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Comment on "The persistence of the water budget myth and its relationship to sustainability" by J.F. Devlin and M. Sophocleous, Hydrogeology Journal (2005) 13:549–554

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Introduction

Devlin and Sophocleous (2005) have written a thoughtful and provocative article on the subject of sustainable pumping and sustainable groundwater-resources development. In the subject article, sustainable pumping was defined as "a pumping rate that can be maintained indefinitely without dewatering an aquifer". Sustainable groundwater-resources development is, according to the subject article, a broader concept that encompasses groundwater use and its environmental and human repercussions. Devlin and Sophocleous (2005) contend that the definitions of sustainable pumping and sustainable groundwater-resources development have been confused by some in the groundwater community, and, that the confusion has led to the "water budget myth" (see also Bredehoeft 2002). The water budget myth is—according to Devlin and Sophocleous (2005)—the "idea that sustainable pumping must not exceed the recharge rate in a given aquifer". A substantial portion of the subject article is devoted to proving that the water budget myth is conceptually flawed.

This commentary presents an alternative interpretation of the relation between sustainable pumping and sustainable groundwater-resources development to that advocated by Devlin and Sophocleous (2005). This alternative interpretation renders superfluous the distinction between sustainable pumping and sustainable groundwater-resources and, as corollary, makes the water budget myth an innocuous—if not laudable—concept. In addition, this commentary argues that sustainable pumping, as defined in the subject article, has very limited practical applicability in the context of groundwater extraction under variable climate. This commentary argues that sustainable pumping must be adaptive and take into account climate fluctuations, especially protracted drought.

Sustainable pumping solutions

Nowadays, groundwater extraction is accomplished primarily with wells outfitted with pumps. Groundwater pumping is the main tool of groundwater-resources development, whose key objective is water supply for human consumption and crop production. In an aquifer, the total groundwater extraction is the sum of the extractions by all wells tapping the aquifer. The total extraction is the pumping rate, or, merely, pumping, in the aquifer. Sustainable pumping has been defined by Loáiciga (2003a) as groundwater extraction that strives to satisfy water-supply requirements without deleterious impacts on the environment. These impacts include baseflow reduction and effects on streams and lakes, groundwater-quality deterioration, land subsidence, and drying of vegetation by falling water tables, to cite a few well-known ones (see, for example, Zektster et al. 2005, for a review of groundwater-extraction impacts). Loáiciga's (2003a) definition of sustainable pumping is more encompassing than that presented in Devlin and Sophocleous (2005), the latter focusing on the prevention of aquifer dewatering. It is also broader in that pumping can be variable over time and, therefore, adaptive, although it is not, in general, as comprehensive as the concept of sustainable groundwater-resources development. The latter sometimes includes schemes for conjunctive use, such as artificial recharge, that may involve inter-basin water transfers. It also may include optimizing the use of multiple water sources, groundwater among them. However, barring conjunctive-use strategies and the availability of multiple water sources, it is evident that Loáiciga's (2003a) definition of sustainable pumping could be used almost synonymously with the concept of groundwater-resources development from the practical standpoint of seeking to extract groundwater for beneficial purposes.

Let us examine the implications of Loáiciga's (2003a) definition of sustainable pumping on the relation between

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pumping rate and aquifer recharge. In the following derivation, it is assumed that pumping (Q) is constant, so that a direct comparison can be made with results presented in Devlin and Sophocleous (2005). The recharge rate (R) depends on the climate, herein represented by precipitation (P), and perhaps on the pumping rate. R is "any volume of water flowing into an aquifer over a unit time period", as defined in Devlin and Sophocleous (2005). V denotes groundwater storage. D is aquifer discharge in the sense of Devlin and Sophocleous (2005), that is, any "volume of water flowing out of an aquifer over a unit time period", excluding pumping. D includes flows that sustain springs and baseflow to streams. For the sake of specificity, it is assumed in this work that discharge conforms to a linear-reservoir release, so that $D=\gamma V$, in which $0<\gamma<1$. The mass-balance equation that governs groundwater-storage evolution is then:

$$R - \gamma V - Q = \frac{dV}{dt} \tag{1}$$

Groundwater storage at an initial time $t_0 \equiv 0$ equals V_0. The solution to Eq. (1) is as follows (R is time independent for $t \geq 0$ in this first solution):

$$V(t) = V_0 e^{-\gamma t} + \frac{(R - Q)}{\gamma}\left(1 - e^{-\gamma t}\right) \tag{2}$$

