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Time to reach near-steady state in large aquifers

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[1] A new analytical solution of the flow equation has been developed to estimate the time to reach a near-equilibrium state in mixed aquifers, i.e., having unconfined and confined portions, following a large hydraulic perturbation. Near-equilibrium is defined as the time for an initial aquifer perturbation to dissipate by an average 95% across the aquifer. The new solution has been obtained by solving the flow system of a simplified conceptual model of a mixed aquifer using Laplace transforms. The conceptual model is based on two assumptions: (1) the groundwater flow can be reduced to a horizontal 1-D problem and (2) the transmissivity, a function of the saturated thickness, is assumed constant on the unconfined portion. This new solution depends on the storativity of the unconfined portion, the lengths of the unconfined and confined portions and the transmissivity, assumed to be constant and equal in both portions of the mixed aquifer. This solution was then tested and validated against a numerical flow model, where the variations of the saturated thickness and therefore variations of the transmissivity were either ignored, or properly modeled. The agreement between the results from the new solution and those from the numerical model is good, validating the use of this new solution to estimate the time to reach near-equilibrium in mixed aquifers. This solution for mixed aquifers, as well as the solutions for a fully confined or fully unconfined aquifer, has been used to estimate the time to reach near-equilibrium in 13 large aquifers in the world. For those different aquifers, the time to reach near-equilibrium ranges between 0.7 kyr to 2.4×10^7 kyr. These results suggest that the present hydraulic heads in these aquifers are typically a mixture of responses induced from current and past hydrologic conditions and thus climate conditions. For some aquifers, the modern hydraulic heads may in fact depend upon hydrologic conditions resulting from several past climate cycles.

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1. Introduction

[2] Estimating the current hydrodynamic state of aquifers is crucial for modeling them accurately. One requires knowledge of whether an aquifer system is in steady state with respect to recharge and discharge or if it is in a transient state where recharge does not equal discharge.

[3] Changes in recharge, discharge, or hydraulic parameters can result in the groundwater system being in disequilibrium which will initiate some transient groundwater behavior. Different mechanisms such as geologic processes [*Luo*, 1994; *Neuzil*, 1995; *Gonçalvès et al.*, 2004], or morphologic and climatic variations [*Love et al.*, 1994; *Gonçalvès et al.*, 2004; *Jost et al.*, 2007] can lead to hydrodynamic changes. Transient behaviors of groundwater systems are related to a balance between the origin of the perturbation and the resulting flows, which tend to dissipate it. A major control of this dissipation is the aquifer diffusivity, the ratio of aquifer transmissivity to storativity.

[4] In aquitards with low permeability, long-term transient behavior can occur due to their low hydraulic diffusivity [*de Marsily*, 1986; *Neuzil*, 1995]. Conversely, in aquifers with higher hydraulic diffusivity, one would expect the transient behavior to occur over shorter time periods as they adjust more rapidly to any hydraulic perturbation [*Neuzil*, 1995]. However, several studies, based on numerical models, have examined the effect of past climatic conditions on present-day hydrodynamics [*Burdon*, 1977; *Lloyd and Farag*, 1978; *Dieng et al.*, 1990; *Love et al.*, 1994; *de Vries*, 1997; *Coudrain et al.*, 2001; *Houston and Hart*, 2004; *Jost et al.*, 2007; *Sy and Besbes*, 2008]

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Table 3. Hydrodynamic Parameter Values for Different Large Aquifers in the World: The Eastern and Western Part of the GAB (GAB-e and GAB-w, Respectively), the Guarani Aquifer (GA), the Nubian System Aquifer (NSA), the Aquitaine Basin (AB), the Albian and Dogger in the Paris Basin (PB-A and PB-D, Respectively), the Hungarian Aquifer (Unconfined and Confined Aquifers, HA-u and HA-c, Respectively), the Western Siberia Basin (WSB), the North China Plain (Unconfined and Confined Aquifers, NCP-u and NCP-c), and the Ogallala Aquifer (OA)

