Saline groundwater modelling

Submitted to:

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Submitted by:

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Date: 15th July

Vertical interface between fresh and saline groundwater

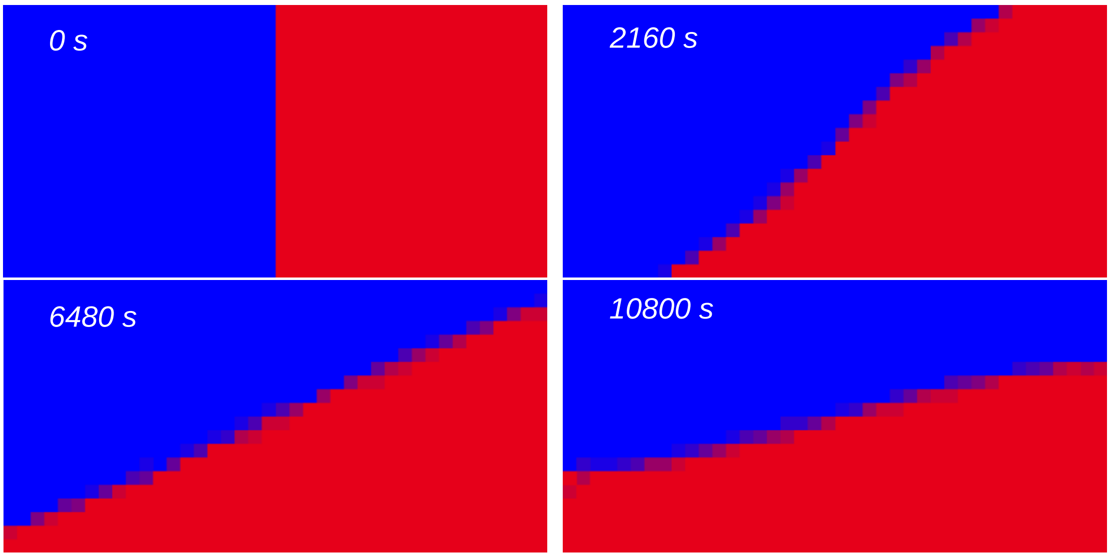
Introduction

A hypothetical problem: a vertical fresh-saline interface in a homogeneous aquifer with the following geometry: horizontal L=1.0 m by vertical D=0.5 m. Interface approximation is simulated, which means: Dmol=0 m2/s, aL=aTH=aTV= 0 m en Rd=1 (so no retardation). The other soil parameters are: hydraulic conductivity k=10-3 m/s and porosity n_e=0.1.

Parameters			
Layers	20	K_{hor}	10^{-3}m/d
Rows	1	T	$2.5*10^{-5}$m^2/s
Columns	40	Anisotropy K_{hor}/K_{ver}	1
Δx	0.025m	n_e	0.1
Δy	1m	α_L	0m
Δz	0.025m	α_T	0m
Stress periods	15		
Initial concentration	0 and 35000mg/l		
buoyancy	0.025		

Exercise 001:

Check the concentration and the flow face results and explain what is going on.



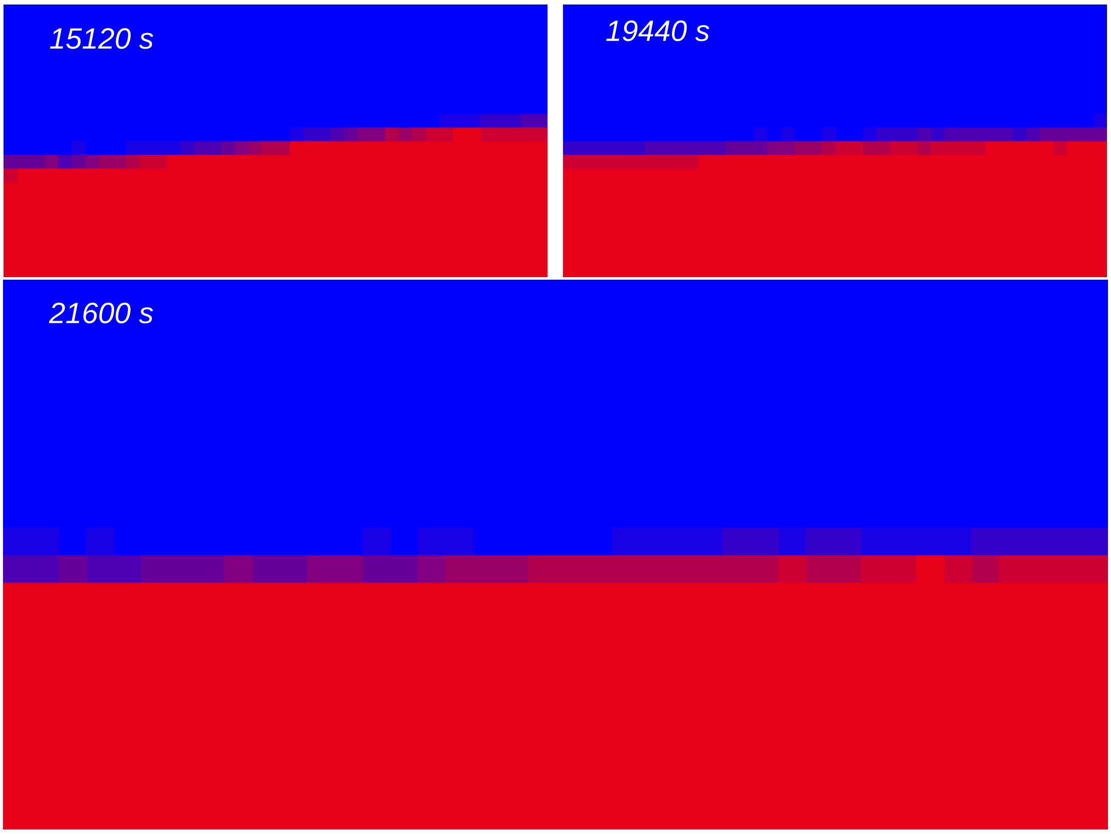
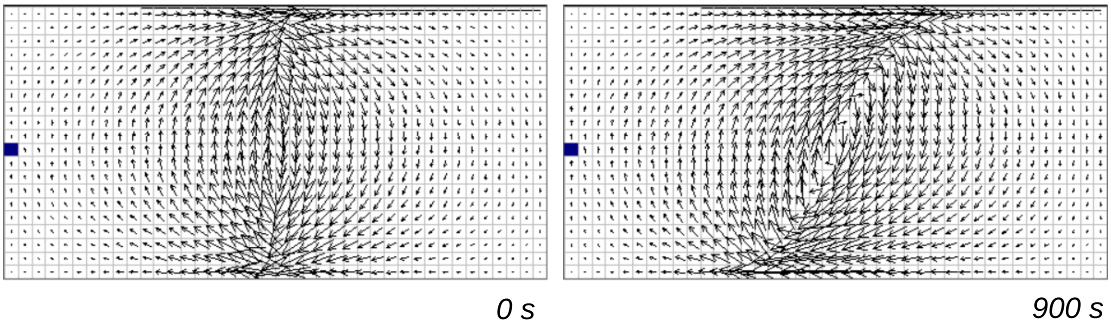


Figure 1. Evolution of the interface between fresh and saline groundwater.

