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Does sea-level rise have an impact on saltwater intrusion?

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ABSTRACT

Climate change effects are expected to substantially raise the average sea level. It is widely assumed that this raise will have a severe adverse impact on saltwater intrusion processes in coastal aquifers. In this study we hypothesize that a natural mechanism, identified here as the "lifting process," has the potential to mitigate, or in some cases completely reverse, the adverse intrusion effects induced by sea-level rise. A detailed numerical study using the MODFLOW-family computer code SEAWAT was completed to test this hypothesis and to understand the effects of this lifting process in both confined and unconfined systems. Our conceptual simulation results show that if the ambient recharge remains constant, the sea-level rise will have no long-term impact (i.e., it will not affect the steady-state salt wedge) on confined aquifers. Our transient confined-flow simulations show a self-reversal mechanism where the wedge which will initially intrude into the formation due to the sea-level rise would be naturally driven back to the original position. In unconfined systems, the lifting process would have a lesser influence due to changes in the value of effective transmissivity. A detailed sensitivity analysis was also completed to understand the sensitivity of this self-reversal effect to various aquifer parameters.

1. Introduction

Saltwater intrusion is a serious environmental issue since 80% of the world's population live along the coast and utilize local aquifers for their water supply. In the US alone, it is estimated that freshwater aquifers along the Atlantic coast supply drinking water to 30 million residents living in coastal towns located from Maine to Florida [1]. Under natural conditions, these coastal aquifers are recharged by rainfall events, and the recharged water flowing towards the ocean would prevent saltwater from encroaching into the freshwater region. However, over exploitation of coastal aquifers has resulted in reducing groundwater levels (hence reduced natural flow) and this has led to severe saltwater intrusion. Cases of saltwater intrusion, with varying degrees of severity and complexity, have been documented throughout the Atlantic coastal zone. For example, in May County, New Jersey, more than 120 water supply wells have been abandoned because of saltwater contamination [2]. A recent USGS [1] study provides a summary of saltwater intrusion problems and various mitigation techniques. International organizations have identified saltwater intrusion as one of the major environmental issues faced by several coastal cities in India, China, and Mexico [3]. Researchers have also reported that variations in the sea level and the associated wedge movement can influence the near-shore and/or large-scale submarine discharge patterns and impact nutrient loading levels across the aquifer–ocean interface [4–8]. Therefore, understanding the dynamics of saltwater intrusion in coastal aquifers and its interconnection to anthropogenic activities is an important environmental challenge.

While anthropogenic activities, such as over pumping and excess paving in urbanized areas, are the major causes of saltwater intrusion, it is anticipated that increases in the sea level due to climate change would aggravate the problem. Nevertheless, only a few studies have focused on understanding the combined effects of climate change and anthropogenic impacts [4]. Feseker [9] completed a numerical modeling study to assess the impacts of climate change and changes in land use patterns on the salt distribution in a coastal aquifer. The model used parameters to reflect the conditions similar to those observed at the CAT-field site located in the northern coast of Germany. The study concluded that rising sea level could induce rapid progression of saltwater intrusion. Furthermore, the time scale of changes resulting from the altered boundary conditions could take decades or even centuries to impact groundwater flows and hence the present day salt distribution might not reflect the long term equilibrium conditions. Leatherman [10] investigated the effects of rising sea-level on salinization in an aquifer in Texas. Meisler et al. [11] used a finite-difference computer model to analyze the effect of sea-level changes on the development of the transition

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zone between fresh groundwater and saltwater in the northern Atlantic Coastal Plain (from New Jersey to North Carolina). Navoy [12] studied aquifer–estuary interactions to assess the vulnerability of groundwater supplies to sea level rise-driven saltwater intrusion in a coastal aquifer in New Jersey. Oude Essink [13] used a three-dimensional transient density-driven groundwater flow model to simulate saltwater intrusion in a coastal aquifer in the Netherlands for three types of sea-level rise scenarios: no rise, a sea-level rise of 0.5 m per century, and a sea-level fall of 0.5 m per century. They concluded that sea level rise of 0.5 m per century would increase the salinity in all low-lying regions closer to the sea. Dausman and Langevin [14] completed SEAWAT simulations for a coastal aquifer in Broward County, Florida, and demonstrated that if the sea-level rise becomes greater than 48 cm over the next 100 years then several local well fields would be vulnerable to chloride contamination. Melloul and Collin [15] evaluated the potential of sea-level rise to cause permanent freshwater reserve losses in a coastal aquifer in Israel. They quantified the saltwater intrusion effect due the lateral movement of seawater and due changes in the groundwater head. For the assumed sea-level rise of 0.5 m, about 77% of the loss was due to the lateral movement and about 23% was due to the head change. Ranjan et al. [16] used the sharp interface assumption to analyze the effects of climate change and land use on coastal groundwater resources in Sri Lanka. Giambastiani et al. [17] conducted a numerical study to investigate saltwater intrusion in an unconfined coastal aquifer of Ravenna, Italy. Their result showed that the mixing zone between fresh and saline groundwater will be shifted by about 800 m farther inland for a 0.475 m per century of sea-level rise. Loáiciga et al. [18] employed hydrogeological data and the finite-element numerical model FEFLOW to assess the likely impacts of sea-level rise and groundwater extraction on seawater intrusion in the Seaside Area aquifer of Monterrey County, California, USA. Sea-level rise scenarios were consistent with current estimates made for the California coast, and varied between 0.5 and 1.0 m over the 21st century. These authors concluded that sea-level rise would have a minor contribution to seawater intrusion in the study area compared to the contribution expected from groundwater extraction.

