Title

Ground-Water/Surface-Water Interactions in a Karst Aquifer

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Ground-water/surface-water interactions in a karst aquifer

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Abstract

Ground-water/surface-water interactions in of the largest aquifer systems in the United States were analyzed in this article. The Edwards karst aquifer of Texas exhibits unique ground-water recharge processes. It is also located in a region of pronounced precipitation variability, the dominant controlling factor of ground-water recharge. The evolution of ground-water storage effected by recharge, pumping, and spring flow in the Edwards Aquifer has provided new evidence about the role of hydrologic, climatic, ecologic, and social factors in the determination of sustainable aquifer management policies. Historical data and numerical simulations were used to analyze pumping impacts within an integrated framework of sustainable aquifer production.

Key words

Ground-water recharge, karst aquifer, stream flow, spring flow, numerical model.

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Introduction

Ground-water/surface-water interactions are fundamental in the evolution of aquifer storage. They manifest themselves primarily in the form of percolation, base flow, stream and lake seepage, and spring flow. Percolation (vadose-zone flux onto water tables) and influent stream and lake seepage are gains to aquifer storage and their sum is called ground-water (natural) recharge. Artificial recharge by humans must be added to natural recharge wherever it is practiced to calculate the total contribution to aquifer storage. Base flow and spring flow are effluent fluxes from an aquifer, just as is seepage toward lakes and ocean floors (Zektser and Loáiciga, 1993). Ground-water pumping is the most common artificial ground-water depleting flux. All of the previous fluxes effect aquifer hydraulics in complex ways. This article examines the role of ground-water natural recharge in the determination of sustainable aquifer yield. Data from one of the largest aquifer systems in the United States illustrate the principles laid out in this article

Ground-water recharge and aquifer storage

Let us consider an aquifer in which ground-water pumping (Q), recharge (R), base flow (B), and spring-flow discharge (G) take place. From water-balance considerations in a period of duration T, it is evident that the change in ground-water storage is given by the following integral:

$$S(T) - S(0) = \int_0^T \left[R(t) - Q(t) - G - B\right] dt \qquad T \geq 0 \tag{1}$$

in which S(0) and S(T) are the storages at times zero (initial storage) and T, respectively.

Pumping (Q) may be measured accurately with well meters. It commonly exhibits a strong seasonal pattern, rising during periods of low precipitation (i.e., during dry seasons) and declining during wet seasons. The recharge flux (R) in equation (1) depends strongly on the amount of precipitation, and, thus, it tends to replicate the seasonality and inter-annual variability observed in the climate specific to the region where the aquifer is found.

Spring flow (G) can be measured when it is concentrated as a point-source at the ground surface. When it takes place as an extended seepage face, it must be estimated indirectly (e.g., by chemical balance). Base flow is estimable by means of chemical balance as well as by empirical hydrograph decomposition procedures.

The estimation of recharge R in equation (1) may be approached by several methods. Common ones are: (1) method of stream-flow hydrograph separation (Meyboom, 1961); (2) water-level fluctuation method (see, e.g., Loáiciga and Hudak, 2001); (3) tracers method (see, e.g., Rodriguez-Estrada and Loáiciga (1995); (4) hydrologic-budget method (Loáiciga et al., 2000), and numerical methods (Freeze, 1969). Of particular interest herein, is the estimation of recharge from the changes in flow along an influent stream. Consider the diagram of Figure 1. Stream flows upstream and downstream of the recharge area are denoted by Q_U and Q_D, respectively. The runoff contribution to stream flow within the recharge area is Q_I. Conservation of water in the stream between the upstream and downstream points dictates that the recharge in that reach of the stream is given by:

$$R = Q_U + Q_I - Q_D \qquad (2)$$

Equation (2) implies that the change of storage in the stream within the recharge area is negligible. If not, its right-hand side would have an additional term representing that change in storage. All the fluxes in equation (2) are averages over a specified time interval.

