiley.com/doi/abs/10.1111/gwat.12306

Lerner, D.N., 2002. Identifying and quantifying urban recharge: a review. Hydrogeology Journal, 10:143-152

Maliva, R., Missimer, T., 2011. Aquifer Storage and Recovery and Managed Aquifer Recharge Using Wells. https://www.slb.com/resource-library/book/aquifer-storage-and-recovery-and-managed-aquifer-recharge-using-wells

Milczarek, M., Harding, J., Graham, A., Toy, D., Preliminary Assessment of Increased Natural Recharge Resulting from Urbanization and Stormwater Retention within the City of Chandler. https://www.researchgate.net/publication/299579764_Preliminary_Assessment_of_Increased_Natural_Recharge_Resulting_from_Urbanization_and_Stormwater_Retention_within_the_City_of_Chandler

Milczarek, M., Keller, J., Woodside, G., Hutchinson, A., Rice, R., Canfield, A., 2020. The Orange County Water District Riverbed Filtration Pilot Project: Water Quality and Recharge Improvements Using Induced Riverbed Filtration. http://www.gsanalysis.com/publications/Milczarek_20et_20al_OCWD_20ISMAR7.pdf

Monterey Peninsula Water Management District, 2005, Monterey Peninsula, Carmel Bay, and South Monterey Bay Integrated Regional Water Management Plan and Integrated Coastal Watershed Management Plan, 18p. https://www.mpwmd.net/wp-content/uploads/2015/08/Proj_Sum_1.pdf

Pirnie, M. et al., 2011. An Assessment of Aquifer Storage and Recovery in Texas. http://www.twdb.texas.gov/innovativewater/asr/projects/pirnie/doc/2011_03_asr_final_rpt.pdf

Pyne, D., 2017. Colorado Water: Aquifer Storage and Recovery. http://wsnet2.colostate.edu/cwis31/ColoradoWater/Images/Newsletters/2017/CW_34_4.pdf

Scanlon, B., Reedy, R., Faunt, C., Pool, D., and Uhlman, K., 2016. Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. https://iopscience.iop.org/article/10.1088/1748-9326/11/3/035013

Sheng, Z., 2005. An aquifer storage and recovery system with reclaimed wastewater to preserve native groundwater resources in El Paso, Texas. https://www.sciencedirect.com/science/article/pii/S0301479705000216

Smith, B., Miller, G., and Sheng, Z. 2017. Assessing aquifer storage and recovery feasibility in the Gulf Coastal Plains of Texas. https://www.sciencedirect.com/science/article/pii/S2214581817302628

Stefan, C. and Ansems, N, 2017. Web-based global inventory of managed aquifer recharge applications. https://link.springer.com/content/pdf/10.1007/s40899-017-0212-6?wt_mc=alerts.TOCjournals&utm_source=toc&utm_medium=email&utm_campaign=toc_40899_4_2https://inowas.com/tools/t17-global-mar-portal/

Stone, M.L., Garrett, J.D., Poulton, B.C., and Ziegler, A.C., 2016, Effects of aquifer storage and recovery activities on water quality in the Little Arkansas River and Equus Beds aquifer, south-central Kansas, 2011–14: U.S. Geological Survey Scientific Investigations Report 2016–5024, 88 p., http://dx.doi.org/10.3133/sir20165042.

Stroud, Hubert B. and Kilmer, M. K., 2016, Developing a Sustainable Water Supply in the American West: The Case of Rio Rancho, New Mexico: Suburban Sustainability, vol. 4: Iss. 1, Article 1. http://scholarcommons.usf.edu/subsust/vol4/iss1/1

TIFP, 2017. Instream Flow study of the Lower San Antonio River and Lower Cibolo Creek, edited, p. 336, Texas Instream Flow Program. https://www.sara-tx.org/about/projects/instream-flow-study-lower-san-antonio-river-lower-cibolo-creek

TIFP, 2018. Instream flow study of the Middle and Lower Brazos River, edited, p. 326, Texas Instream Flow Program. http://www.twdb.texas.gov/surfacewater/flows/instream/middle_lower_brazos/index.asp

TWDB, 2017. Water for Texas. https://www.twdb.texas.gov/waterplanning/swp/2017/doc/SWP17-Water-for-Texas.pdf?d=1578931562091

USGS, 2019. Las Vegas ASR. http://www.groundwatergeek.com/asr-by-state/nevada/las-vegas

Webb, M., 2015. Aquifer Storage and Recovery in Texas: 2015. http://www.twdb.texas.gov/publications/reports/technical_notes/doc/TechnicalNote15-04.pdf

Yang, Q., and B. R. Scanlon, Bureau of Economic Geologiy, 2019, How much water can be captured from flood flows to store in depleted aquifers for mitigating floods and droughts? A case study from Texas, US, Environ. Res. Lett., 14(5), 054011. https://iopscience.iop.org/article/10.1088/1748-9326/ab148e/meta

Appendix B- Description of GIS Files for Screening Tools

Hydrogeological Parameter Screening GIS Approach

The Hydrogeological Parameter Screening section contains a discussion and detailed table of the sources of data for each of the parameters relevant to hydrogeological suitability for ASR and AR. Parameterization of the statewide (10,000 ft x 10,000 ft) grid was generally performed in the following ways, depending on the data source:

Primary strategies:

1. GAM: One of the most common data sources were the TWDB groundwater availability models (GAMs). The GAM numerical grid are of varying resolutions, mostly in miles or fractions of miles. In all cases, the numerical grids were more refined that the statewide grid. The strategy for moving parameter values from the statewide grid to the numerical grid was to perform zonal statistics using the statewide grid as the zone definition, and the finer numerical grid as the value source.
2. BRACS: For some aquifers, e.g. the Blossom Aquifer, a BRACS study served as the primary resource. For these cases, raster coverages were available for estimates of structure, water levels, etc. For rasters, zonal statistics were used where the statewide grid was the zone definition, and the raster served as the value source.
3. Where spatially varying data was not available, constant values were estimated from literature sources. These constant values were simply assigned directly to the statewide grid for those cells that defined the relevant aquifer.

Additional strategies:

1. SSURGO data for estimating vertical hydraulic conductivity. One exception to the three strategies described above was the estimate of vertical hydraulic conductivity. For this the statewide SSURGO dataset, which contains estimates of vertical hydraulic conductivity by soil horizon, was intersected to the statewide grid. When multiple soil horizons were available at a given location, a weighted harmonic mean was calculated for each SSURGO soil polygon prior to intersection.
2. Average topographic slope. A statewide 30m DEM from TNRIS was used to first calculate slope, using the spatial analyst “slope” tool. That zonal statistics were then used on that “slope” raster, where the statewide grid was the zone definition and the slope raster served as the value source.

These strategies produced the estimated parameter values that are included in feature classes for each of the 31 aquifers, with separate feature classes for ASR and AR.

Hydrogeological Parameter Screening GIS Files

ASR_AR_Hydrogeologic_Screening_20200923.gdb

Title final_hydro_ASR_score_GRID
Type Feature Class
Description Simplified feature class with combined final values from Hydrogeologic Parameter Screening for ASR. Used in Final Suitability Rating.
Source None
Date September 23, 2020

Title final_hydro_AR_score_GRID
Type Feature Class
Description Simplified feature class with combined final values from Hydrogeologic Parameter Screening for AR. Used in Final Suitability Rating.
Source None
Date September 23, 2020

Title [AqCode]_us_fd
Type Feature Dataset
Description A feature dataset for each aquifer ([AqCode] is the four letter aquifer designation) containing two feature classes, one for ASR and one for AR.
Source None
Date September 23, 2020

Title [AqCode]_ASR_fs
Type Feature Class
Description A feature class for each aquifer ([AqCode] is the four letter aquifer designation) that contains the average parameter values, normalized parameter scores, scoring weights, categorical scores, and hydrogeologic suitability scores for ASR. Parameter values populated on statewide grid as described above.
Source Multiple. Parameter sources, weights, and scores calculated as described in the Hydrogeological Parameter Screening section.
Date September 23, 2020

Title [AqCode]_AR_fs
Type Feature Class
Description A feature class for each aquifer ([AqCode] is the four letter aquifer designation) that contains the average parameter values, normalized parameter scores, scoring weights, categorical scores, and hydrogeologic suitability scores for AR. Parameter values populated on statewide grid as described above.
Source Multiple. Parameter sources, weights, and scores calculated as described in the Hydrogeological Parameter Screening section.
Date September 23, 2020

Excess Water Screening GIS Approach

The Excess Water Screening section contains a discussion and detailed tables of the sources of data for each of the parameters relevant to excess water from surface water (and stormwater), reclaimed water, and groundwater. Parameterization of the statewide (10,000 ft x 10,000 ft) grid was performed, as discussed in the Excess Water Screening methodology section.

Excess Water Screening GIS Files

ASR_AR_excess_water_screening_20200923.gdb

Title Final_Excess_Score_GRID
Type Feature Class
Description Final Grid- Simplified feature class with combined final values from Excess Water Screening. Used in Final Suitability Rating.
Source None
Date September 23, 2020

Title Excess_Groundwater_GRID
Type Feature Class in Geodatabase
Description Final Grid- Score and Parameter Data for highest scoring major or minor aquifer by grid cell. Unique record per cell.
Source TWDB Draft 2022 State Water Plan database (DB22)
Date September 23, 2020

Title Excess_Reclaimed_Water_GRID
Type Feature Class in Geodatabase
Description Final Grid- Score and Parameter Data for Excess Reclaimed Water by grid cell. Unique record per cell. Point data from Reclaimed_Water_Points was summed if within grid cell
Source TCEQ TPDES Geodatabase and EPA Enforcement and Compliance History Online (ECHO)
Date September 23, 2020

Title Excess_Surface_Water_GRID
Type Feature Class in Geodatabase
Description Final Grid- Score and Parameter Data for Excess Surface Water by grid cell. Unique record per cell. Combines Reservoir_Storage_GRID, Surplus_Appropriated_Surface_Water_GRID, and Unappropriated_Flow_WAM_Points_GRID data together
Source TCEQ WAM, TCEQ WAM Control Point Geodatabase, TWDB DB22, TWDB Water for TX
Date September 23, 2020

Title Excess_Groundwater_Major_GRID
Type Feature Class in Geodatabase
Description Intermediate Grid- Score and Parameter Data for Excess Groundwater by grid cell. Many to one record per cell for major aquifers coincident with each other.
Source TWDB Draft 2022 State Water Plan database (DB22)

Date September 23, 2020

Title Excess_Groundwater_Minor_GRID
Type Feature Class in Geodatabase
Description Intermediate Grid- Score and Parameter Data for Excess Groundwater by grid cell. Many to one record per cell for minor aquifers coincident with each other.
Source TWDB Draft 2022 State Water Plan database (DB22)
Date September 23, 2020

Title Reservoir_Storage_GRID
Type Feature Class in Geodatabase
Description Intermediate Grid- Score and Parameter Data for existing reservoir locations >5000 acft by grid cell.
Source TWDB Water Data for Texas
Date September 23, 2020

Title Surplus_Appropriated_Surface_Water_GRID
Type Feature Class in Geodatabase
Description Intermediate Grid- Score and Parameter Data for surplus appropriated surface water from TWDB DB22 (after WMS in RWPs). Unique record per cell. Combines Surplus_Appropriated_Surface_Water_Reservoirs_GRID and Surplus_Appropriated_Surface_Water_Run_of_River_GRID.
Source TWDB Draft 2022 State Water Plan database (DB22)
Date September 23, 2020

Title Surplus_Appropriated_Surface_Water_Reservoirs_GRID
Type Feature Class in Geodatabase
Description Intermediate Grid- Score and Parameter Data for surplus appropriated surface water from Reservoirs from TWDB DB22 (after WMS in RWPs). Sum of surplus appropriated supply points within given cell.
Source TWDB Draft 2022 State Water Plan database (DB22)
Date September 23, 2020

Title Surplus_Appropriated_Surface_Water_Run_of_River_GRID
Type Feature Class in Geodatabase
Description Intermediate Grid- Score and Parameter Data for surplus appropriated surface water from Run of River sources from TWDB DB22 (after WMS in RWPs). Sum of surplus appropriated supply points within a given cell.
Source TWDB Draft 2022 State Water Plan database (DB22)
Date September 23, 2020

Title Unappropriated_Flow_WAM_Points_GRID
Type Feature Class in Geodatabase

Description Intermediate Grid- Score and Parameter Data for available unappropriated flow from TCEQ WAM Run 3- No return flows.   Highest ranking WAM point within a given cell (Unappropriated_Flow_WAM_Points).
Source TCEQ WAM, TCEQ WAM Control Point Geodatabase,
Date   September 23, 2020

Title Reservoir_Storage_Points

Type   Feature Class in Geodatabase
Description Point File- Native data of reservoirs in Texas and conservation pool capacity for identifying potential opportunities for storing excess water for ASR recharge, balancing, and/or scalping to provide operational benefits.
Source TWDB Water Data for Texas
Date   September 23, 2020

Title Reclaimed_Water_Points
Type   Feature Class in Geodatabase
Description Point File- Native Data for Discharge Locations and Projected Discharges based on growth identified in county demand projections in 2022 Draft State Water Plan.
Source TCEQ TPDES Geodatabase, EPA Enforcement and Compliance History Online (ECHO), TWDB approved demand projections for 2022 State Water Plan
Date   September 23, 2020

Title Surplus_Appropriated_Surface_Water_Reservoirs
Type   Feature Class in Geodatabase
Description Point File- Native data for Appropriated Surplus Water (after accounting for WMS) in the 2022 Draft State Water Plan. Applied as point in centroid of reservoirs.
Source TWDB Draft 2022 State Water Plan database (DB22)
Date   September 23, 2020

Title Surplus_Appropriated_Surface_Water_Run_of_River
Type   Feature Class in Geodatabase
Description Point File- Run of River locations with Appropriated Surplus Water (after accounting for WMS) in the 2022 Draft State Water Plan
Source TWDB Draft 2022 State Water Plan database (DB22)
Date   September 23, 2020

Title Unappropriated_Flow_WAM_Points
Type   Feature Class in Geodatabase
Description Point File- Native data for control points in TCEQ WAM Run 3 and statistics performed on raw data used to assimilate on grid level
Source TCEQ WAM, TCEQ WAM Control Point Geodatabase,
Date   September 23, 2020

Water Supply Needs Screening GIS Approach

The Water Supply Needs Screening section contains a discussion and detailed tables of the sources of data for each of the parameters relevant to municipal, manufacturing, and steam electric water needs from the 2022 draft State Water Plan. Parameterization of the statewide (10,000 ft x 10,000 ft) grid was performed, as discussed in the Water Supply Needs Screening methodology section.

Water Supply Needs Screen Screening GIS Files

ASR_AR_water_supply_needs_screening_20200923.gdb

Title **Final_Needs_Score_GRID**
Type Feature Class
Description Final Grid- Simplified feature class with combined final values from Water Supply Needs Screening. Used in Final Suitability Rating.
Source None
Date September 23, 2020

Title **Manufacturing_GRID**
Type Feature Class in Geodatabase
Description Final Grid- Score and Parameter Data for Manufacturing Water Needs by grid cell. Unique record per cell, assimilated based on point data from Manufacturing_WUG. Needs summed to grid level.
Source TWDB Draft 2022 State Water Plan database (DB22)
Date September 23, 2020

Title **Municipal_GRID**
Type Feature Class in Geodatabase
Description Final Grid- Score and Parameter Data for Municipal Water Needs by grid cell. Many to one records per cell for municipal service areas coincident with each other.
Source TWDB Draft 2022 State Water Plan database (DB22) and MUN WUG DB22 WUG boundary coverage from TWDB Draft 2022 State Water Plan
Date September 23, 2020

Title **Steam_Electric_GRID**
Type Feature Class in Geodatabase
Description Final Grid- Score and Parameter Data for Steam Electric Water Needs by grid cell. Unique record per cell, assimilated based on point data from Steam_Electric_WUG. Needs summed to grid level.
Source TWDB Draft 2022 State Water Plan database (DB22)
Date September 23, 2020

Title **Manufacturing_WUG**
Type Feature Class in Geodatabase

Description Point File- Native data points from TWDB Water Use survey (2017) for which DB22 data for Manufacturing Users by County is applied.
Source TWDB-provided Manufacturing shapefile associated with Water Use Survey submitted by Manufacturing water users in 2017
Date September 23, 2020

Title **Municipal_WUG**
Type Feature Class in Geodatabase
Description Polygon- Native data from TWDB DB22 and 2022WUGs shapefile for which DB22 data for Municipal Users is applied.
Source TWDB-provided 2022WUGs shapefile associated with TWDB Draft 2022 State Water Plan
Date September 23, 2020

Title **Steam_Electric_WUG**
Type Feature Class in Geodatabase
Description Point File- Native data points from TWDB Water Use survey (2017) for which DB22 data for Steam Electric Users by County is applied. Parameter Data to roll up into grid cell.
Source TWDB-provided Steam_Electric_Power_Plants_2017 shapefile associated with Water Use Survey submitted by Steam Electric water users in 2017
Date September 23, 2020

Final Suitability Rating GIS Approach

The Final Suitability Screening section contains a discussion and detailed table of the sources of data for each of the parameters relevant to final ASR or AR suitability. Parameterization of the statewide (10,000 ft x 10,000 ft) grid was performed, as discussed in the Final Suitability Rating methodology section.

