TNO Built Environment and Geosciences

Princetonlaan 6
P.O. Box 80015
3508 TA Utrecht
The Netherlands

www.tno.nl

T +31 30 256 42 56
F +31 30 256 44 75
Info-BenO@tno.nl

TNO report

2006-U-R-172/A

Impact of the 26-12-04 Tsunami on groundwater systems and groundwater based water supplies

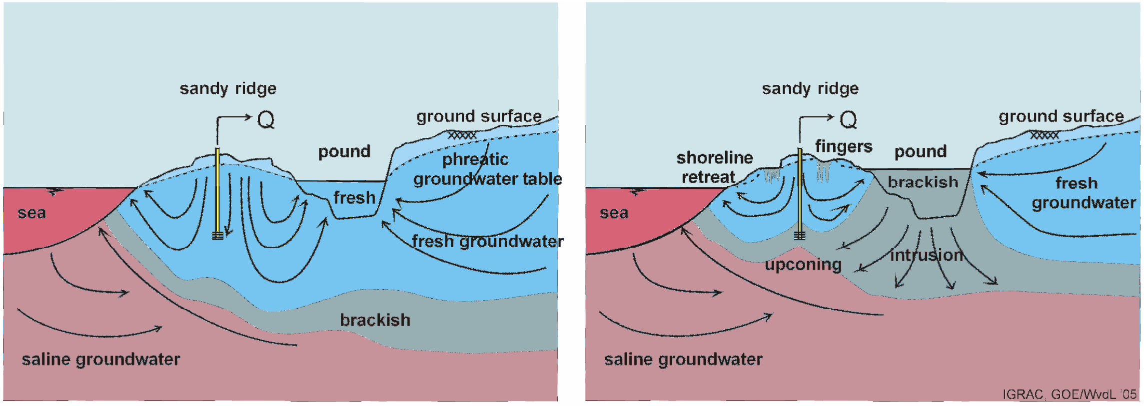
Date	February 22, 2005
Authors	G.H.P. Oude Essink, W. van der Linden
Projectnumber	005.53021
Number of pages	19
Number of appendices	2

Contents

Appendices

1 Introduction

The 26-12-04 tsunami has affected groundwater systems in the low-lying coastal zones of the stricken areas. Figure 1 gives a sketch of possible impacts on freshwater resources in coastal aquifers. Questions can be asked about how serious the impacts of the floods on fresh groundwater resources are: about how harmful they are from a drinking water point of view, and about how long it takes before the contaminated freshwater resources are clean again for consumption.



Before the Tsunami

After the Tsunami

Figure 1: Schematic representation of the possible effects of the 26-12-04 tsunami on coastal groundwater systems: upconing of brackish groundwater under abstraction wells, intrusion of brackish or saline water from ponds, fingering of brackish water from pools, reduction in freshwater volume due to shoreline retreat, etc…

In this note, we summarize some possible mechanisms that might have occurred in several affected areas. Unfortunately, the complexity of the phenomenon of salt water intrusion does not allow us to extent our conclusions for these specific cases to a global/overall groundwater impact assessment of the tsunami. Local circumstances, such as hydrogeology and soil characteristics, vary too much to come up with only one impact assessment. An important aspect of this complexity is for instance the rate of infiltration of sea water on top of the land. Aquifers that are overlain by clayey and/or loamy low-permeable aquitards will probably be less intruded than aquifers that consist of coarse sand. In addition, the shorter the floods occur, the less infiltration is taking place. Therefore, large differences in impacts by the tsunami of fresh groundwater resources can be expected.

2 Conceptual models of salt water intrusion in coastal aquifers

By analyzing several possible situations in the subsoil that may have occurred, we have tried to describe the relevant processes of salt water intrusion in the coastal aquifers by means of conceptual models (figure 2 and 3). Numerical models have been used to support our analysis (see Appendix A). The main hypothesis is that sea water that flooded the land may have intruded into the subsoil, causing density driven flow through salt water fingers.

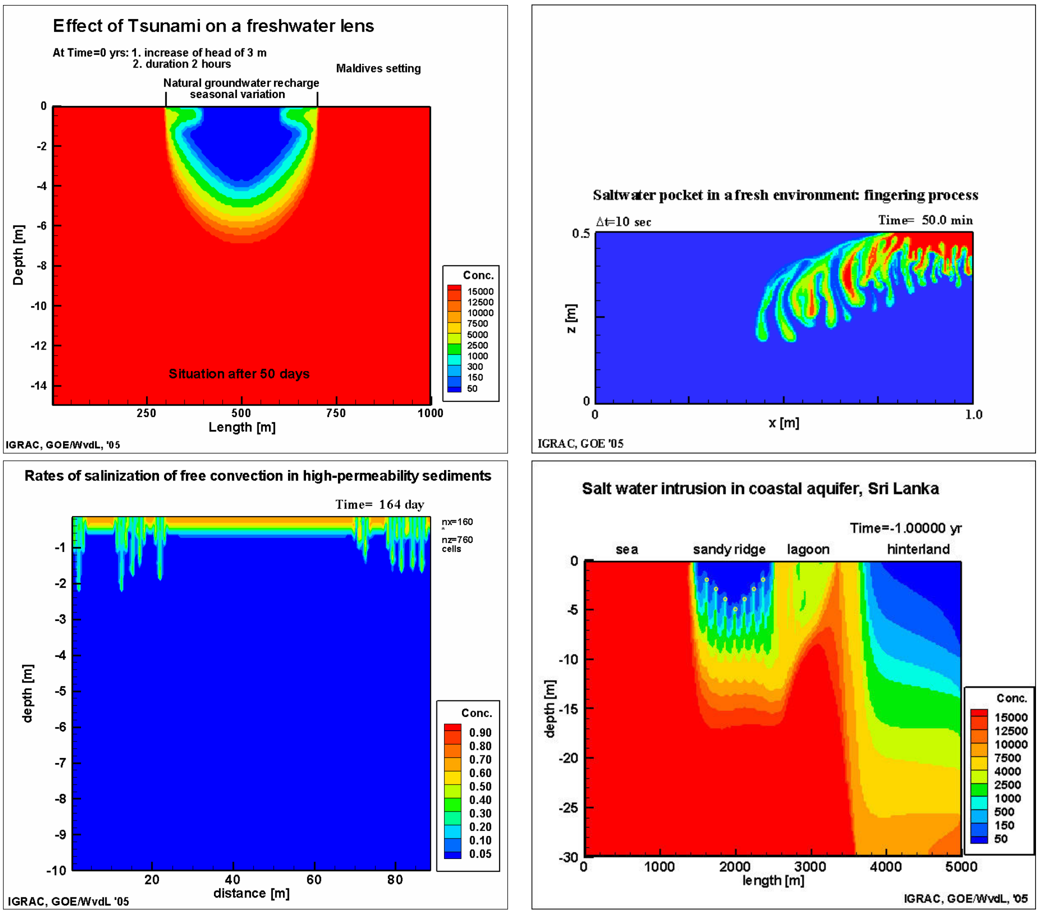


Figure 2: Conceptual models are used to analyse the impact of the tsunami on groundwater resources: Concept 1: evolution of a freshwater lens after flooding by sea water, Concept 2: fingering processes in the subsoil, Concept 3: salinisation due to flow caused by density differences (free convection), Concept 4: freshwater lens in a coastal aquifer with a brackish lagoon.

