1   **Does Sea-level Rise Have an Impact on Saltwater Intrusion?**

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3   Sun Woo Chang [1], T. Prabhakar Clement[1*], Matthew J. Simpson[2], Kang-Kun Lee[3].

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7   [1]Department of Civil Engineering, 212 Harbert Engineering Center, Auburn University, Auburn,

8   AL, USA 36849-5337

9   [2]Discipline of Mathematical Sciences, Queensland University of Technology, G.P.O. Box 2434,

10   Brisbane, Queensland 4001, Australia

11   [3]School of Earth and Environmental Science, Seoul National University, Seoul 151-742, Korea

12

13   *Corresponding author

14   Phone : (+1) 334-844-6268

15   Fax: (+1) 334 -844-6290

16   Email : clemept@auburn.edu (Prabhakar Clement)

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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 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 eighty percent 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 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. 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

1   reserve losses in a coastal aquifer in Israel. They quantified the saltwater intrusion effect due the

2   lateral movement of seawater and due changes in the groundwater head. For the assumed sea-

3   level rise of 0.5 m, about 77% of the loss was due to the lateral movement and about 23% was

4   due to the head change. Ranjan et al. [16] used the sharp interface assumption to analyze the

5   effects of climate change and land use on coastal groundwater resources in Sri Lanka.

6   Giambastiani et al. [17] conducted a numerical study to investigate saltwater intrusion in an

7   unconfined coastal aquifer of Ravenna, Italy. Their result showed that the mixing zone between

8   fresh and saline groundwater will be shifted by about 800 m farther inland for a 0.475 m per

9   century of sea-level rise. Loaiciga et al. [18] employed hydrogeological data and the finite-

10 element numerical model FEFLOW to assess the likely impacts of sea-level riser and

11 groundwater extraction on seawater intrusion in the Seaside Area aquifer of Monterrey County,

12 California, USA. Sea-level rise scenarios were consistent with current estimates made for the

13 California coast, and varied between 0.5 and 1.0 m over the 21st century. These authors

14 concluded that sea-level rise would have a minor contribution to seawater intrusion in the study

15 area compared to the contribution expected from groundwater extraction.

16 The primary focus of most of the field-scale modeling studies discussed above was to understand

17 saltwater intrusion problems related to a specific field site. More recently, Werner and Simmons

18 [19] completed a conceptual modeling study using a steady-state, sharp-interface analytical

19 model and focused on developing a general understanding of the impacts of sea-level rise on

20 groundwater aquifers that might have different types of boundary conditions. They used a

21 relatively simple analytical model to provide a first-order assessment of the impacts of sea level

22 changes on saltwater intrusion on aquifer systems with two types of boundary conditions. Their

23 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 Figure 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-

1 utilized, urbanized coastal aquifers that already have low groundwater levels. Currently, it is

2 expected that the rising sea level will enhance saltwater intrusion and potentially contaminate

3 many freshwater reserves. Figure 1b depicts a commonly assumed conceptual model [19, 23-27]

4 that illustrates how the rising sea level would impact the groundwater quality by forcing the

5 wedge to migrate inland. This conceptual model, however, ignores the fact that when the

6 seawater rises at the sea-side boundary the system would pressurize and the water-table level

7 might be "lifted" throughout the aquifer. Figure 1c illustrates a revised conceptual model. This

8 revised model accounts for the lift in the groundwater level over the entire system due to the

9 changes in the sea-side boundary condition. It is expected that after a long period (i.e., at or near

10 steady state) this lifting effect would approximately raise the entire fresh water body (measured

11 from the bottom of the aquifer) by an extent similar to the sea-level rise (i.e., a similar order of

12 magnitude). One could intuitively expect this lifting mechanism to counteract and reduce the

13 impacts due to the sea-level rise. However, it is unclear to what extent this lifting process could

14 reduce the overall impacts due to sea-level rise. In this study, we employ this revised conceptual

15 model to hypothesize that changes in the sea-level might have little or no impact on saltwater

16 intrusion when the net flux through the system is unchanged. The overall goal of this conceptual

17 study is to test the validity of this hypothesis, and understand its ramifications under transient

18 conditions in idealistic confined and unconfined systems.

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20 **3.   Details of the Numerical Experiment**

21 The base-case problem considered in this study was adapted from Werner and Simmons'

22 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 to 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 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 1,025 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)

1   flow was delivered from the top boundary at the rate of 5×10^{-5} m/day. These regional and

2   recharge flows were simply selected to locate the initial location of the saltwater toe in between

3   300 to 500 m. The hydraulic conductivity was set to 10 m/day, specific storage was set to 0.008

4   m^{-1} in each confined layer, and porosity to 0.35. Longitudinal and transversal dispersivity values

5   were assigned to be 1 m and 0.1 m, respectively. The initial sea level was set at 30 m to simulate

6   a base-case steady-state wedge. This steady-state wedge was later used as the initial condition in

7   all subsequent sea-level rise simulations.

8   The MODFLOW-family variable density flow code SEAWAT [29] was used in this

9   study with the central difference weighting option. The modeling approach was validated by

10   solving Henry's steady-state solution [30] [31] and also laboratory data provided by Goswami

11   and Clement [32], and Abarca and Clement [33]. Several sets of numerical experiments were

12   completed to explore various types of flow conditions and parameter values. The first set of

13   experiments only considered confined-flow conditions and the results were used to explore

14   certain novel salt-wedge reversal mechanisms that have not been reported in the published

15   literature. Later simulations consider both confined and unconfined flow conditions.

16   **4.   Results and Discussions**

17   **4.1. Impacts of sea-level rise on confined flow conditions**

18   The goal of the first steady-state simulation is to estimate the initial saltwater wedge profile that

19   would exist in the system prior to sea-level rise. Figure 2 (continuous line) shows the 50%

20   isochlor of the initial steady-state concentration profile for the base-case, confined-flow system.

21   This 50% concentration profile is defined as the base saltwater wedge. The figure shows that

22   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 Figure 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 Figure 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 Figure 3. These profiles show that when the sea-level was instantaneously raised, the wedge initially started to move inward; however, after about 8,000 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.

1   Figure 4 shows the transient variations in the toe position of the saltwater wedge (X_T).

2   The data shows that, under assumed flow conditions, the salt wedge first advanced into the

3   aquifer for about 8,000 days and reached a maximum distance of 432 m (from the sea boundary)

4   and then started to recede. The figure also shows the simulated transient freshwater head levels

5   at the right side boundary. This freshwater head data is an excellent surrogate for quantifying the

6   progression of the aquifer "lifting" process, postulated in Figure 1c. This dataset shows that the

7   initial head at the right boundary, as predicted by the model prior to the sea-level rise, was 31 m.