The process of interface moving is presented in Figure 1. This is simulated by MOC solver of advection without dispersion simulating in PMWIN. In this exercise, the initial concentration condition is that the right part is saltwater with high density, and the left part is freshwater with low density. Due to the difference in density, saline groundwater in the right part will follow underneath freshwater in the left part. In the beginning, because of the high-density gradient, the velocity of the interface is large. With time passing, the interface between saline and freshwater will move to a horizontal interface from the initial vertical position. And the flow face figure is shown in Figure 2 below. This figure indicates that the velocity of the interface is reducing with the process going on, and the velocity is zero at the end of this process, which is also called as a steady-state.



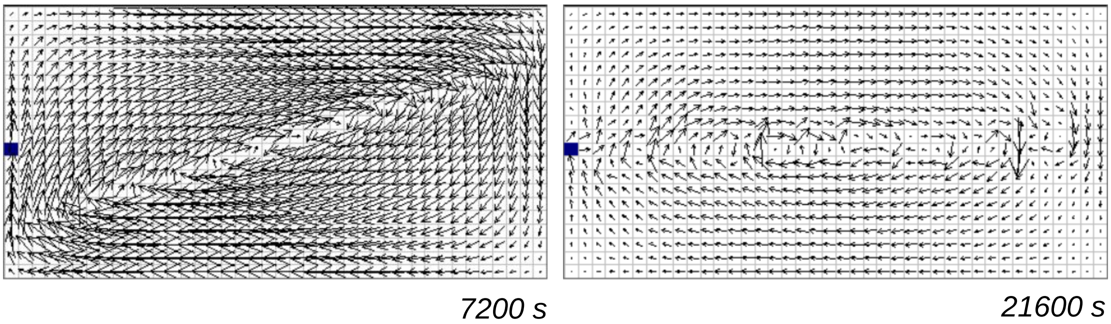


Figure 2. Velocity face of the interface between fresh and saline groundwater.

Why do cells exist with a concentration not equal to fresh or saline groundwater? Why does a large number of these cells disappear as a function of time?

The cells with a concentration not equal to fresh or saline groundwater are the area of mixing. The main reason for producing this dispersion area is mixing. Because of the density difference between fresh and saline water, mixing will occur in the interface area between them. And another reason comes from numerical solution. Numerical dispersion causes more mixing and error than analytical solution. For sure, even using analytical solution, these cells exist because of the mixing process. The brackish water is common between salt and freshwater.

As a function of time, these cells disappear because the state is trending for steady-state. With the velocity of the interface decreasing, the mixing process decreases. And after arriving steady state, due to density difference, saltwater and freshwater will separate again.

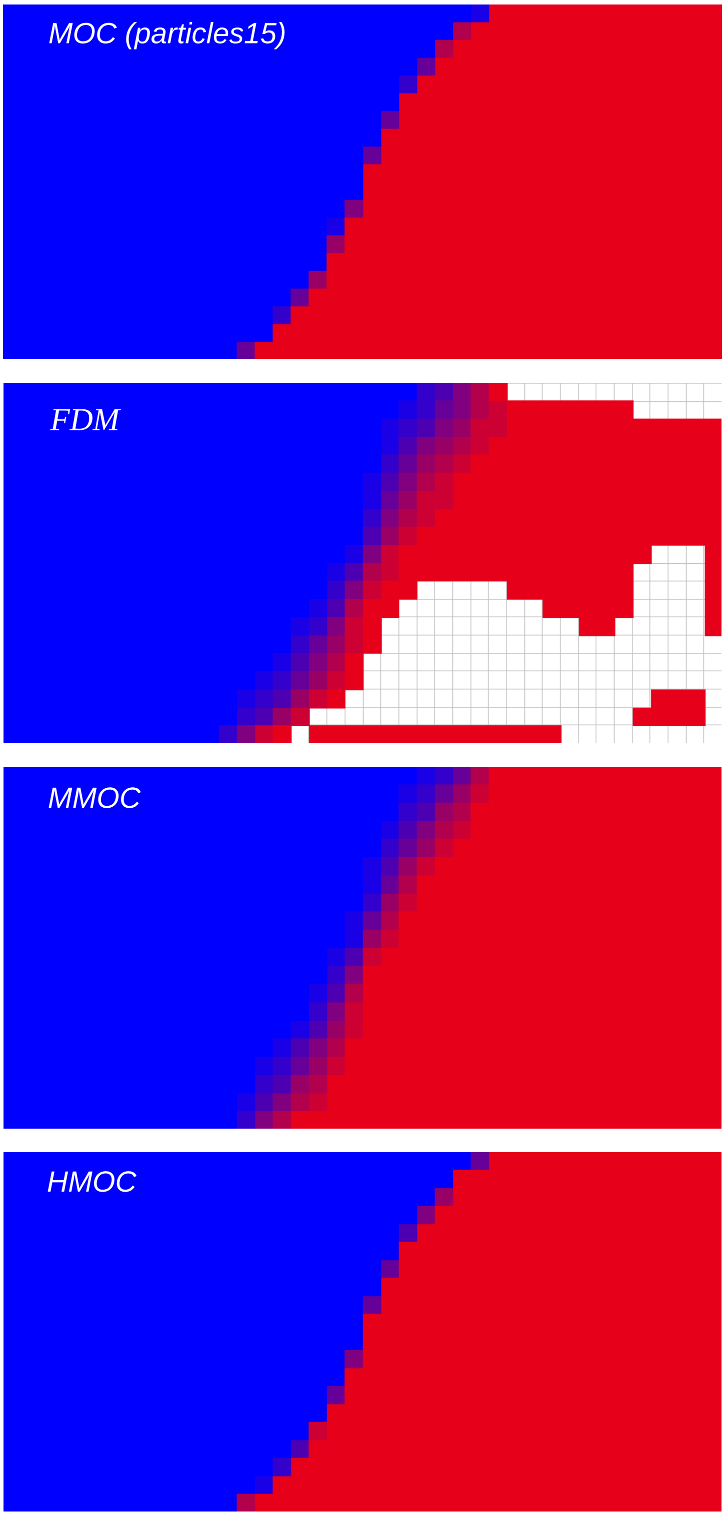
Is the steady-state time reached after 0.25 day (21600sec), based on the concentration distribution?

