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Climate variability, climate change, and Edwards Aquifer water fluxes

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ABSTRACT

The Edwards (Balcones Fault Zone) Aquifer is a high-yield aquifer that provides water for municipal, military, irrigation, domestic, and livestock uses in south-central Texas, and it discharges to several springs that support groundwater ecosystems. Natural water cycling in the Edwards (Balcones Fault Zone) Aquifer is driven by recharge, which depends on precipitation and runoff over the catchment area and recharge zone of the aquifer. This chapter analyzes the water fluxes in the Edwards (Balcones Fault Zone) Aquifer and how they vary with climatic variability and might vary with modern-age climatic change. This work also evaluates the safe yield of the Edwards (Balcones Fault Zone) Aquifer under historic climatic conditions, which is ~400 thousand acre·feet, or 493 × 10^6 m^3, annually. These results have implications for aquifer groundwater extraction and human and environmental water requirements, such that future groundwater extraction must be adaptive to precipitation and recharge fluctuations to preserve groundwater ecosystems.

INTRODUCTION

The Edwards (Balcones Fault Zone) Aquifer has an area of ~9200 km^2. Several streams issue from the aquifer's catchment area (11,300 km^2) and contribute to recharge the aquifer. The Edwards (Balcones Fault Zone) Aquifer and its catchment area encompass all or part of 13 counties in south-central Texas. The aquifer discharges through several springs, the largest being Leona Springs, San Pedro Springs, San Antonio Springs, Comal Springs, Hueco Springs, and San Marcos Springs. These springs support endemic aquatic organisms that form part of unique groundwater ecosystems (Longley, 1981). Groundwater extraction in the aquifer has adversely impacted several of its endemic species (Loáiciga, 2017). The antagonism created by groundwater extraction to provide for human use of groundwater and the decline of spring flow to maintain healthy groundwater ecosystems has been the cause of lengthy legal battles over groundwater management of the aquifer. The water balance in the recharge zone (unconfined part of the Edwards [Balcones Fault Zone] Aquifer) is controlled by aquifer recharge, evapotranspiration (*ET*), groundwater extraction, and groundwater flow to the confined region of the aquifer. The water balance in the confined part of the aquifer is controlled by groundwater inflow from the recharge zone, groundwater extraction by wells, and spring discharges.

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The geologic history and hydrogeology of the Edwards (Balcones Fault Zone) Aquifer have been summarized by Maclay (1995), and they are reviewed in other chapters of this memoir. Loáiciga et al. (2000) and Loáiciga (2003, 2009, 2017) reported studies of groundwater management in the Edwards (Balcones Fault Zone) Aquifer. The following sections analyze the climatic, hydrologic, and hydrogeologic characteristics of the Edwards Aquifer region and its water use and evaluate strategies for long-term groundwater use in the Edwards (Balcones Fault Zone) Aquifer that meet water uses while preserving groundwater ecosystems, that is, providing sustainable groundwater management.

PRECIPITATION AND SURFACE AIR TEMPERATURE IN THE EDWARDS REGION

A perspective of climatic variability and change in the Edwards region is gained by evaluating instrumental records of precipitation and temperature in that region. The National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) compiles and processes climatic data sets for the United States. The data sets are arranged geographically into climatological divisions. There are 344 climatological divisions in the United States. They represent regions within which climatic characteristics are relatively uniform and distinct from other regions. Monthly station temperature and precipitation values are computed from the daily observation within each climatological division. The divisional values are weighted by area to compute statewide values, and the statewide values are weighted by area to compute regional values. The state of Texas, for example, is divided into 10 climatological divisions. Division 6 is named the Edwards Plateau, which encompasses the Edwards (Balcones Fault Zone) Aquifer and its catchment area. Figure 1 displays the divisional annual surface air temperature and its trend during the period 1895–2017. The average annual temperature equals 18.5 °C. An increasing decadal trend in annual temperature is graphed in Figure 1 equal to 0.035 °C/10 yr. The increasing temperature trend is pertinent to this study's analysis because it may be attributed to a rise in the surficial net radiant energy.

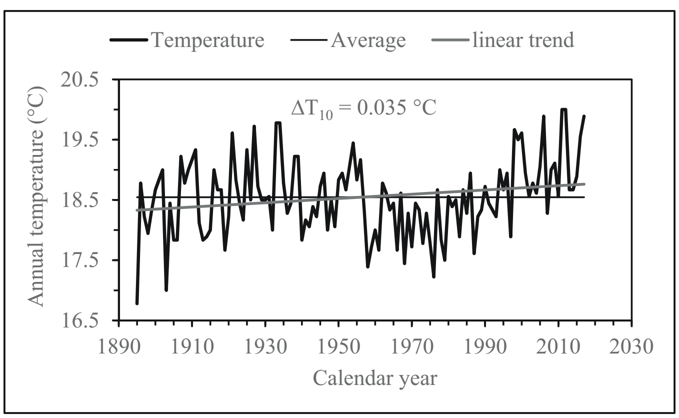

Figure 1. Annual surface air temperature and temperature (T) trend in the Edwards Plateau climatological division. The average annual surface air temperature equals 18.5 °C. Data source: National Climatic Data Center: www.ncdc.noaa.gov/monitoring-references/maps/US-climate-divisions.php (2018).

An increase in surface air temperature also tends to increase the water-holding capacity of surface air. In spite of several complicating nuances, the effect of increasing surface air temperature is to increase the evapotranspiration (*ET*) according to the Penman-Monteith formula (see, e.g., Dingman, 2015). The annual water balance of the Edwards (Balcones Fault Zone) Aquifer is described by the following equation, in which ΔS denotes the annual change in groundwater storage, R_T, Q, D, and ET, respectively denote annual total recharge, groundwater withdrawal (by wells), spring flow, and evapotranspiration:

$$\Delta S = R_T - Q - D - ET. \quad (1)$$

An increase in evapotranspiration tends to decrease groundwater storage, as seen in Equation 1. It is useful to call the difference $R_T - ET$ net recharge, or simply recharge (R), which is the addition of water to aquifer storage. The water balance of the Edwards (Balcones Fault Zone) Aquifer is then rewritten as follows:

$$\Delta S = R - Q - D. \quad (2)$$

The calculation of recharge in the Edwards (Balcones Fault Zone) Aquifer is discussed in a specialized section below.

Figure 2 displays the annual precipitation and the precipitation trend in the Edwards Plateau climatological division during the period 1895–2017. The average annual precipitation equals 59.69 cm. An increasing decadal trend in precipitation was detected equaling 0.16 cm/10 yr.

The historic trend in precipitation acts to increase runoff and, therefore, recharge and groundwater storage, contrary to the effect of increasing evapotranspiration. Recharge depends on runoff, and runoff depends primarily on the amount of precipitation. Runoff also depends on land cover. A region wherein the land cover is modified by urbanization would produce more runoff for the same amount of precipitation because less precipitation would be retained by vegetation and soils. Runoff plays a central role in the calculation of recharge in the Edwards (Balcones Fault Zone) Aquifer, as shown in the section devoted to recharge estimation. These considerations about water balance apply to conditions in the study region in the period 1895–2017. See section on "Climate Change in the Edwards (Balcones Fault Zone) Aquifer," corresponding to climate projections in the twenty-first century.

Land use and land cover have evolved over time, driven by economic development in the Edwards Plateau. Human-induced changes underline how complex it is to make predictions about the hydrologic future in the Edwards Plateau (and other regions) during the twenty-first century and beyond. Humans modify land use and land cover, which impact runoff and evapotranspiration,

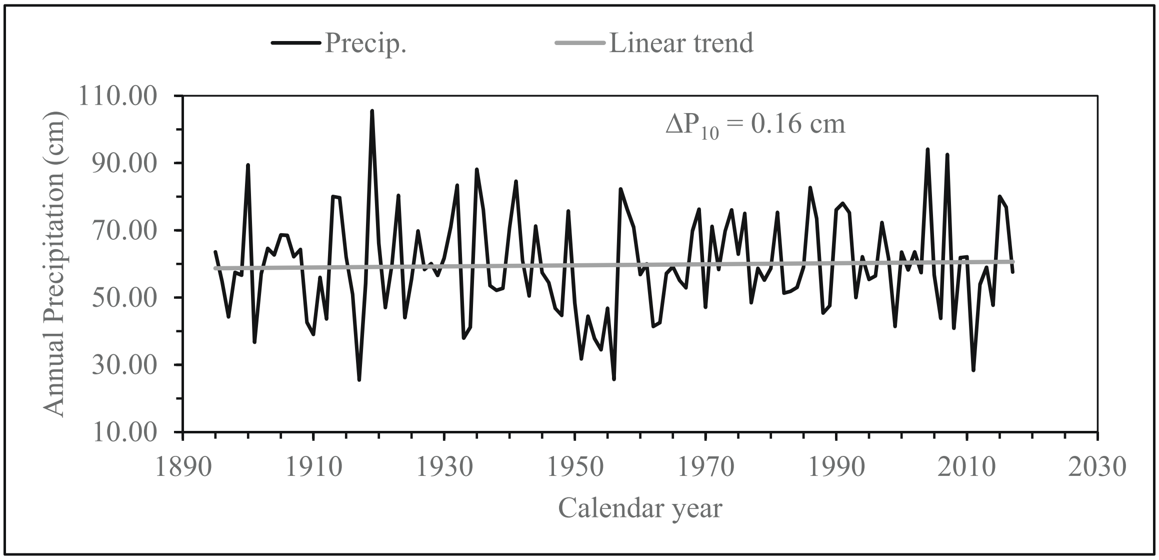

Figure 2. Annual precipitation and precipitation (P) trend in the Edwards Plateau climatological division. The average annual precipitation equals 56.69 cm. Data source: National Climatic Data Center: www.ncdc.noaa.gov/monitoring-references/maps/US-climate-divisions.php (2018).

the latter by modification of vegetative cover and soil cover. Numerical climate models (or coupled atmospheric-oceanic general circulation models, AOGCMs) compute projections of what the future climate might be. These scenarios assume how greenhouse gas concentrations and multiple other factors that influence climatic change will evolve over time. The climate projections produced by the models are therefore conditioned on their assumptions being met. Moreover, there is the additional difficulty introduced by the imperfect representation in the models of the complex Earth-extraterrestrial system governing climatic and hydrologic dynamics.