8   When the sea-level was raised instantaneously from 30 to 34 m, it took about 2,000 days for the

9   right boundary to fully respond to this change. After about 2,000 days, the fresh-water level in

10   the right boundary reached a constant value of about 35 m. The net change in the freshwater

11   level was about 4 m, almost identical to the sea-level rise forced at the left boundary. This

12   implies that the raising seaward-boundary head lifted the entire fresh groundwater system by a

13   similar order of magnitude. This lifting process was able to fully reverse the salt wedge location.

14   The rate of the reversal process would depend on rate at which the groundwater system was

15   lifted (or how quickly the groundwater heads would respond), which would in turn depend on the

16   storage properties of the aquifer and the rate of sea-level rise. In the following section, we

17   provide a detailed analysis that quantifies the sensitivity of the self-reversal process to the value

18   of storage coefficient, rate of sea-level rise and the magnitude of rise. All these simulations used

19   the base-case steady-state solution as the initial condition.

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21   **4.2. Sensitivity analysis of the self-reversal process in confined systems**

22   4.2.1. Sensitivity to specific storage

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1   We first explored the sensitivity of the intrusion mechanism to various values of specific storage

2   (S_s). In this analysis, the value of S_s was varied by an order magnitude with the range 0.0008 to

3   0.008 m^{-1}. In all sensitivity simulations, the other parameters were fixed at base-case levels

4   shown in Table 1. Figure 5a shows the temporal variations in the toe position (X_T) for different

5   values of S_s. The data shows that when S_s was small the system responded rapidly and the

6   intrusion effect was reversed quickly. Also, the maximum intrusion length was small for smaller

7   values of S_s. The maximum values of the predicted saltwater toe position (X_T) were 432, 412,

8   394, and 386 m for the S_s values 0.008, 0.005, 0.002 and 0.0008 m^{-1}, respectively. The figure

9   shows that when S_s is small (at 0.0008 m^{-1}) the change in the salt wedge location was relatively

10   small even for an extreme sea-level rise of 4 m. The total time required to reach the maximum

11   intrusion level (defined as the duration of intrusion) was 6,000 to 8,000 days. These values

12   appear to be relatively insensitive to S_s. Overall, the extent of saltwater intrusion as indicated by

13   the maximum value of X_T was more sensitive to S_s than the duration of intrusion.

14   4.2.2. Sensitivity to the magnitude of sea-level rise

15   The sensitivity of the intrusion length to the magnitude of the sea-level rise was explored by

16   varying the sea level rise within the range of 0.2 to 4 m. Figure 5b shows the transient variations

17   in X_T values for various values of sea-level rise. The maximum values of X_T were

18   approximately proportional to the magnitude of sea-level rise. Also, similar to the previous

19   sensitivity experiment, the time taken to reach the maximum values was about 6,000 to 8,000

20   days, and this time was relatively insensitive to the magnitude of the sea-level rise.

21   4.2.3. Sensitivity to the rate of sea-level rise

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1   Simulations were completed to test the sensitivity of the intrusion process to changes in the rate

2   of sea-level rise. Literature data indicated that the current rate of sea-level rise, observed

3   worldwide, has ranged from 2 to 4 mm/year [34]. Climate change model projections, however,

4   show that the global rate could at least double by the end of this century [35]. A total rise of 4 m

5   was simulated using six different rate scenarios: instantaneous, 1 mm/day for 4,000 days, 0.1

6   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

7   with $S_s = 0.008$ and $S_s = 0.0008$. Figure 5c shows the temporal variations in the simulated toe

8   position (X_T) for all five scenarios. The data demonstrates that the rate of the self-reversal

9   process would depend on the sea-level rise rate. When the rate of rise was low the reversal cycle

10   had a longer duration. The maximum value of the intrusion length, X_T, decreased with decrease

11   in the rate of sea-level intrusion. The time taken to reach the maximum level of intrusion was

12   7,500, 10,000, 40,000 and 80,000 days for instantaneous, 1 mm/day, 0.1 mm/day, 0.05 mm/day

13   sea-level rise rates, respectively. When sea-level was allowed to rise infinitely at a fixed rate, the

14   results reached an irreversible, quasi steady-state level. It is important to note this irreversible

15   intrusion level was primarily an artifact due the relatively large storage value (of 0.008 m^{-1})

16   assumed as the base-case parameter. When we reduced the specific storage value by an order of

17   magnitude (to 0.0008 m^{-1}, a more typical value for confined flow) the head information

18   propagated quickly and the lifting effect became continuously active. Therefore, the system with

19   a higher S_s value experienced immediate reversal and experienced very little intrusion under the

20   continuous-rise scenario. Overall, changes in the rate of sea-level rise influenced the maximum

21   level of intrusion as well as the time required to reach the maximum level. The time required to

22   reach the maximum would, to a large extent, depended on how long the sea rise occurred.

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1   4.2.4. Sensitivity to dispersivity values

2   We explored the sensitivity of the intrusion mechanism to dispersivity coefficients by varying

3   the value within the range of 0.5 m to 2 m for longitudinal dispersivity, α_L, and 0.05 m to 0.2 m

4   for transverse dispersivity, α_T. As Abarca et al [36] pointed out, changing the values of

5   dispersivity would impact the value of X_T (initial X_T decreased when the dispersivity coefficients

6   were increased). Therefore, we defined a parameter "net change in salt wedge location," which

7   was computed as: maximum value of X_T - initial position of X_T, to quantify the changes. Figure

8   5d shows the temporal variations in the toe position (X_T) for different values of dispersivity. The

9   net change in the salt wedge location was in between 44 and 53 m. The time taken to reach the

10   maximum intrusion level and the peak of X_T values were relatively insensitive to changes in the

11   value of dispersivity coefficient.