Final Suitability Rating GIS Files

ASR_AR_final_suitability_rating_20200923.gdb

Title **Final_ASR_suitability_rating_simple**
Type Feature Class
Description Simplified feature class with combined final values from all three individual screenings for ASR.
Source None
Date September 23, 2020

Title **Final_AR_suitability_rating_simple**
Type Feature Class
Description Simplified feature class with combined final values from all three individual screenings for AR.
Source None
Date September 23, 2020

Title **ASR_Final_Suitability_Score**
Type Feature Class in Geodatabase
Description Assimilation of hydrogeological, excess water, and water needs score for final ASR suitability. Unique record per cell, representing the maximum scoring aquifer, excess water, and water needs per grid cell. New information in this tool includes factoring distance in final score for ASR suitability.
Source No new source data. Used information generated from previous screen final grids.
Date September 23, 2020

Title **AR_Final_Suitability_Score**
Type Feature Class in Geodatabase
Description Assimilation of hydrogeological, excess water, and water needs score for final AR suitability. Unique record per cell, representing the maximum scoring aquifer, excess water, and water needs per grid cell. New information in this tool includes factoring distance in final score for AR suitability.
Source No new source data. Used information generated from previous screen final grids.
Date September 23, 2020

Appendix C- Hydrogeological Parameter Screening Details

Table 1 shows a summary of the suitability parameters and the data sources for those parameters derived from GAM or BRACS studies for the 31 major and minor aquifers in Texas. Each table cell notes the source and the coverage type (spatially-varying or constant).

Table 1 - Data Characteristics for Suitability Parameters Sourced from GAM or BRACs Studies

Minor and Major Aquifers	ASRCode	Storage Zone Depth	Available Drawup	Horizontal Hydraulic Conductivity	Aquifer Thickness	Depth to Water Table	Aquifer Storativity	Specific Yield	Available Drawdown	Hydraulic Gradient
Carrizo-Wilcox	CZWX	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Edwards (Balcones Fault Zone)	EBFZ	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Edwards-Trinity (Plateau)	ETPT	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV
Gulf Coast	GLFC	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV
Hueco-Mesilla Bolsons	HMBL	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Ogallala	OGLL	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Pecos Valley	PECS	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Seymour	SYMR	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Trinity	TRNT	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV
Blaine	BLIN	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Blossom	BLSM	BRACS,CV	BRACS,CV	BRACS,CV	GAM,SV	BRACS,CV	BRACS,CV	LIT,CV	BRACS,CV	BRACS,CV
Bone Spring-Victorio Peak	BSVP	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV
Brazos River Alluvium	BSRV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Capitan Reef Complex	CRCX	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV
Cross Timbers	CSTB	LIT,SV	LIT,SV	LIT,SV	LIT,SV	LIT,SV	LIT,SV	LIT,SV	LIT,SV	LIT,SV
Dockum	DCKM	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Edwards-Trinity (High Plains)	ETHP	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Ellenburger-San Saba	EBSS	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV

Minor and Major Aquifers	ASRCode	Storage Zone Depth	Available Drawup	Horizontal Hydraulic Conductivity	Aquifer Thickness	Depth to Water Table	Aquifer Storativity	Specific Yield	Available Drawdown	Hydraulic Gradient
Hickory	HCKR	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV
Igneous	IGBL	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Lipan	LIPN	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Marathon	MRTN	LIT,CV	LIT,CV	LIT,CV	GAM,SV	LIT,CV	LIT,CV	GAM,SV	LIT,CV	LIT,CV
Marble Falls	MBLF	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV
Nacatoch	NCTC	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Queen City	QNCT	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Rita Blanca	RTBC	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Rustler	RSLR	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV
Sparta	SPRT	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
West Texas Bolsons	WXBL	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV
Woodbine	WDBN	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	LIT,CV	GAM,SV	GAM,SV
Yegua-Jackson	YGJK	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV	GAM,SV

GAM = extracted from numerical GAM; BRACs = derived from BRACs study; SV = spatially varying;
CV = constant value assigned throughout aquifer

Scoring Method Details

Figure 1 illustrates the process of using Equation 1 to calculate a categorical score. The categorical scores (suitability for recharge, suitability for storage, and suitability for recoverability) are then combined to create final hydrogeologic suitability score. As with the parameter normalized scores, the categorical scores can also be assigned different weights, as determined through discussions of the team with TWDB staff. The final hydrogeologic suitability score is termed the ASR Score (or AR Score) and is calculated as follows:

$$Final\ Score = \frac{\sum_{i=1}^{n} weight_{CS,i}\, CS_i}{\sum_{i=1}^{n} weight_{CS,i}} \qquad \text{(Equation 2)}$$

In Equation 2, *Final Score* is the hydrogeologic ASR or AR suitability score (ASR Score and AR Score will be different for each statewide grid cell). **Figure 2** illustrates the process of using Equation 2 to calculate a hydrogeologic ASR suitability score. A similar process was used to calculate a hydrogeologic AR suitability score, using recharge and storage parameters. **Figure 3** provides an example calculation of final ASR and AR suitability scores for a single grid cell. Note that the different parameters and different weights will lead to different hydrogeologic ASR and AR suitability scores at the same cell.

The final hydrogeologic ASR or AR Score varies from a minimum of zero to a maximum of 1. The ASR Score is comparable across aquifers. Similarly, the AR score is comparable across aquifers. However, the ASR and AR scores are not directly comparable, since the weighting approach is applicable only to the strategy (ASR or AR) being considered.

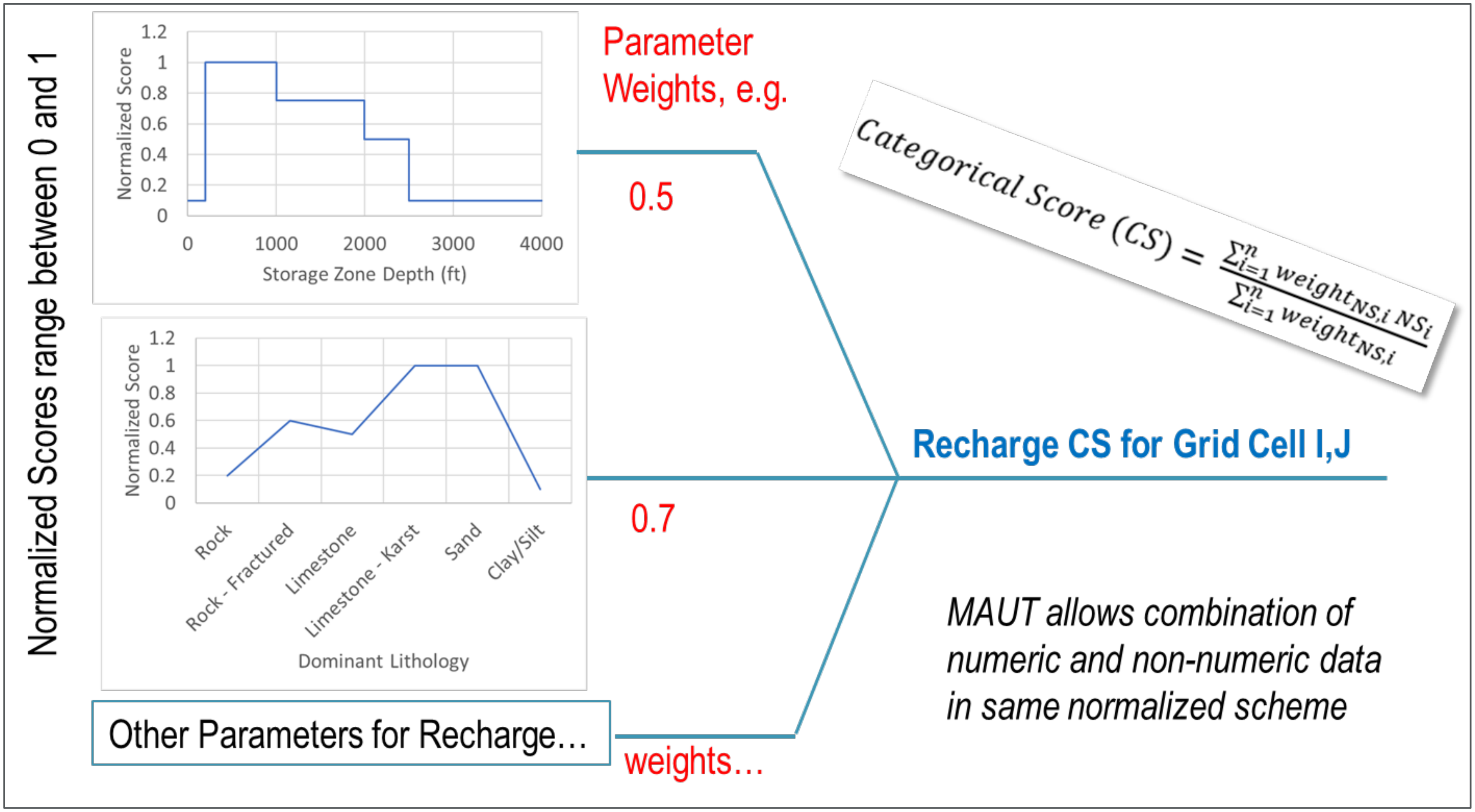


Figure 1. Example of how parameter scores and weights are combined to produce a categorical score (Recharge) for a grid cell.

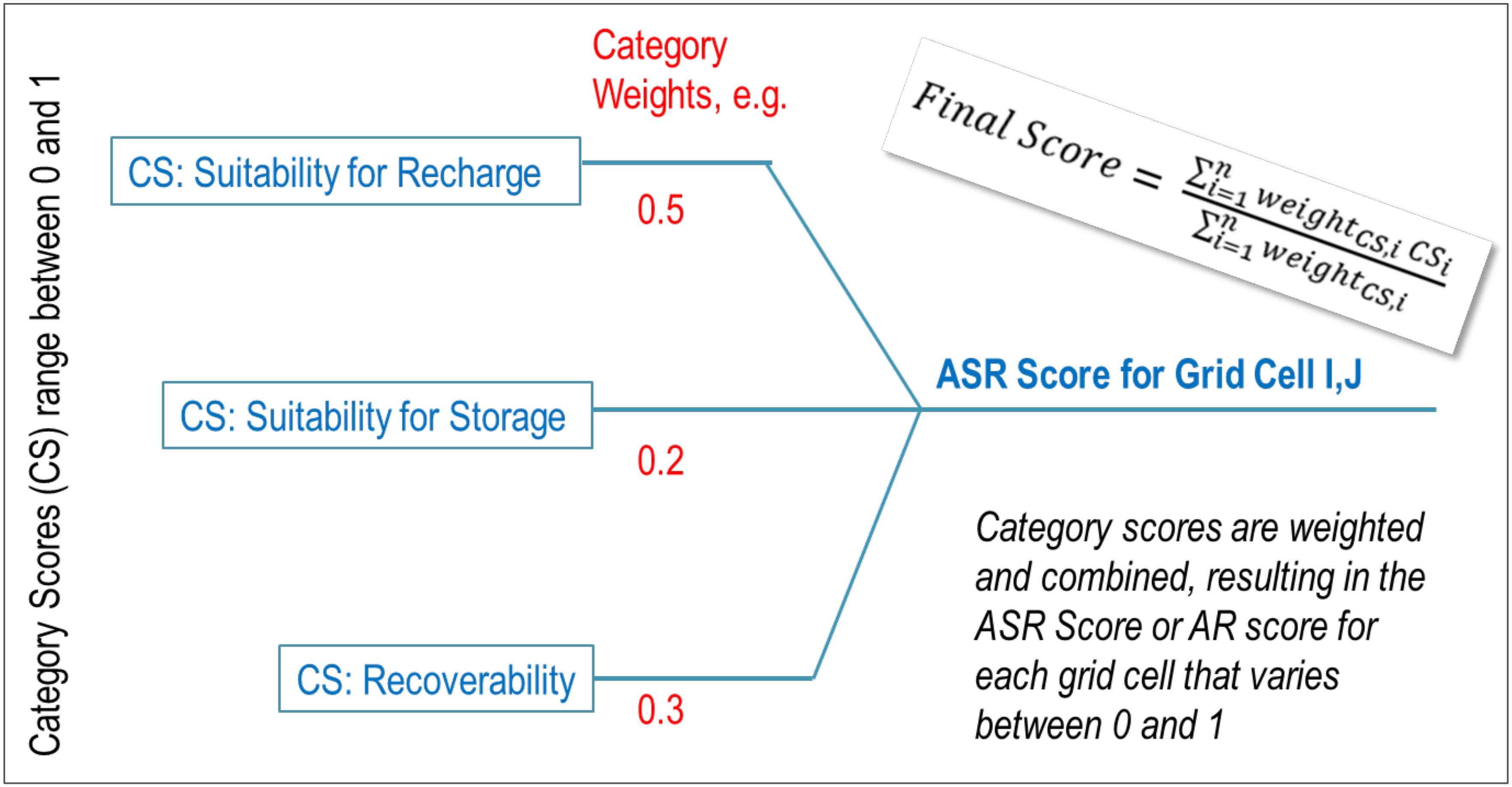


Figure 2. Illustration of how categorical scores and weights are combined to produce a final hydrogeologic suitability score for ASR for a grid cell.

Parameter	Category	ASR				AR			
		Value	Norm. Score (NS)	Wt	NS*Weight	Value	Norm. Score (NS)	Wt	NS*Weight
Vertical Hydraulic Conductivity	Recharge					0.31	0.10	0.25	0.03
Drawup Available	Recharge	76	0.20	0.50	0.10				
Horizontal Hydraulic Conductivity	Recharge	9	0.50	1.00	0.50	1.75	0.30	1.00	0.30
Topographic Slope	Recharge					1.1	1.00	0.50	0.50
Lithology	Recharge	sands	1.00	1.00	1.00	sands	1.00	1.00	1.00
Sediment Age	Storage	57	0.49	1.00	0.49	57	0.49	1.00	0.49
Specific Yield	Storage	0.1	0.75	0.50	0.38	0.1	0.75	1.00	0.75
Depth to Water	Storage					59	1.00	1.00	1.00
Thickness	Storage	437	1.00	0.50	0.50				
Confinement	Recoverability	unconf	0.10	1.00	0.10				
Groundwater Quality	Recoverability	473	0.90	0.75	0.68				
Drift Velocity	Recoverability	0.7	1.00	0.75	0.75				
Drawdown Available	Recoverability	678	1.00	0.50	0.50				
Recharge			0.64	0.33	0.21		0.62	0.71	0.44
Storage			0.68	0.33	0.23		0.88	0.29	0.25
Recoverability			0.68	0.33	0.22				
Final Suitability Score			**0.67**				**0.69**		

Figure 3. Example calculation of final suitability score.