Another dimension of complexity concerns the very large interannual variability in precipitation, which drives the regional hydrologic cycle. Figure 3 depicts the cumulative deviation of

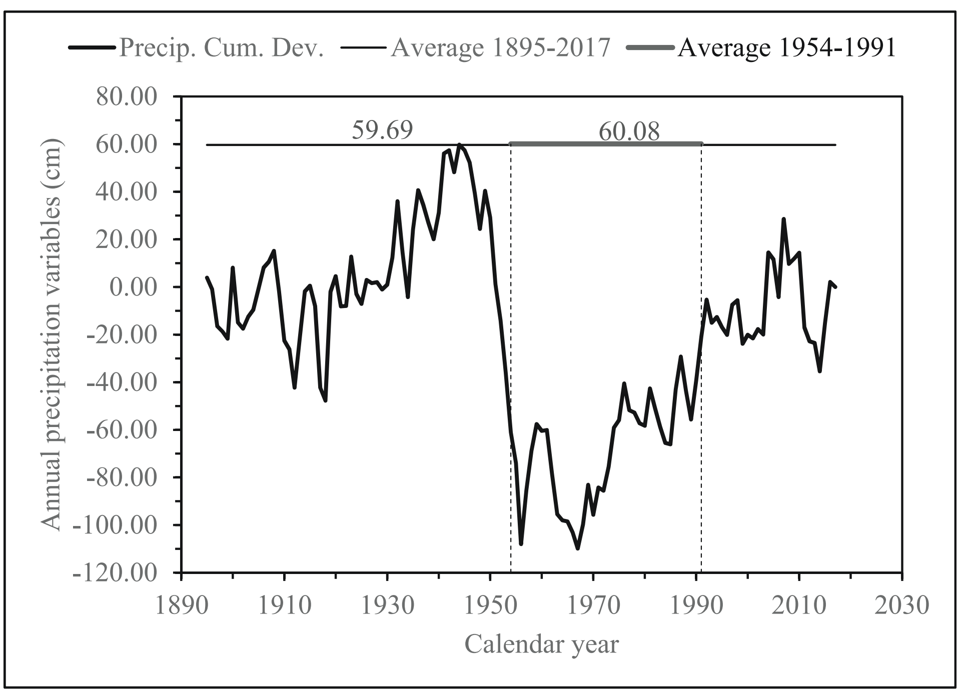

Figure 3. Cumulative deviation of annual precipitation from the average annual precipitation in the period 1895–2017 and during the climatically representative period (1954–1991). Data source: National Climatic Data Center: www.ncdc.noaa.gov/monitoring-references/maps/US-climate-divisions.php (2018).

annual precipitation from the average annual precipitation in the Edwards region. The cumulative deviation is useful in detecting patterns of overall variation of precipitation over time. Figure 3 shows that precipitation rose and declined about a stable level between 1895 and 2017, followed by an overall increasing trend until 1945. This was followed by an overall declining trend until 1967, which includes the historically critical drought in the Edwards region. Thereafter, precipitation experienced a rising trend until 2007. The pattern of overall variation of precipitation remains unclear after 2007 and through 2015. The high variability of annual precipitation results in highly variable runoff in the Edwards region and, thus, in highly variable annual recharge in the Edwards (Balcones Fault Zone) Aquifer, as will be shown below.

Another feature displayed in Figure 3 is the time interval delimiting a climatically representative period for the purpose of determining the safe yield under conditions of relatively stable climate. The climatically representative period identified herein extends from 1954 through 1991. Figure 3 shows that the average annual precipitation during the climatically representative period equals 60.08 cm, which differs by only 0.64% from the long-term average annual precipitation (= 56.69 cm). A climatically representative period has several intervals of wet and dry climate, has an average annual precipitation nearly identical to the long-term average annual precipitation, and begins in a period of declining precipitation, so that groundwater storage is not at full capacity and recharge is possible (Loáiciga, 2017). There may be more than one climatically representative period in a long historic record of precipitation. This means the safe yield may vary depending on the climatically representative period employed for its determination. The safe yield is therefore a statistical entity. It is defined in the section devoted to safe yield determination.

GROUNDWATER STORAGE AND WATER FLUXES IN THE EDWARDS (BALCONES FAULT ZONE) AQUIFER

Figure 4 depicts the annual recharge, spring flow, and groundwater withdrawal in the Edwards (Balcones Fault Zone) Aquifer over the period 1934–2015. Evapotranspiration is not plotted because it is included in the net recharge or recharge (*R*) defined above. The recharge calculation in the Edwards (Balcones Fault Zone) Aquifer depends on balancing of streamflows within the recharge zone. The gauged streamflows are caused by base flow plus effective precipitation, i.e., by precipitation minus evapotranspiration as implied by Equations 1 and 2.

The recharge plotted in Figure 4 takes into account evapotranspirative losses, and it corresponds to $R_T - ET$ introduced in Equation 1. We shall refer to this difference simply as recharge in this work because this is the conventional term used in the calculation of recharge (Puente, 1978; LBG-Guyton Associates & Aqua Terra, 2005). Figure 4 shows that the spring flow follows the pattern of recharge with a short time delay, but it exhibits a smoother

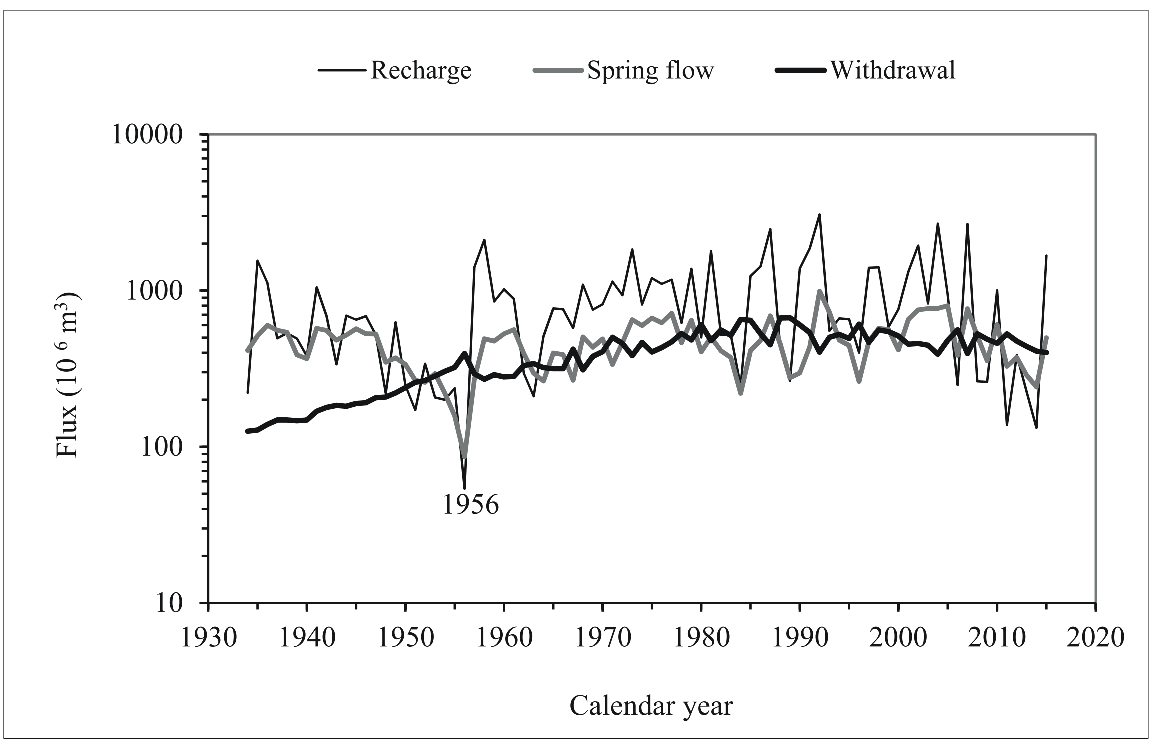

Figure 4. Annual water fluxes in the Edwards (Balcones Fault Zone) Aquifer (1934–2015). Data source: www.edwardsaquifer.net/data.html.

temporal variability. The recharge was smallest in 1956 (53.90×10^6 m^3 = 43.7×10^3 acre·feet) during the historic drought in the Edwards Plateau region. The annual recharge was largest in 1992 (3066×10^6 m^3 = 2.49×10^6 acre·feet). The groundwater withdrawal was lowest in 1934 (125.7×10^6 m^3 = 102×10^3 acre·feet) and exhibited an overall increasing trend until 1989 (669×10^6 m^3 = 542.6×10^3 acre·feet). It declined to 401×10^6 m^3 (= 325.2×10^3 acre·feet) by 2015 as a result of challenges by the U.S. Fish and Wildlife Services (USFWS) and environmental organizations to the reduction of spring flow by groundwater withdrawal. The Edwards (Balcones Fault Zone) Aquifer groundwater discharges naturally as spring flow, which in turn supports endemic aquatic ecosystems vulnerable to reductions in spring flow and groundwater storage. The aquifer groundwater supports spring flows and several economic uses, including municipal, military, irrigation, domestic and livestock, and industrial. The relative magnitudes of the various uses of aquifer groundwater are calculated by defining aquifer discharge as the sum of groundwater withdrawal and spring flow. Spring flow constituted 50.03% of the aquifer discharge in the period 1934–2015. Municipal and military, irrigation, domestic and livestock, and industrial uses accounted for 28.11%, 13.51%, 4.20%, and 4.15% of the aquifer discharge respectively in 1934–2015.

Figure 5 displays the variation in the cumulative change in annual storage and the cumulative deviation of precipitation from its average for the period 1934–2015. The two graphs exhibit very similar temporal patterns. This reaffirms the previously stated fact that recharge is driven by precipitation, which causes runoff, and runoff as streamflow becomes recharge by stream seepage.

Another feature visible in Figure 5 is the maximum and minimum cumulative change in aquifer storage, which equal 3421 and −2522 million cubic meters, respectively. The difference 3421 − (−2522) equals 5943×10^6 m^3 (~4.82×10^6 acre·feet), which is a lower bound to the storage capacity of the Edwards (Balcones Fault Zone) Aquifer (Loáiciga, 2017). Conservatively pricing 1 acre-foot of fresh groundwater at \$500 indicates the value of groundwater reserves in the Edwards (Balcones Fault Zone) Aquifer exceeds 2.4 billion U.S. dollars.