12   4.2.5. Sensitivity to other hydrological parameters

13   It is important to note that the transient reversal patterns would depend on the values of hydraulic

14   conductivity, recharge rate and ambient groundwater flow. Sensitivity to variations in all these

15   model parameters was also explored in this study. Simpler analytical solutions can be used to

16   intuitively infer the sensitivity to individual variations in K, W and Q values under steady

17   conditions. Werner and Simmons [19] followed this approach and completed a detailed

18   sensitivity assessment for a steady-state unconfined problem. In this study, we present the

19   results of selected number of sensitivity tests completed for a transient confined aquifer system

20   using SEAWAT. Figure 6a shows the transient variations in X_T values for different hydraulic

21   conductivity values; K values used are: 5 m/day, 10 m/day and 15 m/day. It should be noted that

22   the simulated profiles have different initial X_T since individually changing any one of these

1 parameters (K, W or Q) would alter the steady-state solution of the base problem. The results

2 show that the peak value of X_T was increased and responding time was short (as expected) when

3 the K value was decreased. Figure 6b shows the transient variations in X_T values for various

4 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

5 = 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}

6 m/day). The data show that when the amount of freshwater flow was increased the peak value of

7 X_T increased and system also had a shorter responding time. It should be noted that if the

8 transport parameters were scaled consistently (for example, increase K and reduce the Q by a

9 similar factor) then there will be very little variation in the peak value of X_T.

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12 **4.3. Impacts of sea-level rise on unconfined Aquifers**

13   To examine the impacts of sea-level rise on unconfined flow conditions, we completed

14 numerical simulations of an unconfined aquifer with dimensions identical to those used in the

15 confined simulation, except the top layer was modified to simulate unconfined flow. The length

16 of the unconfined aquifer was 1,000 m and the total thickness was 35 m. A numerical grid with

17 Δx = 4 m, Δy = 1 m and Δz = 0.4 m (75 confined layers), and a top unconfined layer of Δz = 5 m

18 was used. In all unconfined flow simulations, the value of average hydraulic conductivity was set

19 to 10 m/day, total regional freshwater flow (Q) from the right boundary was set to 0.15 m^3/day,

20 and the areal recharge flux (W) was set to 5×10^{-5} m/day. In order to compare unconfined flow

21 simulation results against confined flow results, an identical instantaneous sea-level rise (rise

1   from 30 to 34 m) scenario was assumed. The specific storage, S_s, was set to 0.008 m^{-1} for all

2   confined layers, and specific yield, S_y, was set to 0.1 for the top unconfined layer.

3   We first completed a base-case, steady-state simulation for the unconfined system to generate

4   the initial conditions that existed prior to the sea level rise. Figure 7 compares the steady-state

5   salt wedge predicted for the unconfined flow system with the wedge predicted for a similar

6   confined flow system (data from Figure 2). The figure shows the both wedges are almost

7   identical, indicating that both confined and unconfined systems would behave in a similar

8   manner at steady-state conditions. The similarity between the two steady-state solutions can also

9   be explained mathematically, as shown in Appendix A.

10   To understand the impacts of sea-level rise on the unconfined aquifer, we instantaneously

11   raised the sea-level by 4 m and let the system reach steady state. Figure 8 compares the initial

12   and final steady-state saltwater wedge profiles in the unconfined system (dotted and continuous

13   lines). These profiles show that, unlike the confined system (compare with Figure 3 results), the

14   saltwater intrusion process is not reversible for the unconfined system. In unconfined aquifers,

15   the initial location of the toe XT_i and the final location of the toe position XT_f are distinctly

16   different. This is because, under unconfined conditions, the sea-level rise increases in the

17   saturated thickness (or transmissivity) of the aquifer. This increased transmissivity allows the

18   wedge to penetrate further into the system, resulting in a new steady-state condition. Comparing

19   the initial and final salt-wedge profiles indicates the initial salt wedge was approximately raised

20   by 4 m, similar to the level of sea-level rise. The groundwater level also rose over the entire

21   aquifer by about 4 m (as illustrated in Figure 1c), all the way to the inland boundary (the

22   predicted groundwater raise at the inland boundary was similar to the data shown in Figure 4).

1   These data indicate that the aquifer lifting process is active in the unconfined system. The lifting

2   process, however, was not able to fully reverse the wedge location since the system evolved from

3   a steady-state solution for the 30-m thick aquifer (with initial toe, XT_i, at about 382 m) to a new

4   steady-state solution for the 34-m thick aquifer (with final toe, XT_f, at about 510 m).   The data

5   points (marked with circles) shown in the figure are steady-state wedge data predicted for a 34-m

6   thick "equivalent confined aquifer."   As expected (see Appendix A for an analytical analysis),

7   the final unconfined steady-state solution matched with an equivalent confined aquifer solution

8   with an appropriate value of aquifer thickness.

9   Figure 9 compares the results of transient changes in toe length predicted for the

10   following three systems: Case-1) standard base-case confined system of 30 m thickness (same as

11   the data shown in Figure 4); Case-2) unconfined flow system with base-case parameters; and

12   Case-3) unconfined system with very high S_s value (0.02 m^{-1}). It is important to note the S_s value

13   used for Case-3 is unrealistically high and this conceptual simulation was completed to

14   demonstrate the existence of certain subtle self-reversal mechanisms. Several observations can

15   be made from the results presented in Figure 9. All three solution started at the initial toe

16   location XT_i = 382 m and for about 1,000 days the unconfined solutions were approximately

17   equal to the confined flow solution. After this time, the unconfined model solutions started to

18   diverge. The Case-2 unconfined flow simulation reached the final steady-state toe position, XT_f,

19   after about 50,000 days, and the system did not show any reversal effect. However, when we

20   repeated the unconfined simulation using high S_s values (Case-3) we could clearly observe the

21   reversal effect. Also, as expected, Case-3 required more time (about 100,000 days) to reach

22   steady-state final toe position XT_f. In summary, the aquifer lifting effect is active in unconfined

23   systems but it is difficult to observe any reversal effects in transient unconfined systems due to

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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 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

1 and the time taken to reach the maximum level. On the other hand, variation in S_s values was

2 more sensitive to the maximum level of intrusion than the duration of intrusion (the time taken to

3 reach the maximum value).

4   It is important to note that the results presented in the conceptual modeling study are

5 based on simulations completed for idealized rectangular aquifers with homogeneous aquifer

6 properties. While the results are useful for developing a large-scale conceptual understanding of

7 the impacts of sea-level rise, evaluation of true impacts would require detailed site-specific

8 modeling efforts [18, 37]. A better understanding the self-reversal mechanism (both its spatial

9 and time scales), identified in this study, would have an enormous implication on managing the

10 impacts of sea-level rise in coastal groundwater aquifers. The results, however, do not imply that

11 one could simply ignore climate change effects on saltwater intrusion process. Rather it implies

12 that we can minimize its risks based on a sound scientific understanding of the transport

13 processes and by developing pro-active management strategies that are appropriate to unconfined

14 aquifers and confined aquifers. It is important to note that this study assumes the fluxes in the

15 system would remain constant. However, site-specific climate change effects could greatly alter

16 the recharge and regional fluxes (these natural hydrological fluxes can change due to variations

17 in the rainfall patterns), therefore the overall problem should be managed in the context of large-

18 scale variations in hydrological fluxes expected to be induced by the climate change effects. In

19 addition, Loáiciga et al. [18] pointed out that variations in groundwater extraction (anthropogenic

20 fluxes) was the predominant driver of sea water intrusion in a model that simulated sea-level rise

21 scenarios for the City of Monterrey, California. Finally, it is very likely that rising heads might

22 increase evapo-transpiration fluxes. This could impact the overall hydrological budget resulting

23 in less recharge reaching the coastal area and this will hinder the self-reversal process.

