TCEQ AS-487 ● November 2023
Radioactive Materials Division

Site Selection Criteria for Aquifer Recharge from Stormwater – with Emphasis on Karst Regions of Texas

Rebecca C. Smyth, Bridget R. Scanlon, and Sarah Fakhreddine

Bureau of Economic Geology,

Jackson School of Geosciences, The University of Texas at Austin

November 30, 2023

Prepared for:
Texas Commission on Environmental Quality

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Contents

List of Acronyms

AOR	area of review
AR	aquifer recharge (abbreviation used in Texas for EAR)
BEG	Bureau of Economic Geology
BEZ	Balcones Fault Zone
BMP	Best Management Practice
BSEACD	Barton Springs Edwards Aquifer Conservation District
CFR	Code of Federal Regulations
CRP	Clean Rivers Program
CWA	Clean Water Act
CWQMN	Continuous Water Quality Monitoring Network
DO	Dissolved Oxygen
EAA	Edwards Aquifer Authority
EAPP	Edwards Aquifer Protection Program
EAR	Enhanced Aquifer Recharge
EPA	Environmental Protection Agency
GIS	Geographic Information Systems
GMA	Groundwater Management Area
GPS	Global Positioning System
IC	Impervious Cover
LIDAR	Light Detection and Ranging
MAR	Managed Aquifer Recharge
MCL	Maximum Contaminant Level
µg/L	micrograms per Liter
mg/L	milligrams per Liter
MRLC	Multi Resolution Land Characteristics
NLCD	National Land Cover Database
OW	Office of Water
ORP	Oxidation Reduction Potential
PAH	Polycyclic Aromatic Hydrocarbon
P.E.	Professional Engineer
P.G.	Professional Geoscientist
PWS	Public Water Supply
RRC	Railroad Commission of Texas
RWPG	Regional Water Planning Groups (Texas)
SDWA	Safe Drinking Water Act
SpC	Specific Conductance
SRWMD	Suwannee River Water Management District (Florida)
SWAP	Source Water Assessment and Protection (Texas)
WSD	Water Supply Division
TAC	Texas Administrative Code
TCEQ	Texas Commission on Environmental Quality
TDS	Total Dissolved Solids
TGPC	Texas Groundwater Protection Committee
TMDL	Total Maximum Daily load
TPDES	Texas Pollution Discharge Elimination System
TPWD	Texas Parks and Wildlife Department
TSS	Total Suspended Solids
TWDB	Texas Water Development Board
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

1 Introduction

With growing scarcity of drinking water resources, it is increasingly important to develop practices to enhance water storage. Enhanced Aquifer Recharge (EAR), also called Managed Aquifer Recharge (MAR), encompasses multiple methods for optimizing groundwater resources (NASEM, 2016; EPA, 2021). The U.S. Environmental Protection Agency (EPA) sponsored a state-of-the-science review on the feasibility of using stormwater for EAR; however, the emphasis is on recharge to clastic aquifers (granular porous media) rather than karst aquifer systems, where fluid migration is dominated by conduit flow (EPA, 2021). In Texas, EAR is referred to as simply Aquifer Recharge (AR) and is distinct from Aquifer Storage and Recovery. The focus of this AR guidance document is selection criteria for sites where stormwater runoff enters aquifers through surface karst features in carbonate rocks (i.e., caves, sinkholes, and other types of solution voids[1]).

Stormwater is water from rain that can infiltrate, evaporate, or runoff and end up in nearby streams, rivers, or other surface water bodies. The traditional goals of stormwater management (e.g., National or Texas Pollutant Discharge Elimination System, NPDES or TPDES[2]), and other federal and state regulatory programs, include surface water pollution-prevention, erosion and flood control, maintaining sufficient volumes of flow in streams and rivers, and protecting water quality in aquifers.

Improvement of natural recharge features to enhance transfer of stormwater runoff to groundwater falls under the jurisdiction of EPA's Underground Injection Control (UIC) program, as authorized by the Safe Drinking Water Act (SDWA). According to specifications in EPA and the Texas Commission on Environmental Quality (TCEQ) rules[3], all features through which surface water is artificially directed via engineered structures to groundwater must be permitted as UIC Class V wells (EPA, 2021). In fact, under a TCEQ rule in Chapter 331 of the Texas Administrative Code 30 TAC 331.2(96), the definition of a Class V Recharge Injection Well includes:

"…an improved sinkhole or cave connected to an aquifer."

A salient topic related to enhancement of groundwater resources through capture of stormwater runoff in karst features is urban stormwater management. As water resources become more critical, the need to balance competing claims for our nation's water (i.e., surface water) will need to be addressed. Surface water in Texas is already overallocated; there are permits for withdrawal of greater volumes of "public" water than are available under current conditions (e.g., Rubenstein et al., 2022).

Dams continue to be planned and built for dual purposes of flood control and water supply, even though they are detrimental to the long-term ecological health of riverine systems, bays and estuaries. Dams also trap sediment that would otherwise be transported and discharged to the Gulf of Mexico to help combat coastal erosion. Reservoirs formed by dams are used for public recreation, such as vacation housing development and motor-boating. Reservoir water quality is compromised by leaks from septic systems and hydrocarbon byproducts (gas and

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[1] Karst features are discussed in detail in Section 4.4 – Hydrogeology.

[2] The National Pollution Discharge Elimination System (NPDES) and the Texas equivalent – Texas Pollution Discharge Elimination System (TPDES) – are discussed in Section 2.1.2, U.S. Clean Water Act.

[3] Texas has primacy for the EPA UIC program.

diesel fuels) associated with these recreational activities. A high rate of evaporation in more arid portions of the state is another drawback to using reservoirs to enhance water resources.

One approach to maintaining a healthy flow of surface water toward the coast is periodic release of water from dams; however, this is not always sustained due to lack of water volume, and scientific and regulatory ambiguities (e.g., NRC, 2005; Arthington et al., 2006; Puig-Williams, 2013). An alternative to building dams to augment water resources for drinking water, and maintaining healthy riverine and coastal systems, both ecologically and physically, could be improved structural storm-control measures.

The current objective of most stormwater management practices, especially in urban settings, is to prevent introduction of pollutants to groundwater. In fact, permanent stormwater control structures often store water in surface ponds with special attention given to the types of pond-liners that best *prevent* infiltration of runoff. In another EPA-sponsored state-of-the-science review, Brumley et al. (2018) evaluated green infrastructure practices on groundwater quality. Forms of green infrastructure technology (e.g., rain gardens, permeable pavement, green roofs, rainwater harvesting) are being utilized in urban environments to capture rainwater closer to the source of contaminants that can be associated with runoff from impervious cover. Because of the potential to pollute shallow subsurface water-bearing zones, there is criticism of green infrastructure if it is not accompanied by filtration mechanisms, or water-quality monitoring (e.g., Andres et al., 2018; Brumley et al., 2018).

The objective of this study is to provide guidance to TCEQ on siting considerations for projects involving aquifer recharge through karst features, with focus on the Edwards and Trinity aquifers of Texas. However, in addition to the UIC Class V permitting process, a relevant question is:

Can traditional stormwater management philosophy be altered to improve aquifer recharge without degrading groundwater quality? By enhancing AR through improvement of karst features, there could be great potential to increase groundwater storage for drought mitigation and to address seasonal water supply demands.

1.1 Report organization

Section 1 – **Introduction** provides a summary of research justification and interactions between surface water and groundwater (above), the defined **Geographic scope** (Section 1.2) of this study, and a short discussion of **Stakeholders** (Section 1.3).

Surface water and groundwater interactions, with their independent sets of regulations, compelled us to provide details on current regulatory limitations. In Texas, and possibly other states too, existing regulatory avenues for development of aquifer recharge through karst surface features are discussed in Section 2 – **Regulatory clarification and constraints**.

Central Texas sites, for which engineered structures to enhance aquifer recharge from stormwater through karst features are already in place, are summarized in Section 3.1 – **Case studies**; we also list sites where natural recharge features have been identified for possible future aquifer recharge development. Summaries of types of structures and general approaches to stormwater management used in states with karst terrain are included in a companion document (Fakhreddine et al., 2021) and Section 3.2 – **General Best Management Practices (BMPs).**

Section 4 – **Site selection guidance** covers requirements for, and scientifically-based limitations of site selection to assure safe implementation of aquifer recharge through karst features using stormwater. Contained in this section are lists of and links to data and map sources, including GIS and/or remote imagery that will be critical to understanding all aspects of site selection.

Section 5 – **Summary** provides this study’s research summary and recommendations.

1.2 Geographic scope

The scope of this document is limited to areas of Texas underlain by Edwards and Trinity aquifers as defined by the Texas Water Development Board (TWDB) (Figure 1). Sites currently in operation or being considered for development of aquifer recharge are located in central Texas. Further work in other parts of Texas underlain by carbonate rocks, other than central Texas, might reveal additional aquifer recharge opportunities.

Edwards/Trinity aquifer areas in Texas mostly correspond to regions the US Geological Survey (USGS) has compiled data from state geological maps to produce coverage of existing karst features, or areas with the potential to form karst features (Figure 1). Details on the multiple subunits of the Edwards and Trinity carbonate aquifers are discussed in Section 4.4.