Factors of importance are:

- Disturbance and reduction of the freshwater lens by the subsurface pressure wave. The extent of this effect cannot be assessed without field observations, but it is expected that mixing of the freshwater with saline water has taken place.
- Local geometry of the inundated areas. If sea water remains some weeks to months in local depressions, lakes and pools, intrusion can easily occur. The

topography of the coastal zone needs to be known in detail to quantify the degree of salinisation of the subsoil.

- Duration of sea water standing on the land. The longer salt water remains on the land, the more intrusion into the subsoil can happen.
- Leaching of salts from the soil. The longer it takes to flush out the salts, the longer it will have a negative effect on the salinity of the groundwater.
- Local weather conditions during the coming months. The higher the natural recharge rate, the quicker salt is flushed out from the groundwater resource. As such, the intensity of the coming monsoon seasons also determines the degree of salinisation.
- The conceptual models do not take these factors into account; therefore actual conditions of the freshwater volume may be worse than represented in the simulations. This will mean that poor groundwater quality conditions will remain longer than simulated.

It can be stated that shallow groundwater in some coastal areas may remain unsuitable as drinking water for about one to two years. This may be concluded from density dependent groundwater flow simulations of the effect on a freshwater lens of the flooding by sea water (concept 1 and concept 4) during and after the 26-12-04 tsunami. However to what extent the tsunami will affect the fresh groundwater resources in specific coastal areas will depend on various factors.

For instance, information from Sri Lanka provides provides reports of saline shallow wells, which remained brackish/saline after cleaning by pumping. Locally it is believed, that it is very likely that after the start of the monsoon, the old situation can be restored rather quickly. However, the pace at which the increased concentrations are removed, will depend on the local geometrical and hydrogeological conditions.

3 Effect of shoreline retreat on fresh groundwater resources in coastal aquifers

Shoreline retreat will also affect fresh groundwater resources in coastal aquifers (see figure 4):

- **Case a.**

A reduction in width of the freshwater lens will diminish the volume of fresh groundwater in the freshwater lens. As a rule of thumb, the decrease of volume is proportional to the decrease in width: e.g. 5% smaller island results in a 5% reduction of fresh groundwater volume. Note that the depth of the freshwater lens is proportional to the square root of the natural groundwater recharge and inversely proportional to the square root of the hydraulic conductivity (see Appendix A).

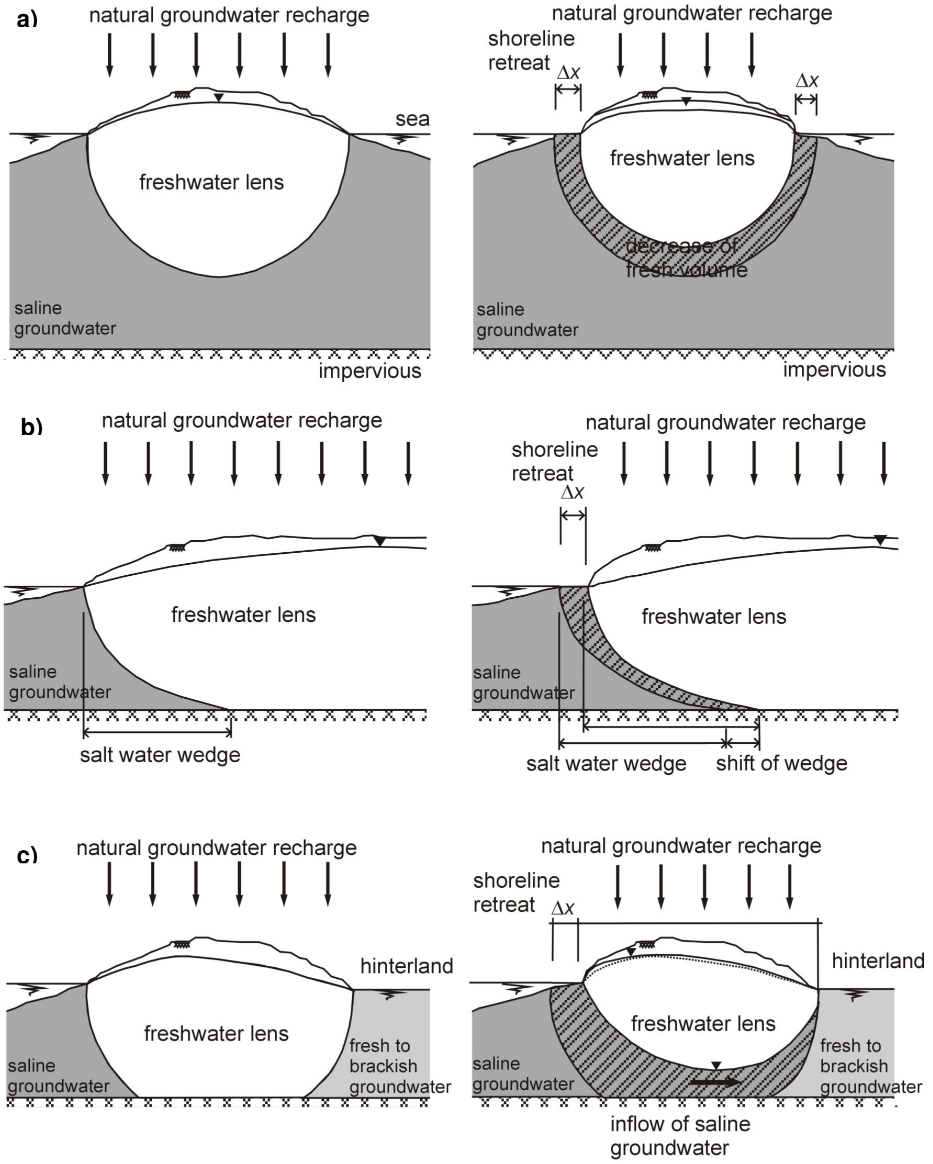


Figure 4: Possible effects on the freshwater resource in coastal aquifers due to shoreline retreat: Case a: freshwater lens under a small island, Case b: salt water wedge in a coastal aquifer with freshwater, Case c: freshwater lens in a coastal aquifer with saline water.