Yes, it is steady state after 0.25 days. As Figures 1 and 2 shown, the interface between salt and freshwater is almost horizontal, and the velocity of particles is close to zero. Actually, the trend of this process between two different density liquid in the aquifer is to arrive at the horizontal steady state.

Exercise 002:

On the best solute solver to reproduce the SEAWAT result.

Figure 3 below shows the different 900s concentration distributions from simulating advection by different solvers. As a result, MOC and HMOC are best solvers to produce SEAWAT results with relatively reasonable concentration distribution and velocity rates. For MMOC method, it is obvious that much more numerical dispersion occurs near the interface. FDM method leads to too much overshooting area, which is over one and presented by white cells in the below figure, and also more numerical dispersion. ULTIMATE solver is the same as FDM, too much overshooting and numerical dispersion.


MOC (particles15)
FDM
MMOC
HMOC

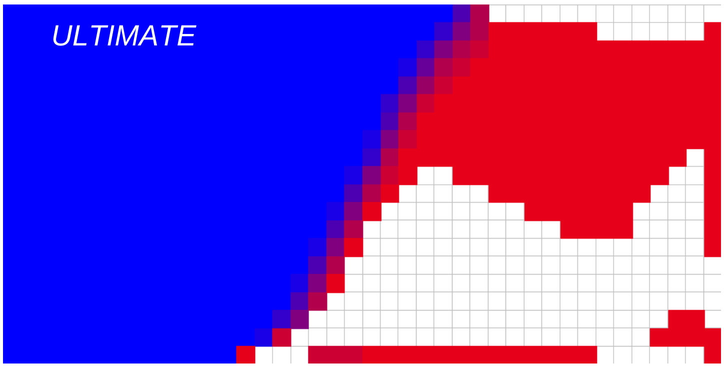
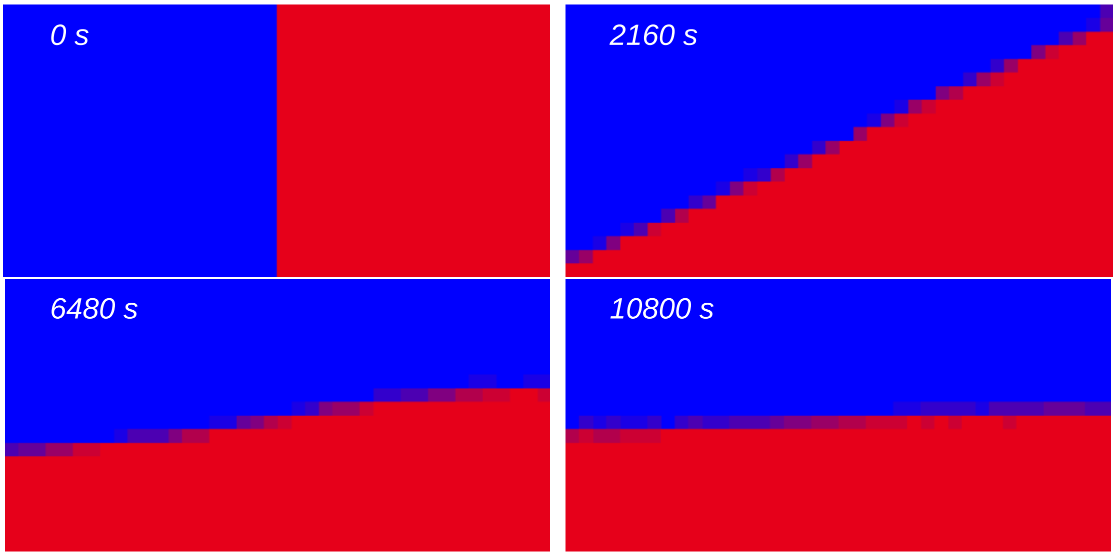


Figure 3. Performance of different advection solvers at 900s.

Exercise 003:

Effect of a larger density of saline groundwater.

Figure 4 presents the evolution of the interface between fresh and saline groundwater with larger density (calculated by MOC solver). Compared with Figure 1, after the density of saline groundwater rising, the velocity is higher, and the time needed to arrive steady state is less. The reason is from the increasing density gradient. Density gradient is the domain driver of this interface moving process between salt and freshwater. More density gradient leads to more rate of advection, which causes the advance of steady state occurring.



