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The Safe Yield and Climatic Variability: Implications for Groundwater Management

by Hugo A. Loáiciga

Abstract

Methods for calculating the safe yield are evaluated in this paper using a high-quality and long historical data set of groundwater recharge, discharge, extraction, and precipitation in a karst aquifer. Consideration is given to the role that climatic variability has on the determination of a climatically representative period with which to evaluate the safe yield. The methods employed to estimate the safe yield are consistent with its definition as a long-term average extraction rate that avoids adverse impacts on groundwater. The safe yield is a useful baseline for groundwater planning; yet, it is herein shown that it is not an operational rule that works well under all climatic conditions. This paper shows that due to the nature of dynamic groundwater processes it may be most appropriate to use an adaptive groundwater management strategy that links groundwater extraction rates to groundwater discharge rates, thus achieving a safe yield that represents an estimated long-term sustainable yield. An example of the calculation of the safe yield of the Edwards Aquifer (Texas) demonstrates that it is about one-half of the average annual recharge.

Introduction

The safe yield (also called perennial yield or basin yield) is a widely used concept in groundwater management. The California Department of Water Resources (2003), among others, defined the safe yield as "the maximum quantity of water that can be continuously withdrawn from a groundwater basin without adverse effect." Typically, the adverse effect has been equated with the long-term progressive drop in groundwater level or "overdraft" (Bouwer 1978), although nowadays a wide range of adverse impacts are considered (see, e.g., Zektser et al. 2005). Those adverse impacts include, but are not limited to, impairment of habitat in groundwater ecosystems (Loáiciga 2003a), loss of plant-community richness by groundwater overdraft (Chen et al. 2006), seawater intrusion (see, e.g., Loáiciga et al. 2012; Werner et al. 2013), land subsidence (see, e.g., Galloway and Burbey 2011; Loáiciga 2014), reduction of base flow to streams (Barlow and Leake 2012), and loss of well yield. The safe yield refers to an average rate of groundwater extraction that is calculated over a period that is climatically representative of the region encompassing the groundwater basin. The representative period must reflect long-term average hydrologic conditions, must include at least one period of overall wet conditions and at least one of overall dry conditions relative to average annual conditions, and have an average precipitation that is close to the average precipitation for the entire period of record (say, within ~1% of the long-term average annual precipitation). Moreover, the beginning of the representative period must be an interval of relatively dry climatic conditions to preclude the potential for rejection of water that would otherwise become recharge, or "rejected" recharge (Theis 1940; Heath 2004). The requirement of relatively dry initial climatic conditions during the climatically representative period assures that the aquifer storage is below capacity thus precluding the occurrence of "rejected" recharge.

The safe yield is a useful baseline number if it is accurately estimated and wisely applied as a management tool. It is commonly employed to apportion groundwater among stakeholders in adjudicated groundwater basins. The safe yields also serves as a baseline for assessing whether or not a basin has been subjected to long-term groundwater extraction that exceeds aquifer recharge, thus causing basin "overdraft" (i.e., protracted decline of groundwater levels). The safe yield's importance as a baseline for allocating groundwater rights and for establishing a long-term groundwater extraction goal has earned it a visible, sometimes contentious, profile. Lohman (1979) wrote that: "The term 'safe yield' has about as many definitions as the number of people who have defined it. There are questions as to the validity of the term, but if it is valid there remains the question as to who should determine it—groundwater hydrologists or

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groundwater managers?" Furthermore, Lohman wrote: "I have a definition which I taught at US Geological Survey Groundwater Short Courses beginning in 1952, namely: the amount of groundwater one can withdraw without getting into trouble. "Withdraw" may mean from flowing or pumped wells, and it may mean continuously, as for many industrial or municipal suppliers, or seasonal, as for irrigation. "Trouble" may mean anything under the sun, such as (1) running out of water; (2) drawing in salt water; or other undesirable water; (3) getting shot, or shot at, by an irate nearby well owner or landowner; (4) getting sued by a less irate neighbor; or (5) getting sued for depleting the flow of a nearby stream for which the water rights have been appropriated."

Lohman's humorous portrayal of the safe yield exposes some of its shortcomings. Difficulty of estimation is one of them, which can be addressed rationally, as demonstrated in this work. Manipulation of safe-yield estimates to support biased viewpoints is another one, which defies scientific reasoning. Several authors have focused attention on sustainable groundwater management that is adaptive to changing climatic and water-use conditions, and considerate of groundwater vulnerabilities (see, e.g., Sophocleous 1997, 2010; Loáiciga 2003b; Alley and Leake 2004; Schwarz et al. 2016). Nevertheless, the safe yield remains a practically relevant concept and is widely used in groundwater management. Court adjudication of groundwater rights almost invariably relies on the safe yield as a benchmark for apportionment. The future protection of regional aquifers may be achieved by establishing and respecting long-term baselines for groundwater extraction expressed in terms of the safe yield, aided by adaptive strategies developed from sustainable groundwater management (Loáiciga 2003b). This work examines and compares methods to estimate the safe yield considering climatic variability and the various fluxes that affect groundwater storage. The methodologies herein presented are illustrated with high-quality data from a regional aquifer.

The Time-Averaged Groundwater Balance Equation

The basin-wide annual changes of groundwater storage and groundwater level, and the inflows into and outflows from groundwater storage are combined in various forms to estimate the safe yield. Figure 1a depicts the evolution of groundwater storage in terms of its inflows and outflows. Storage, inflows, and outflows herein represent basin-wide, annual, values. S_{t-1} and S_t denote the groundwater storage at the beginning and end of year t, respectively, where $t = 1, 2, \ldots, N$, and N denotes the number of years of the representative period used to estimate the safe yield. Calendar years or water years defined over 12 consecutive months (say, from October 1 of anyone year to September 30 of the following year) can be used in the estimation as long as the changes in groundwater storage, groundwater level, and the inflows and outflows are defined consistently. D_t, E_t, Q_t, and R_t denote the discharge from groundwater storage to seas (or rivers, lakes, springs, and wetlands), evapotranspiration from groundwater storage, groundwater extraction (by human action through pumping, generally), and recharge to groundwater storage in year t, respectively. The discharge (D_t), the recharge (R_t), and the evapotranspiration (E_t) may be affected by groundwater extraction. They represent actual water fluxes. They differ from the "native" fluxes that would occur if human use of groundwater did not exist (Heath 2004), which are not measurable in groundwater basins subjected to withdrawal. The estimation of the safe yield relies on the actual fluxes. The recharge is the annual volume of water entering groundwater storage. Some of the recharge may be caused by artificial means such as percolation in spreading basins or with injection wells. Evapotranspiration pertinent to the water balance of aquifers is that in which plant roots tap groundwater. The change in groundwater storage in year t is denoted by ΔS_t $(= S_t - S_{t-1})$.