ASR hydrogeological parameter score

A brief description of the parameters used to score ASR hydrogeological suitability is provided below.

Storage Zone Depth – Storage zone depth is a consideration for cost, temperature, and pumping technology factors affecting project viability. Wells deeper than 2,500 feet would likely require staging of the pump system, lower diameter well screens and as a result would be less productive generally. As a result, the scoring rationale reduces the suitability of wells deeper than 2500 feet and gives them a parameter score of 0.1. Because shallow ASR wells also offer challenges in hydraulic control, confinement and environmental protection, the normalized score was reduced for wells less than 200 feet depth.

Horizontal Hydraulic Conductivity – Horizontal hydraulic conductivity is important for both recharge and recovery in ASR. The parameter is positively correlated to suitability and score increases from 0.2, for values less than one foot per day to 1 for values greater than 30 feet per day. For reference, formations with hydraulic conductivity from 0.1 to 1 foot per day are generally considered marginal aquifers. Also, one can generally assume about one half the average productivity in recharge versus discharge in an ASR well.

Drawup Available – Drawup available is a parameter that is analogous to the more commonly used "drawdown available" (discussed below), but is relevant to recharge rather than recovery. Figure 4 illustrates how drawup available and drawdown available are calculated. The rate of recharge is dependent on both the transmissivity and the amount of positive head above static water level that is applied. The amount of positive static water level at the wellhead that can be applied is the sum of the distance from the head in the aquifer to ground surface, plus whatever additional overpressure can be applied (i.e. the height of head above ground surface that can be applied at the wellhead). Because the amount of overpressure is a well construction factor, we are considering only the distance from the head in the aquifer to ground surface for this parameter. The normalized score varies from a low of 0.1 for 50 feet to 1.0 for 400 feet or more. At 50 feet, overpressuring the wellhead is a likely requirement. At 400 feet, a specific recharge capacity of 1-2 gallons per minute per foot provides a recharge range of 400 to 800 gallons per minute, a desirable range for an ASR well.

Dominant Lithology – The type of aquifer and associated soils has a clear correlation to the suitability of ASR. Sediments that are clastic, have high porosity (low induration), high storativity, and high hydraulic conductivity are considered more favorable. The parameter score divides lithology classes between clay/silt, rock (assumed to be indurated), limestone, sand and gravel with gravel and sand getting the highest scores. For two lithology classes, an additional parameter was included to modify the dominant lithology parameter based upon secondary processes that have the potential to increase aquifer porosity and hydraulic conductivity. These two controls are fractures in indurated rocks and karst development in limestone. An example of the latter is the Edwards Aquifer. This parameter is not applied to the other lithology classes. The method proposed is to add the lithology score to the macro-porosity parameter to get a modified lithology suitability parameter based upon secondary processes altering the hydrologic properties associated with the lithology. **Table 2** shows the 31 aquifers and their assigned dominant lithology types.

Aquifer Thickness – In siting an ASR well, one generally wants to find a high productivity interval with good confinement both above and below. These intervals are typically on the range of 100 to 150 feet thick or less. At this thickness, the recharge water can generally be controlled, and the volume of mixing zone water is minimized and recharge water between wells can comingle. At the scale of this analysis, every 90 square-mile part of Texas aquifers could not effectively be characterized with a representative lithologic column. Therefore, we have used aquifer thickness as a proxy for finding an acceptable recharge interval. As a result, the suitability score increases with aquifer thickness which would imply that the probability of an acceptable recharge interval increases as the thickness increases. The normalized score of 0.1 at 100 feet of thickness reflects that low probability of any given 100 foot interval being an ideal storage zone. At 300 feet, chances of finding 100 feet of productive sand is much higher in a typical aquifer, so the score is set to 1.0.

Aquifer Storativity - Specific Storage is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head in a confined aquifer. Aquifer storativity is equal to the product of specific storage and aquifer thickness for a confined aquifer. The higher the aquifer storage, the more water can be recharged in the aquifer for a given increase in head over a set amount of time. The score for this suitability parameter increases with increasing storativity. The normalized scoring approach reflects a linear change versus logarithmic variation in storativity over the typical range in aquifer storativities, since storativity is typically a log-distributed parameter.

Specific Yield – Specific yield is used as an indicator of storage potential in unconfined aquifers. It is directly correlated to the storage potential of an unconfined aquifer and therefore the score is directly correlated (score increases as specific yield increases). Similar to storativity, the normalized score was varied over the typical range of specific yield values found in Texas aquifers. The lower specific yield values are typically found in aquifers dominated by secondary porosity (such as karst aquifers).

Sediment Age - Sediment age was used as a qualitative indication of aquifer induration. As sediments become older and subject to both deep burial processes and near surface processes, the rocks generally lose porosity and become more indurated. This has a tendency to increase heterogeneity and reduce storativity, both which are important to suitability for ASR. The normalized score was varied from 0.1 to 1 based on sediment age from the start of the Eocene (56 mya) to the start of the Cambrian (541 mya). **Table 2** shows the 31 aquifers and their assigned ages.

Groundwater Quality – Groundwater quality has several implications for AR, including recovery efficiency and treatment costs from constituents in the vadose zone being mobilized into the saturated zone and ultimately the recovered water. At the scale of this analysis, detailed chemical data which may identify areas suitable because of vadose zone constituent mobilization or cause issues with treatment is generally lacking. However, total dissolved solids (TDS) is available for all aquifers at the scale required for this analysis. Generally, the higher the TDS in the receiving aquifer, the lower the recovery efficiency and recoverability, due to the increased size of the mixing zone between the recharge water and native groundwater. The normalized score was just varied linearly within the typical range of TDS for the major and minor aquifers in Texas.

Confinement – Overall confinement, combined with thickness, provides the best opportunity to find good target storage zones. In an unconfined aquifer, recoverability can be a challenge because you lack the ability to control vertical hydraulics. In addition, unconfined aquifers can be more vulnerable to influence from surface activities. The normalized score is has only low and high values (binary field), reflecting the challenge of achieving confinement in unconfined aquifers versus confined aquifers.

Drift Velocity – Drift velocity is the tendency of the centroid of the stored water to drift away from the recharge well location. The greater the drift velocity, the more consideration must be taken on wellfield design in order to ensure good recoverability. Drift velocity is estimated by multiplying the hydraulic gradient by the hydraulic conductivity, then dividing by estimated porosity. A "rule-of-thumb" for the most suitable drift velocity is less than 20 feet per year (David Pyne, personal communication), while as much as 100 feet per year is still acceptable without additional considerations for hydraulic control. Over 100 feet per year may require additional extraction wells or other forms of hydraulic control.

Drawdown Available – Drawdown available is the distance from the static water level to the top of the aquifer for a confined aquifer, or the distance from static water level to some minimum saturated thickness in an unconfined aquifer. **Figure 4** illustrates drawdown available for a confined aquifer. Because productivity is dependent on both transmissivity (hydraulic conductivity multiplied by the completion interval length) and the amount of drawdown created at the well, drawdown available is an important factor in recoverability. The normalized scoring approach is identical to drawup available.

Table 2 – Assigned lithologies and ages

Aquifer	Lithology	Age (mya)
CZWX	sands	62-52
EBFZ	limestone	108
ETPT	limestone	125-100.5
GLFC	sands	24-0
HMBL	sands	18-0
OGLL	sands	12-4
PECS	sands	38-0
SYMR	sands	2-0
TRNT	sands	125-108
BLIN	shale	272-260
BLSM	sands	90-80
BSVP	limestone	280-271
BSRV	sands	0.012-0
CRCX	limestone	272-260
CSTB	sandstone	308-280
DCKM	sandstone	223-200
ETHP	limestone	125-100.5
EBSS	limestone	500-472
HCKR	sandstone	541-509
IGBL	rock	48-27
LIPN	gravels	2.6-0.012
MRTN	limestone	488-299
MBLF	limestone	318-311
NCTC	sands	71-66
QNCT	sands	48-38
RTBC	sands	161-94
RSLR	limestone	260-251
SPRT	sands	48-38
WXBL	sands	23-0
WDBN	sandstone	100-94
YGJK	sands	48-34

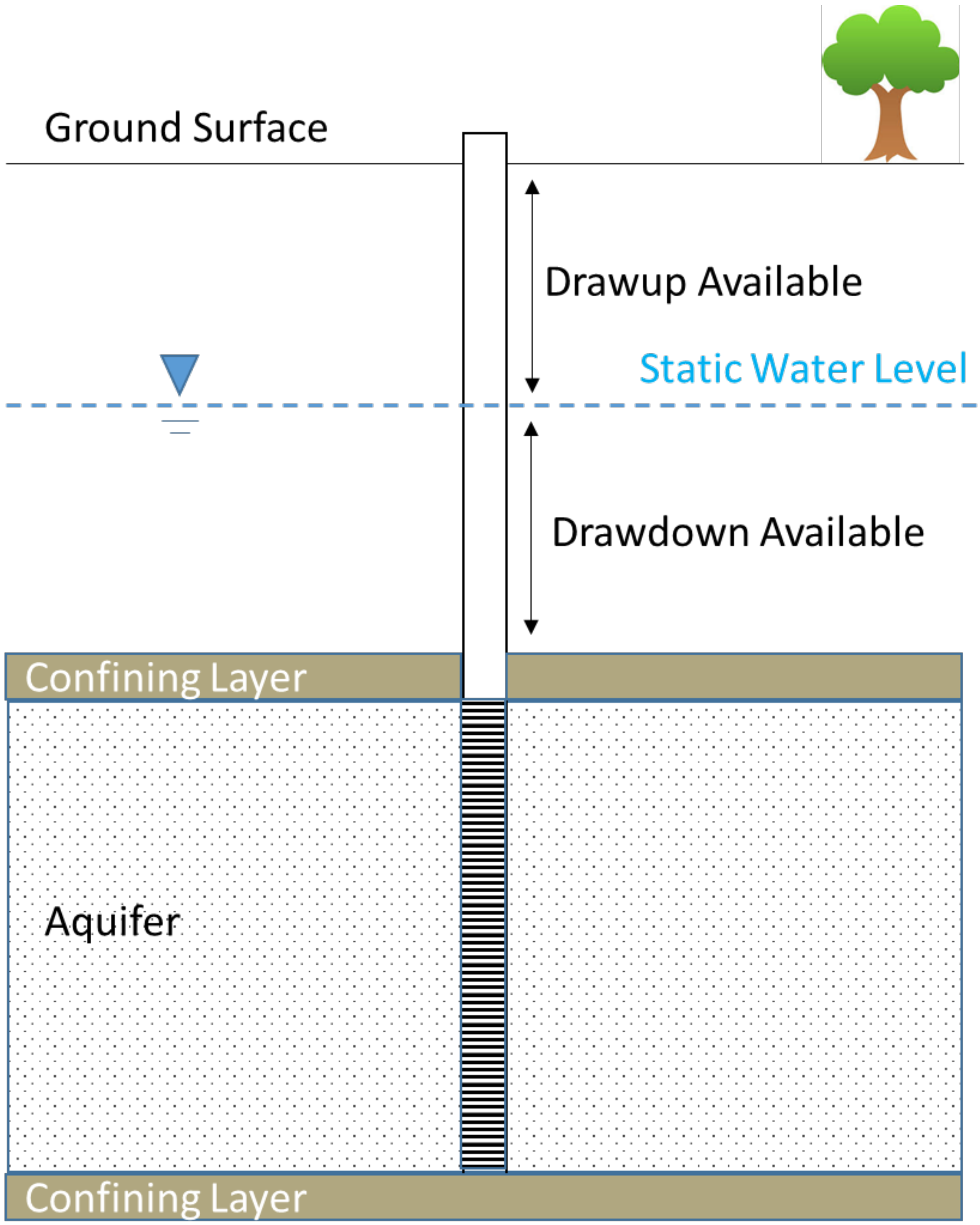


Figure 4. Illustration of drawup available and drawdown available.

AR hydrogeological parameter score

A brief description of the parameters used to score AR hydrogeological suitability is provided below.

Vertical Hydraulic Conductivity – Hydraulic conductivity is a property of an aquifer that describes the ease with which water can move through pore spaces. It depends on the pore structure of the aquifer deposits, the degree of saturation, and on the density and viscosity of the fluid in the pore space. Hydraulic conductivity orthogonal to aquifer bedding is called vertical hydraulic conductivity. Vertical hydraulic conductivity has a large influence on the rate at which water can be recharged from a spreading basin or other surface facility. A vertical hydraulic conductivity of less than 5 ft/day is considered low suitability, while greater than 20 ft/day receives the highest suitability score. The scoring approach for this parameter is primarily based on the direct experience of team members in constructing infiltration ponds.

Horizontal Hydraulic Conductivity – Horizontal hydraulic conductivity is important for both recharge and recovery in AR. The parameter is positively correlated to suitability and score increases from 0.2, for values less than one foot per day to 1 for values greater than 30 feet per day. As with ASR, a 1 foot per day hydraulic conductivity is considered a marginal aquifer, while 30 feet per day or greater is consistent with aquifers having greater than 1,000 gallons per minute (gpm) wells, which are some of the highest producers in Texas.

Topographic Slope – Topographic slope is a control for surface AR in the construction of impoundments. The natural competing runoff characteristics associated with high topographic gradients and high slope areas are more prone to seeps and levee bypass. In addition, costs are higher as the slope increases. Infiltration ponds should be constructed in areas sloping less than 5% (Pedrero and others, 2011; Ahmadi and others, 2017). The breaks used in scoring are based on analysis of statewide topography.

Lithology Type – The type of aquifer and associated soils has a clear correlation to the suitability of AR. Sediments that are clastic, have high porosity (low induration), high vertical hydraulic conductivity and low anisotropy are most suitable for AR. The vertical hydraulic conductivity is discussed above. Anisotropy is very hard to characterize regionally. Soil data and underlying unweathered, parent aquifer material information can be used to characterize the dominant lithology. The scoring approach was identical to that described in the previous ASR section.

Sediment Age - Sediment age was incorporated to provide a qualitative indication of aquifer induration. The scoring approach was identical to that described in the previous ASR section.

Specific Yield – Specific yield is a parameter that describes the storage potential, per unit volume of aquifer, of an unconfined aquifer. The scoring approach was identical to that described in the ASR section.

Depth to Water Table – The depth to water table, which is the thickness of the vadose zone, impacts the suitability of AR both in terms of the available storage potential and the ability for the recharged water to maintain high saturation and therefore high infiltration rates. The score maximizes at thicknesses from 30 to 300 feet. Deeper than 300 feet decreases the score due to the increasing time and water volume required for recharge. The scoring approach for this parameter is primarily based on the direct experience of team members in constructing infiltration ponds and other AR systems.

Weighting

The results of the sensitivity analysis for ASR hydrogeological suitability scoring is shown in **Table 3**, and for the AR hydrogeological suitability scoring in **Table 4**. These tables show the combinations of parameter weights that result in the highest hydrogeologic suitability score for each aquifer. Comparing the "optimum" weighting scheme to the weights that were selected provides insight into how hydrogeologic suitability scores for a particular aquifer would change with changing weights.