The primary focus of most of the field-scale modeling studies discussed above was to understand saltwater intrusion problems related to a specific field site. More recently, Werner and Simmons [19] completed a conceptual modeling study using a steady-state, sharp-interface analytical model and focused on developing a general understanding of the impacts of sea-level rise on groundwater aquifers that might have different types of boundary conditions. They used a relatively simple analytical model to provide a first-order assessment of the impacts of sea level changes on saltwater intrusion on aquifer systems with two types of boundary conditions. Their results showed that the level of intrusion would depend on the type of inland boundary condition assumed in the model. The steady-state, sharp-interface, analytical expression used in the study did not consider saltwater mixing effects and transient effects. The transient effects in unconfined aquifers were later investigated by Webb and Howard [20], using a numerical model that employed constant head boundary conditions, to study the changes in the rates of intrusion for a range of hydro-geological parameters.

The objective of this study is to complete a comprehensive investigation of the transient impacts of the sea-level rise on saltwater intrusion processes in both confined and unconfined coastal aquifer systems that are driven by natural recharge fluxes. The results are then used to develop an intuitive understanding for saltwater intrusion dynamics, which can help better asses and manage the potential long term impacts of sea-level rise on coastal aquifers.

2. Problem formulation and conceptual modeling

A general conceptual model for describing a groundwater flow system near a coastal boundary is shown in Fig. 1a. As shown in the figure, under natural flow conditions, the dense sea water would have the tendency to intrude beneath the fresh groundwater. The spatial extent of the intruded saltwater wedge (designated as the "toe position X_T") would depend on several aquifer parameters including recharge rate, regional aquifer discharge rate, hydraulic properties, and the sea level. Recent climate change studies have shown that the global sea-level, on average, is expected to rise between 18 and 59 cm this century [21]. Worst-case projections show it could be as high as 180 cm [22]. Therefore, environmental planners worldwide are seriously concerned about the impacts of sea-level rise on saltwater intrusion processes, especially in over-utilized, urbanized coastal aquifers that already have low groundwater levels. Currently, it is expected that the rising sea level will enhance saltwater intrusion and potentially contaminate many freshwater reserves. Fig. 1b depicts a commonly assumed conceptual model [19,23–27] that illustrates how the rising sea level would impact the groundwater quality by forcing the wedge to migrate inland. This conceptual model, however, ignores the fact that when the seawater rises at the sea-side boundary the system would pressurize and the water-table level might be "lifted" throughout the aquifer. Fig. 1c illustrates a revised conceptual model. This revised model accounts for the lift in the groundwater level over the entire system due to the changes in the sea-side boundary condition. It is expected that after a long period (i.e., at or near steady state) this lifting effect would approximately raise the entire fresh water body (measured from the bottom of the aquifer) by an extent similar to the sea-level rise (i.e., a similar order of magnitude). One could intuitively expect this lifting mechanism to counteract and reduce the impacts due to the sea-level rise. However, it is unclear to what extent this lifting process could reduce the overall impacts due to sea-level rise. In this study, we employ this revised conceptual model to hypothesize that changes in the sea-level might have little or no impact on saltwater intrusion when the net flux through the system is unchanged. The overall goal of this conceptual study is to test the validity of this hypothesis, and understand its ramifications under transient conditions in idealistic confined and unconfined systems.

3. Details of the numerical experiment

The base-case problem considered in this study was adapted from Werner and Simmons' conceptual model [19] of a seawater intrusion field study completed in Pioneer Valley, Australia. The original problem only considered unconfined flow conditions; in this work, the problem was modified to investigate both confined and unconfined conditions. Our numerical study considered a two-dimensional aquifer system which is 1000 m long and 30 m thick. A rectangular numerical grid, with $\Delta x = 4$ m, $\Delta y = 1$ m and $\Delta z = 0.4$ m, was used. The initial sea level (prior to the rise) was assumed to be at 30 m and the sea level was then allowed to rise instantaneously to 34 m. The net sea-level rise assumed was 4 m, a theoretical worst-case scenario which is approximately double the extreme value predicted by Vermeer and Rahmstorf [22]. The assumed sea-level rise was chosen to approximately mimic the last interglacial period's rapid sea-level rise that reached up to 4–6 m due to rapid loss of ice-sheet [28]. It is important to note that this is not a "true" scenario simulation exercise; our objective is not to forecast the future location of saltwater wedge for a specific system, rather it is to develop a generic conceptual understanding to assess the potential impacts of sea-level rise on saltwater intrusion processes. Therefore, some extreme sea-level rise scenarios were