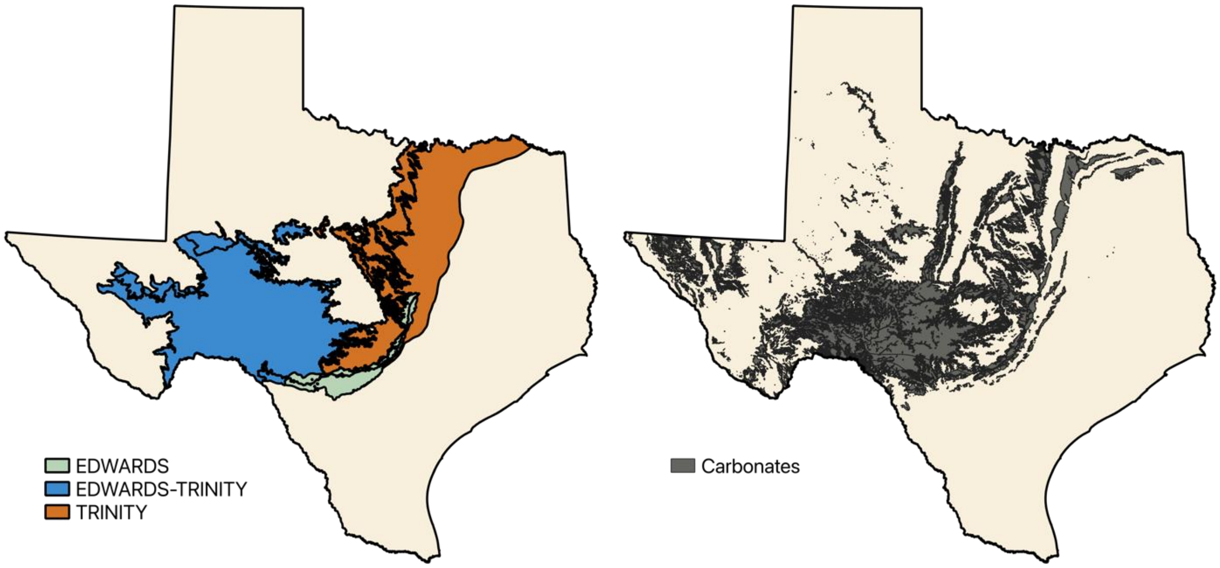

Figure 1. Edwards and Trinity aquifer footprints in Texas (left, modified from TWDB, 2011) and carbonate rocks in Texas with existing or potential karst feature development (right, modified from Weary and Doctor, 2014).

1.3 Stakeholders

Stakeholders – individuals or groups with interest or concern regarding this guidance include:

- Federal and State environmental regulators (EPA, TCEQ, Texas Parks and Wildlife), legislators, and members of Congress;
- Federal and State research entities, such as the USGS, especially scientists within the Oklahoma-Texas Water Science Center, and the Texas Water Development Board;
- River authorities and State Regional Water Planning Groups;
- Groundwater Management Areas, aquifer authorities, and Groundwater Conservation Districts;
- Consultants with expertise in karst hydrogeology in Texas; and
- Concerned citizens.

2 Regulatory clarification and constraints

Only a limited number of U.S., primarily EPA, and State (TCEQ) regulations and guidelines may be required for authorization of aquifer recharge through karst features in Texas (e.g., Class V injection well authorization); regardless, many Federal and State regulatory guidelines and databases are needed to gather critical information related to site selection.

2.1 Federal rules and agencies

The most pertinent federal laws and programs for siting AR projects in Texas are associated with the Safe Drinking Water Act (SDWA). When considering the quality of source water entering AR features, standards from other programs may be applicable. In addition, databases and studies compiled and conducted by agencies, such as the U.S. Geological Survey, may also provide critical information needed for proper site selection.

2.1.1 Safe Drinking Water Act

One purpose of the SDWA is to protect underground sources of drinking water (USDWs) from contamination, as specified in the SDWA summary[4]. Protective measures for both surface water and groundwater resources are included in associated EPA/SDWA regulations.

Under authority of the SDWA, the EPA regulates subsurface injection of fluids through the UIC program, most importantly for this guidance document, the Class V category. The TCEQ has primacy for all classes of UIC injection wells except those related to oil and gas operations (Class II) and carbon sequestration injection wells (Class VI), both of which are regulated by the Railroad Commission of Texas (RRC). Discussion of UIC Class V wells is included in Section 2.2.1 and other locations below.

Also under authority of the SDWA, the EPA sets primary and secondary drinking water standards in the format of maximum contaminant levels (MCLs). Contaminants of concern can be naturally occurring or anthropogenic. In Texas the TCEQ has primacy for regulation of aquifer recharge through UIC Class V structures. An objective of the UIC program – for all classes of UIC wells – is to prevent impacts to public water systems by fluids introduced into USDWs (GWPC, 2022).

An EPA-defined program in the Code of Federal Regulations (CFR) that falls under State jurisdiction is called groundwater under the direct influence of surface water (GWUDI). Consideration of GWUDI might be needed for selection of AR through karst features, especially if the recharged water will be utilized for drinking water. The definition of GWUDI is (40 CFR141.2):

> *Ground water under the direct influence of surface water (GWUDI) means any water beneath the surface of the ground with significant occurrence of insects or other macro-organisms, algae, or large-diameter pathogens such as Giardia lamblia or Cryptosporidium, or significant and relatively rapid shifts in water characteristics such as turbidity, temperature, conductivity, or pH which closely correlate to climatological or surface water conditions. Direct influence must be determined for individual sources in accordance with criteria established by the State. The State determination of direct influence may be based on site-specific measurements of water quality and/or documentation of well construction characteristics and geology with field evaluation.*

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[4] www.epa.gov/laws-regulations/summary-safe-drinking-water-act

2.1.2 Nonpoint source pollution

Stormwater containing contaminants is most often categorized as nonpoint source (NPS) pollution, which is defined as water pollution that does not meet the legal definition of point-source pollution. Examples of NPS pollution are (1) runoff of agricultural- or residential-sourced fertilizers, pesticides, insecticides, or increased dissolved solids, (2) toxic chemicals, oil and grease from energy production or urban areas, (3) sediment-bearing runoff from construction sites, agricultural and forested land, or streambank erosion, (4) acid drainage from abandoned mines, (5) livestock, pet, or human (septic system) waste, and activities related to hydromodification and habitat alteration (EPA, 2022).

Since 1987, the EPA has issued grants to states, territories, and tribes to address NPS pollution under Section 319 Nonpoint Source Management Program[5]. At least one aquifer recharge project in Texas (Antioch Cave) has already benefitted from the 319 program, as detailed in Section 3.1 (Case studies), Fakhreddine et al. (2021), and Fakhreddine and Scanlon (2022).

2.1.3 USGS and other Federal data collection entities

In addition to serving as a regulator, the EPA sponsors data collection and research programs which result in reports that provide useful information for siting an enhanced recharge project for karst aquifers in Texas (e.g., EPA, 2018; EPA, 2021). Other entities with both regulatory and research roles are the U.S. Army Corps of Engineers and U.S. Fish and Wildlife Service (USFWS).

The USGS does not have a regulatory role; however, they collect natural resource data that are critical to siting of enhanced aquifer recharge sites. For example, the USGS National Water Information System[6] includes surface water discharge data throughout the U.S. The USGS National Hydrography Dataset[7] includes detailed maps of watershed systems. Numerous other USGS entities conduct research pertinent to this guidance. Research important to siting of enhanced aquifer recharge structures is conducted by the USGS Oklahoma-Texas Water Science Center (e.g., Mahler et al., 2005).

In the Task 3 report for this project (Fakhreddine and Scanlon, 2022), the USGS National Land Cover Dataset (NLCD) is introduced as a resource to obtain information on changes in land use and impervious cover. Since the conclusion of that report, an updated version of the NLCD has been released (USGS, 2019) and is available through the USGS Earth Resources Observation and Science Center[8]. A specific source for NLCD data that includes urban impervious cover is provided in Section 4.2.

2.2 State rules and agencies

Numerous State of Texas programs apply to enhanced recharge of aquifers in karst terrain. While the TCEQ has the primary regulatory role, the Texas Water Development Board and the RRC have pertinent data collection and maintenance programs.

In Texas, EAR is referred to simply as Aquifer Recharge (AR); this program is administered by TCEQ as defined by rules in Title 30 of the Texas Administrative Code (30 TAC), Chapter 331 –

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[5] www.epa.gov/nps/319-grant-program-states-and-territories

[6] waterdata.usgs.gov/nwis/sw

[7] www.usgs.gov/national-hydrography/national-hydrography-dataset

[8] www.usgs.gov/centers/eros/science/national-land-cover-database

Underground Injection Control, Subchapter H – Standards for Class V Wells, and Subchapter O – Additional Requirements for Class V Injection Wells Associated with Aquifer Recharge Projects.

Definitions critical to the understanding of siting criteria are contained in 30 TAC Section 331.2, which is one of the rules under General Provisions for UIC. An aquifer recharge project is defined in 30 TAC Section 331.2(7) as:

> *A project involving the intentional recharge of an aquifer by means of an injection well authorized under this chapter 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; or*
> *(E) mitigate subsidence.*

An improved sink hole is defined in 30 TAC Section 331.2(55) as:

> *A naturally occurring karst depression or other natural crevice found in carbonate rocks, volcanic terrain, and other geologic settings which has been modified by man for the purpose of directing and emplacing fluids into the subsurface.*

A recharge injection well is defined in 30 TAC Section 331.2(96) as:

> *A Class V injection well used for the injection of water into a geologic formation for an aquifer recharge project, including an improved sinkhole or cave connected to an aquifer.*

In addition to UIC, which is discussed further below, other TCEQ programs could be applicable to siting of an AR project in karst aquifers in Texas — for example, a site that is in final stages of TCEQ approval[9], is under consideration for a Water Rights Permit from the TCEQ Texas Instream Flow Program (TCEQ, 2022).

2.2.1 UIC Class V Well Program

TCEQ has primacy from EPA for the UIC Class V well program in Texas, guidance for which is available at the Class V Injection Wells webpage[10]. A TCEQ Class V injection well authorization is required for nonhazardous fluid being injected into or above an underground source of drinking water. AR through karst features require an authorization and have additional requirements under 30 TAC 331 Subchapter O. For UIC Class V AR applications, a pre-application meeting is encouraged.

Groundwater in karst systems is primarily transported along fractures and through connected voids (conduit flow) rather than by diffuse flow as in clastic aquifers (granular porous media). Hence, preventing movement of injectate (recharged water) outside of the authorized injection zone, as required by TCEQ AR regulations (30 TAC Section 331.264), will be difficult, if not impossible, in a conduit-flow-dominated karst aquifer.

Shaw et al. (2020, p. 11) emphasized the lack of recoverability of water injected for AR in Texas. They dismiss the need for recoverability of AR injectate by noting that AR wells are generally not used for water supply. However, Shaw et al. (2020) also state that the objectives of AR wells

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[9] Details of the Stoneledge Quarry site are contained in Section 3.1 – Case Studies.
[10] www.tceq.texas.gov/permitting/radmat/uic_permits/UIC_Guidance_Class_5.html

are to (1) improve groundwater conditions, (2) improve spring flow and other groundwater-surface water interactions, (3) mitigate subsidence, and (4) other. Given the complex groundwater flow paths in karst aquifer systems, it may not be technically possible to distinguish between “water supply” and the Shaw et al. (2020) objectives for AR.

