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Regional scale impact of tidal forcing on groundwater flow in unconfined coastal aquifers

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SUMMARY

This paper considers the impact of tidal forcing on regional groundwater flow in an unconfined coastal aquifer. Numerical models are used to quantify this impact for a wide range of hydrogeological conditions. Both a shallow and a deep aquifer are investigated with regard to three dimensionless parameter groups that determine the groundwater flow to a large extent. Analytical expressions are presented that allow for a quick estimate of the regional scale effect of tidal forcing under the same conditions as used in the numerical models.

Quantitatively, the results in this paper are complementary to previous studies by taking into account variable density groundwater flow, dispersive salt transport and a seepage face in the intertidal area. Qualitatively, the results are in line with previous investigations. The time-averaged hydraulic head at the high tide mark increases upon a decrease of each of the three considered dimensionless parameter groups: R (including the ratio of the hydraulic conductivity and the precipitation excess), α (the slope of the intertidal area) and A_L (the ratio of the width of the fresh water lens and the tidal amplitude). The relative change of the location and the hydraulic head of the groundwater divide, which together characterize regional groundwater flow, increase as α and A_L decrease, but decrease as R decreases. The difference between the analytical solutions and numerical results is small. Therefore, the presented analytical solutions can be used to estimate the bias that is introduced in a numerical model if tidal forcing is neglected. The results should be used with caution in case of significant wave forcing, as this was not considered.

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1. Introduction

Numerical models are widely used to quantify groundwater flow and salt transport in real-world coastal aquifers (Oude Essink et al., 2010; Sulzbacher et al., 2012; Vandenbohede et al., 2008). Assumptions and simplifications are often needed in these models to cope with computational limitations. A common assumption in regional scale models is to neglect forcing from the sea, such as tides, waves and storm events. Several studies have shown that this assumption leads to underestimated heads near the shore (Cartwright, 2004; Kang, 1995; Nielsen, 1990; Turner et al., 1995). However, the question that remains is: how significant is this effect on a regional scale?

Forcing from the sea results in (periodic) inundation of the intertidal area (Fig. 1b). The zone where groundwater discharges during low tide is generally smaller than the inundation zone during high tide. Consequently, time-averaged groundwater levels are elevated compared to a situation where there is no forcing from the sea (Fig. 2) (Lebbe, 1983; Nielsen, 1990; Vandenbohede and Lebbe, 2005). This effect increases as the slope of the intertidal area and the hydraulic conductivity of the intertidal sediments decreases (Horn, 2006; Nielsen, 1990; Turner et al., 1995) and also influences the groundwater salinity distribution below the intertidal area (Ataieashtiani et al., 1999; Cartwright, 2004; Lebbe, 1983; Robinson et al., 2006; Thorn and Urish, 2012).

Previous related studies have mainly considered the near-shore region, where the forcing on the groundwater levels is most pronounced (Nielsen, 1990; Robinson et al., 2007; Turner et al., 1995). Few studies have indicated the regional scale effects

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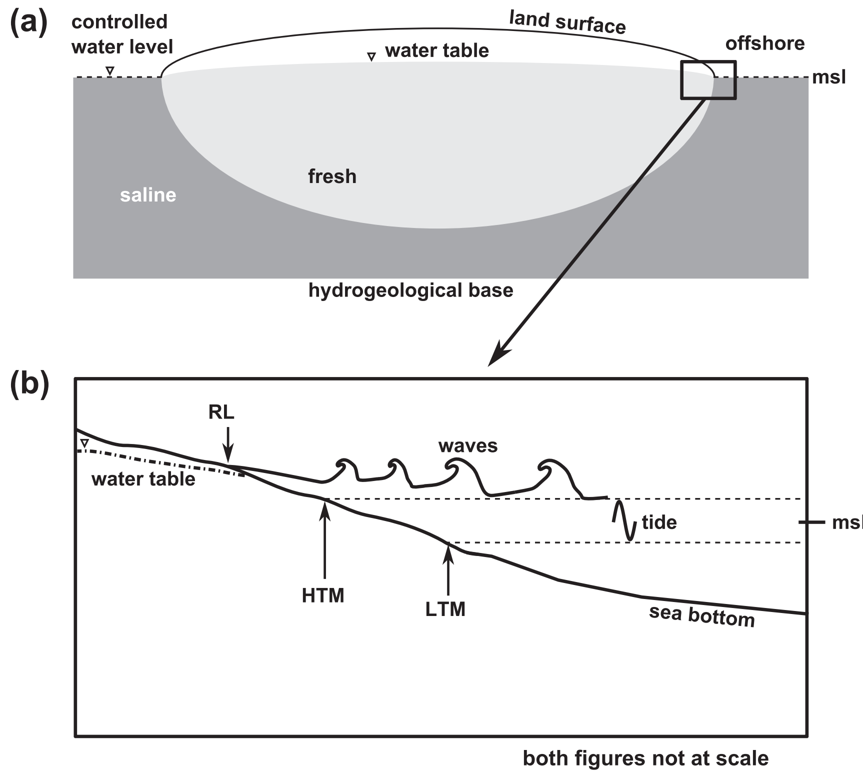