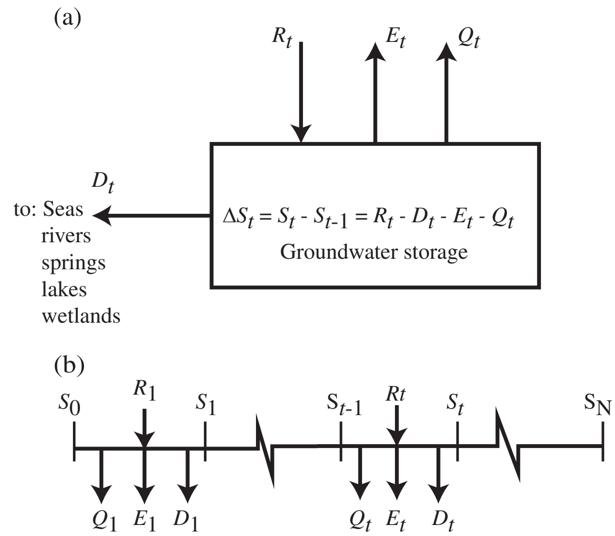

Figure 1. (a) Schematic of groundwater fluxes and storage. (b) Time discretization scheme employed.

Figure 1b depicts the time discretization in years used in this work. The annual change of groundwater storage is given by the following equation:

$$\Delta S_t = R_t - D_t - E_t - Q_t \quad t = 1,\ 2,\ 3,\ \ldots,\ N \quad (1)$$

Time averaging each term on the left- and right-hand sides of Equation 1 produces the averaged groundwater balance equation:

$$\overline{\Delta S} = \overline{R} - \overline{D} - \overline{E} - \overline{Q} \quad (2)$$

in which, for instance, the time-averaged groundwater extraction, $\overline{Q}$, is defined by:

$$\overline{Q} = \frac{\sum_{t=1}^{N} Q_t}{N} \quad (3)$$

Other average fluxes in Equation 2 are defined analogously. The groundwater storage equation (Equation 1) and its time-averaged variant (Equation 2) shall prove useful in the estimation of the safe yield in this work.

Change in Storage from Groundwater Levels

It is common for the aquifer fluxes D_t, E_t, and R_t to be known only approximately or not at all. This is so because of the spatially heterogeneous nature of these fluxes and the complex interactions between climate, vegetation, aquifer characteristics, groundwater basin geometry, and its boundary conditions (see, a review of this topic by the United Nations Educational, Scientific, and Cultural Organization [UNESCO] 2015). Groundwater extraction by wells, on the other hand, can be metered and it is the groundwater flux known with best accuracy, although many groundwater extractors treat these data as confidential and may not share them. Groundwater levels are typically monitored at various wells within a groundwater basin. In this case, the basin-wide annual change of storage can be estimated by resorting to measurements of changes in groundwater levels within the groundwater basin in year t and from estimates of the storativity throughout the groundwater-yielding layers of an aquifer, as follows:

$$\Delta S_t = \sum_{k=1}^{K} S_{Ck}\ \Delta h_{tk}\ A_k \quad k = 1,\ 2,\ \ldots,\ K; \quad t = 1,\ 2,\ \ldots .N \tag{4}$$

in which A_k, S_{Ck}, and Δh_{tk} denote, respectively, the (map) area of aquifer layer k ($k = 1,\ 2,\ \ldots,\ K$), the storativity of layer k of the groundwater basin (see, e.g., Meinzer 1923; Freeze and Cherry 1979; Fetter 2001), and the change in groundwater level in year t in layer k. The calculation of the change in annual storage by Equation 4 requires (1) estimates of the storativities of the aquifer layers by means of formation-specific testing; and (2) knowledge of the 3D geometry of aquifer layers. The implementation of Equation 4 must account for changes in the response of aquifer layers to groundwater withdrawal as they transition from confined to unconfined conditions or vice versa.

Estimation of the Safe Yield from Inflow and Outflow Data

Several authors (see, e.g., Muir 1968) have proposed that the safe yield ($\overline{Q}_{\text{safe}}$) equals the average recharge minus aquifer discharge and minus evapotranspiration. In other words:

$$\overline{Q}_{\text{safe}} = \overline{R} - \overline{D} - \overline{E} \tag{5}$$

Estimating the safe yield with Equation 5 requires average annual recharge ($\overline{R}$), discharge ($\overline{D}$), and evapotranspiration ($\bar{E}$). Substituting Equation 5 into Equation 2 implies that the average change in groundwater storage equals:

$$\overline{\Delta S} = \overline{Q}_{\text{safe}} - \overline{Q} \tag{6}$$

which would equal zero if the average groundwater extraction ($\overline{Q}$) equals the safe yield. The safe yield is therefore equal to the average groundwater extraction rate that produces an average annual change in groundwater storage equal to zero during the climatically representative period. Notice from Equation 6 that an average groundwater extraction less than the safe yield would produce a positive average change in groundwater storage ($\overline{\Delta S} > 0$) during the climatically representative period. It follows from Equations 5 and 6 that if the average groundwater extraction exceeds the safe yield, say, by setting $\overline{Q}$ equal to the average recharge ($\overline{R}$), then the long-term average change in storage would be $\overline{\Delta S} = -\overline{D} - \overline{E}$, implying an overdraft of basin storage ($\overline{\Delta S} < 0$). Cooper et al. (1982) and Bredehoeft (1997) referred to equating the safe yield with the average annual recharge as the "water-budget myth." Empirical evidence has shown that the average groundwater extraction frequently exceeds the average recharge, thus causing basin overdraft. This situation is endemic to groundwater basins exhibiting temporally variable recharge in semi-arid lands where irrigated agriculture is a heavy user of groundwater (Zektser et al. 2005; Sophocleous 2010; Gleeson et al. 2012; Scanlon et al. 2012; Famiggietti 2014).

