The Edwards Aquifer

Jack Sharp and Ron Green

THE GROUNDWATER PROJECT

The Edwards Aquifer

The Groundwater Project

John M. (Jack) Sharp

Professor Emeritus
Department of Geological Sciences
The University of Texas
Austin, Texas, United States of America

Ronald T. Green

Institute Scientist
Southwest Research Institute
San Antonio, Texas, United States of America

The Edwards Aquifer

The Groundwater Project
Guelph, Ontario, Canada

Published by the Groundwater Project, Guelph, Ontario, Canada, 2022.

Sharp, John M.
The Edwards Aquifer / Authors (John M. Sharp and Ronald T. Green) - Guelph, Ontario, Canada, 2022.
90 pages
ISBN: 978-1-77470-029-7
DOI: https://doi.org/10.21083/978-1-77470-029-7

Please consider signing up for the GW-Project mailing list to stay informed about new book releases, events and ways to participate in the GW-Project. When you sign up for our email list it helps us build a global groundwater community. Sign up↗.

Citation: Sharp, John M., and Ronald T. Green, 2022, The Edwards Aquifer↗. The Groundwater Project, Guelph, Ontario, Canada, https://doi.org/10.21083/978-1-77470-029-7.

Cover Image: Barton Springs, Austin, Texas (Photograph provided by Brian Hunt, 2019).

Dedication

This book is dedicated to the many scientists and engineers who have studied the Edwards Aquifer for over a century.

Table of Contents

DEDICATION ..... **IV**

TABLE OF CONTENTS ..... **V**

THE GROUNDWATER PROJECT FOREWORD ..... **VII**

FOREWORD ..... **VIII**

PREFACE ..... **IX**

ACKNOWLEDGMENTS ..... **X**

1 INTRODUCTION **1**

2 STRATIGRAPHY AND STRUCTURE **16**

3 AQUIFER PROPERTIES **20**

3.1 POROSITY AND STORATIVITY 20
3.2 PERMEABILITY 20
3.3 RESIDENCE TIMES 24
3.3.1 Isotopic Ages 26
3.3.2 Tracer Tests 27
3.4 WATER CHEMISTRY 27

4 FLOW SYSTEMS **29**

4.1 DISCHARGE AND RECHARGE 30
4.1.1 Discharge 30
4.1.2 Recharge 31
4.2 SEGMENT FLOW SYSTEMS 34
4.2.1 The San Antonio Segment 35
4.2.2 Barton Springs Segment 39
4.2.3 Northern Segment 41
4.2.4 Kinney Segment 42
4.3 ASSOCIATED EDWARDS AQUIFERS 43
4.3.1 Edwards-Trinity (Plateau) Aquifer 43
4.3.2 Washita Prairies 44

5 AQUIFER ECOLOGY AND ENDANGERED SPECIES **45**

5.1 ENDANGERED SPECIES 46
5.2 BAD-WATER LINE 47

6 LEGAL AND ADMINISTRATIVE SYSTEMS **48**

6.1 NUMERICAL MODELS FOR DEVELOPING MANAGEMENT STRATEGIES 48
6.2 EDWARDS AQUIFER AUTHORITY 49
6.3 OTHER GCDS 51

7 CONCLUSION **53**

7.1 SUSTAINABILITY 53
7.2 CHALLENGES 54

8 EXERCISES **56**

EXERCISE 1 56
EXERCISE 2 56
EXERCISE 3 56
EXERCISE 4 56
EXERCISE 5 56

Exercise 6 56
Exercise 7 56
Exercise 8 57
Exercise 9 57
Exercise 10 57
9 REFERENCES 58
10 EXERCISE SOLUTIONS 84
Solution Exercise 1 84
Solution Exercise 2 84
Solution Exercise 3 85
Solution Exercise 4 85
Solution Exercise 5 85
Solution Exercise 6 86
Solution Exercise 7 86
Solution Exercise 8 86
Solution Exercise 9 86
Solution Exercise 10 87
11 ABOUT THE AUTHORS 88

The Groundwater Project Foreword

The Year 2022 marks an important year for groundwater because the United Nations Water Members and Partners have chosen the theme of this year's March 22 World Water Day to be: "Groundwater: making the invisible visible". The goal of the Groundwater Project (GW-Project) is in sync with this theme.

The GW-Project, a registered charity in Canada, is committed to contributing to advancement in groundwater education and brings a unique approach to the creation and dissemination of knowledge for understanding and problem-solving. The GW-Project operates the website https://gw-project.org/↗ as a global platform for the democratization of groundwater knowledge, founded on the principle that:

> *"Knowledge should be free and the best knowledge should be free knowledge." Anonymous*

The mission of the GW-Project is to promote groundwater learning. This is accomplished by providing accessible, engaging, high-quality, educational materials, free-of-charge online in many languages, to all who want to learn about groundwater. In short, providing essential knowledge tools for developing groundwater sustainably for humanity and ecosystems.

This is a new type of global educational endeavor in that it is based on the volunteerism of professionals from different disciplines and includes academics, consultants and retirees. The GW-Project involves many hundreds of volunteers associated with more than 200 organizations from 27 countries and six continents, with growing participation.

The GW-Project is an ongoing endeavor and will continue with hundreds of books being published online over the coming years, first in English and then in other languages, for downloading wherever the Internet is available. An important tenet of the GW-Project books is a strong emphasis on visualization via clear illustrations that stimulate spatial and critical thinking to facilitate the absorption of information.

The GW-Project publications also include supporting materials such as videos, lectures, laboratory demonstrations, and learning tools in addition to providing, or linking to, public domain software for various groundwater applications supporting the educational process.

The GW-Project is a living entity, so subsequent editions of the books will be published from time to time. Users are invited to propose revisions.

We thank you for being part of the GW-Project Community. We hope to hear from you about your experience with using the books and related material. We welcome ideas and volunteers!

The Groundwater Project Steering Committee

August 2022

Foreword

As a hydrogeologic system, karst has great importance to humanity because it makes up about 10 percent of the earth's land surface and provides water for 10 percent of the global population. This book is about the Edwards Aquifer in Texas, United States of America, which is one of the world's important aquifers. It supplies water to two million people, and is an exceptional example of a hydrogeologically complex aquifer with multiple land uses that is managed by several cooperating organizations who are challenged to balance diverse water uses that pose the threat of excessive pumping and pollution. Because of the great value of the water and land, this aquifer system has been subjected to intensive investigation and monitoring for more than a century. It is an example of governance that has resulted in a reasonably stable groundwater resource with regard to both quantity and quality.

This book covers nearly all of the topics that make up modern hydrogeology in the context of the Edwards Aquifer including groundwater recharge, velocity, discharge, residence time, hydrochemistry, contamination and numerical modeling. Discussion of these topics is intertwined to explain how the Edwards Aquifer functions as a hydrogeologic system. Karst aquifers are commonly the host for ecological activity and a unique characteristic of the Edwards Aquifer is the great variety of organisms that live in the aquifer or are directly dependent upon flow from its springs.

The Groundwater Project book, "Introduction to Karst"↗ by Kuniansky and others (2022) is good background reading for this book.

Dr. Jack Sharp is the Emeritus Carlton Professor of Geology at The University of Texas located on the Edwards Aquifer where he has been involved in matters concerning the Edwards Aquifer for many decades. Dr. Ronald Green is a senior scientist at the Southwest Research Institute in San Antonio, Texas, which is also on the Edwards Aquifer where he has spent most of his career involved in karst science.

John Cherry, The Groundwater Project Leader
Guelph, Ontario, Canada, August 2022

Preface

The Edwards Aquifer in the State of Texas, United States of America (USA), is a very productive and highly studied *karst* aquifer. Karst terrains are created from dissolution of soluble rocks, principally limestone and dolomite. They are characterized by distinctive landforms (like springs, caves, sinkholes) and unique hydrogeology that results in aquifers that are highly productive but vulnerable to contamination. The Edwards Aquifer provides water for over 2 million people as well as for agriculture, industry, recreation, and environmental uses. However, its sustainable use is challenged by rapidly increasing urban population (expected to double in several decades), climate change (increased droughts and floods), urbanization and contamination, the need to protect groundwater ecosystems and their endangered species, and evolving water laws and policies. This book reviews various geologic units of the aquifer and its unique geologic, hydraulic, water quality, ecologic, legal, and environmental aspects.

Despite over a century of study of the Edwards Aquifer, there remain significant challenges to the sustainable use of this aquifer. Better mapping, more detailed field data, improved numerical models, enhanced recharge, more optimal pumping strategies, and new technologies, including desalination and aquifer storage and recovery, will have to be implemented to meet the challenges of the Edwards Aquifer and karst aquifers globally.

Acknowledgments

We hope that this book and the references herein will stimulate those interested in this and similar aquifers to explore the vast and evolving literature. We appreciate the reviews of:

- Brian Hunt, Research Scientist Associate, Bureau of Economic Geology, The University of Texas at Austin, USA;
- Bruce Darling, Consultant, Groundwater & Geochemical Consulting, LLC, USA;
- Marcus Gary, Field Operations Supervisor, Aquifer Science, Edwards Aquifer Authority (EAA), USA;
- Brian Smith, Principal Hydrogeologist, Barton Springs Edward Aquifer Conservation District, USA;
- Eileen Poeter, Emeritus Professor, Colorado School of Mines;
- Alfonso Rivera, Emeritus Chief Hydrogeologist, Geologic Survey of Canada;
- Jac van der Gun, Consultant, Van der Gun Hydro-Consulting, The Netherlands;
- Connie Bryson, Editor, The Groundwater Project, Canada; and,
- Groundwater Project staff, especially Juliana Apolonio.

Brian Smith and John Cherry also reviewed preliminary versions. We thank Brian Smith of the Barton Springs Edwards Aquifer Conservation District (BSEACD), Geary Schindel of the EAA, Ashley Trappe of Baylor University, and Nathan Bendik of the City of Austin, Texas, for their photographs. Jeff Horowitz of The University of Texas, Rebecca (υ^2) Nunu of Southwest Research Institute, and Andy Boggs of Panic Button provided drafting assistance.

We are grateful to Amanda Sills and the Formatting Team of the Groundwater Project for their oversight and copyediting of this book. We appreciate the final review provided by Ineke Kalwij (Kalwij Water Dynamics, Vancouver, British Columbia, Canada). We thank Eileen Poeter (Colorado School of Mines, Golden, Colorado, USA) for reviewing, editing, and producing this book.

1 Introduction

The Edwards Aquifer ranks among the world's largest regional karst aquifers. It supplies 500 gigaliters/year (GL/year) of water (Mace, 2019) for over 2 million people and a wide variety of agricultural, municipal, industrial, environmental, and recreational uses in Texas, USA (Figure 1). Annual groundwater discharge is approximately 49 to 60 percent to springs, 27 to 32 percent to municipalities, 8 to 13 percent to irrigation, 3 to 4 percent for industrial/commercial uses, and 2 percent for domestic and livestock uses (e.g., EAA, 2008, 2019a). The exact proportions vary with precipitation, drought conditions, and other factors. In the literature and common parlance, the Edwards Aquifer or, more precisely, the Edwards (Balcones Fault Zone) Aquifer, refers to the units along the Balcones fault system in the Uvalde-San Antonio-Austin-Salado area which is a part of the Edwards Aquifer System (Figure 2). This book focusses on this aquifer, which extends from east of Del Rio on the USA-Mexico border east through San Antonio, then northeast through Austin and Salado. It covers an area of 5,993 km^2 (2,314 square miles) of which 4,040 km^2 (1,560 square miles) are outcrop. The aquifer is the northwestward extent of the Gulf Coastal Plain and is separated from the Edwards Plateau (Figure 2) and the Texas Hill country by the Balcones Escarpment.

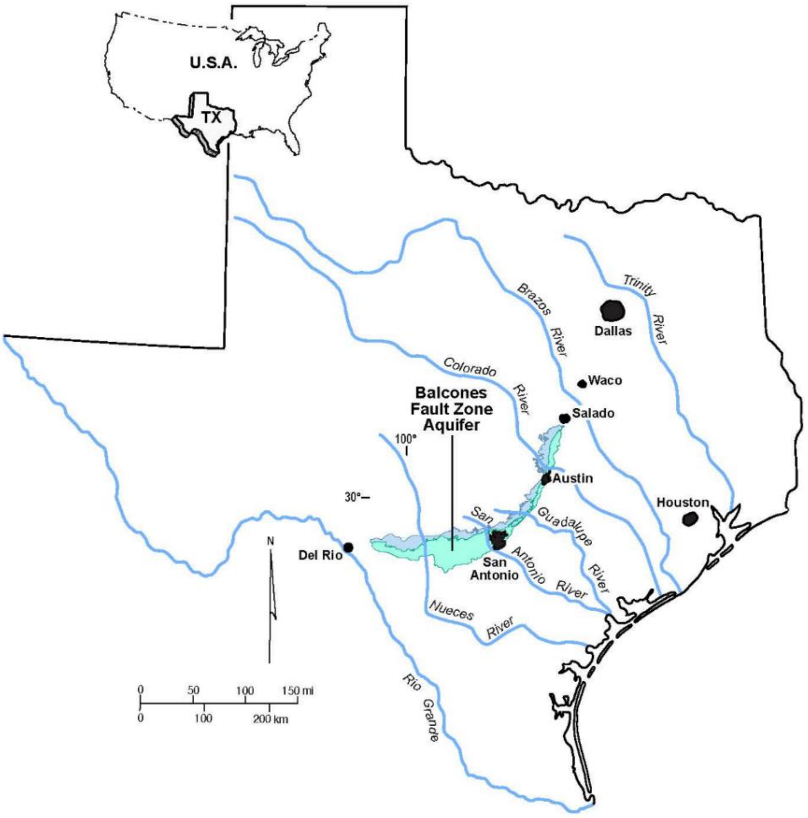


Figure 1 - The Edwards Aquifer of Texas, USA (Balcones Fault Zone). The blue color is the unconfined or recharge zone and the light blue-green color is the confined or artesian zone, both zones are shown in Figure 2 at a larger scale.

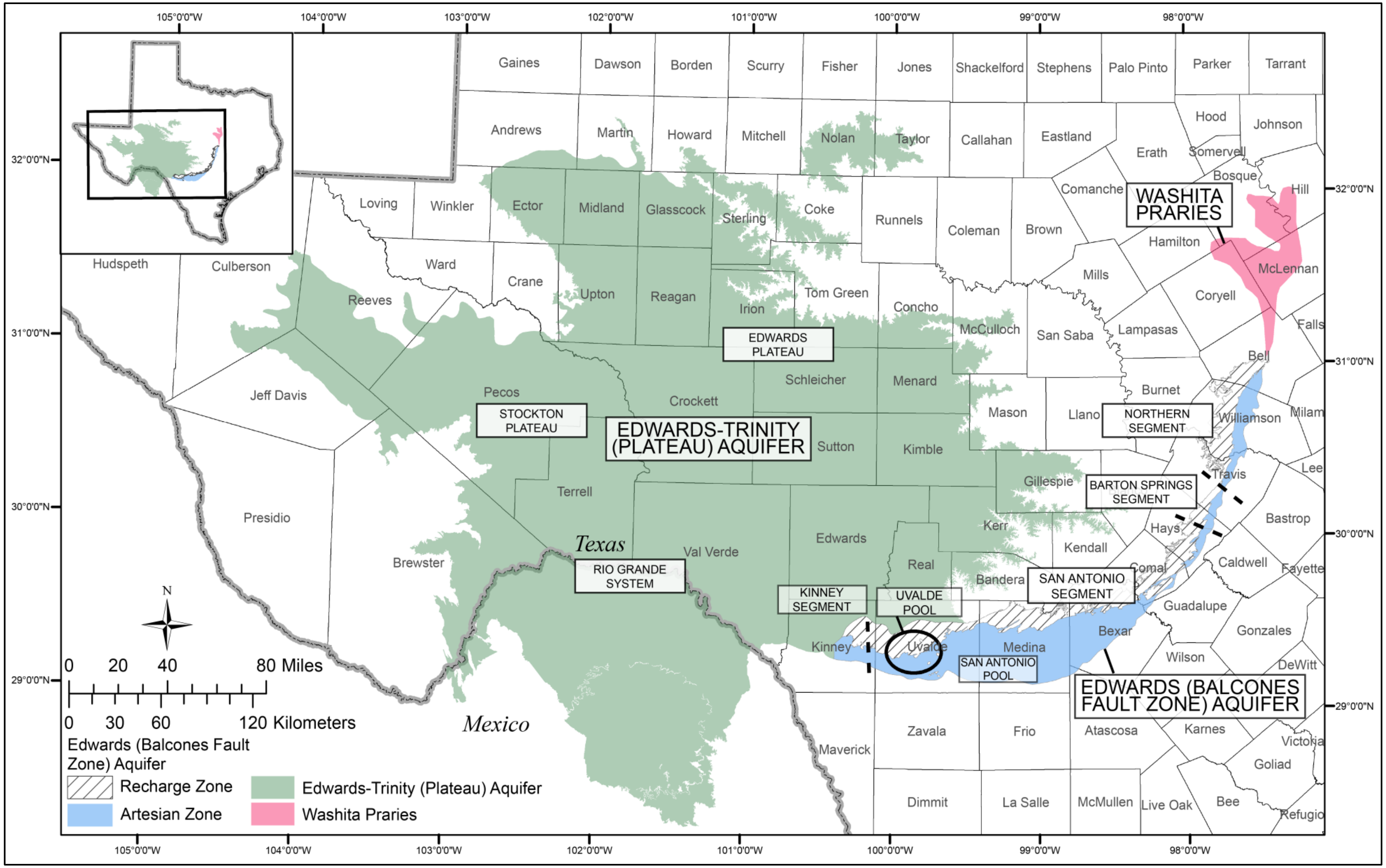


Figure 2 - Map of the Edwards Aquifer strata: Balcones Fault Zone (BFZ); Edwards-Trinity Plateau; Rio Grande System; and, Washita Prairies (modified from Sharp et al., 2019b). Aquifer-equivalent strata extend down dip toward the Gulf of Mexico and into Mexico. Edwards equivalent strata beneath the High Plains of Texas are not shown here. Their location is presented by Mace (2019).

Mean annual temperature increases southward over the aquifer from 18 to 21 °C (Larkin and Bomar, 1983; TWDB, 2012). Mean annual precipitation over the aquifer north of San Antonio to Salado ranges between 800 and 920 mm/year (31 and 36 inches/year). From San Antonio westward, however, precipitation drops to 500 mm/year (20 inches/year). Likewise, annual precipitation varies considerably with extended droughts and occasional very large precipitation events (Slade and Patton, 2003; Henry, 2011). Thus, aquifer management must plan for and adjust to future extreme weather situations. Traditional land use was ranching with irrigated agriculture over the confined zone west of San Antonio with urban areas in Austin and San Antonio. Population growth of approximately 20 percent in the Austin-San Antonio corridor over the past ten years, has greatly expanded urbanization along the Interstate Highway 35 from San Antonio north to Salado, although urbanization has been somewhat limited in aquifer recharge areas by municipal zoning and land purchases (Guerra and Debbage, 2021).

Equivalent aquifer strata extend over a much larger area of the USA and into Mexico (Figure 2). North and west of the Balcones Fault Zone are the Edwards and Stockton Plateaus (Small and Ozuna, 1992; Kuniansky and Ardis, 2004). Aquifer strata also extend beneath the High Plains Aquifer (Fallin, 1989; TWDB, 2022) and north of the Balcones fault system in the Washita Prairies (Yelderman, 1987, 2019). These units can provide significant water to wells, but springs are generally not as large as springs along the Balcones Fault Zone (Figure 2). The formations that comprise the Edwards Aquifer also extend down dip to the Gulf of Mexico Basin and into Mexico (Rose, 1972, 2017; Sharp et al., 1991; Sprouse, 2009).

Prior to development in the area, springs were the major source of discharge from the aquifer and cities developed near them. Some of the major springs of the Edwards Aquifer are shown in Figure 3 through 11, starting from the westernmost to the northernmost, the spring and nearby town or landmark are as follows:

- Las Moras (or Fort Clark) Springs, Bracketville (Figure 3);
- San Antonio Springs at the head of the San Antonio River (Figure 4);
- Hueco Springs, Canyon Lake (Figure 5);
- Comal Spring 1, one of the Comal Springs, New Braunfels (Figure 6);
- Comal River, New Braunfels (combined flow of all Comal Springs, Figure 7);
- San Marcos Spring discharge, San Marcos (Figure 8);
- Main Barton Spring (one of the four Barton Springs), Austin (Figure 9);
- Eliza Spring (one of the four Barton Springs, Figure 10); and
- Salado Springs, Salado (Figure 11).

Figure 3 – Las Moras (or Fort Clark) Springs, Brackettville (photo courtesy of Geary Schindel).

Figure 4 – San Antonio Springs at the head of the San Antonio River (photo courtesy of Geary Schindel).

Figure 5 – Hueco Springs (photo courtesy of Geary Schindel).

Figure 6 – Comal Spring 1, one of the Comal Springs, New Braunfels (Sharp et al., 2019a).

Figure 7 – The Comal River in New Braunfels carries the combined discharge of all Comal Springs. (photo by J.M. Sharp).

Figure 8 – San Marcos Spring discharge, San Marcos (Sharp et al., 2019a).

Figure 9 – Main Barton Spring (one of the four Barton Springs), Austin (photo by J.M. Sharp).

Figure 10 – Eliza Spring↗ (one of the four Barton Springs).

Figure 11 – Salado Springs, Salado (photo courtesy of Ashley Trappe).

In 1975, the Edwards Aquifer in the San Antonio area was the first in the USA to be designated as a sole source aquifer[1] by the United States Environmental Protection Agency (EPA). The aquifer also hosts unique groundwater, cave, and spring ecosystems and is famous for the large springs that discharge from the aquifer along the Balcones Fault Zone (Figure 2 and Figure 12). The cities of Salado, Austin, San Marcos, New Braunfels, San Antonio, Uvalde, Brackettville, and Del Rio (west of the aquifer) developed along the Balcones Fault Zone near springs.

Figure 12 – Edwards Aquifer contributing zone, unconfined (i.e., recharge) zone, confined zone and major springs (modified from Mahler and Musgrove, 2019). The Seco Creek (Valdina Farms) sinkhole recharge feature and the groundwater divides bounding the San Antonio segment are also shown. The dark line through San Antonio denotes the location of a cross section discussed in Section 4.2.

---

[1] A sole source aquifer as defined by the United States Environmental Protection Agency, EPA (2020), is: 1) one that supplies at least 50 percent of the drinking water for its service area, and 2) where there are no reasonably available alternative drinking water resources should the aquifer become contaminated.

In this book, we review the unique characteristics of the Edwards (Balcones Fault Zone) Aquifer, its stratigraphy and structure, flow systems, natural recharge and discharge, water chemistry, aquifer ecology and endangered species, as well as its legal and administrative systems. We also look at the challenges (including future pumping stresses, land use changes, emerging contaminants, climate change, and evolving technologies) that will affect the Edwards Aquifer. Detailed information on many of these topics is provided by Sharp and others (2019a, b). The uniqueness and importance of this aquifer to the general public, industry and the environment have been the subject of many discussions and reports (e.g., Technical Advisory Panel, 1990; Grubb, 1997; Sharp and Banner, 1997; Sharp, 2002; Hardberger, 2019). The literature is vast and the reader is encouraged to refer to the cited sources to obtain details on particular subject areas of interest.

The Edwards Aquifer has been recognized for over a century beginning with Hill (1890) and Hill and Vaughan (1898). Recently, Sharp and others (2019a) compiled a suite of summary papers, but even with a long history of research, there remain significant unknowns and uncertainties. More research is required to understand and manage the Edwards Aquifer successfully and sustainably in the face of significant challenges as Texas, and, in particular, central Texas is challenged with rapid growth and the ensuing aquifer overexploitation (Mace, 2019).

Hill and Vaughan (1898) named the Edwards Limestone Formation, which refers to the firm, white, resistant, shelly, cherty, porous limestone and dolomite above the Glen Rose Formation and below the Georgetown, Del Rio Clay, or Buda formations (Rose, 1972). The Glen Rose, Georgetown, and Buda are carbonate rocks. The Del Rio is a swelling clay shale and acts as an efficient confining unit. Hill (1890, page 17) described "*The Balcones*" Escarpment as being "*accompanied by faulting of several hundred feet*" and elaborated that "*The Spanish speaking people—ever ready with an appropriate descriptive geographical name—have called this scarp west of San Antonio 'El Balcones'*." The scarp separates the Texas Hill Country from the Gulf Coastal Plain provinces (Bureau of Economic Geology, 1996). Hill (1890, page 18), describes the most distinctive feature of the aquifer associated with the scarp as:

> "*… a line of springs which find their way to the surface through the fault and joints overhanging the line of disturbance. The most conspicuous of these are the springs of the Leona, the San Pedro springs at San Antonio, which are the immediate source of the San Antonio River; the springs at New Braunfels, and the spring of San Marcos. Near Austin, the Barton, Mormon, Sieders* [Berry and others (2017) provide a current description]*, and a group of magnificent unnamed springs in the bluffs of the river, immediately west of the city, mark the line. North of the Colorado the springs of Round Rock, Georgetown, Salado, and those southwest of Dallas, mark the line. All of these are great gushing streams of water bursting suddenly from the rocks, and flowing off in large streams, discharging thousands of gallons per hour. They are natural artesian wells made by rents in the rock. It is an*

> *interesting economic fact that anywhere within a few miles of these natural wells, artificial ones can be obtained by boring, as has been done at San Antonio, Fort Worth, Austin and Waco."*

Classification of the Edwards Aquifer requires that its complexity be recognized. An aquifer is defined as a geologic formation, group of formations, or a part of a formation (i.e., a consolidated or unconsolidated geologic unit or set of connected units) that yields water of suitable quality to wells or springs in economically usable amounts (Meinzer, 1923; Sharp, 2017). A geologic formation is a body of rock strata that consists of a certain lithology or combination of lithologies (i.e., a lithologically mappable unit). It is advisable not to confuse the definition of a geologic formation and an aquifer. Aquifers are commonly defined by formation(s) rather than their hydrological connections, which can raise issues for aquifer management. Intra- and inter-aquifer connections remain fundamental research questions.

The Edwards Aquifer is an aquifer *system*—a set of aquifers that are variably connected. However, we refer to it here as a singular aquifer, the Edwards Aquifer (Figure 2). The major components in the Edwards Aquifer system are the Edwards (Balcones Fault Zone) Aquifer, the Washita Prairies, the Edwards-Trinity Plateau, and the Rio Grande system (Table 1). Similar aquifer units extend into Mexico. By definition, this classifies the Edwards Aquifer system as a transboundary aquifer (Sprouse, 2009; Sanchez et al., 2016, 2018; Sanchez and Rodriguez, 2021). Each component is further classified or defined based on its particular attributes.

Table 1 - The Edwards Aquifer system.

Major Component	Subclassification
Balcones Fault Zone system	Northern segment Barton Springs segment • Barton Springs pool • Cold Springs pool San Antonio segment • San Antonio pool • Uvalde pool Kinney segment
Washita Prairies	
Rio Grande system	Devils River catchment Del Rio pool
Edwards-Trinity Plateau	Edwards Plateau Stockton Plateau

The Edwards (Balcones Fault Zone) Aquifer includes three major segments—the San Antonio segment, the Barton Springs segment, and the Northern (north of the Colorado River) segment—and one minor segment, the Kinney segment. *Segments* are defined as subdivisions within an aquifer that are generally hydraulically independent, although hydraulic connection under certain conditions may exist (Land et al., 2011). The Kinney segment is considered minor due to its limited spatial extent when compared with the other major segments. Historically, that portion of the Edwards Aquifer in Kinney County to the east of the groundwater divide located between Mud and Pinto creeks in Kinney County was included in the Uvalde pool of the San Antonio segment (e.g., Maclay, 1995). However, recent studies (Green et al., 2006, 2019c) indicate that this portion is a separate segment that is not hydraulically connected to the remainder of the San Antonio segment. For this reason, that portion of the Edwards Aquifer in Kinney County to the east of the Mud Creek/Pinto Creek groundwater divide is now designated as the Kinney segment.

The Edwards (Balcones Fault Zone) Aquifer has been further delineated into *pools*, which describe semi-detached groundwater basins within a segment (Figure 2 and Figure 12). The San Antonio segment is subdivided into two pools: the larger and more significant San Antonio pool (Green et al., 2019b) and the Uvalde pool (Green et al., 2019a) located to the west (Figure 12). The Barton Springs segment contains two pools, the main pool that primarily discharges to Barton Springs, and a smaller pool that discharges to Cold Springs and directly to the Colorado River (Hauwert et al., 2004; Hunt et al., 2019). Separate pools are not yet identified in the Northern segment. The Northern segment is separated from the Barton Springs segment by the Colorado River. The greater Colorado River watershed and the river itself do not recharge the Edwards Aquifer in any meaningful way. Hence, the Colorado River watershed is not identified as a contributing zone to the Edwards Aquifer (Figure 2 and Figure 12).

The segments and aquifer boundaries are defined by:

- where the aquifer rocks have been eroded;
- where faults abut low-permeability strata (no-flow boundaries);
- groundwater divides (generally treated as no-flow boundaries);
- the Colorado River (separating the Barton Springs and Northern segments); and,
- the bad-water (or saline-water) line[2] (generally treated as a no-flow boundary), which is the southern and eastern border of the aquifer where the water is not potable and where water circulation is limited. The "line" is actually a zone (Figure 13), although in some cases it is delineated by faults.

---

[2] The bad-water line is also referred to as the saline water line. Here we retain the term "bad-water" because of its historical use (water beyond this line was not considered potable) and because these waters range from brackish to saline. Some of the brackish waters are suitable for irrigation and livestock. Furthermore, waters in the bad-water zone are being considered for desalination.