Area of Review

Area of review (AOR) regulations for AR are contained in Subchapter O of the UIC regulations (30 TAC Section 331.263). Requirements include a map showing all artificial penetrations (wells) within the AOR, and the depth, completion information, and use of each well (e.g., water well, oil and gas well, etc.) within a ½-mile radius of each proposed AR well. By definition in the Clean Water Act (CWA), wells can be point-sources of pollution to USDWs. Fulfilling AOR requirements for enhanced recharge of stormwater through karst features should be required for all AR Class V well authorization applications.

If urban stormwater management structures come into use for AR, requirements for pond liners may need to be addressed. For an enlightening review of pond liners, stormwater management structures, and karst features see Hunt et al. (2017).

2.2.2 Other TCEQ Programs with Pertinent Information

In addition to the UIC program, other programs administered under the TCEQ Office of Water may have information or provide guidance for AR site selection, especially with regard to water quality concerns. These programs include the Source Water Assessment and Protection Program (SWAP), Public Water System Supervision Program, Groundwater and Wells, Non-point Source Pollution, Sole Source Aquifer Protection, and Edwards Aquifer Protection Program (EAPP).

- SWAP[11] is under the TCEQ Water Supply Division
  - Source Water Assessment is required by SDWA;
  - Source Water Protection is a voluntary program.
- The Public Water System Supervision Program is under the TCEQ Water Supply Division
- Groundwater and Wells Program[12]
- The Groundwater Planning and Assessment Program is over:
  - Priority Groundwater Management Area program
  - Texas Groundwater Protection Program

The TCEQ EAPP regulates activities having the potential for polluting the Edwards Aquifer and hydrologically connected surface streams in order to protect existing and potential uses of groundwater. EAPP maintains Texas Surface Water Quality Standards in portions of eight counties in central Texas, most of which is underlain by karst terrain.[13] EAPP’s primary goal is to protect water quality of the Edwards Aquifer.

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[11] www.tceq.texas.gov/drinkingwater/SWAP
[12] www.tceq.texas.gov/groundwater
[13] www.tceq.texas.gov/permitting/eapp

2.2.3 TWDB Water Planning

The State of Texas is divided into 16 regional water planning groups (RWPG) that are each responsible for developing regional water plans for their area[14]. These plans are submitted to the TWDB for approval and inclusion in the State Water Plan, which is updated every five years. Other state agencies that participate in state water planning are Texas Parks and Wildlife Department, Texas Department of Agriculture, and the Texas State Soil and Water Conservation Board.

Surface water and groundwater resources fall under two independent divisions of the TWDB. Data collection, analysis and modeling of rivers, streams, reservoirs, bays and estuaries is overseen by the Surface Water Resources Division[15].

The TWDB Groundwater Division[16] oversees all aspects of groundwater planning for 16 Groundwater Management Areas (GMA) of Texas. Rather than coinciding with boundaries of the 16 RWPGs (delineated roughly along major surface water drainage basins), the GMA boundaries[17] roughly follow the major[18] and minor aquifers of Texas.

Approximately 60 percent of water use in Texas is sourced from groundwater. Multiple programs under the TWDB Groundwater Division, such as water level and water quality monitoring, and groundwater availability modeling, all provide invaluable data for any type of water resource planning.

3 Review of pertinent Best Management Practices

The term Best Management Practices (BMPs) refers to engineered structures or *approaches* to stormwater management. Case studies included in Section 3.1 are restricted to known aquifer recharge sites over karst terrain in central Texas, most of which are improved sinkholes. EPA (2021) defines an “improved sinkhole” as a naturally occurring karst depression or other natural crevice, which has been modified by a man-made structure to direct fluids into the subsurface.[19] EPA defines anthropogenic structures such as pipes, swales, ditches, excavations, drains, graded slopes, or any other device that is intended to channel fluids toward or into a sinkhole. In a companion document, Fakhreddine et al. (2021) provide other case study and BMP examples from Chesapeake Bay, Pennsylvania, and Maryland. Discussion of BMPs that are more generally used for stormwater management over all types of terrain is also included in Section 3.2.

3.1 Case studies

Using engineered structures to focus stormwater into sinkholes to enhance groundwater recharge is being conducted on a limited basis, but there are concerns about introduction of nonpoint source pollution into the hydrologically connected karst aquifers. The best documented case of such in Texas is the Barton Springs Edwards Aquifer Conservation District (BSEACD) Antioch Cave BMP project where CWA 319h funds were used to emplace a structure to restrict stormwater with more turbid flow from entering the cave, thereby restricting higher levels of nonpoint source pollutants from entering the Edwards Aquifer (Smith et al., 2011).

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[14] www.twdb.texas.gov/waterplanning/index.asp
[15] www.twdb.texas.gov/surfacewater/index.asp
[16] www.twdb.texas.gov/groundwater/index.asp
[17] www.twdb.texas.gov/groundwater/management_areas/index.asp
[18] www.twdb.texas.gov/groundwater/aquifer/major.asp
[19] A similar definition is contained in 30 TAC Section 331.2(55)

Another Bureau of Economic Geology companion document (Fakhreddine and Scanlon, 2022), contains a detailed description of the Antioch Cave BMP function, and one other enhanced stormwater recharge site that is currently permitted by TCEQ. Through further communication with the BSEACD and other groups assessing or developing enhanced recharge projects in Edwards aquifer karst terrain, we have been able to describe additional case study sites.

Categories of sites included here are: karst features with completed enhanced aquifer recharge structures, karst features with diversion canals from riverine systems built (or planned) to enhance aquifer recharge, and karst features currently receiving untreated runoff in urban areas of Travis and Hays counties.

- Karst features that have had engineered structures built to improve aquifer recharge include:
    - Antioch Cave, Hays County, Texas – details of this site are contained in the Task 3 report for this project (Fakhreddine and Scanlon, 2022).
    - William Russell Karst Preserve (formerly called Blowing Sink Preserve after the largest cave on property), Travis County, Texas – Surface drainage over 70 percent of the site is through multiple sinkholes; the remainder drains to Slaughter Creek.
        - Zara Environmental LLC was contracted by City of Austin Parks and Recreation Dept. and Austin Water Utilities Balcones Canyonland Preserve personnel to build recharge structures over five caves on the site: Wyoka Cave, Brownlee Cave, Sinky Dinky Cave, William's Well (aka Sink in the Woods), and Winter Woods Cave. The purpose was to clean out, stabilize, and prevent further input of debris into the caves by building concrete risers over cave openings. The intended outcome was to enhance aquifer recharge while preserving habitat for rare species, and preventing unauthorized access (CoA, 2014).
- Karst features that have, or are planned to have engineered structures, primarily diversion canals from riverine systems, built to enhance aquifer recharge include:
    - Seco Creek (details of this site are contained in the Task 3 report for this project).
    - Stoneledge Quarry, Hays County (according to the City of Austin Watershed Protection Department, this site is in final stages of permitting) – a proposed diversion canal from Little Bear Creek (a tributary of Onion Creek which discharges to the Colorado River and ultimately Matagorda Bay) to the Stoneledge (a.k.a. Wenzel) Quarry, the base of which intersects a karst feature and an assumed water table for the Barton Springs segment of the Edwards Balcones Fault Zone (BFZ) Aquifer.
        - An interlocal agreement was established between the City of Austin, Lower Colorado River Authority (LCRA), and the BSEACD for LCRA to evaluate impacts on downstream water rights. LCRA found that 24 ac-ft/yr for 10 years would need to be released from lakes Buchanan and Travis to offset planned diversions from Little Bear Creek in order to maintain supplement instream flows (CoA, 2011).
        - HDR Engineering has completed extensive planning for the Little Bear Creek Recharge Enhancement Facility's site development (HDR, 2011) including:
            - Erosion control, vegetative stabilization and protection, and re-vegetation plans.
            - Channel Plan, profile, and cross sections
            - Road and creek access details
        - The permit for this project is still in progress; the process began in 2002 with the City of Austin purchasing the quarry property.

- Karst features that are naturally receiving untreated runoff in urban areas include:
    - In a report to the City of Austin, Watershed Protection Department, Geosyntec (2020) reviewed mitigation options for eight sinkholes receiving untreated runoff that pose a pollution risk to Northern and Barton Springs segments of the Edwards Aquifer. All sites are located in recharge zones of the aquifer. The sites are (Site Descriptions on pg. 8 of Geosyntec, 2020):
        1. Railroad Sinkhole and Cave Opening – Geosyntec (2020) later removed the Railroad Sinkhole site from consideration for mitigation after an engineered sedimentation/filtration control (BMP) was built to intercept runoff from a large office complex. They discovered that outfall from the BMP had been diverted downstream from the sinkhole opening. This is an example of how traditional urban engineered structures may prevent pollution from stormwater runoff but miss an opportunity for enhanced recharge of an aquifer (in this case, the Northern Segment of the Edwards Balcones Fault Zone aquifer).
        2. Anderson Mill/ZBF Upland Sinkhole and Cave Opening – receives untreated highway runoff that could impact a spring in the Bull Creek watershed.
        3. Honeycomb Trailer Park Upland Sinkhole and Cave – receives untreated runoff from a trailer park that could impact springs in the Walnut and Brushy Creek watersheds, which recharge the Northern Segment of the Edwards BFZ Aquifer.
        4. Blackfoot Trail Upland Sinkhole – receives untreated runoff from single family residential, general commercial services, and undeveloped areas; runoff from the developed areas could impact springs in the Walnut and Brushy Creek watersheds, which recharge the Northern Segment of the Edwards BFZ Aquifer.
        5. Divide Swamp Upland Sinkhole – much of the stormwater runoff from impervious areas is treated by a retention/irrigation (wet pond) structure; however, there are two hydrocarbon pipelines within 400 ft of the sinkhole which pose risk to the Slaughter Creek watershed and the Barton Springs segment of the Edwards BFZ aquifer along a flow path that has been traced to Barton Springs.
        6. Brodie Sinkhole and Cave – most of the runoff from impervious areas is treated by sedimentation filtration and retention/irrigation engineered stormwater structures. This feature was included in the Geosyntec mitigation evaluation because of its large (556 acre) drainage area that encompasses the William Russel Karst Preserve. The 254 ft deep Blowing Sink Cave, through which a human can gain access to the local water table of the Barton Springs segment of the Edwards BFZ aquifer, and numerous other karst features lie within the preserve. Even though the preserve is undeveloped, there is concern about the large volume of runoff that could be introduced to the aquifer there. Blowing Sink Cave is discussed further in Section 5.4.2.
        7. Kentucky Upland Sinkhole – receives untreated highway runoff (from Brodie Lane) with additional runoff from a small area (21 acres) of low-density, single-family housing. The sinkhole lies within the Slaughter Creek watershed, which recharges the Barton Springs segment of the Edwards BFZ aquifer, and poses a risk to Barton Springs.
        8. Shady Hollow Upland Sinkhole – This covered sinkhole and reported underlying cave receives untreated stormwater runoff from a 17-acre area of single-family residences. The feature lies within the Slaughter Creek watershed, which recharges the Barton Springs segment of the Edwards BFZ aquifer, and poses a risk to Barton Springs.