- **Case b.**

In most coastal aquifers fresh groundwater is replenished by water from recharge areas at the hinterland. A so-called salt water wedge is present in these systems. The length of wedge highly depends on the outflow of fresh groundwater from the hinterland. On average, viz. in natural circumstances, the length of the wedge is not spectacular, viz. often in the order of tens to hundreds of meters. Under normal circumstances, activities as groundwater extractions in the coastal zone and fresh groundwater outflow reductions, e.g. by reduced recharge due to touristic or agricultural developments, have often caused an inland shift of the salt water wedge The shift of the wedge on itself is proportional to the shift in shoreline retreat. However, after shoreline retreat, saline to brackish groundwater may be closer by groundwater extraction schemes, so upconing of saline groundwater could occur more easily. Note that the length is proportional to the hydraulic conductivity and proportional to the aquifer thickness to the power two (see Appendix A).

- **Case c.**

A special case is occurring when the shoreline retreat causes sea water to intrude into a protected brackish to fresh groundwater reservoir in the hinterland. Then, salt water intrusion might easily occur rather quickly (see concept 4, figure 2).

Conceptual models used to analyse the impact of the tsunami on groundwater resources:

3.1 Concept 1. Evolution of a freshwater lens after flooding by sea water

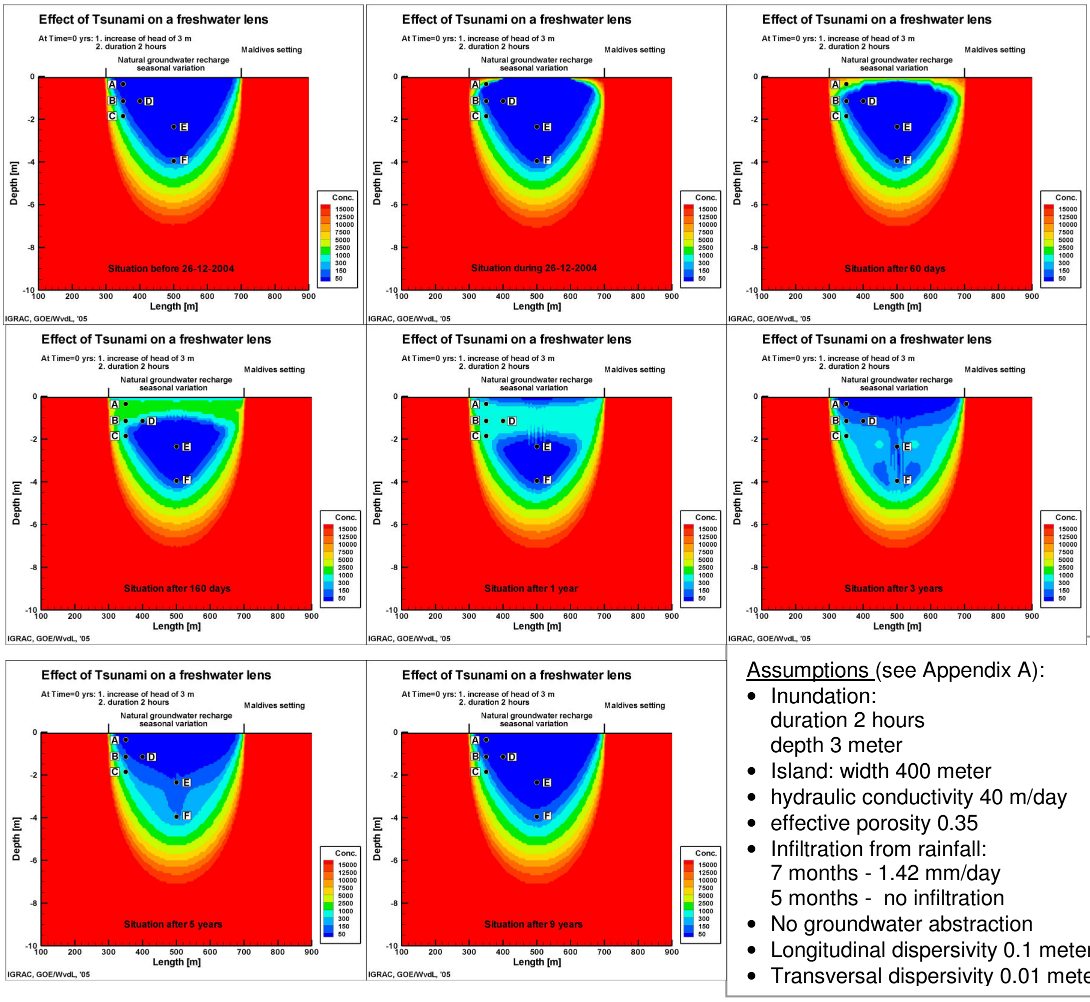
The concept of intrusion of saline water in a freshwater lens is demonstrated using data from the Maldives. The intrusion shows as a brackish front moving through the freshwater lens. The lens itself remains intact, but a front of brackish groundwater passes through the lens. An important feature of this (worst case) concept is that after the tsunami passes the islands, a certain amount of sea water remains on the land. That salty water intrudes into the ground, and will pass through the aquifer the moment rainwater infiltrates into the subsoil. In this concept, we assume that during the dry season of 2005 the amount of rainfall is 10% of an average wet season and that dilution of sea water with rainwater results in a concentration of infiltrated water of 12,000 mg Cl^{-}/l. Hydrodynamic dispersion causes the mixing of fresh, brackish and saline groundwater. Figure 5 shows the results of one out of several simulations.

The positions A-F, indicated in figure 5, represent wells at various locations and different depths. The salinity of the groundwater in a well close to the surface (e.g. well A at -0.35 meter below mean sea level) increases in the first weeks after the intrusion and returns to the original value within a few years. With depth, the increase in salinity is retarded, as well as the return to the original value. How fast exactly depends on factors as the magnitude of the hydraulic conductivity as well as the rate of recharge of freshwater during the monsoon. After the tsunami, the shallower the well, the larger the increase in concentration.

