The persistence of the water budget myth and its relationship to sustainability

John F. Devlin · Marios Sophocleous

Abstract Sustainability and sustainable pumping are two different concepts that are often used interchangeably. The latter term refers to a pumping rate that can be maintained indefinitely without mining an aquifer, whereas the former term is broader and concerns such issues as ecology and water quality, among others, in addition to sustainable pumping. Another important difference between the two concepts is that recharge can be very important to consider when assessing sustainability, but is not necessary to estimate sustainable pumping rates. Confusion over this distinction is made worse by the Water Budget Myth, which comprises the mistaken yet persistent ideas that (1) sustainable pumping rates cannot exceed virgin recharge rates in aquifers, and (2) that virgin recharge rates must therefore be known to estimate sustainable pumping rates. Analysis of the water balance equation shows the special circumstances that must apply for the Water Budget Myth to be true. However, due to the effects recharge is likely to have on water quality, ecology, socioeconomic factors, and, under certain circumstances, its requirement for numerical modeling, it remains important in assessments of sustainability.

Resumé Le développement durable et le pompage durable sont deux concepts très différents qui sont souvent interchangés. Le pompage durable réfère au taux de pompage qui peut ętre maintenu indéfiniment sans épuiser l'aquifère tandis que le terme développement durable est plus général et réfère entre autres à des questions d'écologie et de qualité de l'eau, en plus du pompage durable. Une différence importante entre les deux concepts est que la recharge peut ętre très importante lorsque le développement durable est étudié, tandis qu'elle n'est pas nécessaire pour déterminer le taux de pompage durable. La confusion associée à cette distinction est entretenue par le mythe du bilan de masse, lequel comprend la confondante, mais persistante, idée que (1) le taux de pompage durable ne peut excéder le taux de recharge dans l'aquifère et que (2) le taux de recharge doit par conséquent ętre connu afin d'estimer le taux de pompage durable. L'analyse de l'équation du bilan de masse révèle les circonstances spéciales qui doivent prévaloir pour que le mythe soit vérifié. Par contre, en raison des effets que la recharge peut avoir sur la qualité de l'eau, l'écologie, les facteurs socio-économiques, et dans certaines circonstances, son conditionnement pour la modélisation numérique, la recharge demeure un facteur important pour l'évaluation du développement durable.

Resumen La persistencia del mito del presupuesto de agua y su relacion con la sostenibilidad Sostenibilidad y bombeo sostenible son dos conceptos diferentes que frecuentemente se emplean como sinónimos. El último término se refiere a una tasa de bombeo que se puede mantener indefinidamente sin explotar un acuífero, mientras que el primer término es más amplio e incluye tanto el bombeo sostenible como la ecología y calidad del agua, entre otros. Otra diferenceia importante entre ambos conceptos es que la recarga puede ser my importante parea evaluar sostenibilidad, pero no es necesria para estimar tasas sostenible de bombeo. La confusión entre estos términos distintos se agreva por el mito¨del presupuesto de aguä, que engloba las ideas equivocadas pero persistentes (1) que las tasas de bombeo sostenibles no pueden exceder las tasas de recarga virgen en los acuíferos y (2) de que las tasas de recarga virgen deber ser conocidas para poder estimar las tasas de bombeo sostenible. El análisis de la ecuación de equilibrio del agua muestra las circunstancias especiales que deben ser válidas, para que¨el mito del presupuesto de aguä sea cierto. Sin embargo la recarga continua siendo importante para evaluar la sostenibilidad debido a los efectos que probablemente tiene sobre la calidad del agua, la ecología, factores socioeconómicos, y, bajo ciertas circunstancias la necesidad de tener esta información para modelos numéricos con el objetivo de evaluar la sostenibilidad.