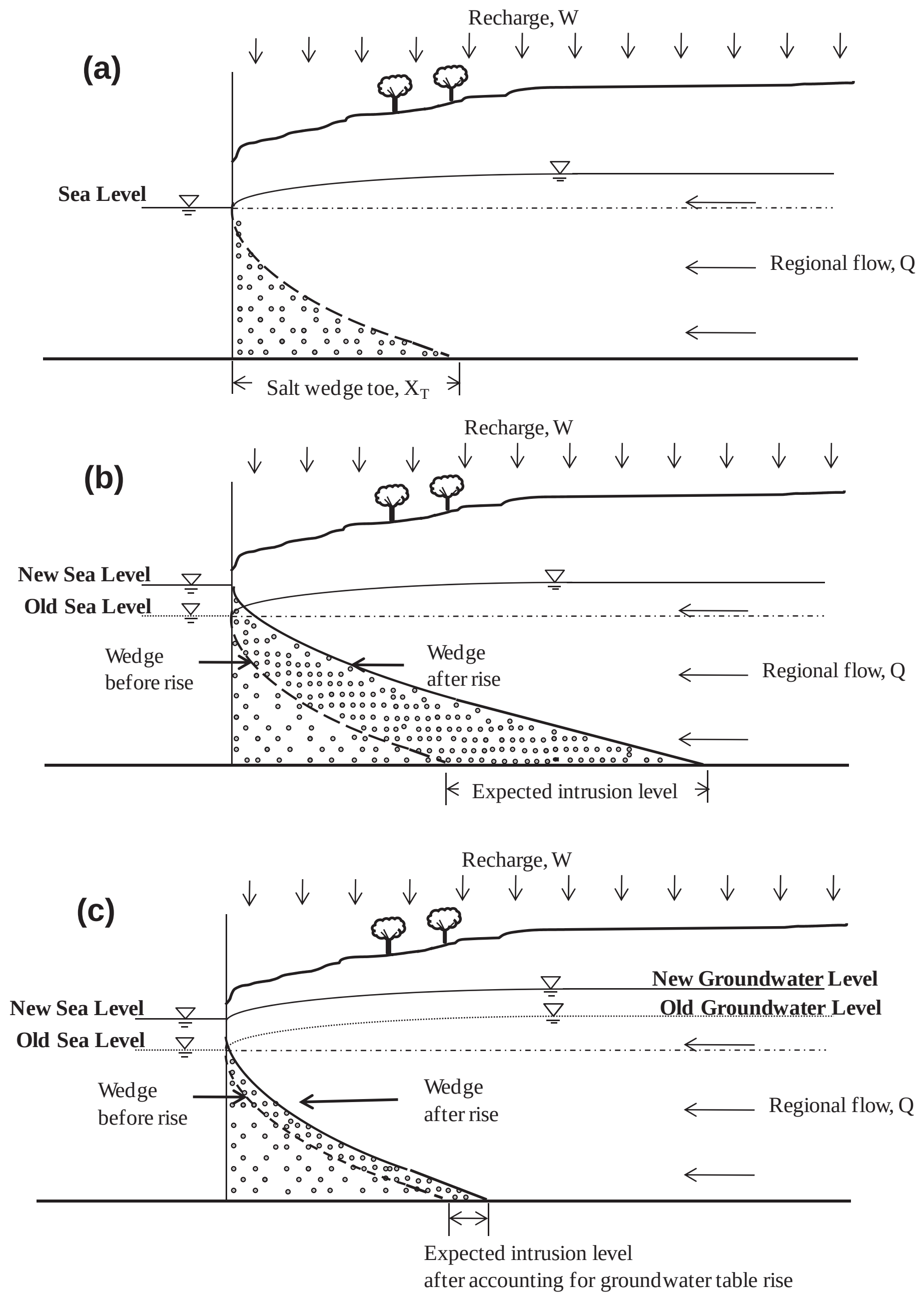

Fig. 1. Comparison of conceptual models used for visualizing the impacts of sea-level rise on a saltwater wedge: (a) initial salt wedge before the sea-level rise, (b) salt wedge profile after sea-level rise based on a traditional conceptual model that ignores the lifting effect, and (c) a new conceptual model that includes the lifting effect.

initially simulated (as the base-case) to better illustrate certain subtle transport mechanisms. Later, as a part of the sensitivity analysis, we explore some realistic sea-level rise scenarios that range from 0.2 m (minimum rise predicted by IPCC) to 4 m (double the maximum rise predicted by Vermeer and Rahmstorf [22]). Also, in all base-case simulations we assumed instantaneous rise (a worst-case scenario) and later in the sensitivity section we have presented the results for other finite rates of sea-level rise.

The seawater density was assumed to be 1025 kg/m^3 with salt concentration of 35 kg/m^3. The regional groundwater flux supplied through the right boundary using a set of artificial injection well nodes. The flux (q, flow per unit depth) supplied from the right boundary was 0.005 m^2/day (or a total flow rate (Q) of 0.15 m^3/day over the 30 m thick aquifer). Recharge (W) flow was delivered from the top boundary at the rate of 5×10^{-5} m/day. These regional and recharge flows were simply selected to locate the initial location of the saltwater toe in between 300 and 500 m. The hydraulic conductivity was set to 10 m/day, specific storage was set to 0.008 m^{-1} in each confined layer, and porosity to 0.35. Longitudinal and transversal dispersivity values were assigned to be 1 m and 0.1 m, respectively. The initial sea level was set at 30 m to simulate a base-case steady-state wedge. This steady-state wedge was later used as the initial condition in all subsequent sea-level rise simulations.

The MODFLOW-family variable density flow code SEAWAT [29] was used in this study with the central difference weighting option. The modeling approach was validated by solving Henry's steady-state solution [30,31] and also laboratory data provided by Goswami and Clement [32], and Abarca and Clement [33]. Several sets of numerical experiments were completed to explore various types of flow conditions and parameter values. The first set of experiments only considered confined-flow conditions and the results were used to explore certain novel salt-wedge reversal mechanisms that have not been reported in the published literature. Later simulations consider both confined and unconfined flow conditions.

4. Results and discussion

4.1. Impacts of sea-level rise on confined flow conditions

The goal of the first steady-state simulation is to estimate the initial saltwater wedge profile that would exist in the system prior to sea-level rise. Fig. 2 (continuous line) shows the 50% isochlor of the initial steady-state concentration profile for the base-case, confined-flow system. This 50% concentration profile is defined as the base saltwater wedge. The figure shows that under the assumed groundwater flow conditions, the toe of the salt wedge advanced to 382 m into the aquifer before sea-level rise. This steady-state condition was used as the initial condition in all subsequent simulations.

The second steady-state simulation aimed to predict the long-term salt-wedge profile after the sea-level rise. The water level at the seaside boundary was abruptly increased from 30 to 34 m to simulate an instantaneous sea-level rise. The system was allowed to evolve for 80,000 days to reach steady-state conditions. The new steady-state solution for the salt wedge simulated by the model after raising the sea level is also shown in Fig. 2 (using circle data points). Interestingly, and rather surprisingly, the model-predicted saltwater profiles for both conditions (pre and post sea-level rise) were identical, indicating that the sea-level rise will have absolutely no impact on the location of the steady-state wedge when the freshwater flux transmitted through the system remained constant (i.e., if the rainfall/recharge pattern was not changed). This non-intuitive result has several important practical implications. The result indicates that the lifting effect postulated in the conceptual model described in Fig. 1c will fully offset the negative impacts of sea-level rise in constant flux confined flow systems.

