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Timescales of seawater intrusion and retreat

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ABSTRACT

Quantifying the timescales associated with moving freshwater–seawater interfaces is critical for effective management of coastal groundwater resources. In this study, timescales of interface movement in response to both inland and coastal water level variations are investigated. We first assume that seawater intrusion (SWI) and retreat (SWR) are driven by an instantaneous freshwater-level variation at the inland boundary. Numerical modelling results reveal that logarithmic timescales of SWI ($\ln T_i$) and SWR ($\ln T_r$) can be described respectively by various simple linear equations. For example, SWI timescales are described by $\ln T_i = a + b\ln h'_{f-s}$, where a and b are linear regression coefficients and h'_{f-s} is the boundary head difference after an instantaneous drop of inland freshwater head. For SWR cases with the same initial conditions, but with different increases in freshwater head, $\ln T_r = c + d\Delta X_T$, where c and d are regression coefficients and ΔX_T is the distance of toe response that can be estimated by a steady-state, sharp-interface analytical solution. For SWR cases with the same freshwater head increase, but with different initial conditions, in contrast, $\ln T_r = e + f\ln\Delta X_T$, where e and f are regression coefficients. The timescale of toe response caused by an instantaneous variation of sea level is almost equivalent to that induced by an instantaneous inland head variation with the same magnitude of water level change, but opposite in direction. Accordingly, the empirical equations of this study are also applicable for sea-level variations in head-controlled systems or for simultaneous variations of both inland and coastal water levels. Despite the idealised conceptual models adopted in this study, the results imply that for a particular coastal aquifer, SWI timescales are controlled by the boundary water levels after variations, whereas SWR timescales are dominated by the distance of toe response.

1. Introduction

The impact of seawater intrusion (SWI), the landward movement of seawater in coastal aquifers, has long been recognised as a global issue e.g. [1–5]. SWI increases the salinity of freshwater resources, potentially rendering them unusable. The occurrence of SWI is most often the consequence of groundwater overexploitation. Other causal factors include changes in climate and the frequency of extreme climate events, and sea-level rise (SLR) [6]. Seawater retreat (SWR), the seaward movement of the freshwater–seawater interface, is likely to occur when the inland head of a coastal aquifer is increased relative to sea level, usually by controlling groundwater extraction and/or aquifer recharge [7,8]. SWI and SWR processes have been identified in a number of field sites using hydrogeochemical tools e.g. [9,10].

SWI is often investigated analytically by assuming a steady-state, sharp interface and using Strack's [11] potential theory. Research based on these methods employ only changes in the steady-state interface to assess SWI e.g. [12–16], and therefore neglect SWI timescales, which have important implications for coastal aquifer management. Here, SWI timescales relate to the duration for the interface to move to prescribed positions or conditions. In the current manuscript, we use the timescale definition of Watson et al. [17], who adopted the time for the interface toe to reach 95% of the new steady-state condition.

Theoretically, extremely slow changes in groundwater heads lead to head and interface timescales of the same magnitude. Under such conditions, a transient problem can be regarded as multiple steady-state problems. However, in the limiting case of an instantaneous change in head (e.g. at the inland and/or sea boundaries), disequilibrium between the interface location and head conditions is produced (referred to herein as "SWI disequilibrium"), whereby there is a delay between SWI and the associated causal stresses. Gradual changes in head cause varying degrees of SWI disequilibrium, depending on the rate of head or sea-level variations [18,19]. SWI disequilibrium also depends on system characteristics such as boundary conditions and hydrogeologic parameters [19], although a systematic evaluation of SWI disequilibrium has not been undertaken. In the current study, we focus on

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systems where SWI disequilibrium has occurred, because SWI timescales are otherwise related simply to the timescales of coastal aquifer stresses and accompanying head changes.

Previous numerical studies have shown that timescales of several years to several centuries are required for coastal aquifers to reach new steady-state conditions in response to rapid SLR. For example, Langevin and Dausman [20] predicted the possible effects of SLR over the next 100 years on SWI into a carbonate aquifer in south Florida, using a simple two-dimensional numerical model. Estimated SWI timescales (times needed for the interface to stabilise after the cessation of SLR) ranged from 8 to 50 years for gradual SLR between 9 and 88 cm. Watson et al. [17] showed that under an instantaneous SLR of 1 m, SWI timescales ranged from decades to centuries for an unconfined flux-controlled coastal aquifer. Chang et al. [18] modelled instantaneous SLR for a confined coastal aquifer. They obtained SWI timescales ranging from decades to several centuries, although SLR does not change the steady-state position of the interface in flux-controlled confined coastal systems [16]. The impacts of a 90-year SLR event on the transient migration of seawater in head-controlled coastal settings were assessed by Webb and Howard [19]. A wide range of SWI timescales, from decades to several centuries, were observed for typical hydrogeologic parameter values. Furthermore, they found that systems with a low ratio of hydraulic conductivity (K [L/T]) to recharge or low porosity (θ [–]) were generally associated with short SWI timescales, i.e. interfaces stabilised within decades following the cessation of SLR.