Received: 1 May 2003 / Accepted: 17 April 2004

J. F. Devlin (✉)
Department of Geology,
University of Kansas,
1475 Jayhawk Blvd., Lawrence, Kansas 66045, USA
e-mail: jfdevlin@ku.edu
Tel.: +1-785-8644994

M. Sophocleous
Kansas Geological Survey,
The University of Kansas,
Lawrence, Kansas KS 66047, USA

Hydrogeology Journal (2005) 13:549–554 DOI 10.1007/s10040-004-0354-0

Keywords General hydrogeology · Groundwater management · Groundwater recharge/water budget

Introduction

The concept of sustainable development of groundwater resources, referred to hereafter as sustainability, and that of sustainable pumping are easily confused. Sustainable pumping refers to a pumping rate that can be maintained indefinitely without dewatering or mining an aquifer, whereas sustainability is a broader term that goes beyond sustainable pumping to include issues such as ecology, water quality, and human and environmental welfare. Another important distinction between them is that although groundwater recharge rates are not required for estimating sustainable pumping rates, they are required for the accurate assessment of sustainability, as discussed further on in this article. For the purposes of this article, the term "recharge" will refer to any volume of water flowing into an aquifer over a unit time period, whereas "discharge" will refer to any volume of water flowing out of that aquifer over a unit time period. The importance of recharge, as it pertains to both of these concepts, has been the subject of discussion for some time and is, perhaps, a source of confusion. The confusion has been particularly acute with regard to sustainable pumping, as indicated by the unremitting Water Budget Myth (Bredehoeft 2002). Briefly, the Water Budget Myth is the idea that sustainable pumping must not exceed the recharge rate in a given aquifer. Although Bredehoeft (2002) and others (Theis 1940; Brown 1963; Bredehoeft et al. 1982) have presented conclusive theoretical proof and supporting discussions that show the Myth is erroneous, it still persists. Here, an attempt is made to further mitigate the confusion by suggesting why the Myth is so readily accepted in the first place, and then to explore the assumptions on which it is based. The first goal in writing this article is to clearly illustrate the limitations of the Myth and to show explicitly, with equations and conceptual examples, why recharge is not necessarily the factor that limits sustainable pumping rates. To achieve this goal, arguments are reviewed that have been introduced before, but previously omitted details are presented that cast the topic in a new light with the hope of simplifying and clarifying the discussion. The second goal is to separate the concepts of sustainable pumping and sustainability, and indicate the circumstances in which it is important to know something about recharge. This paper is of a public education nature, expanding on the exposition recently authored by Bredehoeft (2002).

The Water Budget Myth

The Law of Conservation of Matter (LCM) is a fundamental tenet of modern science, and it is believed to be one of the roots of the Water Budget Myth's tenacity. The appeal of the Water Budget Myth comes from the seemingly logical reasoning that if an aquifer is pumped more than it is recharged, it will one day run out of water. In a fashion consistent with the LCM, this thinking can be expressed as a mass balance (erroneous in its oversimplification, as will be shown) of the form,

$$\mathrm{R} = \mathrm{P} + \mathrm{D}, \tag{1}$$

where R is the recharge rate (L^3/T), generally assumed to come from rainfall and be unaffected by pumping, D is the discharge rate of water that is not captured by the pumping (L^3/T) (to streams, lakes, evaporation, or evapotranspiration, etc.), P is the net pumping rate (L^3/T) and all three terms are positive numbers. The term "net pumping rate" refers to that water permanently removed from the aquifer, i.e., the total pumping less that part of the pumped water that returns to the aquifer as recharge. This distinction is important in cases such as pumping for irrigation. The importance of distinguishing total and net pumping rates was recently discussed in more detail by Kendy (2003). For the sake of simplicity, net pumping is simply referred to as pumping throughout the remainder of this presentation. In writing this equation, several unstated assumptions have been made that can now be explored by contrasting them with the water balance Bredehoeft (2002) discusses,