Fig. 1. (a) Conceptual cross section of the groundwater salinity distribution of a freshwater lens on a regional scale in case of a constant mean sea level. Note that in reality a transition zone between fresh and saline groundwater exists. (b) Forcing on the groundwater below the beach by waves and tides. Infiltration of seawater occurs up to the upper limit of the wave run-up at high tide (RL). In case waves are dominant, RL is situated higher and further inland than the high tide mark (HTM). A comparable effect occurs during low tide regarding the low tide mark (LTM). This wave run-up effect can have a large influence on the time-averaged groundwater levels Nielsen (1999). Note that the groundwater salinity distribution is not shown. (b) was largely adopted from a more detailed figure in Nielsen (1999) (by permission).

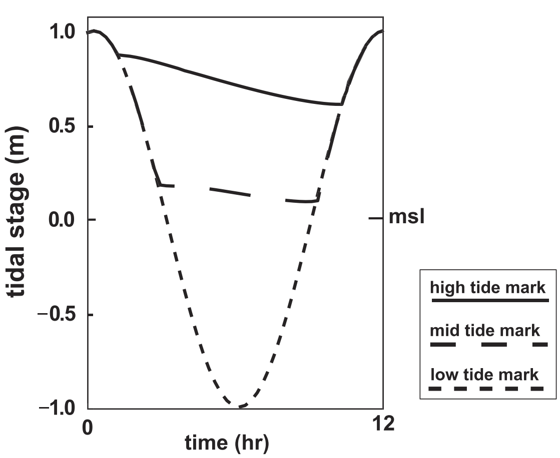

Fig. 2. Conceptual behavior of groundwater levels in an intertidal area around the low tide mark (LTM), the high tide mark (HTM) and in between them (mid tide mark; MTM), over one tidal cycle in case of tidal forcing. The resistance to drainage of the intertidal area is higher than the resistance to infiltration. To obtain a balance between inflow and outflow over a tidal cycle, the time-averaged groundwater levels inland of LTM are higher than mean sea level.

(Nielsen, 1999; Urish and Melih, 1989), despite the potential influence on the location of the groundwater divide and, hence, the amount of water that discharges to the hinterland and to the sea. An important reason to neglect the highly-dynamic processes in numerical models is the high computational effort required. Some regional scale model studies have accounted for the forcing from the sea, by using time-averaged hydraulic heads in the intertidal area that were either based on field observations or manual calibration (Vandenbohede and Lebbe, 2005; Werner and Gallagher, 2006).

The objective of this paper is to provide an estimate of the regional scale effect of tides on hydraulic heads in an unconfined coastal aquifer with an intertidal area. It is important to note here that, depending on the local conditions, waves and storm events can also have a significant, or even larger contribution on the hydraulic heads than tides (Nielsen, 1999) (Fig. 1b) but that this is not considered here. In case waves have a significant influence, the results in this paper should be used with caution.

The term overheight (Nielsen, 1990) is used to indicate the underestimated hydraulic heads in a model where tides are neglected. More specifically, overheight is defined here as the difference in the computed water table between a model where tides are neglected, and a model where tides are taken into account. The influence of tides on both the location and hydraulic head at the groundwater divide is jointly referred to as regional scale overheight. Using numerical models, regional scale overheight is determined for the following hydrogeological cases:

- *Fresh water lens in a deep aquifer*. In this case, the unconfined aquifer is isotropic, homogeneous and the hydrogeological base is deep enough to accommodate the entire fresh water body (Fig. 1a).
- *Fresh water lens in a shallow aquifer*. This case is analogous to the case of a fresh water lens in a deep aquifer, except that the hydrogeological base corresponds with the maximum depth of the fresh - saline transition zone.
- *Fresh water lens in a heterogeneous subsurface*. This case consists of an example of a layered coastal aquifer system in the Netherlands and serves as an illustration of how to use the findings from the cases of the deep and shallow aquifer in a more complex subsurface.

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