The timescales for SWR in response to an instantaneous sea-level drop (SLD) in flux-controlled coastal systems were investigated by Kiro et al. [21]. The interface characteristic timescale was defined as the time required for the seawater in the aquifer to resume its normal circulation pattern. They developed a relation between hydrologic parameters with two characteristic timescales for the responses of the water table ($\tau_{gw} = \frac{\theta L^2}{K_m h_0} \cdot F$) and for the transition zone ($\tau_{TZ} = \frac{\theta h_0 \sqrt{L} \Delta h}{Q_0 (\alpha_L \alpha_T)^{0.25}} \cdot N$), where L [L] is the aquifer length, K_m [L/T] is the maximal hydraulic conductivity (considering directions of anisotropy), h_0 [L] is the flow section thickness, Δh [L] is the magnitude of SLD, Q_0 [L^3/T] is the inland inflow rate, α_L [L] and α_T [L] are longitudinal and transverse dispersivities, and F [–] and N [–] are dimensionless factors approximately equal to 0.55 and 0.18, respectively. In their study, the characteristic water table timescale was defined as the time in which the discharge to the sea decayed to $\exp(-\pi^2/4)$ of its initial value. They found that the response of the transition zone was much slower than the water table response in the Dead Sea region.

Watson et al. [17] observed temporal asymmetry between SWI and SWR in their simulations of SLR and SLD in flux-controlled systems. This phenomenon was also shown by Chang and Clement [22] through laboratory experiments, and therefore, we treat SWI and SWR as individual processes. The characteristics of temporal asymmetry in SWI–SWR needs to be assessed systematically to develop guidance on coastal aquifer remediation from SWI, and issues relating to the reversibility of SWI.

In contrast to sea-level variations, research on the timescales of interface movement in response to inland groundwater head variations is lacking, despite that current regions impacted SWI are arguably most likely driven by inland groundwater head changes caused by pumping or recharge variations rather than SLR e.g. [2,23–25]. Reported studies of timescales associated with these sorts of changes involve only site-specific numerical studies. For example, the numerical modelling results of Dausman and Langevin [26] indicated that the interface in the surficial aquifer system of Broward County, Florida, would take 50 years to move inland and stabilise if the upstream canal stage was decreased by 0.3 m. The relationship between groundwater head changes and timescales for SWI is not clear in a general sense, and therefore, a systematic and quantitative investigation on this topic is needed.

The main purpose of this study is to examine quantitatively and systematically timescales of SWI and SWR, caused by inland groundwater head and/or sea-level variations. Specifically, we aim to develop empirical quantitative relationships between interface timescales and boundary water level variations by performing a large set of two-dimensional numerical experiments using various hydrogeologic parameter combinations. Instead of a flux-controlled system assumed in most previous studies e.g. [17,18,21,22], head-controlled conditions are employed for investigating SLR and SLD, given that such coastal systems experience maximum SWI in response to SLR [12,16], and also have been identified in case studies e.g. [27]. Furthermore, no previous studies have compared the impacts of inland and coastal water level variations on the timescales of SWI and SWR, and this will be conducted in the current study to give a general sense of how different boundaries affect these two timescales.

2. Methodology

2.1. Conceptual model

The conceptual model adopted in this study was a confined coastal aquifer of length L [L] and thickness B [L], as shown in Fig. 1. The left boundary was the coast and the right boundary represented the inland remainder of the aquifer, beyond the coastal fringe, with an initial sea level of h_s [L] and inland freshwater head of h_f [L], respectively. The initial condition was one of steady state. A moving interface was first assumed to result from an instantaneous change of inland freshwater head Δh_f [L]. The final freshwater head became h'_f [L]. For all simulation cases, the water level at the inland boundary was assumed to be always higher than the sea level to form a positive hydraulic gradient toward the ocean, despite that negative values are found in some coastal aquifers e.g. [28]. Such an assumption was taken to avoid active SWI where the interface eventually encroaches on the inland boundary, and to ensure a finite timescale of interface response. To facilitate the discussion, boundary head differences for initial and final conditions were denoted as $h_{f\text{–}s}$ [L] and $h'_{f\text{–}s}$ [L], respectively.

The simplified conceptual model applied in this study allowed for the systematic assessment of SWI and SWR, and the influence of various hydrogeologic parameters on the associated SWI/SWR timescales. Instantaneous and gradual water level variations were compared, and head changes at both inland and coastal boundaries were assessed. We adopted head-controlled inland conditions.

The domain geometry and the values of hydrogeologic parameters considered in the base case followed those of Chang et al. [18]. The homogeneous, isotropic aquifer was 1000 m long and 30 m thick. K, θ, α_L, α_T, and specific storage (S_s [1/L]) were set to 10 m/d, 0.3, 1 m, 0.1 m, and 0.008 m^{-1}, respectively. The freshwater and seawater densities (ρ_f [M/L^3] and ρ_s [M/L^3]) were assumed to be 1000 and 1025 kg/m^3, with corresponding salt concentrations of 0 and 35 kg/m^3, respectively. The values of hydrogeologic parameters in the base case as well as in the later sensitivity analysis are representative of unconsolidated coastal aquifers commonly used for water supply e.g. [29].

The sea level was 30 m above the aquifer basement. In the base case, SWI was simulated by decreasing instantaneously the inland head from 32 to 31 m (Δh_f = 1 m). The head change was reversed for SWR. To develop an empirical relationship between timescales and hydrologic stresses, a sensitivity analysis was conducted using a range of $h_{f\text{–}s}$ and $h'_{f\text{–}s}$ values. SWI and SWR simulations were undertaken using seven different values of $h'_{f\text{–}s}$ and $h_{f\text{–}s}$ (between