$$(R_o + \Delta R_o) - (D_o + \Delta D_o) - P + \frac{dV}{dt} = 0, \tag{2}$$

where D_o = the natural or virgin discharge rate (L^3/T), ΔD_o = the change to the virgin discharge rate due to pumping (L^3/T), dV/dt = the rate of removal of water from storage (L^3/T), R_o = the virgin, recharge rate [prior to pumping, and is the same as R in Eq. (1)] (L^3/T), and ΔR_o = the change to the virgin recharge rate due to pumping (L^3/T). Let the following definitions apply:

$$\mathrm{R} = (\mathrm{R_o} + \Delta\mathrm{R_o}) \tag{3}$$

and

$$\mathrm{D} = (\mathrm{D_o} + \Delta\mathrm{D_o}), \tag{4}$$

meaning that the observed recharge and discharge rates are equal to the virgin rates adjusted for any changes imposed by pumping. Right away an assumption built into Eq. (1) can be seen: in Eq. (1) ΔR_o is not considered, and so is assumed equal to 0. This also means that R in Eq. (1) is equal to R_o in Eq. (3). These assumptions are consistent with the notion that pumping has no affect on recharge, a point that was raised above and will be revisited below.

For sustainable development, the steady-state case must be considered because steady state represents the long-term condition of an aquifer. At steady state, water is no longer being removed from storage, so $dV/dt=0$. This is a second assumption built into Eq. (1), and one that will be applied throughout this discussion. With this in mind, a third unstated assumption in Eq. (1) is that the change in discharge, ΔD_o, is equal to the pumping rate, i.e., $P=-\Delta D_o$, and therefore $P<D_o$. Again, these points will be revisited below [see Eq. (8)].

DOI 10.1007/s10040-004-0354-0

Provided the assumptions above (in particular, $dV/dt=0$ and $\Delta R_o=0$, i.e., $R=R_o$) are justified, it can be explicitly shown that Eqs. (1) and (2) are consistent. Starting with Eq. (2):

$$(R_o + \Delta R_o) - (D_o + \Delta D_o) - P + \frac{dV}{dt} = 0$$

$$(R_o + 0) - (D_o + \Delta D_o) - P + 0 = 0$$

$$R_o - (D_o + \Delta D_o) = PR_o = P + (D_o + \Delta D_o).$$

Substituting Eq. (4) into this expression,

$$R_o = P + D$$

and since $R=R_o$,

$$R = P + D.$$

This development has ended with Eq. (1). In deriving it, the conditions necessary for the Water Budget Myth to be valid were rigorously applied. These are further discussed and expanded upon in the following section. It is said that all myths are based on reality; the derivation of Eq. (1) is the “real” basis for the Water Budget Myth.

Assessing the Assumptions in the Water Budget Myth

The validity of the assumptions that make Eqs. (1) and (2) equivalent, and the corresponding conclusions must now be assessed. First, the notion that $R=R_o$ is brought into question because pumping can affect recharge (1) by increasing recharge if the pumping takes place in areas of rejected recharge (i.e., areas where water tables temporarily rise close to or to the ground surface during rains, causing potential recharge waters to be lost as surface runoff), or (2) by decreasing recharge if the pumping leads to aquifer consolidation and an altered hydraulic conductivity of the recharging units. Other scenarios, in which recharge rates are affected by pumping can also be envisioned. For example, increased recharge can result from irrigation return flow to the aquifer, induced recharge from surface water bodies, interception of groundwater discharging to streams, and increased drainage gradients from the vadose zone to the aquifer resulting from lowering of the water table. All of these scenarios involve conditions that invalidate Eq. (1). For the purposes of this discussion, ΔR_o will be considered a positive quantity, call it $+r$, meaning that recharge is increased by pumping, i.e.,

$$\Delta R_o = +r \qquad (5)$$

Next, the myth holds that determining sustainable pumping rates depends on knowledge of the recharge rates. To evaluate this contention, consider the following. Before pumping begins, when $P=0$ and $\Delta R_o=\Delta D_o=0$, it can be show from Eq. (2) that