Several numerical simulations with different sets of parameters were prepared. The parameters varied were: hydraulic conductivity 10 and 40 m/day, tsunami duration 2 and 4 hours and flood depth 3 and 5 meter, island width 400 m, 1000 m and 2000 m. Also the concept with no sea water remaining on the land has been considered.

A lower hydraulic conductivity reduces the intrusion of sea water into the aquifer.

Conclusion:
Based on the simulations, it can be deduced that the duration of the inundation was probably long enough to contaminate the freshwater lens with sea water in some way. This may result in contaminated parts of the freshwater resources during a period of at least several years (depending on the hydrogeological conditions and not taking into account other negative factors). A front of brackish groundwater passes through the freshwater lens and chloride concentrations go up significantly, especially at the upper part of the freshwater lens. The increase in chloride concentration will probably reach values higher than WHO-limits for drinking water.



Assumptions (see Appendix A):
- Inundation:
  duration 2 hours
  depth 3 meter
- Island: width 400 meter
- hydraulic conductivity 40 m/day
- effective porosity 0.35
- Infiltration from rainfall:
  7 months - 1.42 mm/day
  5 months - no infiltration
- No groundwater abstraction
- Longitudinal dispersivity 0.1 meter
- Transversal dispersivity 0.01 meter

Figure 5 Example of brackish groundwater moving through the freshwater lens.

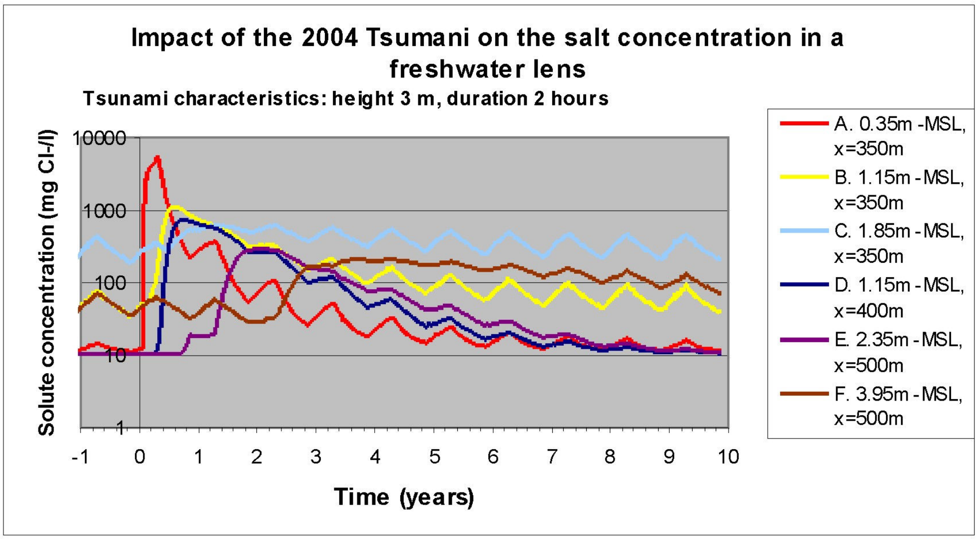
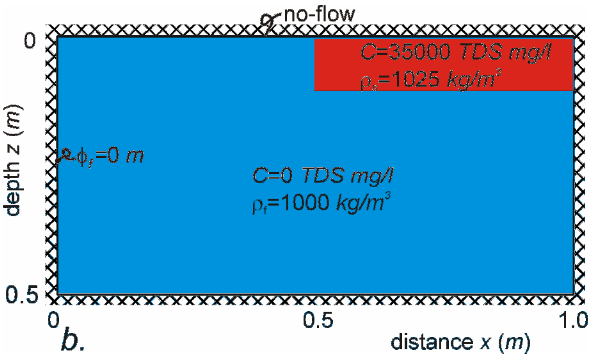


Figure 6: Chloride concentration as a function of time at various depths and at various positions in the freshwater lens. Flooding with seawater occurs at year 0. Seasonal variation in concentration is mainly caused by seasonal variation in recharge.

3.2 Concept 2. Fingering processes in the subsoil

The evolution of the fingering process is demonstrated in this concept. Here we use another geometrical scale (1m*0.5m) than in the freshwater lens concept (1000m*15m). The reason is that the fingers that are actually occurring in case of density inversion (saline groundwater above freshwater) can only be properly modeled in detail when numerical discretisation is very fine.

In the situation of figure 7, a saline groundwater water pocket descends in a fresh groundwater environment as a result of density differences. As the saline water pocket displaces (Figure 8), a mixing zone exists due to hydrodynamic dispersion. After a few minutes, fingers evolve at the bottom of the saline water pocket. At the left side of the pocket, a strong rotating groundwater flow (vortex) exists. As a result, saline groundwater descends here faster than at the right side of the pocket. When the left side of the pocket reaches the bottom (after about 60 min), fresh groundwater underneath the pocket is entrapped. Still the saline groundwater will spread entirely over the bottom of the system due to density difference. With other words, during especially the first tens of minutes of the simulation, fresh groundwater will penetrate saline groundwater, and freshwater fingers are developed. Figure 9 shows the influence of low-permeable layers in another shallow aquifer system.



Assumptions:

- Salt water has already intruded into the right side of the subsoil over a depth of 0.1 m.
- No flow at the boundaries
- Hydraulic conductivity 0.001 m/s = 86.4 m/day
- No anisotropy
- Effective porosity=0.1
- Long. disp.=0.001m
- Trans. disp.=0.0001m
- Molecular diffusion=10-9 m2/s
- [No groundwater abstraction]

Figure 7: Example of a salt water pocket in a fresh groundwater environment: conceptual model.