To further explore this result, we present the transient evolution of the location of the saltwater wedge in Fig. 3. These profiles show that when the sea-level was instantaneously raised, the wedge initially started to move inward; however, after about 8000 days, the direction of wedge movement reversed and the wedge started to move backward until it reached the initial steady-state profile. As far as we are aware, no one has predicted or postulated this self-reversal mechanism. Understanding this self-reversal process has an enormous implication on how water resources managers would perceive and manage the impacts of sea-level rise on saltwater intrusion.

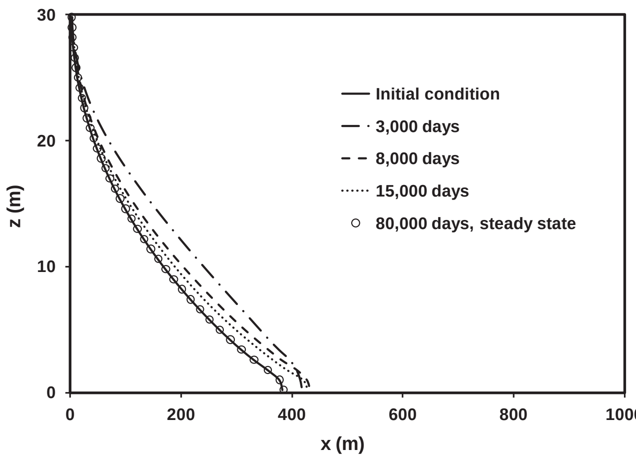

Fig. 3. Transient salt wedge profiles for the confined system.

Fig. 4 shows the transient variations in the toe position of the saltwater wedge (X_T). The data shows that, under assumed flow conditions, the salt wedge first advanced into the aquifer for about 8000 days and reached a maximum distance of 432 m (from the sea boundary) and then started to recede. The figure also shows the simulated transient freshwater head levels at the right side boundary. This freshwater head data is an excellent surrogate for quantifying the progression of the aquifer "lifting" process, postulated in Fig. 1c. This dataset shows that the initial head at the right boundary, as predicted by the model prior to the sea-level rise, was 31 m. When the sea-level was raised instantaneously from 30 to 34 m, it took about 2000 days for the right boundary to fully respond to this change. After about 2000 days, the fresh-water level in the right boundary reached a constant value of about 35 m. The net change in the freshwater level was about 4 m, almost identical to the sea-level rise forced at the left boundary. This implies that the raising seaward-boundary head lifted the entire fresh groundwater system by a similar order of magnitude. This lifting process was able to fully reverse the salt wedge location. The rate of the reversal process would depend on rate at which the groundwater

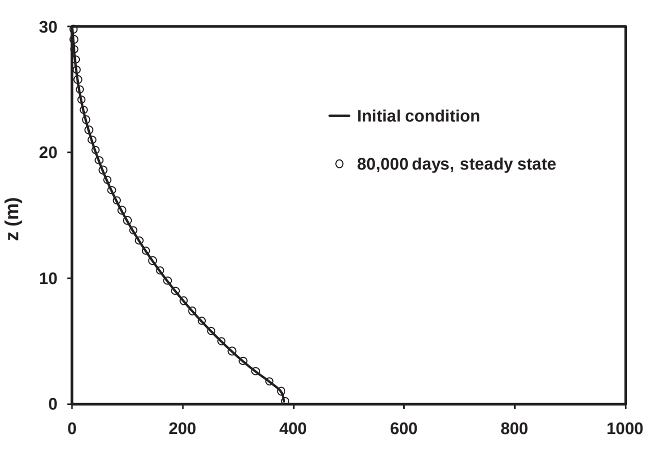

Fig. 2. Comparison of steady-state salt wedges predicted before and after the sea-level rise in the confined system.

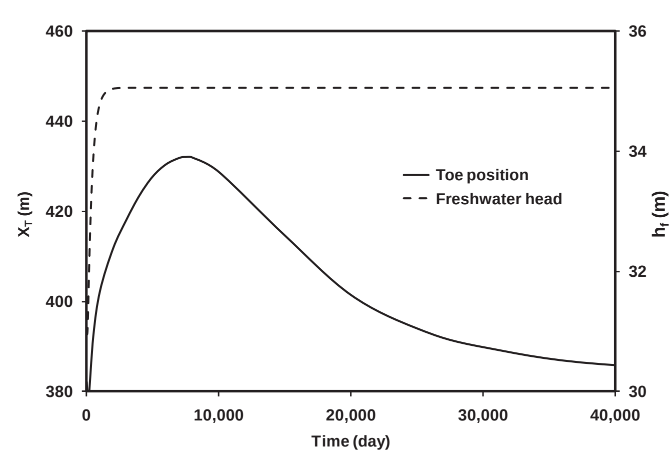

Fig. 4. Transient variations in the toe position (X_T) and freshwater head (h_f) at the inland boundary.

system was lifted (or how quickly the groundwater heads would respond), which would in turn depend on the storage properties of the aquifer and the rate of sea-level rise. In the following section, we provide a detailed analysis that quantifies the sensitivity of the self-reversal process to the value of storage coefficient, rate of sea-level rise and the magnitude of rise. All these simulations used the base-case steady-state solution as the initial condition.

