Numerical investigation on seawater intrusion and water leakage in different types of stratified coastal aquifers

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Abstract

Prediction of seawater intrusion (SWI) will increase the proper planning for withdrawal of groundwater, and it will help the freshwater management in the future. Since heterogeneous aquifers are more widespread than homogeneous one, this study aims to use the density-dependent SEAWAT code to investigate the influence of different combinations of hydraulic conductivity (K) on SWI. The effects of numbers and arrangement of layers with different K are examined on (a) toe position, (b) freshwater–seawater mixing zone thickness (W_t) and (c) leakage from adjacent layers in a steady-state condition. For this purpose, numerous scenarios with different K were simulated and analyzed. The results of horizontally layered aquifers showed that the streamlines are broken on boundary of layers. It was observed that when K is decreased, especially at the middle layer, the refraction angle is increased and consequently W_t is increased. The W_t in vertically layered cases was less than horizontally layered aquifers because of less streamline breakage. Also, random arrangement of K directs the saline flow to higher permeability zones. Thus, the SWI extent in this type of aquifer was more tangible than other types. Because of the difference in hydraulic head at layer borders, the seepage rate significantly increases nearby toe position and the dominant direction is upward. However, in the steady-state condition, the type of flow did not differ significantly for boundary cells of layers at the vicinity of toe position.

Keywords Seawater intrusion · Hydraulic conductivity · Mixing zone thickness · Leakage

1 Introduction

Nowadays, coastal aquifers are endangered by seawater intrusion (SWI) environmental problem [1]. SWI is one of the major causes of groundwater quality degradation at coastal regions; even a small quantity of 2–3% seawater makes the groundwater inappropriate for drinking and agricultural usages [2]. Therefore, in order to tackle SWI problems, proper understanding of coastal aquifer systems and predicting their behavior under different scenarios of natural occurrences and human interventions is necessary [3, 4]. Prediction of future SWI in coastal aquifer is improved by simulating the processes utilizing numerical models [5]. Stratified aquifers are heterogeneous aquifers

in which different geological strata are placed on or beside each other. Similar to homogeneous aquifers, analytical solutions for SWI are continuously developed [6–12]. Their outputs were the prediction of the seawater–freshwater interface, and the effect of various factors on SWI is investigated in their studies [13, 14]. Schincariol and Schwartz [15] developed pioneer experimental studies in solute density-dependent transport into layered systems. They found that the pattern of carrying dissolved ions in the layers is very sensitive to hydraulic conductivity ($K:L/T$), and this type of heterogeneity will cause an increase in the amount of SWI. Dagan and Zeitoun [16] examined the effect of heterogeneity on the shape of the seawater–freshwater interface in horizontally layered aquifers

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with random distribution of hydraulic conductivity. They found that ignoring the stratification effects of aquifers causes uncertainty in predicting the toe position. They also stated that stratification has relatively less effect on the up-conning shape beneath the withdrawing wells in symmetric conditions. Similar results were achieved by Held et al. [17]. They realized that development of geometry and position of toe depends on the degree of heterogeneity of the aquifer. The results of the study by Cameo [18] showed that the heterogeneity causes the toe receding, while it increases both the width and slope of the mixing zone. Kerrou and Renard [19] reported that the results of the two-dimensional studies cannot be generalized to heterogeneous three-dimensional systems. Therefore, the observations made by Held et al. and Cameo were valid only for two-dimensional models [19].

Recently, studies have concentrated on different types of heterogeneity and their proper solutions [10, 20–23]. Shi et al. [24] examined the effect of layered coastal aquifer on SWI by using the analytical method developed by Strack and Ausk (2015) [21]. Their results indicated that in general the initial location and response distance of the interface toe were affected by aquifer stratification [24]. For stratified aquifers, Lu et al. [25] conducted a series of experiments and numerical simulations to investigate the effect of parameters involved in SWI. They examined the layer thickness effects, different K arrangements and dispersion coefficient on mixing zone thickness. The results showed that when a layer with low K overlies a layer with a relatively higher K , upward movement of diluted seawater happens and re-circulated seawater flow penetrates the upper layer. Thus, flow refraction occurs between the two layers, resulting in streamlined separation and a broad mixing zone in the low K layer. They proposed future researches to measure the thickness of mixing zone for other types of stratifications and with different combinations of K . In addition, the amount and type of leakage (freshwater or seawater) from one layer to another layer were not presented in their study. Regarding the leakage behavior in stratified aquifers, Mehdizadeh et al. [9] found that freshwater leakage around toe position tends to revolve around the wedge and then discharge into the sea. Mehdizadeh et al. [26] examined vertical leakage in horizontally layered coastal aquifers under the influence of sea level rise and showed the exchange rate of freshwater and seawater from layers boundary at transient condition.