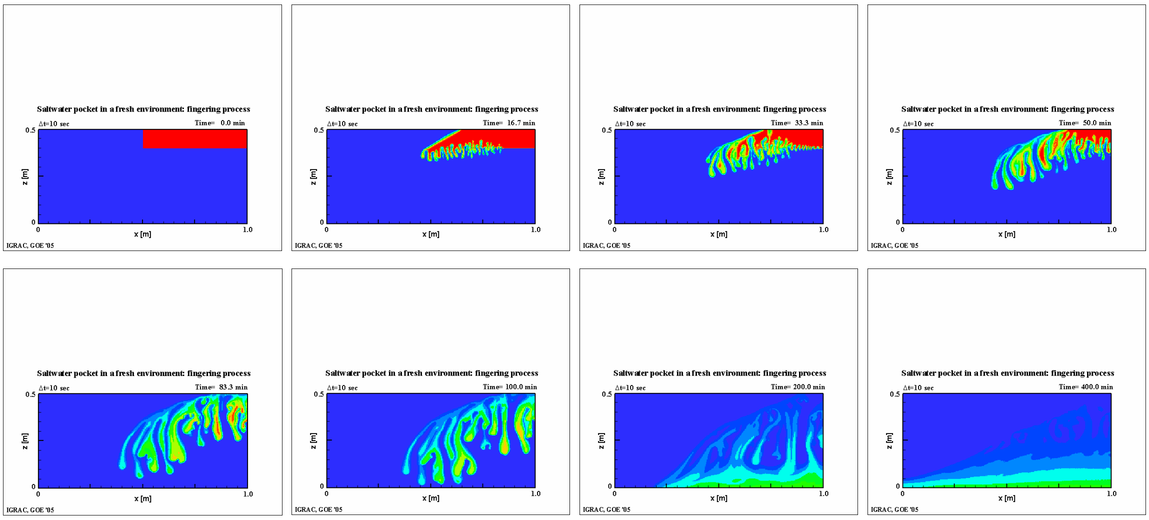


*Figure 8: Evolution of the fingering process in a sand-box of 1m*0.5 m.*

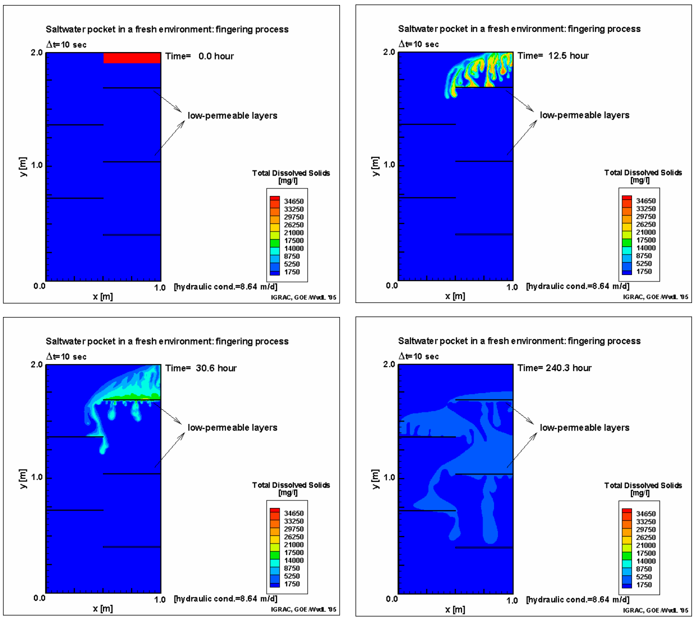
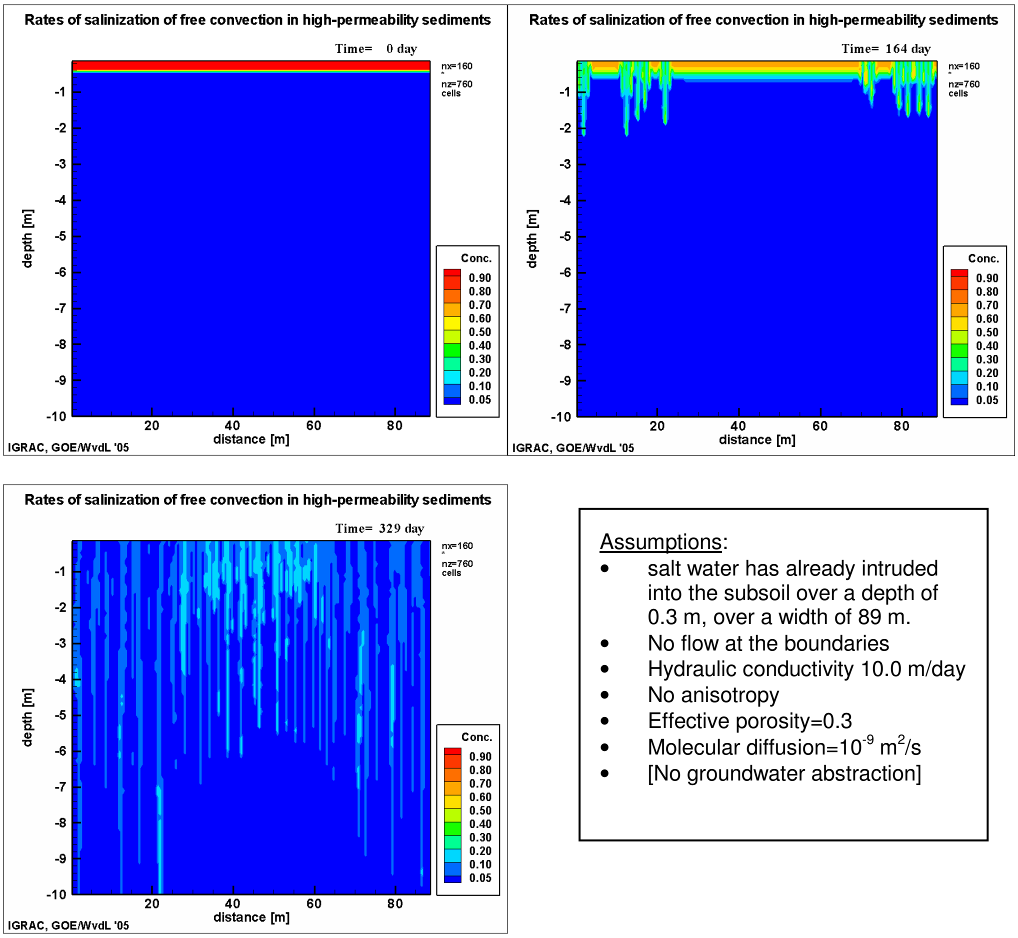


*Figure 9: Evolution of the fingering process in a sand-box of 2m*1 m.*

3.3 Concept 3. Salinisation due to flow caused by density differences only

This concept demonstrates the situation when sea water stands in a pond or lake for many weeks to months. Though rainfall will decrease the chloride concentration and thus the density of the surface water, infiltration of saline to brackish water into the subsoil can occur through dense fingers of saline to brackish groundwater (figure 10).

Whether or not salt to brackish fingers with higher concentrations intrude a porous medium (called the onset of convection) depends on various aspects. For instance, confining deposits like clayey layers on top significantly retard the salinisation of the groundwater reservoir. Processes in the beginning of the intrusion like the development of a boundary layer and the breaking-up of the fingers are important to determine the rate of salinisation.