4.2. Sensitivity analysis of the self-reversal process in confined systems

4.2.1. Sensitivity to specific storage

We first explored the sensitivity of the intrusion mechanism to various values of specific storage (S_s). In this analysis, the value of S_s was varied by an order magnitude with the range 0.0008–0.008 m^{-1}. In all sensitivity simulations, the other parameters were fixed at base-case levels shown in Table 1. Fig. 5a shows the temporal variations in the toe position (X_T) for different values of S_s. The data show that when S_s was small the system responded rapidly and the intrusion effect was reversed quickly. Also, the maximum intrusion length was small for smaller values of S_s. The maximum values of the predicted saltwater toe position (X_T) were 432, 412, 394, and 386 m for the S_s values 0.008, 0.005, 0.002 and 0.0008 m^{-1}, respectively. The figure shows that when S_s is small (at 0.0008 m^{-1}) the change in the salt wedge location was relatively small even for an extreme sea-level rise of 4 m. The total time required to reach the maximum intrusion level (defined as the duration of intrusion) was 6000–8000 days. These values appear to be relatively insensitive to S_s. Overall, the extent of saltwater intrusion as indicated by the maximum value of X_T was more sensitive to S_s than the duration of intrusion.

4.2.2. Sensitivity to the magnitude of sea-level rise

The sensitivity of the intrusion length to the magnitude of the sea-level rise was explored by varying the sea level rise within the range of 0.2–4 m. Fig. 5b shows the transient variations in X_T values for various values of sea-level rise. The maximum values of X_T were approximately proportional to the magnitude of sea-level rise. Also, similar to the previous sensitivity experiment, the time taken to reach the maximum values was about 6000–8000 days, and this time was relatively insensitive to the magnitude of the sea-level rise.

4.2.3. Sensitivity to the rate of sea-level rise

Simulations were completed to test the sensitivity of the intrusion process to changes in the rate of sea-level rise. Literature data indicated that the current rate of sea-level rise, observed worldwide, has ranged from 2 to 4 mm/year [34]. Climate change model projections, however, show that the global rate could at least double by the end of this century [35]. A total rise of 4 m was simulated using six different rate scenarios: instantaneous, 1 mm/day for 4000 days, 0.1 mm/day for 40,000 days, 0.05 mm/day for 80,000 days, and infinite rise at a rate of 0.04 mm/day with S_s = 0.008 and S_s = 0.0008. Fig. 5c shows the temporal variations in the simulated toe position (X_T) for all five scenarios. The data demonstrates that the rate of the self-reversal process would depend on the sea-level rise rate. When the rate of rise was low the reversal cycle had a longer duration. The maximum value of the intrusion length, X_T, decreased with decrease in the rate of sea-level intrusion. The time taken to reach the maximum level of intrusion was 7500, 10,000, 40,000 and 80,000 days for instantaneous, 1 mm/day, 0.1 mm/day, 0.05 mm/day sea-level rise rates, respectively. When sea-level was allowed to rise infinitely at a fixed rate, the results reached an irreversible, quasi steady-state level. It is important to note this irreversible intrusion level was primarily an artifact due the relatively large storage value (of 0.008 m^{-1}) assumed as the base-case parameter. When we reduced the specific storage value by an order of magnitude (to 0.0008 m^{-1}, a more typical value for confined flow) the head information propagated quickly and the lifting effect became continuously active. Therefore, the system with a higher S_s value experienced immediate reversal and experienced very little intrusion under the continuous-rise scenario. Overall, changes in the rate of sea-level rise influenced the maximum level of intrusion as well as the time required to reach the maximum level. The time required to reach the maximum would, to a large extent, depend on how long the sea rise occurred.

4.2.4. Sensitivity to dispersivity values

We explored the sensitivity of the intrusion mechanism to dispersivity coefficients by varying the value within the range of 0.5–2 m for longitudinal dispersivity, α_L, and 0.05 m to 0.2 m for transverse dispersivity, α_T. As Abarca et al. [36] pointed out, changing the values of dispersivity would impact the value of X_T (initial X_T decreased when the dispersivity coefficients were increased). Therefore, we defined a parameter "net change in salt wedge location," which was computed as: maximum value of X_T – initial position of X_T, to quantify the changes. Fig. 5d shows the temporal variations in the toe position (X_T) for different values of dispersivity. The net change in the salt wedge location was in between 44 and 53 m. The time taken to reach the maximum intrusion level and the peak of X_T values were relatively insensitive to changes in the value of dispersivity coefficient.

4.2.5. Sensitivity to other hydrological parameters

It is important to note that the transient reversal patterns would depend on the values of hydraulic conductivity, recharge rate and ambient groundwater flow. Sensitivity to variations in all these model parameters was also explored in this study. Simpler analytical solutions can be used to intuitively infer the sensitivity to individual variations in K, W and Q values under steady conditions. Werner and Simmons [19] followed this approach and completed a detailed sensitivity assessment for a steady-state unconfined problem. In this study, we present the results of a selected number of sensitivity tests completed for a transient confined aquifer system using SEAWAT. Fig. 6a shows the transient variations in X_T values for different hydraulic conductivity values; K values used are: 5 m/day, 10 m/day and 15 m/day. It should be noted that the simulated profiles have different initial X_T since individually changing any one of these parameters (K, W or Q) would alter the steady-state solution of the base problem. The results show that the peak value of X_T was increased and responding time was short (as expected) when the K value was decreased. Fig. 6b shows the transient variations in X_T values for various values of Q and W (0.67 × base values: Q = 0.1 m^3/day and W = 3.3 × 10^{-5} m/day; base values: Q = 0.15 m^3/day and W = 5 × 10^{-5} m/day; doubled the base values: Q = 0.3 m^3/day and W = 1×10^{-4} m/day). The data show that when the amount of freshwater flow was increased the

Table 1
Aquifer properties and hydrological properties used for the base-case problem.