An overview of the studies conducted on SWI in stratified coastal aquifers indicates the necessity of more detailed studies to be conducted on the subject. Study on freshwater and seawater streamlines inside the aquifers as well as the amount, type and direction of leakage from one layer to another layer would help significantly to understand the effect of heterogeneity on SWI. This study

aims to simulate SWI numerically for different scenarios of layered aquifer to investigate (1) mixing zone thickness, (2) toe position at each layer and (3) leakage from one layer to another layer in order to clarify the differences of SWI mechanisms in comparison with homogeneous cases.

2 Materials and methods

2.1 Characteristics of simulated aquifer

The geometry, fluid and porous media properties of the aquifer in this study are adapted from the aquifer presented in the study of Lu et al. [25]. The aquifer length was 500 m which was divided into two sections: a horizontal section below the seaward ($L_s=70$ m) and the horizontal distance of aquifer between the shoreline and landward boundary ($L_L=430$ m). The height of the model was 48 m. The ocean area and the aquifer were separated by coast slope of 0.1. The constant freshwater (H_f/L) and seawater (H_s/L) heads were 46.2 m and 45 m, respectively (Fig. 1).

Aquifers with different layers were defined. In horizontally layered aquifers, two and three layers of soil with different K were placed on each other. In vertically layered aquifers, three layers of soil were placed beside each other, and in aquifers with both horizontal and vertical layers (named as mesh-type aquifer), a random distribution of different K was applied to each layer. In aquifers with three horizontal layers, the thickness of each layer was 15 m except the top layer. The top elevation of the upper layer corresponds to groundwater level. The same approach is applied in aquifers with two layers where the thickness of the underlying layer was 22.5 m and the thickness of the upper layer depends on groundwater level. In aquifers with three vertical layers, due to total length of the aquifer, the width of two layers which were closer to land was considered 167 m and the third layer width equals 166 m. In the mesh-type aquifers, the dimensions of each cell with the same K were considered 167 (length) $\times$ 15 (height) m. (The top elevation of the topmost layer matches groundwater level.)

2.2 Scenarios description

Nineteen scenarios with different K arrangements were introduced for SWI modeling according to Table 1. These scenarios were defined based on differences in direction of layers, number of layers and differences in the magnitude and contrast of K . It is noteworthy to mention that in reality there is no aquifer with vertical layering of different soil types similar to cases simulated in this study; however, this composition will help us understand how freshwater and seawater move into non-horizontally

Fig. 1 Boundary conditions and dimensions of stratified coastal aquifers, **a** horizontally layered, **b** vertically layered and **c** mesh-type aquifer

Table 1 K values in different scenarios of stratified aquifer. (For horizontally layered aquifers, indices 1 to 3, respectively, represent top, middle and bottom layers. For vertically layered aquifers, the indices 1 to 3, respectively, represent seaside, middle and landside layers)