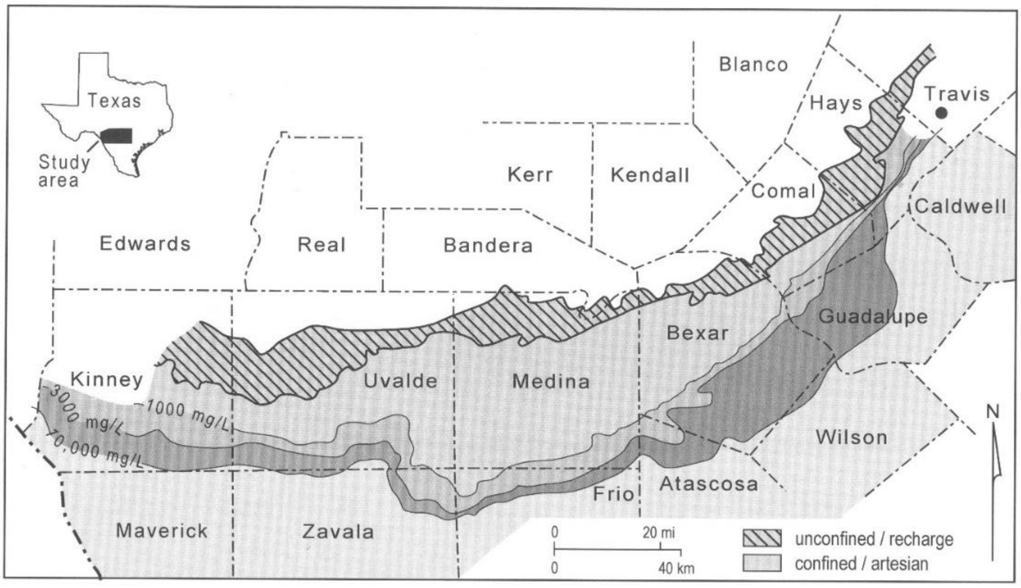


Figure 13 - Bad-water transition zone (Sharp and Smith, 2019) in the San Antonio segment. The dot in the upper right of the figure marks the location of a multiport well (Smith and Hunt, 2019). The transition zone is divided into slightly brackish (dark gray area between the 1,000 and 3,000 milligrams per liter [mg/L] isocons) and brackish (darker gray areas between the 3,000 and 10,000 mg/L isocons).

Fault barriers may create abrupt changes in aquifer properties (Smith et al., 2017). In addition, although isocons (lines or surfaces of equal salinity) are shown as a single line on most maps, the salinity can vary vertically between aquifer units. Water salinity transitions from fresh to brackish (> 10^3 mg/L) or saline (> 10^4 mg/L) across this zone (Sharp and Smith, 2019, Figure 2 therein). Waters are also reducing in the bad-water zone. Bennett and Sayre (1962) were able to map the bad-water line by the absence of hydrogen sulfide (H_2S) up dip of the line, which is also described in Bertetti and Adkins (2020). Although this last boundary is defined by water chemistry, it is also a physical boundary. The aquifer strata downdip have not been subjected to intense post-Miocene karstification. Consequently, there is a major decrease in permeability such that, in numerical models of groundwater flow, the bad-water line is commonly modeled as a no-flow boundary.

The reasons for the increase in salinity are threefold: upwelling fluids from deeper coastward units with saline fluids, dissolution of evaporitic minerals along flow paths, and upward cross-formational flow from the underlying Trinity aquifers. Hoff and Dutton (2017) mapped equivalent freshwater heads in the confined zone and units down dip of the San Antonio segment (Sharp and Smith, 2019, Figure 4 therein) showing the flow of more saline fluids towards the aquifer that has also been inferred from geochemical analyses (e.g., Land and Prezbindowski, 1981; Sharp and Clement, 1988; Abongwa and Den, 2021). In addition, Smith and others (2017) showed that the potential groundwater flow directions for equivalent freshwater heads vary from out of or into the freshwater aquifer depending on wet versus drought conditions, respectively. Figure 14 shows the hydrochemical facies of the bad-water zone. In the northern part of the San Antonio segment and in the Barton Springs segment, the waters are a Na-Cl hydrochemical facies. In the western portion of this segment, waters are a Ca-SO_4 facies indicating the dissolution of gypsum and anhydrite as the major factor. In the Northern segment, upward cross-formational flow becomes increasingly important. Sharp and Clement (1988) and Oetting and others (1996) provide the chemical and isotopic differentiation of the hydrochemical facies of the bad-water zone (Sharp and Smith, 2019, Figure 1 therein). The location of the bad-water line has remained relatively constant despite droughts, high recharge events, and pumping stresses (Sharp and Smith, 2019).

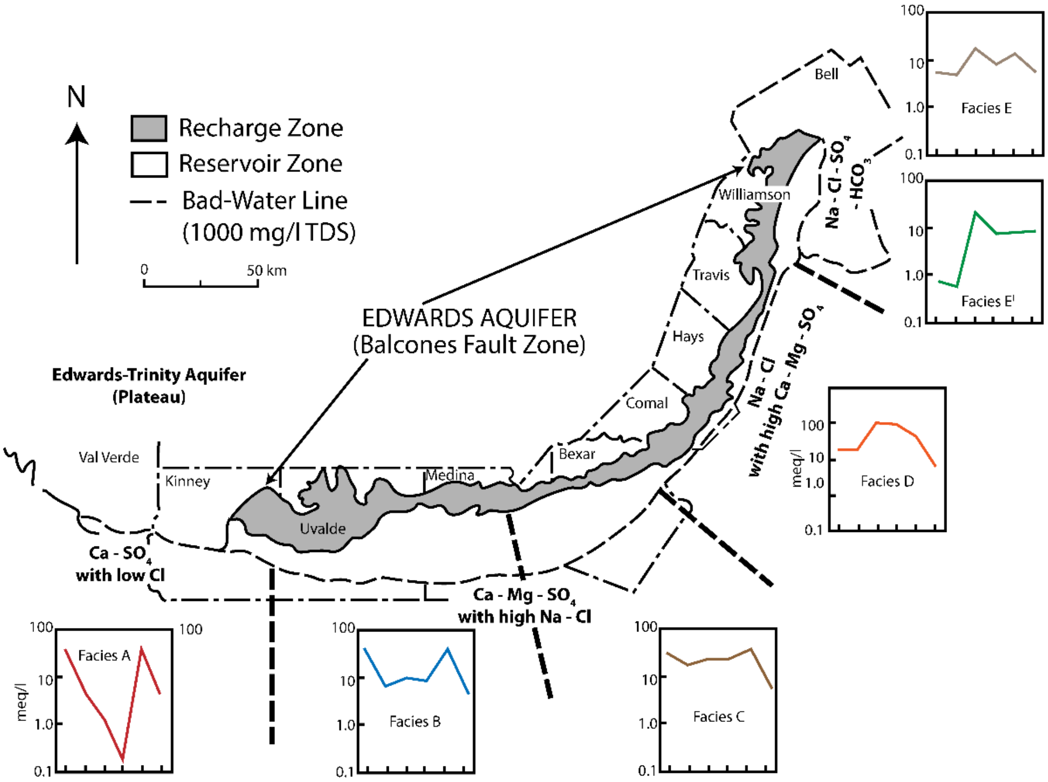


Figure 14 - Bad-water zone facies (modified from Sharp and Smith, 2019). Schoeller diagrams are in milliequivalents per liter (meq/L). Bad-water line (1,000 mg/L) is generalized.

Aquifer boundary definitions are complicated for two reasons.

- Groundwater divides can shift with variations in recharge and, in some cases, may disappear in droughts (Smith et al., 2012).
- Tracing studies (Johnson et al., 2019) and multiport well tests (Smith and Hunt, 2019) have shown that other formations are effectively part of the aquifer, particularly the underlying Upper Glen Rose Formation. In some locales, the Upper Glen Rose Formation (Upper Trinity Aquifer) is faulted against Edwards Aquifer strata in the recharge zone and is hydraulically part of the Edwards Aquifer (Johnson et al., 2010). Near Barton Springs, multiport well tests show the upper strata of the Glen Rose Formation are (vertically) hydraulically connected to the Edwards Aquifer in the confined zone (Smith and Hunt, 2019). Another example is a portion of the Cibolo Creek watershed (north of San

Antonio, Figure 12), comprised of the Lower Glen Rose (Trinity Aquifer), which is mapped as part of the Edwards Aquifer Recharge Zone due to its highly karstic nature and hydrologic connection to the adjacent and down-gradient Edwards Aquifer.

The Edwards Aquifer includes three major hydrologic zones or domains (Figure 12 and Figure 15) that are continually being refined with new data, especially geologic mapping and tracer tests (e.g., Johnson et al., 2010; Hunt et al., 2017; Hackett, 2019; Smith et al., 2020). The zones are important for understanding the hydrogeologic function of the aquifer system and have regulatory (land use) implications. The zones are shown in Figure 15 and are described here.

- The catchment or contributing zone, which provides allogenic recharge (surface water from higher elevations areas that do not overlie the karst, that seeps into dolines or fractures overlying the karst aquifer) to the Edwards Aquifer and includes outcrops of the Trinity Aquifer. This zone is not part of the aquifer as defined by its boundaries, but the streams flowing out of it are the major source of aquifer recharge (Maclay, 1995; Passarello et al., 2012; Hauwert and Sharp, 2014; Mahler and Musgrove, 2019). This area is underlain largely by Trinity geologic units and provides recharge to the Trinity aquifers.
- The recharge (outcrop) zone where aquifer rocks are exposed at the surface and receive autogenic recharge (recharge that is derived from within the carbonate catchment) including both diffuse (from precipitation) and discrete (from losing steams) processes.
- The confined (artesian) zone, which is generally overlain by the low-permeability Del Rio Clay as well as other low-permeability formations.

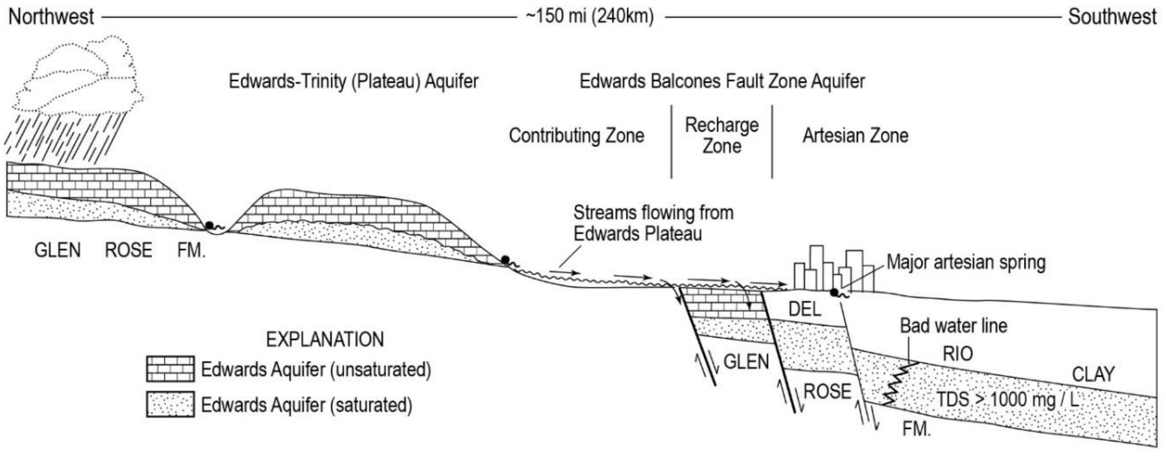


Figure 15 - A generic cross section through the Edwards Aquifers. Major springs discharge in the towns of Uvalde, San Antonio, New Braunfels, San Marcos, Austin, Georgetown, and Salado. Most of the recharge occurs along losing streams in the recharge zone. More detailed, site-specific cross sections can be found in Hunt and others (2019), Johnson and others (2010), Jones (2019), Lindgren and others (2004), Scanlon and others (2001), and Toll and others (2019).

2 Stratigraphy and Structure

The aquifer rocks were formed during the Early Cretaceous on a broad carbonate shelf, referred to as the Comanche shelf, flanked by deeper basins to the south and west (Rose, 1972, 2019; Abbott, 1975; Sharp, 1990), which included the lands northwest of the Stuart City reef (Figure 16). The Maverick and North Texas basins are separated by the San Marcos Platform. The Devils River Reef fringed the Maverick Basin.

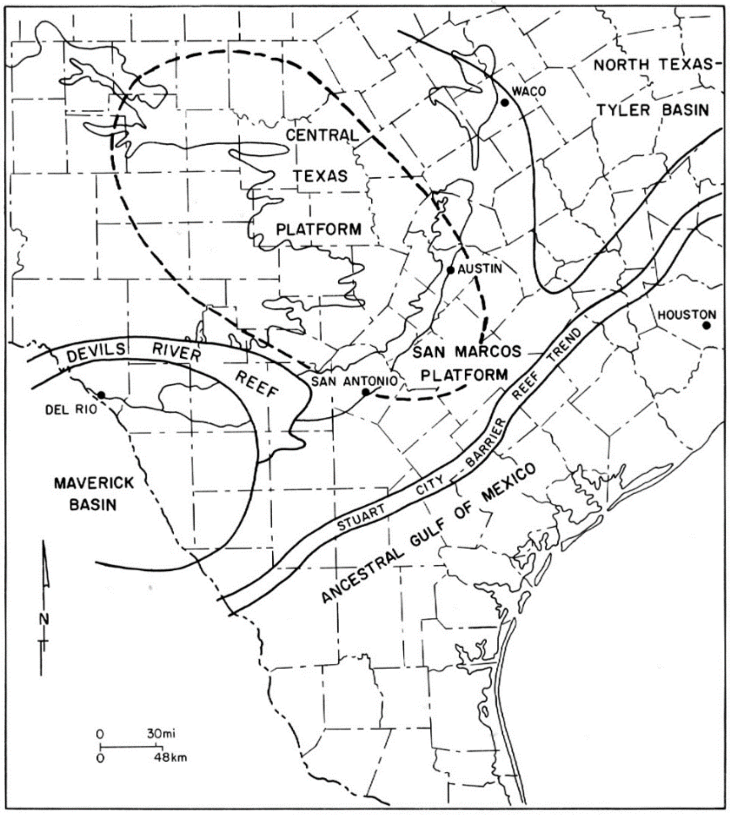


Figure 16 - Cretaceous depositional systems environments (Sharp, 1990; after Rose, 1972).

Aquifer hydrostratigraphy varies over a wide area (Maclay, 1995). The hydrostratigraphy of all segments of the Edwards Aquifer is shown in Figure 17 and reflects the various Cretaceous depositional environments. The aquifer is composed principally of the Edwards Group south of the Colorado River and composed of the Edwards and Georgetown formations north of the Colorado River. The aquifers may include more formations than just the Edwards Group or Edwards Limestone. The aquifer strata generally range in thickness from 60 m (197 feet) to 210 m (689 feet) in the San Antonio and Kinney segments; are about 140 m (460 feet) in the Barton Springs segment; and about 105 m (345 feet) in the Northern segment (TWDB, 2021). The aquifer, unless fault-bounded, thins to zero along the northwestern aquifer boundary.

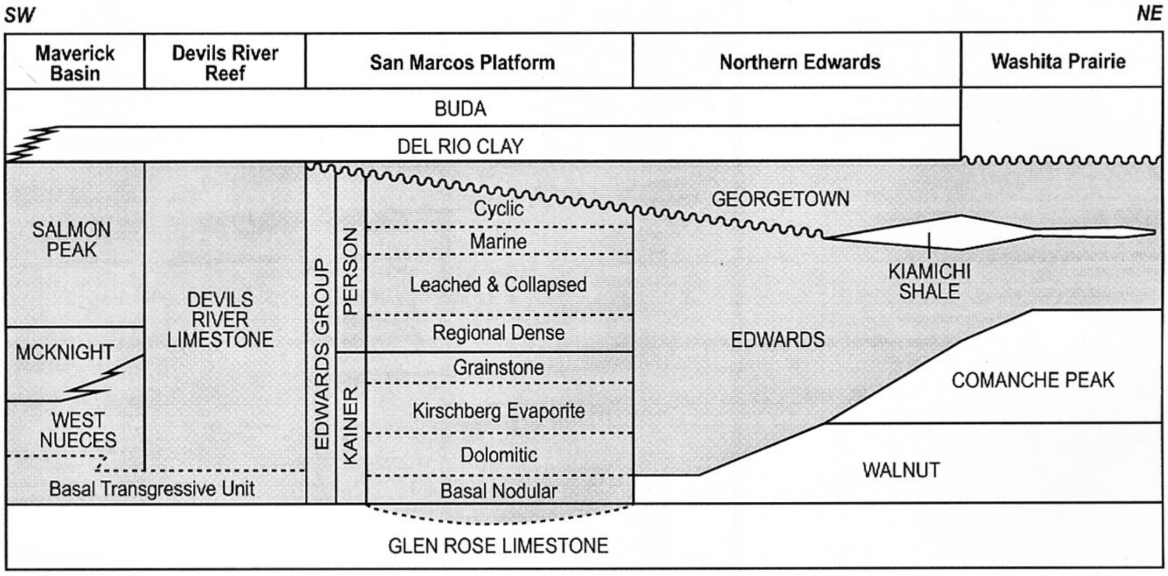


Figure 17 - Hydrostratigraphic units of the geologic formations (in gray) that form the Edwards Aquifer (modified from Sharp et al, 2019b). Formation names are in capital letters; dashed lines separate formation members (modified from Rose, 1972, 2017; Ryder, 1996).

Formation members south of the Colorado River are shown only for the Person and Kainer Formations of the Edwards Group in Figure 17. To complicate matters, the Edwards Aquifer is highly karstified, with rapid turbulent flow occurring in conduits, caves, and other preferential flow pathways formed by dissolution processes in the carbonate rocks. Karstification occurred during two episodes: (i) during the Cretaceous before deposition of the Georgetown Formation and (ii) more significantly after uplift, faulting, and exposure during the Cenozoic. In some areas, faulting has juxtaposed overlying and underlying units so that they act as part of the aquifer. These include the underlying Upper Glen Rose Formation (Hunt et al., 2019), which is part of the Trinity Group, and down-dropped sections of the overlying Buda Limestone and Austin Chalk formations that are hydraulically part of the aquifer in the Uvalde pool (Green et al., 2019b). The underlying and up-gradient portions of the Trinity Group contribute water flow to the aquifer in some areas via cross-formational flow (Clement and Sharp, 1987, 1988; Oetting, 1996; Johnson et al., 2019) or where they are juxtaposed to the Edwards Aquifer by faulting.

The Del Rio Clay is a gray, plastic clay, that was deposited in a shallow sea. It overlies the aquifer in the confined zone. It is an effective confining layer. The mineral composition is about 50 percent clay (10 percent smectite, 20 percent illite, 20 percent kaolinite), 10 percent quartz, 30 percent calcite and 10 percent amorphous material. Permeability data for the formation are lacking because the permeabilities are too low to be determined by most laboratory instruments. The Atterberg limits and swell potential in the Del Rio Clay are very high (Font, 1979; Font and Williamson, 1970), which is consistent with low-permeability clays and shales. The presence of flowing artesian wells, including some very large ones (such as the Catfish Farm well discussed in Section 4.1) over the confined zone of the highly permeable karst aquifer are also consistent with the Del Rio Clay having low permeability. Finally, numerical models do not require leakance through the Del Rio Clay because of its low permeability and the small area where upward cross-formational flow could occur.

Cross-formational flow from the underlying Trinity Group can be significant. This is supported by water balance estimates, numerical modeling, and water chemistry analyses (Clement and Sharp, 1987, 1988; Sharp and Clement, 1988; Oetting et al., 1996).

The geologic structure of the Edwards Aquifer is controlled by the Miocene-age Balcones Fault Zone (Hill and Vaughan, 1898; Weeks, 1945; Rose, 2019), which is an overall down-to-the-southeast system of normal faults associated with the transition between the Edwards Plateau and Gulf Coastal Plain province. The total structural offset can exceed 350 m over a distance of up to 50 km (Weeks, 1945; Collins and Hovorka, 1997). The Balcones Fault Zone cuts and juxtaposes rocks of the Cretaceous carbonate platform and overlying section—part of a regionally extensive carbonate-dominated sequence that extends in outcrop from central to west Texas (Lozo et al., 1959; Bebout and Loucks, 1977; Smith et al., 2000; Rose, 2017; Ferrill et al., 2019). Faulting also controls the outcrop patterns of the Edwards Aquifer, part of the Trinity Aquifer, and flow pathways within these aquifers (George, 1952; Holt, 1956; Arnow, 1963; Ewing and Caran, 1982; Maclay and Small, 1983; Maclay, 1989, 1995; Collins and Hovorka, 1997; Collins, 2000; Hovorka et al., 1998; Clark, 2000a; Ferrill et al., 2004, 2019). Regionally, the fault zone changes trend from nearly east-west between Del Rio and San Antonio to nearly north-south between Austin and Salado.

Locally, faults provide natural pathways for groundwater discharge mostly via springs that discharge within the confined (artesian) zone (Ewing, 1996). Intrusive and extrusive igneous activity in the Uvalde County and Travis County volcanic fields (Sharp, 1990, Figure 7 therein), that occurred approximately 82 to 80 and 74 to 72 million years ago (Miggins et al., 2004; Smith et al., 2008; Ewing, 2016), further complicate the regional structure (e.g., Clark et al, 2013).

At the largest scale, faults control the position and geometry of the aquifer (e.g., contributing, recharge, and confined zones) and, combined with stratigraphy, define regional flow paths. At the broad regional scale, the contributing zone is the southeastern Edwards Plateau at an elevation of > 350 m, the recharge zone is represented primarily by the Edwards Group outcrop belt at average elevations of ~300 m and is coincident with the Balcones Fault Zone. The confined zone lies south and southeast of this beneath the Del Rio Clay and younger sedimentary strata of Cretaceous to Miocene age. Faults and extension fractures—in many cases with permeability enhanced by dissolution—localize recharge and flow and are abundant at all scales within the Balcones Fault Zone and into the subsurface of the confined zone (Ferrill et al., 2019).

The juxtaposition of the Edwards Aquifer with other aquifers, especially the Trinity Aquifer, provides avenues for inter-aquifer communication (e.g., Ferrill et al., 2008; Johnson et al., 2010). On the other hand, juxtaposition against low-permeability layers (Maclay and Small, 1983), concentrations of clay in the fault zones, or mineralization along faults and fractures locally produce seals for compartmentalization and confinement of the Edwards Aquifer. This juxtaposition can lead to communication between the aquifer and permeable layers above and below the confining zones. The hydrologic behavior of faults varies as a function of position along the fault with respect to fault displacement, fault segmentation, and stratigraphic position, as well as the role of subsequent dissolution. At all scales, aquifer permeability parallel to faults is enhanced when compared to that of un-faulted rock (Hauwert et al., 2004).

Fault-block deformation including small faults and extension fractures also cause anisotropic permeability (i.e., permeability that varies with orientation). Faults and extension fractures localize recharge and flow. Groundwater flow and carbonate rock dissolution can enhance the permeability effects of fault and fracture systems. Fault displacements show a pattern of aquifer thinning that is likely to influence fault-block communication and flow paths. Flow-path constriction and tortuosity may be exacerbated by increased fault-segment connectivity associated with large displacements. Faulting over a range of scales can produce strong permeability anisotropy such that maximum permeability is sub-horizontal and parallel to fault-bedding intersections (Ferrill et al., 2019).

In rock layers like those that make up the Trinity and Edwards aquifers, groundwater flow and dissolution can enhance the permeability effects of fault systems. Fault zones commonly form relatively impermeable barriers to across-fault flow; form permeable pathways for along-fault flow; or form both barriers and pathways, often via relay ramps (Arnow, 1963; Caine et al., 1996; Knipe, 1997; Yielding et al., 1997; Ferrill and Morris, 2003a,b and 2007). Relay ramps transfer displacement from one fault to the next and can serve as unbroken groundwater flow pathways through a fault system where faults offset the aquifer or serve as flow barriers (Collins and Hovorka, 1997; Hovorka et al., 1998; Hunt et al., 2015).

3 Aquifer Properties

The Edwards Aquifer, like most karstic carbonate aquifers, is a triple porosity/permeability system, as explained below. The porosity and, in particular, permeability can vary significantly, both spatially and temporally. As a consequence, the estimated residence times of waters produced from wells or spring discharge reflect mixtures of waters with varying age (Hunt et al., 2019).

3.1 Porosity and Storativity

There are three types of porosity for the Edwards: matrix, fractures, and karstic (conduits). Hovorka and others (1996) provide a comprehensive set of porosity data using over 300 core plugs and over 200 well-log analyses. The average total porosity was estimated at 18 percent.

Matrix porosity is highly variable vertically from low values (4 to 12 percent) in dominantly subtidal high stand facies to high values (20 to 42 percent) in grainstones and leached, subtidal dolostones. Porosity can approach 45 percent in zones that have had dolomite dissolution. Hovorka and others (1996) show patterns of horizontal porosity gradation.

Fracture porosity is more difficult to assess. Hovorka and others (1998) estimate fracture porosity of 1.41 percent based upon a 30 m-long survey transect. Aquifer-specific yields are controlled by fracture porosity. Scanlon and others (2001) report specific yield values ranging from 0.001 to 0.06 for fractured areas. Slade and others (1985) estimated a mean specific yield of 0.017 for the Barton Springs segment. Lindgren and others (2004), Maclay and Rettman (1973), and Maclay and Small (1984) give ranges of specific yield (0.025 to 0.200) and storativity (10^{-5} to 8×10^{-4}) for the San Antonio segment.

Conduit (karstic) porosity is also highly variable and difficult to assess directly. Based upon karst feature distributions in outcrops, Hovorka and others (1998) calculated a range in porosity values of 0.5 to 9.43 percent with a median of 2.2 percent. However, it is unclear how well connected the karst voids are in these outcrops and how much they contribute to permeability. The interconnected karstic porosity may be small, but, as in conduits, commonly dominates the flow systems (Worthington, 1999).

3.2 Permeability

Similar to porosity, there are three sets of permeability[3]: matrix, fractures, and conduits (Halihan et al., 2000; Hovorka et al., 2004; Worthington 2004). Hovorka and others

---

[3] Permeability (k, units of L^2) is a function of pore geometry, and describes the ease with which a medium can transmit fluid. It is related to hydraulic conductivity (K, units of LT^{-1}) as defined by Darcy's Law which describes the volumetric flow rate under a given hydraulic gradient by combining k with the fluid density and viscosity.

(1998) compiled the, then existing, hydraulic conductivity data (Figure 18). The median hydraulic conductivity estimated from 680 specific capacity tests was approximately 3.5×10^{-5} m/sec (10 feet/day) but ranged over eight orders of magnitude. A few specific capacity tests reported zero drawdown reflecting extremely high permeability and were assigned small (minimal) drawdowns in order to calculate a permeability value. Matrix hydraulic conductivity from core plugs is shown in Figure 19. Median hydraulic conductivities of matrix core plugs were two orders of magnitude less than those calculated from specific capacity data, which shows that secondary porosity (fractures and karstic features) controls well yields.

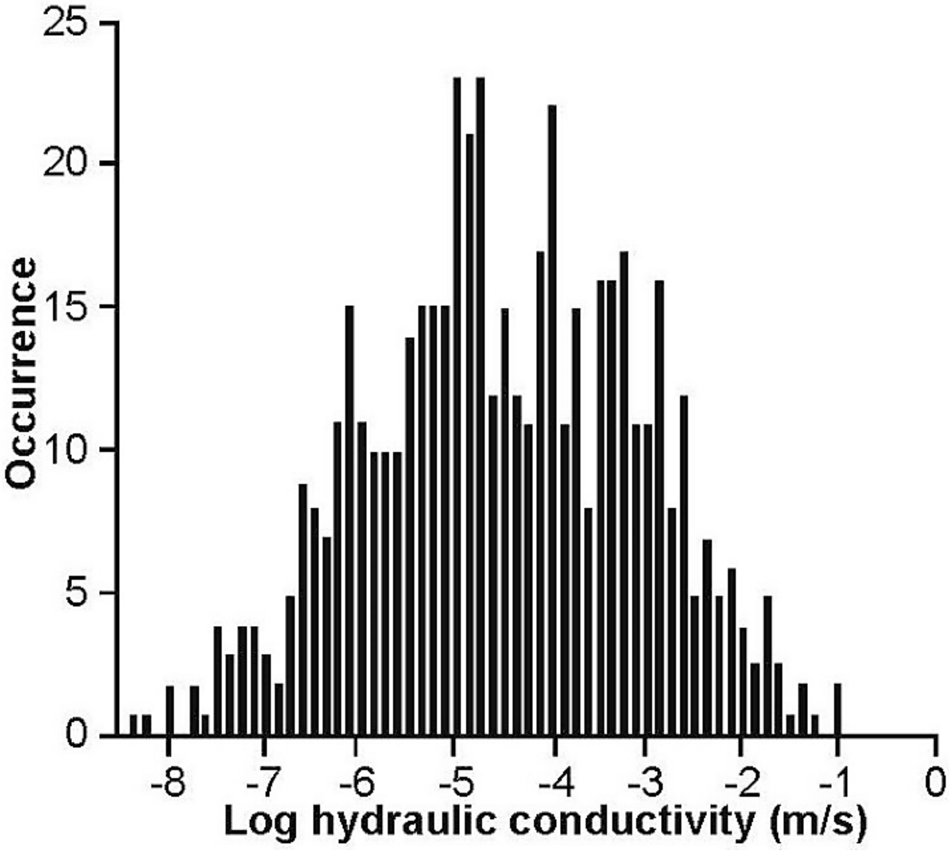


Figure 18 - Hydraulic conductivity for the Edwards Aquifer based on specific capacity data (modified from Hovorka et al., 1998). 1 m/sec = 2.83×10^{5} ft/day = $1.15\text{x}10^{-7}$ m^2.

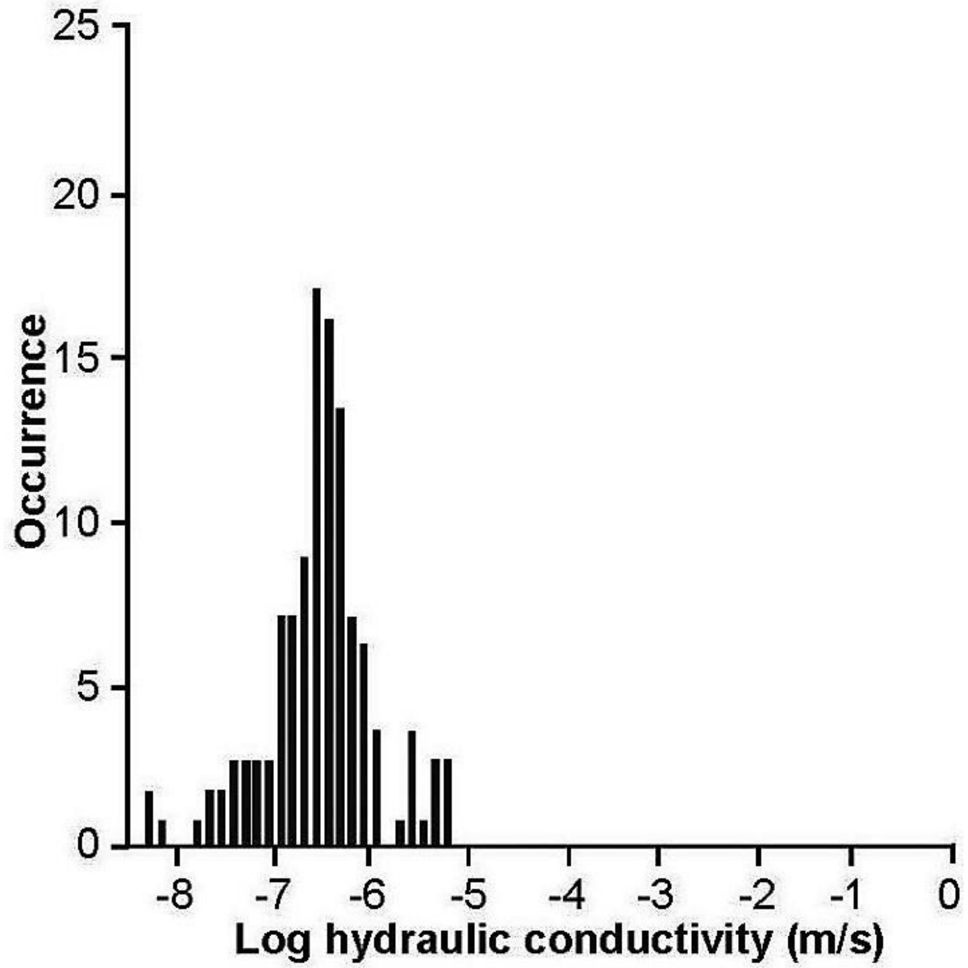


Figure 19 - Matrix hydraulic conductivity for the Edwards Aquifer based on core plug data (modified from Hovorka et al., 1998).