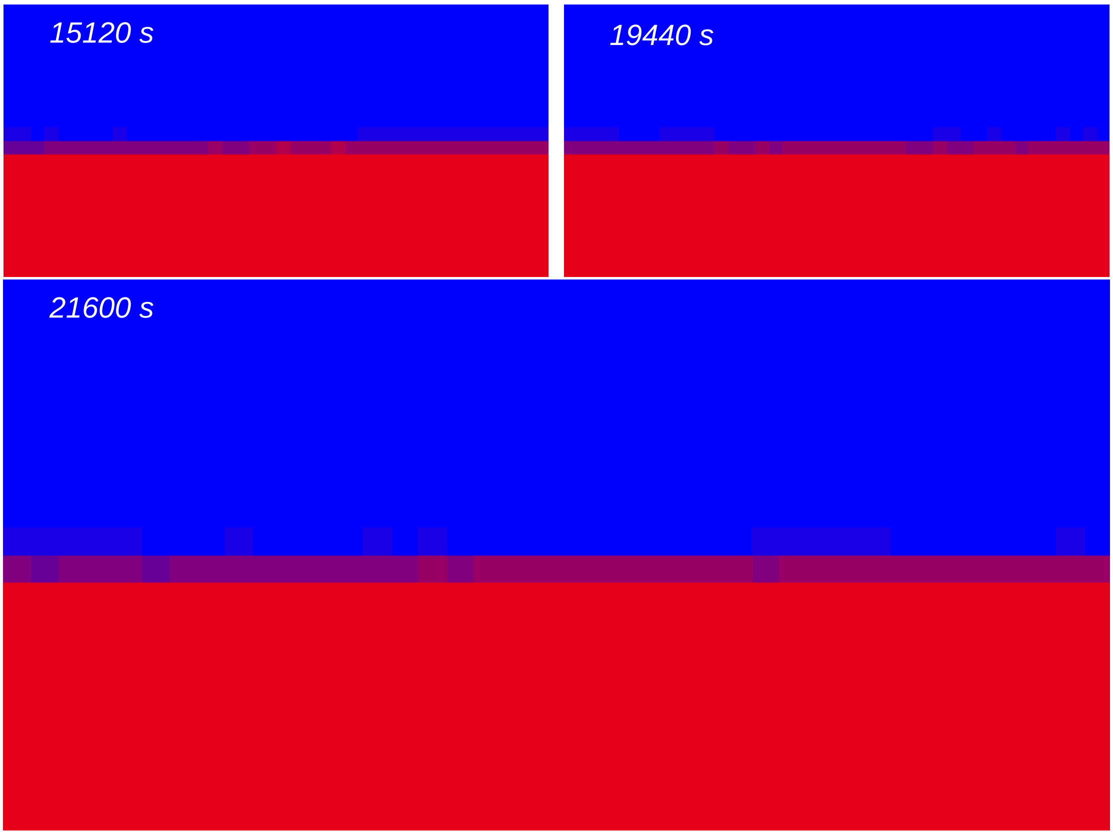
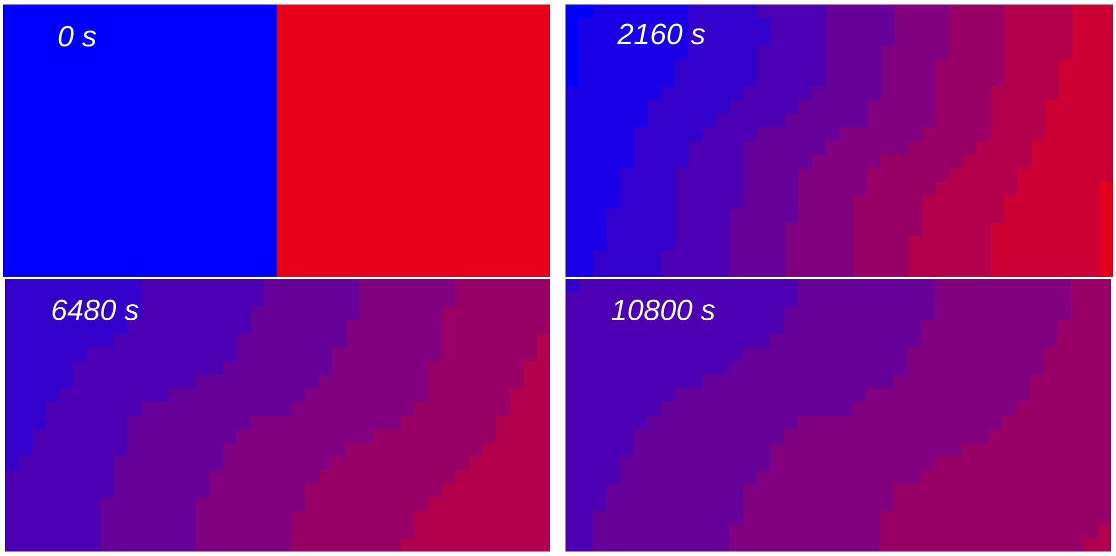


Figure 4. Evolution of the interface between fresh and saline groundwater with larger density.

Exercise 004:

Effect of dispersion.



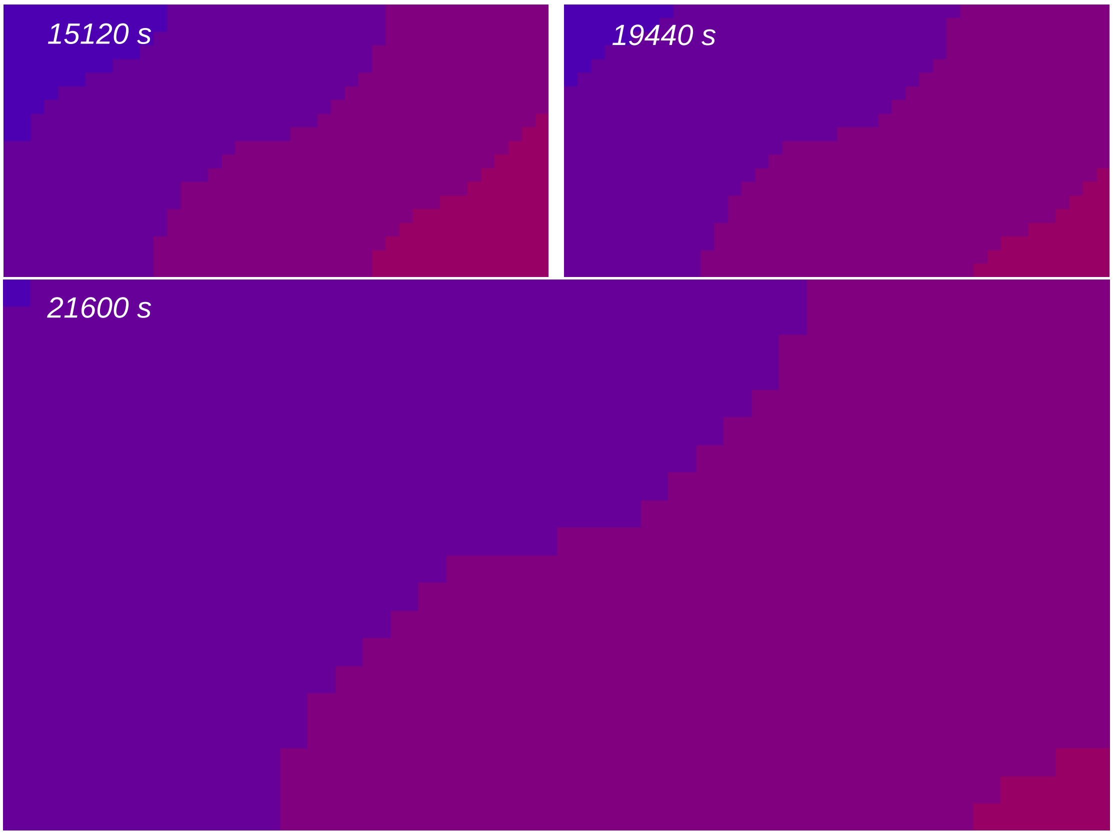


Figure 5. Evolution of the interface under effect of dispersion.

Figure 5 shows the interface under the effect of dispersion. It should be compared with Figure 1 as both of them have the same density of salt groundwater. From the above figures, we can identify the brackish water is more common with the dispersion condition than without dispersion, and the advection process is less clear with dispersion than without dispersion. This is because the simulating dispersion process causes the mixing of salt and freshwater to increase. And even to some extent, we can say dispersion is more domain process in Figure 5 than advection. At the end of simulating, the clear boundary between salt and freshwater disappears and brackish water is full of the whole aquifer.