Scenarios	$K1$ (ms^{-1})	$K2$ (ms^{-1})	$K3$ (ms^{-1})	$K1:K2:K3$
<i>Horizontally layered</i>				
Sc-1	10^{-4}	10^{-4}	10^{-4}	1:1:1
Sc-2	10^{-4}	10^{-5}	10^{-4}	10:1:10
Sc-3	10^{-4}	10^{-3}	10^{-4}	1:10:1
Sc-4	10^{-3}	10^{-3}	10^{-3}	1:1:1
Sc-5	10^{-3}	10^{-4}	10^{-3}	10:1:10
Sc-6	10^{-3}	10^{-2}	10^{-3}	1:10:1
Sc-7	10^{-4}	10^{-6}	10^{-4}	100:1:100
Sc-8	10^{-4}	10^{-7}	10^{-4}	1000:1:1000
Sc-9	10^{-5}	10^{-4}	10^{-3}	1:10:100
Sc-10	10^{-3}	10^{-4}	10^{-5}	100:10:1
Sc-11	10^{-5}	10^{-3}	–	1:100
Sc-12	10^{-3}	10^{-5}	–	100:1
<i>Vertically layered</i>				
Sc-13	10^{-5}	10^{-4}	10^{-3}	1:10:100
Sc-14	10^{-3}	10^{-4}	10^{-5}	100:10:1
Sc-15	10^{-5}	10^{-3}	10^{-5}	1:100:1
Sc-16	10^{-3}	10^{-5}	10^{-3}	100:1:100
<i>Mesh-type aquifer</i>				
Sc-17	See Fig. 5			
Sc-18				
Sc-19				

stratified aquifers. This hypothesis is also true for mesh-type aquifers (i.e. Sc-17 to Sc-19). These scenarios are defined to explain how freshwater and seawater move

into that part of the soil where the permeability is different from the surrounding areas (similar to what happens in heterogeneous aquifers).

2.3 Numerical implementations

SEAWAT modeling code is developed for simulating density-dependent flow and solute transport in saturated porous media [27]. It has been used successfully by many researchers in recent years [9, 28, 29]. The flow equation (i.e. Eq. 1) is solved with finite-difference MODFLOW model, and solute transport equation (i.e. Eq. 2) is solved by MT3DMS model [30, 31]:

$$\nabla \cdot \left[\rho K \left(\nabla h_f + \frac{\rho - \rho_f}{\rho_f} \nabla z \right) \right] = \rho S_s \frac{\partial h_f}{\partial t} + n \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} \quad (1)$$

$$n \frac{\partial C}{\partial t} + \nabla \cdot (n D \nabla C) - \nabla \cdot (v C) = 0.0 \quad (2)$$

where ρ is the fluid density [ML^{-3}]; ρ_f is the freshwater density [ML^{-3}]; K is the hydraulic conductivity tensor of material saturated with the reference fluid; h_f [L] is the equivalent freshwater head; S_s is the specific storage coefficient [L^{-1}]; t is the time [T]; C is salt concentration [ML^{-3}]; n is porosity [$-$]; D is the hydrodynamic dispersion coefficient tensor [$L^2 T^{-1}$]; and v [LT^{-1}] is the water velocity. SEAWAT couples the flow and transport equations through fluid density term by a simple linear function (Eq. 3):

$$\rho = \rho_f + \varepsilon C \quad (3)$$

where ε is a dimensionless constant, and it is equal to 0.7143 for salt concentrations which range from zero to

Table 2 Parameters of soil and fluid for simulated aquifer

Parameter	Value	Unit
Effective porosity* (n)	0.4	
Freshwater density (pf)	1000	kg/m ³
Seawater density (ps)	1025	kg/m ³
Seawater concentration (C ₀)	35	kg/m ³
Longitudinal dispersivity (α _L)	1	m
Transverse dispersivity (α _T)	0.1	m
Flow head convergence criterion	10 ⁻⁴	m
Concentration convergence criterion	10 ⁻⁵	kg/m ³

that of seawater [32]. SEAWAT requires input data and boundary conditions provided in Table 2.

Many studies have shown that the grid size is a key factor that controls the accuracy of flow simulation [33, 34]. In this study, the grid size is selected based on the common criteria of Peclet number (P_e). According to Eq. 4, it is recommended that the grid size should be selected in a way that the P_e becomes less than 4 [35]:

$$Pe = \frac{V \Delta L}{D_m + \alpha_L V} \approx \frac{\Delta L}{\alpha_L} \leq 4 \quad (4)$$

where ΔL [L] is the grid size and D_m [$L^2 T^{-1}$] is molecular diffusion that is considered zero at this study. The cell size as 1.0 m length (Δx) and 0.5 m height (Δz) satisfactorily produces P_e less than 4. To avoid numerical oscillations, Courant number is considered as 0.75 that is less than one recommended by Robinson et al. [36].

