IHE 2012

Density dependent groundwater flow

salt water intrusion (and heat transport)

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Lecture set-up:

- PowerPoint sheets
- Practicals

http://freshsalt.deltares.nl

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Curriculum Vitae

- Delft University of Technology, Civil Engineering: till 1997
  - Ph.D.-thesis: Impact of sea level rise on groundwater flow regimes
- Utrecht University, Earth Sciences: till 2002
  - Lectures in groundwater modelling and transport processes
  - Variable-density groundwater flow
  - Salt water intrusion and heat transport
- Free University of Amsterdam, Earth Sciences: till 2004
  - EC-project CRYSTECHSALIN
  - Crystallisation processes in porous media
- Deltares - Geological Survey of the Netherlands
  - Salinisation processes in Dutch coastal aquifers
  - Effect climate change on freshwater resources
  - Water management effect studies

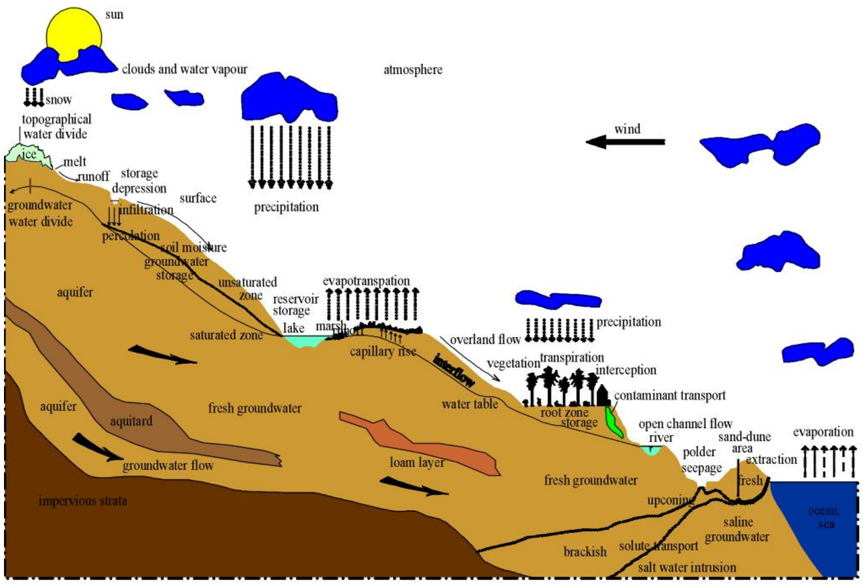
Topics of density driven groundwater flow

1. Introduction
   - water on earth
   - salt water intrusion
   - freshwater head
2. Interface between fresh and saline groundwater
   - analytical formulae
   - upconing example
3. Numerical modelling
   - mathematical background
   - MOCDENS3D, MODFLOW
   - Benchmark problems: Henry, Elder, Hydrocoin, etc.
4. Case-studies
   - hypothetical cases
   - real cases in the Dutch coastal zone

Topics of density driven groundwater flow

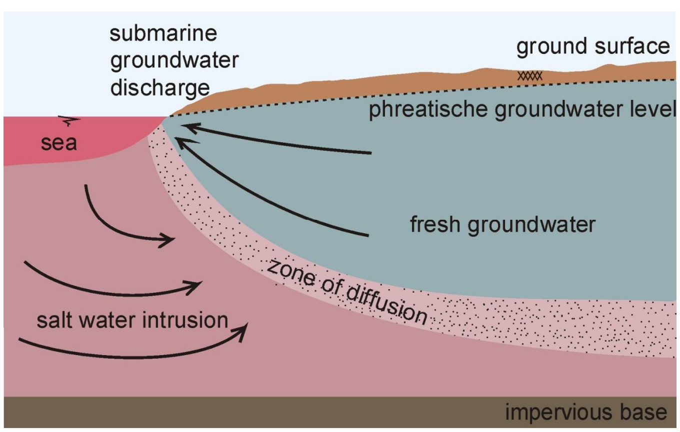
1. Introduction salt water intrusion
   - water on earth
   - concept of salt water intrusion
   - freshwater head
   - compensating measurements
2. Badon Ghyben-Herzberg
   - interface between fresh and saline groundwater
   - analytical formulations
   - upconing example
3. Freshwater head
   - hydrostatic pressure
4. Numerical modelling
   - mathematical background
   - MOCDENS3D, MODFLOW
   - benchmark problems: Henry, Elder, Hydrocoin, etc.
5. Case studies
   - hypothetical cases
   - real 3D cases (a.o in the Dutch coastal zone)

The Hydrological Circle

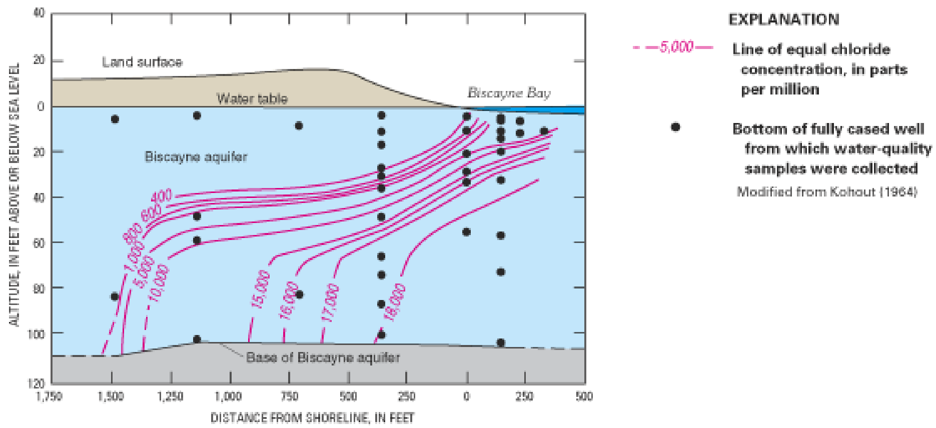


Definition of salt water intrusion

Inflow of saline water into an aquifer which contains fresh water

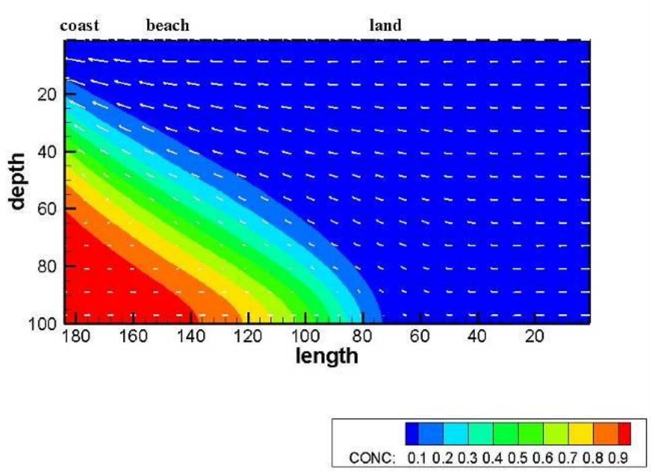


Biscayne aquifer, Florida USA: Henry's case



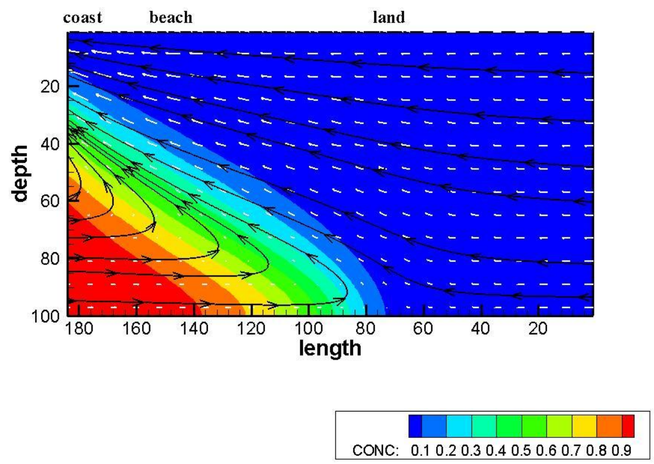
Definition of salt water intrusion

Numerical model: Henry's case



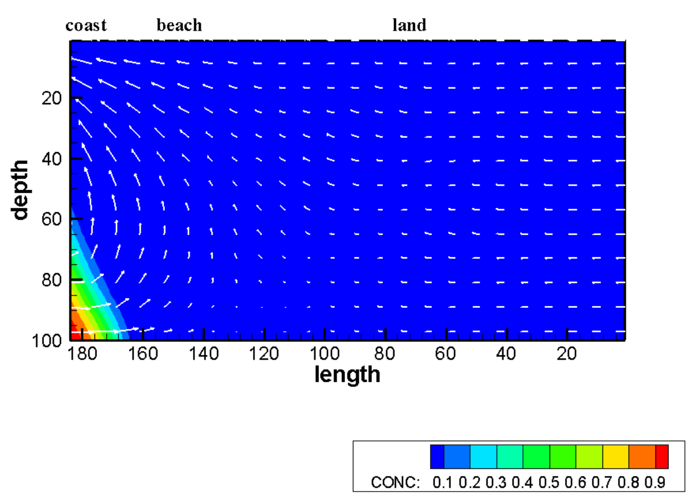
Definition of salt water intrusion

Numerical model: Henry's case

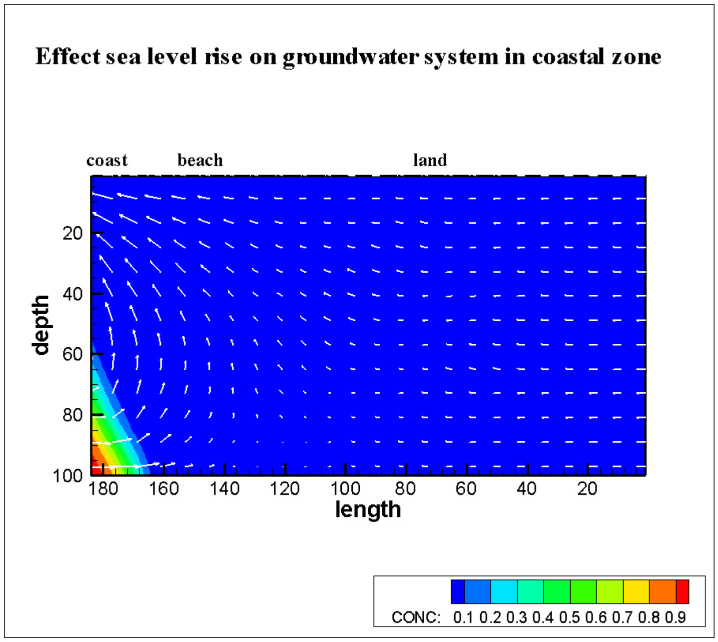


Sea level rise and salt water intrusion

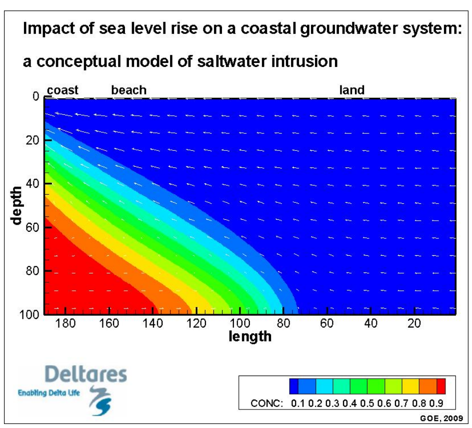
Effect sea level rise on groundwater system in coastal zone

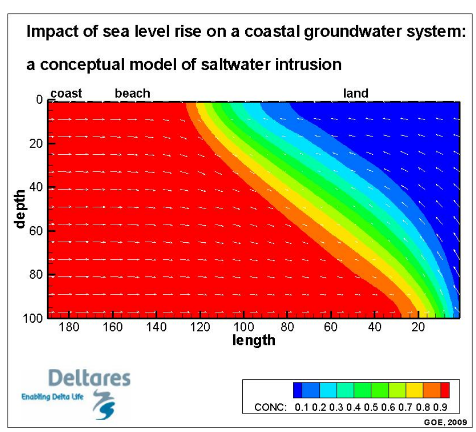


Sea level rise and salt water intrusion

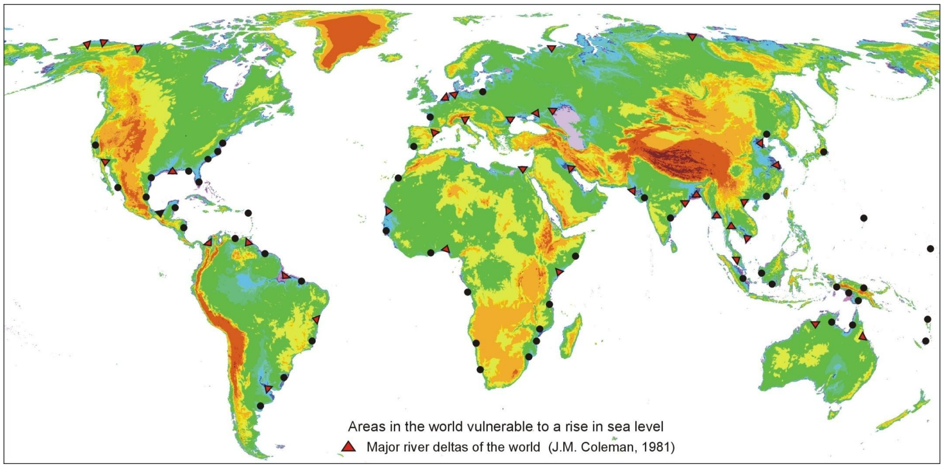


Sea level rise and salt water intrusion





Areas vulnerable to sea level rise



Water on Earth

Some serious developments:

"*shortage of drinking water will be one of the biggest problems of the 21th century*"

"*in 2025, two third of world population will face shortage of water*"

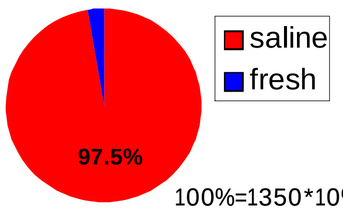
Question:

How much percent of all the water on Earth is fresh?:

a. 0.025 %
b. 0.1 %
c. 2.5 %
d. 10 %

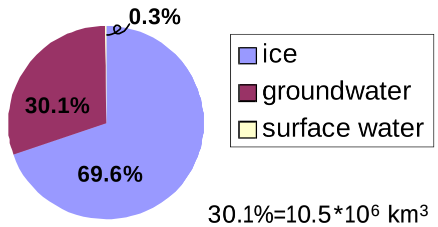
Water on Earth

Total water on Earth



100%=1350*10^6 km^3

Total fresh water on Earth



30.1%=10.5*10^6 km^3

Demand for groundwater (now 30%) increases due to:

- increase world population & economical growth
- loss of surface water due to contamination
- great resource: available in large quantities
- still unpolluted (relative to surface water)

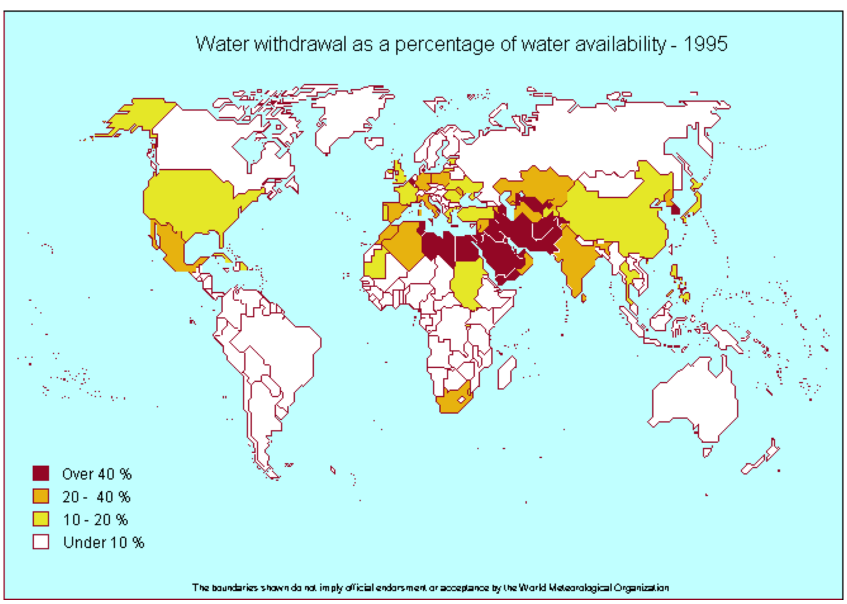
(Source: Cheng, 1998)

Question:

Demand fresh water per capita per day in the Netherlands?:

a. 10 litre/day
b. 25 litre/day
c. 100 litre/day
d. 200 litre/day

Water withdrawal



Reasons and drawbacks of using groundwater

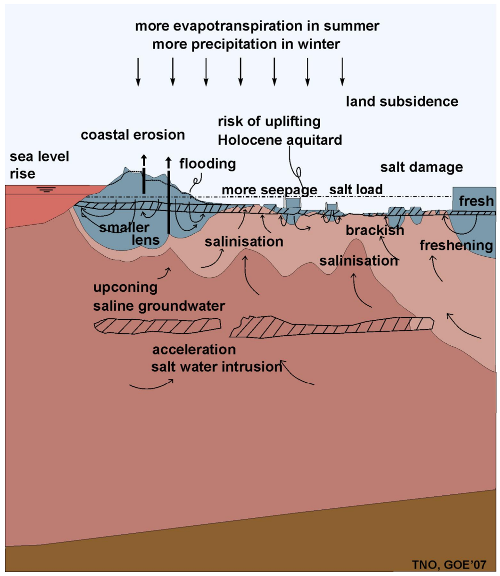
Advantage:
-no seasonal effects
-high quality
-low storage costs
-large quantities
-no spatial limitations

Disadvantage:
-high extraction costs
-local droughts
-high mineral content
-land subsidence....
-salt water intrusion !

(Source: Cheng, 1998)

Concept of a coastal area

Situation in the coastal zone



Land subsidence

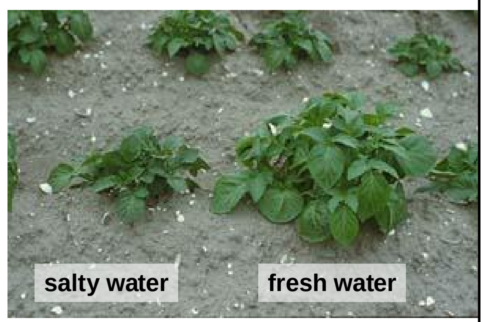
Megacity	Maximum subsidence [m]	Date commenced
Shanghai	2.80	1921
Tokyo	5.00	1930's
Osaka	2.80	1935
Bangkok	1.60	1950's
Tianjin	2.60	1959
Jakarta	0.90	1978
Manila	0.40	1960
Los Angeles	9.00	1930's

Salt in water is a problem for different water management sectors:

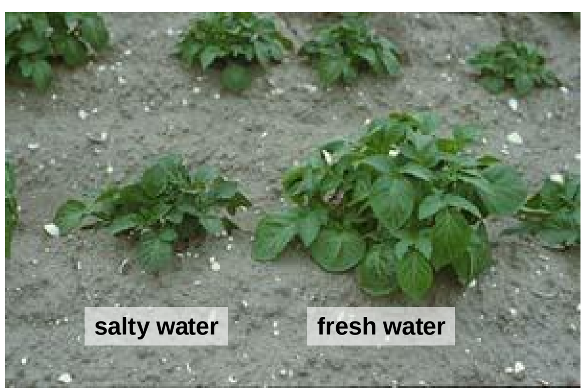
-drinking water:
- taste (100-300 mg Cl^-/l)
- long term health effect
- norm: EC& WHO=150 mg Cl^-/l (live stock=1500 mg Cl^-/l)

-industry:
- corrosion pipes
- preparation food

-irrigation/agriculture:
- production crops
- salt damage



Effects salinisation: salt damage



Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

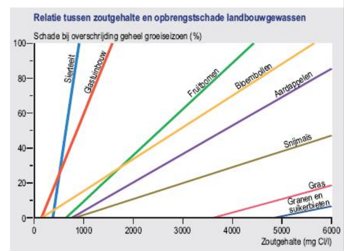
Salt damage to crops

Important parameters:

- Chloride concentration in the root zone
- Land use
- Sensitivity crops

Land use	Threshold value root zone (mg Cl-/l)	Gradient root zone (-)
Grass	3606	0.0078
Potatoes	756	0.0163
Beet	4831	0.0057
Grains	4831	0.0058
Horticulture	1337	0.0141
Orchard (trees)	642	0.0264
Bulb	153	0.0182

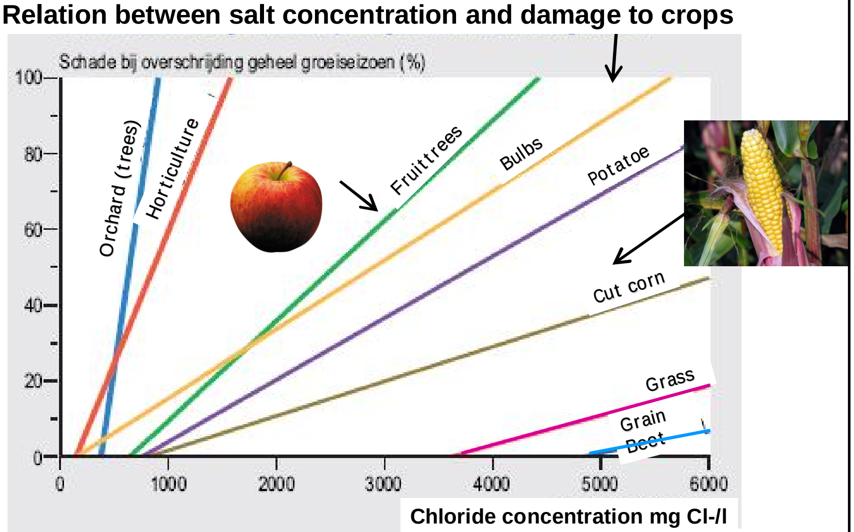
Source: Roest et al., 2003 en Haskoning



Source: MNP, 2005

Salt damage to crops

Relation between salt concentration and damage to crops



Source: MNP, 2005

	Soil moisture		Irrigation water	
	Limi	Gradient	Limit	Gradient
Crop	**mg/l Cl**	**%/mg/l Cl**	**mg/l Cl**	**%/mg/l Cl**
Potatoe	756	0.0163	202	0.0610
Grass	3606	0.0078	962	0.0294
Sugar beat	4831	0.0057	1288	0.0212
Cut Corn	815	0.0091	217	0.0343
Grains	4831	0.0058	1288	0.0218
Fruit trees	642	0.0264	171	0.0991
Orchard (trees)	378	0.1890	101	0.7086
Vegetables	917	0.0158	245	0.0591
Horticulture	1337	0.0141	356	0.0527
Bulbs	153	0.0182	41	0.0683

Why is salinisation a pressing problem?

- 50% of world population lives <60 km from coastline
- economic and tourist activities increase
- enormous increase in extraction
- irreversible process
- increase saltwater intrusion problem world-wide:
  - upconing
  - salt water wedge
  - decrease outflow q_0
- climate change:
  - sea level rise
  - natural groundwater recharge

Origin of saline groundwater in the subsoil

Geological causes:

-marine deposits during geological times
-trans- and regressions in coastal areas (deltas)
-salt/brine dome

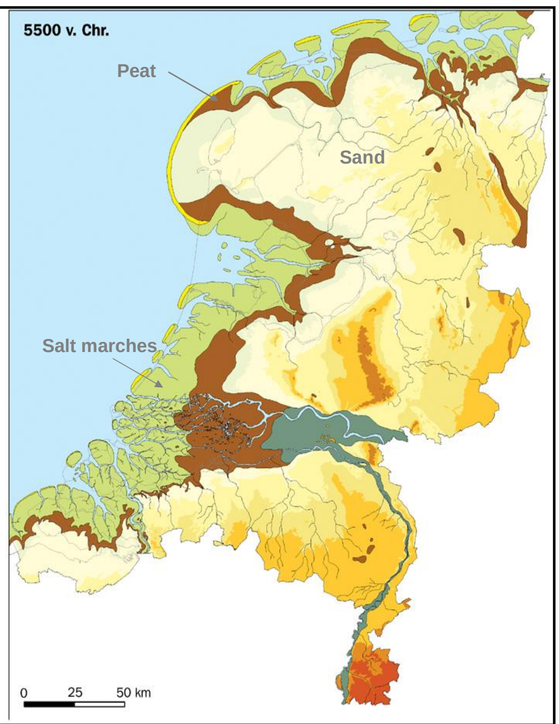
Anthropogenic causes:

-agriculture/irrigation (salt damage Middle East & Australia)
-upconing under extraction wells throughout the world
-upconing under low-lying areas (e.g. Dutch polders)

The Holocene transgressions

Major impact on present regional brackish groundwater systems

7500 BP

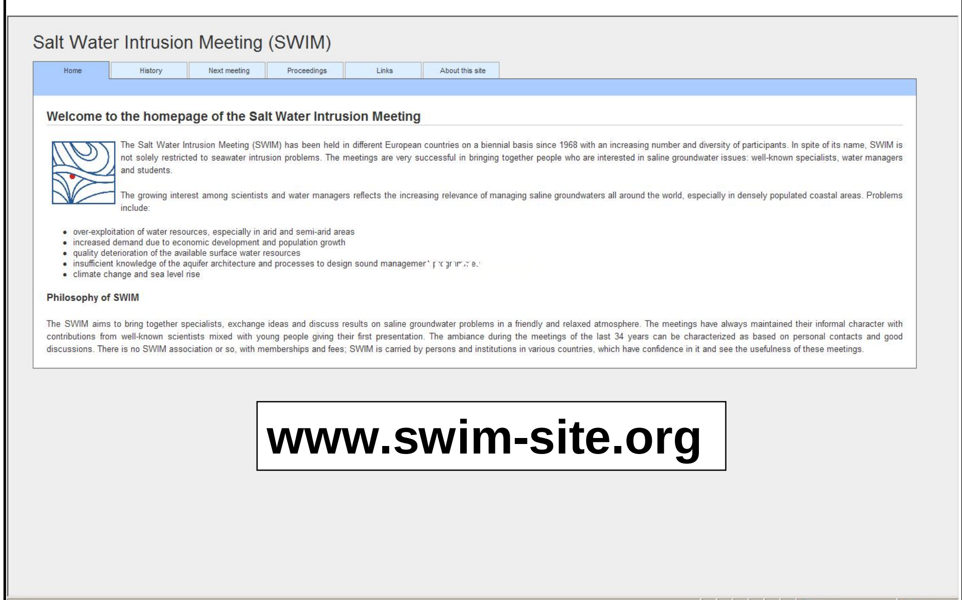


Processes that accelerate salt water intrusion:

- Sea level rise
- Land subsidence
- Human activities

Threats for:

- drinking water supply in dunes:
  - upconing of saline groundwater
  - decrease of fresh groundwater resources
  - recharge areas reduction
- agriculture:
  - salt damage to crops: salt load and seepage
- water management low-lying areas:
  - flushing water channels
- ecology



www.swim-site.org

Salt Water Intrusion Meeting (SWIM)

The proceedings of the Salt Water Intrusion Meeting

The SWIM proceedings span a period of almost 40 years. The proceedings of the first informal meeting consisted of a few pages in German. Successive meetings all had regular proceedings. They provide an excellent overview of the developments in the research of saline groundwater over the past decades.