Table 3 – Weight combinations resulting in highest ASR hydrogeological suitability score

Aquifer	Storage Zone Depth	Hydraulic Conductivity	Drawup Available	Lithology	Thickness	Storativity	Specific Yield	Sediment Age	Confinement	Groundwater Quality	Drift Velocity	Drawdown Available
CZWX	0	0	0	1	1	0	0	1	0	0	1	1
EBFZ	0	1	0	1	1	0	0	1	1	1	1	0.5
ETPT	1	1	0	0	1	0	1	1	0	1	1	0
GLFC	1	1	0	1	1	0	1	1	0	1	1	1
HMBL	0	0	0	1	0	0	1	1	0	0	1	1
OGLL	0	1	0	1	0	0	1	1	0	1	1	0
PECS	0	1	0	1	0	0	1	1	0	1	1	0
SYMR	0	1	0	1	0	0	1	1	0	1	1	0
TRNT	0.5	0	0	1	1	0	0	1	1	0	1	0
BLIN	0.5	1	0	0	1	0	0.5	0	0.5	0	1	0
BLSM	0	0	0	1	0	0	1	1	0	1	1	0
BSVP	1	1	0.5	0	1	0	1	0	0	1	1	1
BSRV	0	1	0	1	0	0	1	1	0	1	1	0
CRCX	0	0	0	1	1	0	1	0	0	0	1	0
CSTB	0	0	1	1	1	0	1	1	0	1	1	0
DCKM	1	0	0.5	1	1	1	0	1	1	0	1	0
ETHP	0	1	0	0	0	0	1	1	0	1	1	0
EBSS	1	0	0	1	1	1	0	0	0.5	0	1	0
HCKR	0	1	0	1	1	1	0	0	0.5	0	1	1
IGBL	1	0	1	1	1	0	0	1	0	1	1	1
LIPN	1	0	0	1	1	0	0	1	0	1	1	1
MRTN	1	0	1	1	1	0	0	0	0	1	1	1
MBLF	0	1	0	1	0	0	1	1	0	1	1	0
NCTC	1	0	0	1	0	0	0	1	0	1	1	0
QNCT	1	0	0	1	1	0	1	1	0	1	1	0
RTBC	0	0	0	1	0	0	1	1	0	1	1	0
RSLR	1	0	0	1	1	1	0	1	1	0	1	1
SPRT	1	0	0	1	0	1	0	1	1	0	1	0.5
WXBL	0	0	0	1	1	0	0	1	0	1	1	0
WDBN	1	0	1	1	0	0	0	1	0	0	1	0
YGJK	1	0	0	1	0	0	1	1	0	1	1	1

Table 4 – Weight combinations resulting in highest AR hydrogeological suitability score

Aquifer	Vertical Hydraulic Conductivity	Hydraulic Conductivity	Slope	Lithology	Sediment Age	Specific Yield	Depth to Water Table
CZWX	0	0	1	1	0	0.5	1
EBFZ	0	1	0	1	0	0	1
ETPT	0	1	0	0	0	0.5	0
GLFC	0	0	1	1	1	1	0
HMBL	0	0	0	1	1	1	0
OGLL	0	0	1	1	1	1	0
PECS	0	0	1	1	1	1	1
SYMR	0	1	1	1	1	1	0
TRNT	0	0	0.5	1	0	1	0
BLIN	0	1	1	0	0	0.5	0
BLSM	0	0	1	1	0	1	0
BSVP	0	1	1	0	0	1	0
BSRV	0	1	1	1	1	1	0
CRCX	0	1	0	1	0	0	0
CSTB	0	0	1	1	0	1	1
DCKM	0	0	1	0	0	0.5	0
ETHP	0	1	1	0	0	0	1
EBSS	0	1	0	1	0	1	0.5
HCKR	0	1	0	1	0	1	0
IGBL	0	0	0	1	1	0	1
LIPN	0	0	0	1	1	0	1
MRTN	0	0	1	1	0	0	1
MBLF	0	0	0	0	0	1	0
NCTC	0	0	1	1	0	0	1
QNCT	0	0	1	1	0	1	0
RTBC	0	0	1	1	0	0	1
RSLR	0	0	1	1	0	0	0.5
SPRT	0	0	0	1	0	0	0
WXBL	0	0	0	1	1	0	0
WDBN	0.5	0	1	1	0	1	0
YGJK	0	0	1	1	0	0	1

Appendix D- Excess Water Screening Details

Excess Surface Water Methodology and Scoring

Surplus Appropriated Surface Water (Reservoirs and Run-of-River)

Methodology

The following methodology was applied to obtain data related to the availability of surplus surface water that is already appropriated.

1. Reservoir and run-of-river surplus surface water supplies for the 2020-2070 (6 decade) period from TWDB DB22 report data was extracted and compiled by county.
2. If surplus water supplies are planned to be utilized by recommended Water Management Strategies, these supplies were removed from consideration as excess water.
3. For Run-of-River Surplus Appropriated Surface Water, DB22 records were provided for basin and county only. HDR identified the longest stream in the respective basin and county and placed a point at the centroid of the reach.
4. For Reservoir Surplus Appropriated Surface Water, the centroid of the reservoir was used as the point.
5. Run-of-river and reservoir point surplus volumes were summed within a grid cell of the surplus appropriated surface water grid layer. The summation of surplus volumes within a grid cell represents surplus appropriated surface water sources being independent of each other and the ability of an ASR or AR project to utilize multiple sources within a grid cell.
6. Scores were calculated at the surplus appropriated surface water grid level. Scoring criteria is detailed below.

Scoring

Surplus appropriated run-of-river and reservoir supply availability volume is scored as follows, based on the 2020-2070 (6 decade) period reported in the 2021 Initially Prepared Plans:

- Average decade surplus amount (2020-2070) < 500 acft/yr - 0
- Average decade surplus amount (2020-2070) between 500 and 2,500 acft/yr - 0.25
- Average decade surplus amount (2020-2070) between 2,500 and 15,000 acft/yr - 0.50
- Average decade surplus amount (2020-2070) between 15,000 and 35,000 acft/yr - 0.75
- Average decade surplus amount (2020-2070) > 35,000 acft/yr – 1

Surplus appropriated run-of-river and reservoir supply availability frequency is proposed to be scored as follows, based on the 2020-2070 (6 decade) period reported in the 2021 Initially Prepared Plans:

- No surplus amount - 0
- Surplus amount in 1 decade - 0.25
- Surplus amount in 2 or 3 decades - 0.50
- Surplus amount in 4 or 5 decades - 0.75
- Surplus amount in all 6 decades - 1

Surplus appropriated run-of-river and reservoir supply availability duration is proposed to be scored as follows, based on the 2020-2070 (6 decade) period reported in the 2021 Initially Prepared Plans:

- No consecutive decades – 0
- 2 consecutive decades – 0.25
- 3 consecutive decades – 0.5
- 4 consecutive decades – 0.75
- 5-6 consecutive decades – 1

Unappropriated Streamflow

Methodology

The TCEQ evaluates the availability of unappropriated streamflow for water right permit applications using the TCEQ Water Availability Models. The following methodology was applied to identify and score the availability of unappropriated streamflow or the excess surface water remaining after all existing water rights and TCEQ adopted environmental flow standards are satisfied.

1. The most recent TCEQ full authorization (Run 3) water availability models (WAMs) for all river and coastal basins in Texas were obtained from TCEQ. The Run 3 WAMs conservatively assume permitted surface water use and storage and no return flows and are the WAMs used by TCEQ staff to evaluate new permit applications such as those for use of surface water for ASR. Statistics considered in scoring the frequency, volume, and duration of available unappropriated surface water and delivered in point geodatabase deliverable are included in **Table 1**.

2. The TCEQ Run 3 WAMs include the TCEQ adopted instream flow standards at most but not all locations. For locations where TCEQ adopted instream flow standards have not been included, the WAMs were modified to include base flow criteria at TCEQ instream flow measuring locations. In river basins for which TCEQ has not adopted instream flow

standards, instream flow requirements were developed using the Lyons Method[1] at select locations where long-term streamflow data is available and included in the WAMs. No other modifications to the WAMs were made so as to maintain consistency across the state and prevent biased alterations to the evaluation of unappropriated streamflow. A table included in the main report summarizes the river and coastal basins in Texas and lists the basins for which TCEQ has adopted instream environmental flow standards and whether such standards are included in the WAM. **Tables 2 and 3** summarize the locations where base flow standards were added to the WAMs and the locations where instream flow criteria based on the Lyons Method were added to the WAMs.

3. The WAMs were applied to calculate monthly unappropriated streamflow at all primary and secondary control points for the existing period of record included in models. WAM control points are located at all water right diversion locations, significant stream confluences, and reservoir locations.

4. Monthly time series of unappropriated streamflow was extracted for every control point from WAM output files and statistical analyses were performed related to the frequency, volume, and duration of available unappropriated surface water for ASR. Statistics for each control point is shown in **Table 1**.

5. The geodatabase of WAM control point locations was obtained from TCEQ and statistics were joined to the geodatabase for each control point.

6. A new appropriation of State water must also comply with adopted TCEQ Freshwater Inflow Standards. Consideration of freshwater water inflow standards was included in the screening by calculating the straight line distance from WAM control points to the coast. To account for the difference in straight line distance and river mile distance to the coast from a WAM control point, a multiplication factor of 2 was applied to the straight line distance. Control points located further upstream from the bay and estuary receive a more favorable score as diversions of surface water further inland will have less effect on freshwater inflows.

7. Scores were calculated for control points.

8. The composite score of the highest ranking control point within a grid cell of the unappropriated streamflow grid layer was selected as the composite score for the grid cell. The highest composite point score is used as opposed to summing the scores of all points

[1] Bounds, R. and Lyons, B. (1979). *Existing Reservoir and Stream Management: Statewide Minimum Streamflow Recommendations*. Texas Parks and Wildlife Department, Austin, Texas.

because available unappropriated streamflow is not independent amongst control points. For example, if unappropriated streamflow is diverted at an upstream point, the amount of unappropriated streamflow at a downstream control point will be reduced.

9. In many instances, WAM control points are not located within a 10 mile grid cell or are located on a small tributary within a grid cell that contains a larger stream. For these instances, composite grid cell scores were interpolated from surrounding grid cells.

Scoring

Table 1 lists the statistics considered for the scoring of the availability of unappropriated streamflow. The following statistics were selected for use in the proposed scoring of volume, frequency, and duration, parameters included in the relative suitability ranking in the excess water screening tool. Scoring of volume, frequency, and duration parameters using the WAM unappropriated streamflow statistics carry 90% of the weight of the available unappropriated streamflow score. Scoring of volume, duration, and frequency related to the consideration of FWI standards carry 10% of the weight of the available unappropriated streamflow score.

Available unappropriated streamflow <u>volume</u> is scored as follows:

- Median Annual Volume is < 500 acft– 0
- Median Annual Volume is between 500 afy and 2,500 afy – 0.25
- Median Annual Volume is between 2,500 afy and 15,000 afy – 0.5
- Median Annual Volume is between 15,000 afy and 35,000 afy – 0.75
- Median Annual Volume is greater than 35,000 afy – 1

Available unappropriated streamflow frequency is scored based on Percentage of Months with Available flow:

- The actual percentage is the score (i.e. if a WAM control point has available flow in 36% of the months, then the score is 0.36)

Available unappropriated streamflow <u>duration</u> is scored as the sum of the following two parameters:

- Maximum consecutive years with available flow greater than the median annual available flow at a control point. A 5-year consecutive period was selected as the breakpoint for scoring based upon statistical analyses of all control points indicating 5-years as the median value for this statistic.
    - o Less than 5 years – 0
    - o 5 years or more – 0.5

- Maximum consecutive years with available flow less than the median annual available flow at a control point. An 8-year consecutive period was selected as the breakpoint for scoring based upon statistical analyses of all control points indicating 8-years as the median value for this statistic.
    - More than 8 years – 0
    - 8 years or less – 0.5

In consideration of TCEQ Freshwater Inflow Standards to Bay and Estuary environments, the distance from control points to the coast is factored into the frequency, duration, and volume of the available unappropriated streamflow as follows:

Straight line distance from the coast multiplied by a factor of 2 for available unappropriated streamflow points:

- Less than 50 miles – 0
- Between 50 and 100 miles – 0.25
- Between 100 and 150 miles – 0.5
- Between 150 and 200 miles – 0.75
- Greater than 200 miles – 1

Existing Reservoir Storage

Methodology

1. Reservoir storage volumes for existing reservoirs were obtained from the TWDB Water Data for Texas website[2], which includes the 117 major monitored water supply reservoirs in Texas. Elephant Butte, located in New Mexico, was not included in the study. For major reservoirs in Texas not listed on the Water Data for Texas website, permitted reservoir storage volumes were obtained from the TCEQ WAMs.

2. Reservoirs not used for water supply purposes were excluded from consideration.

3. The centroid of the reservoir was determined using GIS applications.

4. Reservoir storages were summed within a grid cell of the existing reservoir storage grid layer. The summation of point scores within a grid cell represents reservoir storage being independent of each other and the ability of an ASR or AR project to utilize multiple reservoirs within a grid cell.

5. Scores were calculated at the grid level.

[2] https://waterdatafortexas.org/reservoirs/statewide

Scoring

Existing reservoir storage availability volume is scored as follows:

- No storage or storage less than 5,000 acft[3] - 0
- Storage between 5,000 acft and 100,000 acft - 0.5
- Storage greater than 100,000 acft - 1

Existing reservoir storage availability frequency is scored as follows. If significant reservoir storage is present, the frequency of availability is considered to be always available and receive a score of 1.

- No storage or storage less than 5,000 acft - 0
- Storage greater than 5,000 acft - 1

Existing reservoir storage availability duration is scored as follows. If significant reservoir storage is present, the duration of availability is considered to be unlimited and receive a score of 1.

- No storage or storage less than 5,000 acft - 0
- Storage greater than 5,000 acft - 1

Assimilating Sources of Excess Surface Water

Scores (ranging from 0-1) for the surplus appropriated surface water (reservoirs and run-of-river), unappropriated streamflow, and existing reservoir storage grid layers were summed and capped at a value of one for each cell at the grid layer. Summing the component scores demonstrates flexibility of an ASR or AR project to utilize multiple excess surface water components within a grid cell.

Excess Reclaimed Water

Methodology

The following methodology was applied to estimate the availability of excess reclaimed water.

1. Publicly available geodatabase of TPDES discharge locations were obtained from the TCEQ.

2. Historical effluent discharge amounts for the previous 5 years were obtained from the EPA Enforcement and Compliance History Online (ECHO) database from 2015-2019 at all available TPDES permitted discharge locations to estimate current available reclaimed

[3] The method is consistent with TWDB State Water Plans, which defines major reservoirs as those with conservation pool greater than or equal to 5,000 acft.

water. Average annual discharge (2015-2019) was used as an estimate of current excess water available.

3. County population projections were obtained from TWDB through 2070 and decadal growth rates were calculated by county. Future available reclaimed water volume was projected using current treated effluent discharge amounts from ECHO database and county population projections. The 2040 future projection was selected to evaluate reclaimed water volume, considered to represent the mid-point value of reclaimed water availability for the 2020-2070 State Water Plan planning horizon.

4. ECHO database values and projected available reclaimed water volumes were intersected with TCEQ TPDES discharge locations to assign discharges spatially using a common join identifier.

5. Reclaimed water discharge volumes were summed within a grid cell of the reclaimed water grid layer. The summation of discharge volumes within a grid cell represents reclaimed water discharges being independent of each other and the ability of an ASR or AR project to utilize multiple reclaimed water sources within a grid cell.

6. Scores were calculated at the grid level.

Scoring

Reclaimed water availability volume is scored as follows based on 2040 projected discharges:

- Annual discharge volume < 500 acft/yr - 0
- Annual discharge volume between 500 and 2,500 acft/yr - 0.25
- Annual discharge volume between 2,500 and 15,000 acft/yr - 0.50
- Annual discharge volume between 15,000 and 35,000 acft/yr - 0.75
- Annual discharge volume supply > 35,000 acft/yr – 1

Reclaimed water availability frequency is scored as follows based on 2040 projected discharges estimated to be available (0- no; 1- yes).

Reclaimed water availability duration is scored as 1 if excess water exists. It received 0 score if unavailable.

Excess Groundwater Parameters

Methodology

Excess groundwater water obtained from the Draft State Water Planning Database (draft DB22) on a decadal basis from 2020 through 2070. The source data was generally based Modeled Available Groundwater (MAG) identified through the GCD/TWDB process remaining after considering existing supplies and recommended future water management strategies in support of the regional water planning process. Data was presented by aquifer on a county and river basin level. Each excess groundwater supply and aquifer, county, river basin combination was clipped to the grid level coincident with the Hydrogeological Screening Tool (Task 2) for the 31 major and minor aquifers. Other aquifers, represented about 3% of the overall excess groundwater available from draft DB22 and was not included in the screening tool due to a lack of specific location suitable for clipping to the grid cell with accuracy. Feature classes were developed for Major and Minor aquifers with one to many combinations to account for aquifers that are coincident with one another. The maximum scoring aquifer for excess groundwater for each cell was presented in the Excess_Groundwater_Final_Grid (Final Grid) and assimilated with Final Surface Water and Reclaimed Water Grids for the Final Suitability Rating.