All the scenarios in this study are under steady-state condition. To ensure the adequacy of total simulation time when further SWI stops, the toe position in two consecutive times was checked and a difference less than 5% is considered as a criterion for sufficient time of steady-state condition. The total simulation time ranges from 220 years for cases where a low permeable layer is embedded to 140 years for scenarios with higher permeability. In all scenarios, the time step to solve the flow and transport equations was set to 10 days and 5 days, respectively. Note that the magnitude of K for cells that are sea representatives was considered a very large hypothetical amount (i.e. 10^5 m/s).

In previous studies, the area of mixing zone ($A_t; L^2$) was bounded by the zone between 0.1 and 0.9 normalized concentration contour lines (equal to 3.5 kg/m^3 and 31.5 kg/m^3 , respectively) [37, 38]. The thickness of mixing zone ($W_t; L$) is calculated using Eq. 2 by dividing the measured area to the length of the area ($L_t; L$). The length is the distance of $0.5 C_0$ contour line at top and bottom of aquifer [25]:

$$W_t = \frac{A_t}{L_t} \quad (5)$$

The thickness of mixing zone at each layer became dimensionless for better comparison by the following equation:

$$W^* = \frac{W_t}{W_{th}} \quad (6)$$

where W_{th} is the thickness of mixing zone of homogeneous aquifer. In mesh-type scenarios, the calculation of mixing zone thickness was practically impossible because of irregular SWI, and therefore, the area of mixing zone has been used. According to the following equation, this area becomes dimensionless by dividing it by the area of the mixing zone of homogeneous aquifer (i.e. A_{th}).

$$A^* = \frac{A_t}{A_{th}} \quad (7)$$

2.4 Quantification of leakage

The SWI at different layers in each scenario is dependent on the leakage of seawater or freshwater from one layer into adjacent layer. The leakage rate ($F; L^2/T$) was calculated by the distribution of flow velocity in the aquifer using Darcy's law and continuity equation. To calculate vertical leakage between the boundaries of two neighbor layers, the velocity component which is perpendicular to the edge of the layer should be multiplied by the area of the edge (i.e. $\Delta x \times 1$). The calculated values are verified by the fluxes value derived by SEAWAT. In addition, regarding the distribution of hydraulic head, the positive amount of flow rate refers to upward vertical leakage (from lower layers to upper layers) and the negative amount refers to downward flow direction. In vertically layered aquifers, the positive amount of F value refers to horizontal leakage toward the right-side layers and the negative amount indicates the direction of flow from each layer to left-side layer.

3 Results and discussion

3.1 SWI in horizontally layered aquifers

The SWI in horizontally layered aquifers is shown in Fig. 2. According to Fig. 2, seawater streamlines flowed from the right and top boundaries into the aquifer and then are expanded. As the aquifer is extended below the sea, the up-to-down direction is formed for seawater at upper levels and horizontally movement appears at deeper regions of salt wedge. Freshwater streamlines horizontally move and get closer to the mixing zone. In mixing zone, the seawater streamlines begin to circulate and eventually

Fig. 2 a–f, respectively, SWI in scenarios 1 to 6. White lines are the streamlines with arrows indicating the directions. Dashed lines indicate the interface between two layers

discharge into the sea. The circulation flow pattern is a natural phenomenon that occurs due to the density differences between freshwater and seawater [39].

For homogeneous scenario (Fig. 2a), it can be seen that due to density changes and dispersivity value, a uniform and narrow mixing zone is formed. In Sc-2 (Fig. 2b), the mixing zone of middle layer with lower K has wider W_t . This happens because the streamlines are broken when passing through the boundary of the lower layer to the middle layer due to lower K magnitude of middle layer. By

contrast, when the streamlines pass from the middle layer to the upper layer, they are once again broken. Compared to the homogeneous scenario, it is clearly visible that the W_t amount around the middle layer is increased. According to the refraction law that is known as tangent law, the streamlines of the first layer are broken after contacting the boundary of two layers and continue their way into the next layer. The rest of streamlines path depends on the contrast of K between two layers. The ratio of K is equal to ratio of the tangent of the angles between streamlines and

the line perpendicular to the boundary between the layers. The W_t of the middle layer in Fig. 2c (i.e. Sc-3) is smaller than W_t amount of Sc-2 because the streamlines penetrate from a layer with low K into a layer with high K , and in accordance with the refraction law, the W_t is expected to be lower.