Property	Symbol	Value
Horizontal aquifer length	L	1000 m
Vertical aquifer thickness	B	30 m
Inland groundwater flow rate	Q	0.15 m^3/day
Uniform recharge rate from top	W	5 × 10^{-5} m/day
Hydraulic conductivity	K	10 m/day
Specific storage	S_s	0.008 m^{-1}
Longitudinal dispersivity	α_L	1 m
Transverse dispersivity	α_T	0.1 m
Saltwater concentration	C_s	35 kg/m^3
Saltwater density	ρ_s	1025 kg/m^3
Freshwater density	ρ_f	1000 kg/m^3

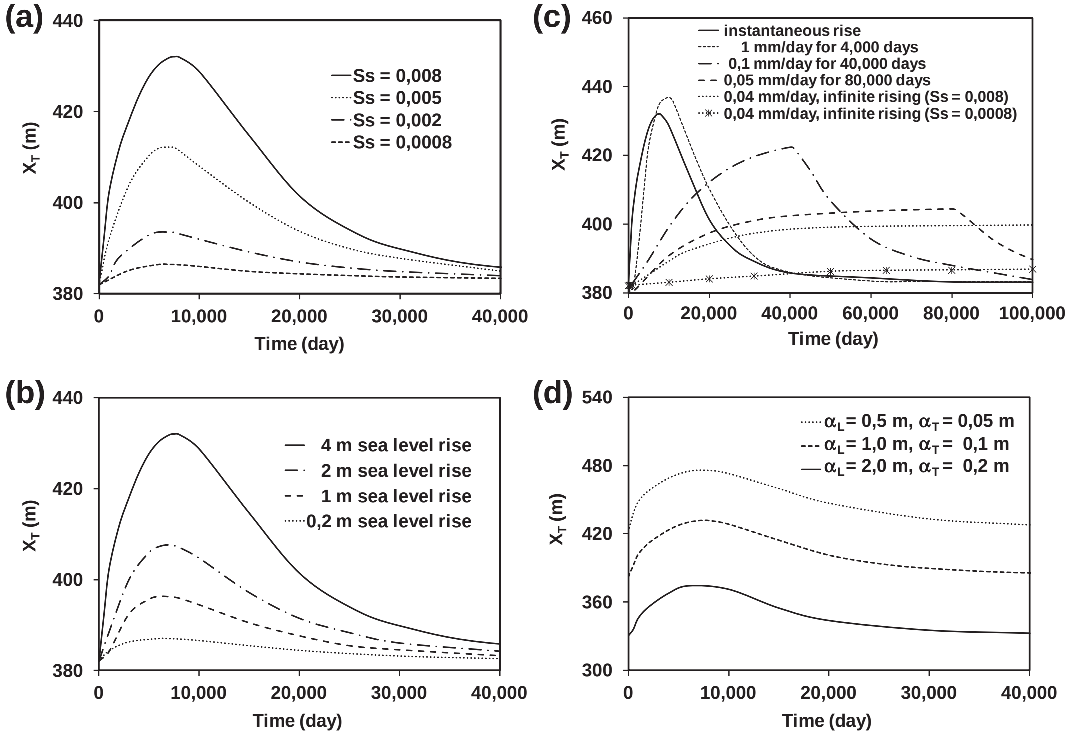

Fig. 5. Sensitivity of the toe position (X_T) to (a) specific storage, (b) the magnitude of sea-level rise, (c) the rate of sea-level rise velocity and (d) the dispersivity coefficients.

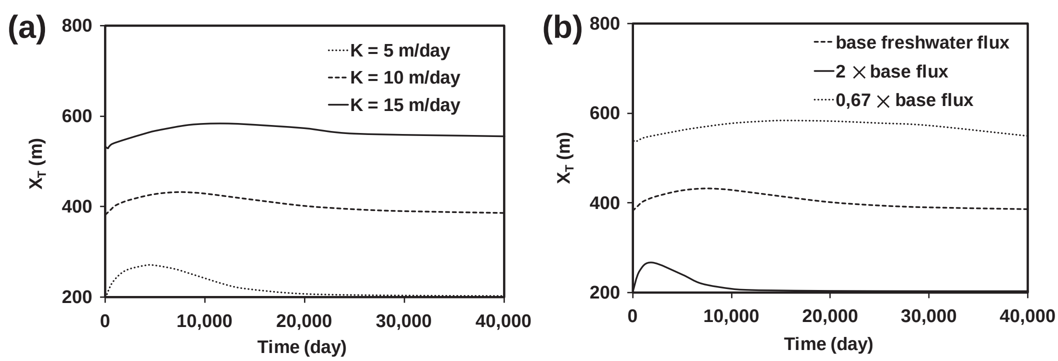

Fig. 6. Sensitivity of the toe position (X_T) to: (a) hydraulic conductivity and (b) freshwater flux.

peak value of X_T increased and system also had a shorter responding time. It should be noted that if the transport parameters were scaled consistently (for example, increase K and reduce the Q by a similar factor) then there will be very little variation in the peak value of X_T.

4.3. Impacts of sea-level rise on unconfined aquifers

To examine the impacts of sea-level rise on unconfined flow conditions, we completed numerical simulations of an unconfined aquifer with dimensions identical to those used in the confined simulation, except the top layer was modified to simulate unconfined flow. The length of the unconfined aquifer was 1000 m and the total thickness was 35 m. A numerical grid with $\Delta x = 4$ m, $\Delta y = 1$ m and $\Delta z = 0.4$ m (75 confined layers), and a top unconfined layer of $\Delta z = 5$ m was used. In all unconfined flow simulations, the value of average hydraulic conductivity was set to 10 m/day, total regional freshwater flow (Q) from the right boundary was set to 0.15 m^3/day, and the areal recharge flux (W) was set to 5×10^{-5} m/day. In order to compare unconfined flow simulation results against confined flow results, an identical instantaneous sea-level rise (rise from 30 to 34 m) scenario was assumed. The specific storage, S_s, was set to 0.008 m^{-1} for all confined layers, and specific yield, S_y, was set to 0.1 for the top unconfined layer.