Additionally, we have collected information on numerous enhanced recharge sites in karst in Florida, including:

- Black Creek Water Resource Development Project in northeastern FL;
- Flatford Swamp Aquifer Recharge Project in southwestern FL;
- Little Orange Creek Recharge Well System in northeastern FL;
- Sunnyhill Restoration Area, Aquifer Recharge via sinkholes in northeastern FL;
- Suwannee River Water Management District in north central FL;
- Comprehensive Everglades Restoration Plan – a combination water supply (through aquifer storage and recovery) and flood protection.

3.2 General Best Management Practices

Stormwater BMPs are ubiquitous, especially in urban environments. Most BMPs aim to prevent infiltration of stormwater in order to preserve water quality in underlying aquifers. The practice of allowing stormwater runoff to recharge shallow aquifers directly from BMPs is in its infancy, including one approach called green infrastructure technology (Brumley et al., 2018). Example types of green infrastructure being used to divert stormwater runoff directly to groundwater, thereby potentially impacting water quality include: porous pavement, retention ponds, shallow injection or drainage wells, and agricultural or roadway drains (Andres et al., 2018). The only green infrastructure features that are under jurisdiction of the TCEQ UIC program are features that directly emplace fluids into aquifers through karst features.

Source control BMPs include permeable friction courses, rainwater harvesting practices (called green roofs in Brumley et al. 2018) and engineered vegetative filter strips. The problem with these practices is that there is no filtration of the stormwater before it enters the shallow subsurface, or associated water quality monitoring (Andres, et al., 2018; Brumley et al., 2018).

Retention ponds are commonly paired with irrigation systems, which could provide some filtration of water prior to it entering a shallow aquifer, if there is an intervening soil zone. Constructed wetlands and other types of engineered filtration systems could be used over karst features; this is a practice widely used in Florida (e.g., Lee et al., 2021).

Based on a statistical comparison of water quality in effluent from structural BMPs versus runoff in undeveloped areas, Richter and Peacock (2015) concluded that linings should be required in basin-type BMPs.

An example of untreated surface water being introduced to the Floridan aquifer via an UIC Class V injection well may be found in a permit application for the Little Orange Creek Recharge Well System in Florida (ASRUS, 2019).

In another example from Florida (Sagul, 2015), the Suwannee River Water Management District (SRWMD) has constructed a drainage well and associated conveyance channel to prevent flooding in a natural drainage basin after subsurface karst cavities in the Floridan aquifer were grouted to alleviate building subsidence. The drainage well is expected to restore natural drainage; however, the site is adjacent to a major roadway, so recharge water will contain contaminants. The SRWMD has also installed monitoring wells to document any changes in groundwater quality.

4 Site selection guidance

This section includes considerations of surface water processes (science of hydrology) and subsurface, or groundwater processes (science of hydrogeology). These two scientific disciplines have traditionally been considered separate but awareness of how closely they are connected has increased, especially for karst environments. Proper siting of enhanced recharge structures in a karst environment will require both hydrologic and hydrogeologic investigations.

Following is a general outline of a site selection process for stormwater discharge to karst recharge features based on numerous reference documents [e.g., Geosyntec (2020), Tennessee Department of Environment and Conservation (TDEC, 2014), and TWDB (2008)], and professional experience of researchers at the Bureau of Economic Geology:

1. Compile existing information, including maps, reports, and data on all known wells, springs, karst features, and man-made conduits such as pipelines for oil and gas, sewer systems, or power systems.
2. Consider land use and land cover constraints. Land use categories are urban, rural/agricultural and uplands or riverine. Flood-prone areas may have high volumes of recharge water available but can also be subject to erosive alteration of streams banks and karst features (sinkholes).
3. Conduct field surveying over as much of the watershed/catchment area as possible. Look for springs, seeps, karst features with surface expression, and possible pollutants (will require a P.G.[20]).
4. Conduct an Area of Review (AOR) survey to identify all artificial penetrations (e.g., wells) that could be impacted by recharge water or used to detect dye from tracer testing.
5. Conduct dye traces to define groundwater flow paths and insure protection of nearby water supply wells or springs.
6. Perform hydraulic load testing to assess suitability of karst features to accept recharge water. Features through which enhanced recharge will take place could be natural karst features such as caves or sinkholes, or man-made features such as quarries.
7. Identify source(s) of recharge water and assess susceptibility to contamination.
8. Design a water quality monitoring program.
9. Complete site engineering designs (will require a P.E.[21]).
10. Prepare site maps that include all karst features, AOR results, and all other pertinent details.
11. Obtain necessary permits.

4.1 Mapping and data resources

The size and character of the capture area of a karst feature that will be used for enhanced recharge must be known for site planning. Geographic Information Systems (GIS) is a state-of-the-art computerized tool for generating maps of all components needed for site selection. Commercial and open-source versions of GIS software can be obtained for users wanting to generate detailed maps for specific projects. A formatting protocol, Geologic Map Schema, for digital publication of geologic maps has been developed by the U. S. Geological Survey (USGS, 2020). Elements of this methodology could be useful for maps submitted with permit applications.

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[20] P.G.: Professional Geoscientist

[21] P.E.: Professional Engineer

Use of GIS for detecting karst feature trends, delineation of springsheds for protecting critical springs (e.g. Comal, San Marcos, Barton, Jacob's Well, etc.), boundaries of jurisdictional entities with limiting/prohibitive rules, location of potential improved features with respect to contributing and recharge zones.

Lidar, light detection and ranging, technology is a laser-based method for generating digital topographic maps. Sources of lidar data for areas within Texas are included below. The technology is so widely used in karst terrain that the USGS has published methodologies for identifying closed depressions using lidar data (e.g., Weary and Doctor, 2014; Doctor and Wall, 2018).

Locations of existing water wells, abandoned oil and gas production wells, and types of UIC wells should be identified within specified radii of features that will be used for enhanced recharge. This is called area of review and is discussed in Section 2.2.2.

Many existing maps are also available for use. Sources of available digital map data include:

- The USGS National Geospatial Program is one source of digital topographic maps[22] available for download. A website maintained by USGS called 3DEP LidarExplorer[23] shows lidar data are available for most of Texas.
- The University of Texas at Austin Library system maintains a website with many useful sources of maps and mapping data with instructions for use. The most applicable is called the Texas Data Portal[24].
- The Texas Natural Resources Information System (TNRIS) has digital elevation models (DEMs) and/or digital terrain models (DTM) and other topographic maps derived from airborne lidar data for many areas of Texas[25]. TNRIS also has satellite and aerial imagery and other useful map data available for download, including watershed boundaries[26].
- The University of Texas at Austin, Bureau of Economic Geology has paper copies of Geologic Atlas of Texas (GAT) maps available at a scale of 1:250,000.
- Digital versions of GAT maps, locations of monitored water wells, and other useful hydrogeological information are available on the Texas Water Development Board (TWDB) webpage[27].
- The RRC maintains a website with locations of some of the horizontal and injection/disposal wells[28] in Texas.
- The University of Texas at Austin, Bureau of Economic Geology, hosts GIS databases[29] for several areas within the Edwards and Trinity aquifers of Texas.
- Multi-Resolution Land Characteristics Consortium[30] website includes land cover data based on Landsat imagery.

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[22] www.usgs.gov/programs/national-geospatial-program/us-topo-maps-america
[23] apps.nationalmap.gov/lidar-explorer/#/
[24] guides.lib.utexas.edu/sources-of-geospatial-data/texas-gis-data
[25] tnris.org/stratmap/elevation-lidar/
[26] data.tnris.org/collection?c=a3246604-801d-438e-a200-f97976a83659#4.82/31.32/-100.08
[27] www.twdb.texas.gov/groundwater/aquifer/GAT/index.asp
[28] www.arcgis.com/home/item.html?id=6304a76feaa24d98b8eaecdcc0f9e4bc
[29] www.arcgis.com/home/item.html?id=6304a76feaa24d98b8eaecdcc0f9e4bc
[30] www.arcgis.com/home/item.html?id=6304a76feaa24d98b8eaecdcc0f9e4bc

- Multi-Resolution Land Characteristics Consortium website includes imperious cover data[31] based on Landsat imagery.
- Natural Resources Conservation Service[32] hosts soil maps online.

4.2 Land cover / land use

A key element to site selection is characteristics of the land surface over which recharge water will flow, and locations where an enhanced recharge structure will be placed. The National Land Cover Dataset, developed by a consortium of federal agencies called Multi-Resolution Land Characteristics Consortium (MRLC), contains multiple geospatial raster datasets based on 30-meter resolution Landsat imagery. The Anderson Level I (General) classes of land cover should provide sufficient detail karst recharge site selection. Eight classes of Level I land use are: Water, Urban, Barren, Forest, Shrubland, Grassland, Agriculture, and Wetland (Anderson et al., 1976). Yang et al. (2003) describes a method to calculate impervious cover that was used by MRLC to develop data sets for urban areas. See Section 4.1 for sources of land cover and urban impervious cover.

The major dichotomies in land use considered here are urban versus rural and uplands versus streambed.