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1   Therefore, site-specific management models for coastal areas should carefully integrate changes

2   in both natural and anthropogenic fluxes with various sea-level rise scenarios.

3

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]:

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

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:

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

1   Where, B is the thickness of the confined aquifer [L]. Equation (2A) is similar to (1A) and the

2   only difference is the $(1 + \delta)$ term. For seawater, the value of the dimensionless parameter $\delta =$

3   0.025, and hence the term $(1 + \delta) \sim 1$.   Therefore, when $B^2 K \sim B_o{}^2 K$ (or when aquifer

4   thicknesses are matched approximately) the X_T values predicted for confined and unconfined

5   flow systems would almost be the same.

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Acknowledgments

References

[1] USGS. Ground-Water Resources for the Future - Atlantic Coastal Zone. US Geological Survey Fact Sheet 085-00;2000.

[2] Lacombe PJ, Carleton GB. Saltwater intrusion into fresh ground-water supplies, southern Cape May County, New Jersey, 1890-1991.1992. pp. 287-98.

[3] WWD. Groundwater: the Invisible Resource. 1998. http://www.worldwaterday.org/wwday/1998/.

[4] Li H, Jiao JJ. Tide-induced seawater-groundwater circulation in a multi-layered coastal leaky aquifer system. Journal of Hydrology 2003;274(1-4):211-24.

[5] Michael HA, Mulligan AE, Harvey CF. Seasonal oscillations in water exchange between aquifers and the coastal ocean. Nature 2005;436(7054):1145-8.

[6] Robinson C, Li L, Prommer H. Tide-induced recirculation across the aquifer-ocean interface. Water Resour Res 2007;43(7):W07428. doi: 10.1029/2006wr005679

[7] Li L, Barry DA, Stagnitti F, Parlange JY. Submarine groundwater discharge and associated chemical input to a coastal sea. Water Resour Res 1999;35(11):3253-9. doi: 10.1029/1999wr900189

[8] Li H, Boufadel MC, Weaver JW. Tide-induced seawater-groundwater circulation in shallow beach aquifers. Journal of Hydrology 2008;352(1-2):211-24.

[9] Feseker T. Numerical studies on saltwater intrusion in a coastal aquifer in northwestern Germany. Hydrogeology Journal 2007;15(2):267-79.

[10] Leatherman SP. Coastal geomorphic response to sea level rise : Galveston Bay, Texas, in Barth M.C., Titus J.G. (eds) Greenhouse effect and sea level rise : a challenge for this generation. Reinhold, New York;1984. pp. 151-78.

[11] Meisler H, Leahy PP and Knobel LL. The effect of eustatic sea-level changes on saltwaterfreshwater relations in the northern Atlantic Coastal Plain: U.S. Geological Survey Water-Supply Paper 2255, 28 p.;1985.

[12] Navoy AS. Aquifer-estuary interaction and vulnerability of groundwater supplies to sea level rise-driven saltwater intrusion: Pennsylvania State University, USA 1991.

[13] Oude Essink GHP. Salt Water Intrusion in a Three-dimensional Groundwater System in The Netherlands: A Numerical Study. Transport in Porous Media 2001;43(1):137-58. doi: 10.1023/a:1010625913251

[14] Dausman A, Langevin C. Movement of the saltwater interface in the Surficial Aquifer System in response to hydrologic stresses and water-management practices, Broward County, Florida: USGS Scientific Investigations Report : SIR 2004-5256.2005.

[15] Melloul A, Collin M. Hydrogeological changes in coastal aquifers due to sea level rise. Ocean & Coastal Management 2006;49(5-6):281-97.

[16] Ranjan P, Kazama S, Sawamoto M. Effects of climate change on coastal fresh groundwater resources. Global Environmental Change 2006;16(4):388-99. doi: 10.1016/j.gloenvcha.2006.03.006

[17] Giambastiani BMS, Antonellini M, Oude Essink GHP, Stuurman RJ. Saltwater intrusion in the unconfined coastal aquifer of Ravenna (Italy): A numerical model. Journal of Hydrology 2007;340(1-2):91-104.

[18] Loáiciga HA, Pingel TJ, Garcia ES. Sea Water Intrusion by Sea-Level Rise: Scenarios for the 21st Century. Ground Water 2011:no-no. doi: 10.1111/j.1745-6584.2011.00800.x

[19] Werner AD, Simmons CT. Impact of Sea-Level Rise on Sea Water Intrusion in Coastal Aquifers. Ground Water 2009.47(2):197-204. doi: 10.1111/j.1745-6584.2008.00535.x.

[20] Webb MD, Howard KWF. Modeling the Transient Response of Saline Intrusion to Rising Sea-Levels. Ground Water 2010. doi: 10.1111/j.1745-6584.2010.00758.x

[21] IPCC. Climate change 2007: Impacts, adaptation and vulnerability. in: ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson, (Eds.). Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press Cambridge;2007.

[22] Vermeer M, Rahmstorf S. Global sea level linked to global temperature. Proc Natl Acad Sci 2009.106(51):21527-32. doi: 10.1073/pnas.0907765106

[23] Cheng AHD, Halhal D, Naji A, Ouazar D. Pumping optimization in saltwater-intruded coastal aquifers. Water Resources Research 2000;36(8):2155-65.

[24] Fetter CW. Applied Hydrogeology. Prentice Hall, N.J., 2001.

[25] Strack ODL. A single-potential solution for regional interface problems in coastal aquifers. Water Resources Research 1976;12(6):1165-74.

[26] Mantoglou A. Pumping management of coastal aquifers using analytical models of saltwater intrusion. Water Resources Research 2003;39(12):1335.

[27] Custodio E, Bruggeman GA. Groundwater problems in coastal areas. Studies and reports in hydrology 45. UNESCO, Paris;1987.