					T (m^2 s^{-1})		S		Sy		3τ (years)	
Aquifers	Type	L_c (km)	L_u (km)	b (m)	Min	Max	Min	Max	Min	Max	Min	Max
GAB-e[a]	m	1450	50		1.5×10^{-3}	1.0×10^{-2}	2.5×10^{-4}	5.0×10^{-4}	0.10	0.23	7.7×10^4	1.2×10^6
GAB-w[a]	m	325	75		1.5×10^{-3}	1.0×10^{-2}	2.5×10^{-4}	5.0×10^{-4}	0.10	0.15	2.9×10^4	4.4×10^5
GA[b,c]	m	320	80		1.0×10^{-5}	1.0×10^{-4}	1.0×10^{-6}	1.0×10^{-3}	0.10	0.20	8.7×10^3	1.8×10^5
NSA[d]	m	530	220		3.0×10^{-3}	1.0×10^{-1}	2.0×10^{-4}	3.3×10^{-3}	0.10	0.27[m]	1.6×10^4	1.5×10^6
AB[e]	m	180	20		1.0×10^{-4}	3.2×10^{-2}	6.0×10^{-5}	4.0×10^{-4}	0.07	0.34	8.9×10^2	1.3×10^6
		L_c (km)	L_u (km)	b (m)	K (m s^{-1})		Ss (m^{-1})		Sy		3τ (years)	
PB-A[f,g]	m	300	20	100	1.0×10^{-6}	1.0×10^{-3}	1.0×10^{-4}	5.0×10^{-4}	0.12	0.30	1.7×10^3	2.7×10^6
PB-D[f,g]	m	390	30	250	1.0×10^{-8}	1.0×10^{-5}	5.0×10^{-5}	5.0×10^{-4}	0.15	0.20	1.5×10^5	1.7×10^8
HA[h]	u		140	750	1.0×10^{-5}				0.18	0.30	4.5×10^4	7.5×10^4
HA[h]	c	140			1.0×10^{-6}		1.0×10^{-6}	1.0×10^{-4}			1.9×10^3	1.9×10^5
WSB[i]	c	1750			5.0×10^{-9}	4.5×10^{-5}	1.0×10^{-6}	1.0×10^{-3}			6.5×10^3	5.9×10^{10}
NCP[j,k]	u		770	60	2.1×10^{-5}	8.0×10^{-4}			0.15		1.8×10^5	6.8×10^6
NCP[j,k]	c	770			2.3×10^{-5}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-3}			5.6×10^4	2.4×10^6
OA[l]	u		320	200	1.0×10^{-5}	7.0×10^{-4}			0.04	0.22	2.7×10^3	1.1×10^6

[a] *Welsh* [2007].
[b] *Bonotto* [2006].
[c] *Kimmelmann e Silva et al.* [1989].
[d] *Sefelnasr* [2007].
[e] *Douez* [2007].
[f] *Jost* [2005].
[g] *Marty et al.* [1993].
[h] *Tóth and Almàsi* [2001].
[i] *Cramer et al.* [1999].
[j] *Chen et al.* [2004].
[k] *Han* [2008].
[l] *Nativ and Smith* [1987].
[m] *Anderson and Woessner* [1992].

$$\tau = \frac{L^2}{D_h} \tag{22}$$

[59] Depending on whether the aquifer is confined or unconfined, D_h is defined as T/S or T/Sy, respectively. The purpose of Figure 5 is to give some guidelines about the large values of the time to near-equilibrium. In Figure 5, four aquifer behaviors can be characterized as a function of the value of their times to near-equilibrium:

[60] 1. short response time aquifers with a $\tau < 1$ yr, with a possible transient behavior resulting from seasonal climate variations;

[61] 2. aquifers with a τ ranging between 1 yr and 10 kyr, with a possible transient behavior resulting from decennial climate changes as e.g., the Pacific Decadal Oscillation [*Alley et al.*, 2002];

[62] 3. aquifers with a $\tau > 10$ kyr, in which the hydraulic heads result at least from the present and Pleistocene hydrodynamic boundary conditions;

[63] 4. aquifers with a $\tau > 100$ kyr, which is the length of a Milankovitch's cycle since the last 1 Ma [*Tiedemann et al.*, 1994; *Naish et al.*, 1998]. For this group, these results suggest that aquifers are rarely expected to be in steady state with respect to their hydraulic behavior.

[64] The t_{NE} for 13 large aquifers in the world have been estimated. From those aquifers, the Great Artesian Basin east and west (Australia), the Dogger and Albian aquifers in the Paris Basin (France), the Nubian Sandstone System (Egypt-Libya-Chad-Sudan), the Aquitaine Basin (France), and the Guarani Aquifer (Brazil-Paraguay-Uruguay-Argentina) are characterized by unconfined parts of the aquifers on the borders of their basins. The Hungarian Aquifer and the Western Siberia Basin (Russia) have shallow unconfined aquifers and deep totally confined aquifers. The North China Plain has unconfined and confined aquifers. The Ogallala Aquifer in the Southern High Plains (USA) is a large unconfined aquifer.

[65] For all these aquifers, t_{NE} values were calculated from equations (8), (3), or (17) according to the confined, unconfined, or mixed characteristics of the aquifers. The parameter values used for these calculations are summarized in Table 3 and the minimum and maximum value of t_{NE} for each aquifer is shown in Figure 5. For the mixed aquifers, an equivalent hydraulic diffusivity had to be used to accurately represent the t_{NE} obtained from equation (17). For example, for the GAB-e with the L and D_h given in Table 3 and plotted in Figure 5, $3\tau_m$ will range between 5 and 3×10^4 kyr, instead of 70 and 1×10^3 kyr obtained from the solution formula (equation (17)). So an equivalent D_h allowing to reproduce the $3\tau_m$ values obtained from equation (17) was used.

[66] The t_{NE} values obtained for all the aquifers range between 0.7 kyr and 2.4×10^7 kyr. Therefore, all these aquifers may present a long transient behavior after a