4.2.1 Urban versus rural setting

Pollutant-laden stormwater in urban settings may contain byproducts from heavy industry, impervious cover runoff (e.g., PAHs (polycyclic aromatic hydrocarbons) from asphalt parking lots (Mahler et al., 2005), other hydrocarbons and associated by-products, and metals from vehicles and other sources. Point- (subject to NPDES/TPDES rules) and nonpoint-sources (subject to TCEQ rules) of urban pollution have been documented to impact surface water; in fact, an area covered with impervious surfaces can generate nine times the volume of runoff seen from a wooded area of the same size (EPA, 1996). Schueler and others developed the impervious cover model, which relates stream health to amount of impervious cover (IC) in a subwatershed (Schueler et al., 2009):

- <10% IC – streams can maintain hydrologic function and a healthy ecosystem,
- 10-25% IC – streams begin to degrade physically (increased erosion) and ecologically,
- 25-60% IC – streams are degraded in terms of channel stability, water quality, and biological diversity.

Kiaghadi and Rifai (2019) found acute impacts to water quality from flooding in the greater Houston metropolitan area after Hurricane Harvey in 2017, most likely associated with industrial activity. Watersheds without such industrial activity experienced minimal water quality impacts and recovered more rapidly.

The consensus of stakeholders (gained through personal communication and public reporting) is that use of improved sinkholes for enhancing aquifer recharge should NOT take place in urban areas because of high densities of impervious cover. However, if stormwater control structures that, for example, store water in ponds lined to prevent infiltration, are converted to enhanced recharge structures with engineered filtration systems, runoff from urban sites might be more appropriate for aquifer recharge rather than allowing the water to be lost through evaporation.

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[31] www.mrlc.gov/data/type/urban-imperviousness
[32] www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/geo/

As reported in Fakhreddine and Scanlon (2022), data on quality of stormwater runoff in rural areas (or open space category of land use) are scarce compared to those for urban areas. Source water for enhanced recharge in rural settings could have pollutants from agriculture (pesticides, herbicides, and fertilizers), organics/nutrients from septic systems, and livestock waste. Information from programs sponsored by the U.S. Natural Resources Conservation Service, such as Agricultural Waste Pesticide Collection and Animal Waste Management could be consulted to identify potential sources of contamination of stormwater entering an AR site in rural areas.

4.2.2 Upland versus riverine

In Texas, upland regions of karst terrain have varying thicknesses of soil, soil composition, and soil moisture content, all of which can influence groundwater infiltration (Cha et al., 2022; Delle Rose, 2022). However, the more important controlling factor for upland karst features is whether it is filled with soil, or man-made debris. A soil-filled karst feature can enhance natural filtration of pollutants from stormwater. Hence, the erodibility of soils surrounding an upland feature should be considered in site selection.

Sinkholes can be open or filled with sediment/soil; those filled have greater contaminant filtration and sorption capacity than those that are open; however, if a sinkhole is improved by removal of soil fill, this contaminant removal capacity could be compromised by increased volume and rate of flow. Filled sinkholes also have a greater capacity for attenuation of pollutants through precipitation reactions and filtration. However, as has been demonstrated through case studies (Section 3.1, William Russell Karst Preserve), removing naturally accumulated debris, and/or human trash from sinkholes can enhance the quantity and quality of recharge water.

4.3 Source water

The availability of a sufficient volume of surface water, or stormwater runoff, with acceptable water quality will need to be established for an AR site. Sources of recharge water could be rivers or streams during flood events or high-flow periods, and stormwater runoff from native land surfaces or engineered stormwater structures.

The following is taken from a study referenced in Yang and Scanlon (2019): Large volumes of stormwater runoff from extreme flood events can depress the land surface along the Texas Gulf Coast. Using changes (subsidence and subsequent rebound) in Global Positioning System (GPS) vertical solutions for land surface elevations after over 59 inches of rain in six days, Milliner et al. (2018) documented the fate of flood waters. Their results revealed that a third of the water was captured (as surface water, soil moisture, and groundwater) and two thirds ran off into the Gulf. They also documented that the one-third of captured stormwater was mostly lost to evapotranspiration after about five weeks. Rainfall events are not usually so extreme and such sophisticated GPS analysis is not common, but the same concept applies: large-volume stormwater runoff might be available for capture and used to enhance groundwater resources via AR.

Farther inland, where riverine systems cross karst aquifer outcroppings, careful study is needed to identify threshold rainfall events where stormwater runoff could be captured via AR Surface water modeling is one type of study that could indicate the best locations for AR (See Section 4.5). Multiple scales of studies and potential impacts need to be considered. In NRC (2005) and TWDB (2008), the riverine-scale nomenclature adopted for environmental flow studies in Texas are: a) sub-basin, b) segment, c) reach, d) mesohabitat (e.g., pools), and e) microhabitat (e.g., substrate type or water depth). To aid cross-discipline studies, it would be good to use consistent nomenclature for scale of different surface water bodies.

In upland regions, or terrestrial karst settings, natural sources of concentrated stormwater runoff for artificial recharge will be scarce, especially because most of the carbonate rocks crop out in more arid portions of the State. Internally draining, topographic basins, which often overlie sinkholes, might be the most common terrestrial setting in which to capture stormwater runoff for enhanced recharge. An example is the William Russell Karst Preserve presented in Section 3.1.

Manmade stormwater management structures, which are primarily found in urban areas, will provide larger volumes of potential recharge water. Many of these structures are present throughout the metropolitan areas of Central Texas. An example of stormwater management facility that could be modified and used for enhanced recharge is the Railroad Sinkhole site presented in Section 3.1.

Other site selection considerations for sources of water that will be used for enhanced recharge pertain to water quality. Prior to site selection, all point and non-point sources pollution that could impact the quality of recharge water entering a karst feature will need to be located. If contaminants coming from an injection well or a discrete fracture were to impact the quality of water being directed to an AR feature, either (1) engineered improvements to improve water quality, or (2) plugging of the well will need to be implemented. Detailed discussions of source water quality considerations are contained in companion documents for this guidance (i.e., Fakhreddine et al., 2021 and Fakhreddine and Scanlon, 2022).

4.4 Hydrogeology

Natural recharge in karst environments of Texas occurs by recharge of rainfall and runoff over outcroppings of carbonate rocks that have higher matrix porosity and permeability, or through upland karst-derived surface features (e.g., sinkholes, caves with surface-openings) located in lower matrix porosity-permeability rocks (Hauwert et al., 2004). It is thought that a larger volume of recharge to karst aquifers in central Texas occurs when rainfall or surface water enters transmissive faults and fractures, or swallets (water-covered sinkholes) along streambeds that are directly underlain by carbonate rocks (Slade et al., 1986). In a study of discrete versus diffuse recharge to the Edwards aquifer system in central Texas (Camp Bullis Training Site of Joint Base San Antonio), Sun et al. (2020) concluded that most of the recharge is discrete, sourced from perennial baseflow in major rivers and smaller losing streams.

Approximately 60 percent of water use in Texas is sourced from groundwater. Multiple programs under the TWDB Groundwater Division, such as water level and water quality monitoring, and groundwater availability modeling, all provide invaluable data for any type of water resource planning (TWDB, 2022). The Cretaceous-age, karstified Edwards and Trinity carbonate aquifers of Texas are the focus of this guidance (Fig. 1). As defined by the TWDB (Fig. 2), these major aquifers are from west to east (1) outcrop and subcrop portions of the Edwards-Trinity Plateau, (2) outcrop and subcrop portions of the Edwards Balcones Fault Zone (BFZ), and (3) outcrop and subcrop portions of the Trinity. Streams crossing outcrop portions of the Trinity aquifer greatly contribute to recharge in the Edwards BFZ aquifer. Subcrop portions of the Trinity underlie the Edwards BFZ in parts of central Texas, and in places are in hydrologic connection (e.g., Green et al., 2011).

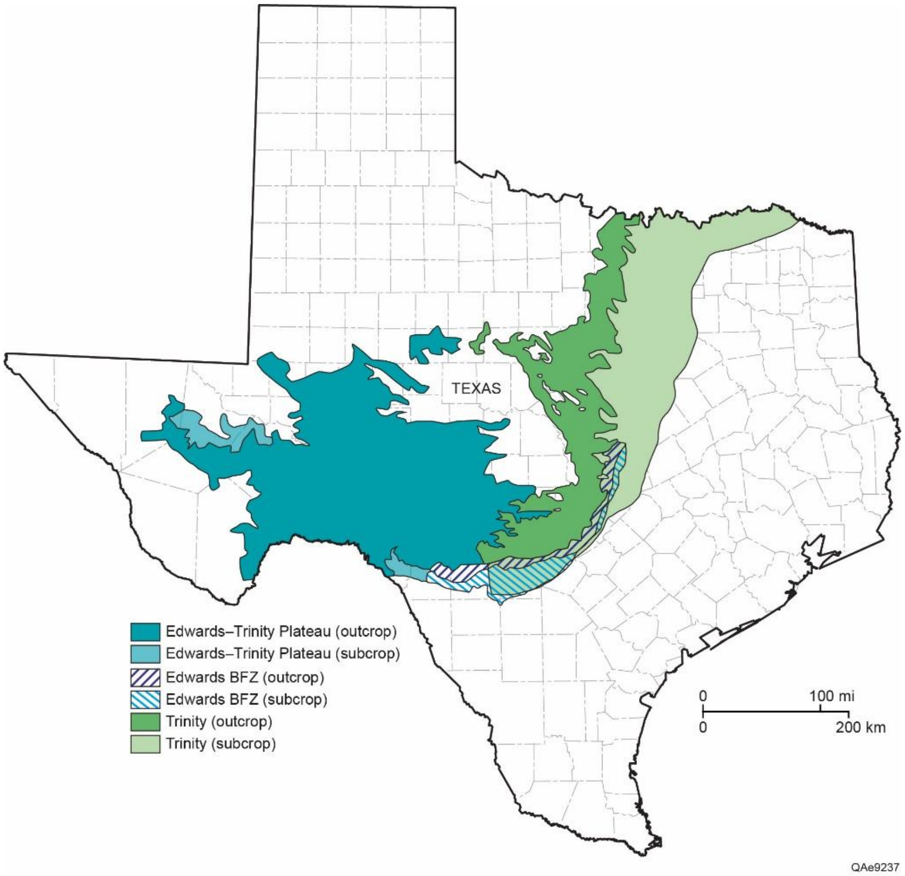

Figure 2. Major carbonate aquifers of Texas. Modified from TWDB (2022).