[28] Blanchon P, Eisenhauer A, Fietzke J, Liebetrau V. Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. Nature 2009;458(7240):881-4.

[29] Langevin C, Shoemaker WB, Guo W. Modflow-2000, The USGS Geological Survey modular ground-water model – documentation of the Seawat-2000 version with the variable density flow process (VDF) and the integrated MT3DMS transport process (IMT). US Geological Survey;2003.

[30] Henry HR. Effects of dispersion on salt encroachment in coastal aquifers. US Geological Survey Water-Supply Paper;1964. pp. C71-C84.

[31] Simpson MJ, Clement TP. Improving the worthiness of the Henry problem as a benchmark for density-dependent groundwater flow models. Water Resour Res 2004;40(1):W01504. doi: 10.1029/2003wr002199

[32] Goswami RR, Clement TP. Laboratory-scale investigation of saltwater intrusion dynamics. Water Resources Research 2007.43(4). doi: 10.1029/2006WR005151.

[33] Abarca E, Clement TP. A novel approach for characterizing the mixing zone of a saltwater wedge. Geophys Res Lett 2009;36(6):L06402. doi: 10.1029/2008gl036995

[34] McCarthy JJ. Reflections On: Our Planet and Its Life, Origins, and Futures. Science 2009.326(5960):1646. doi: 10.1126/science.1184937.

[35] Anderson J, Milliken K, Wallace D, Rodriguez A, Simms A. Coastal Impact Underestimated From Rapid Sea Level Rise. Eos Trans AGU 2010.91(23):205-6. doi: 10.1029/2010EO230001

[36] Abarca E, Carrera J, Sánchez-Vila X, Dentz M. Anisotropic dispersive Henry problem. Advances in Water Resources 2007;30(4):913-26.

[37] Abarca E, Carrera J, Sánchez-Vila X, Voss CI. Quasi-horizontal circulation cells in 3D seawater intrusion. Journal of Hydrology 2007;339(3-4):118-29.