CALCULATION OF RECHARGE IN THE EDWARDS (BALCONES FAULT ZONE) AQUIFER

The method to calculate annual recharge in the Edwards (Balcones Fault Zone) Aquifer was developed by Lowry (1955) and Petitt and George (1956), and refined by Garza (1962, 1966). It was summarized as a U.S. Geological Survey (USGS) report

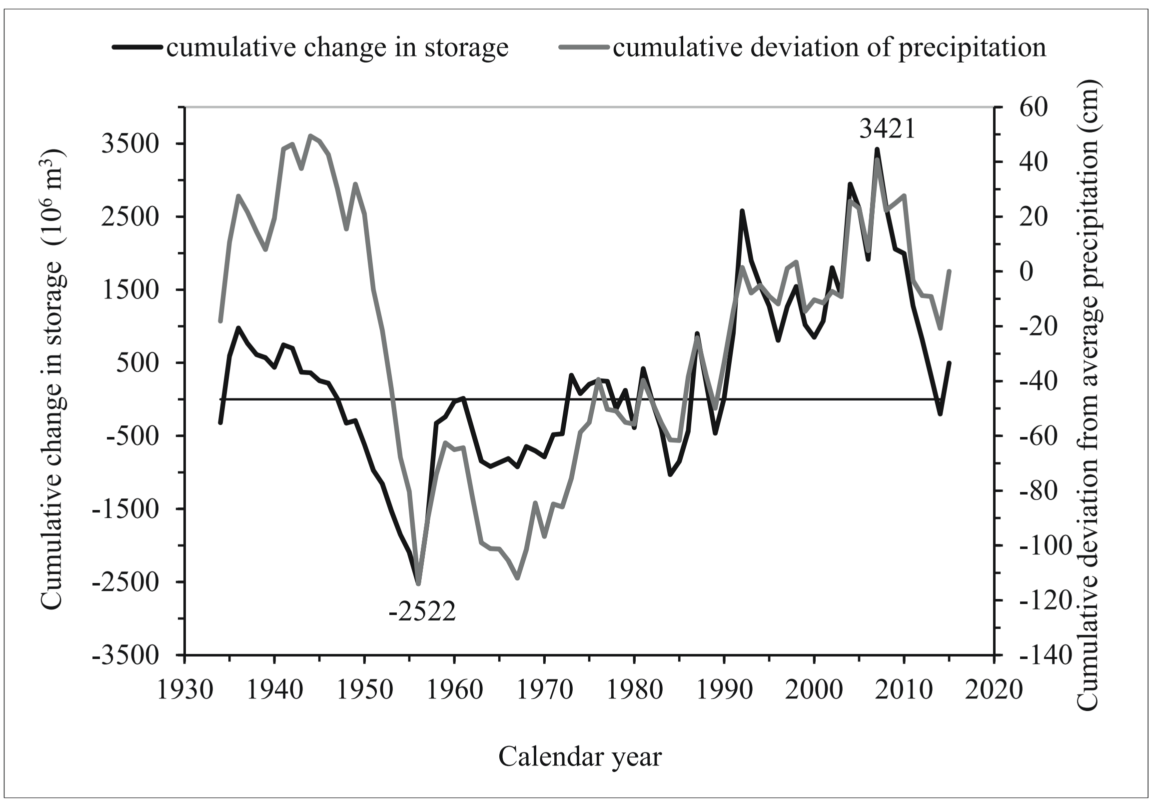

Figure 5. Cumulative change in annual storage and cumulative deviation of precipitation from its average annual value for the period 1934–2015 in the Edwards (Balcones Fault Zone) Aquifer. Data source: National Climatic Data Center (for precipitation): www.ncdc.noaa.gov/monitoring-references/maps/US-climate-divisions.php (2018).

by Puente (1978). The method calculates monthly recharge, and these monthly values are summed to produce the annual recharge. LBG-Guyton Associates & Aqua Terra (2005) refined the USGS method by making recharge calculations over shorter durations, say, hourly, by means of hydrologic simulations with HSPF (hydrologic simulation program in Fortran). The short-term simulations were then summed to yield longer-term estimates of recharge. The USGS recharge-calculation method is illustrated by referring to a generic cross section through the Edwards Plateau and the Edwards (Balcones Fault Zone) Aquifer shown in Figure 6.

The generic cross section shown in Figure 6 includes the three hydrologic components governing recharge and its disposition. Those are the catchment or contributing area, the recharge zone, and the artesian region. The catchment area includes the Edwards Plateau aquifer ("a" through "b" in Fig. 6). Streams originate in the catchment area and flow through the recharge zone and toward the Gulf of Mexico. The catchment area's perimeter is delimited by the letters "a" and "c." The recharge zone is where the Edwards limestones outcrop. These are karstified carbonate rocks that make up the aquifer's porous matrix. Stream seepage within this zone is the source of the recharge to

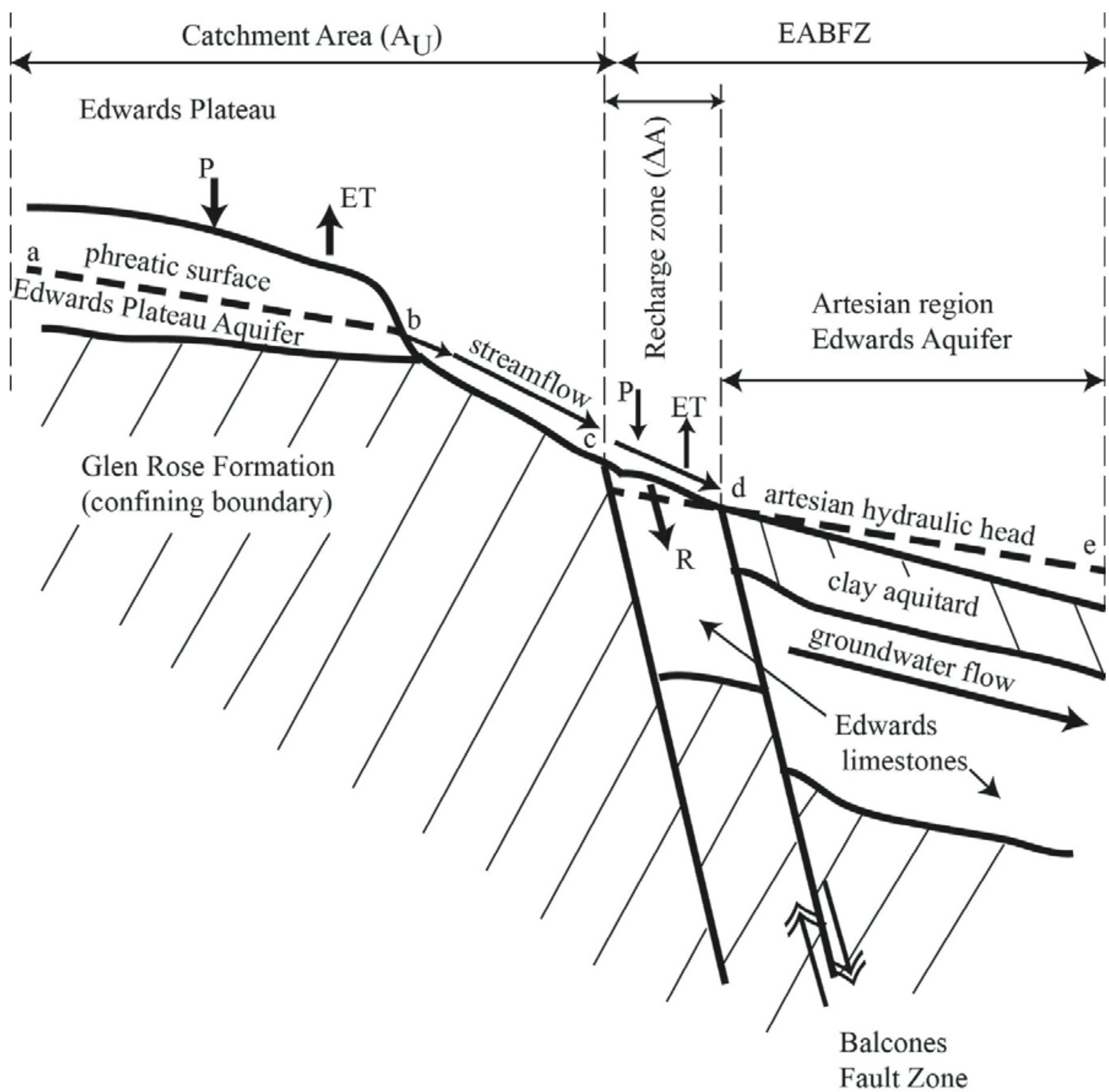

Figure 6. Generic cross section through the catchment area, recharge zone, and artesian region of the Edwards (Balcones Fault Zone) Aquifer (EABFZ). Streams originate in the catchment area (A) and flow through the recharge zone and toward the Gulf of Mexico. Lowercase letters: a–c—catchment area, including the Edwards Plateau aquifer (a through b; perimeter a through c); c–d—recharge zone; d–e—confined artesian region. Capital letters: P—precipitation; R—recharge; ET—evapotranspiration.

the aquifer. The recharge zone is delimited by the letters "c" and "d." Groundwater transitions from the unconfined recharge zone to the confined artesian region, which is delimited by the letters "d" and "e."