At the 18th SWIM in Cartagena it was agreed that efforts will be undertaken to make all SWIM proceedings available through the internet. Currently, the proceedings of the 16th and 17th SWIM and the abstracts of the 18th and 19th SWIM are available from this web site. The proceedings of other meetings will become available as soon as they have been digitized.

Available for download:

- Abstracts of the 19th Salt Water Intrusion Meeting, Cagliari, Italy
- Abstracts of the 18th Salt Water Intrusion Meeting, Cartagena, Spain
- Proceedings of the 17th Salt Water Intrusion Meeting, Delft, The Netherlands
- Proceedings of the 16th Salt Water Intrusion Meeting, Wolin Island, Poland
- Proceedings of the 15th Salt Water Intrusion Meeting, Ghent, Belgium

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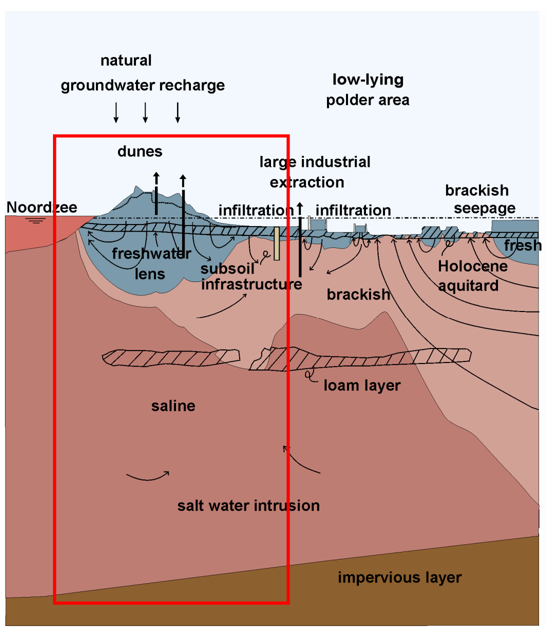
Salt Water Intrusion Meeting (SWIM)

Proceedings of the 17th Salt Water Intrusion Meeting, Delft, The Netherlands

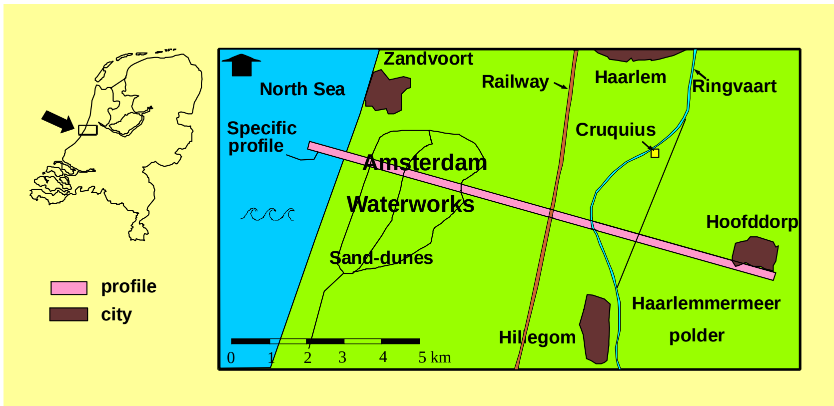
My first density dependent groundwater flow and solute transport model in 1990!

Saltwater intrusion in the Netherlands



Saltwater intrusion in the Dutch coastal zone

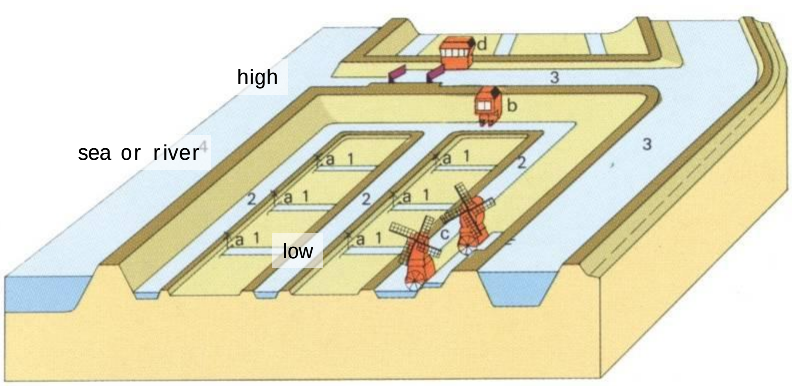
Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



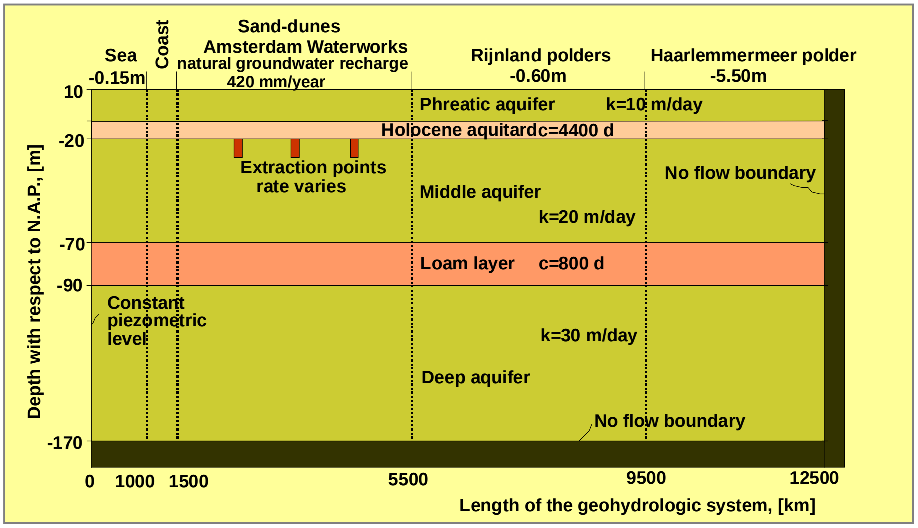
The polder system

A polder is:

a sophisticated system to drain the excess of water in a low-lying area

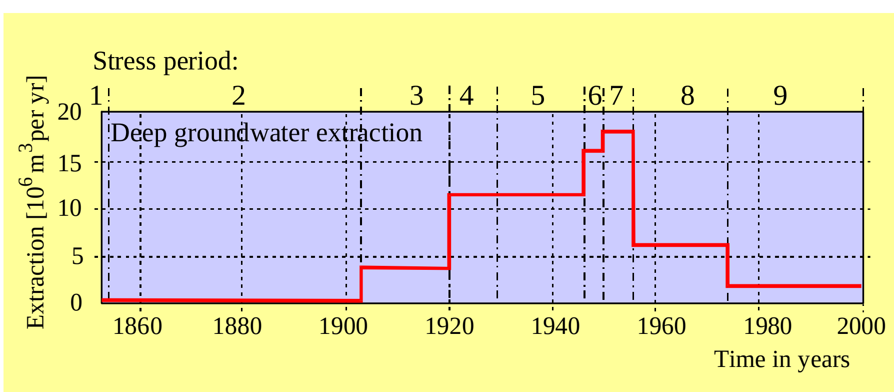


Geometry, subsoil parameters, boundary conditions

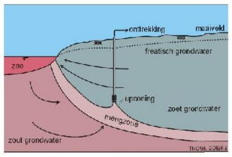


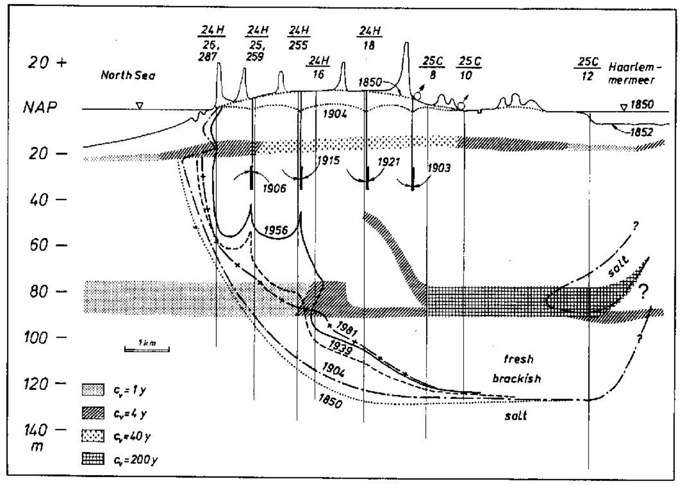
Saltwater intrusion in the Dutch coastal zone

Grondwater extractions out of the middle aquifer in the sand-dune area of Amsterdam Waterworks



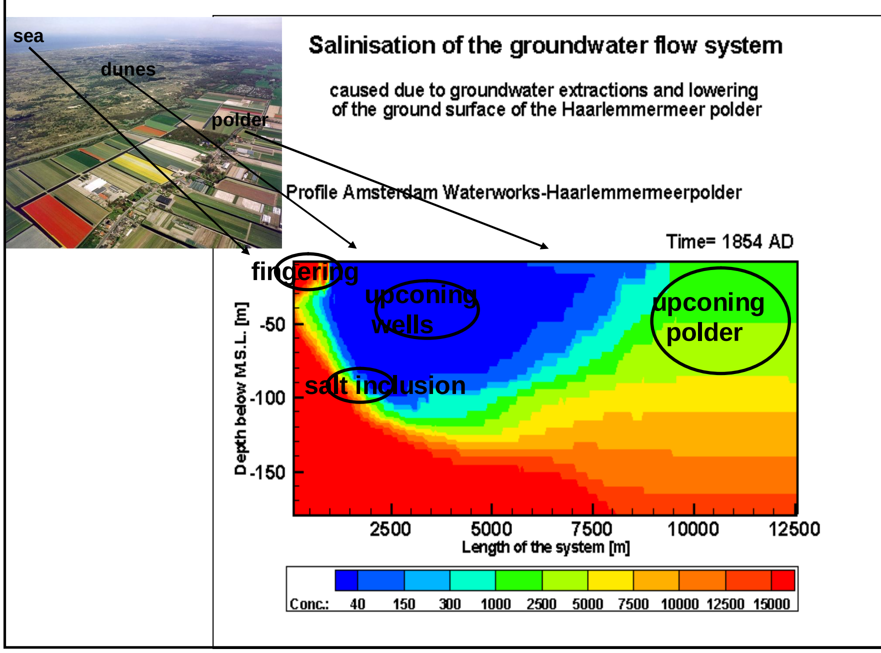
Upconing of brackish-saline groundwater



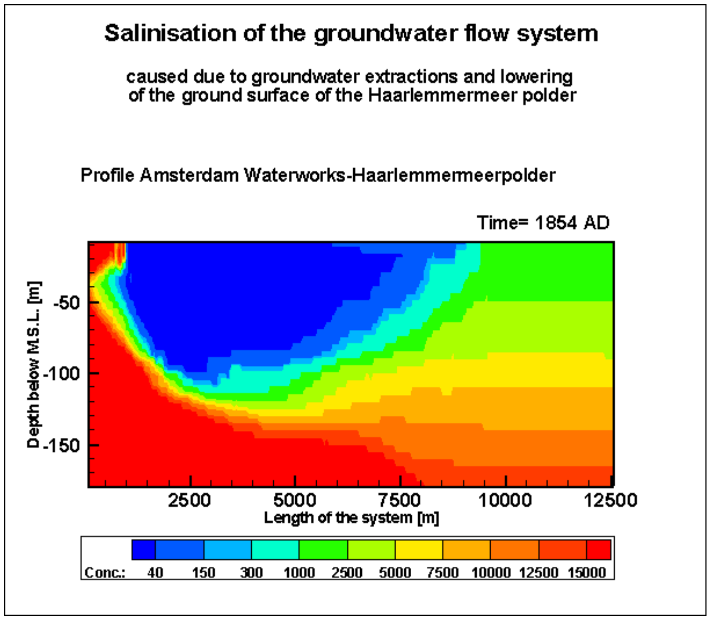


Stuyfzand, 1993

Saltwater intrusion in the Dutch coastal zone



Saltwater intrusion in the Dutch coastal zone



Compensating measures

Possible solutions to stop salt water intrusion:

- Restriction of groundwater extractions through permits
- Co-operation between authorities and water users
- Desalinisation of saline water
- Technical countermeasures of salt water intrusion
  - six examples

