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Aquifer storage capacity and maximum annual yield from long-term aquifer fluxes

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Author
Loáiciga, Hugo A

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Aquifer storage capacity and maximum annual yield from long-term aquifer fluxes

Hugo A. Loáiciga

Abstract Long-term time series data of aquifer recharge, groundwater extraction, and discharge are used to estimate aquifer storage capacity and maximum annual yield. Aquifer storage capacity is defined as the maximum volume of water that can be stored in an aquifer. It is estimated using a transient water-balance approach. The maximum annual yield is defined as the maximum combined groundwater extraction plus discharge that can be sustained in an aquifer judged by the historical record of recharge. It is determined according to a graphical mass-curve method. These two quantities are useful in aquifer characterization and groundwater management, the apportionment of groundwater rights and aquifer storage and recovery operations being two frequent applications. Time series data from the Edwards Aquifer, Texas, USA, illustrate the application of the methods presented.

Résumé Des données sur le long terme de la recharge d'aquifère, de l'exploitation de l'eau souterraine et de la vidange sont utilisées pour estimer la capacité d'emmagasinement de l'aquifère et la capacité annuelle maximum. La capacité d'emmagasinement de l'aquifère est définit comme le volume maximum de l'eau qui peut être emmagasinée dans le réservoir. Elle est estimée en utilisant une approche par bilan hydrologique en transitoire. La capacité annuelle maximum est définit comme la combinaison de l'extraction de l'eau souterraine et de la vidange, combinaison qui peut être jugée durable ou non au regard de l'examen des valeurs de recharge. Elle est déterminée au moyen d'une méthode de courbe des valeurs cumulées. Ces deux quantités sont très utiles pour caractériser les aquifères et pour gérer les eaux souterraines, l'imputation des droits aux eaux souterraines, et du fait que les opérations de recharge des aquifères et de récupération sont très fréquentes. Les données temporelles provenant de l'aquifère Edwards, Texas, USA, illustrent l'application de la méthode présentée.

Resumen Para estimar la capacidad de almacenamiento de un acuífero y su rendimiento máximo anual, se han utilizado series temporales largas de datos de recarga al acuífero, de extracciones de agua subterránea y de descarga. La capacidad de almacenamiento de un acuífero se define como el volumen máximo de agua que puede ser almacenado en el mismo. Se estima utilizando una aproximación con un balance de agua en régimen transitorio. El rendimiento máximo anual se define como el máximo resultante de la combinación de la extracción de aguas subterráneas y la descarga que puede ser sostenido por un acuífero según los registros históricos de recarga y se define según un método gráfico masa-curva. Estos dos valores son útiles en la caracterización de los acuíferos y en la gestión de las aguas subterráneas, el reparto de los derechos sobre las aguas subterráneas y las operaciones de almacenaje y recuperación de los acuíferos, que son dos aplicaciones frecuentes. Las series de tiempo para el Acuífero Edwards, Texas, USA, ilustra la aplicación de los métodos presentados.

Keywords Groundwater development · Groundwater recharge/water budget · Aquifer storage · Spring flow

Introduction

This article presents a method to estimate an aquifer's storage capacity and its maximum annual yield. Aquifer storage capacity is defined as the maximum volume of water that can be stored in an aquifer. It is estimated using a transient-water balance approach. The maximum annual yield is determined according to the classical (graphical) mass-curve method used in sizing surface-water reservoirs (see Linsley and Franzini 1979), modified in this work to estimate aquifer yield. The maximum annual yield is the rate of groundwater extraction plus discharge that depletes an aquifer's storage capacity through its historical critical drought period, yet leaves groundwater in storage during more favorable (non-drought) recharge periods. Aquifer dis-

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H. A. Loáiciga (✉)
Dept. Geography,
University of California,
Santa Barbara, CA 93106, USA
e-mail: hugo@geog.ucsb.edu

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charge is defined as the sum of spring flow, baseflow contributions to stream flow, seepage to lakes and the ocean floor, and evapotranspirative losses. Estimates of aquifer storage capacity are useful from hydrogeologic and management viewpoints. Adjudication of water rights and the planning of aquifer storage and recovery operations (artificial recharge) are examples of actions requiring the knowledge of aquifer storage capacity. The maximum annual yield constitutes an upper bound to the sustained rate of depletion of groundwater from aquifer storage. It accounts for (1) groundwater extraction, (2) discharge, (3) aquifer storage capacity, (4) and long-term recharge characteristics. The maximum annual yield is neither a safe aquifer yield nor a sustainable extraction rate. The latter is defined as the groundwater withdrawal that satisfies water-supply requirements without deleterious hydrogeologic or environmental impacts (see Loáiciga 2003, 2006, for more details about this definition of sustainable groundwater extraction). Safe yield is a groundwater extraction that, for an acceptable level of aquifer storage, cannot exceed the sum of induced recharge plus the decrease in aquifer discharge produced by removal of groundwater from storage (Theis 1940; Heath 1987; Fetter 2001; Devlin and Sophocleous 2005). The reader is referred to in-depths essays on groundwater's safe yield and its sustainable extraction (Alley et al. 1999; Alley and Leake 2004, for example), two terms whose definitions escape universal consensus.