Halihan and others (1999) compiled permeability data from Hovorka and others (1993, 1995, and 1998), Mace (1997), and regional models (Klemt et al., 1979; Maclay and Land, 1988; Thorkildsen and McElhaney, 1992) to show permeabilities for the matrix (small-scale), wells (well-scale), and karstic conduits (regional scale). The data from well-scale (1,072 tests) and small-scale (493 tests) permeability tests approach log-normal distributions as indicated by the nearly straight line they form in Figure 20. The regional-scale permeabilities inferred from the numerical models are consistent with conduit flow.

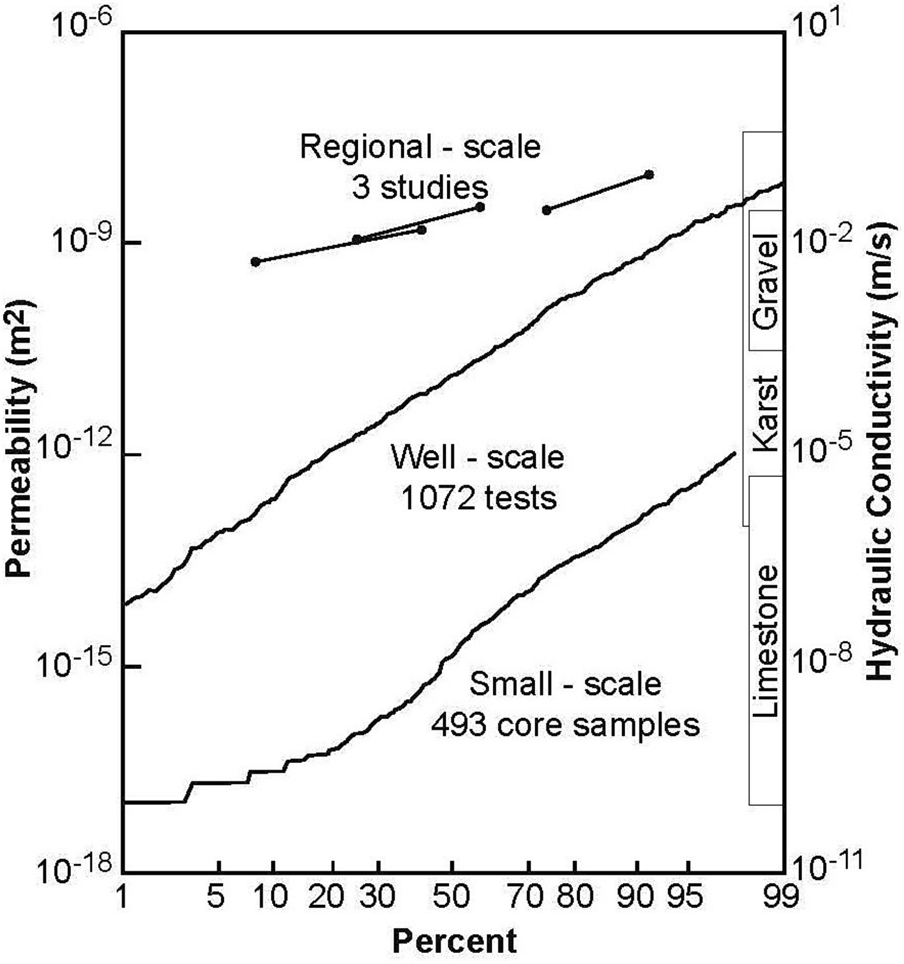


Figure 20 - Permeability scale effect for the San Antonio segment (after Halihan et al., 1999, 2000; Hovorka et al., 1993 and 1995). The three, regional-scale studies (Klemt et al., 1979; Maclay and Land, 1988; Thorkildsen and McElhaney, 1992) each estimated ranges of permeability. Permeability ranges for limestone, gravel, and karst (modified from Freeze and Cherry, 1979, page 29) are illustrated in boxes on the right for comparison. The cumulative-distribution function of a normal (i.e., Gaussian) distribution plots as a straight line on the probability scale, which is shown as percent on the horizontal axis. The cumulative-distribution function of the log permeability of the test data form a nearly straight line indicating they are nearly log-normally distributed. It is common for permeability of geologic formations to be log-normally distributed (e.g., Figure 18 and Figure 19).

Halihan and others (1999) showed that the well-scale permeability distribution for this set of data could be replicated by 50 Monte Carlo realizations of fracture models using the cubic law and fracture aperture spacing data from Hovorka and others (1998). The regional-scale model permeability values were intermediate between those reflecting laminar conduit flow (greater than the regional-scale values) and fully turbulent conduit flow (less than the regional-scale values) as shown in Figure 21. Regional conduit flow is best modeled as turbulent, but is highly dependent on the local conduit geometry.

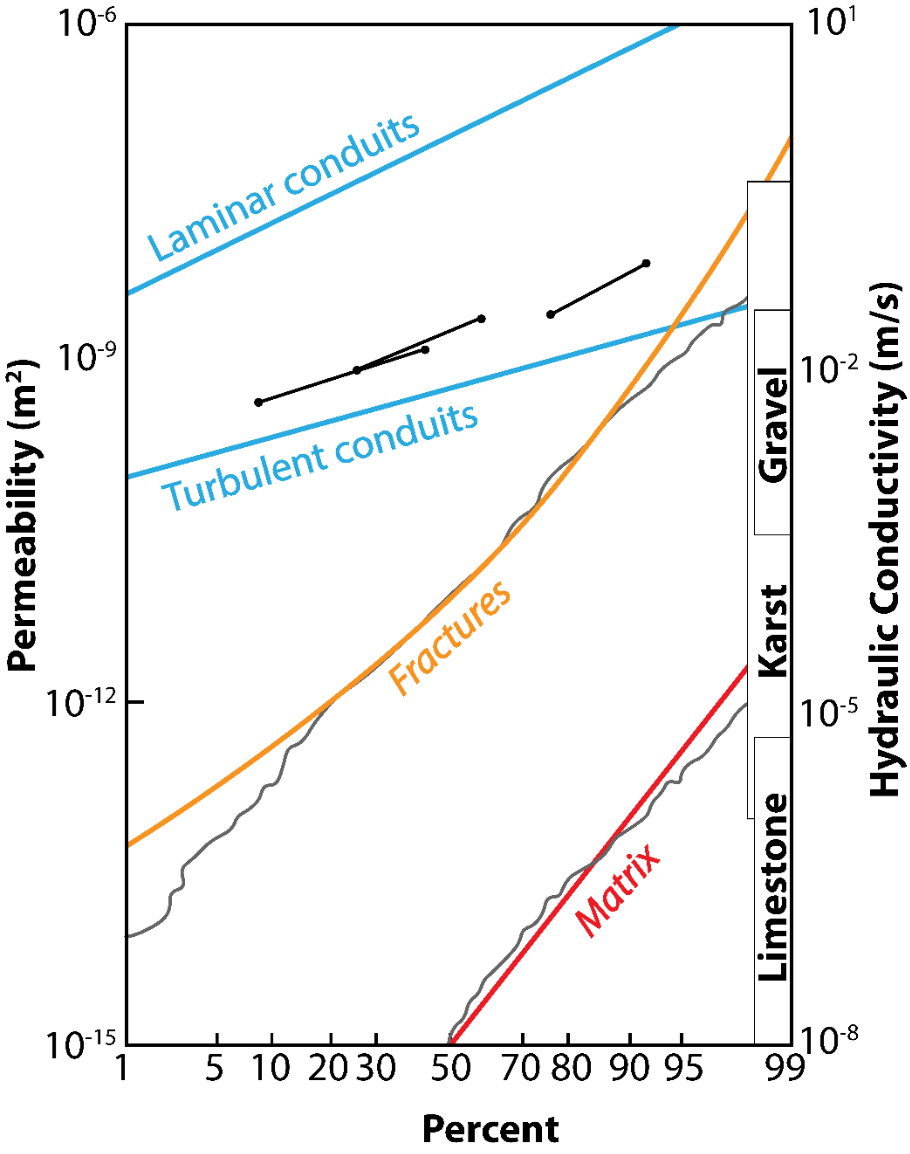


Figure 21 - Modeled permeabilities for Edwards Aquifer matrix (red), fractures (orange), and conduits (blue) compared to data (black) from Figure 20 (after Halihan et al., 1999, 2000). Permeability ranges for the matrix, fractures, and for laminar and turbulent flow in conduits were calculated based on Gupta (1989) and Halihan and others (1999) from 493 core plugs and roadcut measurements of 776 fracture apertures and 2785 conduit diameters (Hovorka et al., 1998).

3.3 Residence Times

Calculating groundwater residence times in karst aquifers is challenging due to the variable mixture of young conduit flow water and potentially much older matrix water. In light of this limitation, groundwater residence times for the Edwards Aquifer have been calculated by numerical model simulations, isotopic age dating, and tracer tests. Residence times are relatively short in the aquifer but increase downdip into the brackish water zones (the bad-water zone) as described by Hunt and others (2019). In the freshwater zone, both confined and unconfined, water is recent with inferred ages ranging from days to a few thousand years. Musgrove and others (2019b) estimate mean groundwater ages ranging from 7 to > 700 years. This large range in residence times is also observed in spring discharge, which is expected because of the three sets of permeability.

For a given hydraulic gradient, flow rates can be expected to vary by orders of magnitude in the conduits, fractures, and matrix. The shortest residence times are found in the recharge zone where there is discrete recharge or along conduit flow paths (with the fastest groundwater flow velocities). Tracer testing is the best method for measuring the quickest rates of flow from a recharge feature to wells or springs. Traditional groundwater models may have difficulty estimating travel times in karst aquifers with well-developed conduit networks (Worthington et al., 2002; Smith et al., 2005b). Apparent ages in the bad-water zone are much older and it can be inferred that the ages of waters with total dissolved solids (TDS) over 4,000 mg/L are on the order of 20,000 years. Waters farther down dip in the Gulf of Mexico sedimentary basin are inferred to be still older (Sharp and Smith, 2019; Hoff and Dutton, 2017; Darling, 2016; Land and Prezbindowski, 1981).

Traditional groundwater models are poor tools for estimating travel times in mature karst aquifers with well-developed conduit networks (Smith et al., 2005b). Based on model flow lines, Jagucki and others (2011) report that over 50 percent of the water from public-supply wells near San Antonio was less than two years old (Figure 22).

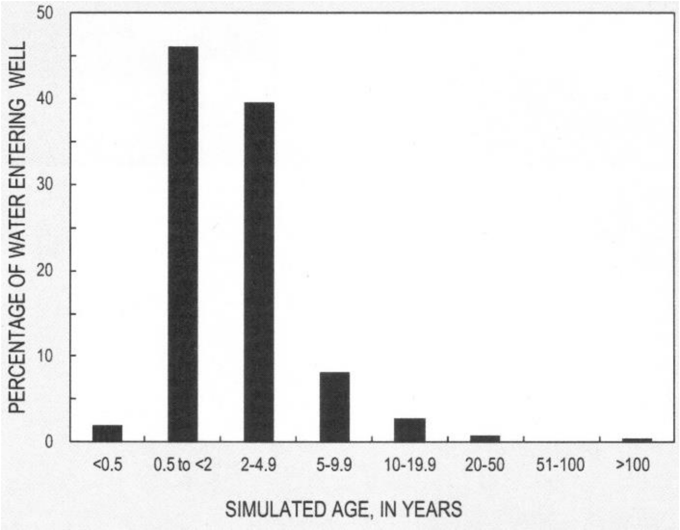


Figure 22 - Mix of water ages for a public supply well near San Antonio (Jagucki et al., 2011).

Lindgren and others (2011) used particle-tracking simulations to estimate travel times to 10 study wells. The simulated particle ages ranged from less than one day to more than 1,900 years. Their modeled particle ages for models calibrated to the observed tritium data gave residence times ranging from 2.5 to 15 years for the shallower and deeper wells, respectively.

Kuniansky and others (2001, Table 1 therein) used head data from 1978 to 1979 to calculate ranges of travel times for flow from recharge areas near the Edwards Plateau to San Marcos and Comal springs. The shortest estimate was from 14 to 160 years for a flow path from the Blanco River to San Marcos Springs and the longest was 350 to 4,300 years for a hypothetical flow path from the West Nueces River to Comal Springs. The models used matrix porosity values averaging 22 to 26 percent. If fracture porosity/permeability values had been used, the calculated travel times would have been shorter. In addition, these travel times were calculated with a porous-media model. Travel times calculated with a model that represented preferential flow paths would be shorter.

3.3.1 Isotopic Ages

Tritium (^{3}H or T), ^{14}C, and ^{3}He isotopes have been used to infer groundwater age in the Edwards Aquifer. Campana and Mahin (1985) used a discrete-state computer model and tritium data to estimate mean ages for water in the confined zone of the San Antonio segment. The mean groundwater ages ranged from 16 to 132 years. Since the decay of the 1963 tritium bomb pulse has become significant, the use of tritium in dating groundwater has become more difficult. Nonetheless, the presence of tritium indicates relatively young groundwater. Darling (2016) plotted 25 samples of water analyses of Edwards Aquifer waters that had both ^{14}C and T data. Recently recharged ("young") waters would have higher levels of T (in tritium units) and percent modern carbon (pmc, percent modern ^{14}C) with the understanding that both isotopes decay, but at different rates. The linear regression between T and pmc is $T = 2.50 – (100\ \text{percent} - 3.47\,pmc)/100$. The data show mixing of young and older waters. If the pmc is less than 35 percent, then mixing cannot be calculated because the tritium is essentially gone.

^{14}C dating is complicated because the dissolution of carbonate minerals in the aquifer contributes dead (nonradiogenic) ^{13}C. Thus, *pmc* decreases because of both radioactive decay and the introduction of dead C so that precise age dating is not possible. However, some general trends can still be discerned. Maclay and others (1980) provided a review of hydrochemical data for the San Antonio region, including samples from the brackish-water zone. For five waters with over 4,000 mg/L TDS, the apparent age dates were all over 26,000 years before present; a water with 1,220 to 1,280 mg/L gave an apparent age date of 12,000 years before present. These ages are consistent with the origin of the brackish waters in this area, which are upwelling from the Gulf of Mexico Basin (Sharp and Clement, 1988; Hoff and Dutton, 2017).

Tritium (^{3}H), ^{14}C, and ^{3}He were used by Hunt and others (2016) to infer groundwater ages in the Uvalde pool. These ages ranged from less than 2 years in the recharge zone to over 26 years in the vicinity of the brackish-water line and to the east in the direction of the regional flow. Many of their apparent ages showed mixing of modern (< 60 years old) and premodern waters. Mixing was most evident when waters approached 1,000 mg/L but mixing was also inferred in the unconfined zone based on excess helium concentration anomalies, which are consistent with subsurface discharge of premodern groundwater from the underlying Trinity Aquifer into the younger groundwater of the Edwards Aquifer.

Recent work by Musgrove and others (2019a,b) is consistent with the age ranges of these other studies (< 10 to > 700 years). Water in the San Antonio pool confined zone is a mix of older and younger waters (with the young ages between 24 to 30 years and the older ages variable depending on the depth/location in the aquifer). These ages and mixtures are consistent with rapid recharge, rapid flow in the karst aquifer that is attested to by tracer tests, the triple porosity (matrix, fracture, conduit) aquifer system, and inflows of older water from underlying and downdip units.

3.3.2 Tracer Tests

Johnson and others (2019) reviewed tracer test results for the Edwards Aquifer. These test results showed very high flow velocities. In the Barton Springs segment, tracer tests delineated flow paths in separate pools (groundwater basins). Groundwater velocities ranged from 915 to 9,150 m/day (Hauwert et al., 2004). Hunt and others (2019) reported flow rates of 110 to 4,931 m/day to Barton Springs. Water-chemistry data for Barton Springs indicate that discharge is a mix of waters from several different flow paths.

In the San Antonio segment, Rothermal and Ogden (1987) measured straight-line flow velocities of 640 m/day to Hueco Springs. Smith and others (2012) calculated straight-line velocities ranging from < 1 to 3,600 m/day to San Marcos and Barton springs. In Bexar County, tracer tests indicate that the Upper Trinity Aquifer was in direct hydraulic connection with the Edwards Aquifer. Tracers injected into the Trinity Aquifer traveled toward the Edwards Aquifer with straight-line tracer velocities ranging from 13 to 5,300 m/day (Johnson et al., 2010). In Kinney County, 13 tracer tests indicated slow to rapid (up to 1,350 m/day) groundwater velocities (Johnson and Schindel, 2015).

3.4 Water Chemistry

Water quality in the aquifer is generally excellent. Few contaminant concentrations ever exceed human health-based benchmarks (Bush et al., 2000; Lindsey et al., 2009; Tremallo et al., 2016; Smith et al., 2001, Musgrove et al., 2019b). The waters are less than 1000 mg/L total dissolved solids (TDS) and generally less than 500 mg/L (Figure 23), and are a calcium-magnesium-bicarbonate hydrochemical facies (e.g., Welder and Reeves, 1962; Guyton and Associates, 1979; Groschen, 1996; Hunt et al., 2019, Jones, 2019). A few wells show sulfate or chloride as the most common anion, but these are nearly always associated with the saline-water transition zone or have contributions from underlying aquifers. Nonetheless, detectable concentrations of contaminants indicate that anthropogenic activities on the land surface affect the aquifer (Bush et al., 2000; Jagucki et al., 2011; Mahler and Musgrove, 2019a). Despite intense utilization of the aquifer and urbanization over the recharge zone, water quality has remained good, mostly attributable to dilution due to high flow rates although a few wells show elevated levels of pathogens and nitrate. Urbanization and land cover are important factors affecting aquifer vulnerability (Opsahl et al., 2018). Leaks of sewage in the recharge zone have created local, short-lived *E. coli* contamination in wells and in Barton Springs (Mahler et al., 2011), which may be closed for several days after heavy rainfall events. Jagucki and others (2011) documented that pesticide compounds (atrazine, deethylatrazine, and simazine) and volatile organic compounds (tetrachloroethene [PCE], chloroform, bromoform, and dibromochloromethane) can occur in untreated water at concentrations *"much less than established drinking-water standards, where such standards exist."* In the vicinity of the bad-water line, groundwater becomes brackish (> 1000 mg/L) to saline (> 10,000 mg/L) with naturally-occurring elevated levels of sodium, chloride, and sulfate (Figure 14 and Figure 23).

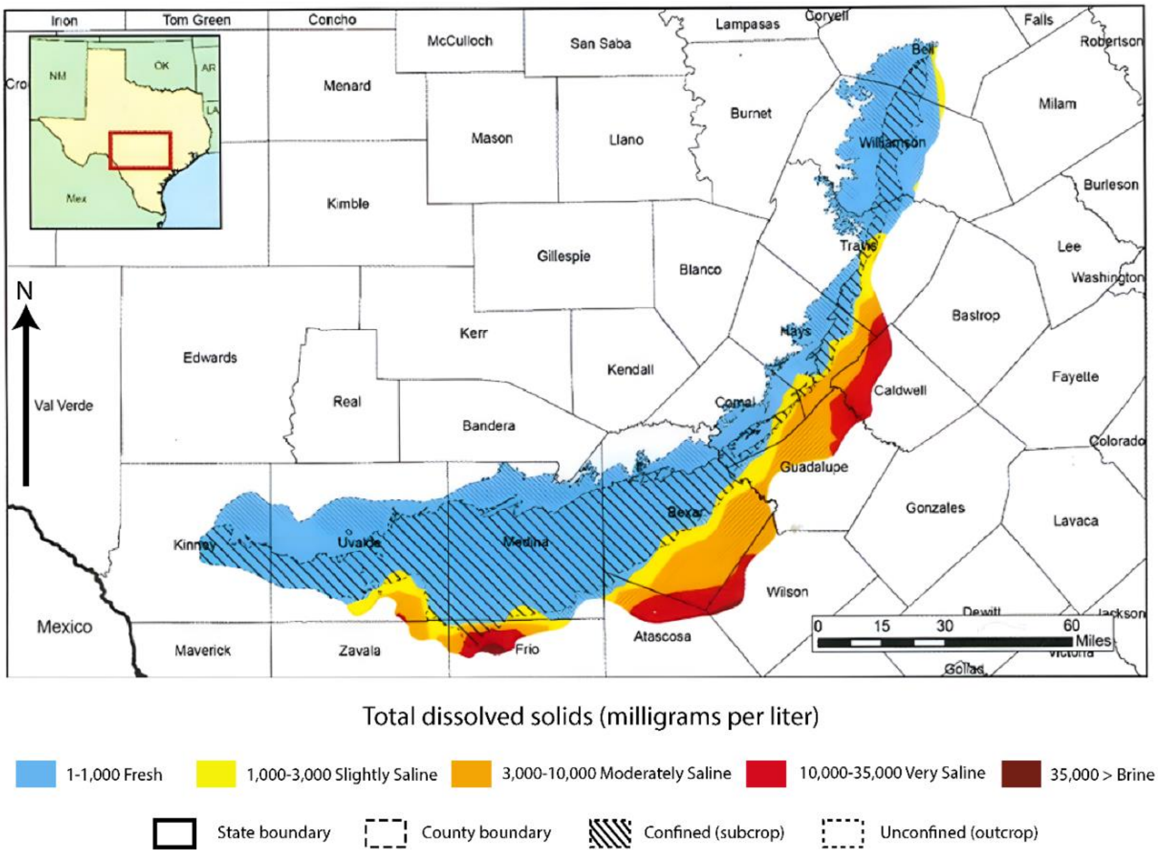


Figure 23 - Total dissolved solids in the Edwards Aquifer (modified from TWDB, 2016).

The bad-water zone has been relatively stable over time with six hydrochemical facies identified, which are created by different combinations of dissolution of evaporite and other minerals, mixing with basinal brines, dedolomitization, and cross-formational flow from underlying formations. The bad-water line on the maps approximates the 1000 mg/L isocon but is actually a transition zone (Figure 13). Flow in this zone is restricted, the waters are reducing, and recent studies (e.g., Engel, 2007; Abongwa and Den, 2021) suggest that microbes play important chemical and physical roles. However, the bad-water zone has sufficient water in storage and sufficient permeability so desalination or aquifer storage and recovery (ASR) could render it a viable water source option in the future (Smith et al., 2017).

4 Flow Systems

Numerical models have been used to simulate groundwater flow, changes in groundwater storage (water levels), and significantly, spring flow from the Edwards Aquifer. Estimating water budgets has been a central objective of numerical modeling. A key outcome of the conceptual and numerical modeling is the nearly one-to-one relationship between increases in pumping and decreases in spring flow under low-flow conditions (Brune and Duffin, 1983; Smith and Hunt, 2004; Hunt et al., 2011). Water resource managers rely on these groundwater flow models to characterize groundwater-flow conditions in the Edwards Aquifer to serve as the basis for predicting the effects of water-resource management decisions, particularly on spring flow. There are recognized limitations and shortcomings in all numerical groundwater models, such as the particular modeling software selected, uncertainty about the underlying conceptual model and its implementation in the ensuing numerical model. Nonetheless, models are the preferred tool for groundwater resource management (De Marsily, 1986; Anderson and Woessner, 2015; Scanlon et al., 2003; Hartmann et al., 2014; Green et al., 2019d).

The Edwards Aquifer is regional in scale with properties and characteristics that vary spatially and often temporally. Capturing these extreme heterogeneities imposes a large cost with regard to computation time and data-input requirements. At the same time, aquifer management concerns are usually defined at the local scale, requiring sufficient high resolution to account for local-scale characteristics of the aquifer. For these reasons and others, no single numerical model has been developed to simulate flow for the entirety of the Edwards Aquifer. Numerical models have been developed for segments and subsets of the Edwards Aquifer, including the San Antonio segment (Maclay and Land, 1988; Lindgren et al., 2004; Fratesi et al., 2015; Liu et al., 2017), the Barton Springs segment (Scanlon et al., 2001; Winterle et al., 2009; Hutchison and Hill, 2011), Kinney County (Hutchison et al., 2011a), and the Devils River watershed (Toll et al., 2017). In addition, there are regional-scale models, referred to as Groundwater Availability Models, which span large areas of the Edwards Aquifer and related aquifers, such as the Edwards-Trinity and Trinity aquifers (Anaya and Jones, 2004, 2009; Hutchison et al., 2011b; Jones et al., 2009). Although lumped-parameter (Wanakule and Anaya, 1993; Barrett and Charbeneau, 1996; Loáiciga et al., 2000) and solute-transport (Lindgren et al., 2011) models of the Edwards Aquifer have been developed, this discussion focuses on distributed groundwater-flow models. Post-2000 models of the greater Edwards Aquifer area were mostly developed as part of the Texas Water Development Board's (TWDB) Groundwater Availability Model (GAM) program (Mace et al., 2008).

4.1 Discharge and Recharge

4.1.1 Discharge

It has long been recognized that natural aquifer discharge is primarily due to the large springs that characterize the Edwards Aquifer, with well pumpage as the second major discharge. In some cases, springs discharge directly into alluvial systems (e.g., Leona Springs) or as base flow to major streams or rivers (e.g., Medina River in the San Antonio pool (Green et al., 2019a). Some discharge from the Cold Springs pool to the Colorado River (Hauwert et al., 2004; Hunt et al., 2019). There is also limited cross-formational flow to other aquifers, which has dropped significantly as well yields increased and potentiometric surfaces lowered. There are fewer flowing artesian wells than in the time of Hill (1890) and upward cross-formational flow is a minor source of the discharge because of the effectiveness of the Del Rio Clay as a confining unit.

There is (or was because of lower heads due to well pumping) the potential for upward cross-formational flow. Many wells in the Edwards Aquifer confined zone are (or were) free flowing, particularly during periods of greater rainfall. An extreme example of this is the Catfish Farm well (**Figure 24**), which was one of the world's largest free-flowing wells capable of flowing on the order of 2.5 m^3/sec (40,000 gallons per minute). This well is now closed, but this video ▶ demonstrates both the great productivity resulting from the high permeability and some of the political issues that arise when dealing with the Edwards Aquifer.

Figure 24 - Catfish farm well (Photo by Greg Eckhardt, 1995).

On a regional scale, cross-formational flow as a process of natural discharge has not been quantified, but it is small. This is supported quantitatively by numerical model simulations.

4.1.2 Recharge

Recharge to the aquifer can be estimated in two ways: indirect and direct. The indirect (lumped system) method is to assume steady-state flow for years so that recharge from all sources must equal the measured or estimated long-term discharge. This method depends on the accuracy of discharge data and does not address spatial or temporal variations or analyze different sources of recharge that are important for understanding hydrogeological processes and for aquifer management.

Direct estimates generally show that the largest source of recharge is from losing streams that flow over the contributing and recharge zones. The second-largest source of direct recharge is from precipitation on the recharge zone as diffuse recharge (e.g., Hauwert and Sharp, 2014). Cross-formational flow from The Edwards-Trinity Aquifer is another form of recharge. Although there are no direct measurements of cross-formational flow, the current model of the San Antonio Segment of the Edwards Aquifer (Liu et al., 2017) uses a value of 74,000 acre-feet/year (91.2 GL/year) and the Texas Water Development Board's Trinity model (Jones et al., 2009) uses a value 110,000 acre-feet/year (136 GL/year). That would account for 10 to 20 percent of the average input to the Edwards Aquifer. Smaller amounts come from anthropogenic sources (urbanization, artificial recharge, and irrigation return flow (Garcia-Fresca, 2004; Passarello et al., 2012 and 2014).

Estimates of recharge from losing streams are based on stream gaging and estimates of precipitation in contributing zone watersheds. Puente (1978) established the basic method of estimating recharge from losing streams by stream gaging above and below the recharge zone. The difference was the calculated recharge. Puente's estimates are shown in Table 2.

Table 2 - Estimated recharge from losing streams for the San Antonio and Kinney segments of the Edwards Aquifer by basin (after Puente, 1978). 1 GL is one-million cubic meters.

River basin	acre-feet/year	GL/year
Nueces and West Nueces Rivers	102,200	126
Frio and Dry Frio Rivers	98,700	122
Sabinal River	35,400	44
Between the Sabinal and Medina Rivers	86,000	106
Medina Lake	55,800	69
Between Medina River and Cibolo Creek	64,200	79
Cibolo and Dry Creeks	95,000	117
Blanco River	34,700	43

Puente's method forms the basis for direct stream-loss recharge calculation, but it has had to be modified because of several factors. First, the great variability in rainfall at local scales along the Balcones Escarpment (e.g., Nielsen-Gammon, 2013; Nielsen et al., 2015) makes prediction of stream flow and subsequent recharge from losing streams difficult when using broad-scale precipitation measurements. Second, geological mapping and tracer tests have led to revised delineations of the recharge zone. Tracer tests in Bexar

County (Johnson et al., 2019) show that the Upper Glen Rose Formation is more hydraulically similar to the Edwards Aquifer than the rest of the Trinity Aquifer. Accordingly, the upper Glen Rose Formation acts as part of the Edwards Aquifer recharge zone (Figure 17). Supporting this conceptualization are multiport well data in the Barton Springs segment that show that the Edwards Aquifer and the Upper Glen Rose Formation function as a single aquifer (Smith and Hunt, 2019). The long-accepted basic aquifer framework that negligible recharge to the Edwards Aquifer occurs in the contributing zone can be expected to be modified to reflect this finding and thus result in refined conceptualizations in the future.