Evolution of a freshwater lens in a coastal area

Introduction

Analysis of a homogeneous aquifer with the following geometry: horizontal L=10 km by vertical D=150 m. The profile is two-dimensional. Discretisation: 100*15 rectangular cells, so Dx=100 m and Dz=10 m. Hydrostatic pressure at the left and right boundary: viz. freshwater head only increases with depth due to density differences. In the central part of the aquifer, over a length of 40 cells (4 km) a natural groundwater recharge is taking place at t=0 year, with a rate of 360 mm/year. Initially the salt concentration is equal to 19000 mg Cl-/l. In the beginning, no hydrodynamic dispersion is taken into account: Dmol=0 m2/s, aL=aTH= aTV=0 m, as well as Rd=1 (no retardation). Other soil parameters are: hydraulic conductivity k=20 m/d; porosity ne=0.35 and anisotropy=kvert/khor=0.1. From a solute solver point of view: we use the Finite Difference solver with a Courant number of 0.75. Convergence criterion is 10-8 m and numerical time step Dt =1.0 year.

Parameters			
Layers	15	K_{hor}	20m/d
Rows	1	T	200m^2/d
Columns	100	Anisotropy K_{hor}/K_{ver}	10
Δx	100m	n_e	0.35
Δy	1	α_L	0m
Δz	10m	α_T	0m
Stress periods	3	Recharge	360mm/y
Initial concentration	19000mg/l	Recharge concentration	0mg/l
buoyancy	0.025		

Exercise 001:

Geometry of the problem and observation points: fwlens001.

1. Check PMWIN input files: heads, time-characteristics, IBOUND, MODFLOW; SEAWAT parameters.
2. Run SEAWAT.
3. Check the concentration results.
4. Place some observation wells at interesting points, to see the change in concentration can be seen as a function of time.
5. Create an EXCEL-figure with the output of the observation wells. How fast has the lens 95% of its final volume?

A4: The three Chloride concentration wells were installed in the study area. The locations and coordinates together with depth are shown in the Figure 1 and Table 1.

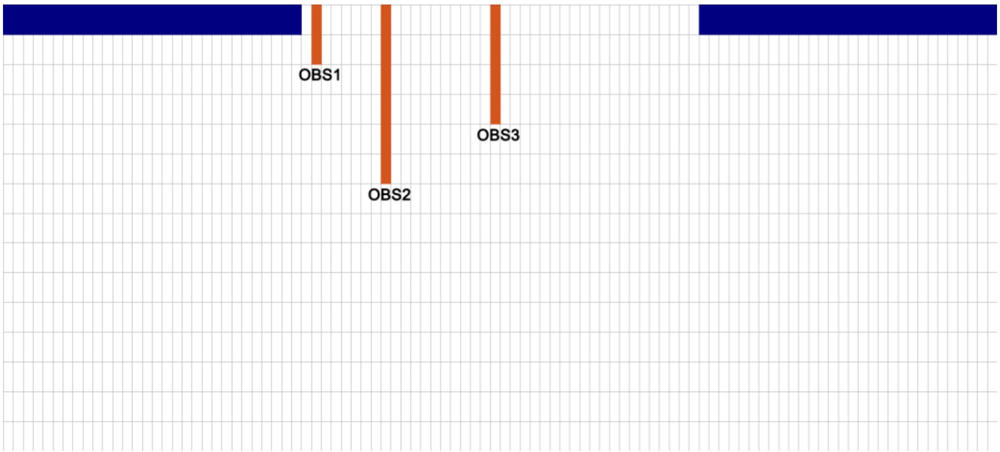


Figure 1. The locations of the OBS1, OBS2 and OBS3.

Table 1. The locations of the concentration observation wells.

Name	X	Y	Cells
OBS1	3161.669	0.5	(2,1,32)
OBS2	3637.549	0.5	(6,1,39)
OBS3	4641.46	0.5	(4,1,50)

After running at the last transport step of 225 years, the chloride concentration against time breakthrough curves of these three observation wells were produced and presented in Figure2.

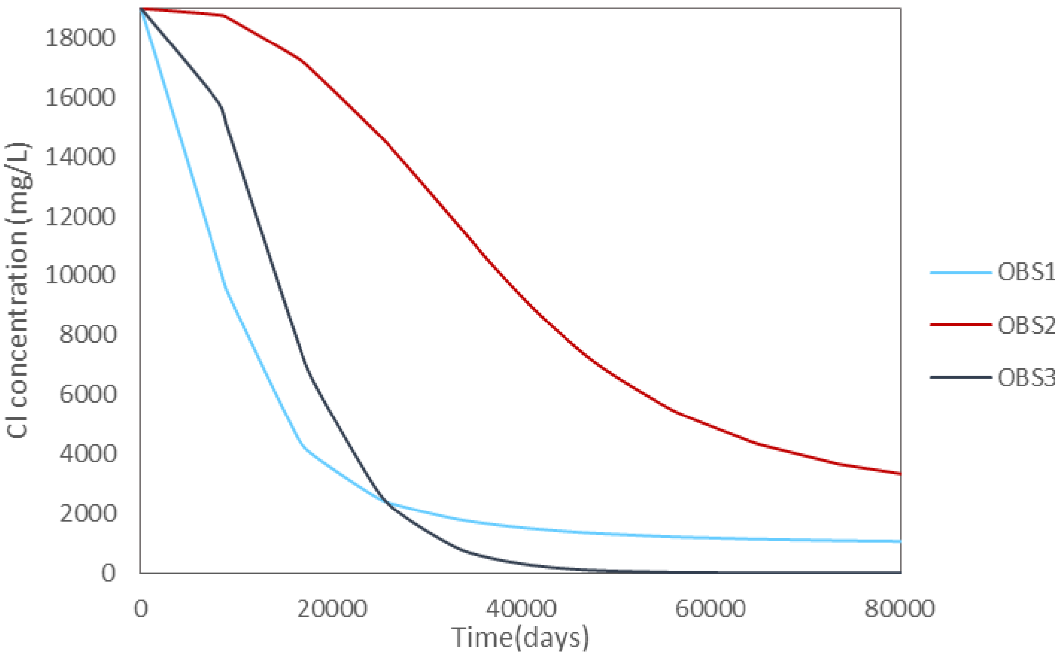


Figure 2. the Cl concentration breakthrough curves of the OBS1, OBS2, OBS3.