The constraint $\overline{\Delta S} = 0$ defines the safe yield and its relation to human-impacted recharge, discharge, and evapotranspiration. Specifically, in the absence of groundwater extraction the time-averaged groundwater storage Equation 2 becomes:

$$\overline{\Delta S} = \overline{R}_0 - \overline{D}_0 - \overline{E}_0 \tag{7}$$

in which $\overline{D}_0$, $\bar{E}_0$, and $\overline{R}_0$ denote, respectively, the average annual discharge, evapotranspiration, and recharge that would occur without groundwater extraction (these are sometimes called average "native" fluxes). These average native fluxes are not observable in developed groundwater basins, and, thus, are not operationally useful. Yet, they provide an insight on the meaning of the safe yield. The average annual change in groundwater storage ($\overline{\Delta S}$) should approach zero in a climatically representative period when native fluxes prevail, in which case Equation 7 implies that:

$$\overline{R}_0 = \overline{D}_0 + \overline{E}_0 \tag{8}$$

If groundwater extraction is introduced the average annual native discharge, evapotranspiration, and recharge become $\overline{D} = \overline{D}_0 - \overline{\Delta D}_0$, $\overline{E} = \overline{E}_0 - \overline{\Delta E}_0$, and $\overline{R} = \overline{R}_0 \pm \overline{\Delta R}_0$, respectively, where $\overline{\Delta D}_0$, $\overline{\Delta E}_0$, and $\overline{\Delta R}_0$ represent, respectively, the average annual change in native discharge, in native evapotranspiration, and in native recharge. Notice that groundwater extraction reduces the average annual native discharge and evapotranspiration, whereas the average annual native recharge could be reduced or increased by groundwater extraction depending on the recharge mechanism and its dependence on groundwater storage. The time-averaged groundwater storage Equation 2 is rewritten as follows by virtue of Equation 8:

$$\overline{\Delta S} = \overline{R}_0 \pm \overline{\Delta R_0} - \left(\overline{D}_0 - \overline{\Delta D_0}\right) - \left(\overline{E}_0 - \overline{\Delta E_0}\right) - \overline{Q} = \pm\overline{\Delta R_0} + \overline{\Delta D_0} + \overline{\Delta E_0} - \overline{Q} \qquad (9)$$

The safe yield is the average annual groundwater extraction that renders the average annual change in groundwater storage equal to zero during a climatically representative period. Therefore, from Equation 9, letting $\overline{Q} = \overline{Q}_{\text{safe}}$ and $\overline{\Delta S} = 0$:

$$\overline{Q}_{\text{safe}} = \pm\overline{\Delta R_0} + \overline{\Delta D_0} + \overline{\Delta E_0} \qquad (10)$$

Equation 10 states that the safe yield equals the sum of the average annual changes in native recharge, in native discharge, and in native evapotranspiration caused by groundwater extraction.

Estimation of the Safe Yield from Groundwater Extraction and the Change in Groundwater Storage

The time-averaged groundwater storage Equation 2 can be rewritten as follows:

$$\overline{\Delta S} + \overline{Q} = \overline{R} - \overline{D} - \overline{E} \qquad (11)$$

Commonly, the fluxes on the right-hand side of Equation 11 are poorly known due to the difficulties inherent to the estimation of recharge, discharge, and evapotranspiration. The average groundwater extraction, $\overline{Q}$, on the other hand, is measured with relative ease or can be approximated with proxy data. The average change in groundwater storage is estimable from changes in groundwater levels as indicated by Equation 4, followed by time averaging of ΔS_t to calculate the average change of groundwater storage ($\overline{\Delta S}$). It is known from Equation 5 that the right-hand side of Equation 11 is an estimator of the safe yield. Therefore, the safe yield can also be estimated as follows:

$$\overline{Q}_{\text{safe}} = \overline{\Delta S} + \overline{Q} \qquad (12)$$

Equation 12 is employed when the average groundwater storage is estimated from changes in groundwater levels. Equation 12 implies that the average groundwater extraction equals the safe yield if the average change in groundwater storage is zero during the representative period, as concluded above. Furthermore, it follows from Equation 12 that the safe yield is less than the average annual groundwater extraction if the average change in groundwater storage is negative during the representative period. This is so because a negative average change in groundwater storage indicates that groundwater storage was depleted during the representative period. Thus, the average groundwater extraction must be reduced to achieve long-term stable groundwater storage during the climatically representative period. The opposite is true when the average change of groundwater storage is positive during the representative period. In this instance, the average groundwater extraction may be increased to achieve the safe yield. Equation 12 is more frequently used than Equation 5 to estimate the safe yield because it does not involve the estimation of recharge, discharge, and evapotranspiration, a difficult task in many aquifers.

Graphical Estimation of the Safe Yield from Basin-Wide Changes in Groundwater Level ($\widehat{\Delta h}_t$ vs. Q_t)

It might be the case that groundwater data are limited to measurements of groundwater levels and monitoring of groundwater extraction in a basin. This situation is common. One approach to circumvent the paucity of data in this instance is to resort to the basin-wide, annual, change in groundwater level $\left(\widehat{\Delta h}_t\right)$ and its relation to groundwater extraction, Q_t. The relation between $\widehat{\Delta h}_t$ and Q_t can be exploited to estimate the safe yield (this method appears to have originated with R.A. Hill, in Conklin [1946], 297). To this end, one employs an area-weighted average of the groundwater levels measured throughout the basin to estimate $\widehat{\Delta h}_t$:

$$\widehat{\Delta h}_t = \frac{1}{A}\sum_{k=1}^{K} \Delta h_{tk} A_k \quad t = 1,\ 2,\ \ldots,\ N \qquad (13)$$

in which A_k represents the map area of the kth aquifer layer, A equals the sum of the areas A_k, and Δh_{tk} denotes the annual change of the groundwater level within aquifer layer k.

The time series of $\widehat{\Delta h}_t$ is graphed against the time series of groundwater extraction Q_t, from which the groundwater extraction value that produces a zero change in the basin-wide groundwater level is determined and set equal to the safe yield. There are physically based arguments to support this graphical approach to the estimation of the safe yield. First, groundwater extraction reduces groundwater levels. Secondly, it was concluded above that the average change in groundwater storage equals zero when the average groundwater extraction equals the safe yield. Therefore, by selecting an annual groundwater extraction that makes the annual change in groundwater storage equal to zero one achieves the safe yield by implementing that rate of groundwater extraction during a representative period. The accuracy of the method embodied by Equation 13 relies on having adequate spatial coverage of the aquifer by wells so that the basin-wide average groundwater level change is representative of conditions over the aquifer.

Graphical Estimation of the Safe Yield from Changes in Groundwater Storage (ΔS_t vs. Q_t)

The arguments made in the previous section to justify the graphical estimate of the safe yield from basin-wide changes in the groundwater level are equally valid in justifying the graphical estimation of the safe yield from the change in groundwater storage. Basically, this method graphs the annual change in groundwater storage, ΔS_t, against the annual groundwater extraction, Q_t, from which the groundwater extraction value that produces a zero change in groundwater storage is determined and set equal to the safe yield. The change in annual groundwater storage is estimated by Equation 4. This method is primarily useful as a confirmatory estimate of the safe yield obtained with the simpler $\widehat{\Delta h_t}$ vs. Q_t graphical method.