Because of similar arrangement of K in Sc-4 to Sc-6 with Sc-1 to Sc-3, it can be seen that the magnitude of K had almost no meaningful effect on the mixing zone profile when the constant head boundary condition is applied at the present study. However scenarios with bigger K have slight wider W_t near the shoreline. Similar conclusion is achieved by Lu et al. [25].

Figure 3 shows the results of SWI for Sc-7 to Sc-12. In Sc-7 and Sc-8, the middle layer has significantly less permeability than the adjacent top and bottom layers. According to the refraction law, the streamlines in the middle layer are vertical. With regard to very low permeability of middle layer, the seawater did not flow into that layer. This evidence is clearer for Sc-8. According to Fig. 3b, because of low permeability of the middle layer, the brackish water at the bottom layer directly discharged into the sea from a fine window instead of moving to upper layers.

The comparison of Sc-9 and Sc-10 shows the importance of vertical leakage. Since the dominant seawater

Fig. 3 a–f, respectively, SWI in Sc-7 to Sc-12

movement direction is from upper layers to lower layers, huge seawater intruded from top higher K layer to lower one at Sc-10. That makes the intrusion to be more appreciable than Sc-9. Instead, the mixing zone is wider at Sc-9. This is due to the fact that more horizontally freshwater mixes with seawater and continuous flow refraction enhances. Same concept can be considered for two horizontally layered aquifers as depicted in Fig. 3e, f. Aquifers with low permeability at top layers have negligible top-to-down saline water leakage that leads to less SWI compared to cases with higher K at their upper zones.

It is observed that the streamlines near sea border and in mixing zone tend to oscillate. Since the finer cell sizes and smaller time steps almost have the same results, the numerical accuracy and modeling stability should be corrected. The continuous variation in density in mixing zone certainly affects the result and may lead to irregular development of streamlines. Moreover, seawater intrudes into the aquifer from vertical boundary and seabed simultaneously for the studied aquifer. These perpendicular directions of seawater flow path around the sea boundary will influence the streamline fluctuation. In region close to sea boundary, the effect of vertical movement of seawater that

is leaked from seabed is diminished as it reaches aquifer bed, and the seawater direction tends to be more horizontal along with less oscillation.

3.2 SWI in vertically layered aquifers

The results of SWI simulation for vertically layered aquifer of Sc-13 to Sc-16 are presented in Fig. 4. As Fig. 4a demonstrates, the flow has not penetrated into the middle layer and salt wedge toe stopped at the vicinity of layer border. The disinclination for more intrusion originated from independent behavior of seaside layer that has lower permeability with vertically preferred seawater movement. In Fig. 4b, the seawater rapidly occupies the seaside high K layer and then flows to other layers. The vertical seawater flow from seabed plays an important role in SWI into seaside layer. In Fig. 4c, the placement of a relatively permeable layer between two layers of lower permeability caused a rapid transfer of freshwater and seawater into the middle layer and made the mixing zone to shape horizontally because of horizontal streamlines. When an aquitard is placed between two permeable layers, as Fig. 4d shows, the flow will not intrude into the landside layer.

Fig. 4 a–d, respectively, SWI in Sc-13 to Sc-16

In vertically layered aquifers, the layer that is proximate to the sea border has an important role in transferring the salinity as this is the only layer at which seawater can intrude into the aquifer, whereas, in horizontally layered aquifer, the salinity can flow into all layers simultaneously.