Scoring

Excess groundwater supply availability volume is assumed to be the minimum MAG over the 2020-2070 planning period. The scoring of this parameters is as follows:

- Min MAG < 500 acft/yr - 0
- Min MAG between 500 and 2,500 acft/yr - 0.25
- Min MAG between 2,500 and 15,000 acft/yr - 0.50
- Min MAG between 15,000 and 35,000 acft/yr - 0.75
- Min MAG > 35,000 acft/yr - 1

Excess groundwater supply frequency is scored as follows, for consistency with the appropriated surface water excess water approach:

- MAG less than 500 acft/yr in all decades - 0
- MAG greater than 500 acft/yr in 1 decade - 0.25
- MAG greater than 500 acft/yr in 2 or 3 decades - 0.50
- MAG greater than 500 acft/yr in 4 or 5 decades - 0.75
- MAG greater than 500 acft/yr in all 6 decades - 1

Excess groundwater supply availability duration is proposed to be scored as follows, based on the 2020-2070 (6 decade) period reported in the 2021 Initially Prepared Plans:

- MAG greater than 500 acft/yr in no consecutive decades – 0
- MAG greater than 500 acft/yr in 2 consecutive decades – 0.25
- MAG greater than 500 acft/yr in 3 consecutive decades – 0.5
- MAG greater than 500 acft/yr in 4 consecutive decades – 0.75
- MAG greater than 500 acft/yr in 5-6 consecutive decades – 1

Table 1 – Proposed Data and Statistics to be Considered in Scoring of Excess Water Screening Parameters[1,2]

Excess Water Source	ID	Parameter	Statistic	Data Source	Locations
Surface Water	WAM Control Point No.	Frequency	Percentage of Years with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of All Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of January Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of February Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of March Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of April Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of May Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of June Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of July Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of August Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of September Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of Oct Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of November Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency	Percentage of December Months with Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	90th Percentile of Monthly Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	75th Percentile of Monthly Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	50th Percentile of Monthly Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	25th Percentile of Monthly Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	10th Percentile of Monthly Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	5th Percentile of Monthly Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	1st Percentile of Monthly Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	90th Percentile of Annual Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	75th Percentile of Annual Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	50th Percentile of Annual Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	25th Percentile of Annual Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	10th Percentile of Annual Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	5th Percentile of Annual Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Volume	1st Percentile of Annual Available Flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Duration	Max Consecutive Months with Available Flow Less than median flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Duration	Max Consecutive Months with Available Flow Greater than median flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Duration	Max Consecutive Years with Available Flow Less than median flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Frequency/Duration	Max Consecutive Years with Available Flow Greater than median flow	TCEQ WAMs	All WAM Control Points
Surface Water	WAM Control Point No.	Volume/Duration/Frequency	Distance from Coast	TCEQ GIS Database	All WAM Control Points
Surface Water	County	Volume/Duration/Frequency	2020-2070 Surplus Reservoir Supply	TWDB DB22	All Counties
Surface Water	County	Volume/Duration/Frequency	2020-2070 Surplus Run-of-River Supply	TWDB DB22	All Counties
Reclaimed water	County	Volume/Duration/Frequency	2020-2070 Surplus Reclaimed water Supply	TWDB DB22	All Counties
Reclaimed water	County	Volume/Duration	Future Reclaimed water Supply Surplus	EPA ECHO Database	All Counties
Groundwater	Aquifer Name	Volume	Minimum Available MAG (2020-2070)	TWDB DB22	All aquifers, by river basin in each county
Groundwater	Aquifer Name	Frequency	1= MAG available; 0= MAG not available	TWDB DB22	All aquifers, by river basin in each county
Groundwater	Aquifer Name	Duration	Number of consecutive decades for which minimum MAG is available	TWDB DB22	All aquifers, by river basin in each county

[1]Ranking and scoring of data and statistics will be developed after statistical analysis is completed.

[2]Parameters listed will be included in a point geodatabase separate, and as a pre-cursor to the excess screening tool grid geodatabase.

Table 2 – Summary of Base Flow Criteria Locations Added to WAMs

Gage	Name	Gage	Name
Colorado[1]		**Nueces[3]**	
8123850	Colorado River above Silver	8190500	West Nueces River near Brackettville
8126380	Colorado River near Ballinger	8192000	Nueces River below Uvalde
8147000	Colorado River near San Saba	8194000	Nueces River at Cotulla
8127000	Elm Creek at Ballinger	8194500	Nueces River near Tilden
8136500	Concho River at Paint Rock	8195000	Frio River at Concan
8128000	South Concho River at Christoval	8196000	Dry Frio near Reagan Wells
8143600	Pecan Bayou near Mullin	8198000	Sabinal River near Sabinal
8146000	San Saba River at San Saba	8198500	Sabinal River at Sabinal
8151500	Llano River at Llano	8200000	Hondo Creek near Tarpley
8153500	Pedernales River near Johnson City	8201500	Seco Creek at Miller Ranch near Utopia
8158700	Onion Creek near Driftwood	8205500	Frio River near Derby
Guadalupe-San Antonio[2]		8206600	Frio River at Tilden
8167000	Guadalupe River at Comfort	8206700	San Miguel Creek near Tilden
8167500	Guadalupe River near Spring Branch	8208000	Atascosa River at Whitsett
8171000	Blanco River at Wimberley	8210000	Nueces River near Three Rivers
8172000	San Marcos River at Luling	8211000	Nueces River near Mathis
8173000	Plum Creek near Luling	8211520	Oso Creek at Corpus Christi
8175000	Sandies Creek near Westhoff	8211900	San Fernando Creek at Alice
8178880	Medina River at Bandera	**Rio Grande[1]**	
8181500	Medina River at San Antonio	8375000	Rio Grande at Johnson Ranch
8181800	San Antonio River near Elmendorf	8377200	Rio Grande at Foster Ranch
8186000	Cibolo Creek near Falls City	8446500	Pecos River near Girvin
8188500	San Antonio River at Goliad	8449400	Devils River at Pafford Crossing near Comstock
		Brazos-Colorado Coastal[1]	
		8117500	San Bernard River near Boling
		Colorado-Lavaca Coastal[1]	
		8162600	Tres Palacios River near Midfield
		Nueces-Rio Grande Coastal[3]	
		8211520	Oso Creek at Corpus Christi
		8211900	San Fernando Creek at Alice
		San Antonio-Nueces Coastal[2]	
		8189500	Mission River at Refugio

Note: For basins with multiple tiers of base flow included in the TCEQ standards, the seasonal Low (Dry) base flow values were selected to provide reasonable estimates of availability and consistency with the Lyons Method instream flow criteria used for basins without adopted TCEQ standards. The Low (Dry) base flow values in the TCEQ standards are generally approximate to the 25^{th} percentile base streamflow statistic and are comparable to Lyons Method values computed as 40% or 60% of the median monthly streamflow.

1-Seasonal Low (Dry) base flows from the TCEQ standards were added to the WAMs.

2-Seasonal Low (Dry) base flows from the Guadalupe-San Antonio BBEST report were added to the WAM at the Guadalupe River Basin measurement points. The TCEQ adopted the high base flows recommended by the BBASC along with a 50% rule applicable between base and subsistence. As a result, the Low (Dry) base flow values (without a 50% rule) will provide more reasonable approximations of water availability than simple insertion of the high base flow values that appear in the Guadalupe River Basin standards.

3-Only one tier of base flow criteria are included in the adopted TCEQ standards and these criteria were added to the WAMs

Table 3 – Summary of Locations Lyons Method Instream Flow Criteria were added to WAMs

USGS Gage	Name	Beginning of POR	End of POR	Notes
Canadian				
7228000	Canadian River nr Canadian, TX	4/1/1938	4/27/2020	
Cypress				
7346000[1]	Big Cypress Bayou nr Jefferson, TX	8/1/1924	4/27/2020	Below Lake O' the Pines
7346070	Little Cypress Bayou nr Jefferson, TX	6/1/1946	4/27/2020	
7346045	Black Cypress Bayou at Jefferson	9/1/1968	4/27/2020	
Red				
7308500	Red River nr Burkburnett, TX	7/11/1924	4/27/2020	
7316000	Red River near Gainesville, TX	10/1/1936	2/5/2020	
7335500	Red River at Arthur City, TX	10/1/1905	4/28/2020	
7337000	Red River at Index, AR	10/1/1936	4/27/2020	
Sulphur				
7343200	Sulphur River nr Talco, TX	10/1/1956	2/5/2020	
7343500	White Oak Creek nr Talco, TX	12/1/1949	2/5/2020	
7344210[2]	Sulphur River nr Texarkana, TX	10/5/2007	4/27/2020	Below Wright Patman Lake

1-The period of record before impoundments in Lake O' the Pines (1924-1957) was used to calculate instream flow criteria in accordance with recommendations in 2008 Technical Report[4] for the TCEQ.

2-Due to the relatively short period of record of the Sulphur River near Texarkana gage, naturalized inflows to Wright Patman included in the WAM data input file were used to calculate instream flow criteria.

nr= near

[4] https://www.tceq.texas.gov/assets/public/permitting/watersupply/water_rights/txefsacdesktop.pdf

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Appendix E- Water Needs Screening Details

Description of Parameters included in the Water Supply Needs Screening Tool

Descriptions of all parameters considered are provided below:

Water Needs_Max - This parameter identifies the magnitude of current and future needs by WUG by reporting the maximum need during the 2020-2070 planning period. The scoring cutoffs were based on experience with current and existing ASR studies along with cost and project scaling considerations. It recognizes small to mid-sized needs that could potentially benefit from ASR or AR projects.

Needs ≥ 35,000 acft/yr – 1
Needs ≥ 15,000 and < 35,000 acft/yr – 0.75
Needs ≥ 2,500 and < 15,000 acft/yr – 0.5
Needs ≥ 500 and < 2,500 acft/yr – 0.25
Needs < 500 acft/yr – 0

First Needs Decade - This parameter identifies the immediacy of first water supply need.

2060-2070 – 0.25
2050 – 0.5
2040 – 0.75
2020 to 2030 – 1

Unmet_Needs - This parameter prioritizes WUGs that do not show sufficient future supply in the 2021 Initially Prepared Plans to overcome projected needs.

No – 0
Yes – 1

Per_Volume - This parameter shows needs as a percent of total demand volume as a measure of how much the shortage is given overall supply. This helps to scale-up water needs that might appear low from a magnitude perspective (Water_Needs_Max) but may be significant in terms of the water user.

<10% – 0.25
≥10 and ≤ 25% – 0.5
>25 and ≤ 40% – 0.75
>40% – 1

Sole Supply - This parameter is used as a measure of supply vulnerability. WUGs that only have one supply are more susceptible to service interruptions due to extended drought conditions, water quality upsets, or other future uncertainties.

Yes – 1
No – 0

Existing Supply - This parameter is a proxy to be used later in the Final Suitability Rating to evaluate water quality compatibility.

Unknown or Reuse – 0
Surface water – 0.25
Both – 0.5
Groundwater – 1

Length of Need- This parameter serves as a proxy for project viability for projects considered to meet long-term needs operations. The length of need was not selected as a scoring parameter, with an understanding that it did not appropriately capture the operational flexibility that ASR or AR could provide.

<20 years – 0
≥20 years – 1

Recommended WMS ASR or AR - Identifies WUGs that have shown interest in ASR in the draft 2021 Regional Water Plans. This was not selected as a scoring parameter.

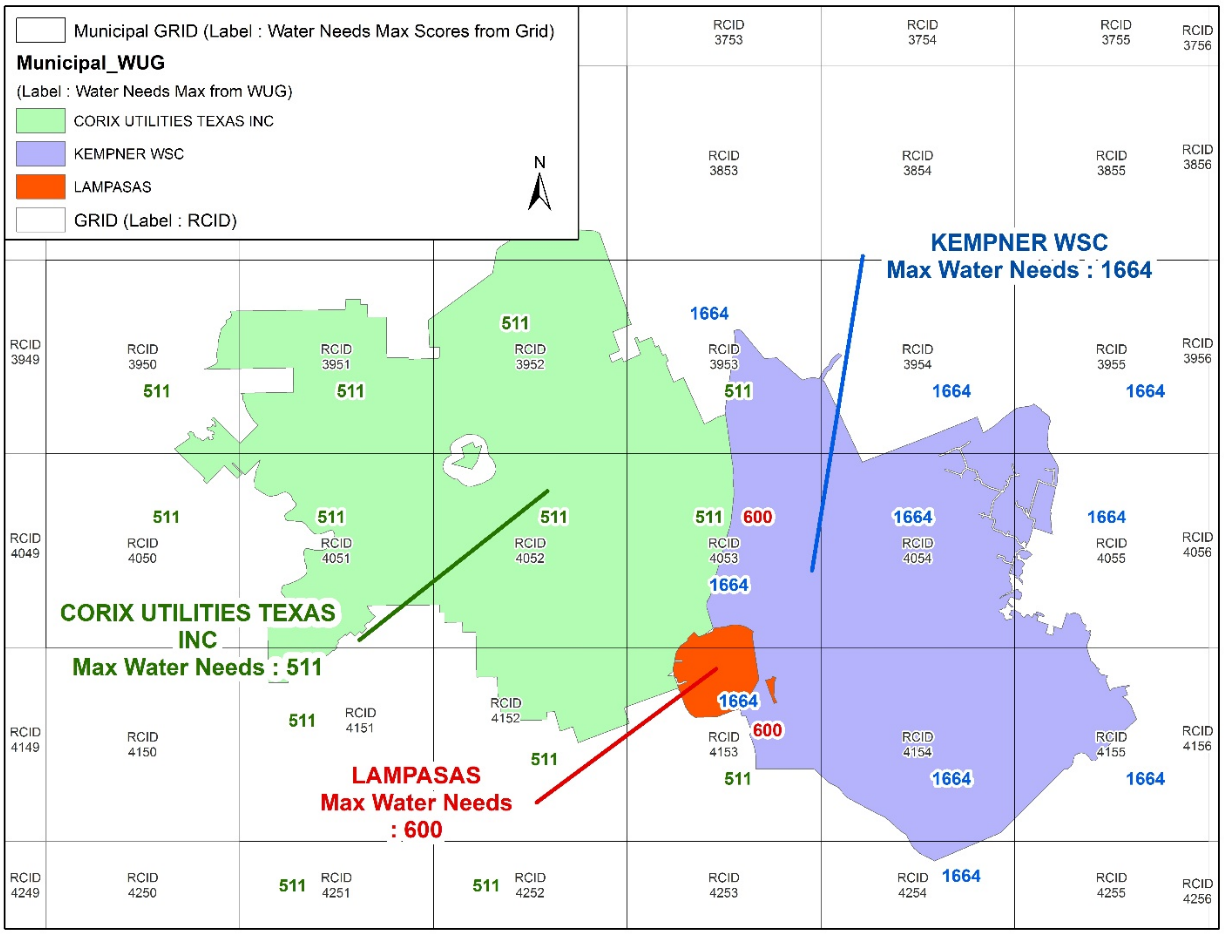
Yes – 1
No – 0

Existing WMS (ASR or AR) - Identifies WUGs that have pursued and implemented ASR. This was not selected as a scoring parameter.