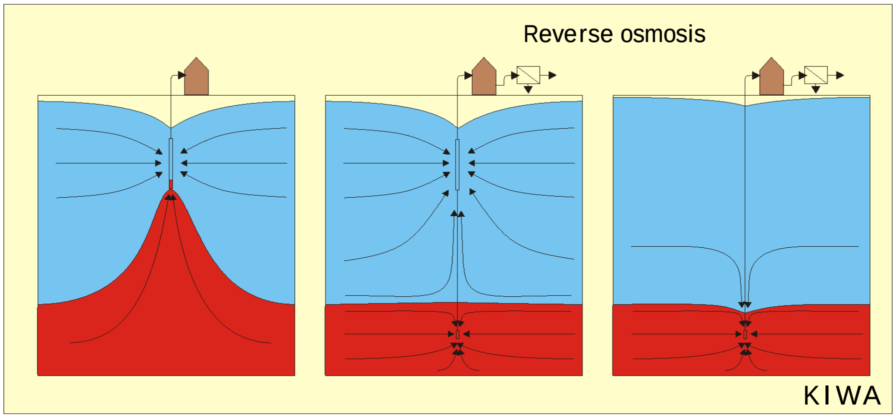
Tools to understand salt water intrusion:

- Monitoring of salinities and piezometric levels
- Numerical modelling of salt water intrusion

Measures to compensate salt water intrusion

- 'The Fresh Holder'
- Extraction of saline/brackish groundwater
- Infiltration of fresh surface water
- Modifying pumping rates
- Land reclamation in front of the coast
- Creating physical barriers (chrystallisation or biosealing)

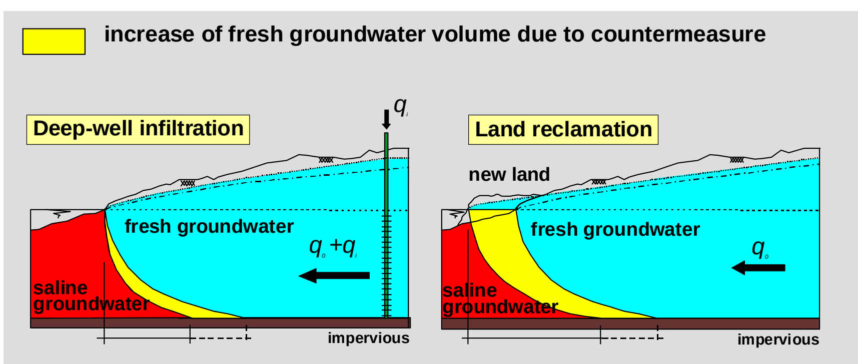
Solution: The Fresh Holder



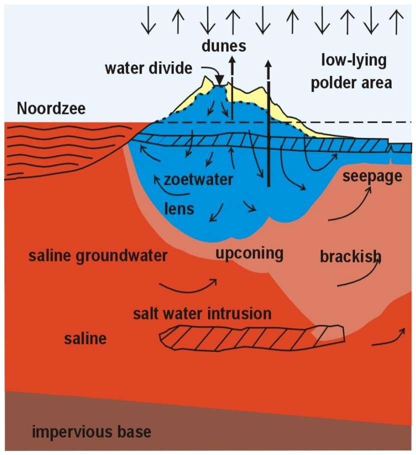
Upconing can be prevented by the extraction of brackish groundwater

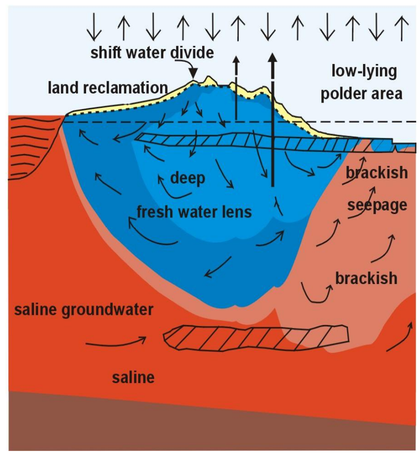
This brackish groundwater can be transformed to water of agricultural water quality by using the membrane filtration technique

Countermeasures of salt water intrusion (1)

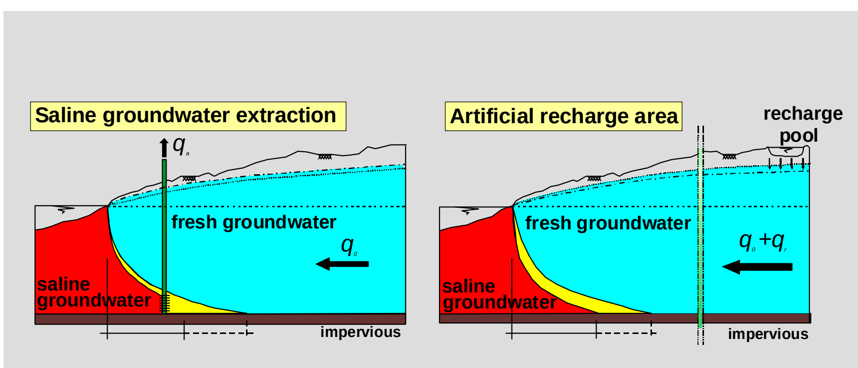


Countermeasures of salt water intrusion (1)

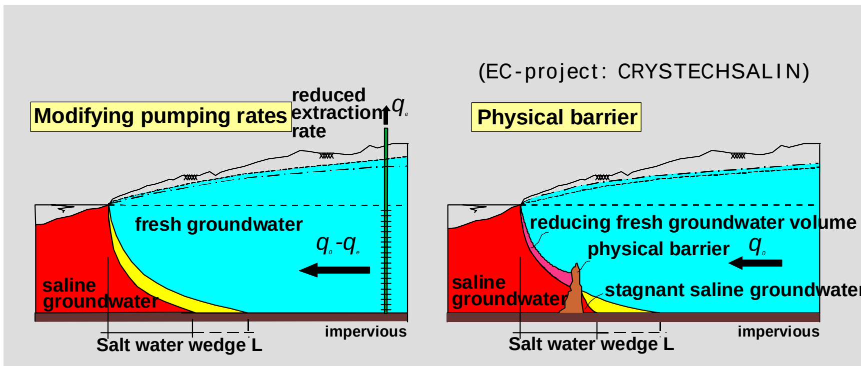




Countermeasures of salt water intrusion (2)

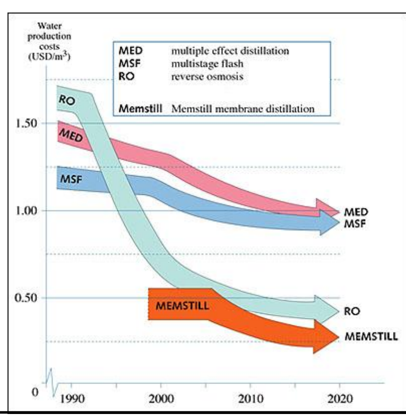


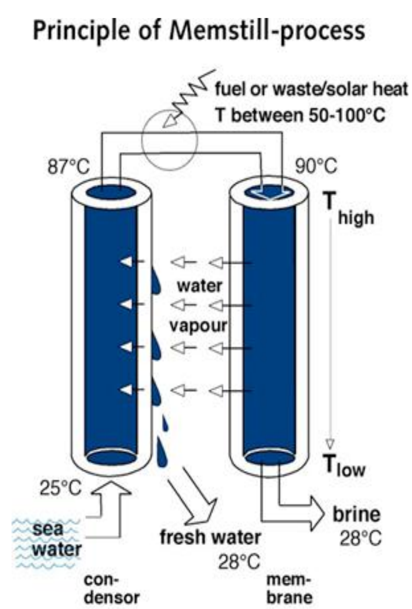
Countermeasures of salt water intrusion (3)



Memstill - technology

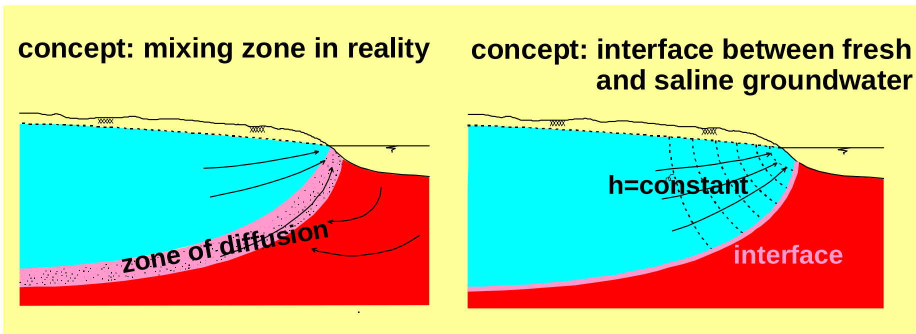
- new, cheap technique
- membrane distillation technique
- no primary energy
- test sites in Rotterdam and Singapore





Badon Ghyben-Herzberg principle (I)

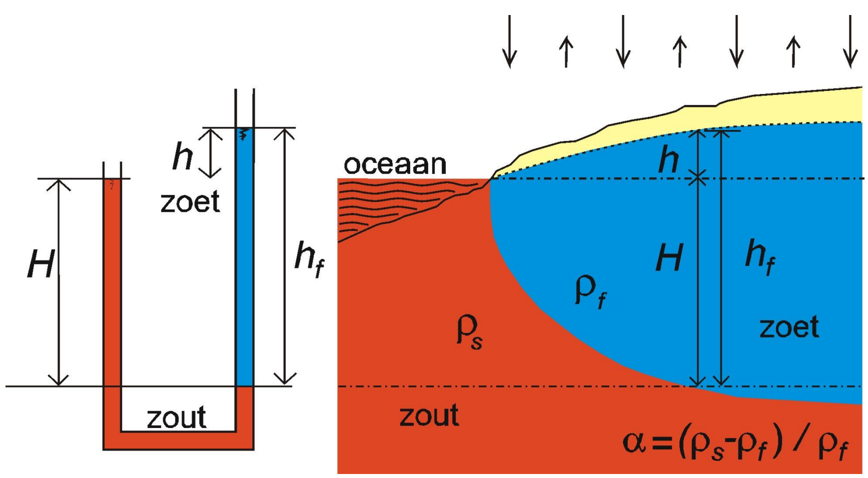
Difference between reality and Badon Ghyben-Herzberg approximation



Badon Ghyben-Herzberg principle

The principle suggests an interface between fresh and saline groundwater

Analogy: iceberg & saline ocean and granite tectonic plate & basalt base

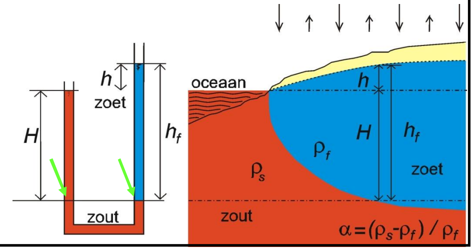


pressure saline groundwater=pressure fresh groundwater

$$\rho_s H g = \rho_f (H + h) g$$

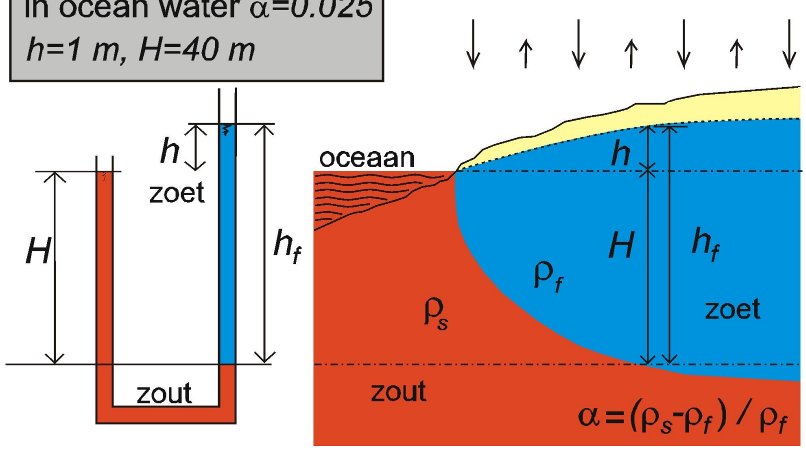
$$h = \frac{\rho_s - \rho_f}{\rho_f} H$$

$$h = \alpha H$$

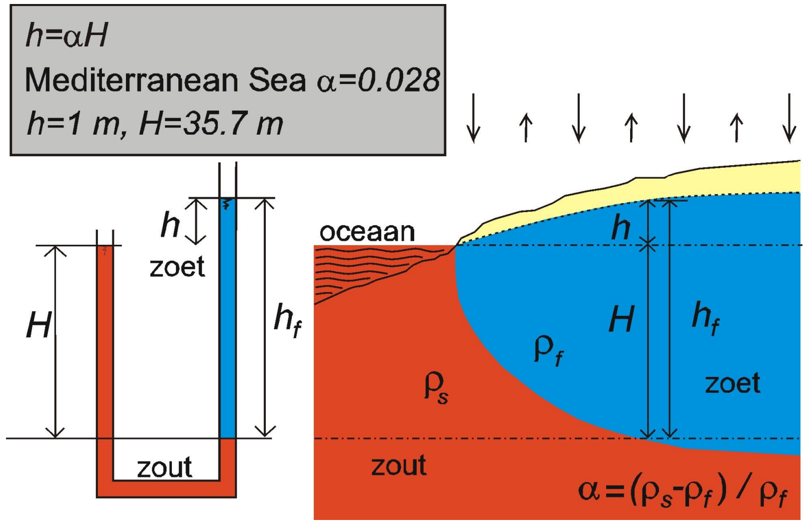


$$h = \alpha H$$

h=αH
in ocean water α=*0.025*
h=1 m, H=40 m



$$h = \alpha H$$



Badon Ghyben-Herzberg principle

- gives analytical solutions (see later and lectures)
- educational

- interface is a simple approximation
- dispersion zone <10m
- relative simple geometries

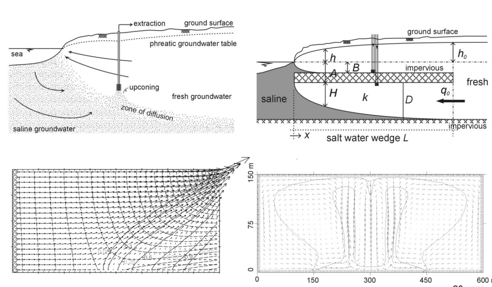
Badon Ghyben-Herzberg principle

What is the case then $h \neq \alpha H$?