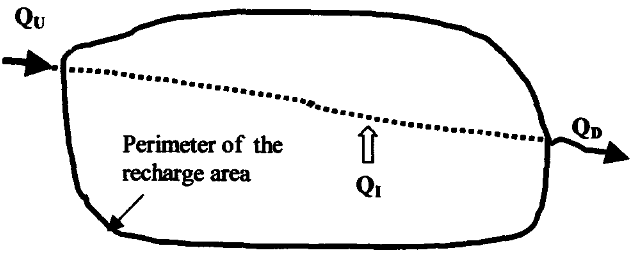

Figure 1. Plan view of a hypothetical recharge area showing fluxes that determine ground-water recharge.

Figure 2 shows the evolution of annual ground-water recharge, pumping, and spring flow from 1934 to 1995 in the Edwards Aquifer of Texas, one of the most productive ground-water systems in the world (Loáiciga et al., 2000). Recharge takes place primarily as stream seepage along aquifer outcrops, in a manner akin to that shown in the scheme of Figure 1, and was calculated by means of equation (2) applied to all the streams crossing the Edwards recharge area.

It is seen in Figure 2 that recharge shows large inter-annual fluctuations, which appear to become larger over time. Ground-water pumping displays a long-term increasing trend, even during the drought of 1936 – 1959. The intermittent lows in ground-water pumping after 1985 were caused by Court orders imposed on the mining of the Edwards Aquifer to protect aquatic habitats in the discharge zone near springs (Loáiciga et al., 2000). Spring flow is concentrated along large fault springs that define the discharge zone of the Edwards aquifer (Loáiciga et al., 2000). It is seen in Figure 2 that it is a smoothed-out and dampened replica of annual recharge. It lags recharge by a short period of time, typically less than one year. The time series of spring flow shown in Figure 2 does not represent natural ground-water discharge because of the effect that ground-water pumping had on spring flow.

Figure 3 shows the change in storage, $\Delta S = S(T) - S(0)$, calculated from equation (1) (in this case base flow is non-existent) for the Edwards Aquifer data shown in Figure 2. It is seen there that during the drought period between 1936 (point 1) and 1956 (point 2) aquifer storage dropped by 3500×10^6 m^3 as a result of ground-water pumping. Between 1956 and 1992 (point 3) there was a recovery of aquifer storage equal to 5100×10^6 m^3. Since the Edwards Aquifer was severely de-watered in 1956 –demonstrated by the drying of major springs- and in 1992 water levels rose to historically high levels after heavy El Niño rainfall, it can be concluded that the Edwards Aquifer extractable storage must be on the order of 5100×10^6 m^3. The role of ground-water /surface-water interactions on aquifer sustainable yield is examined next.

The myth of long-term aquifer yield

The edict "ground-water pumping shall not exceed the long-term average recharge" is used by many as the basis to calculate long-term aquifer. Thus, it is customary to determine average annual recharge and set the aquifer yield to be a percentage of the average recharge. In areas subject to precipitation variability, however, aquifer pumping should be varied according to climatic fluctuations because they control the magnitude of ground-water recharge. In most instances, ground-water pumping must be reduced during droughts to avoid negative environmental impacts. Those impacts include excessive declines in water level, water-quality deterioration, and reduced discharge to streams that support sensitive ecosystems. On the other hand, aquifers that are used a "water banks" are replenished during wet periods (by artificial and/or natural recharge) and a fraction of the recharged water is extracted during dry periods. Sustainable aquifer production calls for flexible pumping strategies, rather than rigid rules based on long-term averages.