The Edwards aquifer contains zones with specific hydrologic properties resulting in wide ranges of hydrologic properties such as permeability and compressibility; hence the ability for groundwater to be quickly transported along complex flow paths (e.g., Hunt et al., 2019).

The Edwards Aquifer is characterized by a triple permeability system, meaning groundwater can be transported through rock matrix, fractures/faults, or conduits [e.g., Mace (1995), Hovorka et al. (1995, 2004), Halihan et al. (2000); and Lindgren et al., (2004)]. Conduits, or interconnected pathways, which allow quick, large-volume groundwater flow, evolve in carbonate terrains through several mechanisms. Details of how conduits have and will continue to form in Edwards-Trinity aquifers have great potential to impact water supply.

Aquifer suitability for enhanced recharge in Texas was evaluated by Shaw et al. (2020). They screened locations based of three sets of criteria:

- Hydrogeologic characteristics [storage potential, transmissivity, infiltration, storativity, recoverability, and limited water quality criteria (total dissolved solids concentration of groundwater)],
- Water available for recharge, and
- Water supply need.

Additional hydrogeologic characterization will be needed prior to selection of specific sites for enhanced recharge using stormwater. The major hydrogeological considerations needed for site selection of enhanced aquifer recharge in karst features of Texas are karst feature identification, sinkhole hydraulics, and surface water – groundwater interaction.

4.4.1 Karst feature identification

Guidance information on karst feature identification and patterns is available in the EAPP guidance manual called Instructions to Geologists for Geologic Assessments on the Edwards Aquifer Recharge/Transition Zones[33]. In this program karst features are defined as one of several types of *sensitive features* because of their recognized ability to recharge the Edwards aquifer. Figure 3 shows examples of types of karst feature zones. Recognition that a particular karst feature may be part of a zone of features will be significant to siting of enhanced recharge projects in karst terrain. This is one reason why a geoscientist with expertise in karst geology will need to have a role in initial site investigation (Item 3 in Section 4.0 above).

A summary of how sinkholes form is contained in Hunt et al. (2017). They describe that in general sinkholes in limestone terrain form through dissolution and gradual collapse, or sudden collapse. The latter are also termed sudden cover-collapse sinkholes. The semi-arid climate, deep water table, and little to no soil cover over limestone bedrock all contribute to the relative lack of sudden cover-collapse sinkholes in central Texas (Hunt et al., 2017). However, interestingly Hunt et al. (2017) document such a feature associated with a compromised liner system underlying an engineered stormwater management structure in Travis County, Texas near Williamson Creek.

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[33] https://www.tceq.texas.gov/downloads/permitting/edwards-aquifer/forms/f-0585-geologic-assessment-instructions.pdf

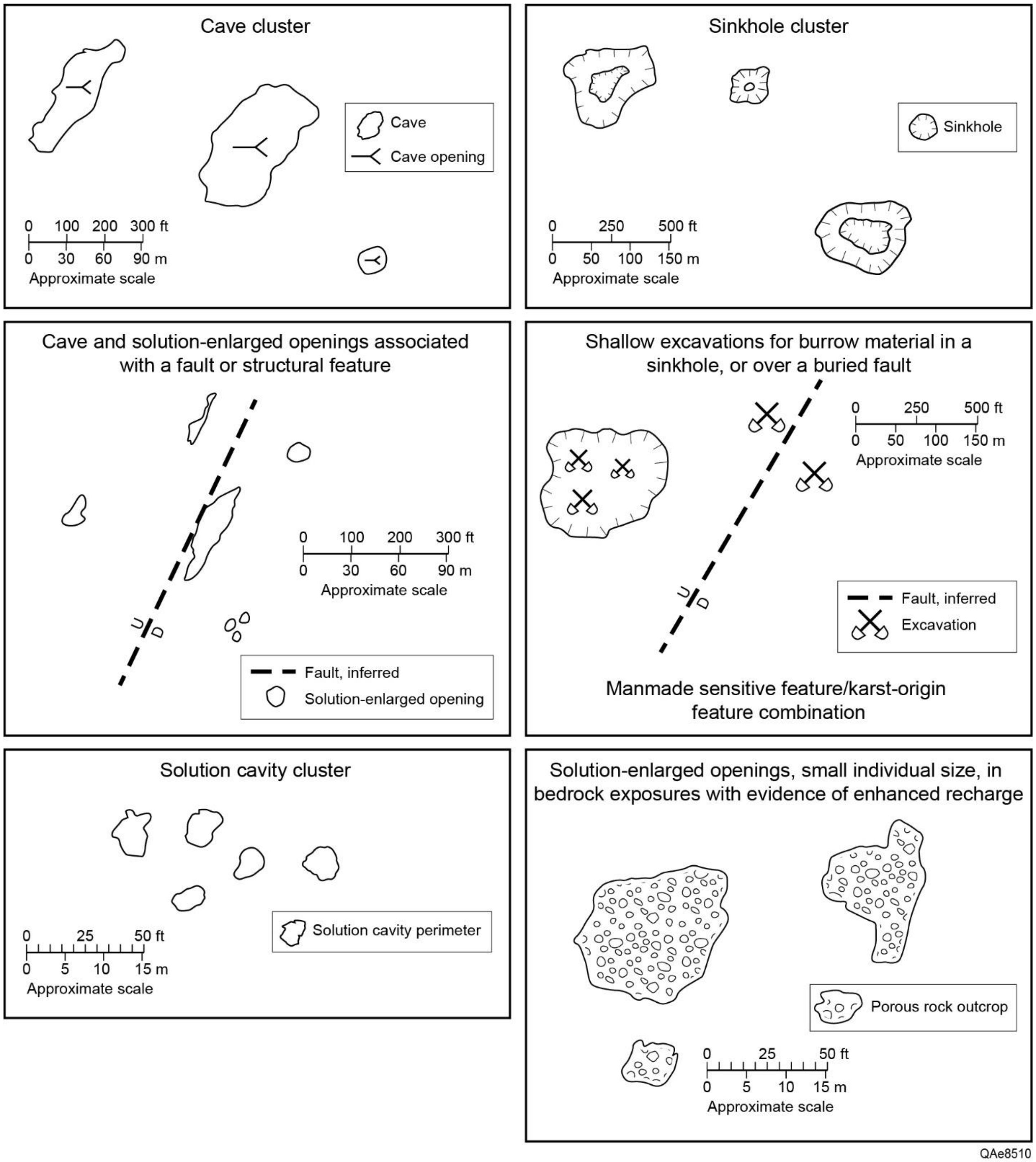

Figure 3. Schematic examples of types of karst-feature zones.

4.4.2 Surface water – groundwater interactions

Surface water – groundwater interaction takes place at differing depths in the subsurface. Groundwater that is in hydrologic connection with surface water occurs primarily in shallow subsurface settings where contaminants in surface water might infiltrate to and/or impact groundwater. Such potential water quality issues are discussed further in Section 4.6.2. By definition, karst terrain is characterized by highly soluble rocks that form well developed underground solution channels. Common associated features are sinking streams, sinkholes, caves, and pipe-like conduits that allow rapid transport of groundwater from surface recharge points to springs (Hunt et al., 2017; partially after White, 1988).

Brumley et al. (2018) define two types of upland stormwater recharge to groundwater that are related to differing subsurface depths. Surface infiltration of stormwater travels through the soil zone into the vadose zone. Subsurface infiltration is where stormwater is directed to a karst feature that is in direct hydrologic communication with an aquifer.

In the eight-county jurisdictional region of the EAPP[34], karst structures that provide hydraulic connection between surface or shallow subsurface stormwater runoff and the Edwards aquifer may be defined as "sensitive features" (30 TAC Section 213.3 (29)) because of the likelihood of untreated stormwater readily entering the aquifer. In other regions with significant karst aquifer systems, such as Florida, Tennessee, and Italy, thick soil or clastic sedimentary layers overlying the carbonate rocks need to be considered when estimating groundwater recharge. There are regions of Texas (e.g., where the Pecos Valley aquifer overlies the Edwards-Trinity Plateau aquifer) where this type of recharge will be more prevalent.

Recharge to karst aquifer in riverine settings commonly takes place through swallet holes, called "stream to sink features" by the Florida Department of Environmental Protection (Lee et al., 2021) because they allow surface water to recharge aquifers directly through sinkholes or solution-enlarged fractures. An extreme example of surface water – groundwater interaction is where streams disappear underground when crossing structural (e.g., faults) or karst features.

Hydrologic testing

Confirmation of the ability of a karst feature to accept surface water recharge should be accomplished through hydrologic testing. Lee et al. (2021) describe how they used hydraulic load (fluid injection) testing in a karst feature in north central Florida in combination with nearby monitoring wells.

It is also important to delineate the subsurface flow paths of recharged water. Short distances between recharge points and groundwater discharge to a spring or stream could possibly impact the quality of discharge water. Hence the importance of both hydraulic load testing and dye-tracing to define flow paths from potential improved karst features to aquifers. To be most informative, dye trace testing should be repeated during both low and high-flow or flood (if possible) conditions.

Other examples of using dye-tracing in karst features being considered for recharge enhancement include:

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[34] www.tceq.texas.gov/permitting/eapp/viewer.html

- The City of Austin is conducting dye-tracing studies to confirm recharge pathways between caves in stream channels and the Barton Springs segment of the Edwards BFZ Aquifer (Heirs, 2022).
- Crooked Oak Cave in Onion Creek, Travis County – the objective is to see if excavating over 25 ft of sediment and organic debris will enhance recharge to the aquifer
- Fenceline Sink in Little Bear Creek, Hays County
- Stoneledge Quarry in Hays County – this work is to confirm hydrologic connection between the quarry and the aquifer.