1. still dynamic situation
2. occurrence resistance layer
3. natural groundwater recharge not constant
4. relative density difference a is not ok
5. occurrence shallow bedrock
6. groundwater extractions

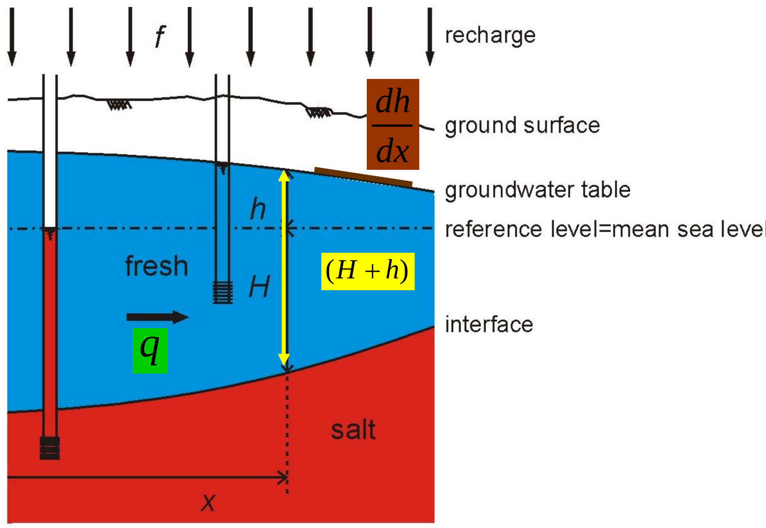
Analytical solutions

See lecture notes *Density dependent groundwater flow* (p. 29-48)



http://public.deltares.nl/display/FRESHSALT/Literature

Unconfined aquifer (1D situation)



Unconfined aquifer (1D situation)

(I) Darcy $q = -k(H+h)\dfrac{dh}{dx}$

(II) Continuity $dq = f dx$

(III) BGH $h = \alpha H$

Unconfined aquifer (1D situation)

$dq = f dx$ integration gives $q = fx + C1$

$$-k(H+h)\frac{dh}{dx} = fx + C1$$

$$h = \alpha H \quad \rightarrow \quad -k(H+\alpha H)\alpha\frac{dH}{dx} = fx + C1$$

$$HdH = -\frac{fx + C1}{k\alpha(1+\alpha)}dx$$

Unconfined aquifer (1D situation)

$$HdH = -\frac{fx + C1}{k\alpha(1+\alpha)}dx$$

integration gives

$$\frac{1}{2}H^2 = \frac{-\frac{1}{2}fx^2 - C1x + C2}{k\alpha(1+\alpha)}$$

$$H = \sqrt{\frac{-\frac{1}{2}fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}}$$

Unconfined aquifer (1D situation)

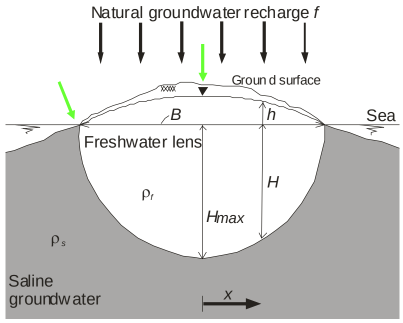
$$H = \sqrt{\frac{-\frac{1}{2} fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}}$$

$$h = \alpha H$$

$$q = fx + C1$$

Example 1: Elongated island

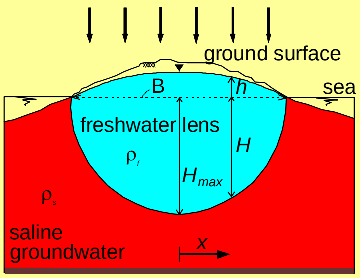
$$H = \sqrt{\frac{-\frac{1}{2} fx^2 - C1x + C2}{k\alpha(1+\alpha)}}$$



Boundary conditions

$$x = 0 : q = 0 \rightarrow C1 = 0$$
$$x = 0.5B : H = 0 \rightarrow C2 = fB^2/8$$

Example of analytical solutions (I)



Depth of fresh-saline interface H

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

$$h = \alpha H$$

Maximal thickness lens

$$H_{\max} = \frac{1}{2} B \sqrt{\frac{f}{k\alpha(1+\alpha)}}$$

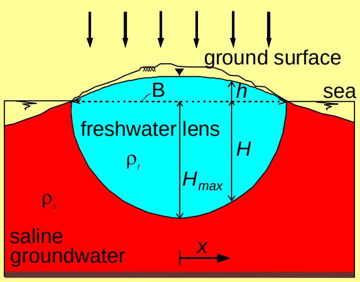
Volume lens

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

Characteristic time $\mathrm{T} = \dfrac{\text{volume of water in lens}}{\text{inflow of water}} = \dfrac{\pi n_e B}{8}\sqrt{\dfrac{(1+\alpha)}{kf\alpha}}$

Lecture notes p. 32

Example of analytical solutions (I)



Depth of fresh-saline interface H

$$B = 2000\text{m},\ f = 0.001\text{m/day}$$

$$k = 10\text{m/day}, \alpha = 0.025$$

$$n_e = 0.35$$

Maximal thickness lens

$$H_{\max} = 62.5\text{m}, h_{\max} = 1.56\text{m}$$

Volume lens (wrong in lectures notes)

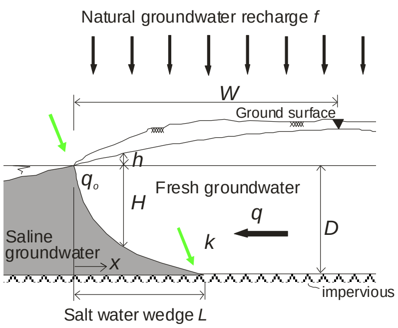
$$V = 35203\text{m}^3/\text{m}'$$

Characteristic time $\mathrm{T} = \dfrac{35203}{2}\text{days} = 48.2\text{years}$

Lecture notes p. 32

Example 2: salt water wedge

$$H = \sqrt{\frac{-\frac{1}{2} f x^2 - C1 x + C2}{k\alpha(1+\alpha)}}$$



Boundary conditions

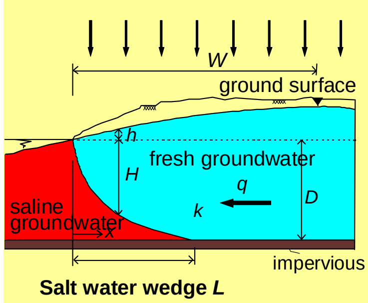
$$x = 0 : q = q_0 \rightarrow q_0 = -fW \rightarrow C1 = q_0$$

$$x = 0 : H = 0 \rightarrow C2 = 0$$

Length of salt water wedge

$$x = L : H = D$$

Example of analytical solutions (II)



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

$$q_0 = -fW$$

$$h = \alpha H$$

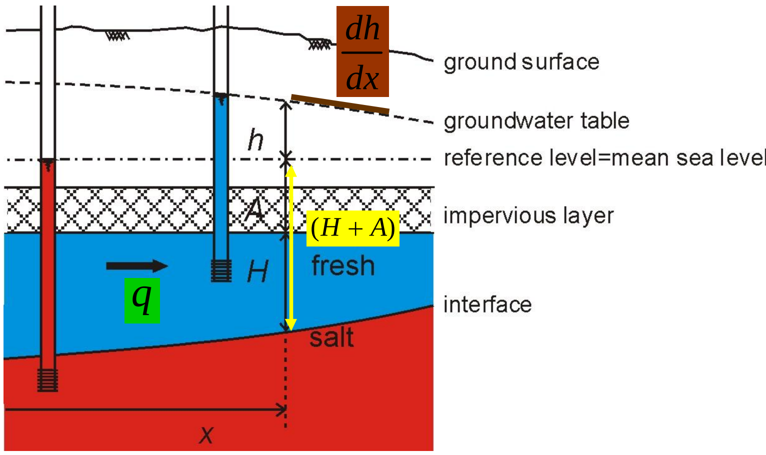
Example:

$$W = 3000\text{m},\ f = 0.001\text{m/day}, \alpha = 0.020, k = 20\text{m/day}, D = 50\text{m}$$

$$L = 175.1\text{m}$$

Lecture notes p. 33

Confined aquifer (1D situation)



Confined aquifer (1D situation)

(I) Darcy $$q = -kH\frac{dh}{dx}$$

(II) Continuity $$q = q_o$$

(III) BGH $$h = \alpha(H + A)$$

Confined aquifer (1D situation)

$$-kH\frac{dh}{dx} = q_0$$

$$HdH = -\frac{q_0}{k\alpha}dx$$

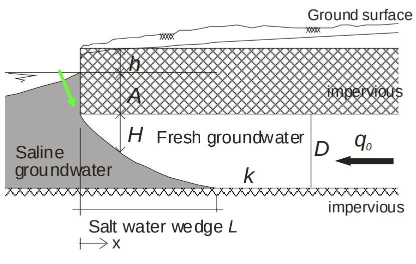
integration gives

$$\frac{1}{2}H^2 = \frac{q_0 x}{k\alpha} + C$$

$$H = \sqrt{-\frac{2q_0 x}{k\alpha} + 2C}$$

Example 3: salt water wedge confined aquifer

$$H = \sqrt{-\frac{2q_0 x}{k\alpha} + 2C}$$



Boundary condition

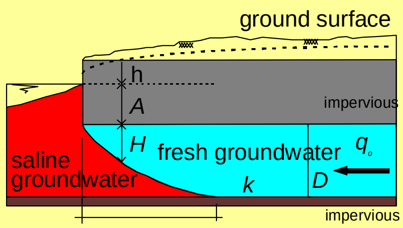
$$x = 0: H = 0 \rightarrow C = 0$$

$$H = \sqrt{-\frac{2q_0 x}{k\alpha}}$$

Length of salt water wedge $x = L: H = D$

$$L = -\frac{kD^2\alpha}{2q_0}$$

Example of analytical solutions (III)



Salt water wedge L

Length of salt water wedge

$$H = \sqrt{-\frac{2q_0 x}{k\alpha}}$$

$$L = -\frac{kD^2\alpha}{2q_0}$$

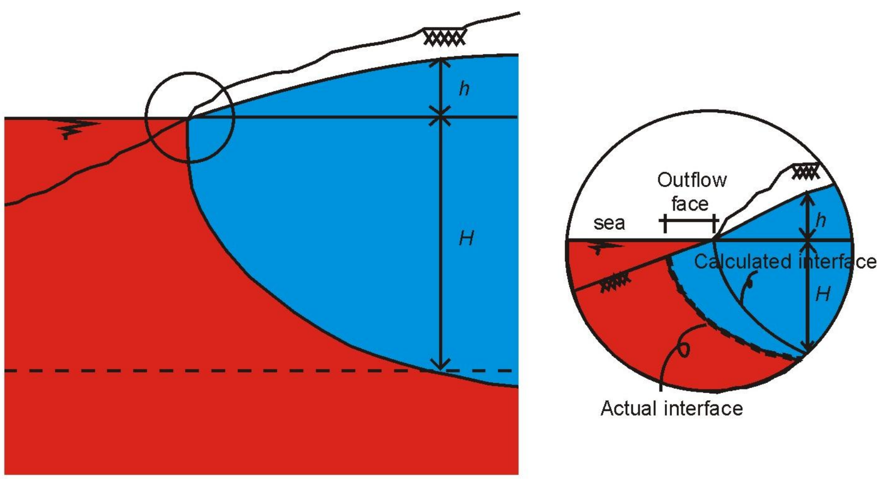
Example:

$$W = 2000\text{m},\ f = 0.001\text{m/day}, \alpha = 0.025, k = 25\text{m/day}, D = 40\text{m}$$

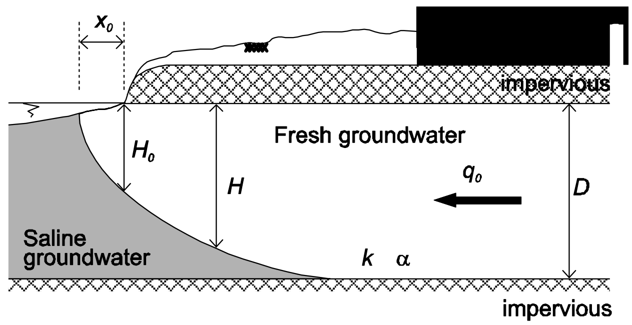
$$L = 250\text{m}$$

Lecture notes p. 35-36

Outflow face (Submarine Groundwater Discharge)



Outflow face (Submarine Groundwater Discharge)

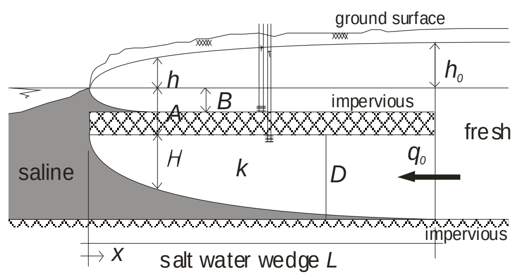


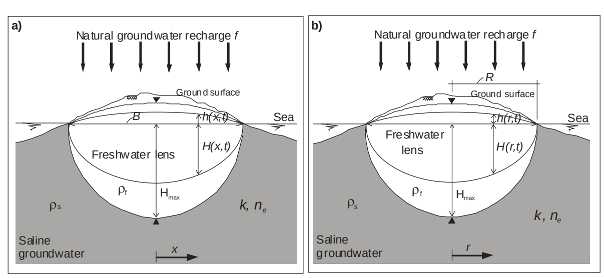
$$x_0 = \frac{q_0}{2k\alpha} \qquad H_0 = \frac{q_0}{k\alpha}$$ Glover (1959)

Example:
x_0= f*L/(2ka) = 0.001m/d*20000m/(2*20*0.025) = 20m (only!)