Estimation of aquifer storage capacity

In a heterogeneous aquifer with storativity $S(x,y)$ and maximum range of hydraulic head fluctuation $b(x,y)$ distributed over the aquifer's area defined by planar coordinates x and y, the aquifer storage capacity (V) is given by the following equation:

$$V = \int_x \int_y S(x,y)\, b(x,y)\, dx\, dy \quad (1)$$

The storativity (or specific yield if unconfined conditions prevail) and hydraulic-head range may be known with some degree of accuracy over sub-areas of an aquifer. A discretized approximation of Eq. (1) can yield representative estimates of aquifer storage capacity when there are adequate pumping-test data and hydrogeologic characterization over an aquifer. The former data are commonly insufficient and expensive to acquire, however.

An alternative approach to estimate aquifer storage capacity is to use long-term measurements of aquifer recharge (R), groundwater extraction, say, by pumping (Q), and discharge (G). In regions beset by pronounced inter-annual climatic variability and protracted drought, long-term hydrogeologic data records should span several decades, sometimes centuries, and include droughts, the longest and most severe of which in the record is called the historical critical drought (Heath 1987; Loáiciga et al. 1993). Let the volume of groundwater in storage at the end of any year t, t=1, 2, 3,...., be denoted by S_t, and the aquifer recharge, groundwater extraction, and discharge during year t be denoted by R_t, Q_t, and G_t, respectively. The water-balance equation for the aquifer is then written as follows:

$$S_t = S_{t-1} + R_t - Q_t - G_t \qquad t = 1, 2, 3, \ldots \quad (2)$$

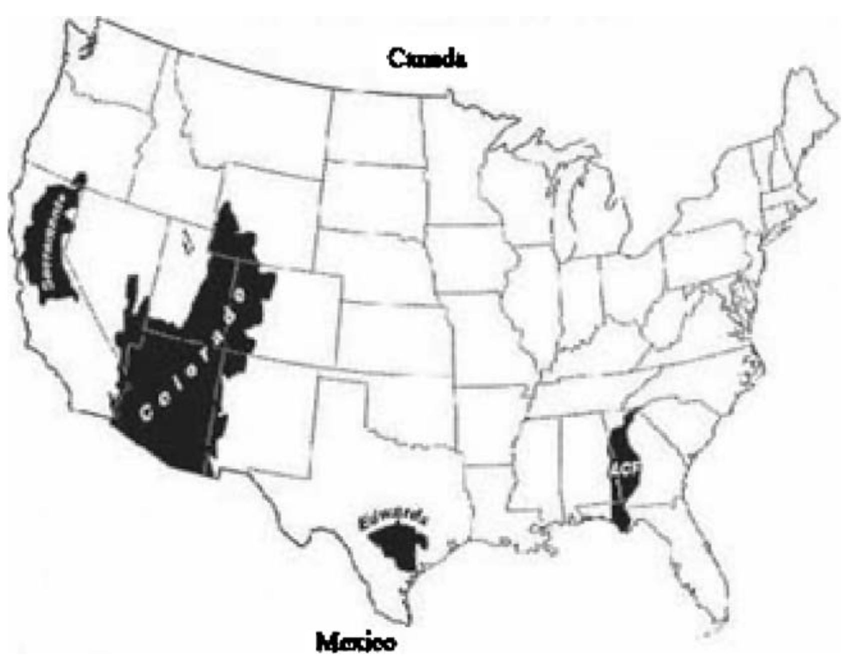

Fig. 1 The Edwards Aquifer in Texas state, USA, and three other river basins vulnerable to climatic change (see Loáiciga et al. 2000): river basins *ACF* (Appalachicola-Chattahoochee-Flint), *Colorado*, and *Sacramento*

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A repeated backward substitution of previous storages into the water-balance Eq. (2) allows for expression of the aquifer storage in terms of an initial storage at time t_0, S_0:

$$S_{\mathrm{t}} = S_0 + \sum_{\mathrm{k}=1}^{t} \left(R_{\mathrm{k}} - Q_{\mathrm{k}} - G_{\mathrm{k}} \right) = S_0 + N_{\mathrm{t}} \quad (3)$$

$$t = 1, 2, 3, \ldots$$

in which N_{t} is the cumulative net gain to aquifer storage in the period (0, t). N_{t} can be positive, negative, or zero, and its sign varies through time.