1   **List of Figures**

Figure 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.
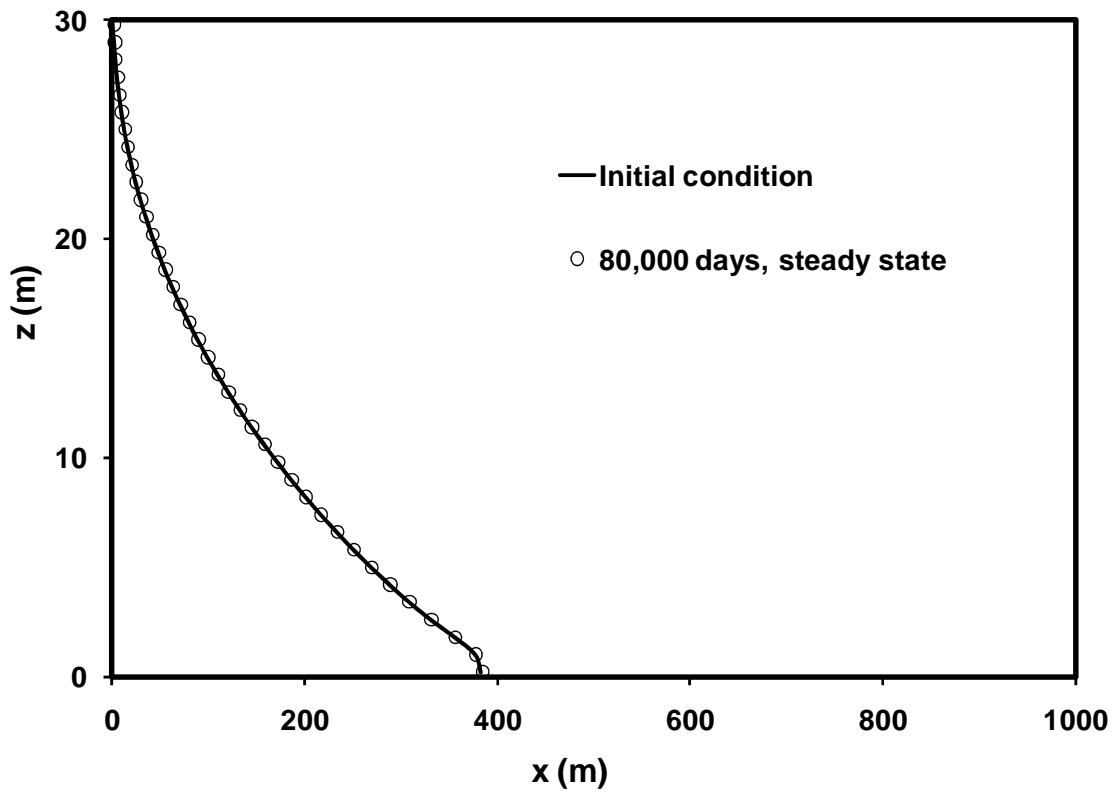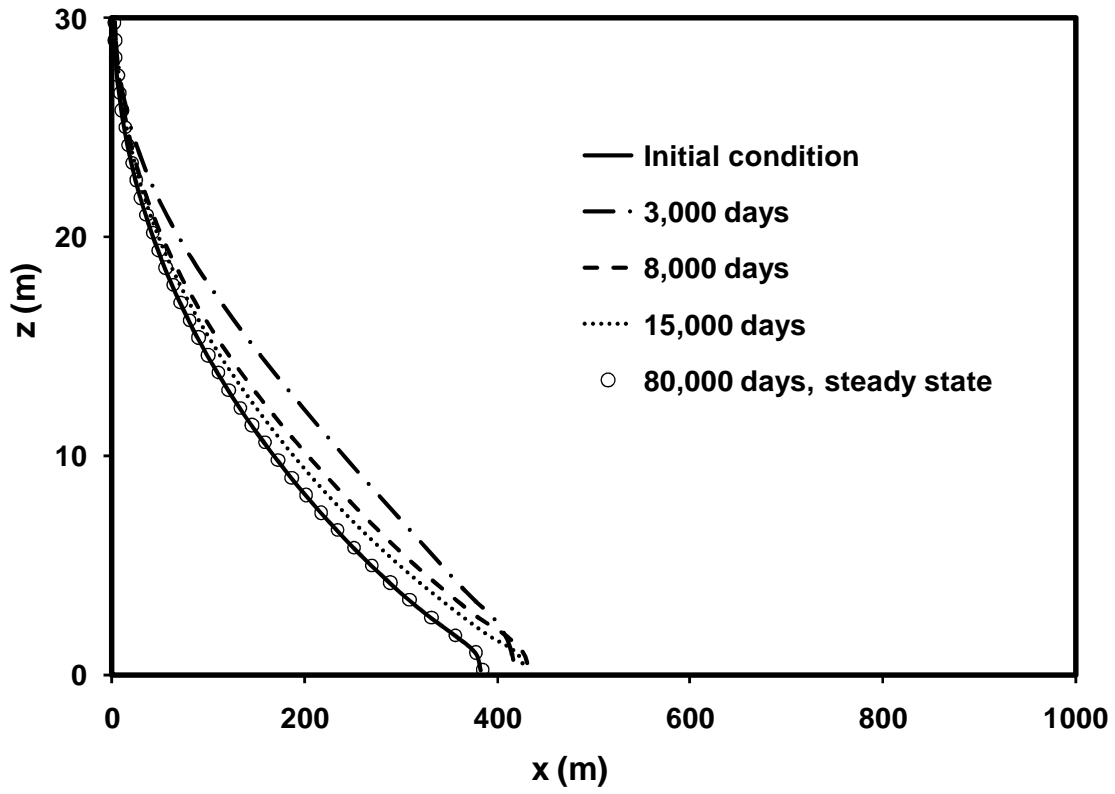
1
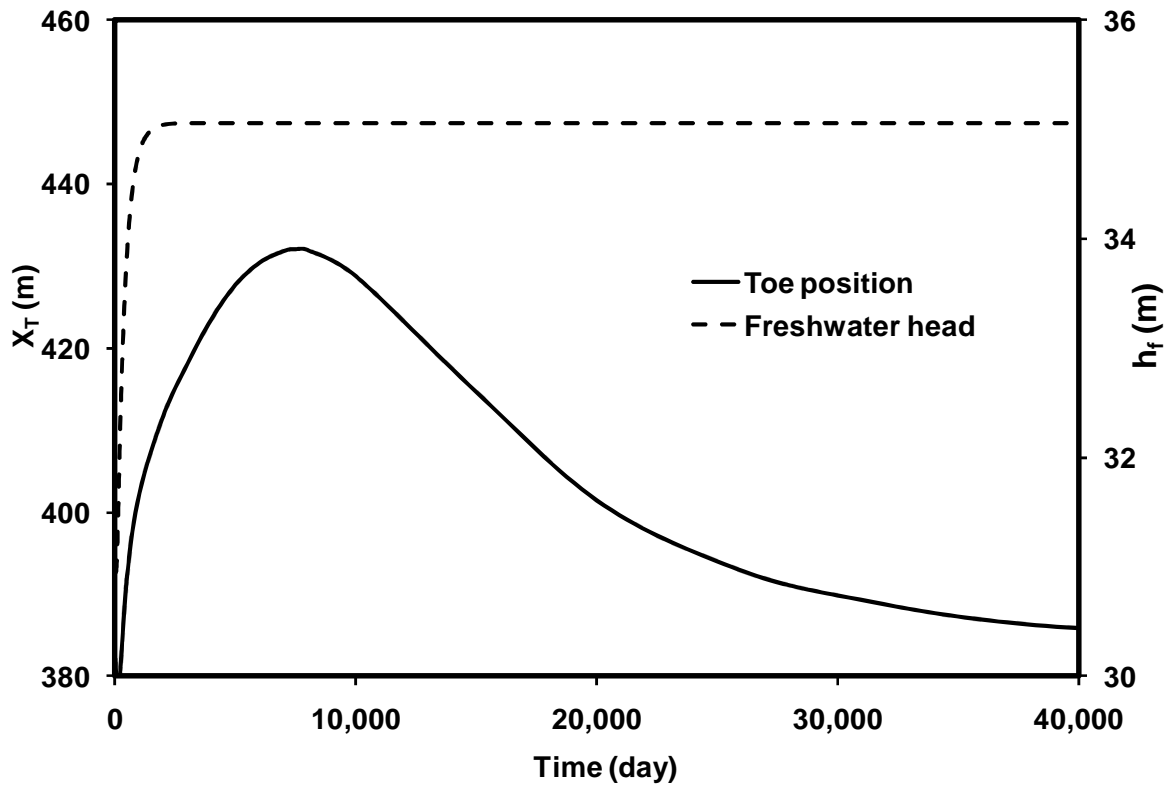2 Figure 2. Comparison of steady-state salt wedges predicted before and after the sea-level rise in the
3 confined system.
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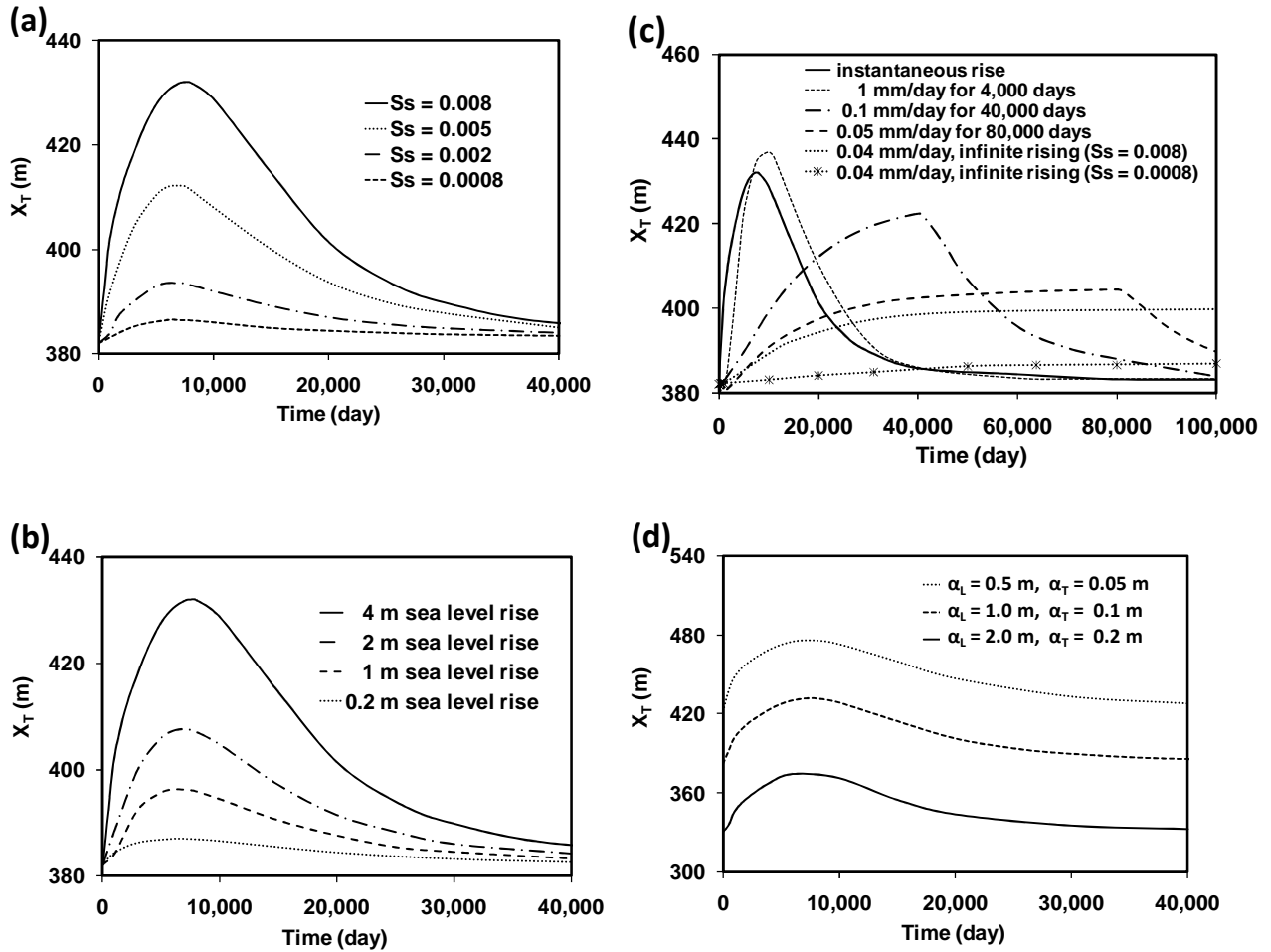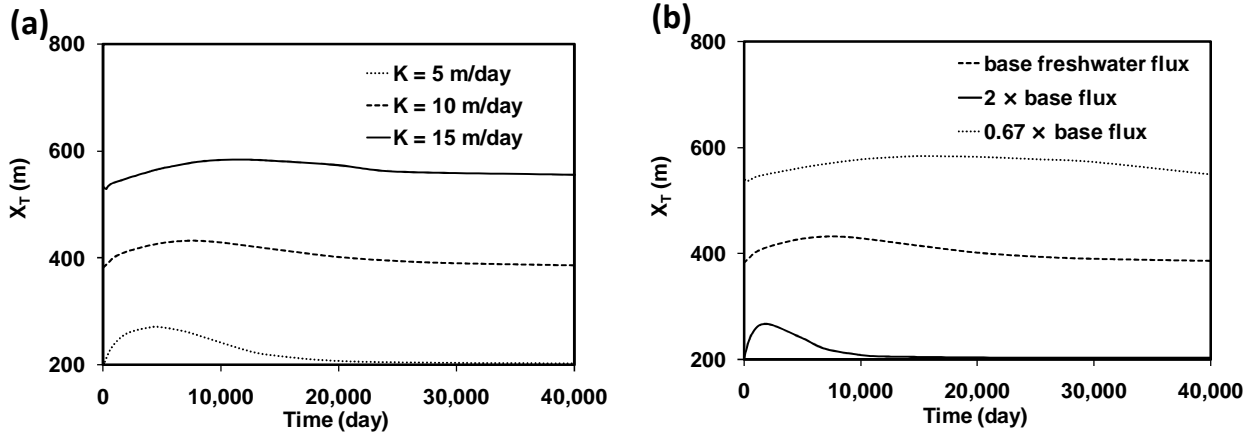2   Figure 3. Transient salt wedge profiles for the confined system.
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2   Figure 4. Transient variations in the toe position (X_T) and freshwater head (h_f) at the inland boundary.