Note: no resistance layer offshore

See the lectures for more cases

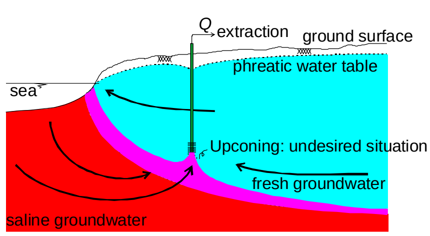




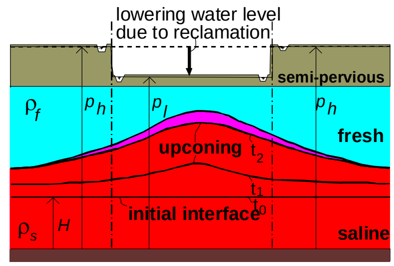
Upconing processes

Upconing of saline groundwater

Under an extraction well



Under a low-lying polder area

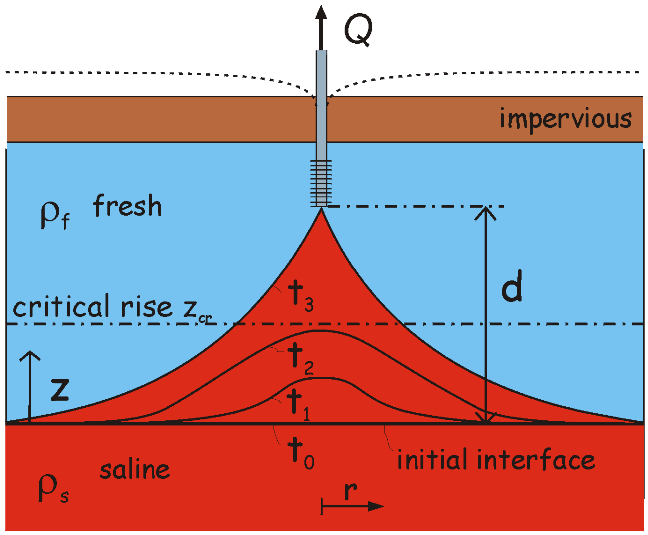


- movement of saline groundwater to extraction wells
- increase in salinity (>150-200 mg Cl-/l)
- lowering of the piezometric head (leads to land subsidence: e.g. Los Angeles: 9 m in the 1930's)

'Solutions': reduce extraction rate, abandon well, inundate polder

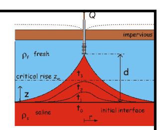
Examples of analytical solutions (IV)

Upconing of saline groundwater under an extraction well



Examples of analytical solutions (IV)

Upconing of saline groundwater under an extraction well

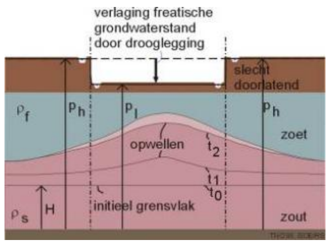


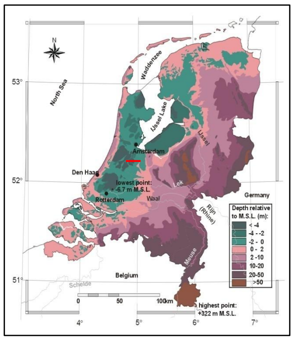
$$z(r,t) = \frac{Q}{2\pi \alpha k_x d}\left[\frac{1}{(1+R'^2)^{1/2}} - \frac{1}{[(1+\gamma')^2 + R'^2]^{1/2}}\right]$$

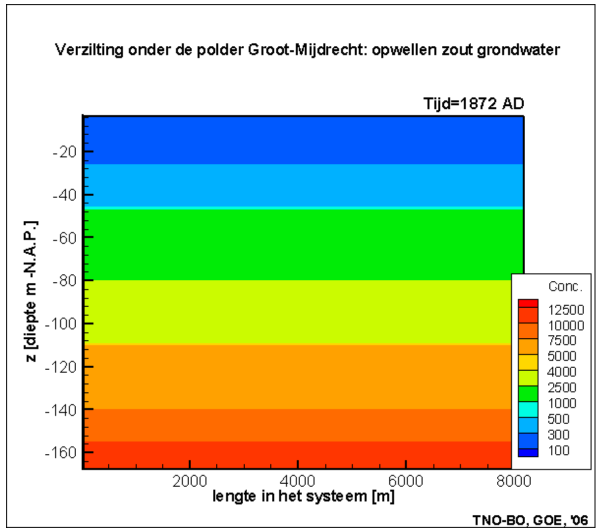
$$R' = \frac{r}{d}\frac{k_z}{k_x}^{1/2} \qquad \gamma' = \frac{\alpha k_z}{2 n_e d} t$$

Dagan & Bear, 1968, J. Hydraul. Res 6, 1563-1573

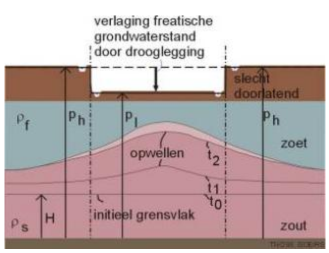
Upconing under a low-lying polder (Groot-Mijdrecht)

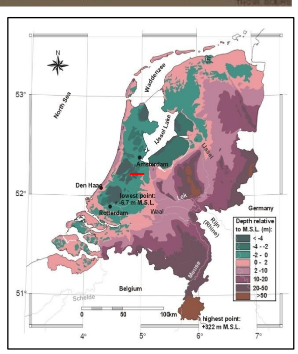


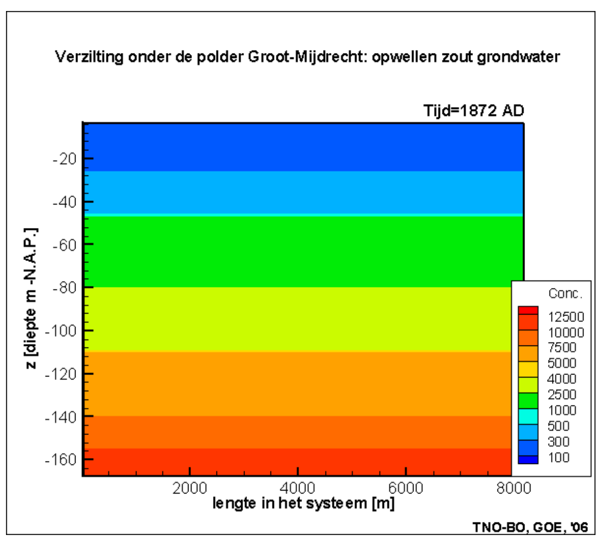




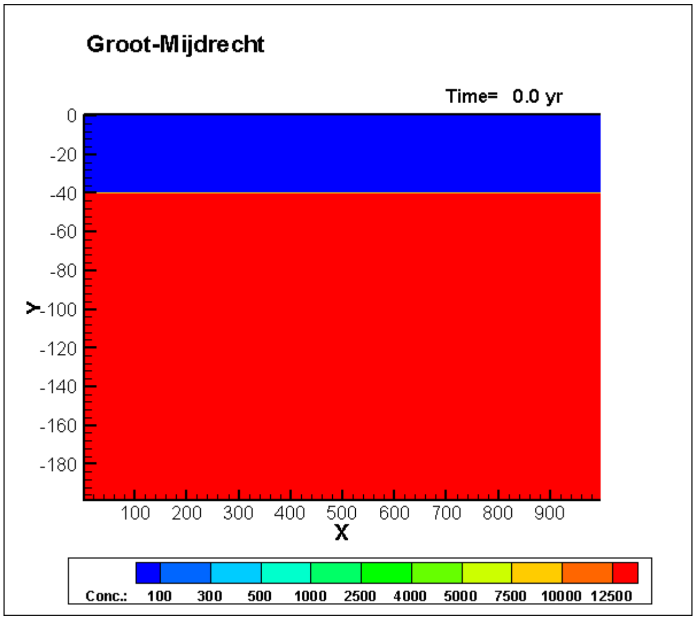
Upconing under a low-lying polder (Groot-Mijdrecht)



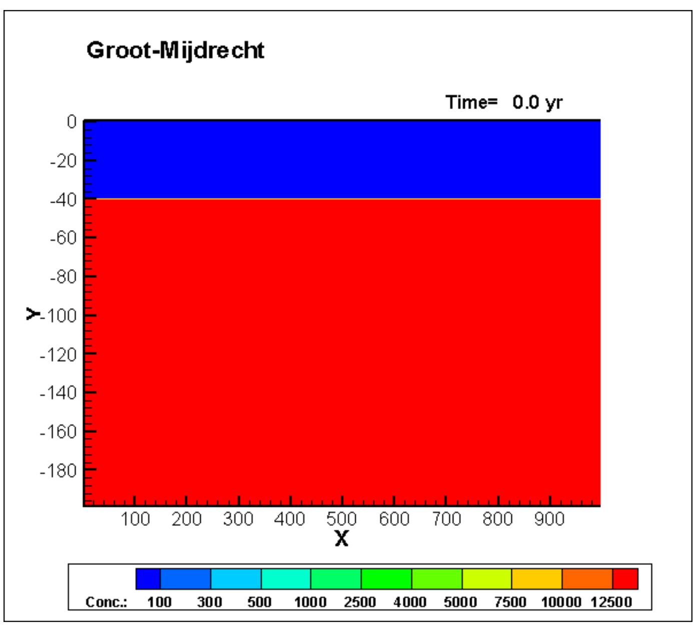




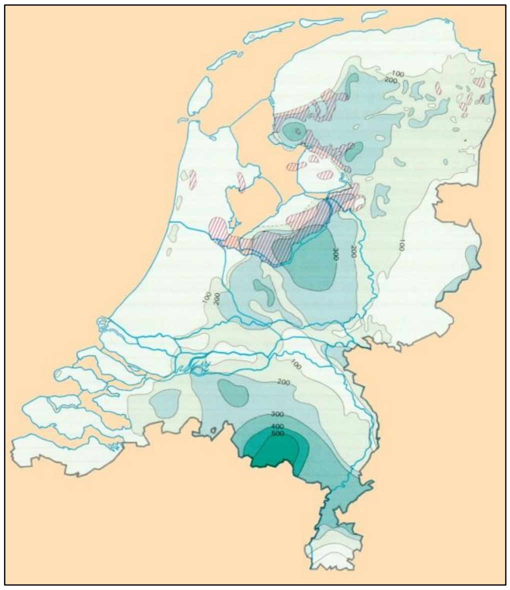
Upconing under a low-lying polder (Groot-Mijdrecht)



Upconing under a low-lying polder (Groot-Mijdrecht)

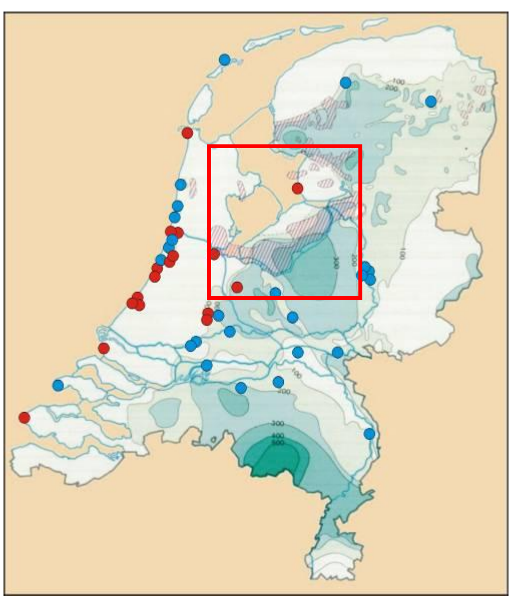


Fresh-salt interface (150 mg Cl^-/l)



- <100 m
- 100-200 m
- 200-300 m
- 300-400 m
- 400-500 m
- >500 m
- >inversion (fresh under salt)