An estimate of aquifer storage capacity using time series of recharge, groundwater extraction, and discharge of length T is given by the difference between the maximum and minimum observed aquifer storages in the period (0, T), $V_{\mathrm{T}} \cong S_{\max}(T) - S_{\min}(T)$. The estimate V_{T} becomes exact for a sufficiently long time series of aquifer data. In view of Eq. (3), the estimate of aquifer storage capacity is given by the range of the cumulative net gain:

$$V_{\mathrm{T}} \cong N_{\mathrm{t\,max}} - N_{\mathrm{t\,min}} \quad (4)$$

in which $t_{\max}$ and $t_{\min}$ are the times at which the maximum and minimum storages occur, respectively, during the period (0, T).

The application of Eq. (4) is illustrated with hydrogeologic data from the Edwards Aquifer south-central Texas, USA. Figure 1 shows the location of the Edwards Aquifer within the United States (see Loáiciga et al. 2000, for an in-depth review of the hydrogeologic characteristics of the Edwards Aquifer).

Figure 2 shows a graph of annual recharge, groundwater extraction (by pumping), and discharge (total spring flow) in the Edwards Aquifer for the period 1934–2005. The time series shown on Fig. 2 have been discussed in Loáiciga and Wolf (2007). Recharge occurs primarily by seepage in streams that cross the outcrop area of the Edwards Formation, a karstic carbonate rock. Recharge is calculated in the Edwards Aquifer by water balance in streams crossing the outcrop area: inflow upstream minus outflow downstream equals recharge. Discharge is tantamount to spring flow, which is measured directly by stream gaging at various locations. The calculated annual recharge and measured spring flow are estimated to be within ±5% of actual values (Loáiciga et al. 2000). The historical critical drought occurred in the period 1947–1956, as seen in the graph of recharge in Fig. 2, which exhibits pronounced inter-annual variability. The dominant recharge process in the Edwards Aquifer is by stream flow seepage through outcropped area of the Edwards Formation, a permeable karstic formation (Puente 1978; Maclay and Small 1984). Groundwater extraction grew steadily from 1934 through the 1980s. Cumulative adverse impacts on several plant and animal species dependent on the Edwards Aquifer's spring flow and water levels led to Court orders curtailing the growth of groundwater extraction in the mid 1980s.

The applicability of this work's methods hinges on long-term records of recharge, discharge, and groundwater

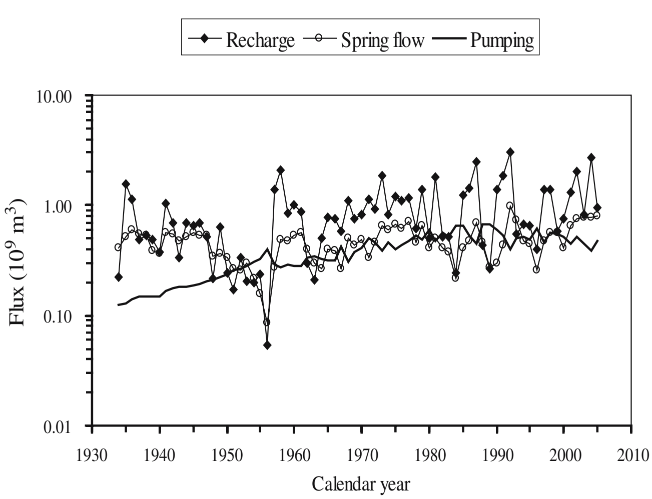

Fig. 2 Annual recharge, spring flow, and pumping in the Edwards Aquifer, 1934–2005 (Source; Edwards Aquifer Authority 2006)

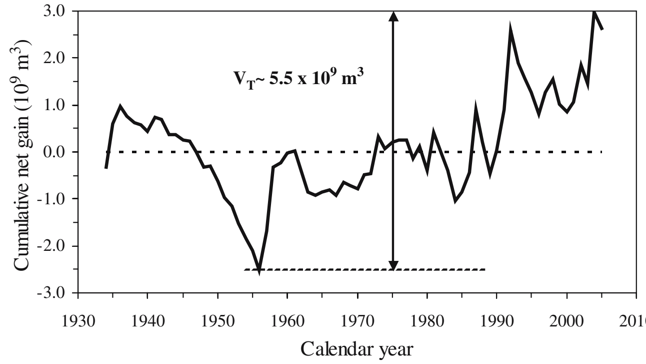

Fig. 3 Estimated Edwards Aquifer's storage capacity using cumulative net-gain data for the period 1934–2005, $V_{\mathrm{T}} \cong 5.5 \times 10^9$ m^3/year