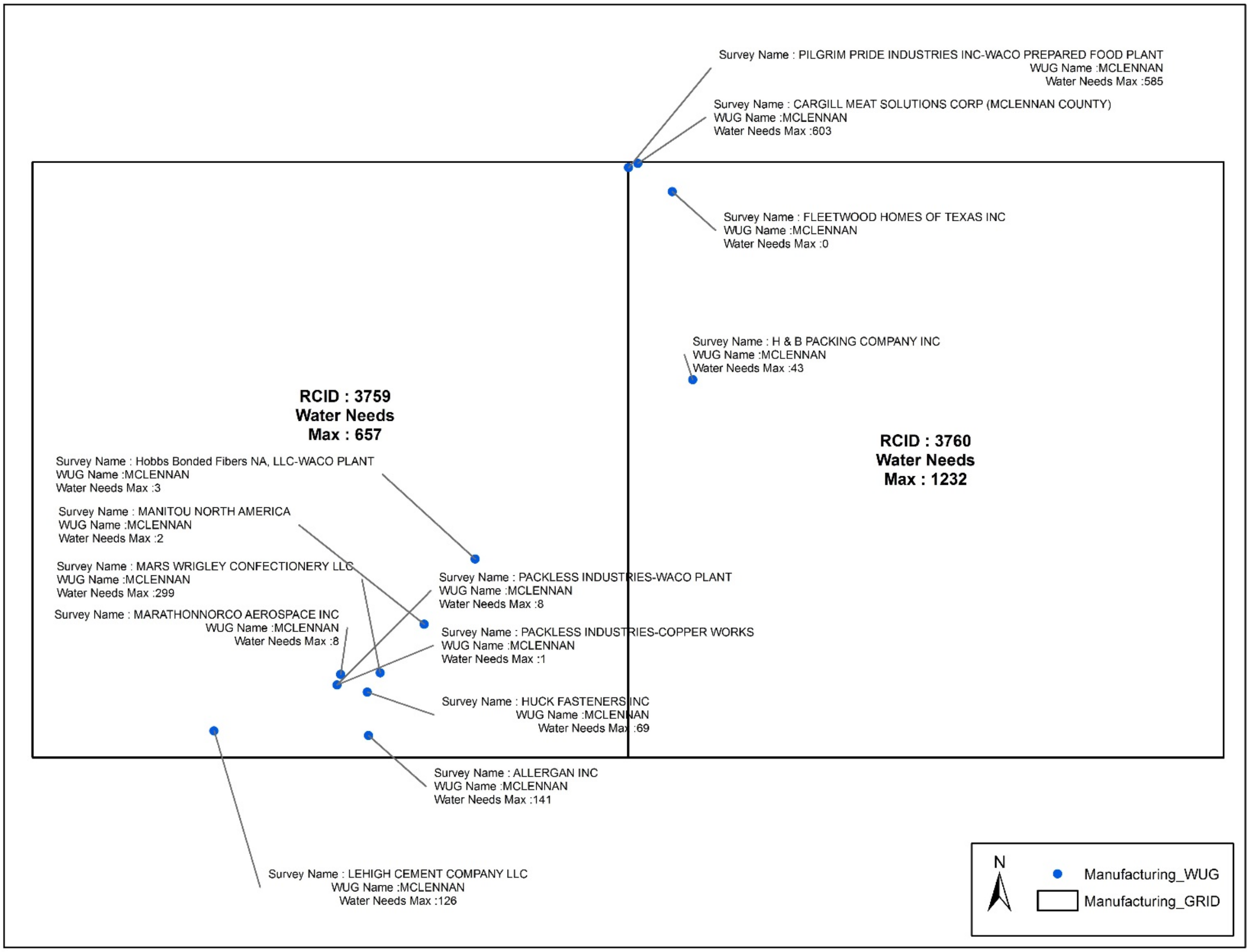
Yes – 1
No – 0

Aggregating Multiple Municipal User Information on the Grid Cell Level

Municipal needs were assigned to grid cells if the cell was located even partially within the TWDB draft DB22 municipal boundaries. At times, several municipal water users overlapped for a given grid cell.   In these cases, the maximum water need scores was assigned to the grid cell as shown below.



For manufacturing water needs analysis, the historic water use was provided on a point basis. The maximum historical water use was assigned to the grid cell (as illustrated below) which was used to apply county-wide water needs based on historical use as a percent of county use.



Appendix F- Final Suitability Rating Details

In this section, we perform a sample calculation for a final ASR suitability rating. The cell we are going to consider is RCID = 4459, but a similar calculation was made for each cell that had a major or minor aquifer present, and both excess water and needs within two cells distance of the cell being considered. For cell 4459, the highest hydrogeological suitability score is 0.69 for the Trinity Aquifer.

Figure YY.1 shows grid cell 4459, and those two cells distance from 4459. Each cell is labeled with the RCID, along with the excess water normalized score and the needs normalized score. The normalized scores were calculated from the sum of the excess water or needs scores.

Recall from Task 3 that excess water scores were estimated for surface water, reclaimed water, and/or groundwater at each cell. If more than one excess water score was present in a cell, the scores were summed, in order to capture the potential added benefit of having multiple scores. So this excess water sum could theoretically be as high as 3, although in practice the maximum sum was 2.75. In order to normalize this sum to a 0 to 1 scale, an approach was taken that attempted to achieve two objectives:

1. Reward scores of greater than 1.0, which mark a potential benefit of having multiple source types.
2. Avoid penalizing individual scores that are close to 1.0, since they may represent a good source, even if only a single type. The approach uses a two-part linear normalization curve that gives a normalized score between 0 and 0.75 for sums between 0 and 1.0. So an excess water sum of 1.0 results in a normalized score of 0.75. For sums greater than 1.0, the normalized score is increased linearly up to 1.0.

The same approach was taken for the normalized needs score, based on the sum of the three contributing need categories. The approach uses a two-part linear normalization curve that gives a normalized score between 0 and 0.9 for sums between 0 and 1.0, and needs sum of 1.0 results in a normalized score of 0.9. For sums greater than 1.0, the normalized score is increased linearly up to 1.0. The difference between the “pivot point” for excess water versus needs was based on an inspection of the distribution of the sums. The needs distribution had many more of the sums clustered at less than 1.0.

Once the normalized scores have been determined, each normalized score is multiplied by the distance weight, resulting in the excess water or needs score that is considered for the calculation. Table 1 shows the results for the 25 cells considered in the calculation. Note the conversion from an excess water or needs “sum” to the corresponding normalized score, then the distance weight used to produce the final excess water or needs score. For example, cell 4257 has an excess water score sum of 1.27 (indicating more than one contributing source) which is normalized to 0.79. The same cell has a needs score sum of 1.00 which is normalized to 0.90. Cell 4257 is more than 20 miles from cell 4459, the cell being considered for the final suitability rating calculation, so the distance weighting is the minimum 0.25. Multiplying 0.79 and 0.90 by 0.25 results in excess water and needs scores of 0.20 and 0.23, respectively.

Once all of the scores have been calculated, the cells with the highest excess water and needs scores are selected for the calculation. In this case, the both highest scores occur in cell 4460. Although it is one cell away from 4459, with a distance weight of 0.64, the excess water and needs scores of 0.55 and 0.61 are the highest of any cell, including cell 4459. Note that for the cell being considered, the distance is zero and so the distance weight is 1.0 (i.e. no distance penalty).

We now have what we need for the calculation of a final ASR suitability rating.

Final_ASR_rating = 0.34(highest_hydro_ASR_score)+0.33(excess_water_score)+0.33(needs_score)

Final_ASR_rating = 0.34(0.69)+0.33(0.55)+0.33(0.61)

= 0.62

The process of making these calculations was completed using Python code, with the GeoPandas library. Geopandas allows reading attribute tables (useful for reading the relevant results from Tasks 2, 3, and 4) and straightforward matrix math. That said, because each cell had to be considered individually, the calculations required about an hour each for ASR and AR.

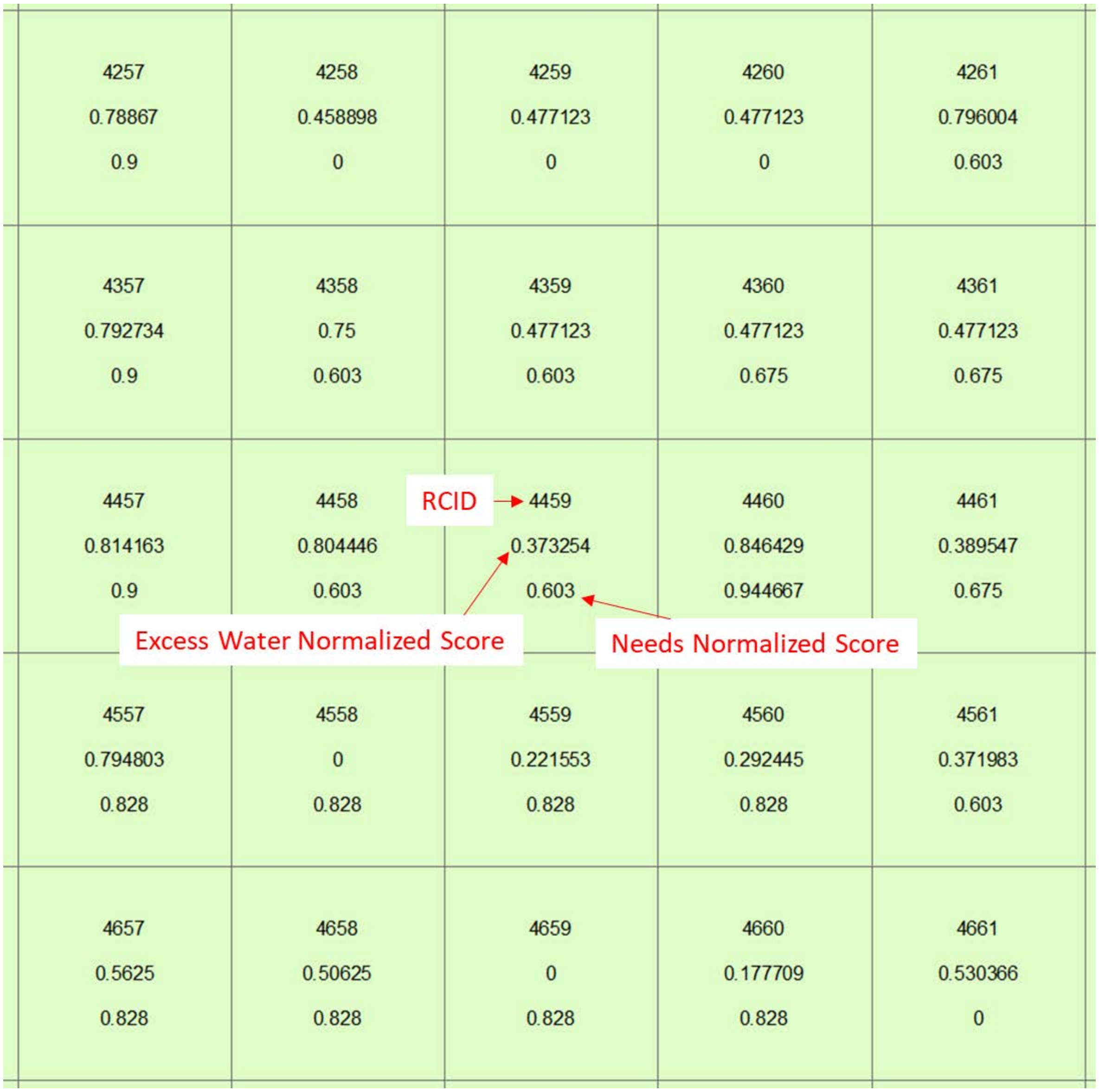


Figure YY.1: Cells considered for inclusion in the calculation of ASR suitability rating for cell 4459.

RCID	Distance	Distance Weight	Excess_Water_Score_Sum	Excess_Water_Normalized_Score	Excess_Water_Score	Needs_Score_Sum	Needs_Normalized_Score	Needs_Score
4257	26.78	0.25	1.27	0.79	0.20	1.00	0.90	0.23
4258	21.17	0.25	0.61	0.46	0.11	0.00	0.00	0.00
4259	18.94	0.29	0.64	0.48	0.14	0.00	0.00	0.00
4260	21.17	0.25	0.64	0.48	0.12	0.00	0.00	0.00
4261	26.78	0.25	1.32	0.80	0.20	0.67	0.60	0.15
4357	21.17	0.25	1.30	0.79	0.20	1.00	0.90	0.23
4358	13.39	0.50	1.00	0.75	0.37	0.67	0.60	0.30
4359	9.47	0.64	0.64	0.48	0.31	0.67	0.60	0.39
4360	13.39	0.50	0.64	0.48	0.24	0.75	0.68	0.34
4361	21.17	0.25	0.64	0.48	0.12	0.75	0.68	0.17
4457	18.94	0.29	1.45	0.81	0.24	1.00	0.90	0.26
4458	9.47	0.64	1.38	0.80	0.52	0.67	0.60	0.39
4459	0.00	1.00	0.50	0.37	0.37	0.67	0.60	0.60
4460	9.47	0.64	1.68	0.85	0.55	1.67	0.94	0.61
4461	18.94	0.29	0.52	0.39	0.11	0.75	0.68	0.20
4557	21.17	0.25	1.31	0.79	0.20	0.92	0.83	0.21
4558	13.39	0.50	0.00	0.00	0.00	0.92	0.83	0.41
4559	9.47	0.64	0.30	0.22	0.14	0.92	0.83	0.53
4560	13.39	0.50	0.39	0.29	0.15	0.92	0.83	0.41
4561	21.17	0.25	0.50	0.37	0.09	0.67	0.60	0.15
4657	26.78	0.25	0.75	0.56	0.14	0.92	0.83	0.21
4658	21.17	0.25	0.68	0.51	0.13	0.92	0.83	0.21
4659	18.94	0.29	0.00	0.00	0.00	0.92	0.83	0.24
4660	21.17	0.25	0.24	0.18	0.04	0.92	0.83	0.21
4661	26.78	0.25	0.71	0.53	0.13	0.00	0.00	0.00

Table YY.1: Summary of scores for cells considered for calculation of ASR suitability rating for cell 4459.

Appendix G- TWDB Comments Received on the Draft Report and Responses

General comments

1. Add an appendix to the final version of this report that includes responses to these comments. *Response: Added Appendix G to include TWDB comments and responses.*
2. For maps, make them larger so the outline of Texas takes up the whole available width of the page minus the margins (6.5”). Consider devoting an entire page for each of the statewide maps. *Response: Done.*
3. For maps, increase the quality of images. Most of the maps are pixelated. *Response: Done.*
4. For maps, increase the size of the legend so labels are legible. *Response: Done.*
5. For maps that have them displayed, add the regional water planning areas and suitability survey grid cells symbols to the legend. *Response: Done.*
6. Consider removing references to task numbers since they only apply to the scope of work in the contract. *Response: Text updated accordingly.*
7. Consider removing the word “tool” from the report, as using this word makes it seem as though an application or software was built. GIS software was the “tool.” Datasets were developed. *Response: Text updated accordingly.*
8. Use past tense since the survey is done. *Response: Done.*
9. Use consistent capitalization for Hydrogeology Parameter Screening, Excess Water Screening, Water Supply Needs Screening, and Final Suitability Rating. *Response: Text updated accordingly.*
10. Use consistent adjectives for the screening and rating. Consider using “high, medium, and low” for the parameter screenings and “minimal, moderate, significant” for the suitability rating. *Response: Text updated accordingly.*
11. Use “statewide” instead of “regional” when referring to the perspective or level of detail of this survey. *Response: Text updated accordingly.*
12. Use “Draft State Water Planning Database (draft DB22)” instead of “DB22,” “2022 draft State Water Plan databases,” “2022 draft State Water Plan” or “Draft DB22” at the being of each section it is used in. Once defined at the beginning of the section, consider using “draft DB22.” *Response: Text updated accordingly.*
13. Use “hydrogeological parameter screening” instead of “hydrogeological suitability.” *Response: Text updated accordingly.*
14. Use “spatially varying” instead of “spatially-varying.” *Response: Text updated accordingly.*
15. Use “86th Texas Legislature” instead of “86th Texas Legislature.” *Response: Text updated accordingly.*

