Effect of paleo-recharge on large regional scale groundwater systems in arid and semi-arid regions

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ABSTRACT

The knowledge of the time to reach a new equilibrium after a hydraulic perturbation is crucial to model accurately the groundwater system. A hypothetical numerical model loosely based on the western margin of the Great Artesian Basin in Australia was used as a demonstration to estimate this time in large unconfined/confined aquifers. The time to reach a new steady state after a hydraulic perturbation, such as the cessation of the recharge in arid and semi-arid regions, is on the order of 50 ky. This time is longer than the present interglacial phase, i.e. 10ky since the last climate transition, and thus the hydrodynamic system is a transient one which is still responding to the paleo-perturbation due to recharge. Moreover, analytical solutions have been used to assess the time to reach a new equilibrium for several large aquifers in the world. The times obtained range between 0.4 and 5.8×10^{10} years. These values suggest that large regional scale aquifer systems are rarely expected to be in steady state with respect to their hydraulic behaviour.

Key words: Great Artesian Basin, Large aquifers, Time constant, Paleo-climate.

1. INTRODUCTION

To accurately model the regional groundwater systems, their current hydrodynamic state has to be determined. Changes in boundary conditions can result in transient groundwater behaviour. The time to reach a new equilibrium after a hydraulic perturbation is given by the time 3τ, where τ is the time constant and depends on the storativity, the transmissivity and the length of the aquifer. It is often assumed that prior to anthropogenic influences that the groundwater system was in steady state; i.e. it is in hydrodynamic equilibrium, because they adjust quite rapidly to any hydraulic perturbation. In this paper, we examine the time required to reach a new steady state after a hydraulic perturbation in large mixed aquifers, i.e., composed of an unconfined and a confined portion. Moreover, the time to reach a new equilibrium will be estimated for several large aquifers in the world.

2. TIME CONSTANT

The time constant is defined as the time required for a decaying exponential function to decrease by 63% of its initial value. In this study, we defined the steady state at 3τ, i.e. 5% of the initial perturbation remains. Analytical solutions exist to estimate the time constant. Domenico and Schwartz (1998) defined the time constant for a homogeneous and fully confined aquifer as:

$$\tau_c = \frac{S\,L_T^2}{T} \quad \text{Equation 1}$$

where τ_c is the time constant for a confined aquifer [T], S is the storativity [-], L_T is the aquifer length [L], T is the transmissivity [$L^2.T^{-1}$].

The time constant for a homogeneous and fully unconfined aquifer is (Reilly and Harbaugh, 2004):

$$\tau_u = \frac{S_y L_T^2}{T}$$ Equation 2

where in addition to Equation 1, τ_u is the time constant for a unconfined aquifer [T] and Sy is the specific yield [-].

These two relations will be used to provide a range a time constant to reach a new equilibrium for several large aquifers in the world.

3. CONCEPTUAL MODEL

To assess the effect of the modification of the recharge on the hydraulic heads in large aquifers a conceptual model loosely based on the western margin of the Great Artesian Basin (GAB) in Australia was used (Figure 1). The conceptual model is a mixed aquifer where the recharge occurs in the unconfined part and the discharge occurs at the end of the confined portion.

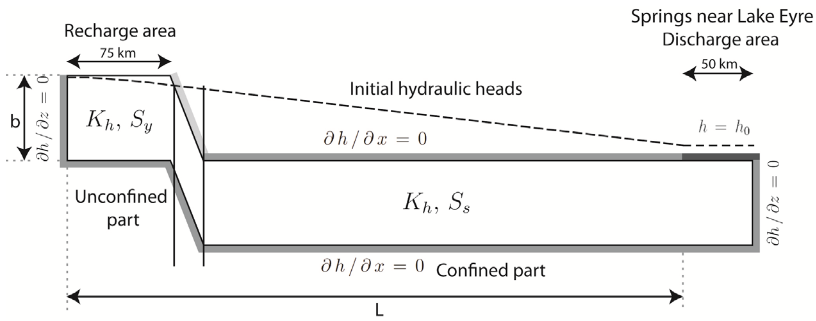

Figure 1: Two-dimensional cross section of the conceptual model, indicating the boundary conditions and the initial hydraulic heads assumed at the end of the Pleistocene.