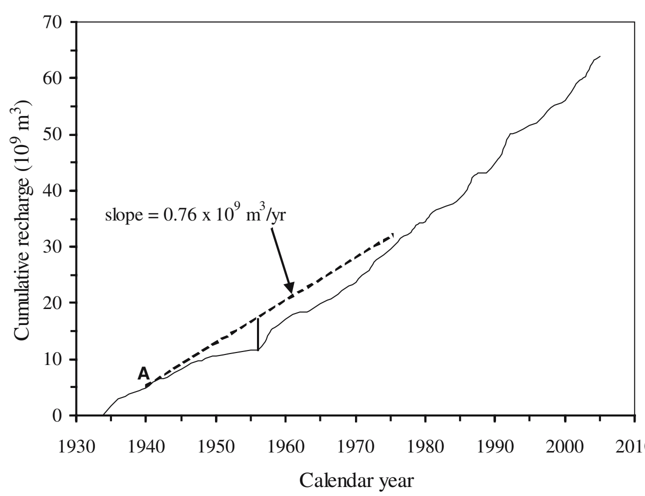

Fig. 4 Estimation of the maximum annual yield (Y_{T}) using long-term cumulative recharge data in the Edwards Aquifer, Texas. $Y_{\mathrm{T}} = 0.76 \times 10^9$ m^3/year, which equals the slope of the tangent through point A that exactly subtends the estimated aquifer storage capacity equal to 5.5×10^9 m^3/year (drawn as a *vertical line* between the cumulative recharge and the tangent at A). See text for details

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extraction that include droughts. The availability of those records may be limited in many parts of the world. When available, the accuracy of their measurements must be of sufficient quality to assure meaningful results.

The net-gain time series was constructed from those shown in Fig. 2, and graphed in Fig. 3. Superimposed on Fig. 3 is the estimate of the Edwards Aquifer's storage capacity, equaling $V_T \cong 5.5 \times 10^9$ m^3/year.

Estimation of the maximum annual yield

The maximum annual yield is estimated using the mass curve obtained by plotting the cumulative annual recharge as shown in Fig. 4. Next, tangents are drawn through high points on the cumulative-recharge curve where there is concave downward curvature. The tangent with the gentlest slope that exactly subtends the estimated aquifer storage capacity (previously determined) constitutes the estimate of the maximum annual yield (see Linsley and Franzini 1979, for a discussion of the mass-curve approach in relation to surface reservoir sizing). The tangent so determined must intersect the cumulative recharge curve when projected forward. Otherwise aquifer storage will not be replenished. For the Edwards Aquifer's recharge data, it is seen in Fig. 4 that the estimated maximum annual yield $Y_T = 0.76 \times 10^9$ m^3/year. This equals the slope of the tangent through point A at time T_A. Y_T is such that starting with an aquifer at storage capacity at time T_A, the combined draft of aquifer storage by groundwater pumping and discharge (discharge is tantamount to spring flow in the Edwards Aquifer) equaling $Y_T = 0.76 \times 10^9$ m^3/year plus the replenishment of aquifer storage by historical recharge would exactly deplete all the groundwater in storage within the historical critical drought (1947−1956). For comparison, the average pumping plus spring flow in the period 1978–1989, the period with the highest average pumping rate since 1934, was 1.0×10^9 m^3/year, larger than the estimated maximum annual yield.

Discussion

The Edwards Aquifer storage was not completely depleted during the heavy-pumping 1978–1989 period because recharge was plentiful then. Nevertheless, spring flow reached low levels because of the large rate of groundwater extraction. This caused adverse impacts on dependent aquatic habitat. It is crucial to recognize that the maximum annual yield is a combined withdrawal by groundwater extraction and discharge. Groundwater extraction that avoids adverse hydrogeologic and environmental impacts is a fraction of the maximum annual yield. A sustainable groundwater extraction rate would be constrained by (1) minimum discharge required to support dependent aquatic habitat, and (2) minimum storage required to meet hydrogeologic and environmental protection criteria (Loáiciga 2006). These constraints render the groundwater extraction rate much less than the maximum annual yield. During periods of drought, in fact, groundwater extraction may have to be halted entirely to allow groundwater in storage to be dedicated to support critical habitat and prevent irreversible impacts (say, saltwater intrusion in coastal aquifers, see Loáiciga et al. 2000; Zektser et al. 2005).

The maximum annual yield constitutes an upper bound to the combined, sustained, loss of aquifer storage by groundwater extraction and discharge. It could be used as an upper limit in the apportionment of groundwater rights among aquifer users, including water to meet ecological requirements. Limits on groundwater extraction have taken heightened significance, given that many aquifers are in a condition of overdraft. In this instance, groundwater extraction exceeds natural recharge leading to steady loss of storage and adverse impacts on aquifers (Zektser et al. 2005).

The method to estimate aquifer storage capacity and the maximum annual yield is applicable under stationary climate or changing climate. This is so because the method is based on actual year-to-year aquifer fluxes, rather than on the averages of these fluxes, which would not be constant under unsteady climatic conditions.

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