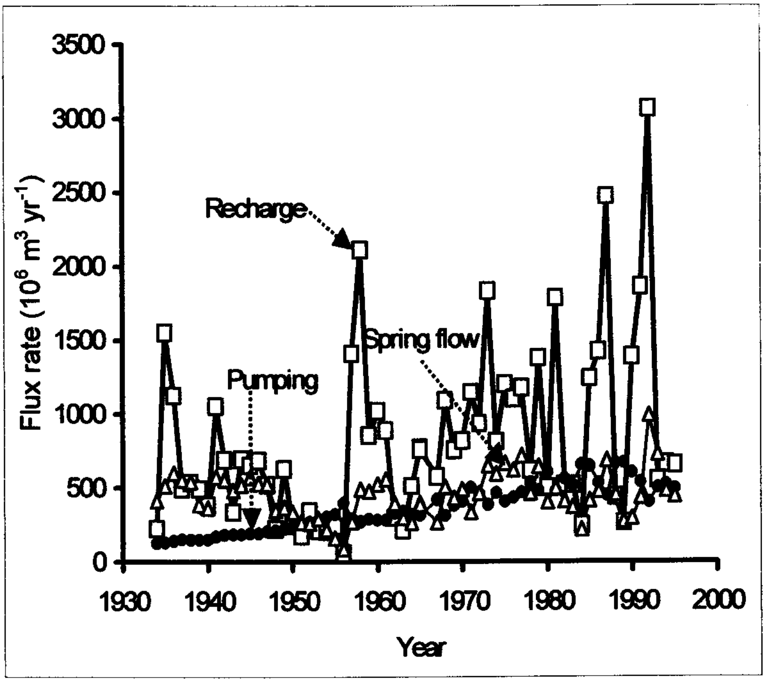

Figure 2. Ground-water pumping (Q), recharge (R), and spring flow (G) in the Edwards Aquifer.

Figure 4 shows a graph of the annual cumulative recharge in the Edwards Aquifer. The cumulative or mass recharge at any time t is simply the sum of annual recharge up to and including year t. The cumulative recharge is used herein to provide a first estimate of long-term ground-water pumping. Assume an extractable ground-water storage of 5100 x 10^6 m^3, which was estimated from Figure 3. One finds that the minimum-slope tangent to the cumulative recharge that encompasses the estimated ground-water storage of 5100 x 10^6 m^3 has a slope of 690 x 10^6 m^3 yr^{-1} (see the tangent drawn through point A in Figure 4). Ignoring spring flow and related impacts that are exacerbated by pumping in the Edwards aquifer, the magnitude of that slope equals the average long-term ground-water pumping that would be consistent with an usable aquifer storage of 5100 x 10^6 m^3.

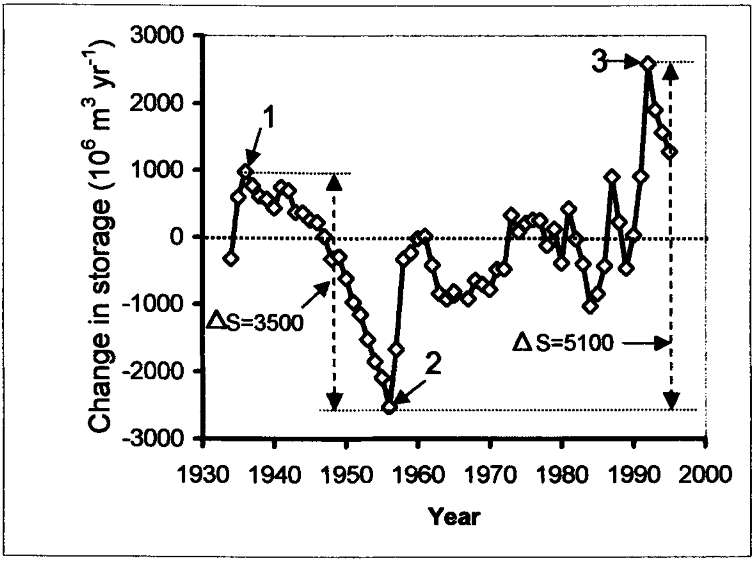

Figure 3. Evolution of aquifer storage driven by pumping, recharge, and spring flow in a variable climate, Edwards Aquifer, Texas.

Detailed ground-water simulations were carried out with a specially calibrated numerical model for the Edwards Aquifer for the low-recharge period 1947-1959 (Loáiciga, 2000). The results are shown in Figure 5. The minimum spring flows at the two largest springs in the Edwards Aquifer, namely Comal and San Marcos springs, were obtained for annual pumping rates varying from 0 to 780 x 10^6 m^3 yr^{-1}. The required minimum spring flow is also shown in Figure 5. It is seen that an annual pumping rate of 120 x 10^6 m^3 yr^{-1} meets the minimum-flow requirement at Comal springs. San Marcos spring flow, however, falls below the required flow even when pumping is reduced to zero. For comparison, during the period 1934-1995, the average pumping in the Edwards Aquifer was on the order of 360 x 10^6 m^3 yr^{-1}, while during the high-growth period 1970-1995 pumping averaged 514 x 10^6 m^3 yr^{-1}. Those levels of historical pumping have created serious management issues in the Edwards Aquifer.