$$(R_o + \Delta R_o) - (D_o + \Delta D_o) - P + \frac{dV}{dt} = 0$$

$$(R_o + 0) - (D_o + 0) - 0 + 0 = 0$$

leading to

$$R_o = D_o, \qquad (6)$$

which corresponds to the original steady state. Pumping can lower groundwater levels and thus reduce the discharge rate of an aquifer. After the onset of “gentle pumping” (defined here as constant pumping with $P>0$ but $P<D_o$), when the declining water levels have stabilized, a modified steady state develops. The mathematical expression of this new steady state, accepting the Water Budget Myth for the moment, is given by substituting Eqs. (3) (where $\Delta R_o=0$) and (6) into Eq. (1),

$$R = P + D$$

$$(R_o + \Delta R_o) = P + D$$

$$(R_o + 0) - D = P$$

resulting in the following expression,

$$P = R_o - D. \qquad (7)$$

This appears to show that recharge rates must be known to determine sustainable pumping rates. However, it turns out that there is enough information, without the recharge rates, to calculate sustainable pumping rates in such systems. This can be shown by combining Eqs. (4), (6), and (7). Beginning with Eq. (7),

$$P = R_o - D$$

substituting Eq. (6) for R_o

$$P = D_o - D$$

and then Eq. (4) for D

$$P = D_o - (D_o + \Delta D_o)$$

leaving

$$P = -\Delta D_o. \qquad (8)$$

This equation shows that the sustainable pumping rate can be determined from the amount of discharge captured with the pumping well, without quantitative knowledge of recharge rates, provided, of course, the original assumption that recharge is unaffected by pumping ($\Delta R_o=0$, $R=R_o$) still holds. This is an important result because recharge rates can be very difficult to estimate accurately, and having a method of estimating sustainable pumping rates without them is highly advantageous.

Because Eq. (8) applies when $\Delta R_o=0$, it may be regarded as a special case. A more general form of the steady state equation ($dV/dt=0$) is obtained by substituting Eq. (6) into Eq. (2), leaving ΔR_o unrestricted.

$$(R_o + \Delta R_o) - (D_o + \Delta D_o) - P + \frac{dV}{dt} = 0,$$

now R_o is substituted for D_o, as in Eq. (6)

$$(R_o + \Delta R_o) - (R_o + \Delta D_o) - P + 0 = 0$$

and simplifying

$$\Delta R_o - \Delta D_o - P = 0$$

$$P = \Delta R_o - \Delta D_o. \qquad (9)$$

Equation (9) is called the capture equation, consistent with the definition by Lohman (1972, p. 3) who wrote, "The decrease in discharge plus the increase in recharge is termed capture." Note that natural discharge from the aquifer is reduced by pumping so ΔD_o is actually a negative number; call it $-d$ (Sophocleous 1998). Recall from Eq. (5) that $\Delta R_o = +r$. Thus, with the substitution of the actual values into Eq. (9), the subtraction becomes a summation of two quantities, i.e., $P = +r - (-d) = r + d$. This means that sustainable pumping rates can be larger than the changes in either recharge or discharge rates alone. Note also that Eq. (9) only contains terms for the changes in recharge and discharge rates, and therefore the value of virgin recharge, R_o, is not needed to calculate a sustainable pumping rate.

So far it can be seen that Eq. (1), the Water Budget Myth, fails in two respects: first, it assumes that that recharge is independent of pumping, a condition not necessarily true in all cases, and second it assumes that recharge rates must be known to calculate sustainable pumping rates, a tenet that is clearly in error.