Finally, stream-gaging data have shown that infiltration along the losing stream reaches is not uniform spatially (e.g., Slade et al., 2002) or temporally. Zahm (1998) found that infiltration in the losing reaches along Barton Creek was not uniform but concentrated in a limited number of locations. Stream-gaging studies on the Nueces River (Kromann, 2015: Hackett, 2019) and the Blanco River (Hunt et al., 2017) show that the location of losing and gaining reaches in rivers that cross the recharge zones are not fixed but may vary with time. Consequently, the precise location of river gages and use of only a few gages can bias estimates of recharge.

Direct recharge from precipitation occurs on the recharge zone as autogenic recharge. This has also been estimated indirectly by subtracting the estimated recharge from losing streams from total discharge (spring flows and wells). This should give a general estimate, but in some early cases before the pools in the segments were clearly defined, this calculation method caused significant underestimation of direct recharge (Hauwert and Sharp, 2014). Direct aquifer recharge is best estimated from water-balance analysis using precipitation, surface runoff, and evapotranspiration data. Hauwert and Sharp (2014) compiled existing data from central Texas flux towers (Figure 25) to show that water available for recharge is a function of total annualized precipitation. In dry years, most precipitation infiltrating the land surface is lost to evapotranspiration.

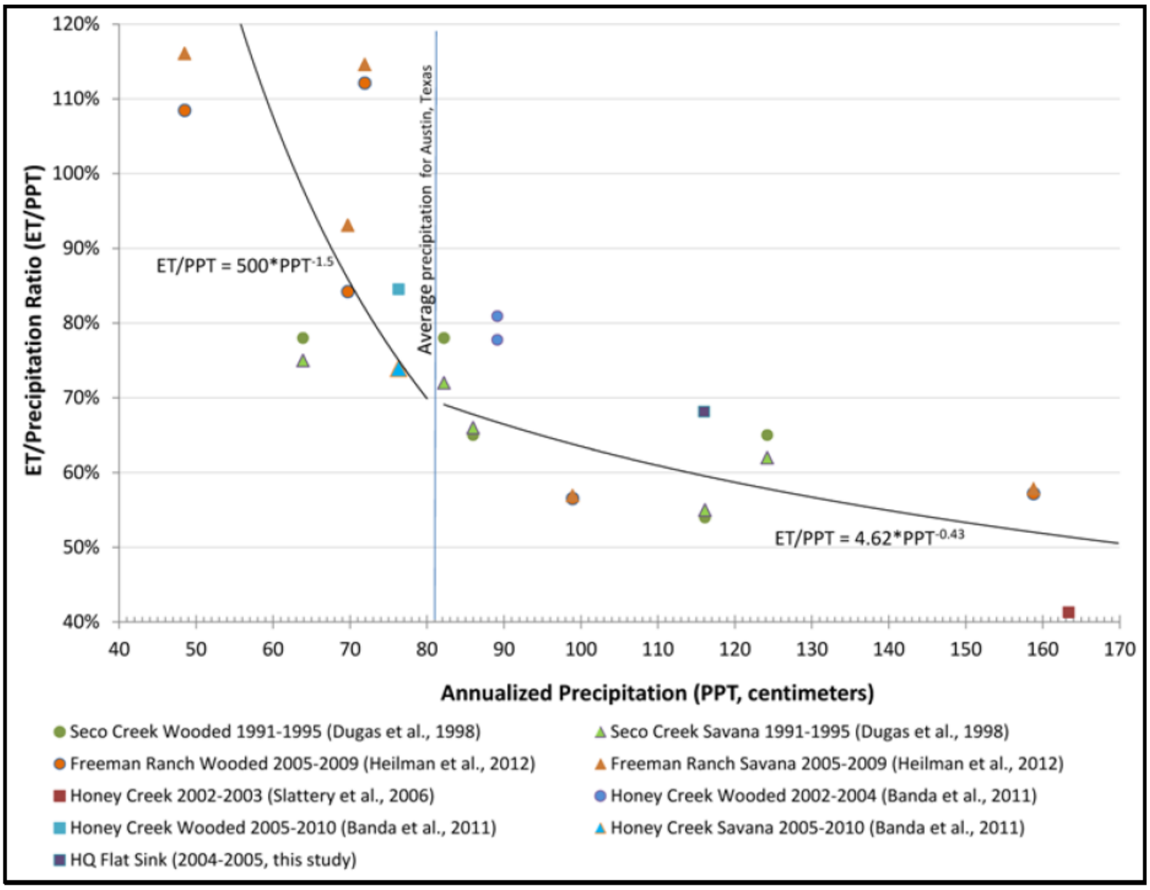


Figure 25 - Central Texas evapotranspiration flux tower data and annual precipitation (from Hauwert and Sharp, 2014).

In wetter years, direct recharge is greater. Hauwert's (2009) data for the Barton Springs segment recharge zone on two control plots with internal drainage (i.e., no surface runoff to streams) indicated that, during the period of study (2005 to 2006), about 30 percent of the precipitation was available for aquifer recharge, which is in the typical range for karst aquifer outcrop areas in sub-humid environments (Hauwert, 2009, **Table 3** therein).

There are other minor sources of recharge such as the effects of urbanization (Passarello et al., 2012, 2014; Sharp, 2019), including water losses from water and sewage lines, irrigation return flow, and artificial recharge. Artificial recharge is where groundwater is recharged by redirecting water across the land surface through canals, infiltration basins, or ponds; adding irrigation furrows or sprinkler systems; maintaining streamflow in losing streams; or injecting water directly into the subsurface through injection wells, injection galleries, or sinkholes. Artificial recharge has been considered as a strategy for the Edwards Aquifer to maintain critical spring flows to preserve endangered aquatic species, specifically by injection wells or galleries near Comal and San Marcos springs (McKinney and Sharp, 1995; Uliana and Sharp, 1996), but has never been implemented. Consideration has also been given to retention dams in the contributing zone that would preserve high flood flows and then release flows gradually to the recharge zone, but, these have only been implemented to a limited degree. The Edwards Aquifer Authority

(EAA) has, however, developed the Seco Creek Sinkhole (Figure 12), see the video here ▶, to receive high stream flows via a diversion ditch from Seco Creek.

The Barton Springs Edwards Aquifer Conservation District (BSEACD) has constructed a concrete structure over a cave in the bed of Onion Creek in south Austin, which directs water in the creek into the Edwards Aquifer (Smith et al., 2011). This system was designed to automatically close a valve during periods of stormwater flow so that the high-turbidity stormwater doesn't enter the aquifer. When the water quality in Onion Creek improves, the valve opens allowing the better-quality water to recharge the aquifer. This decreases the amounts of contaminants entering the aquifer during flood events and increases recharge to the aquifer by preventing the cave from getting clogged with debris.

In areas where there is irrigation on the recharge zone, the possibility exists that there is recharge from irrigation return flow to the Edwards Aquifer. However, this has been considered minimal because many irrigated lands are found in the confined zone where direct recharge to the Edwards Aquifer is negligible. However, recharge due to urbanization (leaky water and sewer systems as well as over-irrigation of parks and lawns) may be significant in large metropolitan areas and areas of expansion such as along the I-35 corridor (Garcia-Fresca, 2004; Passarello et al., 2012 and 2014). This is especially true during periods of very low rainfall. Passarello and others (2012) show that, in the Barton Springs segment, during times of drought urban recharge may be the largest component. Average annual recharge estimates for all four segments are given in Table 3.

Table 3 - Average annual recharge.

Segment	Acre-feet/ year	m^3/s	GL/year	Source
Kinney	69,800	2.71	85.4	Green and Bertetti (2010)
San Antonio	636,200	24.66	778.1	Edwards Aquifer Authority (2019b)
Barton Springs	39,300	1.52	48.1	Scanlon et al. (2001)
	49,300	1.91	60.3	Hunt et al. (2019)
Northern	80,000	3.10	97.8	Jones (2003)

4.2 Segment Flow Systems

The Colorado River in Austin creates the lowest topographic point in the aquifer. It separates the Northern and Barton Springs segments. As illustrated in Figure 12, the Colorado River and its contiguous channel are characterized as hydraulically isolated from the Edwards Aquifer. In Austin, the river receives flow from Barton and Cold Springs on the southern bank and Deep Eddy Springs (northern bank) as well as smaller springs and streams, but the Colorado River does not recharge the aquifer in a meaningful way. Hence, surface water and groundwater flow in the greater Colorado River watershed are hydraulically separate from the Edwards Aquifer. In times of severe drought, the groundwater divide between the San Antonio and Barton Springs segments can disappear and the two segments essentially become one (Smith et al., 2012).

To the west of the San Antonio and Kinney segments, the Devils River watershed discharges from the Edwards-Trinity Aquifer via major springs in the Devils River channel and elsewhere (San Felipe) and to the Rio Grande (Green et al., 2019c). Goodenough Spring, historically the third largest spring in Texas (Brune, 1975; Kamps et al., 2009), is an example of the springs that discharge to the Rio Grande. Springs that are not associated with the Devils River catchment are considered part of the Del Rio pool.

The following subsections summarize the flow systems of the four segments as defined in Figure 2 and Figure 12.

4.2.1 The San Antonio Segment

This segment is the largest of the four segments and extends from a groundwater divide in Kinney County in the west to the groundwater divide with the Barton Springs segment in Hays County (Schindel, 2019). There are two defined pools in the San Antonio segment: the Uvalde and San Antonio pools (Figure 26). More detailed descriptions of the San Antonio segment are provided by Lindgren and others (2004) as well as Green and others (2019a,b). Surface water and groundwater in the San Antonio segment eventually discharge to rivers that flow to the Gulf of Mexico. Surface water and groundwater to the west of the San Antonio segment, including the Kinney segment, discharge to the Rio Grande which also ultimately flows into the Gulf of Mexico.

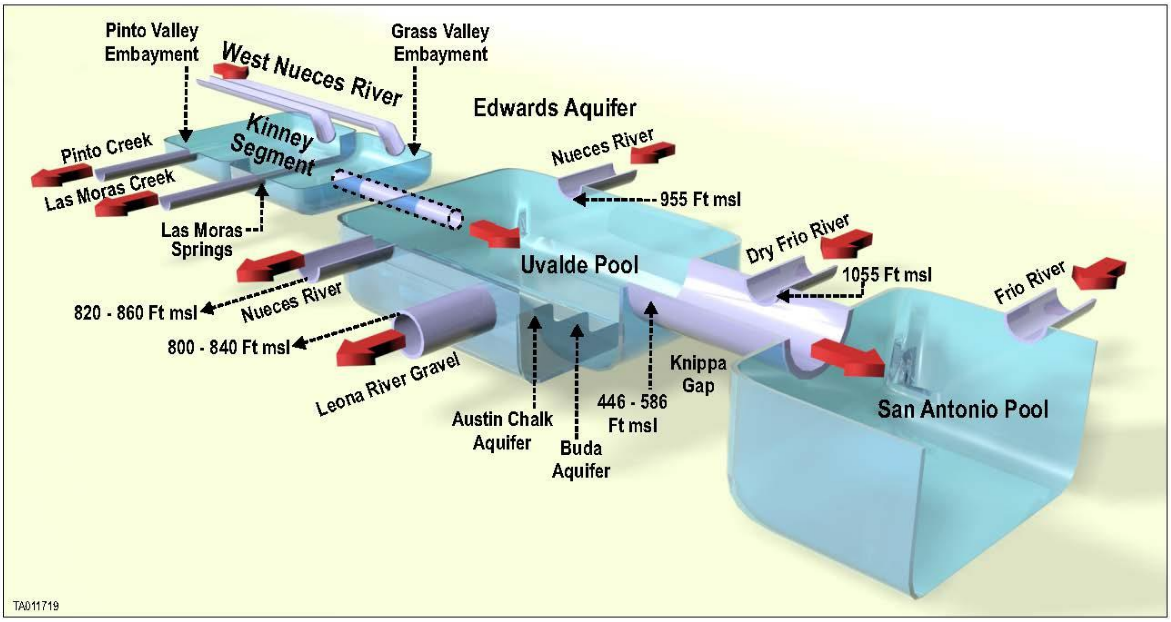


Figure 26 - Conceptual model of sources of groundwater input and loss for the San Antonio and Kinney segments of the Edwards Aquifer (Green et al., 2019a).

Domains of the San Antonio segment numerical groundwater models (Klemt et al., 1975; Maclay and Land, 1988; Lindgren et al., 2004; Lindgren, 2006; Liu et al., 2017) included the recharge and confined zones of the Edwards Aquifer whereas the model domain by Fratesi and others (2015) included the contributing zone of the Edwards Aquifer. Although models of the San Antonio segment (i.e., Klemt et al., 1979; Maclay and Land, 1988; Lindgren et al., 2004; Fratesi et al., 2015; Liu et al., 2017) and the Edwards-Trinity Aquifer (Anaya and Jones, 2004, 2009; Young et al., 2009; Hutchison et al., 2011b) covered at least part of the Edwards Aquifer in Kinney County, only the model by Hutchison and others (2011a) was developed exclusively for the Kinney County portion of the Edwards Aquifer.

Groundwater flow in the contributing and recharge zones of the San Antonio segment has been characterized as essentially north-south in the Uvalde and western San Antonio pools but shifts to northwest-southwest in the central San Antonio pool and to west-east in the eastern San Antonio pool. The Groundwater Availability Model for this segment (Lindgren et al., 2004; Liu et al., 2017) shows groundwater flow in the recharge zone is essentially downdip (Figure 27 and Figure 28), although the direction of flow varies to some degree among the fault blocks. Groundwater flow in the confined zone of the San Antonio segment is essentially parallel to the fault strikes—from west-east in the western and central portions of the San Antonio pool to southwest-northeast in the eastern portion of the segment.

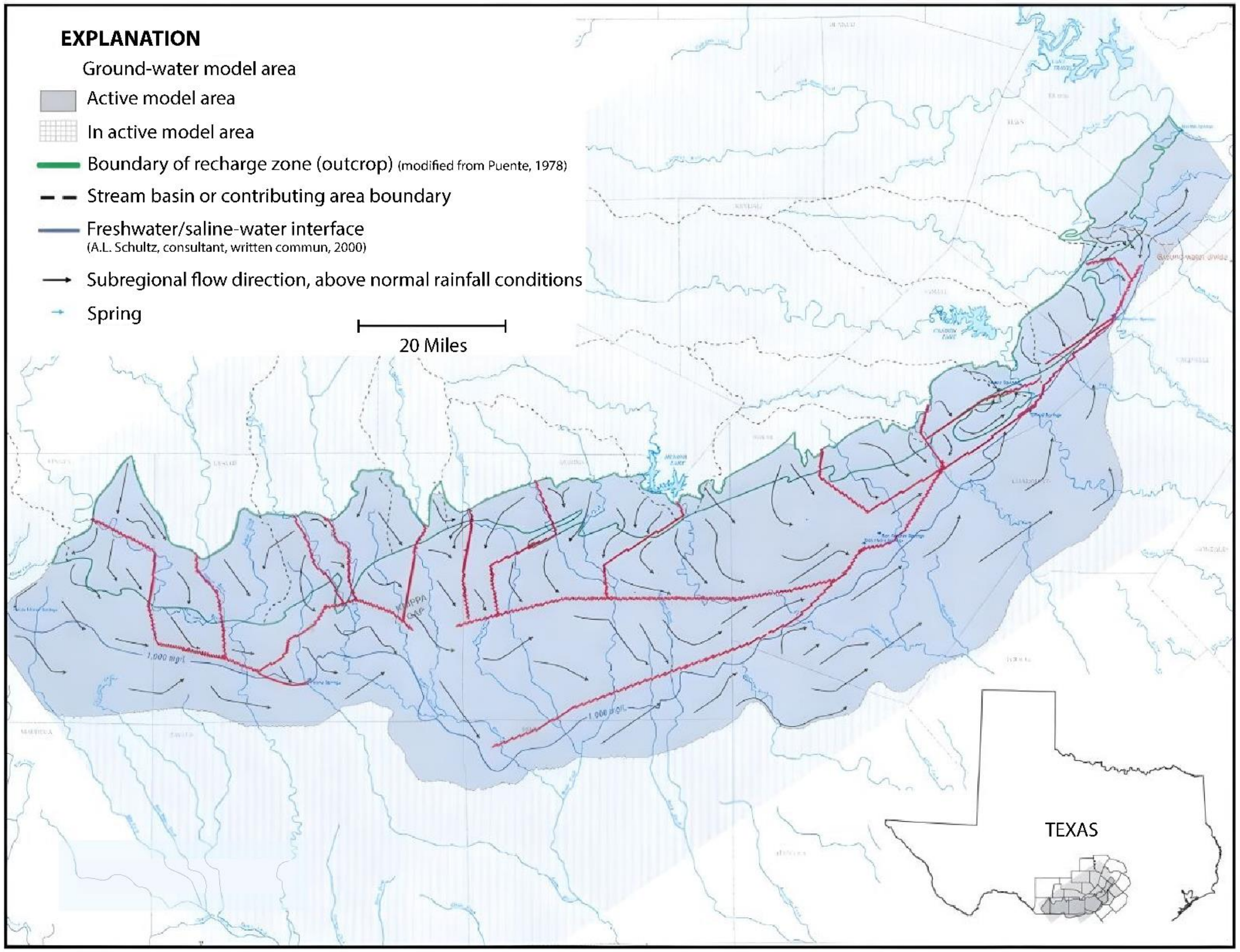


Figure 27 - Simulated flow system for the San Antonio segment for above-normal rainfall conditions (modified from Lindgren et al., 2004). Red lines are simulated karstic conduits.

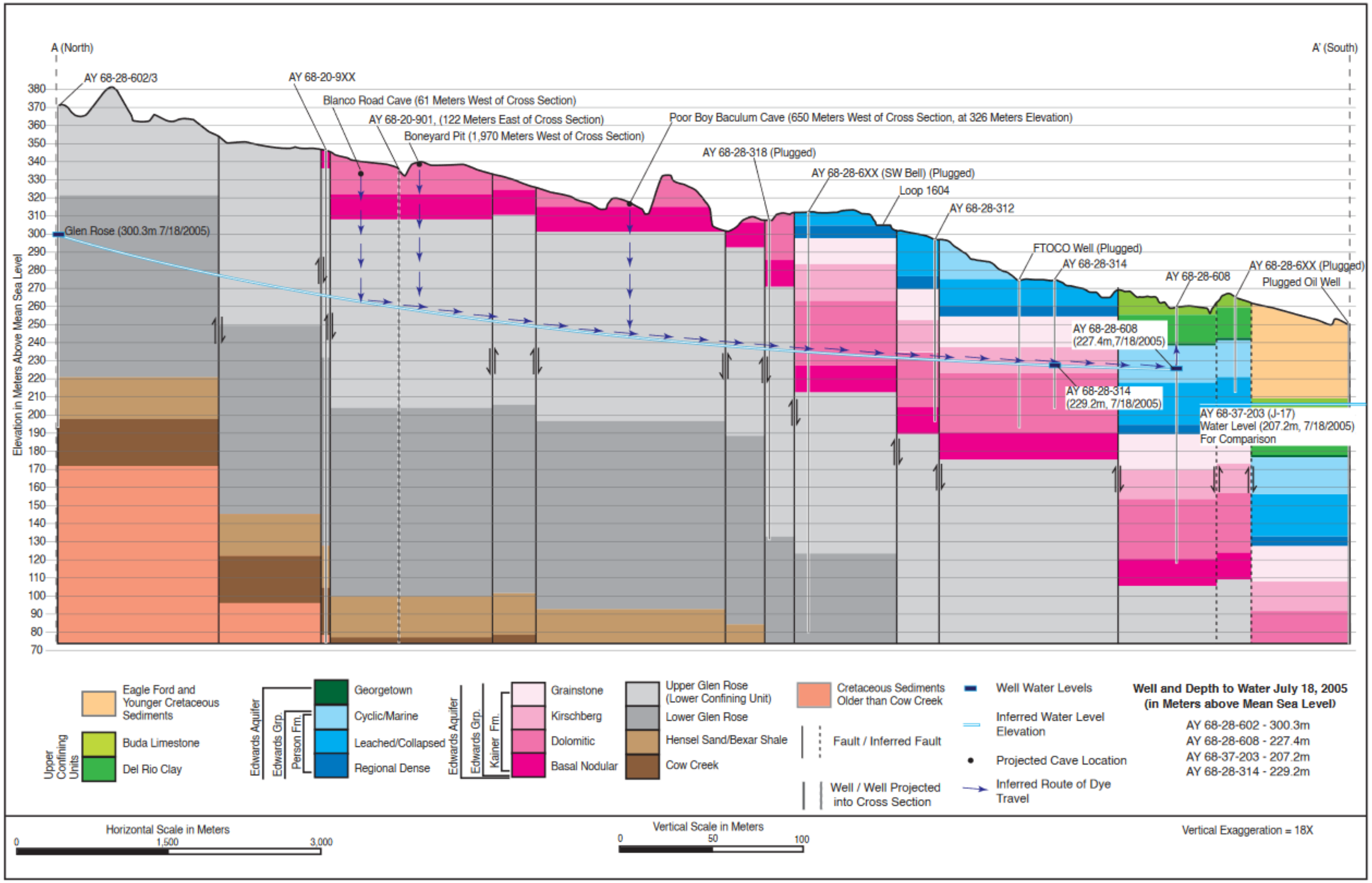


Figure 28 – A cross section through the Edwards Aquifer, Bexar County, showing that the Upper Glen Rose acts as part of the Edwards Aquifer in this area (Johnson et al., 2010). The location of this cross section is shown in Figure 12.

4.2.2 Barton Springs Segment

The Barton Springs segment extends from the groundwater divide with the San Antonio segment in Hays County to the Colorado River. Detailed descriptions are found in Scanlon and others (2001) and Hunt and others (2019). The domains of the Barton Springs segment numerical groundwater models by Scanlon and others (2001, 2003), Smith and Hunt (2004), Winterle and others (2009), and Hutchison and Hill (2011) were essentially the same. All were porous media models except Winterle and others (2009) who attempted to account for karst conduit/diffuse flow using MODFLOW-DCM (Painter et al., 2007). Groundwater flow in the Barton Springs segment has been extensively characterized using tracer testing as shown in **Figure 29** (Hauwert, 2004; Johnson et al., 2012; Hunt et al., 2019, and Zapitello et al., 2019). Flow in the contributing and recharge zones is generally west-east and, like the San Antonio segment, is essentially downdip. Similarly, flow in the confined zone is essentially from the south and west to the northeast, parallel to fault strikes, where it discharges primarily to four springs: Barton Springs Main (Figure 9); Upper Barton Springs ; Eliza Springs(video▶ and Figure 10); and Old Mill Springs. Tracing studies have delineated flow systems shown in **Figure 29**. The Cold Springs pool receives most of its recharge from the Barton Creek catchment and discharges to the Colorado River at Cold Springs. Other smaller springs discharge an undetermined small amount directly to the Colorado River. The Sunset Valley system discharges at Main and Upper Barton springs and perhaps also at Cold Springs. The Manchaca system discharges to all four of the Barton Springs. The location of the groundwater divide separating the Barton Springs segment from the San Antonio segment has been characterized as variable. It migrates between Onion Creek and the Blanco River depending on local head conditions (Smith et al., 2012).

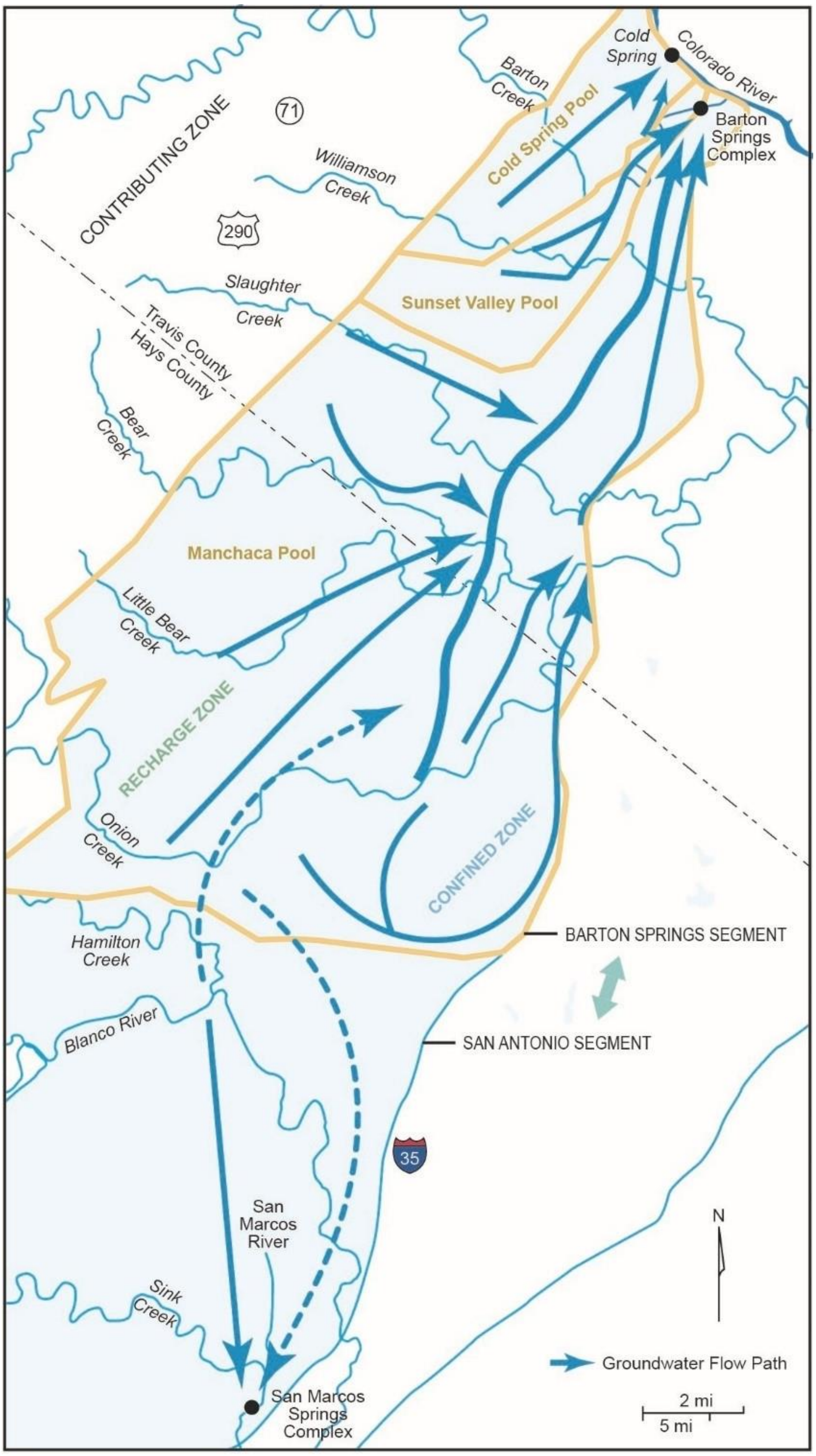


Figure 29 - Barton Springs segment pools and flow paths defined by tracer tests (Zapitello et al., 2019). The Cold Spring pool doesn't discharge directly to Barton Springs, whereas the Sunset Valley and Manchaca pools do. The boundary (groundwater divide) between the Barton Springs and San Antonio segments shifts under different aquifer conditions and in some cases disappears. The dashed flow paths represent groundwater tracing results that crossed the boundary. The divides between all the pools may also shift under different aquifer conditions (Hauwert, 2009).

4.2.3 Northern Segment

The Northern segment extends from the Colorado River in the south to Bell County in the north where the aquifer strata thin out (Figure 2 and Figure 12). The Northern segment of the Edwards Aquifer is not hydraulically contiguous with the Washita Prairies Aquifer located farther to the north (Yelderman, 2019). Jones (2003, 2019) provides more detailed descriptions of the Northern segment. Similar to the Barton Springs segment, groundwater flow in the contributing and recharge zones of the Northern segment is west-east as shown in Figure 30 (Senger et al., 1990; Jones, 2006). Once recharged, flow in the confined zone in the northern portion of the segment discharges at Salado Springs and other springs. Groundwater flow in the southern portion of the segment discharges to the Colorado River. One of the defining characteristics of the Northern segment is the fact that recharge occurs in the uplands and minor streams, while major streams are often sites of spring discharge (Kreitler et al., 1987; Smith et al., 2005a).

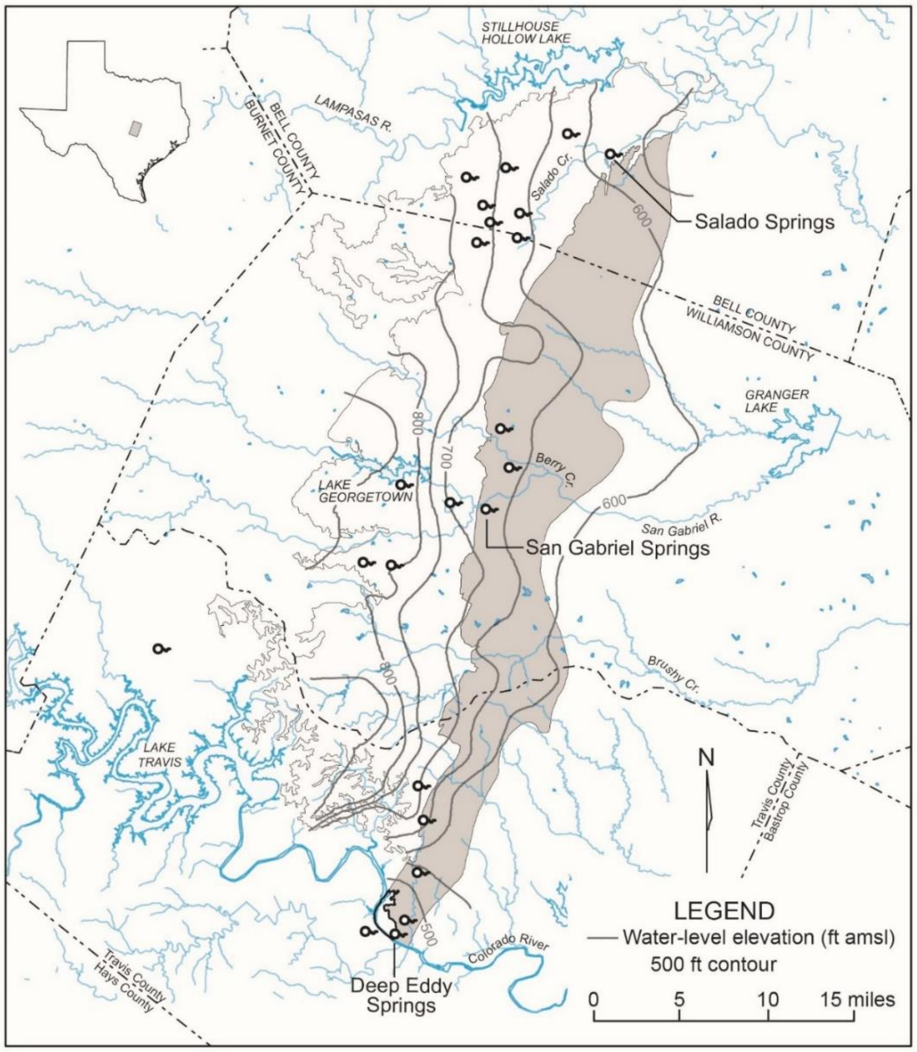


Figure 30 - Steady-state water-level elevations for the Northern segment flow system showing major springs (modified from Jones, 2003). The shaded area is the confined zone (modified from Jones, 2003). 1 mile = 1.6 kilometers.