3.3 SWI in mesh-type layered aquifers

In order to comply more with a heterogeneous aquifer in nature, three scenarios 17, 18 and 19 with a mesh of different K magnitudes are defined, and the results are shown in Fig. 5. The numbers written inside each cell are the ratio of cell K to base K of 10^{-4} m/s. The irregular form of streamlines is more obvious in this case due to variation in K magnitude in each cell. Thus, the dominant streams of flow are depicted only in Fig. 5. It is observed that random arrangement of K causes seawater to dominantly flow to higher K cells, and despite the other horizontally or vertically layered cases, the salt wedge could reach landside boundary.

3.4 Mixing zone thickness

Figure 6 shows the dimensionless W^* value for horizontally layered scenarios. As it is observed, middle

layer permeability reduction leads to the production of a wider mixing zone. Thus, Sc-7 has the greatest W^* amount. However, due to the very low permeability of the middle layer in Sc-8 and the lack of SWI to this layer, the conclusion is excluded for this scenario. Furthermore, according to the refraction law, in Sc-3 and Sc-6 the W^* in the upper layer is greater than other layers. In Sc-6 due to the greater K magnitude, the W^* is bigger than the Sc-3 at top layers.

In vertically layered aquifer of Sc-13, the mixing zone exists only in seaside layer and the W^* is less than 1.0. The W^* gets its greatest value in middle layer of Sc-15 where the layer has the highest permeability. Unlike horizontally layered aquifer, it is observed that in vertically layered aquifer, the mixing zone in layers with higher K is thicker than the lower K layers but vertically layered aquifer produced narrower mixing zone compared to horizontally layered cases (Fig. 7).

The dimensionless area of mixing zone (A^*) for Sc-17, Sc-18 and Sc-19 was, respectively, 11.3, 7.4 and 9.3. All the three scenarios had noticeable bigger mixing zone area than the homogeneous case. In these scenarios, seawater first intruded into higher K cells preferably at lower layers, so Sc-18 seems more stable than other scenarios with less mixing area [34].

Fig. 5 a–c, respectively, SWI in Sc-17 to Sc-19

Fig. 6 Dimensionless W^* parameter for all horizontally layered scenarios

Fig. 7 Dimensionless W^* parameter for all vertically layered scenarios

3.5 Toe position in different scenarios

According to Fig. 8, the amount of toe position (X_t/L ; which is the intersection position of $0.5 C_0$ salinity contour line) and aquifer bed in the homogeneous scenario is more than the other horizontally layered cases [40, 41]. By comparing the scenarios, it can be concluded that as the permeability of middle layer decreases to a lower amount than the two adjacent layers, the SWI reduces. This reduction was evident in Sc-8 and caused more reduction in salt wedge toe compared to homogeneous case. Low K of middle layer causes lower transfer rate of salinity due to the reduced transmissivity [22].

So, the increase in permeability is responsible for the increase in the degree of movement of the iso-contours of the seawater wedge. Similar conclusion is achieved by Hussain and Javadi [42].

In vertically layered aquifers with high permeability of seaside and middle layers, the amount of SWI is significant and X_t is even more than that in horizontally layered cases. The high K of seaside layer increases the transmissivity value and has caused the faster movement of seawater, making the salt wedge to drive forward to the neighbor layers. In Sc-17 to Sc-19 with random layers of different K values, as mentioned in previous parts, the seawater reached the land boundary (Fig. 9).

3.6 Vertical leakage of horizontally layered aquifer

For better clarification, the results of Sc-3, Sc-6, Sc-8 and Sc-12 that have more distinct different water types (i.e. freshwater or seawater) in border of layers are only presented in Fig. 10. Right-side graphs refer to leakage exchange of lower and middle layers, and left-side graphs indicate leakage exchange of the middle and upper layer. In order to compare the type of leakage (seawater or

Fig. 10 Leakage rate and concentration in **a, b** Sc-3, **c, d** Sc-6, **e, f** Sc-8 and **g** Sc-12. The dark solid lines represent leakage amount, the dashed red lines represent the concentration of bottommost upper layer cells and the dotted red lines represent the concentration of topmost lower layer cells

freshwater), the concentration amount at each layer border is also provided in Fig. 10.