Construction of regional and local potentiometric surface or water table maps

Smith and Hunt, (2018, 2021) documented a radial pattern of groundwater flow outward from the Antioch Cave enhanced recharge project in Hays County by constructing potentiometric surface maps at different times using water level data in nearby wells (also see Section 3.1, Fakhreddine et al. 2021, and Fakhreddine and Scanlon, 2022). They thereby demonstrated that the enhancement of aquifer recharge is increasing groundwater resources (i.e., groundwater storage).

Other examples of direct surface water – groundwater interaction, through documentation of groundwater mounding, are reported in Section 3.5 of Brumley et al. (2018). They reference works by multiple sets of authors reporting increased groundwater levels resulting from stream restoration projects, bioretention cells, and regenerative stormwater conveyance systems. From the perspective of groundwater resource enhancement, this confirmation of surface water – groundwater connection is positive. However, Brumley et al. (2018) present the studies as a troubling demonstration of potential for aquifer contamination by subsurface infiltration of stormwater.

4.4.3 Sinkhole hydraulics

In karst aquifers groundwater is primarily transported along solution-enlarged conduits in low-permeability matrix rock. Sinkholes are closed surface depressions with defined catchment areas that allow surface water to be transferred to the subsurface. Surface (i.e., upland) features through which enhanced recharge will take place could be natural karst features such as caves or sinkholes, or man-made features such as quarries (e.g., Stoneledge Quarry in Section 3.1).

A limiting factor for aquifer recharge could be significant soil zones overlying the karstified rocks, or hydraulics – how readily the source water will be able to flow to the aquifer zone. Not all sinkholes may be suitable for enhanced recharge due to subsurface plumbing. Delle Rose (2022) [after Bonacci et al. (2006)] defines three types (really scales) of sinkhole flooding (i.e., hydraulics): (1) where the rate of stormwater flow exceeds the discharge capacity of the sinkhole (i.e., limitation of the surface opening to allow water to infiltrate), (2) the underground karst system is unable to drain the stormwater flow, and (3) the groundwater level rises too rapidly due to diffuse infiltration. Infiltration of stormwater through karst features may also decrease over time from sediment or debris clogging conduits along groundwater flow paths (Brumley et al., 2018).

4.5 Water quality monitoring

Ensuring that the source water used for enhanced recharge is not polluted is paramount, as is continued monitoring after operations have begun. Directing stormwater to enhanced recharge features bypasses natural filtration mechanisms, especially in urban areas with dense impervious cover. The environmental risks to aquifers from enhanced aquifer recharge (i.e., AR in Texas) have only recently been fully realized (EPA, 2021). In karst hydrogeologic settings where recharge is dominated by conduit flow, clogging from transported debris and filtration of stormwater are major concerns in both riverine and uplands settings. Two potential sets of threshold criteria to use in water quality assessment are TMDLs[35] (surface water) and MCLs[36] (drinking water).

An important question for riverine settings is: Do stream systems exist that are not being impacted by urban-sourced pollutants? (This could be answered by more EPA 319 Grant Program studies along specific stream segments – urban vs. rural.) Most likely, there is going to be a “baseload” of pollutants in all surface water of the U.S. Desai et al. (2010) noted an increase in the number of surface water bodies being placed on the CWA 303 (d) list of impaired waters (Nation’s, or surface water) based on violation of TMDL calculations. An unfortunate reality, also noted by Desai et al. (2010) is that urban bayous in metropolitan Houston contain predominantly wastewater under median flow conditions.

Chemical aspects of source water (i.e., stormwater) quality associated with high volume streamflow events are detailed in Fakhreddine and Scanlon (2022); they compared stormwater quality data from the National Stormwater Quality Database (NSQD; Pitt et al., 2018) and the Texas Clean Rivers Program (CRP) to MCLs for drinking water. Stormwater quality at the limited locations for which sufficient data are available, is compromised. While the NSQD and CRP, neither of which are regulatory programs, include many chemical analytes, in practice, most surface water regulatory programs routinely require monitoring of only a few water quality parameters.

In the following sections 4.6.1 and 4.6.2, we discuss the importance of characterizing source water quality prior to selecting a site for enhanced aquifer recharge, and methodologies for continued water quality monitoring at enhanced recharge sites.

4.5.1 Surface water quality analytes

TCEQ’s Continuous Water Quality Monitoring Network (CWQMN) program is a good way to monitor surface water quality for use at enhanced recharge sites. However, for many of the CWQMN sites, the measured parameters are restricted to sample depth, surface water temperature, specific conductance, dissolved oxygen, pH, and salinity. A CWQMN site was established at the Antioch Cave site in Central Texas [see Section 3.1, Fakhreddine et al. (2021), and Fakhreddine and Scanlon (2022)]. There, workers installed an In-Situ 9500 Troll™ to continuously monitor temperature, conductivity, dissolved oxygen, turbidity, and pressure (as a proxy for water level) (Smith et al., 2018). They also collected samples for laboratory analysis of total suspended solids (TSS), total dissolved solids (TDS), turbidity, nitrogen compounds, and total phosphorus – during both high and low flow regimes.

Measurements of turbidity and TSS are commonly used to infer presence or absence of other pollutants that may be attached (adsorbed) to very fine-grained clastic or organic particles entrained in flowing water. Turbidity and TSS are common surface water analytes, but, if possible, they should also be analyzed in groundwater samples.

The TCEQ EAPP (Section 2.2.10) uses TSS as a proxy for all pollutants associated with stormwater runoff and does not require onsite water quality monitoring. Before a stormwater control device can be approved for use, manufacturers are required to submit monitoring data from field testing, but again only for TSS. This practice is widely accepted by the international

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[35] Total Maximum Daily Loads (TMDLs) are defined in Section 2.1.2.

[36] Maximum contaminant levels (MCLs) are defined and discussed in Section 2.1.1.

stormwater engineering community, and in stormwater regulations in other States (e.g., Nasrabadi et al., 2016; Rugner et al., 2013).

However, in Washington, Oregon, and New Jersey regulators have suggested stormwater monitoring for specific contaminants in addition to TSS, which can be introduced to groundwater resulting from increased density of land development (e.g., ODEQ, 2019; NJDEP, 2021). In *Urban Stormwater Management in the United States* (NRC, 2009), which is a report generated by the U.S. National Academies Press, Committee on Reducing Stormwater Discharge Contributions to Water Pollution, it was suggested that monitoring for TSS-alone may not adequately protect water resources from industrial development, including construction. NRC (2009) used a study conducted in central Texas (i.e., Mahler et al., 2005) as an example of how activities related to asphalt application may need to add monitoring requirements for constituents other than/in addition to TSS, such as relevant organics considering the specific site being evaluated.

Escherichia coli (E. coli) is often measured as a proxy for pathogenic bacteria associated with fecal waste. Timing of sample collection for analysis of e. coli is critical as concentrations can vary by up to five orders of magnitude in a day. The organisms die off during the day, with lowest concentrations observed in the afternoon, especially on warm days in shallow surface water with low TSS. They regrow exponentially overnight making mornings the time to measure peak concentrations (Desai and Rafai, 2013).

For surface water being considered for enhanced recharge, additional source water screening for multiple categories of non-point source pollutants: major dissolved ions (inorganic), microbial, nutrients, and trace metals should be required. These four categories are included in the NSQD analysis in Fakhreddine and Scanlon (2022). Identification of surface water bodies with established TMDLs without subsequent water quality sampling and laboratory analysis will not provide sufficient protection for recharge water; however, such identification will guide analyte selection.

4.5.2 Drinking water quality analytes

TCEQ-UIC protects underground sources of drinking water (any groundwater that is less than 10,000 mg/L TDS). Aquifer recharge projects consider MCLs to evaluate the recharge water quality. Drinking water regulations under the SDWA have established primary and secondary MCLs for multiple categories of chemical analytes[37]. These apply to both surface water and groundwater sources of drinking water, except for private water wells serving fewer than 25 people. There is concern about possible contamination of drinking water obtained from private, untreated drinking water sources as a result of enhanced recharge of aquifers from stormwater.

Immediately after multiple storm events, sampling revealed increased concentrations of an herbicide, chloroform (a byproduct from water treatment), and an organic solvent in springs feeding the Barton Springs pool in Austin, Texas, and five streams known to contribute to the spring flow. The contaminants continued to be detected in the contributing streams, even after peak storm flow subsided. This study (Mahler et al., 2006) directly documented impacts of stormwater infiltration on groundwater quality in an urban area. To our knowledge, no such studies have been conducted in rural areas. Sampling and analysis for as many analytes as is reasonable given a particular site setting should be conducted as part of the site selection process.

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[37] www.epa.gov/sdwa/drinking-water-regulations-and-contaminants

To gain a more comprehensive understanding of water quality at a prospective in-stream enhanced recharge site, groundwater quality in shallow wells adjacent to riverine systems should be assessed; groundwater in these wells will most likely be in hydraulic connection with the nearby surface water. Similarly, groundwater quality near an upland enhanced karst recharge site should be characterized prior to initiation of operations. An online database of water quality[38] in wells throughout the State is maintained by the TWDB. If there are no available analyses of samples from wells nearby a potential enhanced recharge site, sampling should be conducted. It may also be necessary to install one or more groundwater monitoring well(s) near an enhanced recharge site if no other groundwater monitoring options are available.

5 Summary

Artificial recharge of aquifers using captured stormwater and other sources of water is considered a sound method for increasing local groundwater supplies. A limiting step in enhanced recharge of aquifers in karst terrain is securing a source of water that is not polluted, nor likely to become polluted in the future. A site in close proximity to focused agricultural or industrial activity (e.g., concentrated feedlot) would have a high likelihood of receiving polluted recharge water in the future. Hence monitoring is important before, during, and after site selection, all of which will inform an adaptive management process.

Construction or improvement of smaller-scale, more numerous stormwater capture features (e.g., Antioch Cave site) could provide great improvement over building dams along rivers. A point made by several researchers (e.g., Leventeli et al., 2010) is that underground storage of water can reduce loss that would occur through evaporation from lakes (formed by dams) and ponds (formed by stormwater capture structures).

Other positive aspects of favoring small-scale stormwater capture for enhanced aquifer recharge, besides evaporative loss of water from large surface water bodies, include (1) no large-scale alterations of land surfaces or loss of historical sites, (2) less impact on water quality from gas-powered recreational vehicles, (3) less trapping of sediment that would otherwise mitigate shoreline erosion, and (4) possibly less of an impact to environmental flows – instream volumes flowing to downstream portions of rivers, bays, and estuaries.