The calculation of recharge in the Edwards (Balcones Fault Zone) Aquifer is based on water balance of the recharge zone. The water balance quantifies water inputs to and water outputs from the recharge zone. One water input to the recharge zone is streamflow measured upstream of the recharge zone, near point "c" in Figure 6. The monthly volume of water entering the recharge zone is denoted by Q_U. The water output from the recharge zone is streamflow measured downstream of the recharge zone, near point "d" in Figure 6. The monthly volume of water output is denoted by Q_L. Part of the precipitation falling within the zone between the upstream and downstream streamflow gauging stations generates runoff that accrues as streamflow. This contribution to streamflow is commonly known as overland flow or direct runoff. The remainder of the precipitation percolates through the exposed Edwards limestones and becomes base flow to streamflow within the intergauge zone, or it is evapotranspired. The direct runoff and base flow generated within the intergauge zone, herein denoted by ΔQ, contribute to streamflow. ΔQ is calculated by separating measured hydrographs at the upstream gauging station caused by all storms occurring with a month into (1) direct runoff plus base flow, and (2) base flow before the storm. Let Q_{tu} denote the monthly water volume of direct runoff plus base flow calculated at the upstream gauging station. The USGS method for calculating recharge (Puente, 1978) assumes ΔQ is proportional to Q_{tu}. The proportionality factor equals the ratio of the intergauging area (ΔA) to the tributary or catchment area at the upstream gauging station (A_U) multiplied by the ratio of precipitation in the intergauging area (ΔP) to the precipitation in the catchment area (P_U):

$$\Delta Q = \frac{\Delta A}{A_U} \cdot \frac{\Delta P}{P_U} Q_{tu}. \tag{3}$$

The intergauge water input ΔQ represents an approximation to the effective precipitation $P - ET$. The monthly recharge (R_M) is calculated by water balance within the recharge zone:

$$R_M = Q_U + \Delta Q = Q_L. \tag{4}$$

The sum of the monthly recharge yields the annual recharge R. The calculation of recharge in the Edwards (Balcones Fault Zone) Aquifer is carried out by implementing Equation 4 in nine river basins encompassing the catchment area and the recharge zone. The aquifer-wide recharge equals the sum of the nine basinal recharges. The nine basins are named Nueces, Frio, Sabinal, Area between Sabinal and Medina, Medina, Area between Medina and Cibolo, Cibolo, Guadalupe, and Blanco. The recharge plotted in Figure 4 represents the Edwards (Balcones Fault Zone) Aquifer annual recharge.

SAFE YIELD IN THE EDWARDS AQUIFER

The safe yield (also called perennial yield or basin yield) is the maximum quantity of water that can be continuously withdrawn from a groundwater basin without adverse effect (for a review of the safe yield, see Loáiciga, 2017; for early definitions, see Lee, 1915; Meinzer, 1923). The adverse effect is commonly observed as long-term progressive decline of groundwater levels, or "overdraft." Overdraft is associated with a number of deleterious impacts (see, e.g., Custodio, 2002; Zektser et al., 2005; Gleeson et al., 2012). Those impacts include seawater intrusion (see, e.g., Loáiciga et al., 2012; Werner et al., 2013), land subsidence (see, e.g., Galloway and Burbey, 2011; Loáiciga, 2013), reduction of base flow to streams (Sophocleous, 2002; Barlow and Leake, 2012), impairment of groundwater ecosystems (Loáiciga, 2003), loss of plant-community richness and density (Chen et al., 2006), loss of well yield and increasing cost of groundwater extraction (Scanlon et al., 2012), and deterioration of groundwater quality (Currell, 2014). The safe yield is an average rate of groundwater extraction calculated over a climatically representative period, defined above. Reliance on a climatically representative period assumes a regional climate in steady state.

Recall that Figures 1 and 2 portray long-term increasing and decreasing trends in surface temperature and precipitation in the Edwards (Balcones Fault Zone) Aquifer, respectively. The increasing precipitation tends to increase runoff and, thus, recharge, whereas the increasing surface temperature tends to decrease runoff and recharge in the Edwards (Balcones Fault Zone) Aquifer. The future of surface temperature and precipitation in the study region through the remainder of the twenty-first century is uncertain. The future change of land cover there, which would impact runoff and recharge, is likewise uncertain. This section's analysis of the aquifer's safe yield, therefore, represents an approximation to the steady-state assumption, which, due to human action and natural processes, does not hold strictly. This section's analysis relies on recharge, groundwater withdrawal, and spring flow data for the period 1934–2015. It is one the longest and best-quality data sets of its kind available. The annual recharge, groundwater withdrawal, and spring-flow data for the Edwards (Balcones Fault Zone) Aquifer are plotted in Figure 4, and the cumulative annual change of storage is plotted in Figure 5. The recharge data and annual change of storage establish large interannual variability, which is superimposed on long-term trends of climatic change. It is evident from the data presented herein that climatic variability expressed in terms of interannual precipitation variability was the dominant factor governing recharge in the Edwards aquifer in the period 1934–2015. Increasing groundwater extraction in the same period coupled with intermittent drought account for spring-flow reduction that has adversely impacted aquifer's groundwater ecosystems (U.S. Fish and Wildlife Service, 2013).

Time-averaging the water balance in Equation 2 over the period of analysis (1934–2015) produces:

$$\overline{\Delta S} = \overline{R} - \overline{Q} - \overline{D}, \tag{5}$$

in which, for instance, $\overline{\Delta S}$ denotes the average annual change of storage in the Edwards (Balcones Fault Zone) Aquifer. Similar definitions hold for the recharge ($\overline{R}$), groundwater withdrawal ($\overline{Q}$), and spring flow ($\overline{D}$) terms on the right-hand side of Equation 5. The safe yield equals the average annual groundwater extraction rate that produces an average annual change in groundwater storage equal to zero during the climatically representative period, $\overline{\Delta S} = 0$ (Loáiciga, 2017). Using this fact in Equation 5 yields the formula for the safe yield ($\overline{Q}_{safe}$) in the Edwards (Balcones Fault Zone) Aquifer:

$$\overline{Q}_{safe} = \overline{R} - \overline{D} - \overline{ET} \cong \overline{R} - \overline{D}. \tag{6}$$

One implication of Equation 6 is that the safe yield does not equal the average annual recharge. Consideration must be given to the average annual spring flow during the climatically representative period. Cooper et al. (1982) and Bredehoeft (1997) referred to equating the safe yield with the average annual recharge as the "water-budget myth." There is ample empirical evidence from many aquifers that average groundwater extraction commonly exceeds the average annual recharge, causing basin overdraft (see, e.g., Gleeson et al., 2012). This situation is endemic to groundwater basins exhibiting temporally variable recharge in semiarid regions where irrigated agriculture is a heavy user of groundwater. The California Sustainability Groundwater Management Act enacted in 2014 is a well-known example of political action intended to reverse overdraft of many aquifers in that state. The estimation of the safe yield with Equation 6 requires accurate estimates of the average annual recharge and spring flow in the Edwards (Balcones Fault Zone) Aquifer. These are available from the data graphed in Figure 4. The average annual recharge and spring flow for the climatically representative period equal 931 and 430 million cubic meters, respectively (755×10^3 and 349×10^3 acre·feet). This implies a safe yield estimate equal to 501×10^6 m^3 (= 406×10^3 acre·feet) in the Edwards (Balcones Fault Zone) Aquifer. The latter is an average annual withdrawal rate. Notice the difference between the safe yield and the average annual recharge.

An alternative and less accurate estimate of the safe yield than that obtained with Equation 6 can be derived by regressing the annual change in groundwater storage against the annual groundwater withdrawal during the climatically representative period. The annual groundwater withdrawal that makes the annual change in groundwater storage equal to zero in the derived regression represents the estimate of the safe yield. This alternative method is useful when recharge, spring flow, and other fluxes entering in the water balance equation of an aquifer are not available. The annual change in groundwater storage must be calculated in this instance by relating the annual basinwide groundwater-level change to the specific yield (for unconfined condition) and storage coefficient (for artesian condition) according to well-known functions (see, e.g., Fetter, 2001; Loáiciga, 2017). The illustration of this second method to estimate the safe yield calculates the change of annual storage from the recharge, groundwater withdrawal, and spring flow data based on Equation 2. The change of annual groundwater storage so calculated was then regressed against the annual groundwater withdrawal during the climatically representative period. Figure 7 shows the graph of the annual change in storage versus the annual groundwater withdrawal. The estimated safe yield in this instance equals 492×10^6 m^3 (= 399×10^3 acre·feet).

A third method for evaluating the safe yield relies on regressing the annual basinwide change in groundwater level versus the annual groundwater withdrawal. The annual basinwide change in groundwater level must be obtained from groundwater level distributed across the aquifer. It represents a spatial average of groundwater level change representative of conditions within the basin (Loáiciga, 2017). The safe yield equals the annual groundwater withdrawals that make the annual basinwide change of groundwater level equal to zero. Figure 8 displays the regression of the annual change in groundwater level versus the annual groundwater withdrawal. The safe yield in this case equals 483×10^6 m^3 (= 392×10^3 acre·feet). The three estimates of the safe yield indicate that it is in the neighborhood of ~400,000 acre·feet, or 493×10^6 m^3 annually. This number provides a useful reference for groundwater extraction in the Edwards (Balcones Fault Zone) Aquifer. A groundwater extraction policy exceeding the 400,000 acre-feet annually would lead to groundwater quality deterioration and ecosystem decline in the Edwards (Balcones Fault Zone) Aquifer, akin to conditions existing in the 1970s and 1980s. During severe and protracted drought, actual groundwater extraction must be curtailed to avoid irreversible damage to ecosystems, depending on the aquifer's groundwater storage and spring flow. The tailoring of groundwater extraction to lessen the deleterious impacts of droughts constitutes adaptive management that ensures sustainable groundwater management. Another key management strategy in the Edwards (Balcones Fault Zone) Aquifer is protecting the recharge zone from development that could alter its hydrologic characteristics and water quality (Sharp, 2010).