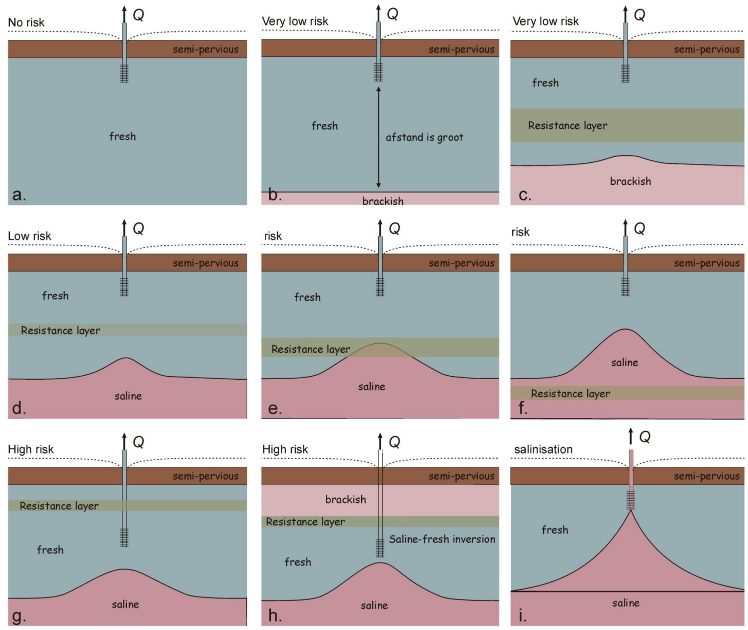
Availability of fresh groundwater



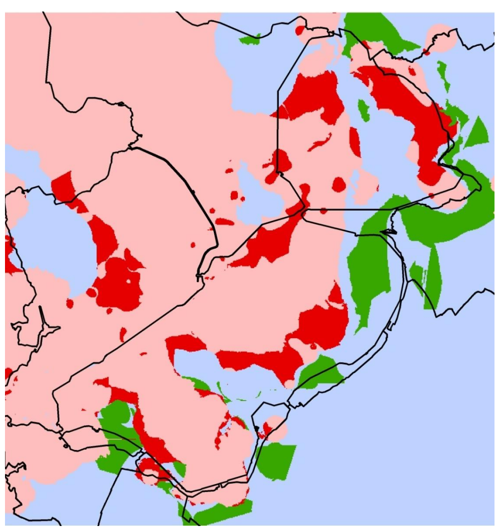
- <100 m
- 100-200 m
- 200-300 m
- 300-400 m
- 400-500 m
- >500 m
- >inversion (salt above fresh)

- Pumping stations with salinisation
- Pumping stations closed due to salinisation (20%=100 stations)

Different risks of upconing saline groundwater



Upconing in Flevoland



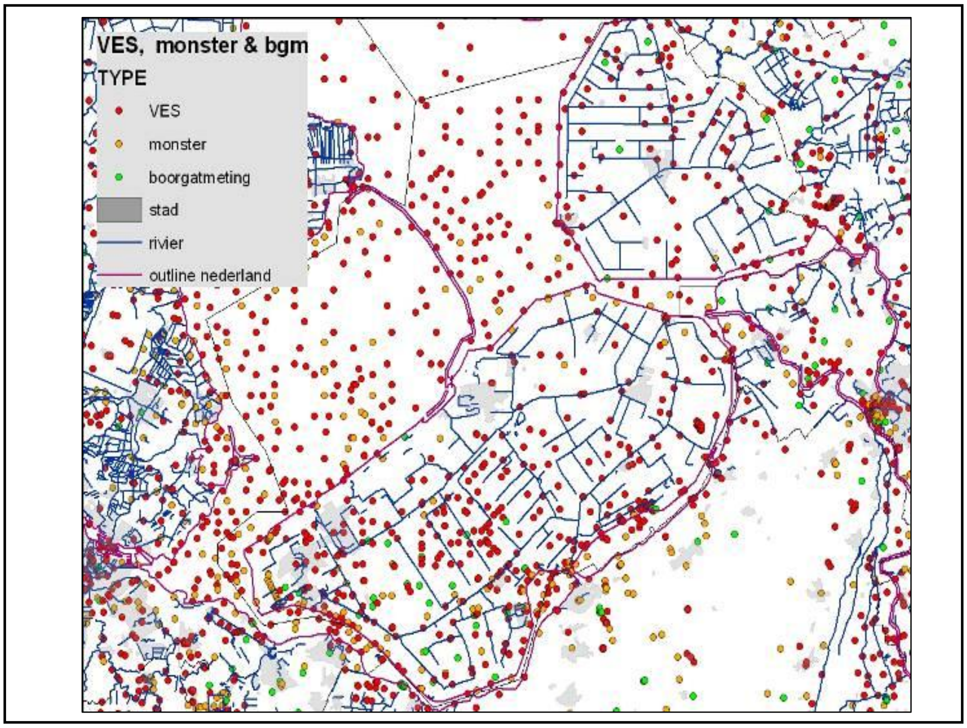
Risk depends on:

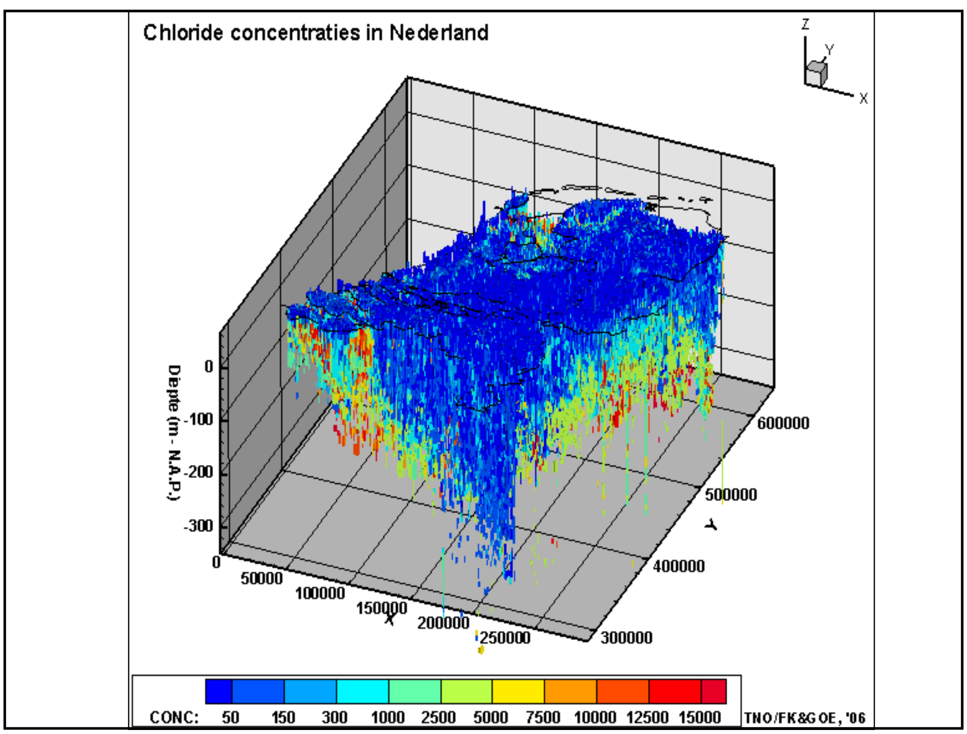
- Initial position interface
- Resistance layers
- Existance inversion
- Extraction rate and scheme

High risk

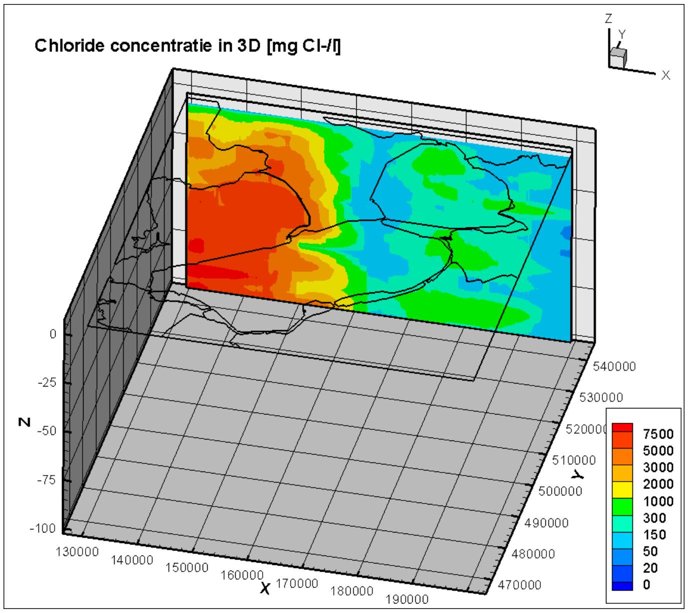
Low risk

Very low risk

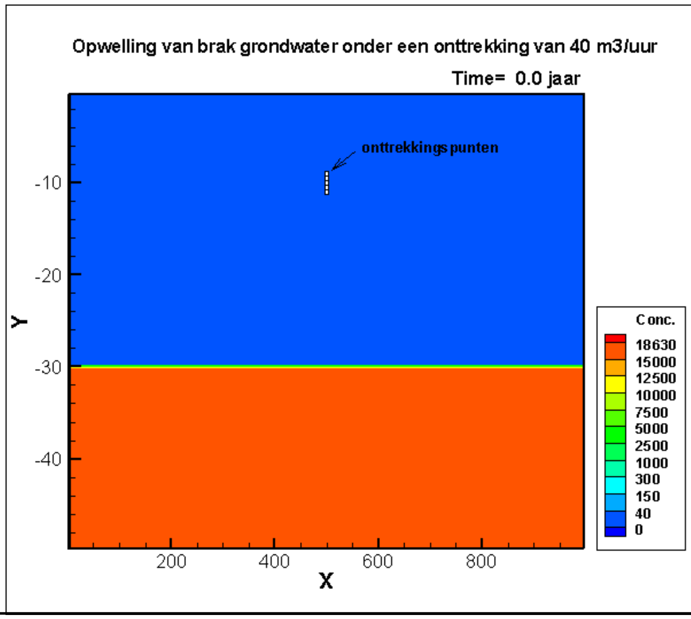

VES, monster & bgm
TYPE
VES
monster
boorgatmeting
stad
rivier
outline nederland


Chloride concentraties in Nederland
Z
Y
X
Diepte (m - N.A.P.)
0
-100
-200
-300
0
50000
100000
150000
200000
250000
X
300000
400000
500000
600000
Y
CONC: 50 150 300 1000 2500 5000 7500 10000 12500 15000
TNO/FK&GOE, '06