Fig. 8 Toe position magnitude for all layers of horizontally layered scenarios. (Distance is measured from vertical sea boundary)

Fig. 9 Toe position value for Sc-13 to Sc-19

Fig. 11 Head values at the boundary of middle and lower layers of Sc-3

For almost all scenarios, the leakage rate abruptly increases around the toe position of each layer. According to Darcy's law, the leakage rate is directly related to hydraulic head difference on both sides of the layers border. As an example, the heads value for the cells at the border of bottom and middle layers of Sc-3 is depicted in Fig. 11. As it illustrates, the variation in terms of fluid type on both sides of the border close to toe position has caused differences in density and consequently makes the hydraulic head difference. Thus, the amount of leakage has been increased in that area. In addition, the dominant direction of leakage is from lower layers to upper layers. This is consistent with other findings of this study, indicating the necessity of freshwater and seawater discharging into the sea. The results also indicate that under steady-state condition, the amount of vertical leakage in most horizontally layered scenarios is negligible. This has a direct connection with the permeability of the middle layer. By increasing the K of this layer, according to Darcy's law, the leakage extent would increase. Mehdizadeh et al. [9] stated that the upward freshwater leakage, when faced the upper layer salt wedge, tends to revolve around it instead of mixing and then discharge into the sea. This behavior causes the differences in water type at each layer border that is more sensible when an aquitard is placed between two permeable layers. At this study, unlike the previous studies, the water type was almost similar to adjacent layer border probably because of steady-state condition.

3.7 Horizontal leakage of vertically layered aquifers

The horizontal leakage of Sc-14, Sc-15 and Sc-16 is presented in Fig. 12. Right-side graphs refer to leakage exchange of seaside and middle layers, and the left-side graphs indicate the leakage exchange of the middle layer and landside layer. Similar to horizontally layered aquifers, wherever the difference in fluid type was considerable on

both sides of layer border (generally near the toe position), the leakage amount is raised. Further, the dominant direction of leakage is in accordance with the movement of freshwater from landside layers toward the layers near the sea. By increasing the K of middle layer, the leakage has increased according to Darcy's law.

4 Conclusion

This study has investigated the effect of layering at coastal aquifers on seawater intrusion characteristics including mixing zone thickness, salt wedge toe position and leakage rate exchange between layers. A large-scale layered aquifer is selected, and various scenarios are defined by changing the magnitude and arrangement of hydraulic conductivity. The seawater intrusion is simulated by dispersive SEAWAT model. The summary of the results is as follows:

(1) In horizontally layered aquifers, when a low permeable layer overlays a higher permeable layer, the thickness of mixing zone in less permeable layer gets broader because the streamlines cross the border of layers and break due to lower hydraulic conductivity of the upper layer and get closer to the layer interface. In general, compared with homogeneous aquifers, the aquifers with horizontal layers have a thicker mixing zone, especially in the middle layer. (2) The hydraulic conductivity of the middle layer plays an important role in transferring water from the borders. In aquifer with three horizontal layers, when the hydraulic conductivity of the upper and lower layers is higher than the middle one, the aquifer will have a significant vertical leakage. This rate will be reduced when the permeability of the intermediate layer is reduced. It was observed that near the salt wedge toe of each layer, the leakage rate suddenly increases. This is due to the difference in fluid density of water type on both sides of layer interface. That influences directly the hydraulic head of the mentioned regions. (3) In the vertically layered aquifers, according to the lower probability of streamline breakage along the layer border, the thickness of the mixing zone is less than the horizontally layered cases. Horizontal leakage rate at these types of aquifers depends strongly on the permeability of the middle layer, and it increases for cases with higher permeable middle layer. (4) In aquifers with combination of horizontal and vertical layers with random distribution of hydraulic conductivity, it is shown that seawater flows in areas with higher permeability. Significant intrusion occurs in these cases, and the erratic movement of seawater will be produced that substantially increases the transition zone area. We believe further investigation is needed for leakage behavior at transient condition where fluid type may differ significantly around each layer border.

Fig. 12 Leakage rate and concentration in **a, b** Sc-14, **c, d** Sc-15 and **e** Sc-16. The dark solid lines represent leakage amount, the dashed red lines represent the salt concentration on left layer and the dotted lines represent the concentration of right layer

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest

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