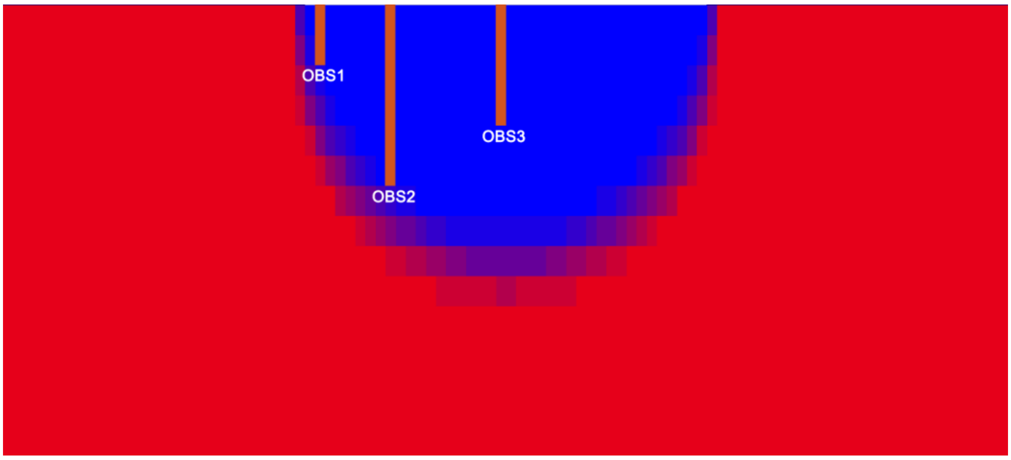


Figure 3: The locations of three observation wells in the Cl distribution map at the last time step.

The Figure 3 shows that the situation of three observation wells at the last time step in the Cl concentration distribution map. From the map, it is clear that the OBS1 locates near the interface between the freshwater and saline groundwater, the OBS3 well is situated at the center of the lens more or less, and the OBS2 is placed between OBS1 and OBS3 with the depth reaching to the mixing zone of freshwater and saline water. In accordance to Cl concentration breakthrough curves, it can be seen that the concentration observed in OBS2 took much more time for decreasing the concentration than that of the OBS1 and OBS3 and until at 225 years it basically tends to be stable at this point but not fully stable. This well is located at the brackish zone with a higher Cl concentration and at the deepest layer comparing to other two wells , due to the fact that the velocity of freshwater recharge flow in the sides is lower than that in the center so that requires more years to reach this depth for refreshing the saline groundwater. In addition, the Cl concentration of OBS3 which is in the center of lens decreases and tend to be stable fast, it is because it is at the center of lens with a higher infiltration rate of fresh water, resulting in the very high degree of refreshing which means the Cl concentration at this location is 0 mg/l at this moment. The OBS1 also tends to be low concentration fast, that is because its location is shallower, which indicates the freshwater reached there quickly, but due to that it is close the interface, inferring that it still has a higher Cl concentration while approaching to be stable. It is noticed that those points farther away from the boundary, the faster being stable Chloride concentration.

A5: Create an EXCEL-figure with the output of the observation wells. How fast has the lens 95% of its final volume?

Numerical Solution

The observation wells of hydraulic heads were placed in the area for observing the change of water heads against time. The locations of the new planned wells are presented in Figure 4 and Table 2.

When the lens reaches it maximum volume, the hydraulic heads become constant. Therefore, we put the observation wells below the fully developed lens to identify the hydraulic heads approach to a constant value at which moment. The time identified by water heads is the time when lens fully is stable.

Table 2. The locations of the head observation wells.

Name	X	Y	Cells
PZ1	3155.15	0.5	(8,1,32)
PZ2	3663.624	0.5	(10,1,32)
PZ3	4563.233	0.5	(12,1,37)
PZ4	4947.849	0.5	(12,1,46)
PZ5	5449.804	0.5	(12,1,55)
PZ6	6342.894	0.5	(10,1,62)

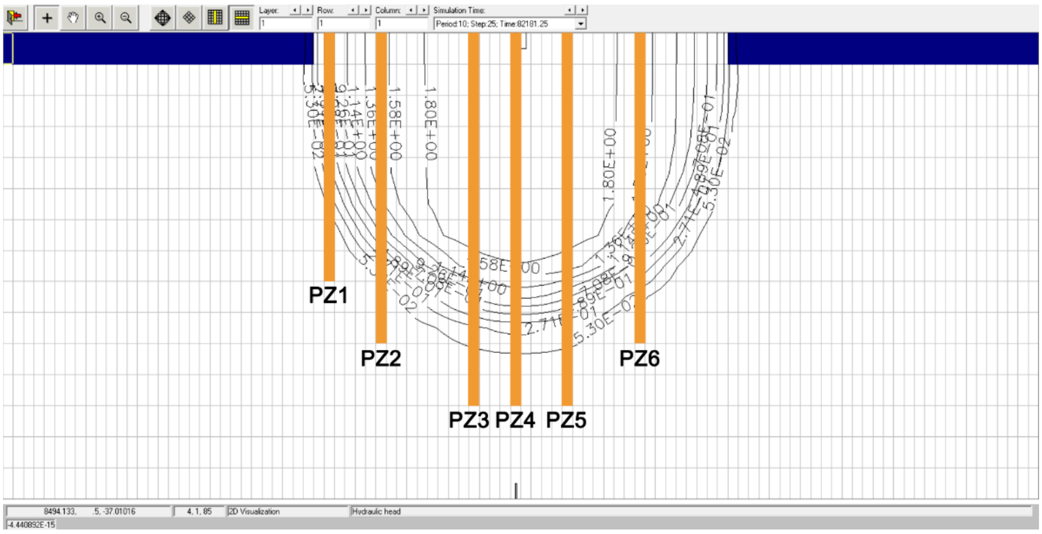


Figure 4. The locations of the groundwater heads observation wells.

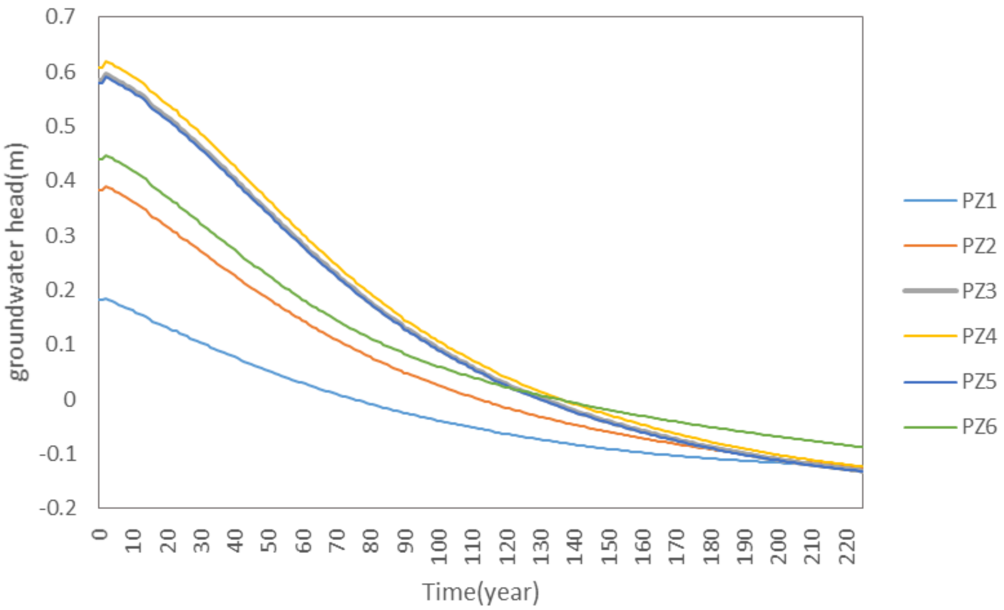


Figure 5. The groundwater head against time of the observation wells.