Estimation of the Safe Yield by Mass-Curve Analysis

Long-time series of the cumulative annual change in groundwater storage reveal conditions of full aquifer storage during very wet periods and conditions of near depleted or depleted aquifer storage during long droughts and heavy groundwater extraction (Loáiciga 2008). The cumulative annual change in groundwater storage in year n, V_n, $(1 \leq n \leq T > N)$ is defined as follows (S_0 denotes the initial groundwater storage):

$$V_n = \sum_{j=1}^{n} \Delta S_j = S_n - S_0 = \sum_{j=1}^{n} \left(R_j - D_j - E_j - Q_j \right) \quad 1 \leq n \leq T > N \tag{14}$$

where T denotes the length of the time series, which includes at least one representative period, and which must be sufficiently long to expose full aquifer storage (herein denoted by $S_{\max}$) and depleted aquifer storage conditions. This may require time series of groundwater storage spanning several decades or centuries depending on the regional climatic variability and the patterns of groundwater extraction. In actuality, the condition of completely depleted aquifer storage may never be observed because some groundwater is retained by capillary forces as the aquifer conditions transition from saturated to partially saturated. This groundwater is not extractable or usable. The completely depleted aquifer storage condition must therefore be understood as that of depleted usable groundwater storage or an approximation to it, which is herein denoted by $S_{\min}$. For this reason, the estimates of the aquifer storage capacity and safe yield presented in this section must be interpreted as lower-bound estimates, that is, if a longer time series were available one might estimate a larger aquifer storage, and, therefore, the estimate of the safe yield would increase.

Let $t_{\max}$ and $t_{\min}$ denote the years in which the cumulative annual change in storage is largest ($V_{\max}$) and smallest ($V_{\min}$), respectively. If follows from Equation 14 that the difference between the maximum and minimum aquifer storages, as herein defined, estimates the aquifer storage capacity, C:

$$C \uparrow S_{\max} - S_{\min} = V_{\max} - V_{\min} = \sum_{j=1}^{t_{\max}} \Delta S_j - \sum_{j=1}^{t_{\min}} \Delta S_j \tag{15}$$

in which the symbol $\uparrow$ means the value on the right-hand side is likely a lower bound of the aquifer storage capacity. It is possible, in principle, to attempt the estimation of the aquifer storage capacity with Equation 4 provided that the change in the storativities of the layers yielding groundwater as they transition from confined to unconfined conditions is known. The application of Equation 4 to estimate the change in annual groundwater storage in layered aquifers is simpler than applying it to estimate the aquifer storage capacity because the volume of groundwater that can be removed in 1 year commonly represents a small fraction of an aquifer's storage capacity. Case-by-case analysis of each situation dictates the data required to estimate the changes in groundwater storage with Equation 4.

The mass-curve method was introduced to hydrogeology by Loáiciga (2008). It employs estimating C of aquifer storage capacity and the cumulative net recharge to estimate the safe yield. The net recharge equals the annual recharge minus the annual discharge and minus the evapotranspiration (if any), $R'_j = R_j - D_j - E_j$. It is possible to estimate the net recharge from the change in annual storage and annual groundwater extraction, or $R'_j \cong \Delta S_t - Q_t$, whenever measurements of recharge, discharge, and evapotranspiration are not available. Therefore, the cumulative net recharge, CR'_n, is given by:

$$CR'_n = \sum_{j=1}^{n} R_j - D_j - E_j \quad 1 \leq n \leq T > N \tag{16}$$

Figure 2 depicts the graphical method to estimate the safe yield by mass-curve analysis. The estimated aquifer

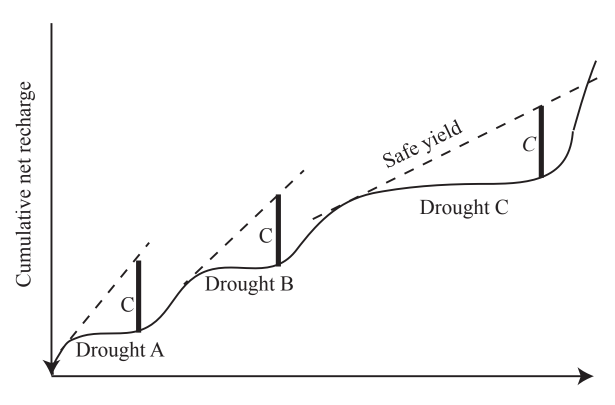

Figure 2. Graphical mass-curve method employed to determine the safe yield corresponding to an aquifer with storage capacity C.

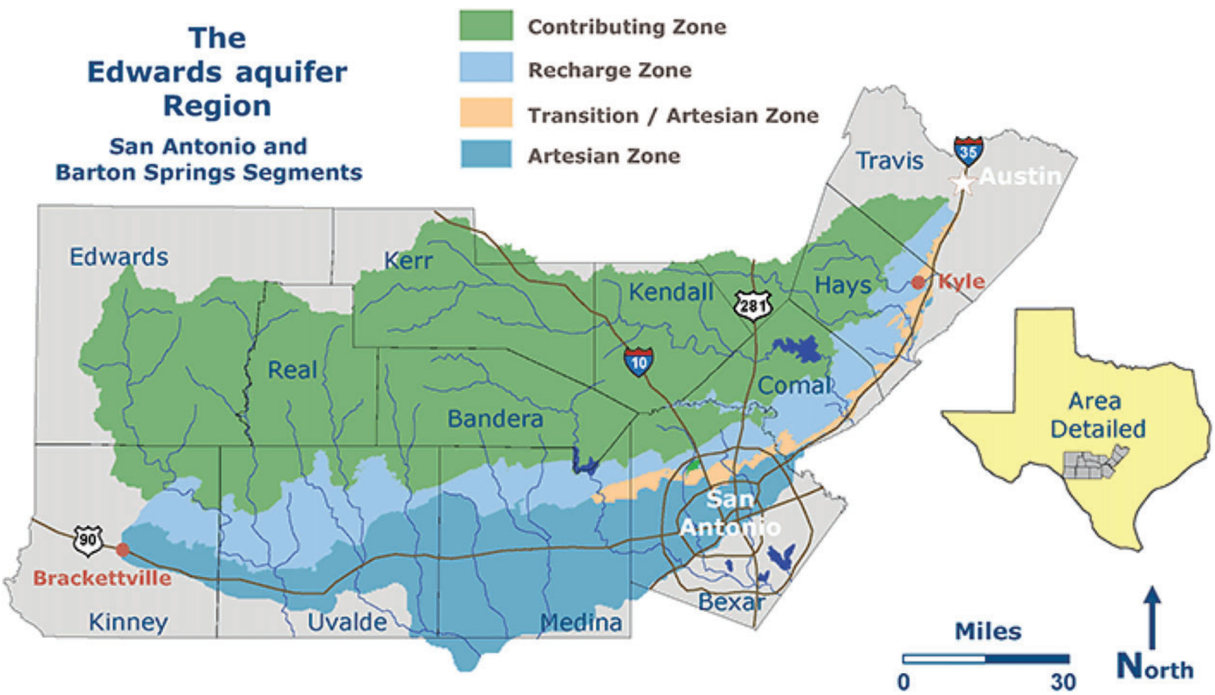

Figure 3. The Edwards Aquifer, Texas (1 mile = 1609.34 m) (from http://www.edwardsaquifer.net/).