Assumptions:

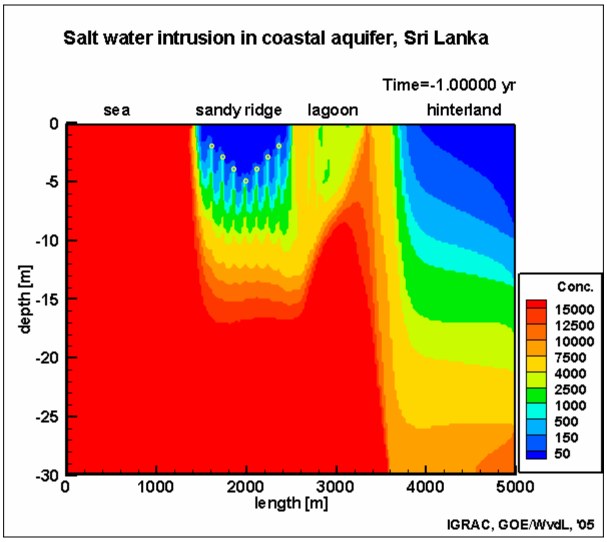
- salt water has already intruded into the subsoil over a depth of 0.3 m, over a width of 89 m.
- No flow at the boundaries
- Hydraulic conductivity 10.0 m/day
- No anisotropy
- Effective porosity=0.3
- Molecular diffusion=10^{-9} m^2/s
- [No groundwater abstraction]

Figure 10: Salinisation due to flow caused by density differences only (free convection) in high-permeable sediments

3.4 Concept 4. Freshwater lens in a coastal aquifer with a brackish lagoon

Consider an aquifer system of 5 km wide and 30 m deep. At the left side, the ocean is present, where the sandy aquifer contains saline groundwater. A sandy ridge with a width of 1 km exists, where during the wet season, fresh rainwater infiltrates. The natural groundwater recharge has been assumed to be some 520 mm (concentration is 45 mg Cl^-/l) during half a year; during the dry season, no water infiltrates. A freshwater lens has evolved below the sandy ridge. Groundwater is abstracted for domestic purposes from many shallow wells. In landward direction we detect a lagoon of some 1.5 km width.

The model represents a typical situation with a wet and dry season. Local data have not been considered; they are unknown. Examples of unknown parameters are the exact groundwater abstraction rate, the natural groundwater recharge from rainfall, hydrogeological parameters like the hydraulic conductivity, the effective porosity, the salt concentration of the lagoon during both seasons, and the salt concentration of the infiltrated rainwater.



<u>Assumptions and model parameters</u>:

- Hydraulic conductivity 10.0 m/day
- No anisotropy
- Effective porosity=0.35
- Lagoon waterlevel: wet season +1.5 m msl, dry season +0.5 m msl
- Lagoon salt concentration: wet season 300 mg Cl^-/l, dry season 5000 mg Cl^-/l
- Groundwater abstraction: 7 wells with 30 m^3/year/m = 0.21 million m^3/year/1000m
- Boundary conditions:
  Land side: hydrostatic pressure 4 m above lagoon,
  salt concentration top 45 mg Cl^-/l, bottom 11,000 mg Cl^-/l
  Sea side: hydrostatic pressure, seawater
  Bottom: no flow, depth -30 m msl
- Model parameters: 200 columns, 150 layers, time step 0.5 month
- Solute transport: 9 particles initially implemented in each cell
- Longitudinal dispersivity 0.1 meter
- Transversal dispersivity 0.01 meter

Figure 11: Conceptual numerical model of the coastal aquifer in Sri Lanka.

Figure 11 shows the solute distribution in the coastal aquifer just before the tsunami. A freshwater lens of some 5 m thickness occurs in the sandy ridge. Upconing is present at the well locations where groundwater is abstracted (see yellow circles). Concentrations in these wells vary with the season: from some 100 mg Cl^-/l at the end of the wet season to 450 mg Cl^-/l at the end of the dry season (e.g. see well B. in figure 12 and 13).

The flooding during the tsunami has the following characteristics: duration 2 hours, head 3 m. Abstraction of groundwater is assumed to stop during one year. Figure 12 shows that the concentrations in the observation points A., C. and D. go up due to the infiltration of sea water during the tsunami. Well B. shows a decrease in chloride concentration in the first year after the tsunami because abstractions have stopped: the upconing of brackish groundwater 'reduces' due to density differences. After one year, the concentration goes up due to the start of the abstraction.

The intrusion shows as a brackish front moving through the freshwater lens. The lens itself remains intact and does not change in size in the period without abstraction after the tsunami. Hydrodynamic dispersion causes the mixing of fresh, brackish and saline groundwater. Figure 13 shows the results of the simulation 0.5 year after the tsunami. The intrusion of the brackish water can be seen just below ground surface.

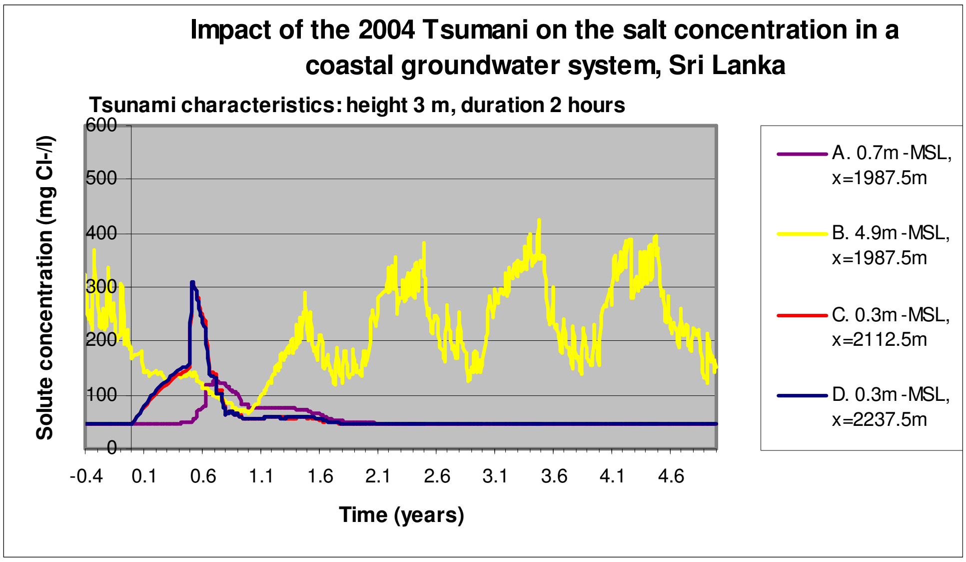


Figure 12: Chloride concentration as a function of time at various depths and at various positions in the freshwater lens. Flooding with seawater occurs at year 0. Seasonal variation in concentration is mainly caused by seasonal variation in recharge.