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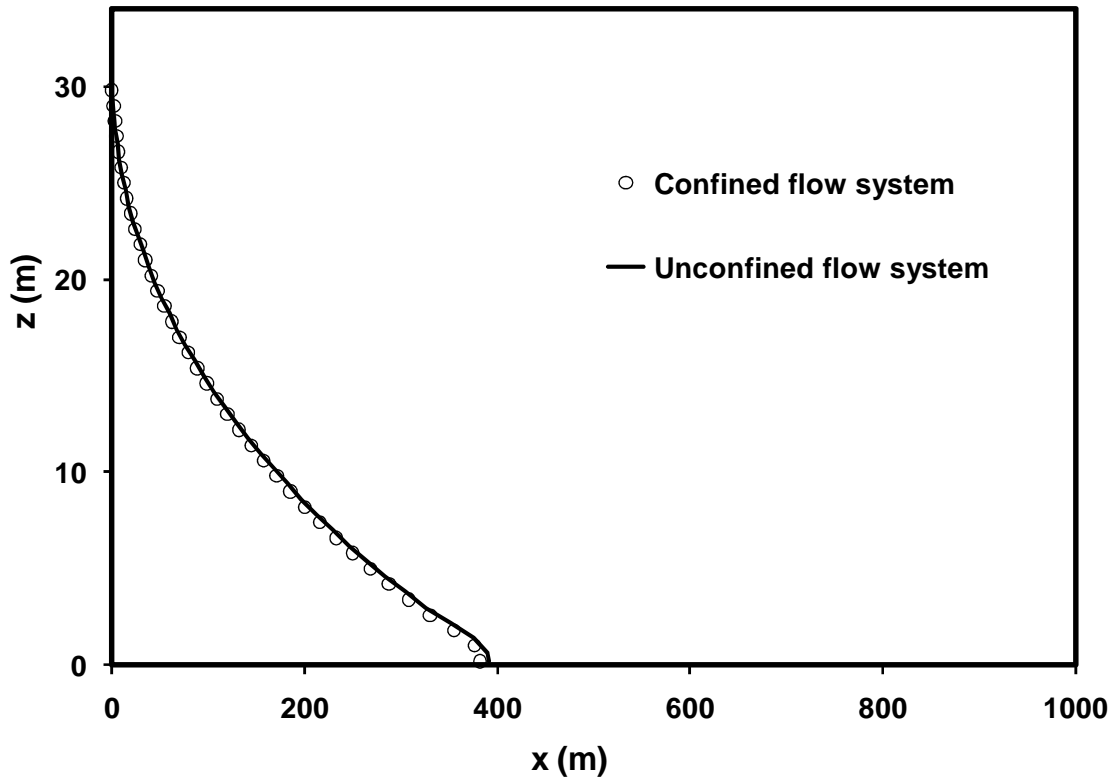
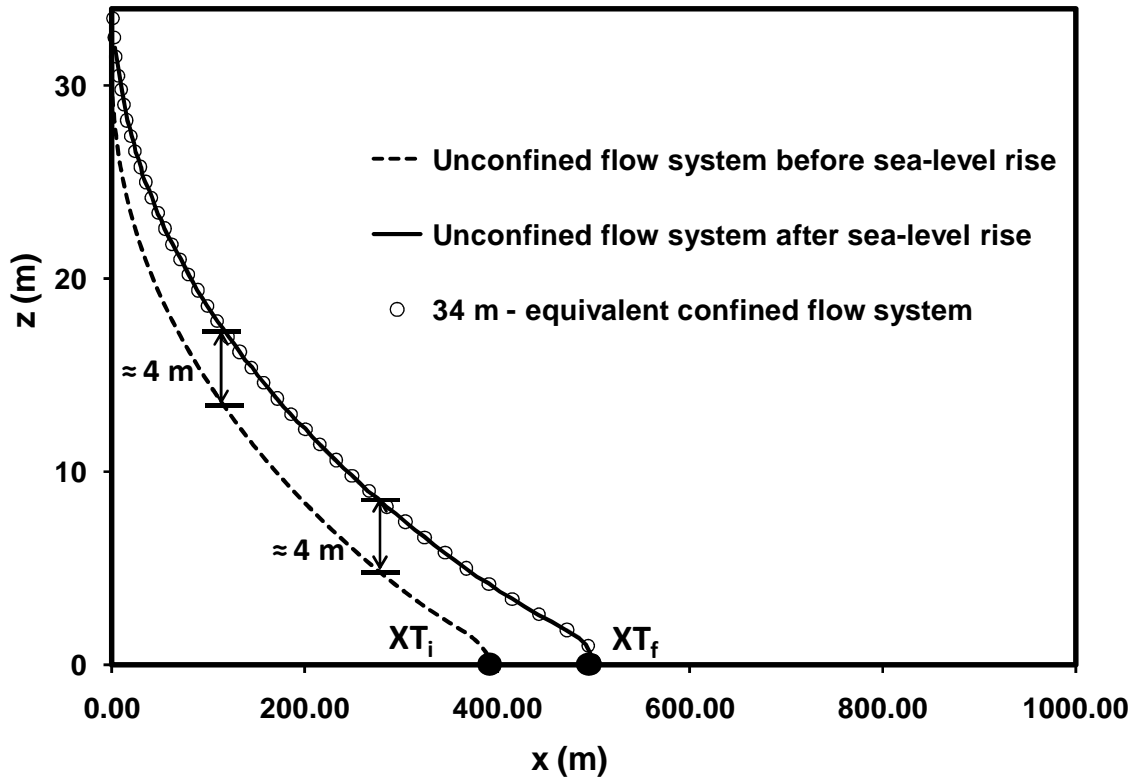Figure 6. Sensitivity of the toe position (X_T) to: (a) hydraulic conductivity and (b) freshwater flux.