4.2.4 Kinney Segment

The Kinney segment extends from a groundwater divide located between Mud Creek and Pinto Creek on the west to an effective structural, hydraulic barrier near the Kinney County and Uvalde County line (Figure 2 and Figure 12). The barrier is a result of natural dewatering of the permeable portion of the Edwards Aquifer (i.e., Salmon Peak) in eastern Kinney County due to structural uplift. Consistent with the geologic structure and supported by tracer testing (Johnson and Schindel, 2015), groundwater flow within the segment is northeast-southwest as shown in Figure 31. Differences in magnesium concentrations (Figure 32) and other constituents (e.g., sulfate) in groundwaters in Kinney and Uvalde counties support the interpretation that groundwater in the Kinney segment is distinct from the Uvalde pool. Based mostly on water chemistry and geologic structure, it is expected that during periods of low to average groundwater elevation groundwater in the Edwards Aquifer will not flow from Kinney County to Uvalde County, but limited flow from west to east may be possible when groundwater elevations are high. Natural discharge from the Kinney segment occurs as spring discharge and underflow through the floodplains of Pinto and Las Moras creeks at the southern (downdip) boundary of the segment.

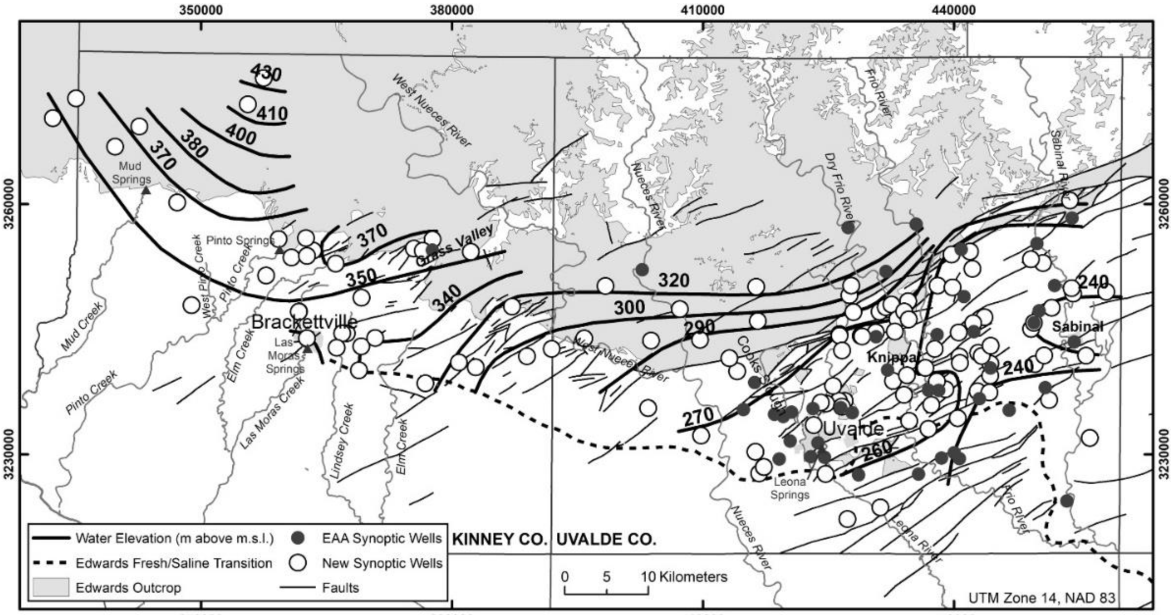


Figure 31 - Potentiometric surface of the western Edwards Aquifer in January/February 2006 (Green et al., 2019d). Coordinates are in Universal Transverse Mercator (UTM) Zone 14, North American Datum 1983 (NAD 83); msl is mean sea level; EAA denotes Edwards Aquifer Authority.

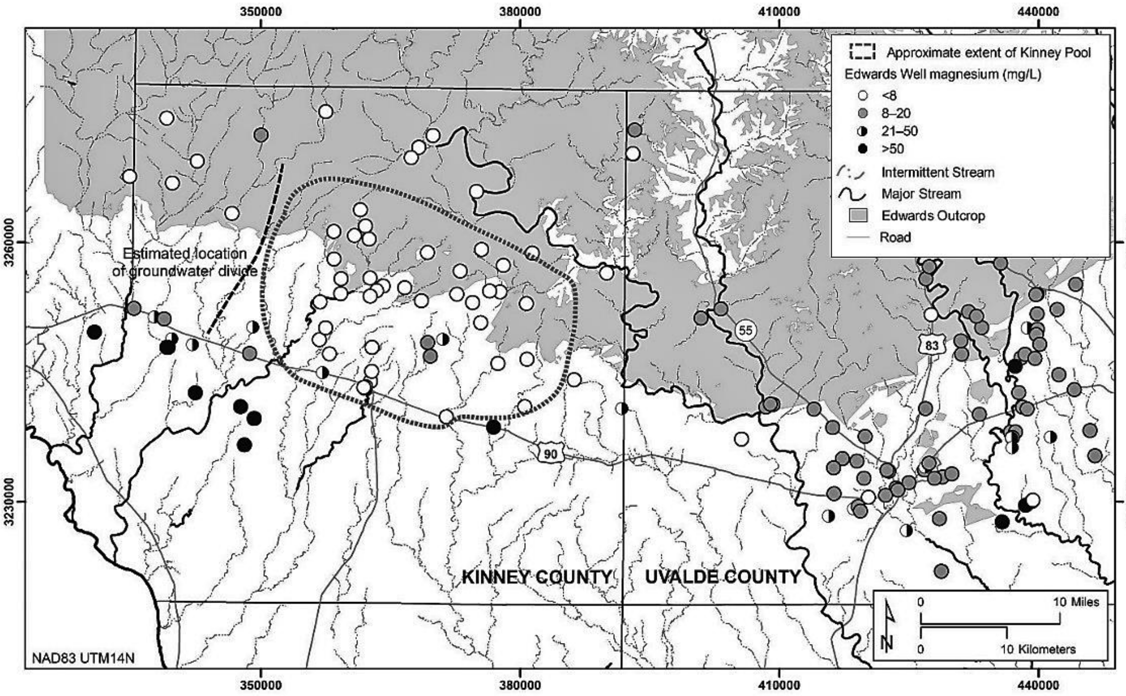


Figure 32 - Map showing the approximate location of the Kinney Pool and measured concentrations of magnesium in Edwards Aquifer wells in mg/L (Green et al., 2019d). Coordinates are in Universal Transverse Mercator (UTM) Zone 14, North American Datum 1983 (NAD 83).

4.3 Associated Edwards Aquifers

There are additional aquifers with similar genesis and lithology to the Edwards (Balcones Fault Zone) Aquifer. Due to a multitude of commonalities, these aquifers are treated in a manner similar to the Edwards Aquifer because society relies on these resources and these aquifers face the same threats. The associated aquifers include the Edwards-Trinity (Plateau) and the Washita Prairies aquifers (Figure 2 and Table 1). The following subsections provide brief descriptions of these aquifers.

4.3.1 Edwards-Trinity (Plateau) Aquifer

The Edwards-Trinity (Plateau) Aquifer is a karstic carbonate aquifer that extends across the uplifted Edwards Plateau in west-central Texas. The plateau west of the Pecos River is referred to as the Stockton Plateau. Key studies of the Edwards-Trinity Aquifer have been conducted by the U.S. Geologic Survey (Kuniansky, 1989; Kuniansky and Holligan,1994; Barker et al., 1994; Barker and Ardis, 1996), the Texas Water Development Board (Walker, 1979; Rees and Buckner, 1980; Mace et al., 2000; Jones and Anaya, 2009, 2019; Mace and Angle, 2004; Jones et al., 2011; Hutchison et al., 2011), and Green and Bertetti (2010). The combined groundwater flow system of the Edwards-Trinity (Plateau) Aquifer and the Hill Country portion of the Trinity Aquifer covers about 100,000 km^2 (39,000 square miles). The aquifers are the primary source of water for the Edwards Plateau and the Texas Hill Country and sustain numerous springs and streams in the region. The sensitivity of the aquifers to drought and well discharge has raised concerns over the availability of water from these aquifers.

Studies of the Edwards-Trinity (Plateau) Aquifer and Hill Country portion of the Trinity aquifers indicate that groundwater discharge takes the form of:

- flow to streams and springs;
- evapotranspiration;
- pumpage from wells; and,
- cross-formational flow through the Balcones Fault Zone boundary to the Edwards (Balcones Fault Zone) Aquifer and underlying parts of the Trinity Aquifer.

Recharge to these aquifers occurs by diffuse and discrete infiltration through the aquifer outcrops.

4.3.2 Washita Prairies

The Washita Prairies Aquifer (Figure 2) is a shallow, unconfined aquifer that provides water to small perennial springs, rural households, and livestock (Cannata, 1988; Collins, 1989; Myearick, 1989; Bernhardt, 1991; Legg, 1995; Clark, 2000b; and Yelderman, 1987, 2019). This aquifer is relatively thin (< 50 m). The Georgetown and Edwards formations form the aquifer similar to the Northern segment of the Edwards Aquifer. Permeability is less than other Edwards aquifers discussed above. Because the aquifer is west of the Balcones Fault Zone, there is less fracturing and less karstification. Weathering created higher effective porosity and permeability in the uppermost aquifer strata. Fracture permeability controls the flow system. The water-table elevation mimics surface topography and responds rapidly to precipitation. Most discharge occurs in local second-order streams.

5 Aquifer Ecology and Endangered Species

One of the unique characteristics of the Edwards Aquifer is the great variety of organisms that live in the aquifer (called *stygofauna*) or are directly dependent upon flows from its springs. With 91 described stygobite species and at least another 14 awaiting taxonomic description, the subterranean aquatic fauna of Texas is globally renowned (Longley, 1981; Culver and Sket, 2000). The Edwards Aquifer species diversity ranks among the highest recorded for any aquifer worldwide. The Edwards (Balcones Fault Zone) Aquifer contains significant diversity, including at least 65 described species (Krejca and Reddell, 2019, Table 1 therein), 34 described species at the artesian well in San Marcos, and 14 described species at nearby Ezell's Cave. The Edwards-Trinity Plateau Aquifer has the second greatest diversity in Texas aquifers.

Aquifer development created the opportunity for a splendid variety of aquatic fauna to invade the subsurface. The carbonates were deposited in a shallow sea. Marine invertebrates of those seas were the first precursors to stygobite fauna. With uplift and erosion, some of these marine species stayed with the land. Some adapted to living in caves and to life in freshwater. Marine invertebrates [e.g., isopods (*Cirolanidae*), amphipods (*Hadziidae*, *Ingolfiellidae*, and *Sebidae*), shrimp-like species (*Bogidiellidea*), worm-like crustaceans (*Bathynellacea*), and crustaceans found in thermal springs (*Thermosbanacea*)] were some of the earliest stygobites in Texas (Krejca and Reddell, 2019). During and after uplift and karstification, freshwater invertebrates, including crangonyctid amphipods, asellid isopods, palaemonid shrimp, copepods, ostracods, snails, fish, flatworms, arachnids, and insects including elmid and dytiscid beetles, were introduced.

In addition to this variety of species available for cave adaptation, the history of uplifts, faulting, karstification, stream incision, and springs formed many ecological niches within the aquifer as well as barriers to communication. For instance, stream incision by the Colorado River divides the Barton Springs and the Northern segments. In the recharge zone of the San Antonio segment, the evolutionary development of cave spiders is a function of when fault blocks became available as vadose zone habitats (White et al., 2009). These barriers isolate subterranean populations and create the opportunity for speciation and endemism (Krejca, 2005).

The aquifer's remarkable biological diversity also includes two groups of highly *troglomorphic* (cave-adapted) vertebrates, *Eurycea* salamanders (13 species, including some spring and some cave forms) and Ictalurid catfish (three species). Given this diversity, it is surprising how little is known about the biology of the species. The invertebrates, in particular, span the range of taxa, including snails, flatworms, ostracods, copepods, amphipods, isopods, shrimp, mites, beetles, and even an unstudied and perhaps the world's only aquifer-adapted leech (*Mooreobdella species*). Many of these groups lack taxonomic experts to describe new species or assign names to the existing collections

(Krejca and Reddell, 2019). There is concern that spring ecosystems might fail before taxonomists can describe the species present (Gary et al., 2019; Smith et al., 2020), with the looming issues of water quality and quantity essential to the continued survival of these ecosystems. The known endangered species of the aquifer (discussed in Section 5.1) create challenges to the future development and management of the aquifer. Payne and others (2019) discuss the efforts to maintain habitat for endangered species in Comal and San Marcos springs. In addition, the microbial ecosystems of the aquifer have only recently started to receive attention. Some of them are unique, such as those along the aquifer's brackish-water line, which is discussed in Section 5.2.

5.1 Endangered Species

Krejca and Reddell (2019, Table 2 therein) list 66 threatened, endangered, and petitioned spring and cave species in the state of Texas, which are either state-listed, federally-listed, or have been petitioned for listing as endangered. Table 4 lists the nine federally-listed endangered species that live in the Edwards Aquifer or its major springs. Of these, the Peck's Cave amphipod, the Comal Springs dryopid beetle, and the Texas and Austin blind salamanders are stygobites that are living in the aquifer. The others live primarily in spring discharge systems. The EAA (2020) is also considering three additional species that have been petitioned for endangered species status in its habitat conservation plan, the Edwards Aquifer diving beetle, the Comal Springs salamander, and the Texas troglobitic water slater. The EAA↗ has established two refugia for the breeding and maintenance of endangered species should re-introduction to the spring systems be necessary.

Table 4 – Federally-listed endangered species in the Edwards Aquifer.

Common name	**Species name**	**Group**
Texas wild rice	*Zinzania texana*	plant
Peck's Cave amphipod	*Stygobromus pecki*	invertebrate
Comal Springs riffle beetle	*Hetereimus comalensis*	invertebrate
Comal Springs dryopid beetle	*Stygoparnus comalensis*	invertebrate
Fountain darter	*Etheostoma fonticola*	fish
San Marcos gambusia	*Gambusia georgei*	fish
Texas blind salamander	*Eurycea rathbuni*	amphibian
Barton Springs salamander	*Eurycea sosorum*	amphibian
Austin blind salamander	*Eurycea waterlooensis*	amphibian

Two other fishes are listed as threatened by the State of Texas, the toothless blindcat fish (*Trogloglanis patersoni*) and the wide-mouthed blindcat (*Satan eurystomas*). The latter has not been observed since 1978 (Krejca and Reddell, 2019; Hendrickson, 2019). It may be extinct, but the wells in the limited area south of downtown San Antonio, where the fish was known to occur, are now part of the San Antonio city water system and are no longer accessible for sampling. Another fish species, the San Marcos gambusia, was last collected in 1983 and is now listed as extinct (EAA, 2020). The endangered species listing will continue to evolve. Figure 33 shows some of the endangered species.

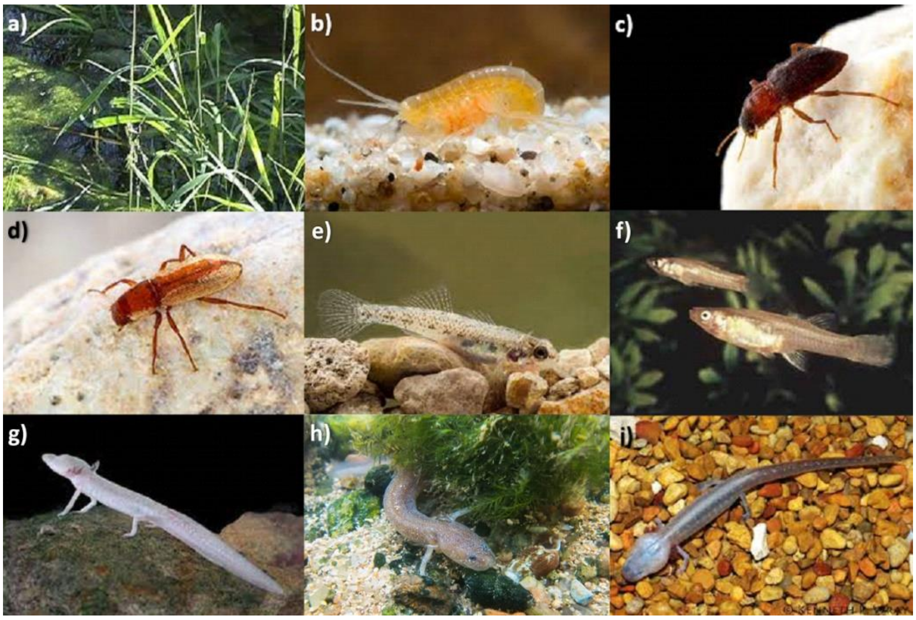


Figure 33 - Endangered species of the Edwards Aquifer (figure provided by Juliana Apolonio): a) Texas wild rice; b) Peck's Cave amphipod; c) Comal Springs riffle beetle; d) Comal Springs dryopid beetle; e) Fountain darter; f) the now extinct San Marcos gambusia; g) Texas blind salamander; h) Barton Springs salamander (photo provided by Nathan Bendik); and, i) Austin blind salamander.

5.2 Bad-water Line

The Edwards Aquifer freshwater system interfaces with down-dip anoxic, sulfide-rich brackish (TDS > 10^3 mg/L) to saline (> 10^4 mg/L) "bad water." The interface between these two waters has sulfur-reducing bacteria that form the base of a chemolithoautotrophic ecosystem at great depths (100 to 600 m) in which organisms can obtain the necessary carbon for metabolic processes from carbon dioxide in the environment (Engel, 2007). This autochthonous system (energy derived from within) is unlike normal cave systems and supports a greater species richness than adjacent sites, which are allocthonous (where nutrients enter the aquifer from the surface). It is inferred that small-scale dissolution is enhanced along the bad-water interface. To date, these findings are restricted to the San Antonio area, but the nutrients generated along the brackish-water line may support ecosystems over a broader range of the aquifer.

The Edwards Aquifer ecosystem is complex and highly varied. Understanding of the system has evolved with the examination of microbial processes (e.g., along the brackish-water line) and DNA analyses of aquatic organisms (e.g., Devitt, 2019). It should be expected that new organisms that are dependent on the aquifer will be discovered. Loss of spring flows during droughts is a major threat to the ecosystem. This threat led to new water laws and management policies. Lowering water tables and increased water pollution are threats to species that have limited habitat ranges.

6 Legal and Administrative Systems

Hardberger (2019) summarizes the development of Texas water law as it pertains to groundwater in general, and to the Edwards Aquifer in particular. In Texas, groundwater and surface water are managed by separate doctrines. Surface water is state-owned and governed by the doctrine of prior appropriation (i.e., water rights are determined by priority of beneficial use). Groundwater law has been evolving and is based on a series of court cases and legislative actions. In Texas, like soil, groundwater is the property of the surface landowner. The 1904 East case confirmed the absolute ownership of water or the "rule of capture" for beneficial use, limited only by the exception that malicious use and, later, subsidence of adjoining properties, were not permitted. The Texas Supreme Court has indicated that rule-of-capture might not be an appropriate doctrine but left the doctrine in place. Since the 1990s, there have been three major changes:

- Groundwater Conservation Districts (GCDs) were designated as the preferred method for groundwater management, emphasizing that local control and protection of endangered species in the Edwards Aquifer springs necessitated pumping restrictions. GCDs are required to develop and implement effective management plans for the groundwater resources in their designated areas. In addition, the state established Groundwater Management Areas (GMAs) (Texas Water Development Board↗) to provide for conservation, protection, recharging, preventing waste of groundwater and "groundwater reservoirs" (i.e., aquifers) as well as controlling subsidence caused by groundwater withdrawal. Many GCDs are defined by county boundaries. GMAs incorporate a number of adjoining GCDs.
- Recent court decisions ruled that landowners have a vested property right in the groundwater below their land prior to its capture (the Day case) and that restricting pumping of groundwater was a "taking" that required compensation of the land owner (the Bragg case). Legal constraints will be an important factor in determining the future development of the Edwards Aquifer and associated water resources.
- Habitat conservation plans↗ have been developed to protect ecosystems at Comal, San Marcos, and Barton springs (BSEACD, 2018). Payne and others (2019) summarize the Habitat Conservation Plan developed for the San Antonio Segment in this video▶.

6.1 Numerical Models for Developing Management Strategies

The State of Texas and other government entities have developed groundwater models for the major Texas aquifers↗ that have provided new insights into the groundwater resources on which much of the state relies. Several regional-scale groundwater flow models cover parts of the Edwards Aquifer (Green et al., 2019d). Post-2000 models were mostly developed as part of the Texas Water Development Board's Groundwater Availability Model (GAM) program (Mace et al., 2008). These models target portions of the Edwards Aquifer: Northern segment (Jones, 2003), Barton Springs segment (Scanlon et al., 2001, 2003; Smith and Hunt, 2004; Winterle et al., 2009; Hutchison and Hill, 2011), and the Edwards (Balcones Fault Zone Aquifer) San Antonio segment (Klemt et al., 1979; Maclay and Land, 1988; Lindgren et al., 2004; Lindgren, 2006; Fratesi et al., 2015; Liu et al., 2017). The GAMs are implemented within Texas' unique system of Groundwater Conservation Districts (GCDs) and Groundwater Management Areas (GMAs) to assist in establishing desired future conditions and management strategies to ensure adequate water resources for the future of the state (Mace et al., 2008).

In addition, there are GMAs for the Edwards-Trinity Aquifer (Anaya and Jones, 2004, 2009; Young et al., 2009; Hutchison et al., 2011b) and the Hill Country Trinity Aquifer (Mace et al., 2000; Jones et al., 2009), although the focus of these models included the Trinity Aquifer. There was also a U.S. Geological Survey Regional System Aquifer Analysis model that targeted the Edwards Plateau, but also covered the western portions of the Edwards Aquifer (Kuniansky and Holligan, 1994; Kuniansky, 1995).

The Edwards Aquifer is also managed by two GMAs↗ and is near another. GMA 10 covers the Edwards Aquifer from the previously designated groundwater divide at Las Moras Springs in Kinney County to the Colorado River. GMA 10 includes nine overlapping GCDs all of which overlie the Edwards Aquifer. GMA 8 includes a much broader area including the counties north of the Colorado River where the Edwards Aquifer is present as well as also large areas to the north and west of the aquifer. GMA 8 includes 24 GCDs, only one of which covers the Edwards Aquifer (i.e., the Clearwater GCD in Bell County). GMA 9 does not include the Edwards Aquifer but manages the Trinity Aquifer which is juxtaposed with the Edwards Aquifer by faulting. As a result, the Trinity Aquifer provides cross-formational flow and baseflow that subsequently recharge the Edwards Aquifer.

Two agencies are specifically responsible for managing the Edwards Aquifer: the Edwards Aquifer Authority, which was established under a different law and is not a GCD, and the Barton Springs Edwards Aquifer Conservation District (BSEACD).

6.2 Edwards Aquifer Authority

The EAA↗ succeeded the Edwards Underground Water District (EUWD), which was formed after the 1951-1956 drought of record (Illgner and Schindel, 2019). The EAA was established in 1996 after lawsuits for protecting endangered species in Comal and San Marcos springs revealed the need for aquifer management. Several events set the stage for water management in Texas and the creation of the EAA, but the EAA was eventually granted regulatory responsibilities including issuing permits for wells, setting limits on groundwater pumpage, and developing a habitat conservation plan (Payne et al., 2019) to protect endangered species.

The period of 1951 to 1956 is recognized officially as the drought of record (DOR) for central Texas. For the San Antonio segment, the mean annual recharge from 1934 to 2015 was estimated at over 700,000 acre-feet (860 GL), but annual recharge for the DOR was only slightly more than 163,000 acre-feet (200 GL). Spring flows declined during the DOR. Comal Springs, which had an average discharge of 286 cubic feet per second (cfs) which is approximately 8,100 liters per second (lps), did not flow for 144 days during the summer of 1956 (EAA, 2012). The combination of no spring flow and rapidly increasing groundwater pumping led to a study to create a GCD for the San Antonio segment of the aquifer. However, the City of San Antonio insisted that rule-making authority be removed from the enabling legislation and the EUWD became the fourth GCD in Texas (there are currently over 100 GCDs), but the first without regulatory authority. This prevented the EUWD from regulating pumping from the aquifer or protecting flow at Comal and San Marcos springs. Nonetheless, the EUWD established a comprehensive groundwater data collection program, conducted research on aquifer hydrogeology, and developed a conservation plan, which included a leak-detection program.

With the passage of the Endangered Species Act (ESA) in 1973, species in both Comal and San Marcos springs have been listed as endangered. A 1991 lawsuit filed by the Sierra Club asserted that the U.S. Fish and Wildlife Service (FWS) was negligent in providing sufficient safeguards for the endangered aquatic species in Comal and San Marcos springs. In November 1992, the judge ruled in favor of the Sierra Club in response to which the Texas legislature created the EAA.

The EAA Act abolished the EUWD, addressed the EUWD regulatory deficiencies, and added other regulatory powers to the newly formed EAA. Its boundaries were also revised to reflect areas that receive water from the aquifer, not just land directly overlying the aquifer. The EAA covers all or parts of eight counties (map available↗) including Uvalde, Medina, Atascosa, Bexar, Comal, Guadalupe, Hays, and Caldwell counties.

Directives in the enabling legislation included:

- setting the maximum amount of pumping permits to be issued;
- setting guaranteed minimums for each permit category (municipal, industrial, and agricultural);
- only applicants with historical use during a defined historical period qualified for a permit;
- a filling deadline for permit claims was set;
- all permitted wells were required to have flow meters;
- the EAA has a lifetime responsibility for meter costs for irrigation wells;
- the EAA must have a drought plan; and,
- the EAA must have a conservation plan.

Governance of the EUWD and the EAA were markedly different. The EUWD had been governed by a 12-member elected board. The EAA's proposed governance was a nine-person appointed board. This delayed startup as the Department of Justice did not accept replacing an elected board with an appointed board in Texas. Consequently, the Legislature followed up in 1995 with an amendment by adding a 15-member elected board from single-member districts.

To protect the endangered species, maintain spring habitats, and optimize use of the aquifer, the EAA has instituted several policies. One is establishing critical drought period triggers (based on 10-day averages) with mandated reductions in water withdrawals (Table 5) to sustain spring flows in periods of drought.

Table 5 – Triggers for critical period stages (based on 10-day averages) and withdrawal (pumping) reductions for the San Antonio segment (EAA, 2021). Index well water elevations are in feet above mean sea level (amsl) and spring flows are in cubic feet per second. 100 cfs ≈ 2.83 m^3/s. Stage 5 for Comal Springs has two triggers a 10-day and a 3-day rolling average of 45 and 40 cfs, respectively.

Trigger	Stage I	Stage II	Stage III	Stage IV	Stage V
San Antonio Pool					
Index well J-17 (msl)	< 660	< 650	< 640	< 630	< 625
San Marcos Springs flow (cfs)	< 96	< 80	-	-	-
Comal Springs flow (cfs)	< 225	< 200	< 150	<100	< 45/40
Withdrawal reduction	20%	30%	35%	40%	44%
Uvalde Pool					
Index well J-27 (msl)	-	< 850	< 845	< 842	< 840
Withdrawal reduction	-	5%	20%	35%	44%

In addition, the EAA and various municipal authorities (e.g., the San Antonio Water System) have sought additional water supplies from other aquifers, river systems and desalination; created an aquifer storage and recovery system (EAA, 2019c); and, instituted a regional water conservation program to encourage municipal water conservation and a Voluntary Irrigation Suspension Program (VISPO). VISPO authorizes financial compensation to eligible holders of irrigation rights to suspend pumping when water levels fall to a critical level defined as 193.55 m (635 feet) amsl at index well J-17 (Payne et al., 2019).

6.3 Other GCDs

Other active GCDs managing the Edwards Aquifer are the Barton Springs Edwards Aquifer Conservation District (BSEACD), the Clearwater Underground Water Conservation District (CUWCD), and the Kinney County Groundwater Conservation District (KCGCD). Other overlapping GCDs manage the overlying (Carrizo-Wilcox and alluvial) and underlying (Trinity) aquifer systems (map available↗).

The BSEACD↗ was established in 1987 to serve the municipalities in portions of Hays, Travis, Caldwell, and Bastrop counties that depend on the aquifer. It is also responsible for portions of the underlying Trinity Aquifer. The BSEACD has established a set of drought status stages for curtailing pumping (Table 6). These restrictions are intended to preserve the endangered species that appear in all four of the springs and are based on an index well close to the springs. The well stages are correlated to spring discharge (e.g., a well water level of 141.0 m (462.7 feet) above mean sea level corresponds to spring discharge of 0.566 m^3/s (20 ft^3/s). An additional index well (the Lovelady well) is situated in the transition zone between the fresh and brackish Edwards Aquifer about 6 km (3.8 miles) south of Barton Springs. Water levels in the Lovelady well are more stable than spring discharge as local rainfall can cause short-term fluctuations in spring discharge.

Table 6 – Drought status stages and pumping reductions for the Barton Springs segment (BSEACD, 2021a, b). Index well water elevations are in feet above mean sea level (msl) and spring flows are in cubic feet per second (cfs). 100 cfs = 2.83 m^3/sec.

Drought status stage	Lovelady index well (msl)	Barton Springs flow (cfs)	Pumping reductions A, B, C&D wells
No drought	> 478.4	> 38	*
Stage II Critical	462.7 - 478.4	20 - 38	20, 50, 100%
Stage III Critical	457.1 - 462.7	14 - 20	30, 75, 100%
Stage IV Critical	453.4 - 457.1	10 - 14	50, 100, 100%
Emergency response	< 453.4	< 10	> 50, 100, 100%

*Voluntary conservation is encouraged from May through September even under no drought status. Pumping reductions do not apply to small domestic and livestock water wells. Most other (mostly municipal and industrial) wells are type A. Well classes are defined in BSEACD (2021b).