16. Use "survey" instead of "study" or "project" when referring to this survey. *Response: Text updated accordingly.*
17. Use "water availability model (WAM)" instead of "water available model." Once defined at the beginning of the section, consider using "WAM." *Response: Text updated accordingly.*
18. Use "water supply needs' instead of "needs." *Response: Text updated accordingly.*
19. Use "municipal" instead of "MUN," "manufacturing" instead of "MANU," and "steam electric" instead of "SE." *Response: Text updated accordingly.*
20. Use "Final Suitability Rating" instead of "Statewide Final Suitability Score" or "Final Suitability Score" or "Final Suitability Rating Score" or "Project Suitability Score." *Response: Text updated accordingly.*
21. Make the second to last step of each screening approach "Use the magnitude of the [insert screening name] screening scores to rank grid cells into three general categories of relative suitability, "low," "medium," or "high." *Response: Revised approach as suggested and updated text accordingly.*
22. Make the last step of each screening approach is to aggregate overlapping scores into a single scored layer for the screening. *Response: Revised approach as suggested and updated text accordingly.*
23. Add a "Final score selection for grid cells" section for each screening methodology to explain how multiple input layers and features were assimilated into a single score per grid cell. Table 21 states that the actual work of combining excess water sources and water supply needs took place during their respective screenings. It will make each of these sections a standalone screening with results. Consider moving related text from the final suitability rating section to these screening sections and replacing the individual category maps with the aggregated score maps. Consider symbolizing these maps based on the conjunctive use and regional partnership values mentioned in list item 5a on page 79. *Response: Done. We considered symbolizing conjunctive use and regional partnership values, however felt that the stand-alone data presented in summary maps provided greater flexibility to the stakeholders and minimized confusion for readers. Conjunctive use and regional partnership opportunities remain in Final Suitability Rating discussion.*
24. For each of the screening details appendices, add the details for how multiple features/layers were aggregated into one set of values per grid cell. *Response: Added discussion for each screening tool in main body of report.*
25. Consider adding a "Conclusions" section with a concise, high level summary of the overall results and limitations of the survey at the end of the report. *Response: Added.*
26. Consider adding an appendix explaining the technical details of calculating the Final Suitability Rating. A diagram showing a map of an aquifer grid cell with the excess

water and water supply needs scores from different grid cells would be helpful. It could also include an explanation of what software and tools were used to select the excess water and water supply needs cells out of the 24 cells surrounding the aquifer grid cell. *Response: Added Appendix F to describe the process of selecting maximum scoring excess water and water supply needs cells surrounding the aquifer cell.*

27. Review the report, geodatabases, and public data display content to ensure uniform terminology is used between them all. *Response: Done.*

Executive summary

Background

28. Page 1, first paragraph, first sentence: Change "instructing" to "directing." *Response: Text revised accordingly.*
29. Page 1, Bullet 1: Change it to "*The first screening focused on hydrogeological characteristics, such as storage potential, transmissivity, infiltration characteristics, storativity, recoverability, and water quality.*" *Response: Text revised accordingly.*
30. Page 1, Bullet 2: Change "for storage" to "for storage and recharge." When only stating storage seems like it only address ASR and not AR. *Response: Text revised accordingly.*
31. Page 1, Bullet 3: Change bullet to state the following: "*The third screening focused on identifying the current and future water supply needs. To use the most current information available, the water supply needs were based on the Draft State Water Planning Database (draft DB22) (submitted March 2020).*" *Response: Text revised accordingly.*
32. Page 2, first paragraph: Consider removing these definitions as they conflict with the ones defined at the beginning of the executive summary. *Response: Text removed as suggested.*

Results

33. Page 2, first paragraph, second sentence: Consider removing this sentence because it is confusing. *Response: Text removed as suggested.*
34. Page 2, second paragraph, first sentence (originates from Hydrogeological Parameter Screening, Results section. Quantify "some areas." Does it mean 50 percent or 10 percent? Report ASR results in percent that has no data, is less suitable, is moderately suitable, and is most suitable for the whole state to give the reader a big picture perspective. *Response: Added this information as requested.*
35. Page 2, third paragraph: Need to rework this paragraph. This paragraph should only present results for AR. This paragraph should discuss AR results for statewide, major

aquifers, minor aquifers, and any comparison to existing operating projects in Texas. Please note the El Paso Water Utilities is an AR project. Report AR results in percent that has no data, is less suitable, is moderately suitable, and is most suitable for the whole state to give the reader a big picture perspective. If we compare AR and ASR results, this should be in a new paragraph. *Response: Paragraph reworked as requested.*

36. Page 3 and 4, Figures ES1 and ES2: Consider removing these maps so the executive summary focuses on the final suitability rating or adding the summation maps for excess water and water supply needs. *Response: Removed hydrogeological parameter screening maps for brevity in executive summary.*
37. Page 4, excess water discussion: The results for each type of excess water should also report statewide results in percentage. *Response: Added this information as requested.*
38. Page 4, last paragraph and sentence: It is confusing to say "surface water reliability in drought conditions" in the same sentence. Shouldn't a drought mean less availability and reliability? Consider rephrasing this sentence. *Response: Added clarification that this supply was based on draft DB22. Regional water planning supplies are limited based on drought of record conditions.*
39. Page 5, first paragraph: Consider adding a sentence explaining how stormwater is represented in this analysis. *Response: Added clarification at the beginning of paragraph.*
40. Page 5, 3rd paragraph: This paragraph on the highest scoring groundwater areas is confusing. Consider editing it to be concise and clearer. *Response: Added clarification as requested.*
41. Page 6, 2nd paragraph, 2nd sentence: Change "manufacturing needs" to "steam electric needs." *Response: Text revised accordingly.*
42. Page 8, first paragraph, first sentence: Change "regional water planning groups" to "stakeholders such as water utilities, water planners, and government officials." Tools are available to the public in general. *Response: Text revised accordingly.*
43. Page 8, first paragraph, last sentence: Change "regional planners" to "stakeholders." Tools are available to all stakeholders and in general the public. *Response: Text revised accordingly.*
44. Page 9, first sentence: The end of the sentence is unclear and needs to be fixed. *Response: Revised text for clarification.*
45. Page 9, first paragraph, first sentence: Change to "*This statewide survey has many strengths, including giving stakeholders the versatility to use the source data as needed to customize scoring according to parameters they deem most relevant.*" *Response: Updated text as suggested.*
46. Page 9, last paragraph, first sentence: Change "Hydrogeological Parameter screening tool" to "Statewide Survey of Aquifer Suitability for ASR or AR." *Response: Updated text as suggested.*

47. Page 9, last paragraph: Consider removing the second and third sentences about high and low grid cells. They are difficult to read. *Response: Removed as suggested.*
48. Page 9, last paragraph, last sentence: Remove "*in a county or portion of a county*." *Response: Removed as suggested.*

Introduction

49. Page 10, second paragraph: Change the paragraph to read as follows: *"In 2015, the 84th Texas Legislature directed TWDB through House Bill 1, Rider 25 to provide grant support for demonstration projects or feasibility studies that would create new water supplies or increase water availability through innovative storage approaches. This grant funding supported three recently completed ASR demonstration projects for Corpus Christi, New Braunfels Utilities, and Victoria." Response: Revised as suggested.*
50. Page 10, three bullets: Consider removing these bullets that are identical to bullets in the executive summary. *Response: Revised as suggested.*
51. Page 11, first sentence: Consider removing this sentence as it is redundant to the last sentence of the previous paragraph. *Response: Revised as suggested.*

Hydrogeological parameter screening

52. Figures 3 and 4: It was understood that the highest scoring aquifer was used for the final score for each grid cells with more than one aquifer. The only mention of using the highest aquifer suitability score for each grid cell is in the caption for Figures 3 & 4. *Response: Added in the results section.*

Hydrogeological parameter methodology

Methodology for parameter selection

53. Page 13, Table 2, first row, storage zone depth: Consider changing the note to "*Depth to top of aquifer in a confined system. In an unconfined system, storage zone depth is estimated to be 100 feet below the top of the saturated zone*." Does that better capture what was done? *Response: Revised as suggested.*
54. Page 14, Table 2 and 3, Sediment age: Change the notes to match the explanation in Appendix C, "A qualitative indication of aquifer induration." *Response: Text revised accordingly.*
55. Page 14, Table 3: Change "Comment" to "Notes" to match the column names in Table 2. *Response: Text revised accordingly.*

Assumptions, challenges, and limitations

56. Page 15, bullet point 2: Consider rewording this bullet as it is confusing. Do you mean to say, "*When a major or minor aquifer had multiple hydrogeologic units with varying parameter values, the parameters were averaged to one value to represent the aquifer for that grid cell.*"? *Response: Yes. Text revised accordingly.*
57. Consider adding the extent of the official TWDB aquifer boundaries as a limitation. Generally, they do not include the brackish and saline portions of aquifers which could host viable ASR projects. *Response: Good suggestion. Text updated accordingly to include this limitation.*

Data sources

58. Page16: Correct this sentence, it seems to have been from the excess surface water section. *Response: Removed sentence since it is redundant.*

Primary data sources

59. Page 16, First sentence: Remove the word "that." *Response: Text revised accordingly.*
60. Page 16, paragraph on spatially varying data: Edit this paragraph for clarity. *Response: Revised text to clarify.*

Other sources

61. Page 17, Aquifer age: Was the youngest age for non-dipping unconfined aquifers only applied for the AR screening or both AR and ASR screening? For ASR it is likely that the well will not be completed in the shallowest aquifer material. *Response: It was applied to AR only. Midpoint age was used for ASR for all cases. This was clarified in the text.*
62. Page 17, Aquifer age: Add a sentence describing how an age was assigned for the confined portions of an aquifer. *Response: The approach to assigning unconfined and confined aquifers for AR/ASR have been clarified in that section.*
63. Page 17, Aquifer dominant lithology: There is no separate list of references, mentioned in this paragraph, in Appendix C. *Response: References added.*
64. Page 17, Groundwater Quality: For the Cross Timbers Aquifer water quality, was data from the TWDB Groundwater Database solely used or was the chloride concentrations map from "Groundwater Conditions in the Cross Timbers Aquifer" TWDB Groundwater Management Report 19-01 that was based on "Flow and Salinity Patterns in the Low-Transmissivity Upper Paleozoic Aquifer of North-Central Texas" by Nicot and others (2013) used as a guide? *Response: The Nicot and others (2013) data was reviewed and considered, but was not used in the final calculation. We were concerned about reconciling any potential duplication between the two datasets, and didn't think the effort to do so was warranted in this case.*

Integration scale

65. Page 18: Consider changing this paragraph to "*A statewide grid consisting of cells 50,000 feet by 50,000 feet (or 89.5 square miles) was created to allow a spatially consistent evaluation network for the survey. Given the input datasets, statewide perspective, and timeline of this survey, it was both suitable and relevant. This grid size and extent was used as a template for all screenings and the final suitability rating developed during this survey. This created coincident datasets for consistency and ease of integration.*" *Response: Text revised accordingly.*

Aquifer assignments

66. Page 18, 1st sentence: Consider changing it to: "*For each major and minor aquifer, the aquifer extent was intersected with the 50,000 by 50,000 statewide grid. If the centroid of a grid cell occurred in an aquifer polygon, the aquifer was assigned to that grid cell. Grid cell centroids that did not occur in an aquifer did not receive an aquifer assignment.*" *Response: Text revised accordingly.*

Scaling source data to the statewide grid

67. Page 20, paragraph 2: Consider rewriting this description of the aquifer feature classes. It doesn't match Appendix B, page 2 or the draft final geodatabase delivered. In the draft final hydrogeological parameter screening geodatabase, each aquifer has two feature classes, one of AR and one for ASR. Each aquifer feature class contains all the suitability parameters, not just one. *Response: Text rewritten to clarify and to be consistent with final geodatabase.*

Scoring

Method

68. Page 23, paragraph 3, sentence 2: Consider changing this sentence defining category thresholds into a vertical list so it is easier to read. *Response: Done.*

ASR and AR hydrogeological parameter scores

69. Page 24-25, Table 4 and 5, Dominant lithology: Change "limestone/karst" to just "Karst" and "rock/fractured" to "Fractured" to match Appendix C. *Response: Done.*
70. Page 24-25, Table 4 and 5, Dominant lithology: Add that 'Rock' is assumed to be indurated to the explanation under the table, as was indicated in Appendix C. *Response: Done.*
71. Page 25, Table 5: There are two rows of 'Sediment Age'. Keep the one with 56 and 541 as cutoffs and remove the other. *Response: Done.*

Weighting

72. Page 26, paragraph 3, sentence 2: Insert "on" after "effect." *Response: Done.*
73. Page 27, Table 6: Replace "Zuitability" with "suitability." *Response: Revised accordingly.*

Results

ASR and AR scores

74. Page 28: Consider adding a discussion of how many grid cells cover the whole state and what percentage of those ended up with ASR, AR, and both ASR and AR aquifers assigned. *Response: Added this discussion per request.*
75. Page 29, Figure 3 and Page 33, Figure 4: Remove the inset major and minor aquifer maps. *Response: Done.*
76. Page 33, Figure 4 caption: Change "ASR" to "AR." *Response: Corrected text accordingly.*

Excess water screening

Objective

77. Page 36, Paragraph 1, Line 2: Remove "from other sources." *Response: Done.*
78. Page 36, Paragraph 2 Line 4: Remove "opportunities." *Response: Done.*

Approach

79. Page 36, List 1: Change "consider" to "compile data on." *Response: Text updated accordingly.*
80. Page 37, List 5. Change "Parameter" to "parameter." *Response: Revised to Hydrogeological Parameter Screening.*
81. Page 37, final paragraph, 1st line. Replace "dry times" with "times of need." *Response: Text updated accordingly.*

Excess Water Methodology

82. Page 37, paragraph 1, line 4-9: Does the sentence "*Attempts to parse and segregate produced groundwater from individual sources is exceedingly labor intensive*" refer specifically to oil and gas production as stated in the previous sentence? Consider editing these two sentences to be clearer. *Response: Revised to combine sentences for clarity.*
83. Page 38, paragraph 2: Are the previous scores limited to less than one or normalized back to a range of 0 to 1? Edit this paragraph to be clearer. *Response: Yes the previous scores are limited to one. Text has been added to clarify.*

84. Page 42, Figure 5: In the figure caption, state that the orange highlights indicate the level at which availability of excess water sources is scored. *Response: Added note accordingly.*

Excess surface water and stormwater

Methodology

85. Page 43, paragraph 2: Clarify how "*the tool considers existing reservoir storage that provides the opportunity to create excess surface water supplies through reservoir operations*." Include a brief explanation of how the screening criteria accounts for such consideration. If it does not explicitly account for such consideration, please reword this statement to convey the fact that reservoir operations have the potential to create excess surface water supply, but explicit accounting of such supply was beyond the scope of the study. *Response: Revised text accordingly.*
86. Page 43, paragraph 2, last sentence. "Although it is beyond the scope of this study to evaluate reservoir operations, the screening evaluation recognizes this opportunity" is awkward. Consider editing this paragraph. *Response: Revised text accordingly.*
87. Page 44, Final paragraph: Consider editing this paragraph to be the fourth bullet in the list above and explain why the "existing water rights associated with a reservoir" may be different than what was calculated as the reservoir supply. *Response: Revised text accordingly.*

Assumptions, challenges, and limitations

88. Page 45, Bullet 2: Provide a citation for the Lyons Method. *Response: Done.*

Data gaps

89. Page 48, Bullet 1: The limitations of the monthly timestep used in the WAMs, as well as the impractical scenario of attempting to calculate daily timesteps, is well explained in the limitations section above. I don't think it needs reiterated in the Data Gaps section. *Response: Removed text as suggested.*

Excess reclaimed water

90. Page 48, first paragraph, first sentence: Consider the sentence "*Reclaimed water in the form of treated wastewater effluent is included as a potential surface water excess supply source in the screening evaluation.*" Clarify how this was included in surface water, when the statewide study addressed it separately. *Response: Added text for clarification.*
91. Page 48, second paragraph, second sentence: Consider the phrase "*such as direct reuse that is returned to a watercourse.*" Clarify what this means since direct reuse takes reclaimed water via pipeline to the user. *Response: Added text for clarification.*