For a time period that is long, $t \rightarrow \infty$, Eq. (2) becomes:

$$V_\infty = \frac{R - Q}{\gamma} \tag{3}$$

A sustainable pumping rate in the sense of Loáiciga (2003a) is obtained by solving the following problem (where max Q denotes maximization of the sustainable pumping rate):

$$\max \ Q \tag{4}$$

subject to (in which $V_{\min}$ and $D_{\min}$ are the minimum storage and discharge, respectively, that are imposed to avoid unacceptable impacts resulting from aquifer pumping):

$$V_\infty \geq V_{\min} \tag{5}$$

$$\gamma V_\infty \geq D_{\min} \tag{6}$$

The maximization in Eq. (4) expresses the objective of obtaining the greatest amount of groundwater from an aquifer. This objective is constrained by Eqs. (5) and (6), which, by putting limits on groundwater storage and discharge, ensure a proper functioning of the aquifer and avoid deleterious impacts from groundwater extraction. Storage and discharge constraining is a simple, yet, effective way to make the pumping rate optimal and sustainable. The solution to the problem embodied by Eqs. (4), (5) and (6) is:

$$Q = R - \gamma V^* \tag{7}$$

in which V^* is the larger of $V_{\min}$ or $D_{\min}/\gamma$. Equation (7) states that the sustainable pumping rate cannot exceed the recharge R, γV^* being positive. In the case of positive pumping, the pumping Q could be called the water-budget-myth solution in the sense of Devlin and Sophocleous (2005). Yet, it is a meaningful and correctly derived pumping rate under the definition of sustainable pumping proposed by Loáiciga (2003a) and the assumptions set forth earlier in this work.

Devlin and Sophocleous (2005), in the subject article, derived the following pumping rate using a procedure consistent with their definition of sustainable pumping (that is, the aquifer is not dewatered):

$$\widehat{Q} = r + d \tag{8}$$

in which r is the recharge induced by pumping and d is the absolute value of the change in discharge induced by pumping. The fluxes r and d are defined in terms of changes in pre-pumping recharge ($r=\Delta R_0$) and discharge ($d=|\Delta D_0|$), respectively. The induced recharge appearing in Eq. (8) deserves closer scrutiny. Induced recharge could be significant in the "island" aquifer used as an example in the subject article. The island aquifer is surrounded by constant-head boundaries that allow induced recharge following the decline of hydraulic head within the aquifer. More realistically, however, recharge is caused by precipitation-driven percolation to the water table (diffuse recharge) or by stream seepage (see, e.g., Loáiciga et al. 2000). Precipitation is the dominating factor that governs these two mechanisms of recharge, not pumping. The discharge response d in Eq. (8) deserves further examination, also. Notice that the pumping rate in Eq. (8) is unconstrained, and, thus, d can be large enough so as to produce inadmissible impacts. Drying of springs and streams that may cause irreversible damage to sensitive aquatic ecosystems are well-documented impacts of large d (see Loáiciga et al. 2000; Loáiciga 2003b; Zektster et al. 2005, for examples of deleterious impacts associated with reduced aquifer discharge).

In summary, in the subject article, sustainable pumping $\widehat{Q}$, Eq. (8), does not dewater an aquifer. In fact, they set the change in groundwater storage equal to zero, $dV/dt=0$, in obtaining $\widehat{Q}$. On the other hand, it has been argued in this work that $\widehat{Q}$ could be non-sustainable in other respects. It can be reasonably argued that $\widehat{Q}$ circumvents the water budget myth by resorting to a narrow interpretation of sustainability. As a result, the sustainability of the pumping rate $\widehat{Q}$ is questionable. The next section makes the case for adaptive sustainable pumping.