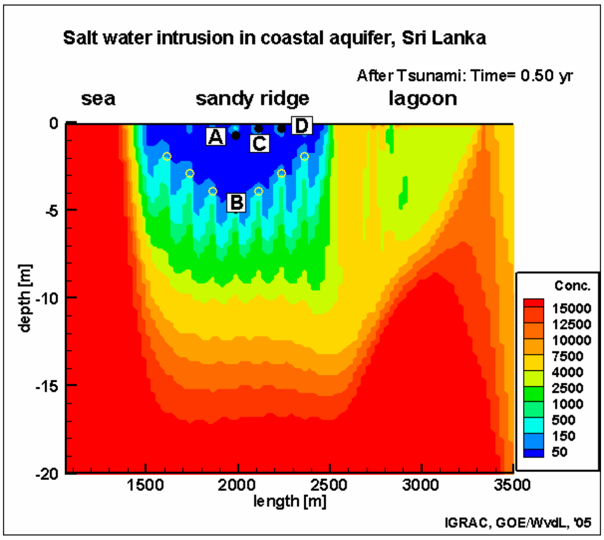


Figure 13: The fresh-salt distribution in the coastal aquifer of Sri Lanka, 0.5 years after the flooding. The position of the observation points in the groundwater system is also shown.

Conclusion

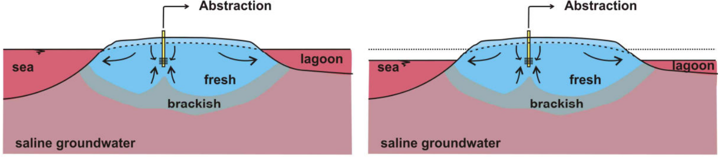
The tsunami affects the chloride concentration in the coastal aquifer, but increases in concentration are not spectacular. Within some years, depending on the rainfall, the increase in concentration is probably vanished. However possibly the situation modelled is not the worst case situation. When sea water remains in pools and/or local depressions, salt water intrusion will last longer. Less rainfall in the months after the tsunami will prolong the effect of the intrusion. Continued leaching of salts from the soil by infiltrating rainfall is not modelled. The effect of the mixing of saline water with freshwater due to the pressure of the wave is not considered.

Remark

Local circumstances just around the drinking water wells can not be modelled with this regional conceptual model; finer models with more detail should be used to simulate the effect of the tsunami on this scale.

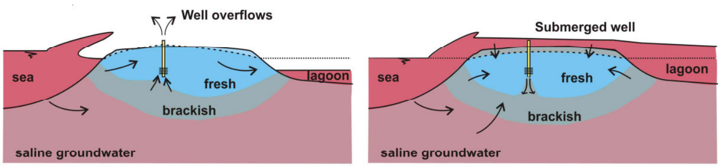
4 Impact on fresh groundwater of a coral island during a tsunami

The sequence of events which can take place when a tsunami hits a coral island is demonstrated in six steps (see also figure below):



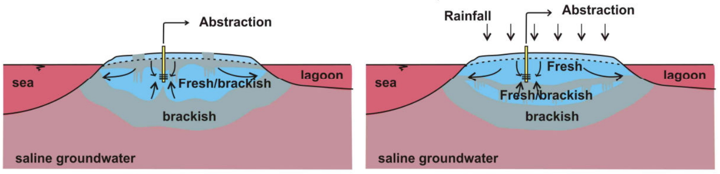
1. Before the Tsunami

2. Just before the Tsunami:
Lowering of sea- and lagoonwater level



3. Just before the Tsunami:
Subsurface pressure wave precedes surface wave

4. During the Tsunami: Flooding of island,
mixing of water due to sudden pressure changes



5. After the Tsunami
Freshwater mixed with brackish water

6. After the Tsunami
Recharge by rainfall replaces brackish water

Figure 14: Impact on fresh groundwater of a coral island during a tsunami.

1. Before the tsunami: a freshwater lens is recharged by infiltration of rainfall (and also by infiltration of waste water) and is pumped from shallow wells. The abstraction causes an upconing of brackish and saline water, which in case of overpumping results in high salinity levels in the pumped water.
2. Just before the tsunami: the waterlevel in the sea and in the lagoon is lowered. This is of a short duration and has negligible impact on the fresh groundwater.
3. Arrival of the tsunami: a subsurface pressure wave precedes the surface wave (because the surface wave quickly looses speed when reaching the island) and causes an upward movement of the freshwater lens. Water levels in wells rise. Previously fresh parts of the aquifer turn brackish. Hydrogeological properties (permeability, storage) may change, especially in locations where outflow of groundwater is easy (e.g. at wells or rock fractures).
4. During the tsunami: the island is completely flooded and saline water infiltrates through the unsaturated zone especially in areas with permeable soils. Salt water fills wells and enters the aquifer. Other pollutants present on the surface are spread with the water and will also contaminate the groundwater.
5. Shortly after the tsunami: the floodwater recedes and saline water remains in pools and puddles, increasing the duration of the infiltration. The saline water mixes with the fresh groundwater and intrudes the freshwater lens in brackish fingers. Pumping of wells will remove the saline water in the infiltrated well, but care should be taken not to attract brackish water by over pumping.
6. After the tsunami: rainfall will recharge the freshwater and slowly brackish groundwater will move down to the freshwater/saltwater mixing zone.

Gradually the situation before the tsunami is restored. However conditions may have changed (local increase of permeability affects the upcoming and the position of the mixing zone) and wells with previously fresh water may now be brackish.