Methodology

92. Page 48, first paragraph: Provide range of discharge volumes in ECHO Database. Did you consider all discharge volumes? *Response: Added footnote. Yes all discharge volumes were considered, however discharges associated with power generation and other industrial uses was removed as discussed in Assumptions, challenges and limitations.*
93. Page 49, second sentence: Clarify what you mean by "*ECHO discharge data for municipal users does not show significant variability, as outdoor water use does not influence municipal discharge.*" Is there no significant variability over the day or the year? What other factors influence municipal discharge? *Response: Added text for clarification.*
94. Page 49, footnote: Change author from Erika Mancha to Simon Schmitz, Mickey Leland intern. *Response: Updated accordingly.*

Excess groundwater

Assumptions, challenges, and limitations

95. Page 51, Bullet 1, Line 1: This first sentence explains how excess water was calculated very succinctly. Move it to the first paragraph of the methodology subheading above. *Response: Text updated accordingly.*
96. Page 52, Bullet 2: This bullet about "other Aquifer" is a data gap. Move it to that subheading by incorporating it with bullet 2 of the Data Gaps. *Response: Text updated accordingly.*

Scoring

97. Page 52, Paragraph 1, Final sentence: "*Consideration to the scoring has been given to approximate the level of data necessary for the evaluation.*" This sentence is unclear. Consider editing it to clarify that that scoring is weighted on these features and normalized. *Response: Text updated for clarity.*
98. Page 55, Paragraph 3: The duration parameters for reservoir storage are defined as "*No storage or storage less than 5000 acft*" for 0 and "*Storage greater than 5000 acft*" for a score of 1. These are not durations in time like the other parameters have. Consider adding a sentence to explain why this choice was made. *Response: Added sentence for clarity.*

Results

99. Page 56, last paragraph: Consider including mention of the length of the naturalized flow input data record available for the Lower Colorado River Basin compared to other

river basins, and mention whether the limited availability as seen in study results could be due to new drought-of-record conditions over the lower basin. *Response: Updated discussion accordingly.*

100. Page 60, 1st paragraph: Consider adding the number of grid cells and the percent of total grid cells the areas with 0, 0-0.25, 0.25-0.5, 0.5-0.75, and greater than 0.75 scores. Also state the reason, even if obvious, for 0 score. *Response: Added information for low, medium, and high categories for consistency with other screening results.*

Future work

101. Page 63, bullet 5: Clarify if you refer to "existing and/or future" reclaimed projects greater than 1,000 ac-ft/yr. *Response: Text updated for clarity.*

Water supply needs screening

102. Page 64: Explain or define water supply needs (or how it was calculated) and unmet needs. *Response: Added text for clarity in the approach and footnote at the bottom of table with definition of unmet needs.*

Approach

103. Page 64, item #5: It states that "*Evaluate results of the needs score to identify regions with higher magnitude of needs*." However, the results do not discuss any regional implication. *Response: Updated text in response to previous comment, and this comment no longer applies.*

Water Supply Needs Screening

104. Page 65, item #4, 2nd paragraph: Add '(County-Other)'- "Municipal water supply needs are presented in TWDB draft DB22 for both individual (discrete) WUGs and on a county-wide level for municipal WUGs (County-Other) that have a smaller service area capacity." *Response: Text revised accordingly.*

105. Page 66, 5.b, 2nd paragraph: Water users are required to submit water use information (not voluntary but self-reported) and it goes through a quality control review process. Texas State Law (Section 16.012m of the Texas Water Code) REQUIRES all recipients of the Survey of Ground and Surface Water Use to submit a completed survey. Remove the following struck out phrase: "*For MANU and SE needs, the TWDB provided point location information based on 2017 Historical Water Use information and ~~Water users volunteer the historical water use information and it often has discrepancies. However, it is the best available dataset to assign county-wide data to site-specific locations. For this~~*

~~*reason,*~~ *the TWDB shapefile was used as a proxy for assigning MANU and SE needs within a county."* *Response: Text revised accordingly.*

106. Page 66, 5.b: Add ", less than # percent of the total manufacturing demand" to the sentence: *"All other points that plotted incorrectly were removed"* *Response: Text added accordingly.*
107. Page 66, 5.c: Revise 'County-Other needs' to 'county-wide needs' or 'county-aggregated needs'. *Response: Text revised accordingly.*
108. Page 67, 6: Add "MUN, MANU and SE water" to the sentence below:
"The following process was used to merge *MUN, MANU and SE* water needs information into grid cells." *Response: Text revised accordingly.*
109. Page 67, 6.a: Change '…MUN WUG TWDB DB22 WUG boundary coverage…' to 'draft DB22 municipal WUG boundary'. *Response: Text revised accordingly.*
110. Page 67, 6.b: Remove 'county-wide' from the sentence. *Response: Text revised accordingly.*
111. Page 69, last paragraph: Include specific category names (IRR, Live and County-Other) that were not included because there is no locational information to distribute them (because MANU and SE were included even thought there were county-wide aggregated demands in draft DB22). *Response: Text revised accordingly.*

Scoring

112. Page 71: 1st paragraph: Add a brief explanation why those 3 parameters were identified for scoring. *Response: Text added for clarity.*

Results

113. Page 72: Explain how the results or this tool serve as a guide for regional water planning stakeholders. *Response: Added text as suggested.*
114. Page 72, Figure 12: The scores show that highest scoring needs are in metropolitan areas of Texas Triangle including Dallas-Fort Worth, San Antonio and Houston. Consider mentioning Houston in the sentence. *Response: Text revised accordingly.*

Future Work

115. Page 75: Consider breaking the single bullet into multiple bullets. *Response: Text revised accordingly.*

Final suitability rating

Combining parameters

Methodology

116. Page 79, list item 5b, last sentence: Edit this sentence to be clearer. Should it explain that when multiple excess water and water supply needs with similar scores exist within the 24 grid cells surrounding an aquifer cell, the scores with the shortest distance were used? *Response: The point was that the excess water/needs cells did not have to be coincident with the aquifer cell being considered, but that closer cells were scored more favorably. The text was edited to be clearer.*
117. Page 80, Table 21, row Excess_Water_NS and Needs_Score_NS: Change the note to reference Figure 15 instead of Figure 1. *Response: Done.*
118. Page 80, Table 21, row Needs_Score_NS: Change the Data source to "Final Suitability Rating" *Response: Done.*
119. Page 81, Table 21, row Final_Suitability_Score (ASR and AR separately), Change "*Excess_Water_Score*0.33 + Needs_Score*0.33*" to "*Excess_Water_NS*0.33 + Needs_Score_NS*0.33*" to match the field names used earlier in the table. *Response: Done.*

Assumptions, challenges and limitations

120. Page 82, last bullet: Consider removing this bullet since groundwater quality was addressed in the Hydrogeological Parameter Screening and water compatibility was addressed in the previous assumptions bullet and the following assumptions bullet. *Response: Removed as suggested.*
121. Page 83, first bullet: Incorporate this bullet on water compatibility into a previous bullet that discusses conditions that are beyond the scope of the Statewide Survey of Aquifer Suitability for ASR and AR Projects. *Response: Done.*

Data gaps

122. Page 83, Data gaps: Since the percent coverage for excess water not identified is given, consider adding the percent coverage where water supply needs were not identified. *Response: Done.*

Scoring

123. Page 84, 2nd and 3rd bullets: Change these to the normalized score. *Response: Revised to match Table 21.*
124. Page 85, Table 22: Update this table to reflect the fields in Table 21. *Response: Done.*

Overall findings and conclusions.

125. Page 85, 1st paragraph: Consider adding observations of the distribution of ratings compared to existing and planned ASR facilities in Texas. *Response: We considered this response, and have included additional language in the hydrogeological parameter screening discussion related to this. Utilities that have pursued ASR and/or AR projects have different objectives including seasonal peaking or system redundancy that are not comparable to the Excess Water or Water Supply Needs Screening methodology.*
126. Page 85, 1st paragraph, last sentence: It is surprising that the Edwards Balcones Fault Zone aquifer was one of four aquifers receiving the highest ASR Final Suitability Ratings since the assumption is the transmissivity of this karst aquifer would be too high to have good recoverability. Consider explaining the parameters of these aquifers that allowed them to score so high. It looks like the water supply needs may have had a strong effect. *Response: Great catch! Further inspection revealed an error in the calculation of the drift velocity. Correcting this error had a minor effect on most aquifers, but with hydraulic conductivities in the 100s – 1000s of ft/d, and many drift velocities now estimated at >1,000 ft/yr, the correction had the largest effect on the EBFZ hydro ASR score. So the EBFZ no longer is characterized by these highest final suitability ratings.*
127. Page 85, 2nd paragraph: It is surprisingly the exact same number of aquifers are represented in the ASR and AR Final Suitability Ratings since there were 285 less AR aquifer grid cells. *Response: The number of minor aquifers with ASR ratings was actually 16. This correction has been made.*
128. Page 85, 2nd paragraph: Consider discussing what made the top four aquifers so widespread and high scoring. *Response: Added discussion.*
129. Page 86-87, Figure 17 & 18, Make these maps shine! They are the big finale of the survey and should be the best maps in the report. *Response: Done.*

Public data display

Assumptions, challenges, and limitations

130. Page 89, sentence between the bullet lists: Change "Hydrogeological Parameter screening tool" to "StoryMap and ArcGIS Online content such as the web map application." *Response: Revised text accordingly.*

Appendix A – Literature review

131. Appendix A, page 2, 1st sentence: Replace it with the following: "*In 2015, the 84th Texas Legislature directed TWDB through House Bill 1, Rider 25 to provide grant support for demonstration projects or feasibility studies that would create new water supplies or increase water availability through innovative storage approaches. This grant funding supported three recently completed ASR demonstration projects for Corpus Christi, New Braunfels Utilities, and Victoria*." *Response: Done.*

Appendix B – GIS Files

132. Update the GIS files list to correspond to changes made to the draft final geodatabases. *Response: Done.*

Appendix C – Hydrogeological parameter screening details

133. Add the separate list of references for "Aquifer Dominant Lithology" mentioned on page 17 of the Hydrogeological Parameter Screening section of the report to the end of Appendix C. *Response: Added.*
134. Add the results of the sensitivity analysis for ASR and AR mentioned on page 26 of the Hydrogeological Parameter Screening section of the report to the end of Appendix C. *Response: The results of the weighting sensitivity analysis are shown in Tables 3 and 4 of Appendix C.*
135. Page 2, Table 1: Add LIT = Literature explanation with the others beneath the table. *Response: Added.*
136. Page 2, Table 1: Change BRACs to BRACS. *Response: Revised accordingly.*

ASR hydrogeological parameter score

137. Page 8, Sediment Age, second sentence: This sentence is confusing. Consider changing it to "*Older sediments are often subject to deep burial processes and longer exposure to surface processes. This often reduces their porosity and ability to store and transport groundwater*." *Response: Revised accordingly.*
138. Page 9, Groundwater Quality: Change AR to ASR to match the methods section. *Response: Revised accordingly.*
139. Page 9, Confinement, sentence 2: revise style of sentence, remove "you." *Response: Revised accordingly.*

140. Page 9, Confinement, last sentence: Edit "is has." *Response: Corrected.*

Appendix D – Excess water screening details

141. Page 1, Scoring, Line 1: Volume does not need to be underlined. *Response: Revised accordingly.*
142. Page 5: Existing Reservoir Storage methodology, point 1: Include a clarification that the reservoir storage volumes available from the TWDB Water Data for Texas website are only for 117 major monitored water supply reservoirs in Texas. *Response: Revised accordingly.*
143. Page 5: Existing Reservoir Storage methodology, point 1: Mention if storage data for Elephant Butte, located in New Mexico, was included in the study. *Response: Additional clarification added.*
144. Page 6, Assimilating Sources of Excess Surface Water: Add better details for combining all the excess surface water into one feature class. *Response: Additional clarification added.*
145. Page 7, Paragraph 2: Reclaimed water frequency is measured here in volume and matches what was used for any score other than zero for volume. Consider removing the volume from this section as a qualifier and simply stating this is based on if reclaimed water is estimated to be available. The volume of this is already stated in another attribute if the user wants to check. *Response: Revised accordingly.*
146. Page 7, Paragraph 3: Reclaimed water duration is measured here in volume and matches what was used for frequency. Consider removing the volume from this section as a qualifier and simply stating this is based on if reclaimed water is estimated to be available. The volume of this is already stated in another attribute if the user wants to check. *Response: Revised accordingly.*
147. Page 8, Excess Groundwater Parameters, Methodology: Review this paragraph for grammatical errors and revise accordingly. *Response: Revised accordingly.*
148. Page 10, Table 1: Rows 29–32, Column 4: These four rows contain XX's for cfs and acre-feet numbers. Were these XX's placeholders that should be replaced with numbers? *Response: Updated to clarify analysis based on median flow conditions.*
149. Page 13, Table 3: Name column: "nr" was never defined. Please write it out as "near." *Response: Added footnote.*

Geodatabase comments

(See details of comment resolution provided in the next comment section focused on geodatabases)

150. Provide the MXDs and layer files used for map figures. *Response: Done.*
151. Rename the geodatabases (GDBs) to be intuitive and tidy for public use. *Response: Done.*
152. For the hydrogeological parameter, excess water, and needs GDBs, add the composite grid cell layer that contains the final values used for the final suitability rating. This way, each GDB can be a standalone product. In addition to the final score number, include a field for the category name (i.e. high, medium, low). *Response: Done.*
153. Consider adding metadata at the geodatabase level. Include reference to the final report, HB 721, use limitations, credit, and a short summary of the purpose and contents of the geodatabase. Utilize text in the report appendices. *Response: Done.*
154. Review the feature class metadata for errors and completeness. *Response: Done.*
155. Compact and compress the GDBs. *Response: Done.*
156. Reconcile GDB names, feature class names, field names, field aliases, and attribute values between the GIS files and the report. *Response: Done.*
157. Review the feature classes for anomalies. *Response: Done.*

Public data viewer comments

In a conference call with TWDB on 9/4 the comments below were discussed. Comments that required out-of-the-box programming were mutually agreed to not be pursued. The final StoryMap ArcGIS deliverable addresses remaining comments.

158. **Data completeness** – All feature classes in the four geodatabases need to be available in the web map application. Compact and compress the geodatabase before uploading to ArcGIS Online (AGOL) to reduce the number of credits needed to store them. *Response: Done.*
159. **Graphic identity** – All the maps need to share graphic identity between the report, StoryMap, and web map application. Graphic identity includes labels, symbols, and colors. *Response: Done.*
160. **Story Map interactive maps** – Considering limitations to the interactive maps within the StoryMap, the final "slide" of Hydrogeology, Excess Water, Needs, and Final Suitability Rating can just have the final grid cell feature classes as their interactive map. Provide a legend in the sidecar for each interactive map. Since more than one layer can't be displayed in StoryMaps, choose the ASR layers for hydrogeological parameter screening and final suitability rating. Make a note in the sidecar text that the

AR results are also available and can be viewed in the web map application. *Response: Done.*

161. **Story Map navigation** – Add tabs or bookmarks to jump to different sections of the StoryMap since navigating it takes so much scrolling. *Response: Done.*
162. **Content management** – All content on AGOL needs to have a Description, Terms of Use, and Credits. Ownership needs to be transferred to IWT staff. *Response: Done.*
163. **Curated information** – Is there an out of the box widget for clicking on a score grid cell and selecting the related features from other layers and displaying a subset of pre-selected fields? For example, click on as ASR Final Suitability Rating grid cell and it also highlights the location and names of the excess water sources and water supply needs used to rate the grid cell. *Response: There is not an out of the box widget with this capability. In order to address this we simplified the high level feature class maps for interactive display, which pars down data fields to summarize scoring.*
164. **Placeholder links** – In the StoryMap, have links to the TWDB contract webpage, report, literature review tables, generalized aquifer characteristics related to ASR table, and GIS Data zipfile. *Response: Done.*
165. **Web Map Application Layout and Layers** – Review and update the web map application by verifying all feature classes from the 4 geodatabases are present, grouping similar layers, and renaming layers to be tidy and intuitive. *Response: Done.*
166. **Text edits** – Review the StoryMap text to be concise, readable, and free of grammatical errors. *Response: Done.*