We first completed a base-case, steady-state simulation for the unconfined system to generate the initial conditions that existed prior to the sea level rise. Fig. 7 compares the steady-state salt wedge predicted for the unconfined flow system with the wedge predicted for a similar confined flow system (data from Fig. 2). The figure shows that both wedges are almost identical, indicating that both confined and unconfined systems would behave in a similar manner at steady-state conditions. The similarity between the two steady-state solutions can also be explained mathematically, as shown in Appendix A.

To understand the impacts of sea-level rise on the unconfined aquifer, we instantaneously raised the sea-level by 4 m and let the system reach steady state. Fig. 8 compares the initial and final steady-state saltwater wedge profiles in the unconfined system

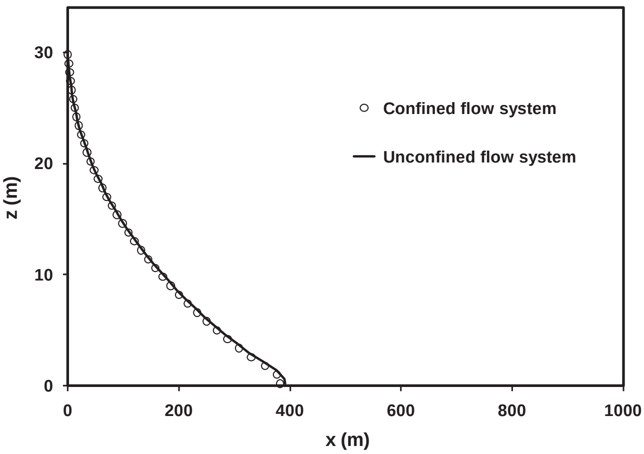

Fig. 7. Comparison of steady-state salt wedges predicted before the sea-level rise (sea level at 30 m) in the unconfined- and confined-flow systems.

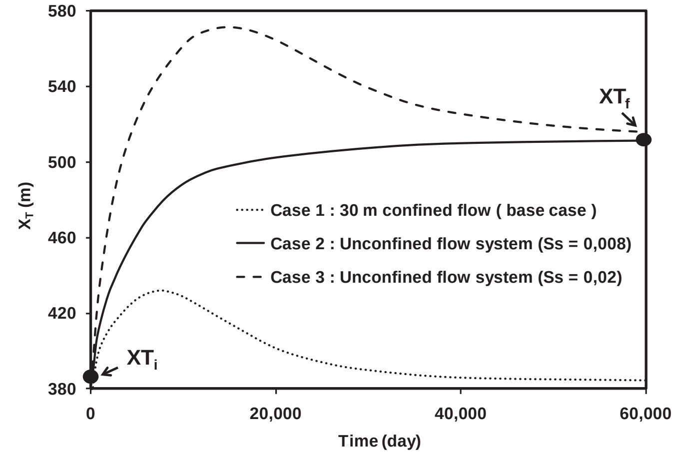

Fig. 9. Comparison of transient variations in toe positions (X_T) predicted for the confined and unconfined flow systems.

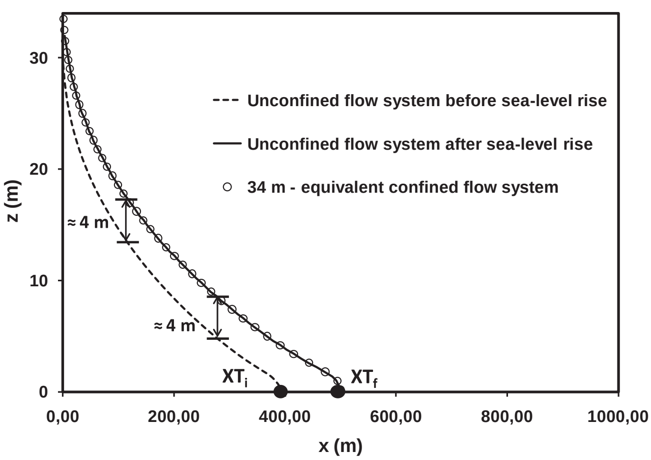

Fig. 8. Comparison of steady-state salt wedges predicted before the sea-level rise in the unconfined system, after the sea-level rise in the unconfined system, and in an equivalent 34-m thick confined-flow system.

(dotted and continuous lines). These profiles show that, unlike the confined system (compare with Fig. 3 results), the saltwater intrusion process is not reversible for the unconfined system. In unconfined aquifers, the initial location of the toe XT_i and the final location of the toe position XT_f are distinctly different. This is because, under unconfined conditions, the sea-level rise increases in the saturated thickness (or transmissivity) of the aquifer. This increased transmissivity allows the wedge to penetrate further into the system, resulting in a new steady-state condition. Comparing the initial and final salt-wedge profiles indicates the initial salt wedge was approximately raised by 4 m, similar to the level of sea-level rise. The groundwater level also rose over the entire aquifer by about 4 m (as illustrated in Fig. 1c), all the way to the inland boundary (the predicted groundwater raise at the inland boundary was similar to the data shown in Fig. 4). These data indicate that the aquifer lifting process is active in the unconfined system. The lifting process, however, was not able to fully reverse the wedge location since the system evolved from a steady-state solution for the 30-m thick aquifer (with initial toe, XT_i, at about 382 m) to a new steady-state solution for the 34-m thick aquifer (with final toe, XT_f, at about 510 m). The data points (marked with circles) shown in the figure are steady-state wedge data predicted for a 34-m thick "equivalent confined aquifer." As expected (see Appendix A for an analytical analysis), the final unconfined steady-state solution matched with an equivalent confined aquifer solution with an appropriate value of aquifer thickness.