storage capacity (C) is plotted vertically at transitions along the curve mass from periods of relative low recharge (droughts A to C in Figure 2) to periods of aquifer replenishment. Lines tangent to high points of the mass curve are drawn that exactly encompass the storage capacity. The tangent with the minimal slope that intersects the mass curve when projected forward in time defines the safe yield, which equals the slope of the tangent line expressed as a volume of groundwater extracted annually. Tangent lines that do not intersect the mass curve when projected forward in time imply extraction rates that do not allow replenishment of the aquifer and are, therefore, unsustainable in the long term. The mass-curve approach for estimating the safe yield relies on the entire record of measurements, and the longer the record, the more likely the estimates of the aquifer storage capacity and the safe yield approximate their actual values.

Results

The Study Area: The Edwards Aquifer, South-Central Texas

The Edwards Aquifer (Balcones Fault Zone section) is located in south-central Texas, as portrayed in Figure 3.

The Edwards Aquifer is a highly productive confined karst aquifer whose hydrogeologic characteristics have been described in detail in several publications (see, e.g., Loáiciga et al. 2000, and http://www.edwardsaquifer.org/). It features an upstream contributing drainage area, a recharge zone (unconfined aquifer), a transition zone (between unconfined and confined conditions), and a confined zone. The Edwards Aquifer encompasses an area approximately 290 km long that ranges from 8 to 65 km in width. It is the primary water source for much of this area, which includes the City of San Antonio and various surrounding communities. The average annual combined discharge to springs ($\overline{D}$) and groundwater extraction by wells ($\overline{Q}$) equals $57{,}419 \times 10^6$ m^3, of which 49.94, 28.02, 13.64, 4.23, and 4.16% are destined to spring discharge, and to municipal and military, irrigation, domestic and livestock, and industrial uses, respectively.

The Edwards Aquifer's groundwater has been the center of dispute over groundwater rights and the impacts of groundwater extraction on several species of animals and plants endemic to its aquatic ecosystem, among which are the fountain darter (*Etheostoma fonticola*, a fish), the Comal Springs riffle beetle (*Heterelmis comalensis*), the Texas wild-rice (*Zizania texana*), and the Texas blind salamander (*Eurycea rathbuni*). Maintaining adequate discharge (spring flow in this case) (D_t) is imperative to preserve aquatic ecosystems in the Edwards Aquifer (Loáiciga et al. 2000; US Fish and Wildlife Service 2013). Groundwater discharge to various receiving water bodies (springs, lakes, wetlands, and seas) is not "wasted water" as it is sometimes argued to justify unsustainable groundwater mining.

Historical Data, Climatic Variability, and the Representative Period

Figure 4 depicts time series of annual recharge, discharge (spring flow), and groundwater extraction (pumping) in the Edwards Aquifer from 1934 through 2014. Recharge in the Edwards Aquifer is calculated from the change in streamflow in the various streams that cross the recharge area and from the runoff generated within the recharge area. Streamflow is measured at gauges located

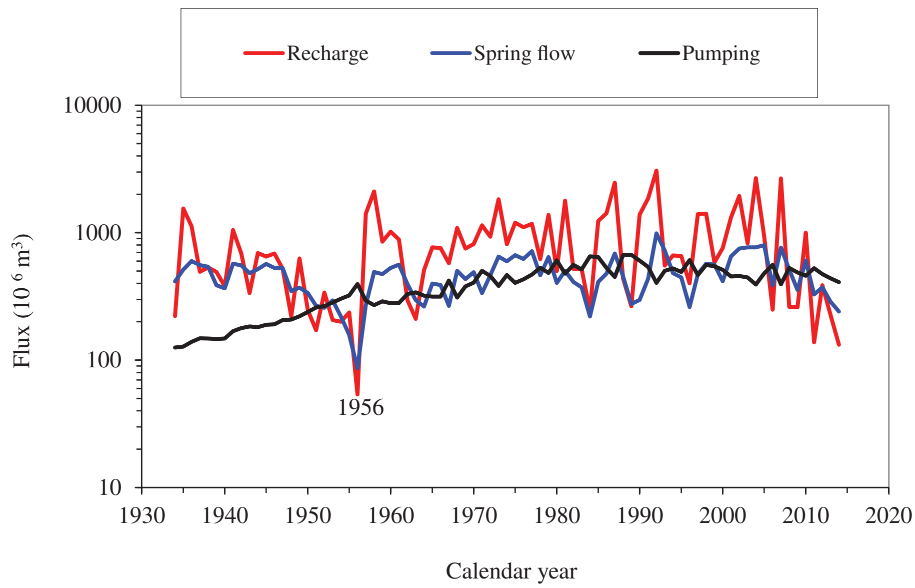

Figure 4. Graphs of the annual recharge (R_t), groundwater extraction (Q_t), and discharge (spring flow, D_t) in the Edwards Aquifer, 1934 to 2014. The smallest recharge occurred in 1956.

immediately upstream and downstream from the recharge area in various streams. The differences between these measured streamflows are adjusted by runoff produced within the recharge area and summed to calculate the aquifer recharge (Puente 1978; Loáiciga et al. 2000) Evapotranspiration is negligible in the Edwards Aquifer for groundwater flows through a confined layer overlain by a thick aquitard (Loáiciga et al. 2000). Spring flow discharge is measured at various springs that comprise the discharge zone of the Edwards Aquifer. Recharge, discharge, and groundwater extraction data are compiled by the Austin (Texas) office of the United States Geological Survey. It is seen in Figure 4 that the spring flow follows the pattern of recharge albeit with a delay and smoothed temporal variation. In some years, the spring flow discharge exceeded recharge. The graph of groundwater extraction depicted in Figure 4 indicates that it increased steadily from 1934 through about 1992, when groundwater extraction reached a historical maximum of 992.24×10^6 m^3. In some years, the groundwater extraction exceeded recharge and spring flow discharge.