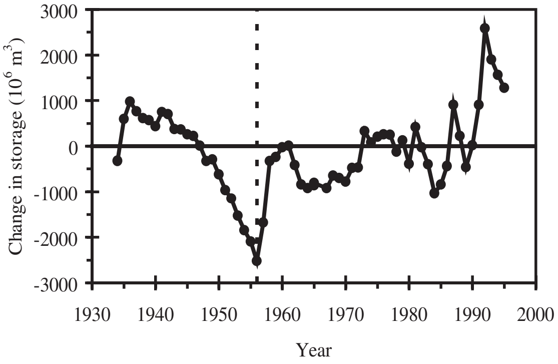

Fig. 1 Change in groundwater storage in the Edwards Balcones Fault Zone Aquifer, Texas, 1934–1995. Between 1935 and 1956 the aquifer suffered overdraft. After 1956 overdraft and recovery are interspersed

Adaptive sustainable pumping

Real-world groundwater extraction is beset by changes in the principal source of recharge, which is precipitation, and, in particular, by protracted drought. Pumping could influence recharge, although this is usually minor when compared with precipitation changes. Thus, the recharge rate is written in the form $R[P(t), Q]=R(t)$ to recognize that precipitation (P) varies with time, and that precipitation and pumping determine R, rendering the latter time dependent. The mass-balance Eq. (1) can be re-written as follows:

$$R(t) - \gamma V(t) - Q(t) = \frac{dV(t)}{dt} \tag{9}$$

whose solution is:

$$V(t) = V_0 e^{-\gamma t} + e^{-\gamma t}\left[\int_0^t e^{\gamma v} \cdot (R(v) - Q(v))dv\right] \tag{10}$$

Notice that sustainable pumping is a time function $Q(t)$, instead of a pumping rate that can be maintained indefinitely. Sustainable pumping is the function $Q(t)$ that maximizes long-term groundwater extraction and satisfies the minimum storage and discharge constraints, namely:

$$\max \int_0^T Q(t)dt \tag{11}$$

where T is the duration of the groundwater extraction horizon, subject to:

$$V(t) \geq V^* \qquad t \geq 0 \tag{12}$$

where V^* is the larger of $V_{\min}$ or $D_{\min}/\gamma$ and the storage $V(t)$ is given by Eq. (10). The solution of the adaptive sustainable pumping problem (11) and (12) is challenging. One must provide a functional expression for $R[P(t), Q]$ and then search for the function $Q(t)$ that satisfies Eqs. (11) and (12). The adaptive sustainable problem, therefore, requires knowledge of the recharge function in order to obtain the pumping function. One could name this the "adaptive water budget fact". Approximate solutions to the adaptive sustainable pumping problem (11) and (12) have been presented in Loáiciga et al. (2000) and Loáiciga (2003b) for a regional karst aquifer the Edwards Balcones Fault Zone Aquifer in Texas, USA—which features highly variable interannual recharge and aquatic ecosystems vulnerable to reduced springflow and baseflow. The Edwards is one of the most productive aquifers in the United States.

This commentary ends with a review of data presented in Fig. 1, which shows observed long-term groundwater storage in the Edwards Balcones Fault Zone Aquifer from 1934 through 1995. Figure 1 shows that storage fluctuated widely in the cited period. Sometimes it declined caused by overdraft, when pumping exceeded recharge for several years, and sometimes it exhibited recovery, when recharge exceeded pumping for several years. The complex situation shown in Fig. 1 is more the norm rather than the exception in groundwater pumping. Groundwater storage does not easily achieve steady-state or constant asymptotic values. If pumping is not tuned to recharge groundwater, storage dwindles, and, with it, so does aquifer discharge. Severe environmental impacts are to be expected in this situation.

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