CLIMATE CHANGE IN THE EDWARDS (BALCONES FAULT ZONE) AQUIFER

Much has been written about climate change (see, e.g., the classic work by Budyko, 1977). It is known from geologic evidence that Earth's climate has been evolving for as long as our planet has existed. The focus over the last four decades has been on the role humans might have on climate change, specifically, on the human-caused increase of greenhouse gases by burning of fossil fuels, primarily in the post–Industrial Revolution era (since ca. A.D. 1760), and its effects on climate change. The United Nations' Intergovernmental Panel on Climate Change (IPCC) has published several reports on the topic of human-influenced

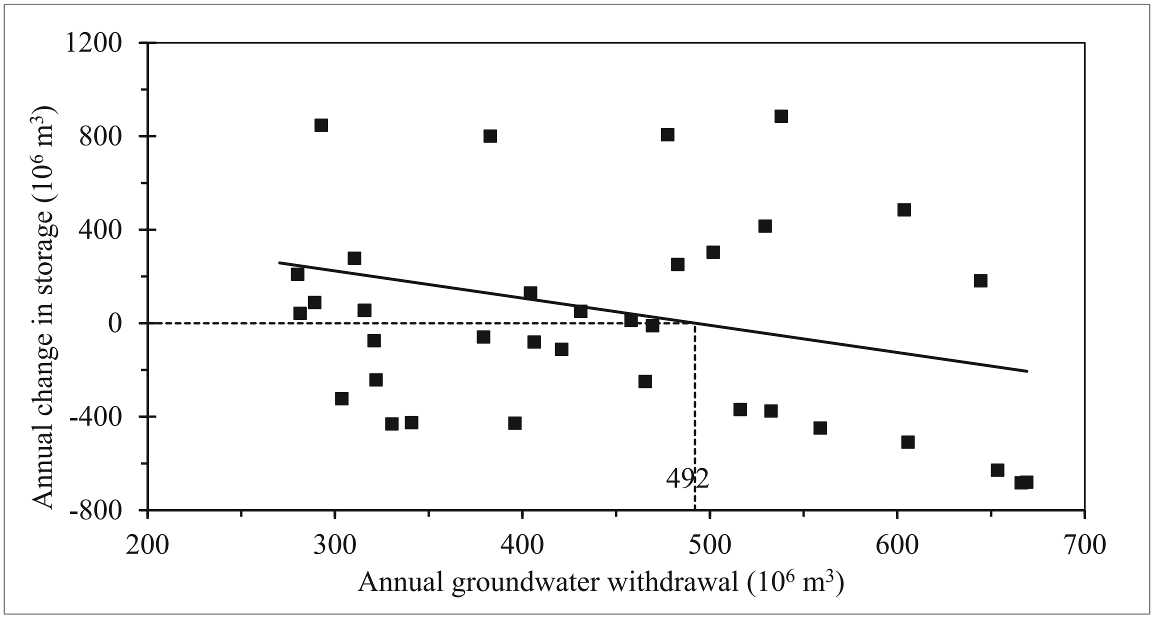

Figure 7. Estimate of the Edwards (Balcones Fault Zone) Aquifer safe yield from the regression of the annual change in storage vs. the annual groundwater withdrawal. The estimated safe yield equals 492×10^6 m^3/yr (= 399×10^3 acre·feet).

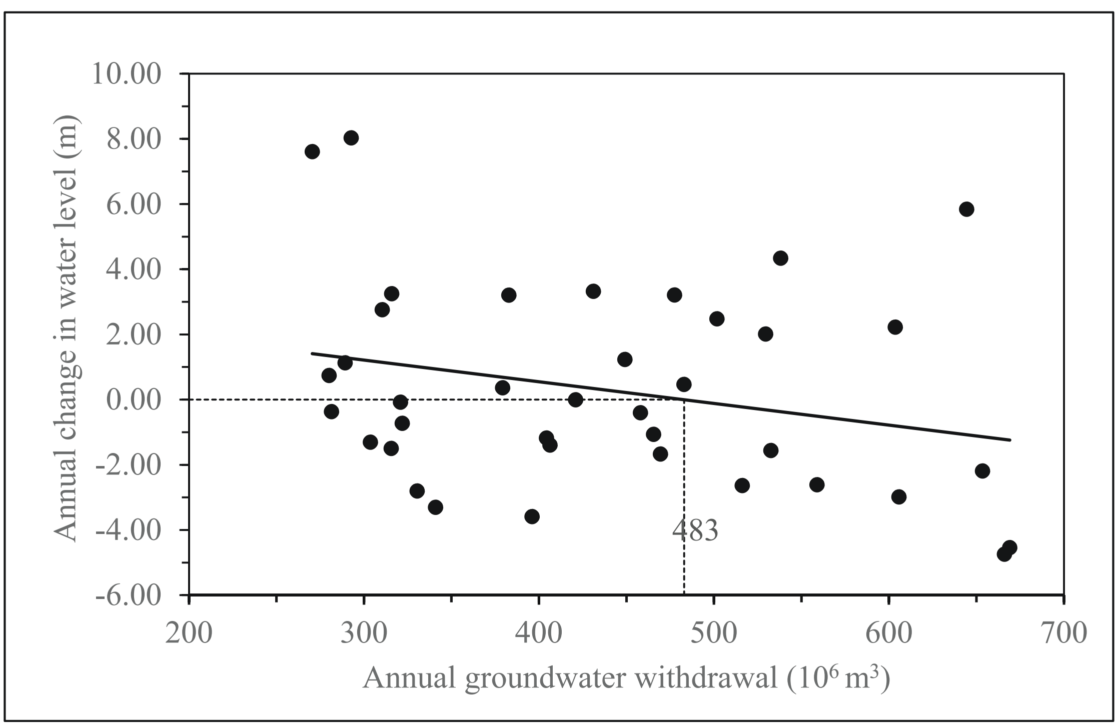

Figure 8. Estimate of the Edwards (Balcones Fault Zone) Aquifer safe yield from the regression of the annual change of groundwater level vs. the annual groundwater withdrawal. The safe yield in this case equals 483×10^6 m^3/yr (= 392×10^3 acre·feet).

climate change. More relevant to this memoir are the climate assessments written by the United States Global Change Research Program (USGCRP). The USGCRP is supported by several federal agencies with jurisdictions covering all aspects of the Earth system and beyond. Among them are the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the U.S. Geological Survey (USGS), the U.S. Environmental Protection Agency (USEPA), and the U.S. Fish and Wildlife Service (USFWS). The reader is referred to the USGCRP's 2017 4th National Climate Assessment (USGCRP, 2017, volume I) for historical review of historic climatic trends in the United States since the beginning of the twentieth century, and for climate projections for part of the twenty-first century. This memoir summarized in Figures 1 and 2 the historic patterns of surface precipitation and precipitation, respectively, in the Edwards Plateau climatic division recorded in the period 1895–2015. The USGCRP (2017) fourth National Climate Assessment reported, among other variables, seasonal precipitation projections for the United States. The projections depicted in Figure 9 were calculated with several climate models as part of the Coupled Model Inter-comparison Project, Fifth Phase (or CMIP5). The projections from each model were averaged over the period 2070–2099. Those averages were weighted across the models, and the resulting values were expressed as the percent change relative to the 1976–2005 average seasonal precipitation. Furthermore, the projections displayed in Figure 9 correspond to the Representative Concentration Pathway 8.5 (RCP8.5). This is one among several scenarios of future greenhouse gases emissions that have been created by climate scientists to input into climate models. Atmospheric carbon

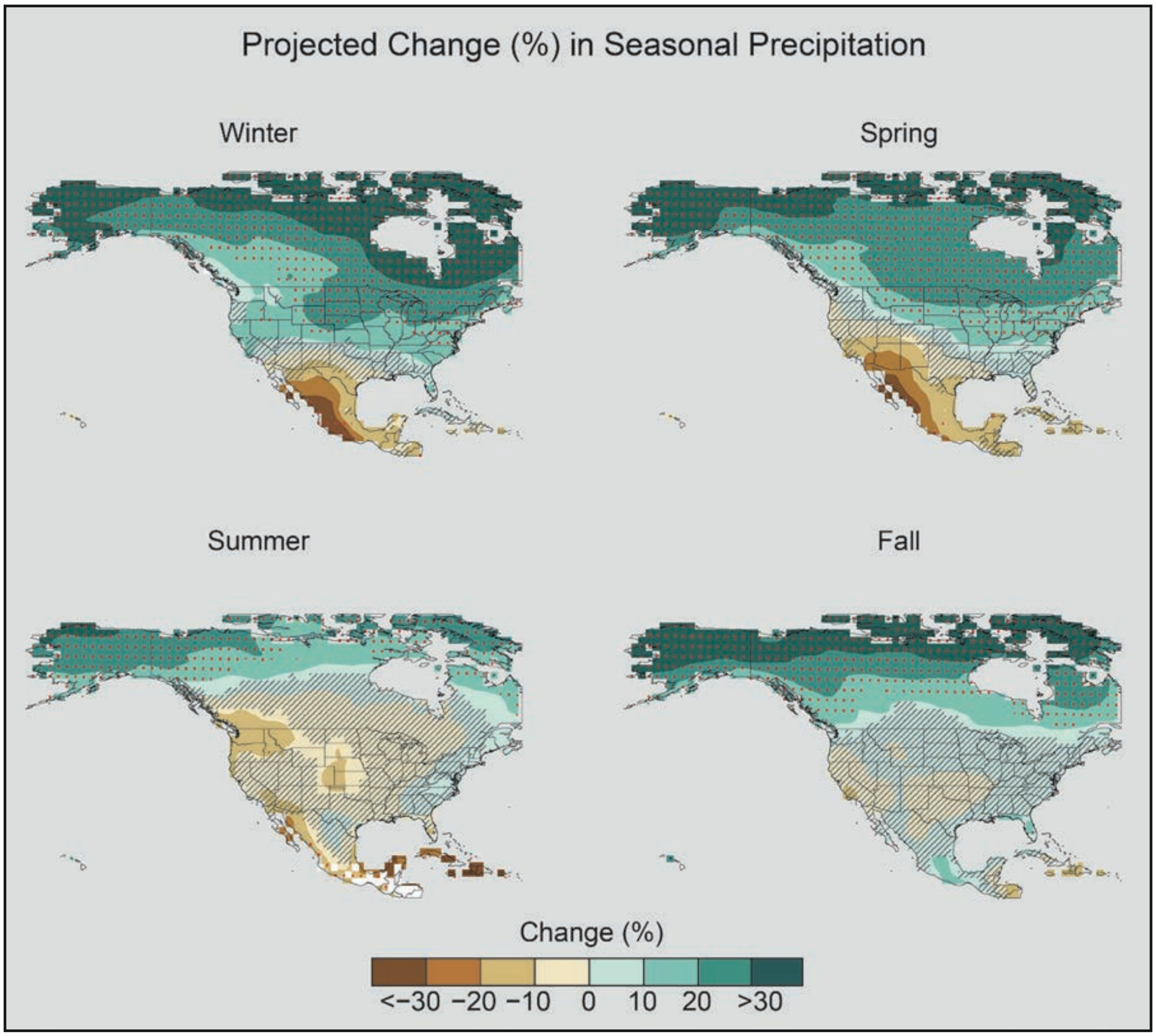

Figure 9. Projected change (%) in total seasonal precipitation from CMIP5 simulations for 2070–2099, shown on a map of the United States. Stippling indicates that changes are assessed to be large compared to natural variations. Hatching indicates that changes are assessed to be small compared to natural variations. Blank regions (if any) are where projections are assessed to be inconclusive. See text for details. Source: USGCRP (2017) National Climate Assessment.

dioxide levels for RCP8.5 rise from current-day levels of ~410 up to 936 ppm by the end of this century. CO_2-equivalent levels (including emissions of other non-CO_2 greenhouse gases, aerosols, and other substances that affect climate) reach more than 1200 ppm by 2100, and global temperature is projected to increase in the range 5.4° to 9.9 °F (3° to 5.5 °C) by 2100 relative to the 1986–2005 average. It is crucial to underscore the fact that the climate projections shown in Figure 9 represent greenhouse gas scenario–based simulations. The climate projections do not consider how land cover and land use might change from present through 2099 because those changes would be speculative given the dynamic nature of future socioeconomic change. The land cover and land use in the recharge zone of the Edwards (Balcones Fault Zone) Aquifer have substantial effects on aquifer storage, as explained above.