Now examine another, more subtle, assumption that has underlain the argument so far, and that further affects the validity of the Water Budget Myth. In making the mass balance relationships above [Eq. (1)], an assumption is implicitly made of a closed system (note that because there is flow through the system, it is not truly closed), or more precisely, a fixed directional flow system. In a truly fixed directional system, water only enters through prescribed pathways and only leaves through different prescribed pathways. A properly functioning kitchen sink is an example of this. Water enters from the faucet and leaves by the drain; it never enters from the drain and never leaves through the faucet. Aquifers, on the other hand, are not necessarily fixed directional systems. Even if they behave as fixed directional systems under some conditions, they may change when those conditions change. Bredehoeft's island aquifer was a good example of this (Bredehoeft et al. 1982; Bredehoeft 2002). Briefly, the island aquifer consisted of a small land mass surrounded by a lake. The land mass was underlain by an aquifer (Fig. 1). With no development, the aquifer received recharge only from rain, and discharged into the surrounding lake across the island boundaries; Eq. (6) described the system. When the aquifer was pumped gently, the capture zone of the well remained within the island boundaries and Eq. (1) applied.

So far, the system has behaved as a fixed directional system. With the onset of pumping, there were two discharge boundaries (the well and the island boundary) and one recharge boundary (the top of the aquifer, recharged by precipitation) and they maintained their respective roles during the entire period of gentle pumping. However, things change when the pumping rate is increased beyond the "gentle" range. If the pumping rate is increased to the point that the capture zone reaches the island boundary (now $P > D_o$), then lake water might begin to enter the system — what used to be a discharge