Figure 5 depicts a graph of the cumulative rainfall departure from the average annual rainfall during the entire period of analysis (1934 to 2014). It also shows the values of the average annual rainfall during the entire period of analysis and during the representative period (1954 to 1989), which are equal to 77.09 and 76.23 cm, respectively.

Figure 5 portrays an overall declining trend of rainfall that began in 1936 and ended in 1970. This was followed by an overall increasing trend that lasted through 2004, and by an apparent declining trend thereafter. Within these long climatic fluctuations there were interspersed periods of wetness and dryness. The representative period herein chosen (1954 to 1989) began during a drying phase, had several wet, and dry periods and an average annual rainfall (76.23 cm) very close to that of the entire period of record (77.09 cm). Other representative periods could be identified; yet, the chosen period meets all the required criteria well. The high-climatic variability of the Edwards Aquifer region demonstrates the need for long historical data with which to identify a representative period and capture meaningful hydrogeologic fluctuations. An 80-year long rainfall record allowed the identification of a climatically representative period that is 35-year long in the Edwards Aquifer. The length of climatic records needed to correctly identify climatically representative periods is region-dependent, and there are no generalizable rules in this respect other than decades-long, even centuries-long, rainfall times series might be needed.

Lower-Bound Estimate of the Edwards Aquifer's Storage Capacity

Figure 6 depicts the cumulative annual change in groundwater storage in the Edwards Aquifer during the period 1934 to 2014, which was calculated with Equation 14.

The lower-bound estimate of the aquifer storage equals the difference between the maximum and minimum of the cumulative change in storage, according to Equation 15. Therefore, the estimated lower bound of the aquifer storage capacity is $C = 3421 - (-2522) = 5943$ (10^6 m^3).

Mass-Curve Analysis Applied to the Edwards Aquifer

Figure 7 depicts the mass-curve analysis for the Edwards Aquifer corresponding to the period 1934 to 2014. The slope of the tangent line equals the safe yield, which in this case amounts to 342×10^6 m^3/year and corresponds to the estimated lower bound of aquifer storage (5943×10^6 m^3).

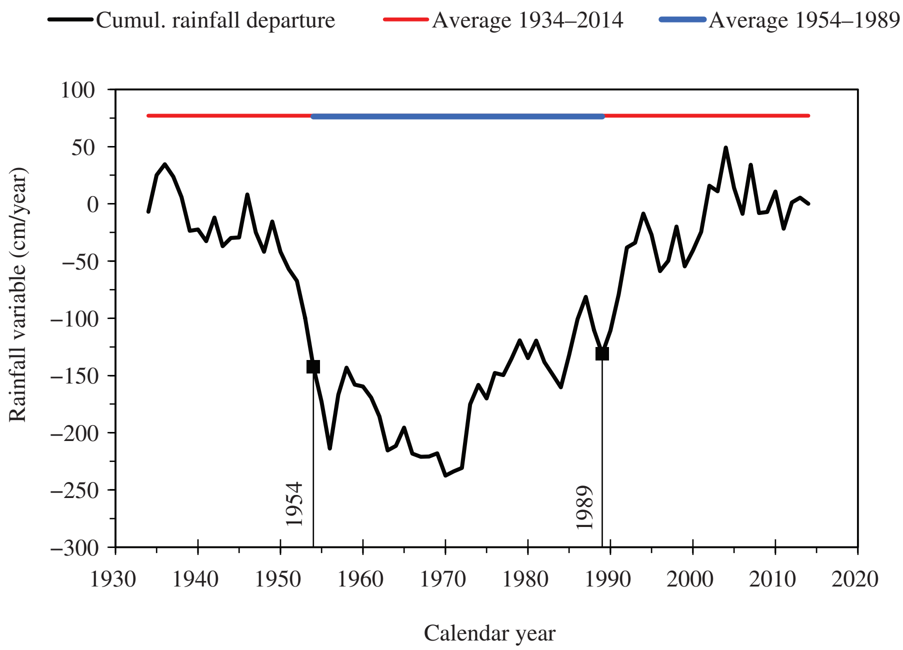

Figure 5. Graph of the cumulative rainfall departure from the average annual rainfall in the Edwards Aquifer region, 1934 to 2014. The climatically representative period is 1954 to 1989.

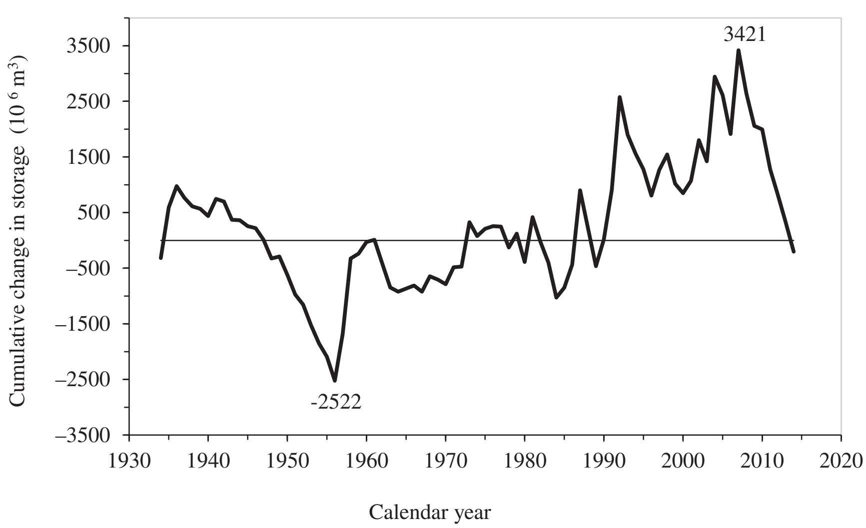

Figure 6. Cumulative change in storage in the Edwards Aquifer, 1934 to 2014.

Graphical Estimates of the Safe Yield from Changes in the Annual, Basin-Wide, Groundwater Level and from Changes in the Annual Groundwater Storage

Figure 8 shows the graph of the basin-wide annual change in groundwater level in the Edwards Aquifer against the annual groundwater extraction corresponding to the representative period. The annual change in groundwater level was calculated with daily water level data available from the Edwards Aquifer Authority for the three indicator wells (J-17, J-27, Hondo Well). The J-17 well's water level data date back to 1932. The safe yield is the annual groundwater extraction rates corresponding to zero change in annual groundwater storage, or an annual extraction equal to $419 \times 10^6\, m^3$ in the case of Figure 8.