Figure 9 indicates that the projected changes in spring, summer, and fall precipitation in the Edwards region appear to be small compared with natural variations. The summer and fall precipitations are of special significance in the Edwards region because they include the hurricane season in the Gulf of Mexico, when the most intense precipitation, and therefore runoff, occurs over the Edwards (Balcones Fault Zone) Aquifer. The projected winter precipitation in Figure 9 indicates borderline change that is small compared with natural variations and reduction in the range of 10%–20%. Runoff depends on precipitation. It is logical to assume that seasonal runoff changes would have similar patterns to those projected for seasonal precipitation. The USGCRP (2017) National Climate Assessment does not report runoff projections. Runoff in the Edwards region governs recharge to the Edwards (Balcones Fault Zone) Aquifer, as shown by Equation 4.

Figure 10 portrays projected changes in annual average temperatures (in °F). Changes are the difference between the average temperature for the mid–twenty-first century (2036–2065) or late century (2070–2099) and the average for near present (1976–2005). Each map depicts the weighted multimodel average temperature, in a manner analogous to that described in the discussion of Figure 9. Increases are statistically significant over the entire United States. This means more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change. The projections depicted in Figure 10 correspond to lower (RCP4.5) and higher (RCP8.5) greenhouse gases scenarios. The latter scenario was defined above. The RCP4.5 scenario prescribes atmospheric CO_2 concentrations less than 550 ppmv by 2100. CO_2-equivalent concentrations, including all emissions from human activities, reach 580 ppm under RCP4.5 by 2100.

The temperature projections shown in Figure 10 corresponding to the RCP4.5 scenario indicate increases in average annual air surface temperature within the Edwards region in the ranges of 2 °F through to 4 °F (1.1 °C through 2.2 °C) and 4 °F through 6 °F (2.2 °C through 3.3 °C) in the mid–twenty-first century and late century, respectively. The temperature projections associated with the RCP8.5 scenario fall in the ranges 4 °F through 6 °F (2.2 °C through 3.3 °C) and 6 °F through 8 °F (3.3 °C through 4.4 °C) by mid–twenty-first century and late twenty-first century, respectively. In summary, the historic temperature patterns and the USGCRP's (2017) scenario-based temperature projections point to surface warming in the Edwards region. This may mitigate the increases in runoff within the Edwards region by increasing precipitation trend observed between 1895 and 2015. The next section presents an alternative approach to projections of precipitation in the Edwards region that can be applied to develop associated projections of impacts in the Edwards (Balcones Fault Zone) Aquifer.

An Approach to Projecting Recharge and Groundwater Withdrawal Impacts

The runoff coefficient (K) equals the ratio of runoff (Q) to precipitation (P) in a region:

$$K = \frac{Q}{P}. \tag{7}$$

From Equation 7, we have:

$$Q = K\,P. \tag{8}$$

This approach for creating runoff projections relies on a precipitation ratio. Specifically, let P_{1CO2} and P_{2CO2} denote the precipitation simulated by general circulation models (GCMs) under the scenarios corresponding to the baseline CO_2 atmospheric concentration and twice the baseline CO_2 concentration, respectively. The baseline CO_2 concentration corresponds to the 1990 level (360 ppmv). The current CO_2 concentration is ~410 ppmv. The precipitation simulations from leading GCMs are weighted to calculate an average projected precipitation. The precipitation-ratio method scales historical precipitation (P_{history}) to make a projection of the precipitation under a 2× CO_2 scenario as follows ($P_{2CO2\ scenario}$; Loáiciga, 2003):

$$P_{2CO2\ scenario} = \frac{P_{2CO2}}{P_{1CO2}} \cdot P_{history}\,, \tag{9}$$

where $P_{2CO2}/\,P_{1CO2}$ denotes the precipitation ratio. Assume P_{1CO2} and P_{2CO2} are statistically independent and unbiased estimators of the precipitation under 1× CO_2 and 2× CO_2 conditions, respectively. Taking the expected value of the left- and right-hand sides of Equation 9 indicates the expected value of $P_{2CO2\ scenario}$ equals the expected value of the precipitation under the 2× CO_2 scenario. The historical precipitation may represent average, wet, or dry climatic periods, in which case, the projected precipitation in Equation 9 would yield respectively a projection of average, wet, or dry conditions under the 2× CO_2 scenario. Precipitation ratios were calculated for the conterminous United States as part of the National Center for Atmospheric Research's (NCAR) Vegetation Ecosystem Modeling and Analysis Project (VEMAP) database (see Kittel et al., 1995). The precipitation ratios were calculated

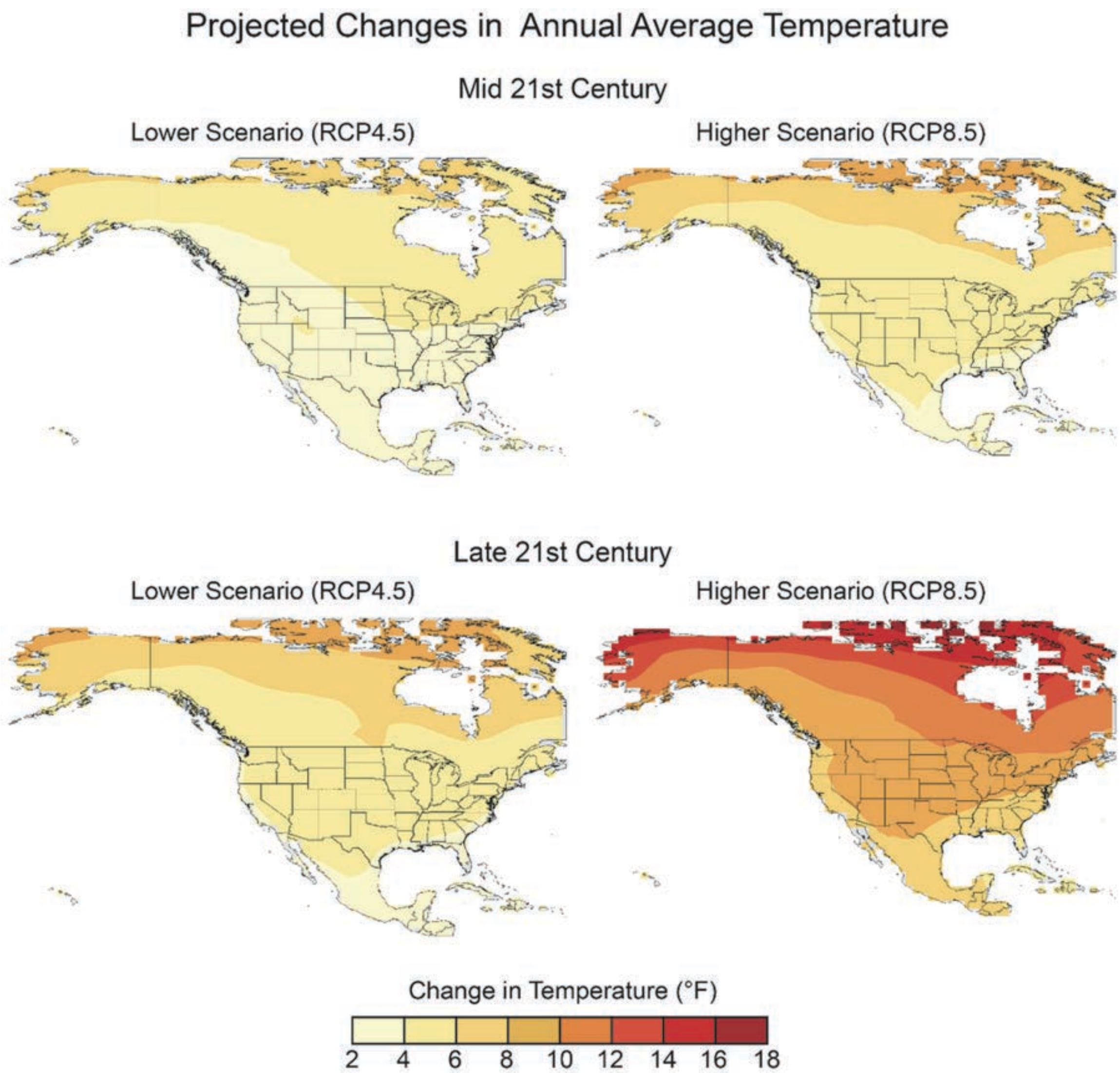

Figure 10. Projected changes in annual average temperatures (°F), shown on a map of the United States. Changes are the difference between the average for mid-century (2036–2065; top) or late century (2070–2099, bottom) and the average for near-present (1976–2005). RCP—Representative Concentration Pathway. See text for details. Source: USGCRP (2017). (°F = 1.8 °C + 32, where °C denotes degrees Celsius.)

at 0.5° latitude × 0.5° longitude resolution for the conterminous United States, including the Edwards Plateau region. Multiplying Equation 9 by the runoff coefficient K yields:

$$KP_{2CO2\ scenario} = \frac{K \cdot P_{2CO2}}{K \cdot P_{1CO2}} \cdot KP_{history}. \quad (10)$$

Using Equation 8 in Equation 10 leads to the projected runoff under a 2× CO_2 scenario:

$$Q_{2CO2\ scenario} = \frac{P_{2CO2}}{P_{1CO2}} \cdot Q_{history}. \quad (11)$$

Notice the runoff projection in Equation 11 assumes that the runoff coefficient remains unaltered as time goes on (GCMs make this assumption). Equation 11 establishes that the precipitation ratio scales historical runoff to 2× CO_2 runoff when the runoff coefficient remains constant. Let the precipitation ratio be denoted by r. Multiplying the left- and right-hand sides of Equation 4 by the precipitation ratio produces the projected aquifer recharge associated with the 2× CO_2 scenario (R_{M2CO2}):

$$r\,R_M \equiv R_{M2CO2} = r\,Q_U + r\,\Delta Q - r\,Q_L, \quad (12)$$

$$R_{M2CO2} = Q_{UCO2} + \Delta Q_{CO2} - Q_{LCO2}, \quad (13)$$

in which $r\,Q_U = Q_{UCO2}$, $r\,\Delta Q = \Delta Q_{CO2}$, and $r\,Q_L = Q_{LCO2}$. A projection of future recharge in the Edwards (Balcones Fault Zone) Aquifer is thus obtained by applying the VEMAP precipitation ratios to historical recharge as shown in Equations 12 and 13. The projected recharge is applied in a numerical groundwater flow model of the Edwards (Balcones Fault Zone) Aquifer to project aquifer response to groundwater withdrawal in a changed climate corresponding to 2× CO_2 (= 760 ppmv in this study) atmospheric concentration. Groundwater simulation in the Edwards (Balcones Fault Zone) Aquifer is described in the next section.