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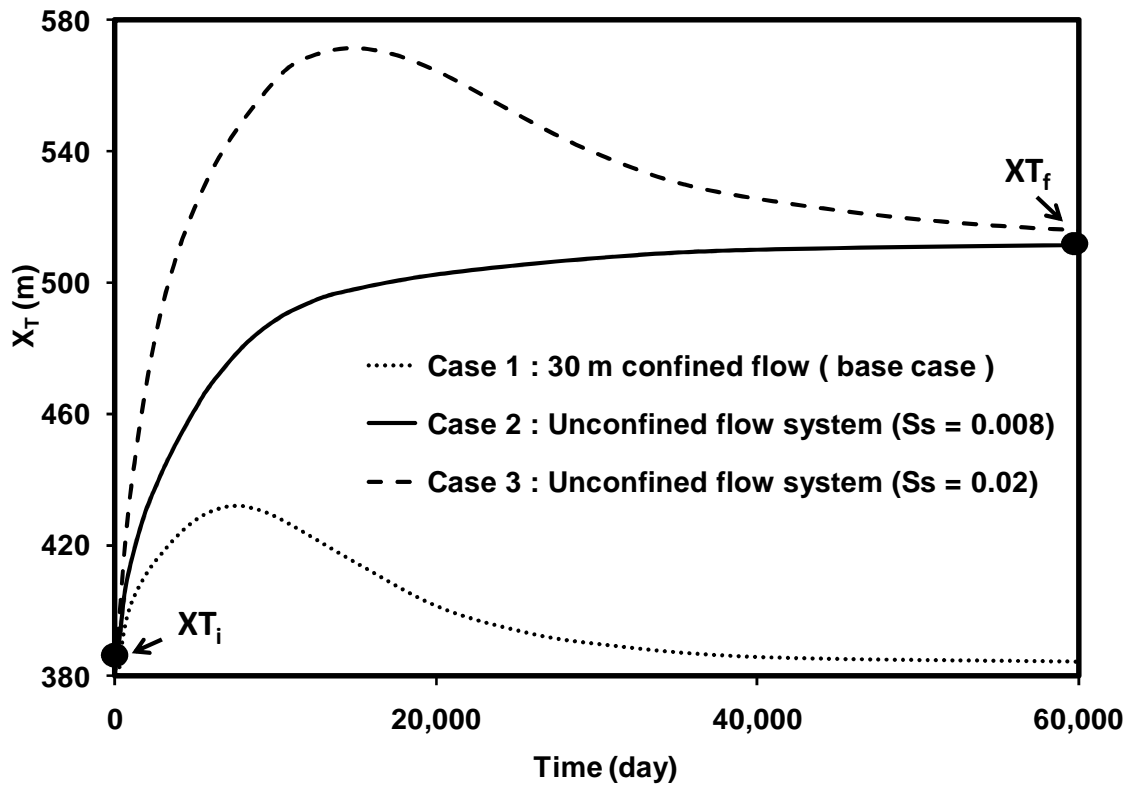3 the unconfined- and confined-flow systems.

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Figure 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.

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

1 **List of Tables**

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

3

1   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,	Ss	0.008 m^{-1}
Longitudinal dispersivity	α_L	1 m
Transverse dispersivity	α_T	0.1 m
Saltwater concentration	Cs	35 kg/m^3
Saltwater density	ρ_s	1,025 kg/m^3
Freshwater density	ρ_f	1,000 kg/m^3

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