From Figure 5, it can be found that the groundwater heads of the observation wells nearly became a constant value at the end of simulation time about 220 years. Besides, from the Figure 6, it shows the process of the hydraulic heads of the lens reaching the stable situation. Though these graphs, it is also known that the water heads changed fast at the beginning, while after 200 years, there is almost no change in hydraulic heads and the shape of freshwater lens has nearly reached to the steady-state situation, furthermore, in the saline groundwater area, there is no flow anymore because of no hydraulic gradient. Hence, the time at 220 years is regarded as the numerical solution for the model.

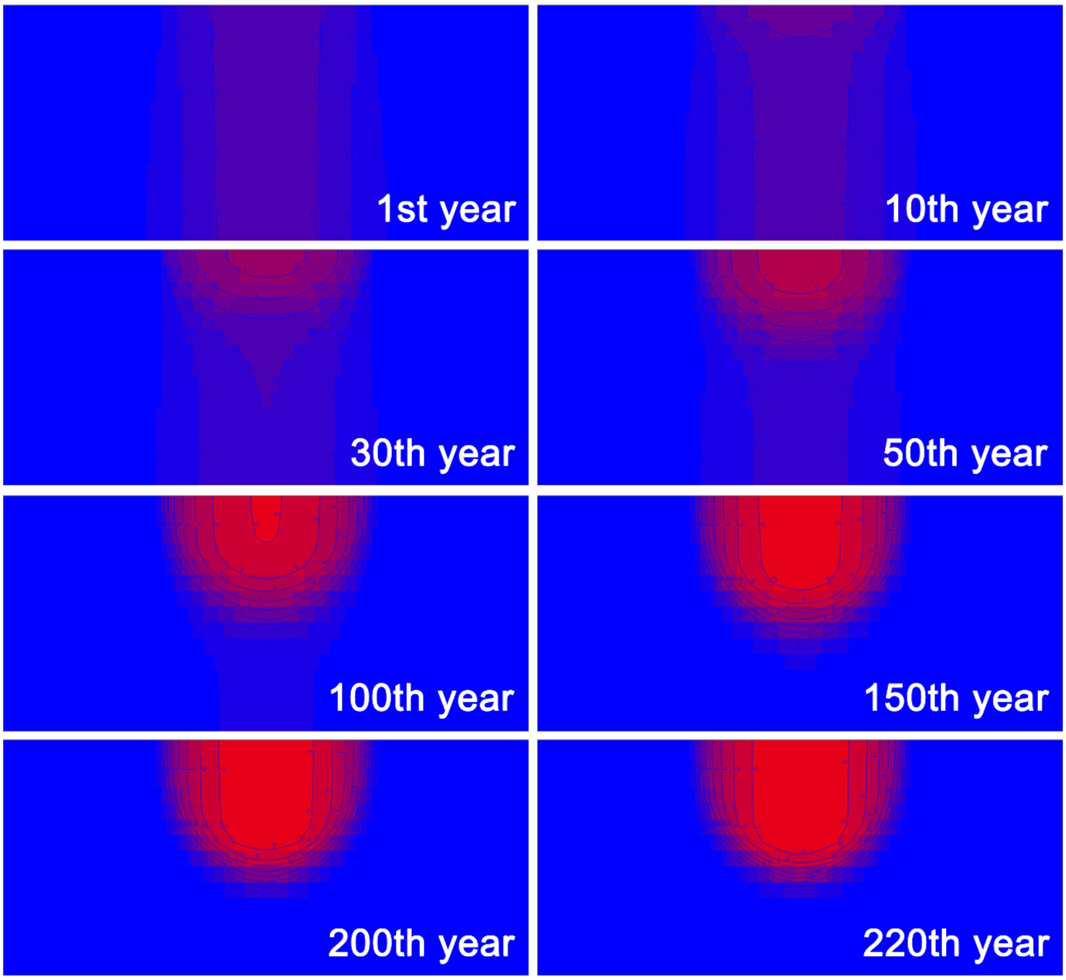


Figure 6. The groundwater heads at different period.

Analytical Solution

In this part, the equations were introduced to calculate the analytical solution of the position of the fresh-saline interface and final volume of the freshwater lens when it approaches to the steady state, and then the time when the lens developed fully also can be calculated. Furthermore, the comparison between the numerical solution and analytical solution was done.

The equation 1 is for calculating the interface between freshwater lens and saline water as shown below. The Figure 7 shows the interface of the fresh-saline water calculated by Eq.1

$$H=\sqrt{\frac{f(0.25B^2-x^2)}{k(1+\alpha)\alpha}} \qquad \text{(Eq.1)}$$

• H = depth of the fresh-salt interface below mean sea level (L),

• f = natural groundwater recharge per day (LT−1),

• x = horizontal position (distance from the axis of symmetry) (L),

- α = relative density difference $(\rho s - \rho f)/\rho f$ (−),
- B=width of the sand-dune (L)
- k=Hydraulic conductivity

Table 3. The values of the parameters.