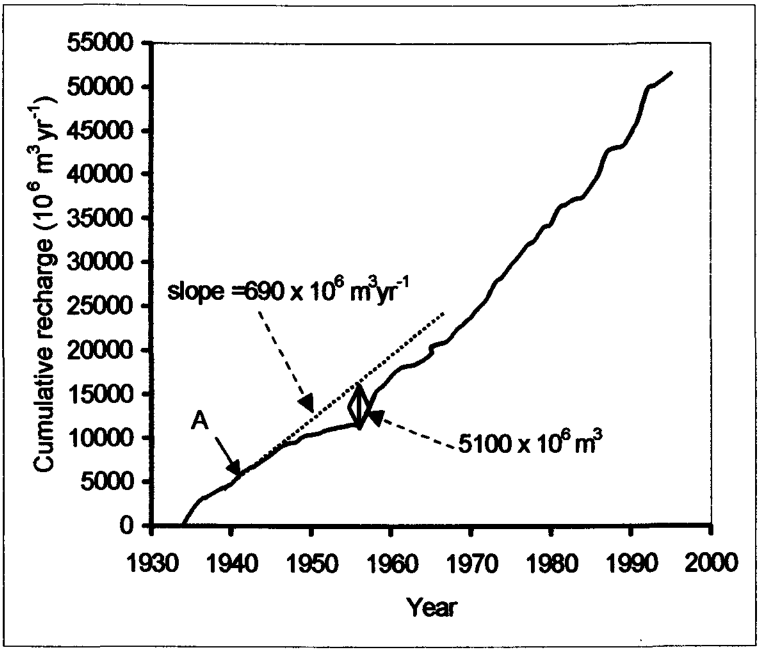

Figure 4. Cumulative recharge in the Edwards Aquifer and long-term yield estimated from it.

Conclusions

This work has addressed the role of ground-water/surface-water interactions on ground storage and in planning aquifer-management strategies. One must consider also the effects that ground-water pumping has on ecosystems supported by ground-water, and, although not specifically shown in this work, on water-quality and ground-subsidence effects. Ground-water management is best accomplished when the effect of precipitation variability on recharge is taken into account, and when pumping is tied to climatic fluctuations. The integrated consideration of hydrological, climatic, ecological, and social effects of ground-water pumping is the cornerstone of successful, long-term, aquifer-management strategies.

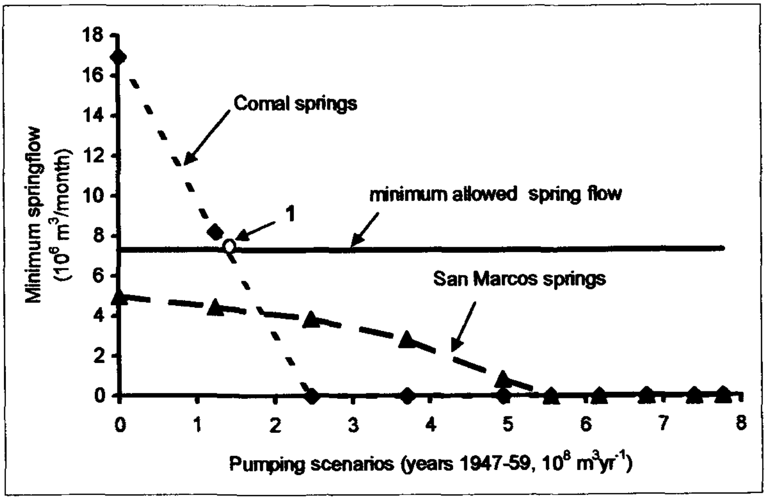

Figure 5. Spring flows in the Edwards aquifer for a range of annual pumping scenarios.

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