The CUWCD↗ was established in 1989 and is responsible for groundwater management in Bell County. Its mission is to develop and implement effective groundwater management to protect the water resources in the county. The KCGCD's↗ goal is to balance conservation and preservation, as well as efficient and beneficial use of groundwater, along with protection of the private property rights of landowners for the benefit of present and future citizens of the county.

7 Conclusion

The Edwards Aquifer ranks as one of the great karst aquifers of the world supporting over 2 million people and agricultural, municipal, industrial, and recreational uses in a region of rapid population growth. It hosts unique groundwater, cave, and spring ecosystems. The aquifer has its own unique legal and management systems. The aquifer has been used sustainably but faces challenges.

7.1 Sustainability

The Edwards Aquifer water quality has remained suitable even with increased pumpage and the effects of urbanization, agriculture, and industry. This is because most of the agricultural irrigation is over the confined zone, which supports better soils, and because intense recharge events dilute and disperse local contamination sources and events. In terms of water quantity, the aquifer has remained stable since 1934, based on data from the San Antonio segment (Figure 34). These data show there are times of low recharge and low spring flows, but periods of high recharge essentially refill the aquifer. Estimates of total recharge from 1934 to 2019 approximately equal the estimated total discharge. Pumpage has remained relatively stable since the 1960s despite population growth because of conservation, use of other water resources, and drought-triggered withdrawal reductions specified by the EAA and the BSEACD (Table 5 and Table 6). This demonstrates that management policies now being implemented have achieved a good deal of success.

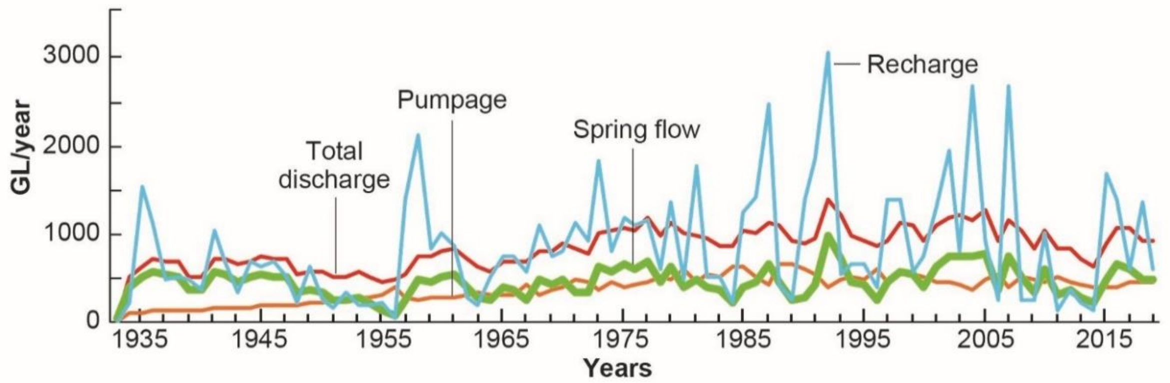


Figure 34 - Recharge and discharge by wells and springs for the San Antonio and Kinney segments, 1934 to 2019 (Edwards Aquifer Authority 2019a,b). Red is total discharge, orange is pumpage, green is spring flow, blue is total recharge.

The Edwards Aquifer is sustainable in the long term, but pumping will have to be reduced during periods of low recharge and spring flow, and severe consequences could develop for water-supply wells and endangered species during extended periods of extreme drought. Different areas are addressing sustainability with different approaches and differing degrees of success. The BSEACD, for example, is advocating sustainable management of the Barton Springs segment of the Edwards Aquifer. However, the paradox of the karstic Barton Springs segment is that rapid recharge allows this segment of the aquifer to be sustainable in the long-term, but the aquifer is vulnerable and has limited groundwater availability during drought periods (Hunt et al., 2019).

7.2 Challenges

Challenges to future development and sustainable use of this aquifer include the following (Sharp et al., 2019a).

- Increased demand for water: The area overlying the aquifer from San Antonio to Austin to Waco is one of the fastest-growing metropolitan areas in the USA (Mace, 2019). The population of this area is predicted to nearly double by 2050 (Potter and Hoque, 2014).
- Effects of urbanization on groundwater systems (Sharp, 2019; Beal et al., 2020): Most of the growth is expected to be urban and suburban, expanding over the recharge and contributing zones. This creates the potential for contamination and changing rates and locations of recharge.
- Effects of projected climate change (Loáiciga and Schofield, 2019): Projections are for higher temperatures and greater variations in precipitation and, therefore, variation of recharge. Groundwater extraction will have to be adapted to these fluctuations and trends.
- New, emerging types of contaminants (Mahler and Musgrove, 2019): Numerous chemicals are used in our urban society and the Edwards Aquifer, like most karst aquifers, is highly vulnerable to contamination. This raises questions about its use both as a water resource and for the well-being of aquifer/spring-dependent species.
- Accommodating surface-water/groundwater interactions and conduit/matrix flow dynamics in numerical models (Scanlon et al., 2003; Hartmann et al., 2014): Studies of the Edwards Aquifer revealed spatial and temporal variations in aquifer properties and processes. These have long been issues for groundwater models that are important for quantitative understanding the aquifer system.
- Managing aquifers in the context of evolving Texas water law and administrative policies (Hardberger, 2019; Payne et al., 2019): Management practices need to evolve not only as laws and policies evolve but also as our understanding of the aquifer’s endangered species, conduit flow systems, and basic hydrogeology evolves. For instance, intra- and inter-aquifer connections and delineation of recharge areas continue to be topics of research.

The regional water planning groups have identified and recommended several water management strategies (George et al., 2011). These include drilling new wells to meet increased water demand, constructing small dams along streambeds to enhance aquifer recharge, and reallocating supplies from irrigation to municipal users. They have also recommended expanding existing aquifer storage and recovery (ASR) facilities, such as the one that stores water from the Edwards Aquifer in the Carrizo-Wilcox Aquifer in southern Bexar County.

Finally, the adaptation of new technologies will be needed for future characterization, development, and management of the aquifer. These include:

- new ASR projects (Smith et al., 2017; Deeds and Blumberg, 2019) in the underlying Trinity Aquifer and the brackish/saline Edwards Aquifer;
- desalination of brackish water including from the bad-water zone (Mancha and Walker, 2019);
- surface geophysics to characterize the system (Saribudak, 2019);
- tracer testing for define flow paths more accurately (Johnson et al., 2019);
- multiport wells to understand vertical variations in hydraulic properties (Smith and Hunt, 2019); and,
- the use of DNA in characterization of aquifer ecology (Devitt, 2019).

Continued hydrogeologic study, including detailed aquifer vulnerability mapping and flow path delineation, is needed to improve understanding of the Edwards Aquifer and how it can meet the demands of society. Water laws and management policies must be able to adapt to meet these challenges in light of growing knowledge of the Edwards Aquifer and growing demand for water.

8 Exercises

Exercise 1

How might climate changes affect water availability for the projected population growth in areas using the Edwards Aquifer? What policies or infrastructure might ameliorate any anticipated negative effects of climate change?

Click for solution to Exercise 1↴

Exercise 2

How will increasing urbanization likely affect the Edwards Aquifer? What policies or infrastructure might ameliorate any anticipated negative effects of urbanization?

Click for solution to Exercise 2↴

Exercise 3

What are the major unanswered hydrogeological questions about the Edwards Aquifer?

Click for solution to Exercise 3↴

Exercise 4

Briefly describe Texas water law. Is the Edwards Aquifer adequate to support future water needs? Why or why not?

Click for solution to Exercise 4↴

Exercise 5

How well do the numerical models represent the triple porosity/permeability Edwards Aquifer? Under what conditions or for what purposes are current models useful?

Click for solution to Exercise 5↴

Exercise 6

What is the history or evolution of porosity/permeability development in the Edwards Aquifer?

Click for solution to Exercise 6↴

Exercise 7

How can the spatial distribution of stygobites species, especially those that are entirely within the aquifer (e.g., *Trogloglanis patersoni* and *Satan eurystomas*) be determined?

Click for solution to Exercise 7↴

Exercise 8

What controls the location of groundwater divides in the Edwards Aquifer?

Click for solution to Exercise 8⤵

Exercise 9

How is a karst aquifer fundamentally different from a clastic aquifer (i.e., the High Plains Aquifer)? How is a karst aquifer fundamentally different from a crystalline rock aquifer (i.e., a fractured igneous or metamorphic rock aquifer)?

Click for solution to Exercise 9⤵

Exercise 10

How do we simulate flow in a karstic conduit? What are some of the key variables required for simulating groundwater flow in karst?

Click for solution to Exercise 10⤵

9 References

Abbott, P.L., 1975, On the hydrology of the Edwards Limestone, south-central Texas. Journal of Hydrology, volume 24, issues 3-4, pages 251-269, https://doi.org/10.1016/0022-1694(75)90084-0↗.

Abongwa, P.T., and W. Den, 2021, Evolution of a deep fluid in a surficial environment using stable carbon and sulfur isotopes: Case of the transitional zone of the Edwards Aquifer in South Central Texas. Water, Air, & Soil Pollution, volume 232, issue 213, https://doi.org/10.1007/s11270-021-05159-3↗.

Anaya, R., and I. Jones, 2004, Groundwater availability model for the Edwards-Trinity (Plateau) and Cenozoic Pecos alluvium aquifer systems, Texas. Texas Water Development Board, Austin, Texas, 208 pages, https://www.twdb.texas.gov/groundwater/models/gam/eddt_p/EDDT_P_SAF6_Materials.pdf↗, accessed on March 03, 2022.

Anaya, R., and I. Jones, 2009, Groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers of Texas. Texas Water Development Board, Austin, Texas, report 373, 103 pages, https://texashistory.unt.edu/ark:/67531/metapth576358/↗, accessed on March 03, 2022.

Anderson, M.P., W.W. Woessner, and R.J. Hunt, 2015, Applied groundwater modelling: Simulation of flow and advective transport. Academic Press, New York, USA, 564 pages, https://doi.org/10.1016/C2009-0-21563-7↗.

Arnow, T., 1963, Ground-Water Geology of Bexar County, Texas. United States Geological Survey, Water-Supply Paper 1588, 37 pages, https://pubs.usgs.gov/wsp/1588/report.pdf↗, accessed on March 3, 2022.

Barker, R.A., and A.F. Ardis, 1996, Hydrogeological framework of the Edwards-Trinity Aquifer System, West-Central Texas. United States Geological Survey, Professional Paper 1421-B, pages B1-B61, https://pubs.er.usgs.gov/publication/pp1421B↗, accessed on March 03, 2022.

Barker, R.A., P.W. Bush, and E.T. Baker Jr, 1994, Geologic history and hydrogeologic setting of the Edwards-Trinity Aquifer System, West-Central Texas. United States Geological Survey, Water-Resources Investigations Report 94-4039, 52 pages, https://pubs.usgs.gov/wri/1994/4039/report.pdf↗, accessed on March 3, 2022.

Barrett, M.E., and R.J. Charbeneau, 1996, A parsimonious model for simulation of flow and transport in a karst aquifer. Journal of Hydrology, volume 196, pages 47-65, https://repositories.lib.utexas.edu/bitstream/handle/2152/6745/crwr_onlinereport96-3.pdf?sequence=2&isAllowed=y↗, accessed on March 03, 2022.

Beal, L., J. Senison, J. Banner, M.L. Musgrove, L. Yaser, N. Bendik, C. Herrington, and D. Reyes, 2020, Stream and spring water evolution in a rapidly urbanizing watershed, Austin, Texas. Water Resources Research, e2019WR025623, volume 56, 17 pages, https://doi.org/10.1029/2019WR025623↗.

Bebout, D.G., and R.G. Loucks, 1977, Cretaceous carbonates of Texas and Mexico: Applications to subsurface exploration, University of Texas, Austin, Texas. Bureau of Economic Geology, Report of Investigations 89, 322 pages, https://doi.org/10.23867/RI0089D↗.

Bennett, R.R., and A.N. Sayre, 1962, Geology and ground water resources of Kinney County, Texas. Texas Water Commission, bulletin 6216, 163 pages, https://www.twdb.texas.gov/publications/reports/bulletins/doc/B6216/B6216.pdf↗, accessed on March 3, 2022.

Bernhardt, G.T., 1991, Surface-Groundwater Study, Washita Prairie, Central Texas. Unpublished Master of Science thesis, Baylor University, Waco, Texas, USA, 143 pages.

Berry, J.L., P.W. Dickerson, D.A. Johns, A.J. Cherepon, S.R. Pope, and S.E. Hiers, 2017, Less Frequented Springs of the Austin Area, Texas. Austin Geological Society Guidebook 37, 82 pages, https://store.beg.utexas.edu/ags/3433-ags-gb-37-less-frequented-springs-of-the-austin-area-texas.html↗, accessed on March 3, 2022.

Bertetti, F.P., and J.R. Adkins, 2020, Background water level and water quality report: New Braunfels utilities aquifer storage and recovery project. Edwards Aquifer Authority, Report 20-01, 91 pages.

Brune, G., 1975, Major and Historical Springs of Texas. Texas Water Development Board, Report 189, 94 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R189/R189.pdf↗, accessed on March 03, 2022.

Brune, G., and G. Duffin, 1983, Occurrence, availability, and quality of ground water in Travis County, Texas. Texas Department of Water Resources, Report 276, 219 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R276/R276.pdf↗, accessed on March 03, 2022.

BSEACD, 2018, Barton Springs Edwards Aquifer Conservation District, Final habitat conservation plan for managed groundwater withdrawals: Barton Springs segment of the Edwards Aquifer, Austin, Texas. Report to the U.S. Fish and Wildlife Service, 246 pages.

BSEACD, 2021a, Barton Springs Edwards Aquifer Conservation District, Drought status chart, https://bseacd.org/uploads/Stage2_drought_flyer_06_10_21.pdf↗, accessed on March 03, 2022.

BSEACD, 2021b, Barton Springs Edwards Aquifer Conservation District, Rules and bylaws, volume 1, rules 1-4, https://bseacd.org/uploads/BSEACD_Rules_MASTER_032819.pdf↗, accessed on March 03, 2022.

Bureau of Economic Geology, 1996, Physiographic Map of Texas 1996, The University of Texas. Bureau of Economic Geology, Austin, Texas, USA, 3 pages, https://store.beg.utexas.edu/free/SM0005D.pdf↗, accessed on March 03, 2022.

Bush, P.W., A.F. Ardis, L. Fahlquist, P.B. Ging, C.E. Hornig, and J. Lanning-Rush, 2000, Water quality in south-central Texas, Texas, 1996-98. United States Geological Survey, Circular 1212, page 32, https://pubs.usgs.gov/circ/circ1212/↗, accessed on March 03, 2022.

Caine, J.S., J.P. Evans, and C.B. Forster, 1996, Fault zone architecture and permeability structure. Geology, volume 24, issue 11, pages 1025-1028, https://pubs.geoscienceworld.org/gsa/geology/article-abstract/24/11/1025/187969/Fault-zone-architecture-and-permeability-structure?redirectedFrom=fulltext↗, accessed on March 03, 2022.

Campana, M.E., and D.A. Mahin, 1985, Model-derived estimates of groundwater mean ages, recharge rates, effective porosities and storage in a limestone Aquifer. Journal of Hydrology, volume 76, pages 247-264, https://www.sciencedirect.com/science/article/pii/0022169485901362↗.

Cannata, S.L., 1988, Hydrogeology of the Washita Prairie Edwards Aquifer, Central Texas. Unpublished Master of Science thesis, Baylor University, Waco, Texas, USA, 205 pages.

Clark, A.K., 2000a, Vulnerability of ground water to contamination, Edwards Aquifer Recharge Zone, Bexar County, Texas, 1998. United States Geological Survey, Water-Resources Investigations Report 00-4149, 9 pages, 1 sheet, https://pubs.er.usgs.gov/publication/wri004149↗, accessed on March 03, 2022.

Clark, A.K., D.E. Pedraza, and R.R. Morris, 2013, geologic framework, structure, and hydrogeologic characteristics of the Knippa gap area in eastern Uvalde and western Medina Counties, Texas. United States Geological Survey, Scientific Investigations Report 2013-5149, 35 pages, 1 plate, http://pubs.usgs.gov/sir/2013/5149/↗, accessed on March 03, 2022.

Clark, B.R., 2000b, Modeled Groundwater Velocities in Fractured Limestone. Unpublished Master of Science thesis, Baylor University, Waco, Texas, USA, 74 pages.

Clement, T.J., and J.M. Sharp Jr, 1987, Hydrochemical facies of the Edwards Aquifer, Williamson and Bell Counties, Texas, *in* Hydrogeology of the Edwards Aquifer in the Northern Balcones and Washita Prairie Segments, editors, J.C. Yelderman Jr, R.M. Slade Jr, J.M. Sharp Jr, and C.M. Woodruff Jr Geological Society of America, (South-Central Section) Guidebook, pages 61-70, https://store.beg.utexas.edu/ags/129-ags011.html↗, accessed on March 03, 2022.

Clement, T.J., and J.M. Sharp Jr, 1988, Hydrochemical facies in the bad-water zone of the Edwards aquifer, Central Texas: Proceedings of the Ground Water Geochemistry Conference. National Water Well Association, Dublin, Ohio, pages 127-149, https://www.researchgate.net/publication/336448013_Water_quality_and_the_bad-water_saline-water_zone_of_the_Edwards_Balcones_Fault_Zone_Aquifer↗.

Collins, A.D., 1989, Geochemistry and flow characteristics of springs discharging from the Washita Prairie Edwards Aquifer, Central Texas. Unpublished Master of Science thesis, Baylor University, Waco, Texas, USA, 213 pages.

Collins, E.W., 2000, Geologic Map of the New Braunfels, Texas, 30×60 Minute Quadrangle: Geologic Framework of an Urban-Growth Corridor along the Edwards Aquifer, South-Central Texas: University of Texas at Austin. Bureau of Economic Geology, Miscellaneous Map 39, 28 pages, scale 1:100,000, 1 sheet.

Collins, E.W., and S.D. Hovorka, 1997, Structure map of the San Antonio Segment of the Edwards Aquifer and Balcones Fault Zone, South-Central Texas: Structural framework of a major limestone aquifer: Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties: University of Texas at Austin. Bureau of Economic Geology, Miscellaneous Map 38, scale 1:250,000, 2 sheets.

Culver, D.C., and B. Sket, 2000, Hotspots of subterranean biodiversity in caves and wells. Journal of Cave and Karst Studies, volume 62, issue 1, pages 11-17, https://caves.org/pub/journal/PDF/V62/v62n1-Culver.pdf↗.

Darling, B.K., 2016, Geochemical evaluation of hydrogeologic interaction between the Edwards and Trinity aquifers—Travis, Hays and Comal Counties, Texas, 34 figures, http://dx.doi.org/10.13140/RG.2.1.1751.3361↗.

Deeds, N.E., and F. Blumberg, 2019, Aquifer storage and recovery in the Edwards Aquifers, Texas, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel. Geological Society of America, Memoir 215, chapter 21, pages 253-258, https://doi.org/10.1130/2019.1215(21)↗.

De Marsily, G., 1986, Quantitative hydrogeology, Groundwater hydrology for Engineers. Academic Press, London, United Kingdom, 440 pages, https://eugenestanleyjuke.files.wordpress.com/2017/04/quantitative-hydrogeology-groundwater-hydrology-for-engineers-by-ghislain-de-marsily.pdf↗.

Devitt, T.J., 2019, Evolution of Edwards-Trinity Aquifer biodiversity: Insights from phylogeography *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel. Geological Society of America, Memoir 215, chapter 26, pages 299-308, https://doi.org/10.1130/2019.1215(26)↗.

Edwards Aquifer Authority (EAA), 2008, Edwards Aquifer Authority, Hydrologic Data Report for 2008, Report Number 09-02, 193 pages, https://www.edwardsaquifer.org/wp-content/uploads/2019/04/2009_2008HydrologicData.pdf↗, accessed on March 03, 2022.

EAA, 2019a, Edwards Aquifer Authority, Groundwater Discharge and Usage: Edwards Aquifer Authority Hydrologic Data Fact Sheets, 11 pages, https://www.edwardsaquifer.org/wp-content/uploads/2021/03/2020-EAHCP-Appendix-C.pdf↗, accessed on March 03, 2022.

EAA, 2019b, Edwards Aquifer Authority, Groundwater Recharge: Edwards Aquifer Authority Hydrologic Data Fact Sheets, 7 pages, https://www.edwardsaquifer.org/wp-content/uploads/2021/03/2020-EAHCP-Appendix-C.pdf↗, accessed on March 03, 2022.

EAA, 2019c, SAWS Twin Oaks ASR, Edwards Aquifer Recovery Implementation Program Executive Summary, 2 pages, https://www.edwardsaquifer.org/wp-content/uploads/2019/02/05-03-_1.pdf, accessed 18 May 2022.

EAA, 2020, Edwards Aquifer Authority, https://www.edwardsaquifer.org/habitat-conservation-plan/about-eahcp/covered-species/↗, accessed on May 5, 2022.

EAA, 2021, Edwards Aquifer Authority, Triggers, Stages, Withdrawal Reductions—Chart, 1 page, https://www.edwardsaquifer.org/documents_post/triggers-stages-withdrawal-reductions-chart/↗, accessed on March 03, 2022.

Engel, A.S., 2007, Observations on the biodiversity of sulfidic karst habitats. Journal of Caves and Karst Studies, volume 69, issue 1, pages 187-206, https://caves.org/pub/journal/PDF/v69/cave-69-01-187.pdf↗.

EPA, 2020, United States Environment Protection Agency, Sole Source Aquifers for Drinking Water, https://www.epa.gov/dwssa↗, accessed on March 4, 2022.

Ewing, T.E., 1996, Rocks, Landscapes, and Man: Urban Geology of the San Antonio Area (second edition). South Texas Geological Society, San Antonio, Texas, Guidebook 96-1, 133 pages, https://archives.datapages.com/data/south-texas-geosoc-specpubs/data/014/014001/i_stb-sp014i.htm↗, accessed on March 03, 2022.

Ewing, T.E., 2016, Texas through Time: Austin, Texas, University of Texas at Austin. Bureau of Economic Geology, 431 pages, https://www.beg.utexas.edu/node/1529↗, accessed on March 03, 2022.

Ewing, T.E., and S.C. Caran, 1982, Late Cretaceous volcanism in south and central Texas – Stratigraphic, structural, and seismic models. Gulf Coast Association of Geological Societies Transactions, volume 32, pages 137-145, https://archives.datapages.com/data/gcags/data/032/032001/0137.htm↗, accessed on March 03, 2022.

Fallin, J.A.T., 1989, Hydrogeology of Lower Cretaceous strata under the southern high plains of Texas and New Mexico. Texas Water Development Board, Report 314, 39 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R314/Report%20314.pdf↗, accessed on March 03, 2022.

Ferrill, D.A., and A.P. Morris, 2003a, Dilational normal faults. Journal of Structural Geology, volume 25, pages 183-196, https://doi.org/10.1016/S0191-8141(02)00029-9↗.

Ferrill, D.A., and A.P. Morris, 2003b, Erratum to: "Dilational normal faults" [Structural Geology 25 (2003) 183-196]. Journal of Structural Geology, volume 25, pages 827, https://doi.org/10.1016/S0191-8141(02)00196-7↗.

Ferrill, D.A., and A.P. Morris, 2007, Second erratum to "Dilational normal faults" [Journal of Structural Geology 25 (2003) 183-196]. Journal of Structural Geology, volume 29, pages 1419-1420, https://doi.org/10.1016/j.jsg.2007.04.002↗.

Ferrill, D.A., A.P. Morris, and R.N. McGinnis, 2019, Geologic structure of the Edwards (Balcones Fault Zone) Aquifer *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel. Geological Society of America, Memoir 215, chapter 14, pages 1717-188, https://doi.org/10.1130/2019.1215(14)↗.

Ferrill, D.A., A.P. Morris, D.W. Sims, R. Green, N. Franklin, and D.J. Waiting, 2008, Geologic controls on interaction between the Edwards and Trinity Aquifers, Balcones fault system, Texas, South Texas. South Texas Geological Society Bulletin, volume 48, number 8, pages 21-45, https://archives.datapages.com/data/south-texas-geosoc-bulletins/data/048/048008/21_stb480021.htm↗, accessed on March 04, 2022.

Ferrill, D.A., D.W. Sims, D.J. Waiting, A.P. Morris, N. Franklin, and A.L. Schultz, 2004, Structural framework of the Edwards Aquifer recharge zone in south-central Texas. Geological Society of America Bulletin, volume 116, pages 407-418, https://doi.org/10.1130/B25174.1↗.

Font, R.G., 1979, Geotechnical properties of unstable clay-shales in North Central Texas. The Texas Journal of Science, volume 31, issue 2, pages 119-124, https://eurekamag.com/research/019/074/019074090.php↗.

Font, R.G., and E.F. Williamson, 1970, Urban Geology of Greater Waco—Part IV: Engineering. Baylor Geological Studies, issue 12, 35 pages, https://www.baylor.edu/geosciences/doc.php/287337.pdf↗, accessed on March 03, 2022.

Fratesi, S.E., R.T. Green, F.P. Bertetti, R.N. McGinnis, N. Toll, H. Başağaoğlu, L. Gergen, J. Winterle, Y. Cabeza, and J. Carrera, 2015, Development of a finite-element method groundwater flow model of the Edwards Aquifer: Final Report, Southwest Research Institute. Edwards Aquifer Authority, 180 pages, https://www.edwardsaquifer.org/science_docs/development-of-a-finite-element-met hod-groundwater-flow-model-for-the-edwards-aquifer/↗, accessed on March 03, 2022.

Freeze, R.A., and J. Cherry, 1979, Groundwater. The Groundwater Project, Guelph, Ontario, Canada, 604 pages, https://gw-project.org/books/groundwater↗, accessed on March 4, 2022.

Garcia-Fresca, B., 2004, Urban effects on groundwater recharge in Austin, Texas. Unpublished Master of Science thesis, The University of Texas, Austin, Texas, USA, 173 pages, https://repositories.lib.utexas.edu/handle/2152/65777↗, accessed on March 03, 2022.

Gary, M.O., B.B. Hunt, B.A. Smith, J.A. Watson, and D.A. Wierman, 2019, Evaluation for the development of a Jacob's well groundwater management zone Hays County, Texas: Technical report to Hays Trinity Groundwater Conservation District, Hays County, Texas. Meadows Center for Water and the Environment, Texas State University, San Marcos, USA, Report 2019-05, 58 pages, https://gato-docs.its.txstate.edu/jcr:15e1d5ca-395e-4233-9ae7-c7769d20b407↗, accessed on March 03, 2022.

George, P.G., R.E. Mace, and R. Petrossian, 2011, Aquifers of Texas. Texas Water Development Board, Report 380, 172 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R380_AquifersofTexas.pdf↗, accessed on March 03, 2022.

George, W.O., 1952, Geology and ground-water resources of Comal County, Texas. United States Geological Survey, Water-Supply Paper 1138, 126 pages, https://pubs.usgs.gov/wsp/1138/report.pdf↗, accessed on March 03, 2022.

Green, R.T., F.P. Bertetti, N.M. Franklin, A.P. Morris, D.A. Ferrill, and R.V. Klar, 2006, Evaluation of the Edwards Aquifer in Kinney and Uvalde Counties, Texas, Southwest Research Institute. Edwards Aquifer Authority, 113 pages, https://www.edwardsaquifer.org/wp-content/uploads/2019/05/2006_Green-etal_KinneyUvaldeEvaluation.pdf↗, accessed on March 03, 2022.

Green, R.T., and F.P. Bertetti, 2010, Investigating the Water Resources of the Western Edwards-Trinity Aquifer, Sutton County Groundwater Conservation District. Geosciences and Engineering Division Southwest Research Institute, 79 pages. https://static.squarespace.com/static/535a88f6e4b0fbad919ef959/t/53864143e4b040c8980a7073/1401307459476/WesternEdwardsTrinityFinalRev1.pdf↗, accessed on March 03, 2022.

Green, R.T., F.P. Bertetti, B. Fratesi, and R.N. McGinnis, 2019a, Uvalde Pool of the Edwards (Balcones Fault Zone) Aquifer *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel. Geological Society of America, Memoir 215, chapter 5, pages 47-60, https://pubs.geoscienceworld.org/gsa/books/book/2156/chapter/121759450/Uvalde-Pool-of-the-Edwards-Balcones-Fault-Zone)↗ , accessed on March 3, 2022.

Green, R.T., F.P. Bertetti, B. Fratesi, and G.M. Schindel, 2019b, San Antonio Pool of the Edwards (Balcones Fault Zone) Aquifer *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel. Geological Society of America, Memoir 215, chapter 4, pages 29-46, https://pubs.geoscienceworld.org/gsa/books/book/2156/chapter/121759447/San-Antonio-Pool-of-the-Edwards-Balcones-Fault↗, accessed on March 03, 2022.

Green, R.T., F.P. Bertetti, and R.N. McGinnis, 2019c, Kinney Pool: Defining the western boundary of the Edwards (Balcones Fault Zone) Aquifer, Texas *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel. Geological Society of America, Memoir 215, chapter 6, pages 61-74, https://pubs.geoscienceworld.org/gsa/books/book/2156/chapter/121424145/Kinney-Pool-Defining-the-western-boundary-of-the↗, accessed on March 03, 2022.

Green, R.T., J. Winterle, and B. Fratesi, 2019d, Numerical groundwater models for Edwards Aquifer systems, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America, Memoir 215, chapter 3, pages 19-28, https://pubs.geoscienceworld.org/gsa/books/book/2156/chapter/122197361/Numerical-groundwater-models-for-Edwards-Aquifer↗, accessed on March 03, 2022.

Groschen, G.E., 1996, Hydrogeologic factors that affect the flowpath of water in selected zones of the Edwards Aquifer, San Antonio region, Texas. United States Geological Survey, Water-Resources Investigations Report 96-4046, 73 pages, https://doi.org/10.3133/wri964046↗.

Grubb, H.W., 1997, The Edwards Aquifer: Conflicts surrounding use of a regional water resource. Journal of Contemporary Water Research and Education, volume 106, issue 1, 7 pages, https://opensiuc.lib.siu.edu/cgi/viewcontent.cgi?article=1299&context=jcwre↗, accessed on March 03, 2022.

Guerra, J.F., and N. Debbage, 2021, Changes to urban land use throughout the Edwards Aquifer: A comparative analysis of Austin, San Antonio, and the Interstate-35 corridor. Applied Geography, volume 133, 11 pages, https://doi.org/10.1016/j.apgeog.2021.102480↗.

Gupta, R.S., 1989, Hydrology and Hydraulic Systems. Prentice-Hall, Englewood Cliffs, New Jersey, USA, 739 pages.