A numerical model was used to represent the behaviour of this conceptual model to the cessation of the recharge at the transition Pleistocene-Holocene. The numerical code MODFLOW was used to model the groundwater flow. The initial conditions of the model are assumed to be those at the Pleistocene-Holocene transition. At the end of the Pleistocene, the groundwater system is assumed in steady state with a high water level in the unconfined part (Figure 1). At the beginning of the Holocene, the recharge is assumed to stop and a transient simulation was run until a new steady state was reached.

4. RESULTS AND DISCUSSION

4.1. Hydrodynamic state of the aquifer

The time to reach the new steady state for a large mixed aquifer was estimated from the evolution of the hydrodynamic state, represented by the evolution of the ratio of the discharge rate. A time of 55 ky was obtained. This result is not intended to represent the actual condition on the western part of the GAB. Nevertheless, it provides the evidence that this kind of aquifers may show a transient behaviour today, i.e. 3τ is bigger than the time since the last hydrodynamic perturbation which is the cessation of the recharge 10 ky ago. This result suggests that large mixed aquifers may not be in equilibrium with the modern climate and that a part of the modern hydraulic heads result from long-term behaviour inherited from wetter paleo-climate.

4.2. Theoretical time constants for several large aquifers in the world.

We calculated the time to reach a new equilibrium for several large aquifers in the world, which can be classified in three different groups. The confined aquifers group: the Hungarian Aquifer (HA-c), the North China Plain (NCA-c) and the Western Siberia Basin (WSB). The unconfined aquifers group: the Hungarian Aquifer (HA-u), the North China Plain (NCP-u) and the Ogallala Aquifer (OA). And the mixed aquifers group: the western and eastern part of the Great Artesian Basin (GAB-w and GAB-e, respectively), the Dogger and the Albian in the Paris Basin (PB-D and PB-A, respectively), the Nubian system Aquifer (NSA), the Guarani Aquifer (GA) and the Aquitain Basin (AB)

The time constants for the confined aquifers were calculated with Equation 1, and Equation 2 was used to assess those of the unconfined aquifers. For the mixed aquifers, the two end members (confined and unconfined behaviour) were used to assess a range of time constant, knowing that the confined equation will give an underestimation and the unconfined assumption will give an overestimation of the time constant for a mixed aquifer. The results of these calculations are presented on Figure 2. The 3τ values obtained range between 0.4 and 5.8×10^{10} y and for all the aquifers the upper limit is higher than 10 ky, i.e. time since the last climate transition. These results suggest that all these aquifers will present a long transient behaviour and thus they are probably not in equilibrium with their current boundary conditions. Thus the modern hydraulic heads in theses large aquifers are a complex mixture of both current and past conditions.

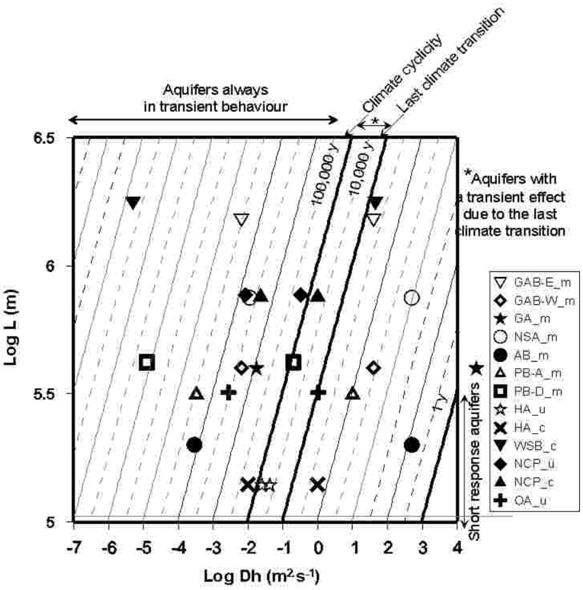

Figure 2: Time to reach a new equilibrium in year as a function of the hydraulic diffusivity ($m^2.s^{-1}$) and the aquifer length (m).

5. CONCLUSIONS

The time to reach a new steady state obtained in this study, although assessed on a theoretical conceptual model or from analytical solutions for homogeneous aquifers, are important and suggest that they are probably not in equilibrium with their present boundary conditions. The hydraulic heads observed in this kind of large aquifers are thus a complex mixture of both current and past conditions. And then, these aquifer systems may present long transient behaviour and thus the assumption of steady state prior to anthropogenic activities should not be used and transient models should be run.

Acknowledgements

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