The graph in Figure 8 exhibits a scattered relation between the groundwater level and the groundwater extraction. This is explained by the fact that the groundwater level is a direct proxy variable for groundwater storage, which, in turn, also depends on recharge and discharge (spring flow), which are not explicitly accounted for in the graph of Figure 8.

Figure 9 depicts the graph of the annual change in groundwater storage vs. the annual groundwater extraction corresponding to the representative period. The annual change in groundwater storage was calculated with Equation 1. In this case, the safe yield equals $449 \times 10^6\, m^3$/year.

The scatter of the graph of Figure 9 is explained by the fact that the change in groundwater storage depends

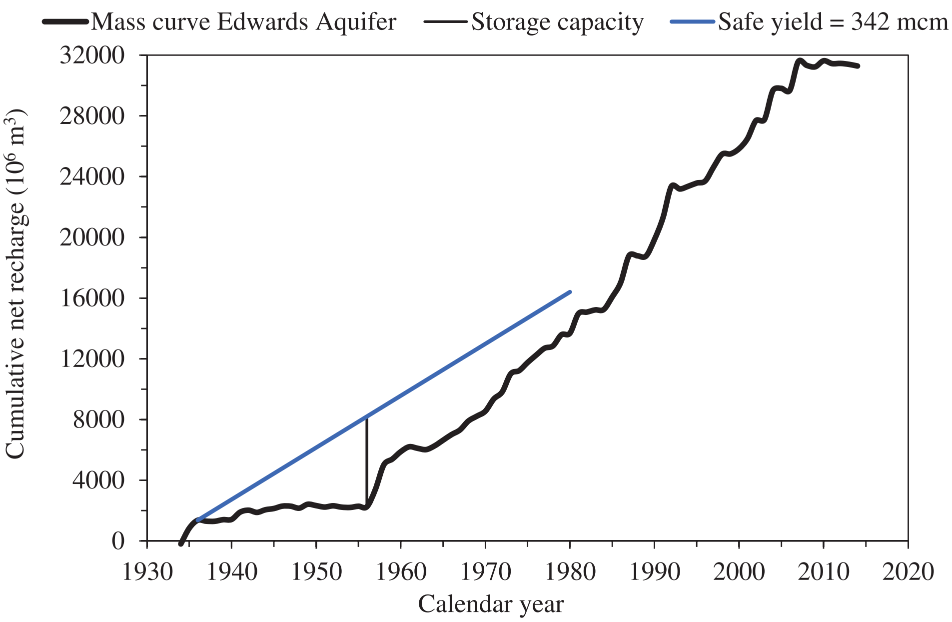

Figure 7. Mass curve for the Edwards Aquifer depicting an estimated aquifer capacity of at least 5943 x 10^6 m^3 and a safe yield equal to 342 x 10^6 m^3/year (mcm).

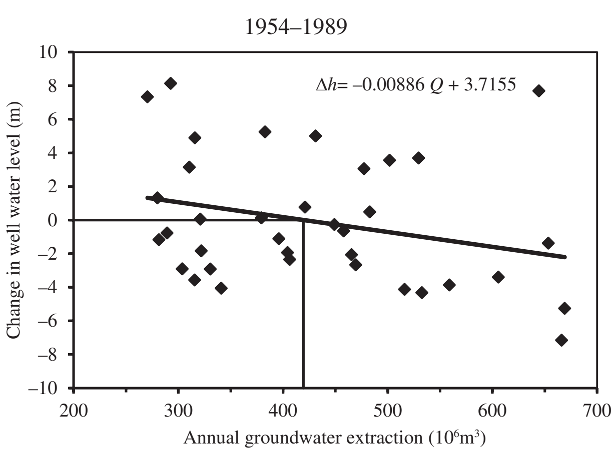

Figure 8. Basin-wide annual change in groundwater level vs. the annual extraction rate, with a corresponding safe yield equal to 419 x 10^6 m^3/year.

not only on groundwater extraction but also on recharge and discharge (spring flow), which are not explicitly accounted for in the graph of Figure 9.

Graphical estimates of the safe yield were also obtained for the period 1934 to 2014 for the sake of comparison with those obtained for the representative period 1954 to 1989. The results are discussed in the next section.

Summary of the Estimates of the Safe Yield

Table 1 lists the calculated average annual water fluxes and the average annual change of groundwater storage in the Edwards Aquifer during the representative period (1954 to 1989) and the entire record of historical data (1934 to 2014).

It is seen in Table 1 that the average annual groundwater extraction ($\overline{Q}$), the average annual recharge ($\overline{R}$), and the average annual change of storage ($\overline{\Delta S}$) were larger during the representative period (1954 to 1989) than during the entire period of record (1934 to 2014). The average annual spring flow discharge ($\overline{D}$), on the other hand, was smaller during the representative period than that of the entire period.

Table 2 lists the estimated safe yields with the various methods presented in this work. It includes estimates corresponding to the representative period (1954 to 1989), and, for comparison purposes, to the entire record of historical data (1934 to 2014).

The safe yield estimates obtained with the average recharge-minus-average discharge method ($\overline{R} - \overline{D}$) and the average change in storage method ($\overline{\Delta S} + \overline{Q}$) are identical in this instance ($= 459 \times 10^6$ m^3/year) because the average change in storage was calculated from water balance involving measured fluxes of recharge, discharge, and groundwater extraction (see Equation 2), and not from changes in water levels and values of storativity within the groundwater basin. The graphical methods, that is, the change-in-groundwater level vs. extraction rate and the change-in-storage vs. extraction rate methods produced safe yield estimates equal to 419×10^6 and 449×10^6 m^3/year, respectively. The latter two estimates are smaller than the safe yield calculated with the $\overline{R} - \overline{D}$ and $\overline{\Delta S} + \overline{Q}$ methods, but within 10% of it.