A APPENDIX

A freshwater lens on an island

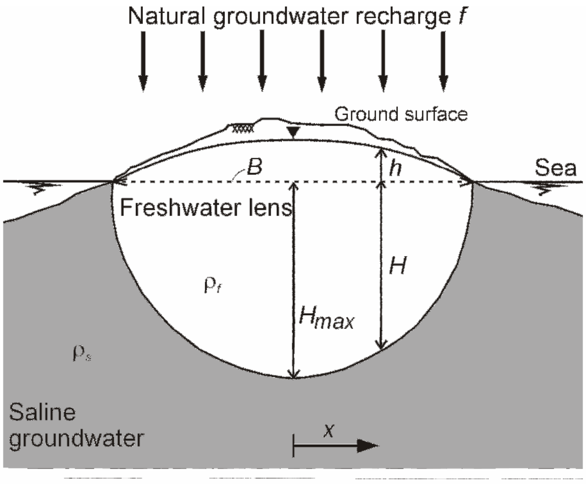


Figure I: Maldives case: the fresh-salt interface in an elongated island

Based on a quick analysis of the conditions in the Maldives, we have deduced the following values:

- B=width of island=400 m
- f=natural groundwater recharge: we've used the Hanimaadhoo 10 yrs average rainfall figures, and estimated that only 20% would supply the groundwater reservoir. Result for the worst case situation: each year 5 months no recharge and 7 months recharge. In total per year an amount of 303.4 mm (ref: http://www.meteorology.gov.mv/default.asp?pd=climate&id=3):
- k=hydraulic conductivity=40 m/day, worst case: it is assumed that the aquifer is good permeable, that the freshwater lens is shallow and the effect of the tsunami is relatively large.
- ρ_s, ρ_f = density of saline and fresh groundwater, 1025 and 1000 kg/m^3, respectively.
- $\alpha=(\rho_s-\rho_f)/\rho_f$=relative density difference=0.025, which is an accurate value for systems in ocean water.

Analytical estimate:

Based on the following analytical formula, the depth of a steady-state freshwater lens H is calculated as:

$$H = \sqrt{\frac{f\left(0.25B^2 - x^2\right)}{k(1+\alpha)\alpha}}$$

In addition, the volume of water in the freshwater lens per stretched meter width is equal to:

$$V = \frac{1}{4}\pi(1+\alpha)H_{\max}Bn_e$$

When the natural groundwater recharge is averaged to 303.4 mm over 1 year, viz. f=0.831mm/day, then the deepest position of the interface H_{max} (in the middle of the lens at x=0) is 5.7 m and the highest phreatic groundwater level 0.14 m. With an effective porosity n_e equal to 0.35, the volume V=641 m^3/m' and the characteristic time to fill the freshwater lens with recharge water is T=5.3 year. This means that without pumping, it takes about 16 years (3T) before the freshwater lens has 99.5 % of its original shape again: in groundwater terms, this reaction time can be characterized as rather quick.

A salt water wedge in a shallow aquifer

In many shallow phreatic aquifers, the freshwater body originally touches the impervious base, thus creating a salt water wedge of length L, see figure II. At the shore fresh groundwater flows out of the groundwatersystem. The corresponding boundary
conditions are:

$x = 0 \rightarrow q = q_0$ and $x = 0 \rightarrow H = 0$

where

- W = width of the coastal aquifer up to the water divide over which the natural groundwater recharge replenishes the coastal aquifer (L),
- q_0 = -fW = natural groundwater outflow at the coastline x=0 (L^2T^{-1}).

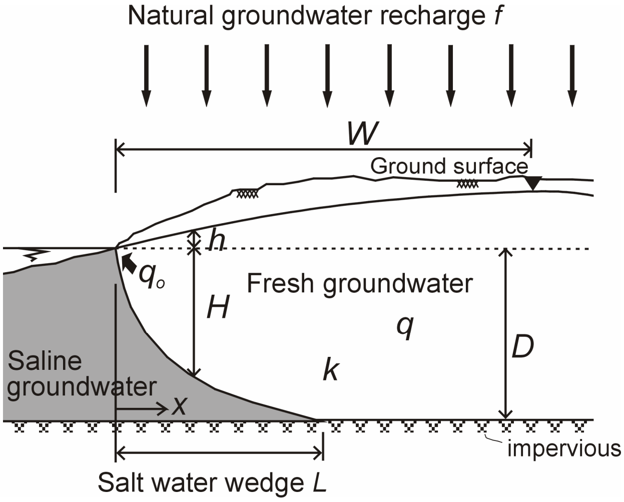


Figure II: Salt water wedge in a shallow coastal aquifer.

It is assumed that saline groundwater is stagnant. At the length of the salt water wedge x=L, the interface touches the impervious base at depth D. By using this boundary condition, the following length of the salt water wedge L can be deduced:

$$L = -\frac{q_0}{f} - \sqrt{\left(\frac{q_0}{f}\right)^2 - \frac{k}{f} D^2 (1+\alpha)\alpha}$$

The depth of a steady-state freshwater lens H is calculated as:

$$H = \sqrt{\frac{-fx^2 - 2q_0 x}{k(1+\alpha)\alpha}}$$

For example, if the W=2000 m, f=0.83 mm/day, α=0.025, k=40 m/day and D=20 m, then the length of the salt water wedge L is 127 m.

B APPENDIX Computer code MOCDENS3D

The used computer code is called MOCDENS3D. This code is based on MODFLOW and MOC3D, both from the USGS and widely used throughout the world. The MOCDENS3D code includes variable density groundwater flow and coupled solute transport (the density adaptation was built in 1998). All demonstrated concepts were modeled with the same code. Additional information on www.tno.nl/mocdens3d.

Some recent reviewed references are:

- Oude Essink, G.H.P. 2001. Salt Water Intrusion in a Three-dimensional Groundwater System in The Netherlands: A Numerical Study, *Transport in Porous Media*, 43 (1): 137-158.

- Bakker, M., Oude Essink, G.H.P. & Langevin, C. 2004. The rotating movement of three immiscible fluids, *J. of Hydrology* 287, 270-278.

- Bouw, L. & Oude Essink, G.H.P. 2003. Development of a freshwater lens in the inverted Broad Fourteens Basin, Netherlands offshore, *Journal of Geochemical Exploration*, Vol. 78-79, 321-325.

- Vandenbohede, A. & Lebbe, L., 2002. Numerical modelling and hydrochemical characterisation of a fresh water lens in the Belgian coastal plain. *Hydrogeology Journal* 10(5), 576-586.

- Oude Essink, G.H.P. 2001. Improving Fresh Groundwater Supply - Problems and Solutions, UNESCO International workshop on cities and coasts, Challenges of growing urbanization of the world's coastal areas, 27-30 September 1999, Hangzhou, China, Ocean & Coastal Management, 44 (5/6), 429-449.

- Oude Essink, G.H.P. 2003. Modelling density-dependent groundwater flow in coastal areas, salinisation of the Dutch groundwater flow system, TNO-NITG Information, special issue, 1-6.