parameters	values
f	0.001mm/d
B	4000m
α	0.025
k	20
n_e	0.35

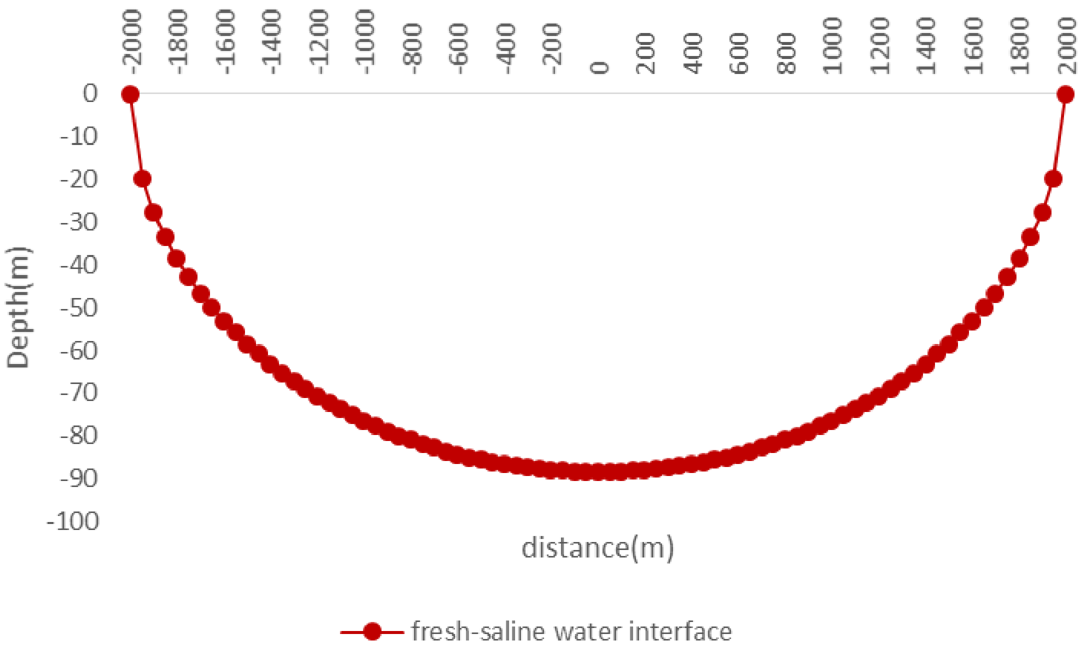


Figure 7. The freshwater lens interface when fully developed.

$$V_\infty = fB\tau = \frac{\pi n_e B^2}{8}\sqrt{\frac{f(1+\alpha)}{k\alpha}} \quad \text{(Eq.2)}$$

$$\tau = \frac{\pi n_e B}{8}\sqrt{\frac{(1+\alpha)}{kf\alpha}} \quad \text{(Eq.3)}$$

Where the τ refers to the characteristic time, V is the maximum volume of the freshwater lens, n_e is the effective porosity.

Based on the Eq.1, Eq.2 and Eq.3, the maximum of the depth of the lens developed, the characteristic time together with the time t when the lens developed to be steady-state situation can be computed. It is noted that the time t is set to 3 τ as the lens reaching to the stability on the basis of the lecture notes. The results are shown in Table 4.

Table 4. The results of the H_{max}, V_{max}, T_{max}.

Parameters	Computed results
H_{max}	88.3452m
V_{max}	99569.16m^3
T_{max}	204 years

From the analytical solution in the Table 4, the time of fully developed fresh lens is 204 years. The numerical solution of time is 220 years simulated in the model. It is obvious that two values using by two methods are close, only 7% difference between them. Hence, the numerical solution can be acceptable.

Exercise 002:

Analytical versus numerical solution for steady-state situation: fwlens002

This exercise was done in the Exercise 001, please check it in Exercise 001.

Exercise004:

Determine the maximum extraction rate without serious upconing of saline groundwater: fwlens004

1. Place in PMWIN/Models/MODFLOW/Flow Packages/Well extraction wells with reasonable rates. Place three observation points in the extraction wells. Note that the concentration under the dunes at t=0 years is initially still 19000 mg Cl-/l.
2. Run SEAWAT.
3. How much groundwater (approximately, in m3/day/m') can be extracted without serious upconing of saline and brackish groundwater (serious means a TDS-concentration>300 mg/l.Make only a coarse and quick calculation. Try to supply 100.000 people with drinking water on an island with a length L of 10 km?
4. What to do to reduce the upconing (no calculations, just give suggestions)?

A3:

From the Figure 8, it is known that there is a little bit upconing saline intrusin happened after 225 years when abstracting rate is set as 1m^2/d /m. With the abstraction capacity increases, the volumn of the fresh water lens decrease with the time. Hence, when abstraction rate is 1m^2/d/m, the total abstraction with a length of 10km is 10000m^3/d, so the one habitat can abtain 0.1m^3/d or 1000L/d, it is enough for dringking water,but can not meet the demand of other water uses.

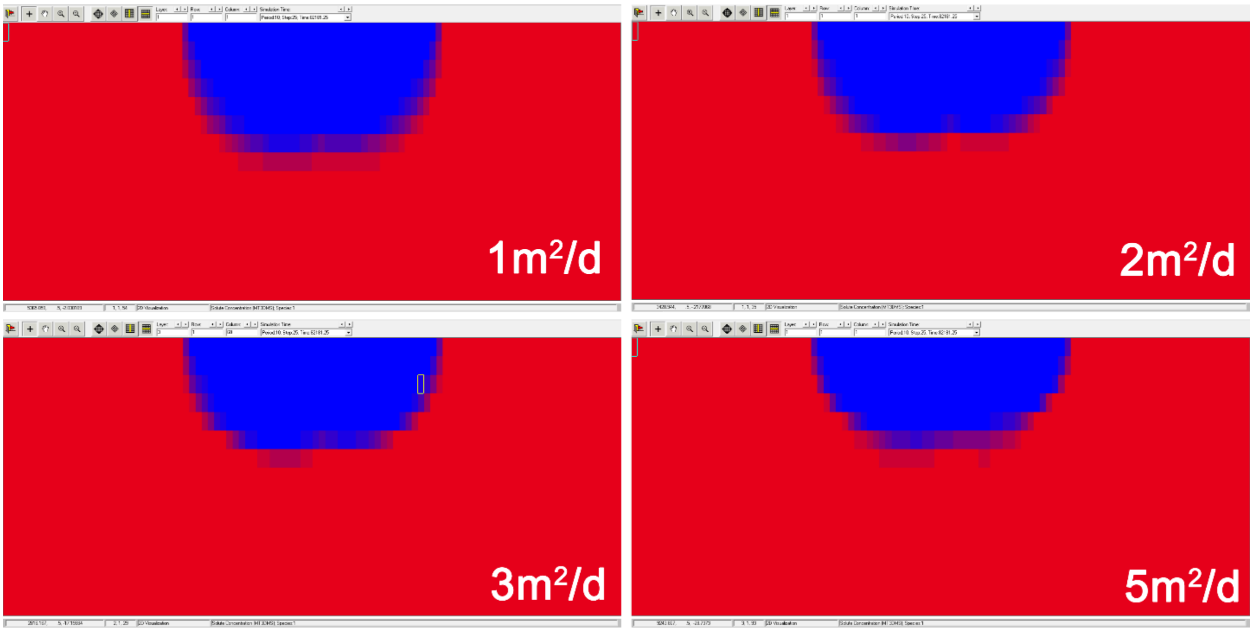


Figure 7: the Cl concentration distribution at different abstraction rate after 225 years

A4: measures to reduce the unconing of saline water

In order to avoid or to limit these negative effects, one should keep the extraction rate, and so the lowering of the piezometric head, below a certain limit. After reducing the extraction significantly, the interface may descend to its original position, though at a very slow pace. Second solution is to replace the extraction well to a location where saline groundwater is positioned at greater depth from the well. Third measure is that improve the monitoring net for monitoring the groundwater level and quality in the area. Last, the abstraction wells can be planned at a lower density and distributed uniformly.