Results of Groundwater Simulations in a Changed Climate (2× CO_2)

The groundwater simulation results presented in this memoir were calculated with the GWSIM model. The GWSIM was developed by the Texas Water Development Board in 1974. It subsequently underwent several revisions by Thorkildsen and McElhaney (1992). GWSIM solves the vertically averaged, two-dimensional equation of groundwater flow:

$$\frac{\partial T \frac{\partial h}{\partial x}}{\partial x} + \frac{\partial T \frac{\partial h}{\partial y}}{\partial y} + N = S\,\frac{\partial h}{\partial t}, \qquad (14)$$

in which h, S, and T denote, respectively, hydraulic head, the storage coefficient, and transmissivity in the Edwards (Balcones Fault Zone) Aquifer. N denotes the excess of recharge over groundwater withdrawal plus spring flow. N takes a negative sign in Equation 14 when groundwater withdrawal plus spring flow exceeds the recharge (Bear, 1979). Otherwise, N is positive in Equation 14. GWSIM solves Equation 14 by means of a finite-difference scheme. GWSIM features empirical formulas for calculating spring flow from hydraulic head. This makes it particularly well suited for simulating the effect of groundwater withdrawal on spring flow, which has been the most contentious issue concerning groundwater withdrawal due to the adverse impacts on vulnerable groundwater ecosystems. Lindgren et al. (2009) evaluated several groundwater flow models, some covering the San Antonio and the Barton Springs segments of the Edwards (Balcones Fault Zone) Aquifer. Figure 11 displays the calculated minimum spring flow at Comal Springs, the largest in the Edwards (Balcones Fault Zone) Aquifer and the American Southwest. The spring flow in Figure 11 is expressed in m^3/s and ft^3/s uniform flow over a 30 d period. The minimum spring flow is shown as function of the annual groundwater withdrawal in 10^6 m^3 (= 810.7 acre-feet). One of the graphs of spring flow versus annual groundwater withdrawal corresponds to average

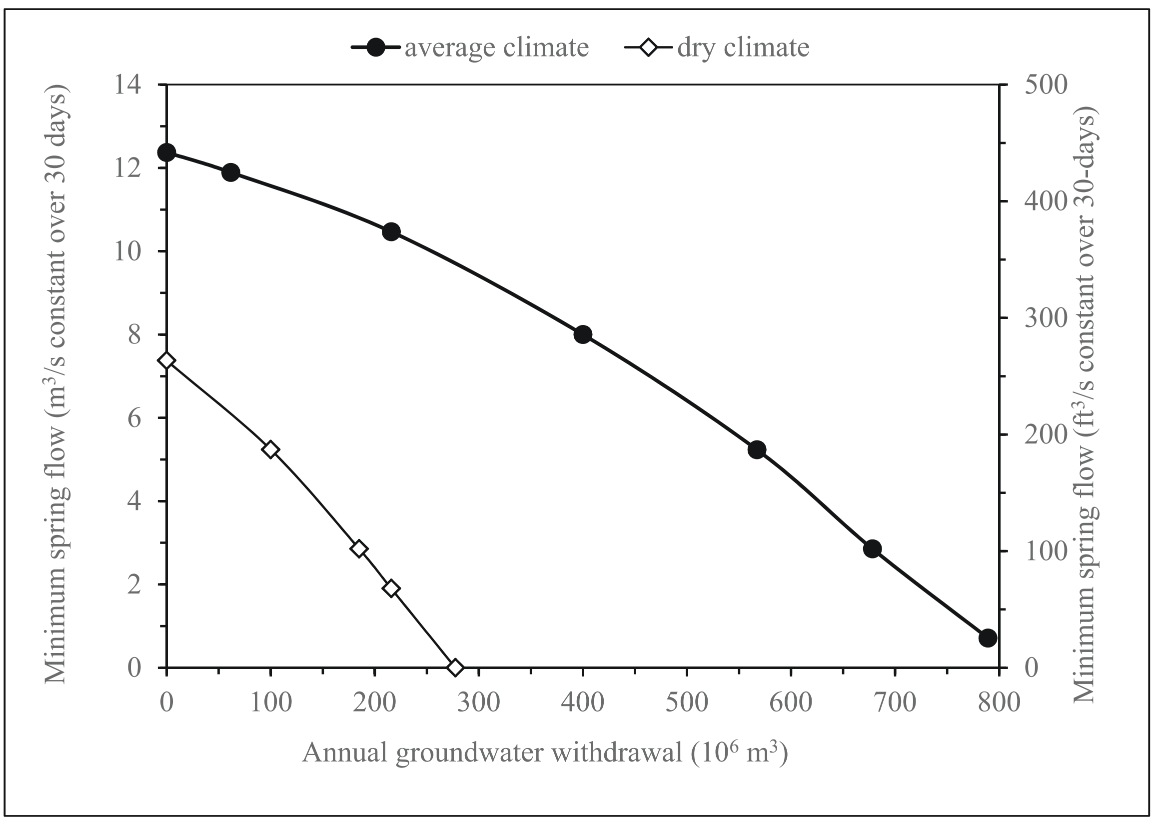

Figure 11. Minimum spring flow at Comal Springs caused by annual groundwater withdrawal for average or dry climate in the Edwards region under the 2× CO_2 scenario.

climate under the 2× CO_2 scenario; the other corresponds to dry climate under the same scenario. The average-climate scenario was obtained by scaling historic recharge in the average-climate period 1978–1989 with Equation 13. The dry-climate scenario was obtained by scaling historic recharge in the dry-climate period 1947–1959 using Equation 12. Average historic recharge during 1978–1989 and 1947–1959 equaled, respectively, 950×10^6 m^3 and 554×10^6 m^3. The minimum spring flow at Comal Springs and several other springs is a primary component of the Recovery Implementation Program and Habitat Conservation Plan (RIP-HCP) that Edwards (Balcones Fault Zone) Aquifer stakeholders must develop and implement (U.S. Fish and Wildlife Service, 2013).

The endangered species currently listed in the Edwards (Balcones Fault Zone) Aquifer are: Texas wild rice (*Zizania texana*), Comal Springs riffle beetle (*Heterelmis comalensis*), Comal Springs dryopid beetle (*Stygoparnus comalensis*), Peck's Cave amphipod (*Stygobromus pecki*), Fountain darter (*Etheostoma fonticola*), Texas blind salamander (*Eurycea [= Typhlomolge] rathbuni*), and the San Marcos gambusia (*Gambusia georgei*). The listed threatened species is the San Marcos salamander (*Eurycea nana*). Minimum spring flow is one of the environmental thresholds to maintain healthy groundwater ecosystems, as are the groundwater level, groundwater quality, and groundwater temperature. There is a striking difference between the minimum spring flow associated with average climate and dry climate in the Edwards (Balcones Fault Zone) Aquifer under the 2× CO_2 scenario. Figure 11 shows that an annual groundwater extraction equal to 493×10^6 m^3 (= 400×10^3 acre·feet), which equals the estimated safe yield of the Edwards (Balcones Fault Zone) Aquifer (see above), would produce a minimum monthly spring flow of ~7 m^3/s (= 247 ft^3/s) at Comal Springs with average climate under the 2× CO_2 scenario. The same amount of annual groundwater extraction would dry up Comal Springs with dry climate under the 2× CO_2 scenario. This finding highlights the importance of tailoring groundwater withdrawal to prevailing climatic conditions, which governs aquifer recharge, to protect groundwater ecosystems. Moreover, the need to adjust groundwater extraction to prevailing climatic conditions holds true for the historic climate, also. The adverse impact of historic groundwater withdrawal in the Edwards (Balcones Fault Zone) Aquifer in excess of the safe yield, and the failure to reduce withdrawal during dry periods are the reasons why the U.S. Fish and Wildlife Service intervened to protect several endangered and threatened species. Figure 11 reaffirms that in the absence of a sound recovery program for the Edwards (Balcones Fault Zone) Aquifer, environmental degradation would continue, and possibly worsen under the considered future climate scenario.

DISCUSSION AND CONCLUSIONS

This memoir has provided evidence of the high climatic variability in the Edwards region and its effects on aquifer recharge, a primary factor governing aquifer storage and water fluxes in the Edwards (Balcones Fault Zone) Aquifer. The historic (1895–2015) surface temperature and precipitation data analyzed in this chapter suggest a slightly rising trend in precipitation in the foreseeable future. This may translate into increased recharge given the direct relation between aquifer recharge and runoff in the Edwards (Balcones Fault Zone) Aquifer. However, the increased recharge may not materialize unless the recharge area is preserved to permit percolation into the outcropping limestones. Clearly, preservation of a pervious recharge zone must be a priority of groundwater management in the Edwards (Balcones Fault Zone) Aquifer (Sharp, 2010).