The data presented in Tables 1 and 2 indicate that the safe yield estimates are all much lower than the average annual recharge for the representative and entire periods. For instance, the average annual recharge during the climatically representative period equaled 892.93×10^6 m/year, whereas the safe yield calculated with the water-balance method for that same period was

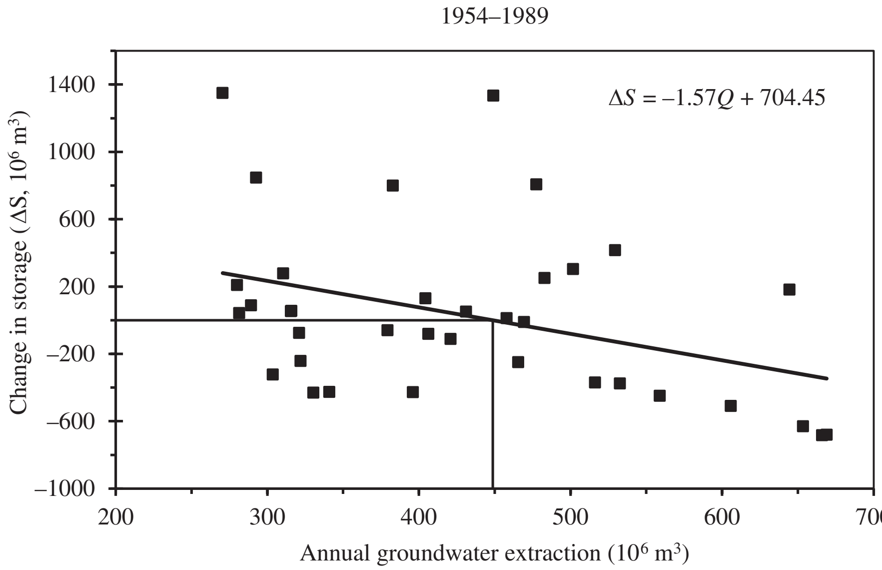

Figure 9. Annual change in groundwater storage vs. the annual extraction rate, with a corresponding safe yield equal to 449 x 10^6 m^3/year.

Table 1
Average Annual Fluxes and Average Annual Change of Storage in the Edwards Aquifer

Period	$\overline{Q}$ (10^6 m^3/year)	$\overline{R}$ (10^6 m^3/year)	$\overline{D}$ (10^6 m^3/year)	$\overline{\Delta S}$ (10^6 m^3/year)
1954–1989	429.87	892.93	433.52	29.53
1934–2014	388.90	853.68	467.46	−2.68

Table 2
Summary of the Estimates of the Safe Yield ($\overline{Q}_{\text{safe}}$)

Method	Period	$\overline{Q}_{safe}$ (10^6 m^3/year)
$\overline{Q}_{\text{safe}} = \overline{R} - \overline{D}$ and $\overline{Q}_{\text{safe}} = \overline{\Delta S} + \overline{Q}$	1954–1989	459
	1934–2014	386
$\widehat{\Delta h}_t$ vs. Q_t graphical	1954–1989	419
	1934–2014	327
ΔS_t vs. Q_t graphical	1954–1989	449
	1934–2014	384
Mass curve graphical	1954–1989	N.A.
	1934–2014	342

N.A., not applicable.

equal to 459×10^6 m/year, about one-half of the recharge. In addition, the safe yields listed in Table 2 show that they are larger during the climatically representative period than during the entire period. The larger average annual recharge and smaller average annual discharge during the climatically representative period relative to the entire period explains the larger safe yield of the former period.

Conclusions

The estimates of the safe yield calculated with the data for the period 1934 to 2014 were all consistently smaller than those corresponding to the climatically representative period. They ranged from 342×10^6 m^3/year (mass-curve method) to 386×10^6 m^3/year ($\overline{R} - \overline{D}$ method). The estimates of the safe yield corresponding to the entire period of data are smaller than those corresponding to the representative period because the latter period had larger average annual recharge and lower average annual discharge (spring flow) than the former period, as shown in Table 1. The safe yield estimates from the entire period of data, being smaller than those for the representative period, would lead, if they become implemented groundwater extraction, to larger aquifer discharge (spring flow) and higher groundwater levels, and, therefore, to healthier Edwards Aquifer's aquatic ecosystems.

The tradeoff implied by implementing the smaller safe yields is that less groundwater would be extracted for human use. The dilemma posed by supplying water for humans on the one hand, and environmental degradation by groundwater extraction on the other hand is at the center of the long-running disputes concerning the appropriate level of groundwater extraction in the Edwards Aquifer and many other aquifers. There have been more than 100 years of litigation and Court decisions over the Edwards Aquifer's groundwater, which culminated with a 2013 decision by the US Fish and Wildlife Service laying out the Edwards Aquifer Recovery Implementation Program (US Fish and Wildlife Service 2013). It is noteworthy that the 1968 Texas Water Plan recommended capping the annual groundwater extraction from the Edwards at 493×10^6 m^6. This recommended cap—which was frequently exceeded—is larger than the largest safe yield presented in Table 2 (equal to 459×10^6 m^6/year). Jensen (1988) reported a regional groundwater management framed in 1988 by several stakeholders in the Edwards Aquifer region (the City of San Antonio, the Edwards Underground Water District which covers Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties, the Guadalupe-Blanco River Authority, the San Antonio River Authority, and the Nueces River Authority) that called for limiting groundwater withdrawal to 75% of the average annual recharge, which equaled 555×10^6 m^3 annually with the data available then. Interestingly, the 1968 and 1988 groundwater withdrawal targets were envisioned primarily as "caps" rather than safe yields that prevent overdraft, or sustainable groundwater extraction strategies that consider spring flow fluctuations.

The safe yield estimates presented in this paper are consistent with its definition as a long-term average extraction rate that assures groundwater storage stability during representative climatic periods. They are useful baseline numbers with which to outline long-term strategies for groundwater management and apportion groundwater rights. Previous studies have shown (see, e.g., Loáiciga et al. 2000; Loáiciga 2003a, 2003b) that the safe yield serves as a baseline for groundwater extraction when climatic conditions are average. It is not an operational rule that works well under all climatic conditions. Therefore, during periods of reduced charge (i.e., drought conditions) the level of groundwater extraction may have to be reduced below the safe yield to preempt adverse impacts to vulnerable ecosystems and water quality degradation. Water conservation, water importation, and alternative water sources (desalination, water recycling, etc.) may be relied upon to replace the reduced groundwater withdrawal. A diversified portfolio of water sources and a well-thought out drought mitigation strategy are essential for sustainable groundwater management. During periods of plentiful recharge (i.e., wet periods) and large aquifer storage groundwater withdrawal may exceed the safe yield. Some of the groundwater withdrawal could be exported to regions needing water, as exemplified by regional water markets emerging throughout the American West. There are practical complications associated with this type of adaptive management strategies given that adverse impacts, say, by declining discharge, develop over time and corrective action takes some time to realize benefits. One possibility to cope with these dynamic aquifer processes is to write groundwater-extraction rules that tie the magnitude of groundwater extraction to the magnitude of discharge: as discharge declines so does the groundwater extraction. This is what was done in the Edwards Aquifer to protect threatened groundwater ecosystems (US Fish and Wildlife Service 2013). To achieve this type of adaptive groundwater management strategy, however, it is paramount to develop an institutional framework acceptable to the majority of groundwater stakeholders and to create a credible and effective enforcement of established groundwater-extraction rules.

Author's Note: The author does not have any conflicts of interest.

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