Guyton and Associates, 1979, Geohydrology of Comal, San Marcos, and Hueco Springs. Texas Department of Water Resources, Report 234, 85 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R234/Report234.asp↗, accessed on March 03, 2022.

Hackett, C.C., 2019, Storage dynamics of the upper Nueces River alluvial aquifer: Implications for recharge to the Edwards Aquifer, Texas. Master of Science Thesis, The University of Texas, Austin, Texas, 99 pages, https://repositories.lib.utexas.edu/handle/2152/78338↗, accessed on May 16, 2022.

Halihan, T., J.M. Sharp, Jr, and R.E. Mace, 1999, Interpreting flow using permeability at multiple scales *in* Karst Modeling, editors, A.R. Palmer, M.V. Palmer, and I.D. Sasowsky, Karst Waters Institute, Special publication, number 5, Charlottesville, Virginia, USA, pages 82-96, https://www.researchgate.net/publication/275832646_INTERPRETING_FLOW_USING_PERMEABILITY_AT_MULTIPLE_SCALES↗.

Halihan, T., J.M. Sharp, Jr, and R.E. Mace, 2000, Flow in the San Antonio segment of the Edwards aquifer: matrix, fractures, or conduits? In Groundwater Flow and Contaminant Transport in Carbonate Aquifers, editors, I.D. Sasowsky and C.M. Wicks, August Aimé Balkema, Rotterdam, pages 29-146, https://www.researchgate.net/publication/275832559_Flow_in_the_San_Antonio_segment_of_the_Edwards_aquifer_matrix_fractures_or_conduits↗.

Halihan, T., C.M. Wicks, and J.F. Engeln, 1998, Physical response of a karst drainage basin to flood pulses: Example of the Devil's Icebox cave system (Missouri, USA). Journal of Hydrology, volume 204, issues 1-4, pages 24-36, https://doi.org/10.1016/S0022-1694(97)00104-2↗.

Hardberger, A., 2019, Texas groundwater law and the Edwards Aquifer in The Edwards Aquifer: The past, present, and future of a vital water resource, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, Geological Society of America Memoir 215, chapter 15, pages 189-198, https://doi.org/10.1130/2019.1215(15)↗.

Hartmann, A., N. Goldscheider, T. Wagener, J. Lange, and M. Weiler, 2014, Karst water resources in a changing world: Review of hydrological modeling approaches. Reviews of Geophysics, volume 52, issue 3, pages 218-242, https://doi.org/10.1002/2013RG000443↗.

Hauwert, N.M., 2009, Groundwater Flow and Recharge within the Barton Springs Segment of the Edwards Aquifer, southern Travis and northern Hays Counties, Texas. Doctor of Philosophy Dissertation, The University of Texas, Austin, Texas, USA, 328 pages, http://repositories.lib.utexas.edu/handle/2152/14107↗.

Hauwert, N.M., D.A. Johns, J.W. Sansom, and T.J. Aley, 2004, Groundwater tracing of the Barton Springs segment of the Edwards Aquifer, southern Travis and northern Hays counties, Texas, Barton Springs/Edwards Aquifer Conservation District and the City of Austin Watershed Protection and Development Review Department, 200 pages, https://bseacd.org/2018/05/groundwater-tracing-study-of-the-barton-springs-segment-of-the-edwards-aquifer/↗, accessed on May 16, 2022.

Hauwert, N., and J.M. Sharp, Jr, 2014, Measuring autogenic recharge over a karst aquifer utilizing eddy covariance evapotranspiration. Journal of Water Resource and Protection, Volume 6, Issue 9, http://dx.doi.org/10.4236/jwarp.2014.69081↗.

Hendrickson, D., and N. Elmer, 2019, Creatures of Halloween: Widemouth Blindcat (Satan eurystomus). Biodiversity Blog, Biodiversity Center, The University of Texas at Austin, https://biodiversity.utexas.edu/news/entry/satan-eurystomus↗, accessed on May 16, 2022.

Henry, T., 2011, A history of Drought and extreme weather in Texas. Energy and Environment Reporting for Texas, https://stateimpact.npr.org/texas/2011/11/29/a-history-of-drought-and-extreme-weather-in-texas/↗, accessed on May 16, 2022.

Hill, R.T., 1890, Classification and origin of the chief geographic features of the Texas region. The American Geologist, volume 5, issue 1, pages 9-29.

Hill, R.T., and T.W. Vaughan, 1898, Geology of the Edwards Plateau and Rio Grande Plain adjacent to Austin and San Antonio, Texas, with reference to the occurrence of underground waters *in* United States Geological Survey, 18th Annual Report, part 2, Washington, USA, Government Printing Office, pages 193-321, https://pubs.usgs.gov/ar/18-2/report.pdf↗, accessed on May 16, 2022.

Hoff, F.Z. Jr, and A.R. Dutton, 2017, Beyond the bad-water line – A model for the occurrence of brackish waters in upper coastal plain aquifers in Texas. Gulf Coast Association of Geological Societies Journal, volume 6, pages 135-149, https://www.gcags.org/Journal/2017.GCAGS.Journal/2017.GCAGS.Journal.v6.09.p135-149.Hoff.and.Dutton.pdf↗, accessed on May 16, 2022.

Holt, C.L.R., 1956, Geology and ground-water resources of Medina County, Texas Water Supply Paper 1422, 213 pages, https://doi.org/10.3133/wsp1422↗.

Hovorka, S.D., A.R. Dutton, S.C. Ruppel, and J.S. Yeh, 1993, Edwards Aquifer storage assessment, Kinney County to Hays County, Texas. University of Texas at Austin, Bureau of Economic Geology, report to the Edwards Underground Water District Report, 104 pages.

Hovorka, S.D., A.R. Dutton, S.C. Ruppel, and J.S. Yeh, 1996, Edwards Aquifer ground-water resources: Geologic controls on porosity development in platform carbonates, South Texas. The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations number 238, 75 pages, https://doi.org/10.23867/RI0238D↗.

Hovorka, S.D., R.E. Mace, and E.W. Collins, 1995, Regional distribution of permeability in the Edwards Aquifer. Edwards Underground Water District, Report 95-02, 128 pages, https://www.edwardsaquifer.org/wp-content/uploads/2019/05/1995_Hovorka-etal_PermeabilityDistribution.pdf↗, accessed on May 16, 2022.

Hovorka, S.D., R.E. Mace, and E.W. Collins, 1998, Permeability structure of the Edwards Aquifer, South Texas – Implications for Aquifer Management. University of Texas at Austin, Bureau of Economic Geology, Report of Investigations 250, 55 pages, https://doi.org/10.23867/RI0250D↗.

Hovorka, S.D., T. Phu, J.P. Nicot, and A. Lindley, 2004, Refining the conceptual model for flow in the Edwards aquifer – Characterizing the role of fractures and conduits in the Balcones Fault Zone Segment. Final Contract Report to Edwards Aquifer Authority, Bureau of Economic Geology, The University of Texas at Austin, Texas, USA, 58 pages, http://www.beg.utexas.edu/files/publications/cr/CR2004-Hovorka-1_QAe6964.pdf↗, accessed on May 16, 2022.

Hunt, A.G., G.P. Landis, and J.R. Faith, 2016, Groundwater ages from the freshwater zone of the Edwards Aquifer, Uvalde County, Texas – Insights into groundwater flow and recharge. United States Geological Survey, Scientific Investigations Report 2015-5163, 28 pages, https://doi.org/10.3133/sir20155163↗.

Hunt, B.B., B.A. Smith, A. Andrews, D.A. Wierman, A.S. Broun, and M.O. Gary, 2015, Relay ramp structures and their influence on groundwater flow in the Edwards and Trinity Aquifers, Hays and Travis Counties, Central Texas, 14th Sinkhole Conference, Rochester, Minnesota, USA, pages 189-200, https://digital.lib.usf.edu//content/SF/S0/05/37/49/00001/K26-03300-RELAY_RAMP_STRUCTURES_AND_THEIR_INFLUENCE_ON_GROUNDWATER_FLOW_IN.pdf↗, accessed on May 16, 2022.

Hunt, B.B., B.A. Smith, M.O. Gary, A.S. Broun, D.A. Wierman, J. Watson, and D. Johns, 2017, Surface-water and groundwater interactions in the Blanco River and Onion Creek watersheds: Implications for the Trinity and Edwards Aquifers of Central Texas. Bulletin of the South Texas Geological Society, volume 42, issue 5, pages 33-53, https://bseacd.org/uploads/Hunt-et-al_2017_STGS-Bulletin_FINAL.pdf↗, accessed on May 16, 2022.

Hunt, B.B., B.A. Smith, and N.M. Hauwert, 2019, Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer, Central Texas *in* The Edwards Aquifer: The past, present, and future of a vital water resource, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, Geological Society of America Memoir 215, chapter 7, pages 75-100, https://doi.org/10.1130/2019.1215(07)↗.

Hunt, B.B., B.A. Smith, and W.F. Holland, 2011, Information in support of the Drought DFC and Drought MAG, Barton Springs segment of the Edwards Aquifer. Barton Springs/Edwards Aquifer Conservation District Technical Note 2011-0707, 5 pages, https://bseacd.org/2014/07/information-in-support-of-the-drought-dfc-and-drought-mag-barton-springs/↗, accessed on May 16, 2022.

Hutchison, W., and M. Hill, 2011, Report: Recalibration of the Edwards (Balcones Fault zone) – Barton Springs Segment – Groundwater Flow Model, Texas Water Development Board, 121 pages, https://www.twdb.texas.gov/groundwater/models/alt/ebfz_b/EBFZ_B_Model_Recalibration_Report.pdf↗, accessed on May 16, 2022.

Hutchison, W.R., I.C. Jones, and R. Anaya, 2011b, Update of the Groundwater Availability Model for the Edwards-Trinity (Plateau) and Pecos Valley Aquifers of Texas. Texas Water Development Board, 61 pages, https://www.twdb.texas.gov/groundwater/models/alt/eddt_p_2011/ETP_PV_One_Layer_Model.pdf↗, accessed on May 16, 2022.

Hutchison, W.R., J. Shi, and M. Jigmond, 2011a, Groundwater flow model of the Kinney County Area, Texas Water Development Board, Unpublished Report, 219 pages, http://www.twdb.texas.gov/groundwater/models/alt/knny/Kinney_County_Model_Report.pdf↗, accessed on May 16, 2022.

Illgner, R., and G.M. Schindel, 2019, Historical note: The Edwards Aquifer Authority in The Edwards Aquifer: The past, present, and future of a vital water resource, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, Geological Society of America Memoir 215, chapter 27, pages 309-312, https://doi.org/10.1130/2019.1215(27)↗.

Johnson, S., G.M. Schindel, and G. Veni, 2010, Tracing Groundwater Flowpaths in the Edwards Aquifer recharge zone, Panther Springs Creek Basin, Northern Bexar County, Texas, Edwards Aquifer Authority Report # 10-01, San Antonio, Texas, 112 pages, https://www.edwardsaquifer.org/wp-content/uploads/2019/02/2010_Johnson-etal_PantherSpringsFlowpaths.pdf↗, accessed on May 16, 2022.

Jagucki, M.L., M. Musgrove, R.J. Lindgren, L. Fahlquist, and S.M. Eberts, 2011, Assessing the vulnerability of public-supply wells to contamination: Edwards Aquifer near San Antonio, Texas. United States Geological Service, Fact Sheet 2011-3142, https://pubs.usgs.gov/fs/2011/3142/pdf/fs2011-3142_Web.pdf↗, accessed on May 16, 2022.

Johnson, S., and G. Schindel, 2015, Tracing groundwater flowpaths in Kinney County, Texas. Edwards Aquifer Authority, Report 15-02, 112 pages, https://www.edwardsaquifer.org/science_docs/tracing-groundwater-flowpaths-in-kinney-county-texas/↗, accessed on May 16, 2022.

Johnson, S., G. Schindel, and J. van Brahana, 2019, Tracer testing in the Edwards Aquifer in The Edwards Aquifer: The past, present, and future of a vital water resource, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, Geological Society of America Memoir 215, chapter 24. Pages 283-292, https://doi.org/10.1130/2019.1215(24)↗.

Johnson, S., G. Schindel, and G. Veni, 2010, Tracing groundwater flowpaths in the Edwards Aquifer recharge zone, Panther Springs Creek Basin, Northern Bexar county, Texas. Edwards Aquifer Authority, Report 10-01, 112 pages, https://www.edwardsaquifer.org/doc_publications/tracing-groundwater-flowpaths-in-the-edwards-aquifer-recharge-zone-panther-springs-creek-basin-northern-bexar-county-texas%EF%BF%BD%EF%BF%BD/↗, accessed on May 16, 2022.

Jones, I.C., 2003, Groundwater Availability Model: Northern segment of the Edwards Aquifer, Texas. Texas Water Development Board, Report 358, 83 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R358/Report%20358%20Northern%20Edwards.pdf↗, accessed on May 16, 2022.

Jones, I.C., 2006, Defining groundwater flow characteristics in the northern segment of the Edwards Aquifer Based on groundwater chemistry. Austin Geological Society Bulletin, volume 2, pages 54-75, https://static1.squarespace.com/static/56e481e827d4bdfdac7fbe0f/t/56f87df24c2f85720ce5e412/1459125760332/Jones%2C+2006%2C+Groundwater+Flow+in+Northern+Edwards+Aquifer.pdf↗, accessed on May 16, 2022.

Jones, I.C., 2019, The northern segment of the Edwards (Balcones Fault Zone) Aquifer in The Edwards Aquifer: The past, present, and future of a Vital Water Resource, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, Geological Society of America Memoir 215, chapter 9, pages 119-130, https://doi.org/10.1130/2019.1215(09)↗.

Jones, I.C., and R. Anaya, 2019, The Edwards-Trinity (Plateau) and Trinity (Hill Country) Aquifer System, Texas *in* The Edwards Aquifer: The past, present, and future of a Vital Water Resource, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, Geological Society of America Memoir 215, chapter 11, pages 137-148, https://doi.org/10.1130/2019.1215(11)↗.

Jones, I.C., R. Anaya, and S. Wade, 2009, Groundwater Availability Model for the Hill Country Portion of the Trinity Aquifer System, Texas. Unpublished Texas Water Development Board Report, 191 pages, https://www.twdb.texas.gov/groundwater/models/gam/trnt_h/TRNT_H_2009_Update_Model_Report.pdf↗, accessed on May 16, 2022.

Jones, I.C., R. Anaya, and S.C. Wade, 2011, Groundwater Availability Model: Hill Country portion of the Trinity Aquifer of Texas. Texas Water Development Board, report 377, 175 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R377_HillCountryGAM.pdf↗, accessed on May 16, 2022.

Kamps, R.H., G.S. Tatum, M. Gault, and A. Groeger, 2009, Goodenough Spring, Texas, USA: Discharge and water chemistry of a large spring deeply submerged under the binational Amistad Reservoir. Hydrogeology Journal, volume 17, pages 891-899, https://doi.org/10.1007/s10040-008-0404-0↗.

Klemt, W.B., T.R. Knowles, G.R. Edler, and.T.W. Sieh, 1979, Ground-water resources and model applications for the Edwards (Balcones Fault Zone) aquifer in the San Antonio region, Texas. Texas Department of Water Resources, Report 239, 88 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R239/Report239.asp↗, accessed on May 16, 2022.

Knipe, R.J., 1997, Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs. Bulletin of the American Association of Petroleum Geologists, volume 81, pages 187-195, https://doi.org/10.1306/522B42DF-1727-11D7-8645000102C1865D↗.

Kreitler, C.W., R.K. Senger, and E.W. Collins, 1987, Geology and hydrology of the northern segment of the Edwards Aquifer with emphasis on the recharge zone in Georgetown, Texas, area. The University of Texas at Austin, Bureau of Economic Geology, report prepared for the Texas Water Development Board, 115 pages.

Krejca, J., 2005, Stygobite phylogenetics as a tool for determining aquifer evolution. Doctor of Philosophy Dissertation, The University of Texas at Austin, Texas ScholarWorks, 99 pages, https://repositories.lib.utexas.edu/handle/2152/1596↗, accessed on May 16, 2022.

Krejca, J., and J. Reddell, 2019, Biology and ecology of the Edwards Aquifer in The Edwards Aquifer: The past, present, and future of a Vital Water Resource, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, Geological Society of America Memoir 215, chapter 13, pages 159-170, https://doi.org/10.1130/2019.1215(13)↗.

Kromann, J., 2015, Surface water recharge in karst: Edwards-Trinity Aquifers-Nueces River system. Master of Science Thesis, The University of Texas at Austin, 194 pages, https://repositories.lib.utexas.edu/handle/2152/44401↗, accessed on May 16, 2022.

Kuniansky, E.L., 1989, Precipitation, streamflow, and baseflow in west-central Texas, December 1974 through March 1977. United States Geological Survey, Water-Resources Investigations Report 88-4218, 2 sheets, https://doi.org/10.3133/wri884218↗.

Kuniansky, E.L., 1995, Multilayer finite-element model of the Edwards aquifer and catchment area, central Texas *in* Proceedings Texas Water '95, A component conference of the first international conference on water resources engineering, Water Resources Engineering Division American Society of Civil Engineers, San Antonio, TX, pages 279–287.

Kuniansky, E.L., and A.F. Ardis, 2004, Hydrogeology and ground-water flow in the Edwards-Trinity Aquifer system, west-central Texas, Regional Aquifer-System Analysis – Edwards-Trinity, United States Geological Survey, Professional Paper 1421-C, 78 pages, https://doi.org/10.3133/pp1421C↗.

Kuniansky, E.L., L. Fahlquist, and A.F. Ardis, 2001, Travel times along selected flow paths of the Edwards Aquifer, Central Texas in United States Geological Survey Karst Interest Group Proceedings, Water-Resources Investigations Report 2001-4011, pages 69-77, https://doi.org/10.3133/wri014011↗.

Kuniansky, E.L., and K.Q. Holligan, 1994, Simulations of flow in the Edwards-Trinity Aquifer system and contiguous hydraulically connected units, west-central Texas. United States Geological Survey, Water-Resources Investigations Report 93-4039, 40 pages, https://doi.org/10.3133/wri934039◎.

Land, L. F., Hunt, B. B., Smith, B. A., & Lemonds, P. J. (2011). Hydrologic Connectivity in the Edwards Aquifer between San Marcos Springs and Barton Springs during 2009 Drought Conditions. Texas Water Journal, 2(1), 39–53. https://doi.org/10.21423/twj.v2i1.1951 Kuniansky, E.L., 1995, Multilayer finite-element model of the Edwards aquifer and catchment area, central Texas: Proceedings Texas Water '95, A component conference of the first international conference on water resources engineering, Water Resources Engineering Division American Society of Civil Engineers, August 16–17, 1995, San Antonio, Tex., p. 279–287

Land, L.S., and D.R. Prezbindowski, 1981, The origin and evolution of saline formation water, Lower Cretaceous carbonates, south-central Texas, USA. Journal of Hydrology, volume 54, pages 51-74, https://doi.org/10.1016/0022-1694(81)90152-9↗.

Larkin, T.J., and G.W. Bomar, 1983, Climatic Atlas of Texas, Texas Department of Water Resources, Report LP-192, 161 pages, https://www.twdb.texas.gov/publications/reports/limited_printing/doc/LP192.pdf↗, accessed on May 16, 2022.

Legg, C.J., 1995, Geochemical investigation of shallow fracture flow groundwater system in the Washita Prairie, Central Texas. Master of Science Thesis, unpublished, Baylor University, Waco, Texas, 103 pages.

Lindgren, R.J., 2006, Diffuse-flow conceptualization and simulation of the Edwards aquifer, San Antonio region, Texas. United States Geological Survey, Scientific Investigations Report 2006-5319, 47 pages, https://doi.org/10.3133/sir20065319↗.

Lindgren, R.J., A.R. Dutton, S.D. Hovorka, S.R.H. Worthington, and S. Painter, 2004, Conceptualization and simulation of the Edwards Aquifer, San Antonio region, Texas. United States Geological Survey, Scientific Investigations Report 2004-5277, 154 pages, https://doi.org/10.3133/sir20045277↗.

Lindgren, R.J., N.A. Houston, M. Musgrove, L.S. Fahlquist, and L.J. Kauffman, 2011, Simulations of groundwater flow and particle-tracking analysis in the zone of contribution to a public-supply well in San Antonio, Texas. United States Geological Survey, Scientific Investigations Report 2011-5149, 93 pages, https://doi.org/10.3133/sir20115149↗.

Lindsey, B.D., M.P. Berndt, B.G. Katz, A.F. Ardis, and K.A. Skach, 2009, Factors affecting water quality in selected carbonate aquifers in the United States, 1993-2005. United States Geological Survey, Scientific Investigations Report 2008-5240, pages 117, https://doi.org/10.3133/sir20085240↗.

Liu, A., N. Troshanov, A. Zhang, and J. Winterle, 2017, Updates to the MODFLOW Groundwater Model of the San Antonio Segment of the Edwards Aquifer. Edwards Aquifer Authority, 78 pages, https://www.edwardsaquifer.org/wp-content/uploads/2019/11/Attachment-4_Updates-to-the-MODFLOW-Groundwater-Model-of-the-San-Antonio-Segment-of-the-Edwards-Aquifer.pdf↗, accessed on May 16, 2022.

Loáiciga, H.A., D.R. Maidment, and J.B. Valdes, 2000, Climate-change impacts in a regional karst aquifer, Texas, USA. Journal of Hydrology, volume 227, issues 1-4, pages 173-194, https://doi.org/10.1016/S0022-1694(99)00179-1↗.

Loáiciga, H.A., and M. Schofield, 2019, Climate variability, climate change, and Edwards Aquifer water fluxes in The Edwards Aquifer: The past, present, and future of a Vital

Water Resource, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, Geological Society of America Memoir 215, chapter 19, pages 223-238, https://doi.org/10.1130/2019.1215(19)↗.

Longley, G., 1981, The Edwards Aquifer: Earth's most diverse groundwater ecosystem? International Journal of Speleology, volume 11, pages 123-128, https://www.edwardsaquifer.org/doc_publications/the-edwards-aquifer-earth%EF%BF%BDs-most-diverse-groundwater-ecosystem/↗, accessed on May 16, 2022.

Lozo, F.E., H.F. Nelson, K. Young, O.B. Shelburne, and J.R. Sandidge, 1959, Symposium on Edwards Limestone in Central Texas. University of Texas at Austin, Bureau of Economic Geology, Publication Number 5905, 235 pages, http://dx.doi.org/10.26153/tsw/5113↗.

Mace, R.E., 1997, Determination of transmissivity from specific capacity tests in a karst aquifer. Ground Water, volume 35, number 5, pages 738-742, https://doi.org/10.1111/j.1745-6584.1997.tb00141.x↗.

Mace, R.E., 2019, The use of water from the Edwards Aquifers, Texas, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, chapter 17, pages 207-212, https://doi.org/10.1130/2019.1215(17)↗.

Mace, R. E., and R. Anaya, 2004, Estimate of recharge to the Edwards (Balcones Fault Zone) and Edwards-Trinity (Plateau) aquifers in Kinney County, Texas: *in* Aquifers of the Edwards Plateau: Texas Water Development Board, editors, R.M. Mace, E.S. Angle, and W.F. Mullican III, Report 360, pages 345-366, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R360/Ch01.pdf↗, accessed on March 3, 2022.

Mace, R.E., and Angle, E.S., 2004, Aquifers of the Edwards Plateau; Texas Water Development Board Report 360, chapter 1, 19 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R360/Intro.pdf↗accessed on March 10, 2022.

Mace, R.E., Chowdhury, A.H., Anaya, R., and Way, S.-C., 2000, Groundwater availability of the Trinity Aquifer, Hill Country Area, Texas—Numerical simulations through 2050: Texas Water Development Board Report 353, 119 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R353/Report353.asp accesses 18 May 2022.

Mace, R.E., R. Petrossian, R. Bradley, W.F. Mullican III, and L. Christian, 2008, A streetcar named desired future conditions – The new groundwater availability for Texas (revised): State Bar of Texas, 7th Annual The Changing Face of Water Rights in Texas 2008, May 8-9, 2008, Bastrop, Texas, chapter 2.1, 21 pages, http://www.twdb.texas.gov/groundwater/docs/Streetcar.pdf↗, accessed on March 3, 2022.

Maclay, R.W., 1989, Edwards Aquifer in San Antonio: Its hydrogeology and management: South Texas Geological Society Bulletin, volume 30, number 4, pages 11–28.

Maclay, R.W., 1995, Geology and Hydrology of the Edwards Aquifer in the San Antonio Area, Texas. U.S. Geological Survey Water-resources Investigations Report 95-4186, 72 pages, https://doi.org/10.3133/wri954186↗.

Maclay, R.W., and P.L. Rettman, 1973, Regional specific yield of the Edwards and associated limestones in the San Antonio, Texas, area. U.S. Geological Survey Open-File Report 72-172, 13 pages, https://pubs.usgs.gov/of/1973/0172/report.pdf↗, accessed on March 3, 2022.

Maclay, R.W., and L.F. Land, 1988. Simulation of flow in the Edwards Aquifer, San Antonio Region, Texas, and refinement of storage flow concepts. U.S. Geological Survey Water-Supply Paper 2336, 48 pages, https://pubs.usgs.gov/wsp/2336a/report.pdf↗, accessed on March 3, 2022.

Maclay, R.W., P.L. Rettman, and T.A. Small, 1980, Hydrochemical data for the Edwards Aquifer in the San Antonio area, Texas. Texas Department of Water Resources Report LP-131, 38 pages, https://www.twdb.texas.gov/publications/reports/limited_printing/doc/LP-131/LP-131.pdf.↗, accessed on March 3, 2022.

Maclay, R.W., and T.A. Small, 1983, Hydrostratigraphic subdivisions and fault barriers of the Edwards Aquifer, south-central Texas. Journal of Hydrology (Amsterdam), volume 61, pages 127–146, https://pubs.er.usgs.gov/publication/70011646↗, accessed on March 3, 2022.

Maclay, R.W., and T.A. Small, 1984, Carbonate geology and hydrology of the Edwards Aquifer in the San Antonio area, Texas. U.S. Geological Survey Open-File Report 83-537, 72 pages, 14 plates, https://pubs.usgs.gov/of/1983/0537/report.pdf↗, accessed on March 3, 2022.

Mahler, B., and M.L. Musgrove, 2019, Emerging contaminants in groundwater, karst, and the Edwards Aquifer, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, chapter 20, pages 239-252, https://doi.org/10.1130/2019.1215(20)↗.

Mahler, B.J., M.L. Musgrove, T.L. Sample, and C.I. Wong, 2011, Recent (2008–10) water quality in the Barton Springs segment of the Edwards aquifer and its contributing zone, central Texas, with emphasis on factors affecting nutrients and bacteria. U.S. Geological Survey Scientific Investigations Report 2011–5139, 66 pages, https://pubs.usgs.gov/sir/2011/5139/sir2011-5139.pdf↗, accessed on March 3, 2022.

Mancha, E., and W.S. Walker, 2019, Desalination: Growing opportunities in Texas, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215, editors, J.M. Sharp, Jr, R.T. Green, and G.M. Schindel, pages 259 -268, https://doi.org/10.1130/2019.1215(22)↗.

McKinney, D.C., and J.M. Sharp Jr, 1995, Springflow Augmentation of Comal and San Marcos Springs, Texas: Phase I – Feasibility Study. Center for Research in Water Resources, The University of Texas, Austin, Technical Report 247, 92 pages, https://www.edwardsaquifer.org/doc_publications/springflow-augmentation-of-comal-springs-and-san-marcos-springs-texas-phase-i-feasibility-study-draft/↗, accessed on March 3, 2022.

Meinzer, O.E., 1923, Outline of Ground-water Hydrology with Definitions. U.S. Geological Survey, Water-Supply Paper 494, 77 pages, https://doi.org/10.3133/wsp494↗.

Miggins, D.P., C.D. Blome, and D.V. Smith, 2004, Preliminary 40Ar/39Ar Geochronology of Igneous Intrusions from Uvalde County, Texas – Defining a More Precise Eruption History for the Southern Balcones Volcanic Province. U.S. Geological Survey Open-File Report 2004-1031, 31 pages, https://doi.org/10.3133/ofr20041031↗.

Musgrove, M., J.E. Solder, S.P. Opsahl, and J.T. Wilson, 2019a, Data for timescales of water-quality change in a karst aquifer, south-central Texas. U.S. Geological Survey data release, [https://doi.org/10.5066/P9247J56.](https://doi.org/10.5066/P9247J56)↗.

Musgrove, M., J.E. Solder, S.P. Opsahl, and J.T. Wilson, 2019b, Timescales of water-quality change in a karst aquifer, south-central Texas. Journal of Hydrology X, volume 4, 100041, https://doi.org/10.1016/j.hydroa.2019.100041↗.

Myearick, M.K., 1989, Aquifer-Stream Interactions and Their Hydrologic Implications in Non-Karstic Limestones, Washita Prairie, Central Texas: unpub. Master of Science Thesis, Baylor University, Waco, Texas, 180 pages.

Nielsen, E.R., R.S. Schumacher, and A.M. Kecik, 2015, The effect of the Balcones Escarpment on three cases of extreme precipitation in central Texas: Monthly Weather Review, volume 144, pages 119-138, https://doi.org/10.1175/MWR-D-15-0156.1↗.

Nielsen-Gammon, J.W., F. Zhang, A.M. Odins, and B. Myoung, 2013, Extreme Rainfall in Texas: Patterns and Predictability. Physical Geography, volume 26, number 55, pages 340-364, https://doi: 10.2747/0272 3646.26.5.340↗.

Oetting, G.C., J.L. Banner, and J.M. Sharp Jr, 1996, Regional controls on the geochemical evolution of saline groundwaters in the Edwards aquifer, central Texas: regional stratigraphic, tectonic, and hydrodynamic controls. Journal of Hydrology, volume 181, pages 251 -283, https://doi.org/10.1016/0022-1694(95)02906-0↗.

Opsahl, S.P., M. Musgrove, B.J. Mahler, and R.B. Lambert, 2018, Water-quality observations of the San Antonio segment of the Edwards aquifer, Texas, with an emphasis on processes influencing nutrient and pesticide geochemistry and factors affecting aquifer vulnerability, 2010-16. U.S. Geological Survey Scientific Investigations Report 2018-5060, 67 pages, https://doi.org/10.3133/sir20185060↗.

Painter, S.L., A. Sun, and R.T. Green, 2007, Enhanced Characterization and Representation of Flow through Karst Aquifers – Phase II. Contract Report to the Edwards Aquifer

Authority and the Southwest Florida Water Management District, 111 pages, https://www.edwardsaquifer.org/science_category/groundwater-movement/↗, accessed on March 3, 2022.