Negative aspects of capturing stormwater for enhanced aquifer recharge include (1) enhanced erosion of karst feature openings, (2) physical alteration of streambeds, (4) alteration of riparian vegetation, (4) damage to terrestrial or cave-dwelling organisms, and (5) potential negative impacts on groundwater quality.

5.1 Recommendations

While permits needed for sites being considered for enhanced recharge of stormwater through karst features are now relatively limited, there are many regulatory and research programs from which essential information is needed. Perhaps considerations for site selection should be included in State regulatory programs discussed in Section 2. Also, there are aspects of other TCEQ regulatory programs that could be considered for permitting of enhanced recharge sites using captured stormwater. An example is the TCEQ EAPP documents pertaining to protection of terrestrial and aquatic life (TCEQ, 2007a, b).

Following a description of example case studies in Section 3.1, we discuss how stormwater runoff captured in widely employed, engineered structures is rarely allowed to infiltrate to

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[38] www.twdb.texas.gov/groundwater/data/index.asp

groundwater (Section 3.2). With careful planning and monitoring these practices, which are commonly referred to as BMPs, could be adapted for the purpose of enhancing groundwater resources.

Section 4 of this guidance is specific to site selection. Understanding the presence and abundance of surface karst or other recharge features, siting of recharge features within a watershed or spring shed, and potential sources of pollution are all critical components of site selection. Figure 4 is a graphical summary of a general process (top to bottom) needed to select a site for enhanced recharge through a karst feature. Parenthetical numbers in text boxes in the figure refer to other sections in this document or tables.

In Section 4.1 – Mapping and data resources, we provide references and links to types of background material that must be reviewed before moving forward with site selection. The next step in site selection is to conduct a reconnaissance field survey. Tasks that should be completed throughout the watershed delineated during the preceding mapping and data resource step, by a P.G. with experience in karst hydrogeology include identification of all:

- wells, springs, and surface water features,
- all other karst features that might be associated with the target enhanced recharge feature (Section 4.4.1),
- faults, fractures or other possible natural fluid-flow conduits,
- man-made fluid-flow conduits such as pipeline rights-of-way,
- landfills or private garbage dumps,
- industrial facilities, and
- agricultural operations.

After consideration of all relevant water quality, and erosional impacts that could prevent selection of an acceptable site (in either a riverine or upland setting), field testing should begin (Table 1, Section 4.4.2).

Table 1. Example field testing techniques and objectives.

Technique	Objective
Dye tracing at low and high-flow conditions	Delineate subsurface flow paths
Hydraulic load testing	Estimate volume of water that recharge feature could accept, and delineation of subsurface flow paths
Water level monitoring	Establish initial (background) water table or potentiometric surfaces
Water quality monitoring	Establish initial (background) quality of source water and groundwater that will be accepting stormwater recharge.

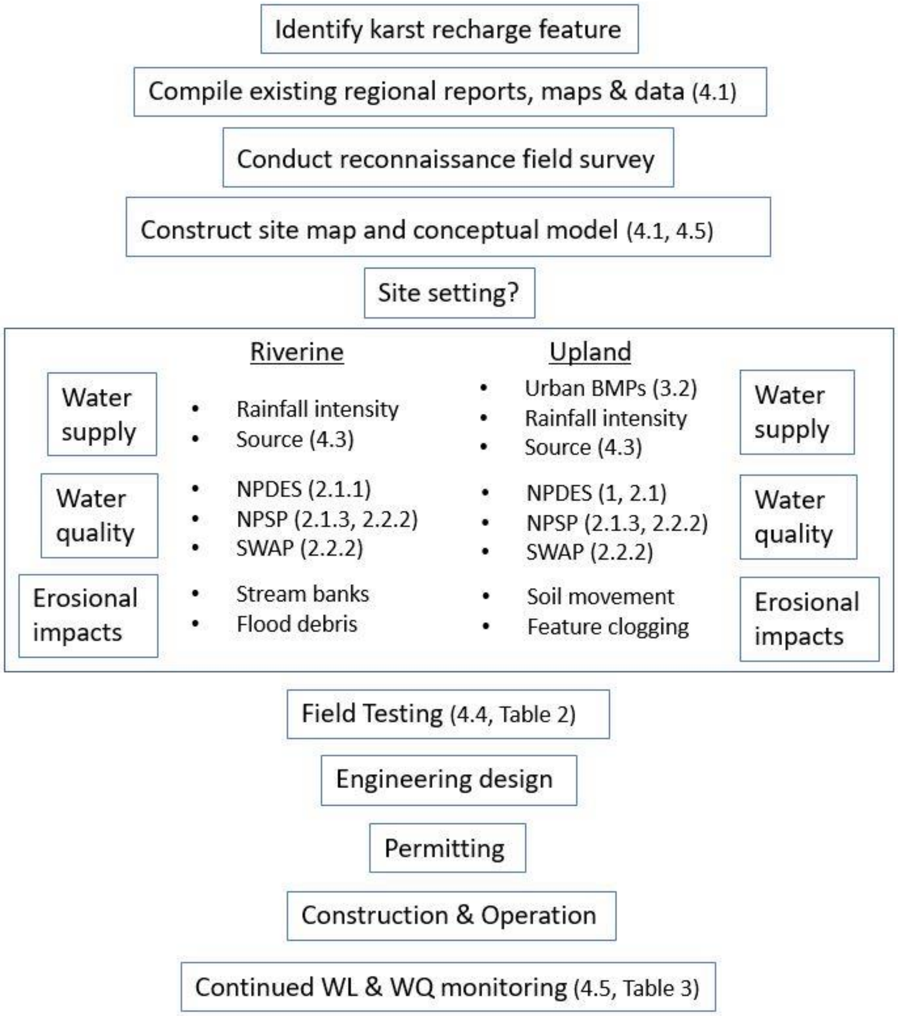

Figure 4. Workflow for site selection process considerations through the operational stage. Parenthetical numbers refer to report sections or tables.

In Section 4.5 we discuss different types of surface water and groundwater models. Models designed to evaluate surface water-groundwater interaction (BRATWURST), as has been initiated by Southwest Research Institute and the Meadows Center may be a suitable approach for evaluating some site selection requirements. Comprehensive modeling suites that cover physical and geochemical processes taking place in surface water and groundwater will be necessary.

For example, the USGS aqueous geochemistry software program PHREEQC (https://www.usgs.gov/software/phreeqc-version-3) could be used to determine if detrimental water-rock reactions might take place when stormwater runoff is mixed with groundwater. Mineral precipitation reactions could clog subsurface conduits and prevent the success of an improved sinkhole or other type of AR project. Mineral dissolution reactions could enhance erosion and thereby damage karst recharge intake features, or release associated naturally occurring, trace metals from aquifer matrix rocks and minerals.

Water quality monitoring (Section 4.6) will be required at multiple phases of the site selection process and throughout the life of the recharge project. Chemical parameters/analytes need to be measured in both the field and laboratory. Relatively inexpensive field screening parameters measured during reconnaissance can provide early indications of pollution and rule out a particular site early in the selection process. Groundwater quality measurements commonly made in field settings include:

- temperature
- pH
- specific conductivity (SpC) (allows screening-level calculation of total dissolved solids [TDS])
- dissolved oxygen (DO)
- oxidation-reduction potential (ORP)
- alkalinity titrations (most accurate way to get concentration of carbonate species)

Common field-based surface water quality measurements include:

- turbidity
- total suspended solids (TSS)

In the Task 3 report for this project, Fakhreddine and Scanlon (2022) provided sources and analyses of water quality data pertinent to this guidance. In addition to conducting sampling and laboratory analysis for the groundwater and surface water field parameters listed above, we also recommend sampling and laboratory analysis for the four categories of parameters (metals, nutrients, microbial, and organic) in their Table 2. Monitoring requirements should consider the source of water being injected. Additional efforts to expand sampling parameters should be considered as new emerging contaminants become regulated. BMPs can be constructed at the injection well (which includes improved sinkholes) to mitigate impacts to groundwater quality, retention ponds to store stormwater and allow suspended sediments to settle out prior to recharging the aquifer. Another example is the Water Quality Protection Lands (WQPL) of the City of Austin which purchases easements in the Onion Creek and Barton Creek watersheds (Thuesen, 2015). This program enhances water quality through various land (vegetation) and karst restoration (cleanout of caves) activities. An additional example is provided by the use of valves in Antioch Cave to exclude the first flush of stormwater from entering the cave as described in Section 3.1 (Case Studies).

Table 2. Select water quality analytes from the Clean Rivers Program.

Category	Analyte	Unit
Metals	Dissolved arsenic (As)	µg/L
Metals	Dissolved cadmium (Cd)	µg/L
Metals	Dissolved chromium (Cr)	µg/L
Metals	Dissolved cobalt (Co)	µg/L
Metals	Dissolved copper (Cu)	µg/L
Metals	Dissolved iron (Fe)	µg/L
Metals	Dissolved lead (Pb)	µg/L
Metals	Dissolved nickel (Ni)	µg/L
Metals	Dissolved zinc (Zn)	µg/L
Nutrients	Ammonia (NH_4)	mg/L N
Nutrients	Biochemical Oxygen Demand (BOD)	mg/L O_2
Nutrients	Dissolved Organic Carbon (DOC)	mg/L
Nutrients	Total Organic Carbon (TOC)	mg/L
Nutrients	Nitrate (NO_3)	mg/L N
Nutrients	Total Kjeldahl Nitrogen	mg/L N
Nutrients	Phosphate (PO_4)	mg/L
Microbial	E. Coli	#/100mL
Microbial	Fecal Coliform	#/100mL
Microbial	Fecal Streptococci	#/100mL
Organic	Atrazine (herbicide)	µg/L
Organic	Benzene (VOC)	µg/L
Organic	Chlorobenzene (SVOC)	µg/L
Organic	Ethylbenzene (VOC)	µg/L
Organic	Fipronil (insecticide)	µg/L
Organic	Polychlorinated Biphenyls (PCBs)	µg/L
Organic	Tetrachloroethylene (VOC)	µg/L
Organic	Toluene (VOC)	µg/L

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