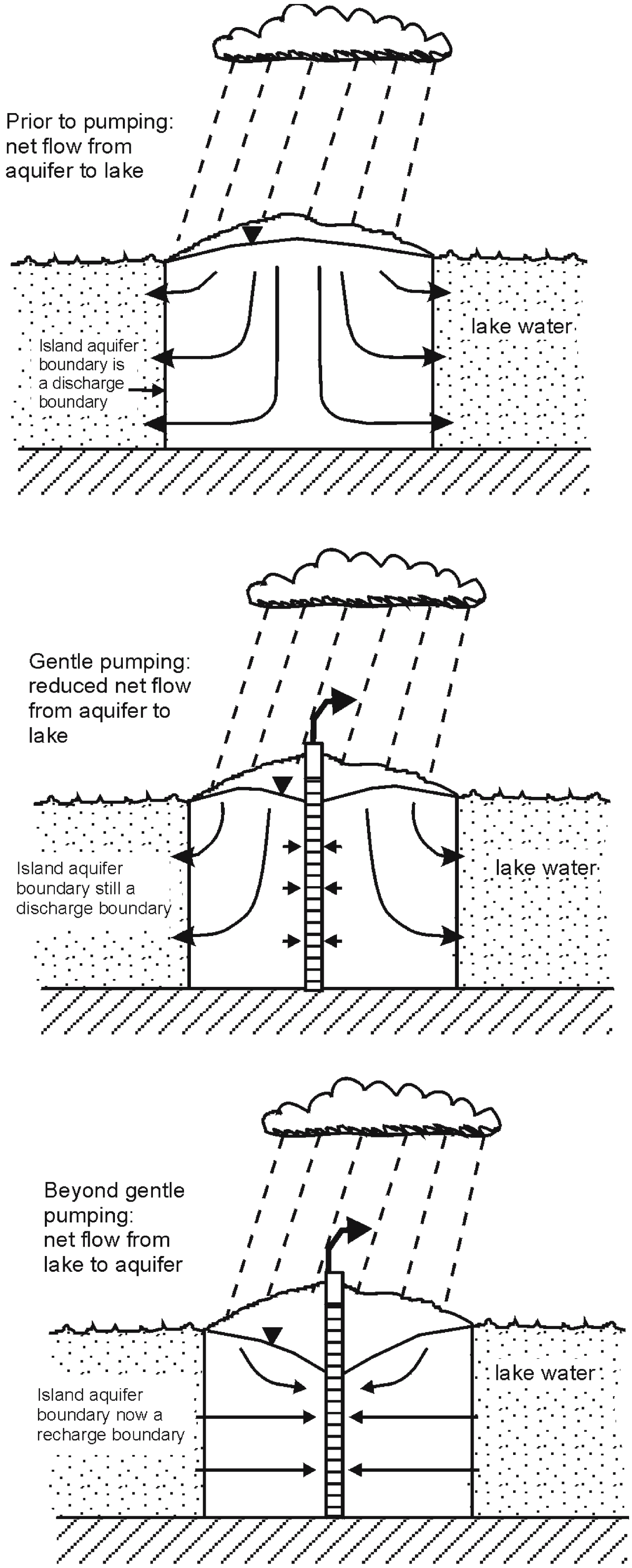

Fig. 1 Island aquifer example showing how the island boundary behaves as a multi-directional boundary, invalidating the assumption of a closed system, and invalidating Eq. (1) (see text)

boundary becomes a recharge boundary and the system is now seen to be multi-directional, or an open system. Equation (7) breaks down, as does Eq. (1) and, therefore, so does the Water Budget Myth. This is a key reason why the mass balance on which the Water Budget Myth is based, fails: the mass balance assumes a closed system with unidirectional flow across the boundaries, but aquifers do not always behave that way.

The concepts of fixed and multi-directional systems can be related to terms in Eqs. (3) and (4) in the following way. When an aquifer begins to behave as a multi-directional system, the pumping rate, P, exceeds the virgin discharge rate, D_o; this means that P also exceeds the virgin recharge rate, R_o, according to Eq. (6). Therefore, a former discharge boundary becomes a recharge boundary, leading to a case of induced recharge, i.e., $\Delta R_o>0$, provided a water source is available. Now, with an overall higher recharge rate [from Eq. (3)], pumping can exceed the virgin recharge rate in a sustainable way, i.e., $P>R_o$. There is one caveat here: sustainability requires that the newly recharging water originate from a source other than the aquifer being pumped. If the water body across the boundary only contains water discharged from the aquifer (e.g., a gaining stream or a groundwater discharge lake), multi-directional behavior will eventually cause that water body to dry up.

Several questions naturally arise from the discussion above: how is the amount of water that pumping wells can capture estimated for fixed directional aquifers, how are the steady state capture rates determined in multi-directional systems, and what is the effect of the number and locations of wells? To answer these questions, the groundwater dynamics must be considered. That is one reason why hydrogeologists measure hydrogeological properties of aquifers and run groundwater models.

The Importance of Recharge to Sustainability

In the discussions of sustainability that have appeared in the literature, statements have been made to the effect that virgin recharge rates are irrelevant to sustainable pumping (Bredehoeft et al. 1982; Bredehoeft 2002). The equations and discussion above have shown the supporting arguments for this view. However, to say that recharge rates are irrelevant to sustainable pumping rates is not the same as saying that the magnitude of the recharge rate is irrelevant to sustainability. As mentioned at the outset of this article, sustainability is a broader concept than simple sustainable pumping, and it depends on the changes that occur to water quality, ecology, and socioeconomic factors, to name a few, and in the establishment of a new steady-state condition for an aquifer (after the onset of pumping). In each of these cases, recharge rates are likely to have some effect. For example, recharge could affect the quality of the water in the aquifer and its nutrient content, thus also impacting associated ecological communities. Sustainability depends on the entire system, or, in the words of Sophocleous (1997, 2000), "not just the trees, but the whole forest; not just the fish, but the marine food chain; not just the groundwater, but the running streams and wetlands, and all the plants and animals that depend on them." Sustainability is a goal for the long term welfare of both humans and the environment.