There is great uncertainty in model-developed projections of future precipitation and surface temperature in the Edwards region, be they from VEMAP or the USGCRP climate projections. This chapter's projections of recharge and minimum spring flow under a 2× CO_2 scenario seem to reinforce what has been observed during the instrumental period of recharge, withdrawal, and spring flow measurements (1934–present). Specifically, groundwater withdrawal must consider two key components. First, a long-term strategy for groundwater withdrawal must include identification of a "sustainable" withdrawal as an annual target not to be exceeded. Our analysis indicates this "sustainable" annual withdrawal may be on the order of ~400,000 acre·feet (or ~493 million cubic meters). We prefer the term "sustainable" withdrawal over safe yield simply to acknowledge that the latter term is strictly applicable to steady-state climate. The second component concerns a strategy for reducing groundwater withdrawal during protracted drought, because in the absence of withdrawal reduction, the minimum spring flow and associated groundwater levels may pose irreversible damage to groundwater ecosystems. Figure 11 is a good place to start devising strategies for withdrawal reduction during drought.

Climate is always evolving. Groundwater extraction has been amply proven to be vulnerable to the tragedy of the commons, whereby a commonly shared resource may be ruined, for humans, the environment, or both, unless flexible and well-thought-out strategies are developed and implemented, subject to adjustments as conditions demand it. Climate change might force us to become more vigilant and careful about managing groundwater. The history of the Edwards (Balcones Fault Zone) Aquifer suggests strongly that the remainder of the twenty-first century might turn out to be similar to what was experienced during the twentieth century: large interannual climatic variability, vulnerability of groundwater ecosystems to groundwater withdrawal, and the realization that even a resource as magnificent as the Edwards (Balcones Fault Zone) Aquifer has a finite carrying capacity.

REFERENCES CITED

Barlow, P.M., and Leake, S.A., 2012, Streamflow Depletion by Wells—Understanding and Managing the Effects of Groundwater Pumping on Streamflow: U.S. Geological Survey Circular 1376, 84 p., https://doi.org/10.3133/cir1376.

Bear, J., 1979, Hydraulics of Groundwater: New York, McGraw-Hill Publishing Co., 567 p.

Bredehoeft, J., 1997, Safe yield and the water budget myth: Ground Water, v. 35, no. 6, p. 929, https://doi.org/10.1111/j.1745-6584.1997.tb00162.x.
Budyko, M.I., 1977, Climatic Changes: American Geophysical Union Special Publication 10, 261 p., https://doi.org/10.1029/SP010.
Chen, Y.-N., Zilliacusb, N., Lia, W.H., Zhang, H.F., and Chen, Y.P., 2006, Groundwater level affects plant species diversity along the lower reaches of the Tarim River, western China: Journal of Arid Environments, v. 66, no. 2, p. 231–246, https://doi.org/10.1016/j.jaridenv.2005.11.009.
Cooper, H.H., Papodopulos, S., and Bredehoeft, J., 1982, The water-budget myth, *in* Geophysics Study Committee et al., Scientific Basis of Water Management: Washington, D.C., National Academy of Science, Studies in Geophysics, p. 51–57.
Currell, M., 2014, Mega-scale groundwater quality challenges and the need for an inter-disciplinary approach: Hydrogeology Journal, v. 22, p. 745–748, https://doi.org/10.1007/s10040-014-1119-z.
Custodio, E., 2002, Aquifer exploitation: What does it mean?: Hydrogeology Journal, v. 10, p. 254–277, https://doi.org/10.1007/s10040-002-0188-6.
Dingman, S.L., 2015, Physical Hydrology: Long Grove, Illinois, Waveland Press, 646 p.
Fetter, C.W., 2001, Applied Hydrogeology: Upper Saddle River, New Jersey, Prentice Hall, 598 p.
Galloway, D.L., and Burbey, T.J., 2011, Regional land subsidence accompanying groundwater extraction: Hydrogeology Journal, v. 19, no. 8, p. 1459–1486, https://doi.org/10.1007/s10040-011-0775-5.
Garza, S., 1962, Recharge, Discharge, and Changes in Ground-Water Storage in the Edwards and Associated Limestones, San Antonio Area, Texas: A Progress Report on Studies, 1955–59: Texas Board of Water Engineers Bulletin 6201, 51 p.
Garza, S., 1966, Ground-Water Resources of the San Antonio Area, Texas: A Progress Report on Studies, 1960–64: Texas Water Development Board Report 34, 36 p.
Gleeson, T., Wada, Y., Bierkens, M.F.P., and van Beek, L.P.H., 2012, Water balance of global aquifers revealed by groundwater footprint: Nature, v. 488, no. 7410, p. 197–200, https://doi.org/10.1038/nature11295.
Kittel, T.G.F., Rosenbloom, N.A., Painter, T.H., and Schimel, D.S., 1995, VEMAP modeling participants, the VEMAP integrated database for modeling United States ecosystem/vegetation sensitivity to climate change: Journal of Biogeography, v. 22, p. 857–862, https://doi.org/10.2307/2845986.
LBG-Guyton Associates & Aqua Terra Consultants, 2005, HSPF Recharge Models for the San Antonio Segment of the Balcones Fault Zone Edwards Aquifer, Parts 1, 2, 3: San Antonio, Texas, LBG-Guyton Associates & Aqua Terra Consultants, report contracted by Edwards Aquifer Authority 02-87-AS, 456 p.
Lee, C.H., 1915, The determination of safe yield of underground reservoirs of the closed basin type: Transactions of the American Society of Civil Engineers, v. 78, p. 148–251.
Lindgren, R.J., Taylor, C.J., and Houston, N.A., 2009, Description and Evaluation of Numerical Groundwater Flow Models for the Edwards Aquifer, South-Central Texas: U.S. Geological Survey Scientific Investigations Report 2009-5183, 25 p.
Loáiciga, H.A., 2003, Climate change and groundwater: Annals of the Association of American Geographers, v. 93, no. 1, p. 30–41, https://doi.org/10.1111/1467-8306.93103.
Loáiciga, H.A., 2009, Long-term climatic change and sustainable groundwater resources management: Environmental Research Letters, v. 4, 035004, https://doi.org/10.1088/1748-9326/4/3/035004.
Loáiciga, H.A., 2013, Consolidation settlement of aquifers caused by pumping: Journal of Geotechnical and Geoenvironmental Engineering, v. 139, no. 7, p. 1191–1204, https://doi.org/10.1061/(ASCE)GT.1943-5606.0000836.
Loáiciga, H.A., 2017, The safe yield and climatic variability: Implications for groundwater management: Groundwater Journal, v. 55, no. 3, p. 334–345, https://doi.org/10.1111/gwat.12481.
Loáiciga, H.A., Maidment, D.R., and Valdes, J.B., 2000, Climate-change impacts in a regional karst aquifer, Texas, USA: Journal of Hydrology (Amsterdam), v. 227, p. 173–194, https://doi.org/10.1016/S0022-1694(99)00179-1.
Loáiciga, H.A., Pingel, T., and Garcia, E., 2012, Seawater intrusion by sea-level rise: Scenarios for the 21st century: Ground Water, v. 50, no. 1, p. 37–47, https://doi.org/10.1111/j.1745-6584.2011.00800.x.
Longley, G., 1981, The Edwards Aquifer: Earth's most diverse ground water ecosystem: International Journal of Speleology, v. 11, p. 123–128, https://doi.org/10.5038/1827-806X.11.1.12.
Lowry, R.L., 1955, Recharge to Edwards Ground-Water Reservoir: Consulting engineer's report to San Antonio City Water Board, 66 p.
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, 64 p.
Meinzer, O.E., 1923, Outline of Ground-Water Hydrology with Definitions: U.S. Geological Survey-Water Supply Paper 494, 71 p.
Petitt, B.M., Jr., and George, W.O., 1956, Ground-Water Resources of the San Antonio Area, Texas: Texas Board of Water Engineers Bulletin 5608, v. I, 80 p.
Puente, C., 1978, A Method of Estimating Natural Recharge to the Edwards Aquifer in the San Antonio Area, Texas: U.S. Geological Survey Water-Resources Investigations Report 78-10, 34 p.
Scanlon, B.R., Faunt, C.C., Longuevergne, L., Reedy, R.C., Alley, W.M., McGuire, V.L., and McMahon, P.B., 2012, Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley: Proceedings of the National Academy of Sciences of the United States of America, v. 109, no. 24, p. 9320–9325, https://doi.org/10.1073/pnas.1200311109.
Sharp, J.M., Jr., 2010, The impacts of urbanization on groundwater systems and recharge: Aqua Mundi, v. 1, p. 51–56, https://doi.org/10.44409/Am-004-10-0008.
Sophocleous, M., 2002, Interactions between groundwater and surface water: The state of the science: Hydrogeology Journal, v. 10, p. 52–67, https://doi.org/10.1007/s10040-001-0170-8.
Thorkildsen, D.F., and McElhaney, P.D., 1992, Model Refinement and Applications for the Edwards (Balcones Fault Zone) Aquifer in the San Antonio Region, Texas: Texas Water Development Board Report 340, 36 p.
U.S. Fish and Wildlife Service, 2013, Final environmental impact statement and record of decision on the Edwards aquifer recovery implementation program habitat conservation plan for incidental take of 11 species (8 federally listed) in 8 Texas counties: Federal Register, v. 78, no. 32, p. 11,218–11,220.
U.S. Global Change Research Program (USGCRP), 2017, Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Dokken, D.J., Stewart, B.C., and Maycock, T.K., eds.]: Washington, D.C., U.S. Global Change Research Program, 470 p., https://doi.org/10.7930/J0J964J6.
Werner, A.D., Bakkerd, M., Posta, V.E.A., Vandenbohedec, A., Lua, C., Ataie-Ashtiania, B., Simmons, C.T., and Barry, D.A., 2013, Seawater intrusion processes, investigation and management: Recent advances and future challenges: Advances in Water Resources, v. 51, no. 1, p. 3–26, https://doi.org/10.1016/j.advwatres.2012.03.004.
Zektser, I.S., Loáiciga, H.A., and Wolf, J., 2005, Environmental impacts of groundwater overdraft: Selected case studies in the southwestern United States: Journal of Environmental Geology, v. 47, no. 3, p. 396–404, https://doi.org/10.1007/s00254-004-1164-3.

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