Fig. 9 compares the results of transient changes in toe length predicted for the following three systems: (Case-1) standard base-case confined system of 30 m thickness (same as the data shown in Fig. 4); (Case-2) unconfined flow system with base-case parameters; and (Case-3) unconfined system with very high S_s value (0.02 m^{-1}). It is important to note the S_s value used for Case-3 is unrealistically high and this conceptual simulation was completed to demonstrate the existence of certain subtle self-reversal mechanisms. Several observations can be made from the results presented in Fig. 9. All three solution started at the initial toe location XT_i = 382 m and for about 1000 days the unconfined solutions were approximately equal to the confined flow solution. After this time, the unconfined model solutions started to diverge. The Case-2 unconfined flow simulation reached the final steady-state toe position, XT_f, after about 50,000 days, and the system did not show any reversal effect. However, when we repeated the unconfined simulation using high S_s values (Case-3) we could clearly observe the reversal effect. Also, as expected, Case-3 required more time (about 100,000 days) to reach steady-state final toe position XT_f. In summary, the aquifer lifting effect is active in unconfined systems but it is difficult to observe any reversal effects in transient unconfined systems due to the changes in the aquifer transmissivity. When an appropriate value of aquifer thickness was used, the steady-solution for an unconfined flow system would be almost identical to an "equivalent confined flow system." The storage available within fully-saturated layers (which act as confined layers) are typically very low and this would allow rapid propagation of head perturbations; therefore, it is difficult to observe reversal effects in any realistic unconfined aquifers.

5. Conclusions

Detailed numerical experiments were completed using the MODFLOW-family computer code SEAWAT to study the transient effects of sea-level rise on saltwater wedge in confined and unconfined aquifers with vertical sea-land interface. The simulation results show that if the ambient recharge remains constant, the sea-level rise will have no impact on the steady-state salt wedge in confined aquifers. The transient confined-flow simulations help identify an interesting self-reversal mechanism where the wedge, which initially intrudes into the formation due to sea-level rise, would be naturally driven back to the original position. However, in unconfined-flow systems this self-reversal mechanism would have a lesser effect due to changes in the value of the effective transmissivity (or average aquifer thickness). Both confined and unconfined simulation experiments show that rising seas would lift the entire aquifer and this lifting process would help alleviate the overall long-term impacts of saltwater intrusion.

The sensitivity simulations show that the rate and the extent of the self-reversal process would depend on the value of specific storage (S_s) and the rate of sea-level rise. When the rate of rise was low the reversal cycle had a larger duration. Overall, the changes in the rate of sea rise had relatively less influence on the maximum level of intrusion and more influence on the and the time taken to reach the maximum level. On the other hand, the maximum level of intrusion was more sensitive to variation in S_s values than the duration of intrusion (the time taken to reach the maximum value).

It is important to note that the results presented in this conceptual modeling study are based on simulations completed for an idealized rectangular aquifer with homogeneous aquifer properties. While the results are useful for developing a large-scale conceptual understanding of the impacts of sea-level rise, evaluation of true impacts would require detailed site-specific modeling efforts [18,37]. A better understanding the self-reversal mechanism (both its spatial and time scales), identified in this study, would have an enormous implication on managing the impacts of sea-level rise in coastal groundwater aquifers. The results, however, do not imply that one could simply ignore climate change effects on saltwater intrusion process. Rather it implies that we can minimize its risks based on a sound scientific understanding of the transport processes and by developing pro-active management strategies that are appropriate to unconfined aquifers and confined aquifers. It is important to note that this study assumes the fluxes in the system would remain constant. However, site-specific climate change effects could greatly alter the recharge and regional fluxes (these natural hydrological fluxes can change due to variations in the rainfall patterns), therefore the overall problem should be managed in the context of large-scale variations in hydrological fluxes expected to be induced by the climate change effects. In addition, Loáiciga et al. [18] pointed out that variations in groundwater extraction (anthropogenic fluxes) was the predominant driver of sea water intrusion in a model that simulated sea-level rise scenarios for the City of Monterrey, California. Finally, it is very likely that rising heads might increase evapo-transpiration fluxes. This could impact the overall hydrological budget resulting in less recharge reaching the coastal area and this will hinder the self-reversal process. Therefore, site-specific management models for coastal areas should carefully integrate changes in both natural and anthropogenic fluxes with various sea-level rise scenarios.

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Appendix A. Analytical comparison of salt-wedge toe positions in unconfined and confined aquifers

The basic concepts used for deriving analytical solutions for salt wedge locations using the sharp-interface approximation are presented by Strack and others [23,25–27]. Using the sharp-interface approach, the toe position (X_T) in a steady-state, unconfined flow system can predicted using the following expression [27]:

$$X_T = \left(\frac{q^*}{W} + L\right) - \sqrt{\left(\frac{q^*}{W} + L\right)^2 - \delta B_o^2 (1+\delta)\left(\frac{K}{W}\right)} \tag{1A}$$

where q^* is is the depth-averaged flow through the boundary per unit width of the aquifer [L^2T^{-1}], B_o is the depth of aquifer bottom measured from the mean sea level [L]. W is the uniform recharge rate [LT^{-1}], δ is equal to $\frac{\rho_s - \rho_f}{\rho_f}$, where ρ_f is the density of fresh water [ML^{-3}] and ρ_s is the density of saltwater [ML^{-3}]. Note the above equation is purely a function of groundwater flows (or fluxes) and it does not depend on boundary head levels. Hence, the location of the saltwater toe position will be insensitive to changes in head levels at the sea-side boundary.

A similar expression for estimating the toe position in a confined flow system can be derived from the expressions presented by Cheng et al. [23] as:

$$X_T = \left(\frac{q^*}{W} + L\right)) - \sqrt{\left(\frac{q^*}{W} + L\right)^2 - \delta B^2 \left(\frac{K}{W}\right)} \tag{2A}$$

where B is the thickness of the confined aquifer [L]. Eq. (2A) is similar to (1A) and the only difference is the $(1 + \delta)$ term. For seawater, the value of the dimensionless parameter $\delta = 0.025$, and hence the term $(1 + \delta) \sim 1$. Therefore, when $B^2K \sim B_o^2K$ (or when aquifer thicknesses are matched approximately) the X_T values predicted for confined and unconfined flow systems would almost be the same.

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