Additionally, any modern assessment of groundwater sustainability requires a computer-modeling component to assess the behavior of the aquifer and its sustainable pumping rate. Today's computer flow models can generally accommodate input for both the quantity of recharge and its spatio-temporal distribution. Local flow patterns can be highly sensitive to variations in these data, so while it may be possible to calibrate a model and calculate a sustainable pumping rate for an aquifer without recharge data, the issues associated with sustainability may not be accurately represented in such a model. For example, the impacts of sustainable pumping on stream levels or water quality in a watershed may be missed without recharge input to the model. The trade-off here is a pragmatic one; some representativeness of the model is sacrificed because of the cost and technical challenges of obtaining accurate recharge data. In any event, for the assessment of sustainability, there is an obvious benefit to collecting and utilizing the best possible estimates of recharge, ensuring that the models are as representative as possible of their aquifer systems.

Based on the above discussion, it is evident that sustainability is a function of recharge, and that recharge rates cannot be ignored in spite of the fact that sustainable pumping rates can be estimated without them. This point was further elucidated in a commentary by Sophocleous and Devlin (2004). As a result, efforts should be made to measure recharge rates as accurately as possible, when an assessment of sustainability is the objective.

In conclusion, support is given to the efforts of those who have attempted to debunk the Water Budget Myth and to generally remind the hydrogeological community of some basic principles that appear to have been forgotten in the interest of simplifying concepts for the lay-public and law-makers. It is believed that the Water Budget Myth has been difficult to dispel (1) because the concepts of sustainable pumping and sustainability are often muddled, leading to confusion over the importance of recharge, and (2) because the Myth appears to be founded on the Law of Conservation of Matter, through an over-simplified mass balance. A quote from Einstein (1879–1955) aptly describes the problem. He reportedly said, "Everything should be made as simple as possible, but not simpler" (see for example, Harris 1995). In keeping with this advice, hydrogeologists, law-makers, and other interested parties should consult Eq. (2), scrutinize the assumptions they make, and apply groundwater models intelligently, rather than default to the Water Budget Myth [Eq. (1)] in decision making, planning, and policy formulation. As Bredehoeft, Brown, and others have previously discussed, and as this paper attempts to show again, aquifers are more complex than an over-simplified mass balance can accommodate — even one with mythical status.

DOI 10.1007/s10040-004-0354-0

References

Bredehoeft JD (2002) The Water Budget Myth revisited: why hydrogeologists model. Ground Water 40(4):340–345

Bredehoeft JD, Papadopulos SS, Cooper HH Jr (1982) The Water Budget Myth. In: Scientific basis of water resource management, studies in geophysics. National Academy Press, Washington, DC, pp 51–57

Brown RH (1963) The cone of depression and the area of diversion around a discharging well in an infinite strip aquifer subject to uniform recharge. In: Bentall R (compiler) Shortcuts and special problems in aquifer tests. US Geological Survey Water-Supply Paper 1545C, pp C69–C85

Harris K (1995) Collected quotes from Albert Einstein. Available at http://rescomp.stanford.edu/~cheshire/EinsteinQuotes.html

Kendy E (2003) The false promise of sustainable pumping rates. Ground Water 41(1):2–4

Lohman SW (1972) Definitions of selected ground-water terms — revisions and conceptual refinements. US Geological Survey, Water Supply Paper 1988, 21 pp

Sophocleous M (1997) Managing water resources systems: why “safe yield” is not sustainable. Ground Water 35(4):561

Sophocleous M (1998) On the elusive concept of safe yield and the response of interconnected stream-aquifer systems to development. In: Sophocleous M (ed) Perspectives on sustainable development of water resources in Kansas. Kansas Geol Surv Bull 239:61–85

Sophocleous M (2000) From safe yield to sustainable development of water resources — the Kansas experience. J Hydrol 235(1–2):27–43

Sophocleous M, Devlin JF (2004) Is natural recharge relevant to groundwater sustainable development? Ground Water (in press)

Theis CV (1940) The source of water derived from wells: essential factors controlling the response of an aquifer to development. Civil Eng 10:277–280

DOI 10.1007/s10040-004-0354-0