Passarello, M.C., S.A. Pierce, and J.M. Sharp Jr, 2012, Estimating urban-induced, artificial recharge A case study for Austin, Texas. Environmental and Engineering Geoscience, volume 18, number 1, pages 25-36, https://doi.org/10.2113/gseegeosci.18.1.25↗.

Passarello, M.C., S.A. Pierce, and J.M. Sharp Jr, 2014, Uncertainty and urban water recharge for managing groundwater availability using decision support. Water Science and Technology Journal, volume 70, number 11, https://doi.org/10.2166/wst.2014.437↗.

Payne, S., N. Pence, and C. Furl, 2019, The Edwards Aquifer Habitat Conservation Plan: Its planning and implementation, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, chapter 16, pages 199-206, https://doi.org/10.1130/2019.1215(16)↗.

Potter, L.B., and N. Hoque, 2014, Texas Population Projections, 2010 to 2050: San Antonio, Texas, Office of the State Demographer, 5 pages, https://demographics.texas.gov/Resources/Publications/2014/2014-11_ProjectionBrief.pdf↗, accessed on May 16, 2022.

Puente, C., 1978, Method of estimating natural recharge to the Edwards aquifer in the San Antonio area, Texas. U.S. Geological Survey Water-Resources Investigations Report, pages 78–10, 34 pages, https://doi.org/10.3133/wri7810↗.

Rees, R., and A.W. Buckner, 1980, Occurrence and quality of ground water in the Edwards-Trinity (Plateau) aquifer in the Trans-Pecos Region of Texas. Texas Department of Water Resources Report 255, 41 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R255/R255.pdf↗, accessed on March 3, 2022.

Rose, P.R., 1972, Edwards Group, Surface and Subsurface, Central Texas. The University of Texas, Bureau of Economic Geology Report of Investigations 74, 198 pages, http://www.beg.utexas.edu/publications/edwards-group-surface-and-subsurface-central-texas↗, accessed on March 3, 2022.

Rose, P.R., 2017, Regional stratigraphy of the Edwards Group and associated formations of Texas (Lower Cretaceous, Comanchean): In defense of the classic view. Gulf Coast Association of Geological Societies Journal, volume 6, pages 111-134., https://www.gcags.org/exploreanddiscover/2017/00279_rose.pdf ↗, accessed on March 3, 2022.

Rose, P.R., 2019, Neogene evolution of the central Texas landscape and the Edwards aquifers after Balcones faulting. Gulf Coast Association of Geological Societies Journal, volume 8, pages 231-267, https://www.gcags.org/exploreanddiscover/2019/00533_rose.pdf↗, accessed on March 3, 2022.

Rothermal, S.R., and A.E. Ogden, 1987, Hydrochemical investigation of the Comal and Hueco spring systems, Comal County, Texas: Edwards Aquifer Research and Data Center Report R1-87, 182 pages, https://gato-docs.its.txstate.edu/jcr:5093ffdb-0728-4e0c-9077-335bd18ffe29/Hydrochemical_Invest.Comal_and_Hueco_Spring.pdf↗, accessed on March 3, 2022.

Ryder, P.D., 1996, Ground Water Atlas of the United States – Oklahoma, Texas. U.S. Geological Survey, Hydrologic Atlas HA 730-E, https://doi.org/10.3133/ha730E↗.

Sanchez, R., L. Victoria, and G. Eckstein, 2016, Identifying and Characterizing Transboundary Aquifers Along the Mexico-U.S Border: An Initial Assessment. Journal of Hydrology, volume 535, pages 101–119, https://doi.org/10.1016/j.jhydrol.2016.01.070↗.

Sanchez, R., L. Rodriguez, and C. Tortajada, 2018, Transboundary Aquifers between Chihuahua, Coahuila, Nuevo Leon and Tamaulipas, Mexico, and Texas, U.S.: Identification and Categorization. Journal of Hydrology: Regional Studies, volume 20, pages 74–102, https://doi.org/10.1016/j.ejrh.2018.04.004 T.↗.

Sanchez, R., and L. Rodriguez, 2021, Transboundary Aquifers between Baja California, Sonora and Chihuahua, Mexico, and California, Arizona and New Mexico, United States: Identification and Categorization. Water, volume 13, page 2878. https://doi.org/10.3390/w13202878↗.

Saribudak, M., 2019, Surface geophysics *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, chapter 23, pages 267-282, https://doi.org/10.1130/2019.1215(23)↗.

Scanlon, B.R., R.E. Mace, B. Smith, S. Hovorka, A.R. Dutton, and R. Reedy, 2001, Groundwater Availability Modeling of the Barton Springs Segment of the Edwards Aquifer, Texas: Numerical Simulations through 2050. Austin, Texas. Bureau of Economic Geology, 99 pages, http://www.beg.utexas.edu/files/publications/cr/CR2001-Scanlon-4_QAe6969.pdf↗, accessed on March 3, 2022.

Scanlon, B.R., R.E. Mace, M.E. Barrett, and B. Smith, 2003, Can we simulate regional groundwater flow in a karst system using equivalent porous media models? Case study, Barton Springs Edwards aquifer, United States. Journal of Hydrology, volume 276, pages 137-158, https://doi.org/10.1016/S0022-1694(03)00064-7↗.

Schindel, G.M., 2019, Genesis of the Edwards (Balcones Fault Zone) Aquifer, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, chapter 2, pages 9-18, https://doi.org/10.1130/2019.1215(02)↗.

Senger, R.K., E.W. Collins, and C.W. Kreitler, 1990, Hydrogeology of the northern segment of the Edwards aquifer, Austin region. The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations Number 192, 58 pages, https://www.beg.utexas.edu/publications/hydrogeology-northern-segment-edwards-aquifer-austin-region↗, accessed on March 3, 2022.

Sharp, J.M., Jr, 1990, Stratigraphic, geomorphic, and structural controls on the Edwards Aquifer, Texas, USA *in* International Association of Hydrogeologists, Selected Papers on Hydrogeology, editors, E.S. Simpson and J.M. Sharp Jr, volume 1, Heise, Germany, pages 67-82, https://www.researchgate.net/publication/313199419_Stratigraphic_geomorphic_and_structural_controls_of_the_Edwards_aquifer_Texas_USA↗.

Sharp, J.M., Jr, 2002, The Edwards Aquifer: Will There Be Water for Texas? Outreach Lecture Series / College of Natural Sciences, University of Texas at Austin, volume 20, DVD, http://www.esi.utexas.edu/talk/edwards-aquifer-texas/↗, accessed on March 3, 2022.

Sharp, J.M., Jr, 2017, A Glossary of Hydrogeological Terms. Department of Geological Silences, The University of Texas, Austin, Texas, USA, 97 pages, http://www.geo.utexas.edu/faculty/jmsharp/sharp-glossary.pdf↗, accessed on March 3, 2022.

Sharp, J.M., Jr, 2019, Effects of urbanization on the Edwards Aquifer, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215 editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, chapter 18, pages 213-222, https://doi.org/10.1130/2019.1215(18)↗.

Sharp, J.M., Jr and J.L. Banner, 1997, The Edwards aquifer – a resource in conflict. Geological Society of America Today, volume 7, number 8, pages 1-9, https://www.geosociety.org/gsatoday/archive/7/8/pdf/i1052-5173-7-8-1.pdf↗, accessed on March 3, 2022.

Sharp, J.M., Jr and T.J. Clement, 1988, Hydrochemical facies as hydraulic boundaries in karstic aquifers – the Edwards aquifer, U.S.A., *in* Proceedings of the 21st I. A. H. Congress, Karst Hydrogeology and Karst Environment Protection, Guilin, People's Republic of China, Geological Publishing House, Beijing, volume 2, pages 841-845.

Sharp, J.M., Jr, R.T. Green, and G.M. Schindel, 2019a, The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215 editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, 312 pages, https://doi.org/10.1130/MEM215↗.

Sharp, J.M., Jr, R.T. Green, and G.M. Schindel, 2019b, Introduction: *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource: Geological Society of America Memoir 215, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, chapter 1, pages 1-7, https://doi.org/10.1130/2019.1215(01)↗.

Sharp, J.M., Jr, and B.A. Smith, 2019, Water quality and the bad-water (saline-water) zone of the Edwards (Balcones Fault Zone) Aquifer, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, chapter 12, pages 149-158, https://doi.org/10.1130/2019.1215(12)↗.

Sharp, J.M., Jr, C.E. Kreitler, and J. Lesser, 1991, Ground Water, *in* The Gulf of Mexico, Geology of North America, Geological Society of America, Boulder, Colorado , editor,A. Salvador, volume J, pages 529-543, https://rock.geosociety.org/Store/detail.aspx?id=DNAGGNAJ↗, accessed on March 3, 2022.

Slade, R.M., Jr, J.T. Bentley, and D. Michaud, 2002, Results of streamflow gain-loss studies in Texas, with emphasis on gains from and losses to major and minor aquifers, U.S. Geological Survey Open-File Report 02-068, 136 pages, https://doi.org/10.3133/ofr0268↗.

Slade, R.M., and J. Patton, 2003, Major and Catastrophic Storms and Floods in Texas. U.S. Geological Survey Open-File Report 03–193, https://doi.org/10.3133/ofr03193↗.

Slade, R.M. Jr., L. Ruiz, and D. Slagle, 1985, Simulation of the Flow System of Barton Springs and Associated Edwards Aquifer in the Austin Area, Texas, U.S. Geological Survey Water-Resources Investigations Report 85-4299, 56 pages, https://pubs.usgs.gov/wri/1985/4299/report.pdf↗, accessed on May 16, 2022.

Small, T.A., and G.B. Ozuna, 1992, Ground-Water Conditions in Pecos County, Texas, 1987. U.S. Geological Survey Water-Resources Investigations Report 92-4190, 68 pages, https://pubs.usgs.gov/wri/1992/4190/report.pdf↗, accessed on March 3, 2022.

Smith, B.A., and B.B. Hunt, 2004, Evaluation of the sustainable yield of the Barton Springs Segment of the Edwards Aquifer, Hays and Travis Counties, Central Texas. Barton Springs/Edwards Aquifer Conservation District. Austin, Texas, 198 pages, https://bseacd.org/uploads/HR_SustYield_BSEACD_report_2004_web.pdf↗, accessed on March 3, 2022.

Smith, B.A., and B.B. Hunt, 2019, Multilevel monitoring of the Edwards and Trinity Aquifers, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, chapter 25, pages 293-298, https://doi.org/10.1130/2019.1215(25)↗.

Smith, B.A., B.B. Hunt, and J. Beery, 2011, Enhanced Recharge to the Barton Springs segment of the Edwards Aquifer, Central Texas: 12th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, St. Louis, MO, January 10-14, 2011.

Smith, B.A., B.B. Hunt, and B.K. Darling, 2017, Hydrogeology of the Saline Edwards Zone, Southeast Travis County, Central Texas. Barton Springs Edwards Aquifer

Conservation District, Report of Investigations 2017-1015, 66 pages, https://bseacd.org/2017/10/hydrogeology-of-the-saline-edwards-zone-southeast-travis-county-central-texas/↗, accessed on March 3, 2022.

Smith, B.A., B.B. Hunt, and S.B. Johnson, 2012, Revisiting the Hydrologic Divide Between the San Antonio and Barton Springs Segments of the Edwards Aquifer: Insights from Recent Studies. Gulf Coast Association of Geological Societies Journal, volume 1, pages 55-68, https://bseacd.org/2014/07/revisiting-the-hydrologic-divide-between-the-san-antonio-and-barton-springs/↗, accessed on March 3, 2022.

Smith, B.A., B.B. Hunt, I.C. Jones, R.J. Lindgren, and G.S. Schindel, 2005a, Ground-Water Availability Modeling of the Three Major Segments of the Edwards Aquifer, Central Texas *in* Abstracts with Programs, Groundwater Summit, National Ground Water Association, San Antonio, Texas April 18-20, 2005. https://bseacd.org/uploads/GAM-Comparison_PosterAbstract_2005.pdf↗, accessed on March 3, 2022.

Smith, B.A., B.B. Hunt, and G.M. Schindel, 2005b, Groundwater flow in the Edwards Aquifer: Comparison of Groundwater Modeling and Dye Trace Results: Sinkholes and the Engineering and Environmental Impacts of Karst, San Antonio, Texas, American Society of Civil Engineers. Geotechnical Special Publication Number 144, pages 131-141, https://ascelibrary.org/doi/abs/10.1061/40796%28177%2915↗.

Smith, B.A., B.B. Hunt, and B.K. Darling, 2017, Hydrogeology of the Saline Edwards Zone, Southeast Travis County, Central Texas. BSEACD Report of Investigations 2017-1015. 66 pages, https://bseacd.org/uploads/Hydrogeology-Saline-Edwards_BSEACD-RI-2017-1015.pdf↗, accessed on March 3, 2022.

Smith, B.A., B.B. Hunt, M.O. Gary, D.A. Wierman, J.A. Watson, and J. Vy, 2020, Springshed delineation in a karst aquifer in Hays County, Central Texas:16th Annual Sinkhole Conference, doi: 10.5038/9781733375313.1048↗.

Smith, B., B. Morris, B. Hunt, S. Helmcamp, D. Johns, and N. Hauwert, 2001, Water Quality and Flow Loss Study of the Barton Springs Segment of the Edwards Aquifer: Barton Springs/Edwards Aquifer Conservation District and City of Austin. Report to the Texas Commission on Environmental Quality, 85 pages plus figures and appendix, https://www.researchgate.net/publication/321873113↗.

Smith, C.I., J.B. Brown, and F.E. Lozo, 2000, Regional Stratigraphic Cross Sections, Comanche Cretaceous (Fredericksburg-Washita Division), Edwards and Stockton Plateaus, West Texas: Interpretation of Sedimentary Facies, Depositional Cycles, and Tectonics: The University of Texas at Smith and Hunt, 2004 Austin. Bureau of Economic Geology, 39 pages, https://store.beg.utexas.edu/cross-sections/2736-cs0011.html↗, accessed on March 3, 2022.

Smith, D.V., R.R. McDougal, B.D. Smith, and C.D. Blome, 2008, Distribution of Igneous Rocks in Medina and Uvalde Counties, Texas, as Inferred from Aeromagnetic Data. U.S. Geological Survey Scientific Investigations Report 2007-5191, 12 pages, 1 plate, scale 1:250,000, https://doi.org/10.3133/sir20075191↗.

Sprouse, P., 2009, Karst and Groundwater in Northeastern Coahuila: An Edwards Aquifer Mirror *in* Proceedings: 15th International Congress of Speleology, volume 1, page 1690, Kerville, Texas, USA: International Union of Speleology, https://repositories.lib.utexas.edu/handle/2152/63665↗, accessed on March 3, 2022.

Technical Advisory Panel, 1990, Technical Factors in Edwards Aquifer Use and Management: Final Report to the Special Joint Texas Senate and House of Representatives Committee on the Edwards Aquifer, 57 pages.

Texas Water Development Board (TWDB), 2012, Texas Water Development Board, Climate of Texas: Water for Texas 2012 State Water Plan, chapter 4, pages 145-155, https://www.twdb.texas.gov/publications/state_water_plan/2012/2012_SWP.pdf↗, accessed on March 3, 2022.

TWDB, 2016, Texas Water Development Board, Groundwater, Edwards (Balcones Fault Zone) Aquifer, Texas Aquifers Study: Groundwater Quantity, Quality, Flow, and Contributions to Surface Water, https://www.twdb.texas.gov/groundwater/docs/studies/TexasAquifersStudy_2016.pdf#page=89↗, accessed on May 16, 2022.

TDWB, 2021, Texas Water Development Board, Groundwater, https://www.twdb.texas.gov/groundwater/index.asp↗, accessed on March 3, 2022.

TWDB, 2022, Texas Water Development Board, Edwards-Trinity (High Plains) Aquifer, https://www.twdb.texas.gov/groundwater/aquifer/minors/edwards-trinity-high-plains.asp↗, accessed on March 3, 2022.

Thorkildsen, D.F., and P.D. McElhaney, 1992, Model refinement and applications for the Edwards (Balcones fault zone) aquifer in the San Antonio region, Texas. Texas Water Development Board Report 340, 33 pages, http://www.twdb.texas.gov/groundwater/models/gam/ebfz_s/R340.pdf?d=8538.284999999632↗, accessed on March 3, 2022.

Toll, N., S.B. Fratesi, R.T. Green, F.P. Bertetti, and R. Nunu, 2017, Water-Resource Management of the Devils River Watershed Final Report. Contract Report for the Devils River Conservancy, 53 pages, https://static1.squarespace.com/static/535a88f6e4b0fbad919ef959/t/59c03afe46c3c404b3975b0d/1505770266524/Devils+River+Final+Report+Rev+3.pdf 1↗, accessed on March 3, 2022.

Toll, N.J., R.T. Green, R.N. McGinnis, L.M. Stepchinski, R.R. Nunu, G.R. Walter, J. Harding, N.E. Deeds, M.E. Flores, and K.D.H. Gulliver, 2019, Conceptual Model Report for the Hill Country Trinity Aquifer Groundwater Availability Model. Contract Report for the Texas Water Development Board, 282 pages, https://www.twdb.texas.gov/groundwater/models/gam/trnt_h/ConceptualModelReport.pdf?d=13839.300000071526↗, accessed on May 16, 2022.

Tremallo, R., S. Johnson, J. Hamilton, J. Winterle, S. Eason, and J. Hernandez, 2016, Edwards Aquifer Authority Hydrologic Data Report for 2015 - Groundwater: Edwards Aquifer Report 15-01, https://www.edwardsaquifer.org/science-and-maps/research-and-scientific-reports/hydrologic-data-reports↗, accessed on March 3, 2022.

Uliana, M.M., and J.M. Sharp Jr, 1996, Springflow augmentation possibilities at Comal and San Marcos springs, Edwards aquifer. Gulf Coast Association of Geological Societies, volume 46, pages 423-432, http://archives.datapages.com/data/gcags/data/046/046001/0423.htm↗, accessed on March 3, 2022.

Walker, L.E., 1979, Occurrence, availability, and chemical quality of ground water in the Edwards Plateau Region of Texas. Texas Department of Water Resources Report 235, 337 pages, https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R235/R235.pdf↗, accessed on March 3, 2022.

Wanakule, N., and R. Anaya, 1993, A lumped parameter model for the Edwards Aquifer, Technical Report Number 163, Texas Water Resources Institute, Texas A and M University, College Station Texas, 83 pages, https://www.researchgate.net/publication/26902640 ↗.

Weeks, A.W., 1945, Balcones, Luling, and Mexia fault zones in Texas. American Association of Petroleum Geologists Bulletin, volume 29, pages 1733–1737, https://doi.org/10.1306/3D9337B0-16B1-11D7-8645000102C1865D↗.

Welder, F.A., and R.D. Reeves, 1962 Geology and Ground-Water Resources of Uvalde County, Texas. Texas Water Commission, Bulletin 6212, 246 pages, https://www.twdb.texas.gov/publications/reports/bulletins/doc/Bull.htm/B6212.asp↗, accessed on March 3, 2022.

White, K., G.R. Davisson, and P. Paquin. 2009, Hydrologic evolution of the Edwards Aquifer recharge zone (Balcones fault zone) as recorded in the DNA of eyeless Cicurina cave spiders, south-central Texas. Geology, volume 37, number 4, pages 339-342, https://doi.org/10.1130/G25373A.1↗.

Winterle, J.R., S.L. Painter, and R.T. Green, 2009, Update of groundwater availability model for Barton Springs segment of the Edwards Aquifer utilizing the MODFLOW-DCM variant for enhanced representation of flow through karst aquifers. Contract Report for the Texas Water Development Board and the Barton Springs Edwards Aquifer Conservation District, 49 pages, https://bseacd.org/uploads/HR_DCM_SWRI_Report_2009.pdf↗, accessed on March 3, 2022.

Worthington, S.R.H., 1999, A comprehensive strategy for understanding flow in carbonate aquifers: *in* Karst Modeling: Karst Waters Institute Special Publication 5, editors, A.N. Palmer, M.V. Palmer, and I.D. Sasowsky, pages 30-37.

Worthington, S.R.H., C. Smart, and W. Ruland, 2002, Assessment of groundwater velocities to the municipal wells at Walkerton *in* Groundwater Theory to Practice D. Stolle, A.R. Piggott, and J.J. Crowder. Proceedings of the 55th Canadian Geotechnical and 3rd Joint IAH-CNC and CGS Groundwater Specialty Conferences, Niagara Falls, Ontario, Southern Ontario Section of the Canadian Geotechnical Society, pages 1081-1086, https://www.researchgate.net/publication/282947211↗.

Worthington, S.R.H., 2004, Conduits and turbulent flow in the Edwards aquifer: Worthington Groundwater, contract Report to Edwards Aquifer Authority, San Antonio, TX., 41 pages, https://gato-docs.its.txstate.edu/jcr:22e2b991-e8d9-4589-bd46-e2e9af765ac4↗, accessed on May 16, 2022.

Yelderman, J.C., Jr, 1987, Hydrogeology of the Edwards Aquifer - Northern Balcones and Washita Prairie Segments. Austin Geological Society Guidebook 11, 91 pages, https://store.beg.utexas.edu/ags/129-ags011.html↗, accessed on March 3, 2022.

Yelderman, J.C., Jr, 2019, The Washita Prairie segment of the Edwards (Balcones Fault Zone) Aquifer, *in* The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource. Geological Society of America Memoir 215, editors, J.M. Sharp Jr, R.T. Green, and G.M. Schindel, chapter 10, pages 131-136, https://doi.org/10.1130/2019.1215(10)↗.

Yielding, G., B. Freeman, D.T. Needham, 1997, Quantitative fault seal prediction. Bulletin of the American Association of Petroleum Geologists, volume 81, number 6, pages 897–917, https://doi.org/10.1306/522B498D-1727-11D7-8645000102C1865D↗.

Young, S.C., J. Doherty, T. Budge, and N. Deeds, 2009, Application of PEST to Re-Calibrate the Groundwater Availability Model for the Edwards-Trinity (Plateau) and Pecos Valley Aquifers, 231 pages, http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0804830820_Edwards-Trinity_PecosGAM.pdf↗, accessed on March 3, 2022.

Zahm, C.K., 1998, Use of outcrop fracture measurements to estimate regional groundwater flow, Barton Springs Segment of Edwards Aquifer: unpub. Mater of Science thesis, The University of Texas, Austin, Texas, 154 pages

Zapitello, S.J., D.A. Johns, and B.B. Hunt, 2019, Summary of Groundwater Tracing in the Barton Springs Edwards Aquifer from 1996 to 2017: City of Austin Watershed Protection Report DR-19-04, 29 pages, https://bseacd.org/2019/12/summary-of-groundwater-tracing-in-the-barton-springs-edwards-aquifer-from-1996-to-2017/↗, accessed on March 3, 2022.

10 Exercise Solutions

Solution Exercise 1

Higher temperatures will increase evapotranspiration over the contributing and recharge zones. Precipitation changes are as yet unclear. Net precipitation may increase or decrease. However, more extensive droughts and more high rainfall events are predicted. These suggest there will be times when the aquifer cannot meet the water needs of a growing population.

Public policies could include restrictions on population growth (which does not seem possible today), mandatory conservation measures, elimination of irrigated agriculture which has a high consumptive use, and conjunctive use (using surface water in times of high stream flow and the aquifer in times of low stream flow).

Infrastructure options might include aquifer storage and recovery, desalination of brackish waters (Texas has abundant brackish waters), and importation of water from distant sources.

Return to Exercise 1↥

Solution Exercise 2

There are both groundwater quantity and quality aspects of urbanization.

The growing population will require more water for domestic, industrial, and irrigation (lawns and gardens). Leaky water mains and sewage lines as well as over-irrigation may increase recharge in the recharge zone whereas increased impervious cover has the opposite effect. Flooding intensity will increase because of impervious ground surface cover and additional storm sewers.

Water quality will be threatened because of leaky sewer systems, spills, and accidents. These can release raw sewage and many different contaminants into the environment and possibly affect spring-dependent ecosystems.

Restriction of urban sprawl over the recharge zones is a possible solution. Quality control of streams flowing from the catchment areas that recharge losing streams is another. Urban planning could consider the possible changes to the groundwater flow systems to increase recharge and control water quality.

Return to Exercise 2↥

Solution Exercise 3

Your answer might involve:

- lack of knowledge of:
    - specific aquifer properties, including aquifer extent, conduit permeability, formation facies, among others;
    - aquifer ecology and endemic species;
- the effects of urbanization;
- new sources of contamination; and,
- the possible effects of climate change.

Return to Exercise 3↥

Solution Exercise 4

Surface water is owned by the state; use of water for purpose other than domestic and livestock use must be permitted. Groundwater is under the English Doctrine in which land owners may pump as much as they desire unless it causes subsidence and consequent inundation of adjacent properties or is done with malicious intent.

Texas emphasizes local control of the groundwater through GCDs. These have a variety of water management actions, including restricting pumping during droughts or because of loss of spring flow habitats. Recently, Texas courts have ruled that groundwater is a property right and restricting one's ability to pump (during droughts) is not constitutional.

Adequacy of the aquifer to support future needs is an open question.

Return to Exercise 4↥

Solution Exercise 5

Current numerical models poorly represent the triple porosity/permeability of the aquifer because the location of the conduits and their permeability as well as the fracture permeability, are not well documented.

The models may give useful estimates of aquifer water budgets and when properly calibrated may predict spring flows and heads within the aquifer. They cannot predict precise flow paths and rates of contaminant transport.

Return to Exercise 5↥

Solution Exercise 6

Description of the evolution of porosity/permeability development in the Edwards Aquifer should include karstification in the Cretaceous period and, more importantly, since uplift after the Miocene; the development of fractures; and the formation of karstic conduits. More detailed answers might include the effects of mixing of allogenic recharge waters with water in equilibrium with the aquifer, the effects of mixing along the bad-water line and epikarst processes.

Return to Exercise 6⮥

Solution Exercise 7

Spatial distribution of stygobites species can be determined via detailed sampling of wells and spring outlets. New DNA analyses of the groundwater may also help.

Return to Exercise 7⮥

Solution Exercise 8

Location of groundwater divides in the Edwards Aquifer are controlled by location of losing streams, temporal and spatial distributions of both recharge and pumping, aquifer offsets (for the Kinney-San Antonio segment divide), fault system permeability, and the Colorado River (which is not a divide but separates the Barton Springs and Northern segments).

During droughts, divides may shift or even disappear, but can reform with increased recharge.

Return to Exercise 8⮥

Solution Exercise 9

In describing how a karst aquifer is fundamentally different from a clastic aquifer, the response should note that, compared to other aquifer types, karst aquifers generally have triple porosity and permeability fields (matrix, fractures, and conduits). Permeability can be highly anisotropic, very high, and range over many orders of magnitude. Recharge in karstic units commonly has both discrete and diffuse components. Discrete recharge through sinkholes and fractures is characteristic of many karst aquifers. Losing streams are common in karstic units. Clastic aquifers may be strongly controlled by variations in bedding facies.

In describing how a karst aquifer is fundamentally different from a crystalline rock aquifer, the response should indicate that crystalline rock aquifers tend to be shallow, have very low storativity, and their permeability is dominated by fracture sets.

Return to Exercise 9⮥

Solution Exercise 10

Flow in the conduits is probably turbulent at times and Darcy's Law may not apply in karstic conduits and fractures. Flow in a karstic conduit is often diffusively represented by an equivalent porous media model. However, it is beneficial to include discrete features in the simulation that can account for pipe or open channel flow within the conduits under laminar and turbulent conditions. Inclusion of discrete features requires a lot of computer processing that is likely to exceed available computing resources and be prohibitively expensive.

Conduit variables include conduit location, effective diameter, roughness, and connectivity with other conduits.

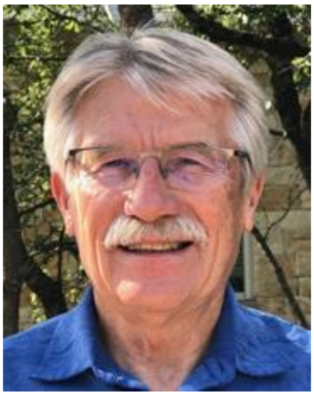
Flow in the matrix is probably laminar with the key variables being permeability, storativity, and strata thickness.

Fracture variables include hydraulic aperture and fracture spacing, orientation and connectivity.

Return to Exercise 10↥

11 About the Authors

Dr. Jack Sharp is the Carlton Professor of Geology Emeritus at The University of Texas. He has a Bachelor of Geological Engineering with Distinction from the University of Minnesota, and a Master of Science and a Doctor of Philosophy from the University of Illinois. He is a Fellow of the Geological Society of America and the Alexander von Humboldt Stiftung and has also held positions with the NSF (National Science Foundation), the USGS (United States Geological Survey), and in Australia (CSIRO—Commonwealth Scientific and Industrial Research Organization—and Flinders University). Jack has been President of the GSA (Geological Society of America) and the Austin Geological Society; Treasurer of the IAH (International Association of Hydrogeologists) and Council of Scientific Society Presidents; Chairman of the US IAH Chapter; and Vice President of the American Institute of Hydrology (AIH). He has edited GSA and IAH monographs; Engineering and Environmental Geoscience; the GSA Bulletin, Hydrological Science and Technology, and Hydrogeology Journal. Honors include the Meinzer and Hydrogeology Division Distinguished Service awards (GSA); the Theis and Founders awards (AIH); the Presidents' Award (IAH); Lifetime Achievement Award (Barton Springs/Edwards Aquifer Conservation District); 2021 Alumni Achievement Award (University of Illinois); Phi Kappa Phi; Tau Beta Pi; and distinguished lectureships—Edwards Aquifer Authority, Farvolden Lecturer (University of Waterloo), and Hoeing Lecturer (Kentucky Geological Survey). He has supervised over 50 undergraduate and precisely 100 graduate theses. Hobbies include gardening, genealogy, fishing, duck hunting, Australia, opera, UT football, and (before bad knees) handball.



Dr. Ron Green's appreciation for hydrology dates to his time as a Peace Corps volunteer in Cameroon Africa in the early 1970s where he worked on a rural water-resource project. After completing his studies in Hydrology at the University of Arizona and a brief stint in environmental consulting, he spent his career at Southwest Research Institute working in applied research. In the early years of his career he focused on safe disposal of highly radioactive waste (HLW) in fractured rock. During subsequent years he worked on assessment of water resources targeting karst terrains in arid and semi-arid environments. He served as chair of the National Cave and Karst Research Institute Board. He recently co-edited a memoir titled "The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource" in which he authored several chapters. He is a Fellow of the Geological Society of America in recognition of his work in flow and transport in karst media.

Please consider signing up for the GW-Project mailing list to stay informed about new book releases, events and ways to participate in the GW-Project. When you sign up for our email list it helps us build a global groundwater community. Sign up↗.