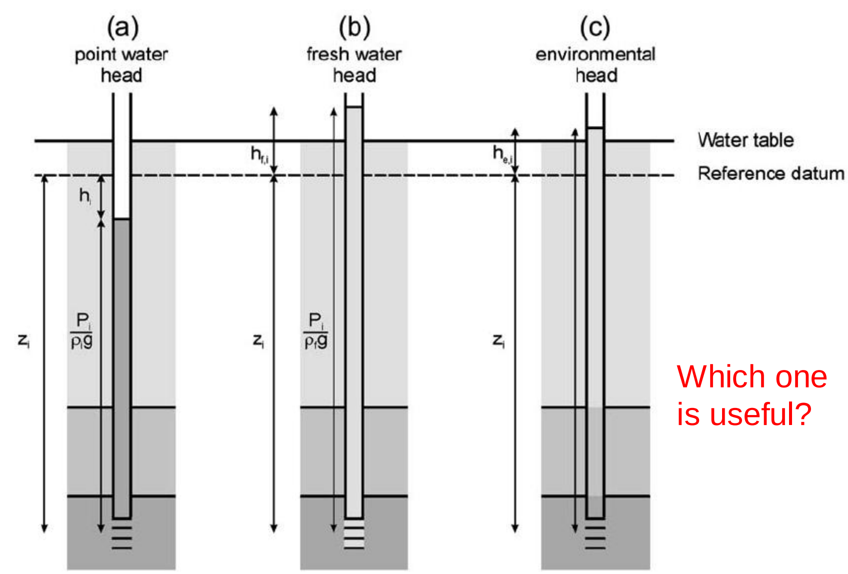
Animation 3D Chloride concentration



Upconing of salt under an extraction

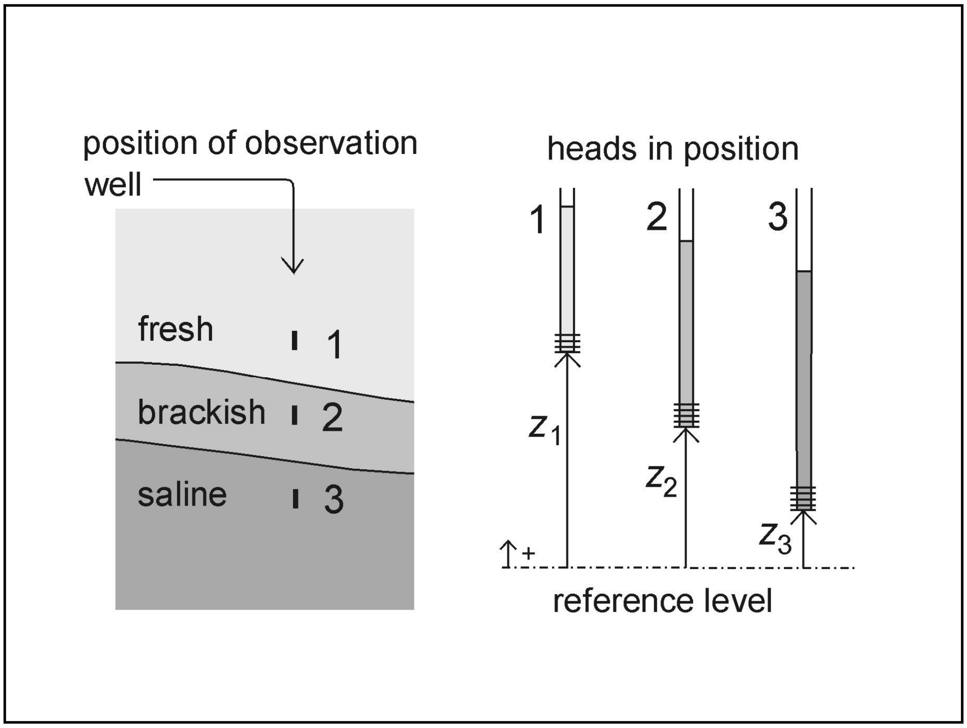


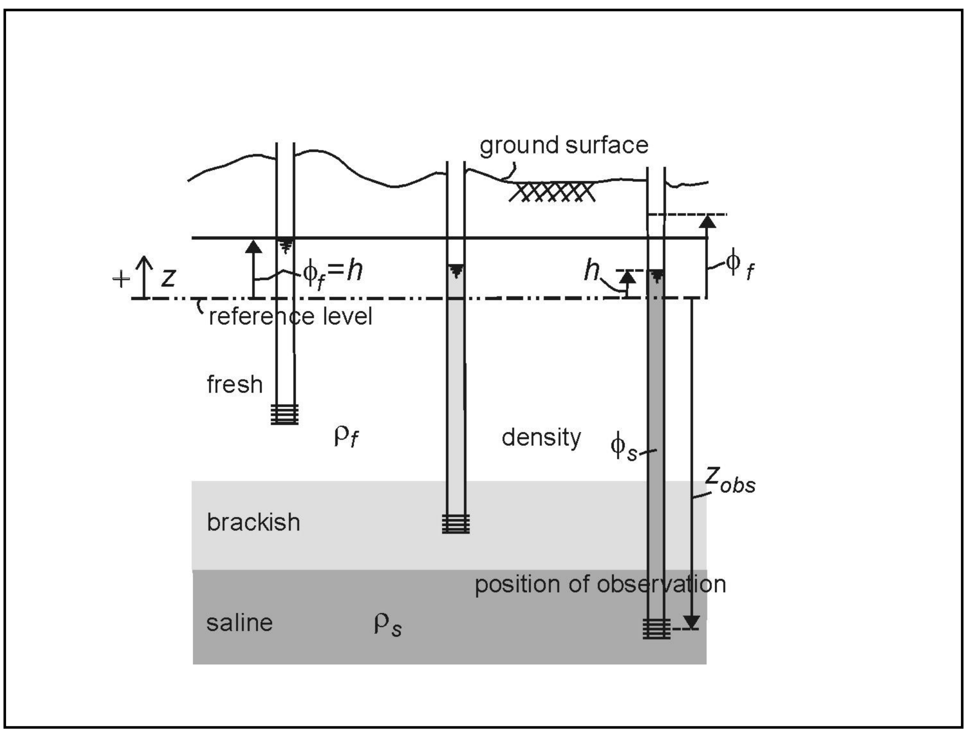
Freshwater head ϕ_f



Which one is useful?

Post, Kooi and Simmons, 2007, Ground Water


position of observation
well
fresh
1
brackish
2
saline
3
heads in position
1
2
3
z_1
z_2
z_3
+
reference level


ground surface
+ z
$\phi_f=h$
h
ϕ_f
reference level
fresh
ρ_f
density
ϕ_s
z_{obs}
brackish
position of observation
saline
ρ_s

$$\phi_f = \frac{p}{\rho_f g} + z$$

1. Groundwater with different densities can be compared
2. Fictive parameter
3. Hydrologists like to use heads instead of pressures
4. Pressure sometimes better
5. Confusing (heads not perpendicular to streamlines)

Freshwater head ϕ_f

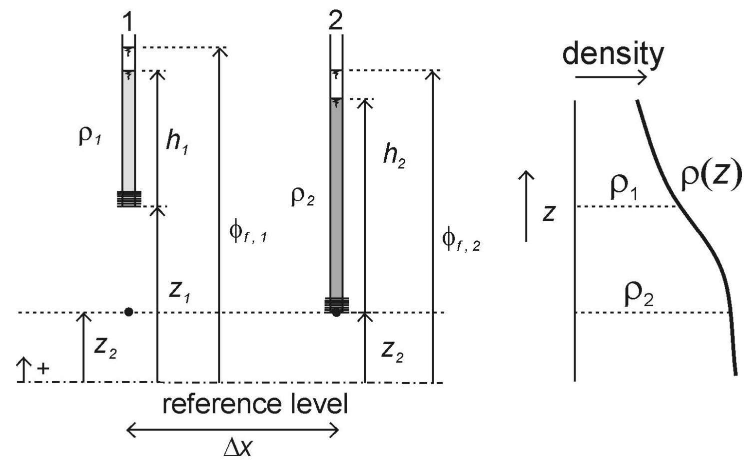
$$h_f = \frac{\rho}{\rho_f} h$$

$$\phi_f = h_f + z$$

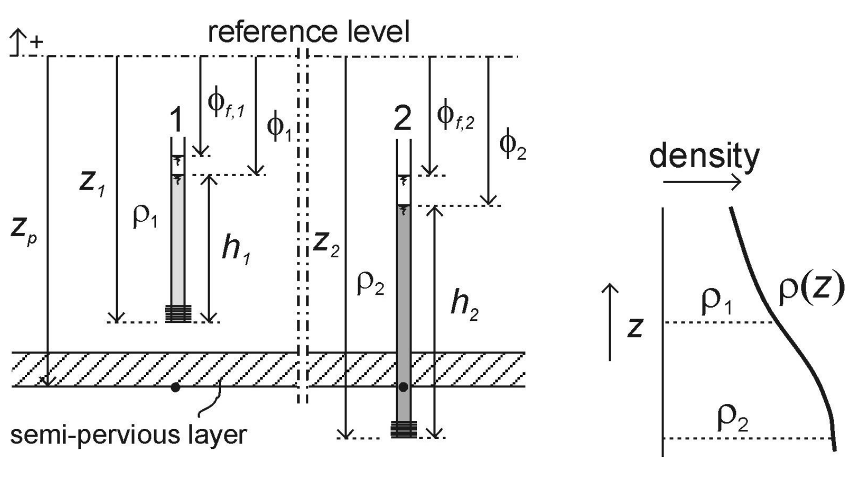
$$\phi_f = \frac{\rho}{\rho_f} h + z$$

e.g.:
ρ_s=1025kg/m3
h=10m
ϕ_f=10.25m

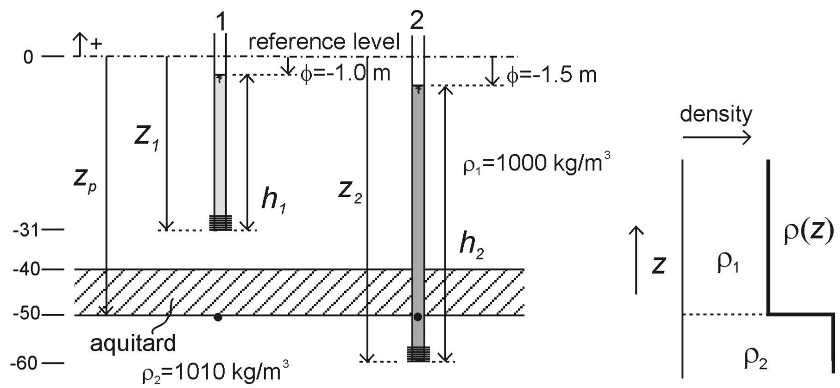
Freshwater head ϕ_f : horizontal flow?



Freshwater head ϕ_f : vertical flow?



Freshwater head ϕ_f



Special case: hydrostatic pressure: q_z=0

$$q_z = -\frac{\kappa_z \rho_f g}{\mu}\left(\frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f}\right)$$

no vertical flow

$$0 = \left(\frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f}\right)$$

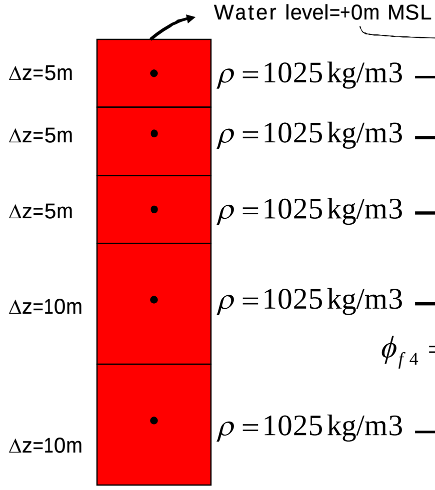
$$\partial \phi_f = -\frac{\rho - \rho_f}{\rho_f} \partial z$$

$$\phi_{f2} = \phi_{f1} - \frac{\rho - \rho_f}{\rho_f}(z2 - z1)$$

↓ +

$$\phi_{f2} = \phi_{f1} + \frac{\rho - \rho_f}{\rho_f}(\Delta z)$$

Hydrostatic boundary condition at the sea



$\rho = 1025\,\text{kg/m3} \longrightarrow \phi_{f1} = 0\,\text{m} + 0.025 * 2.5\text{m} = 0.0625\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow \phi_{f2} = 0.0625 + 0.025 * 5\text{m} = 0.1875\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow \phi_{f3} = 0.1875 + 0.025 * 5\text{m} = 0.3125\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow$

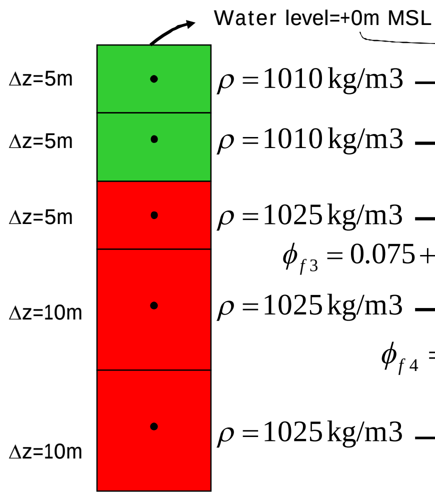
$\phi_{f4} = 0.3125 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.50\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow$

$\phi_{f5} = 0.50 + 0.025 * (5\text{m} + 5\text{m}) = 0.75\text{m}$

$$\phi_{f2} = \phi_{f1} + \frac{\rho - \rho_f}{\rho_f}(\Delta z)$$

Hydrostatic boundary condition at the sea



$\rho = 1010\,\text{kg/m3} \longrightarrow \phi_{f1} = 0\,\text{m} + 0.010 * 2.5\text{m} = 0.025\text{m}$

$\rho = 1010\,\text{kg/m3} \longrightarrow \phi_{f2} = 0.025 + 0.010 * 5\text{m} = 0.075\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow$

$\phi_{f3} = 0.075 + 0.010 * 2.5\text{m} + 0.025 * 2.5\text{m} = 0.1625\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow$

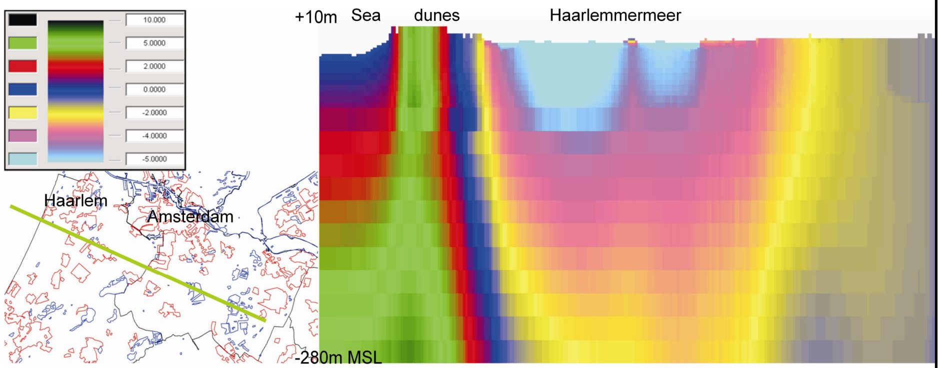
$\phi_{f4} = 0.1625 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.35\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow$

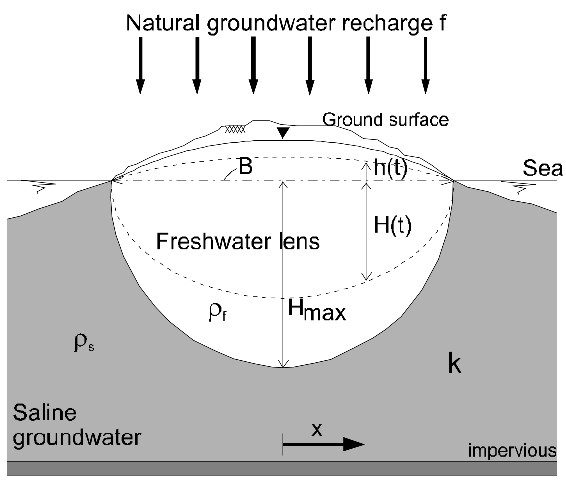
$\phi_{f5} = 0.35 + 0.025 * (5\text{m} + 5\text{m}) = 0.60\text{m}$

$$\phi_{f2} = \phi_{f1} + \frac{\rho - \rho_f}{\rho_f}(\Delta z)$$

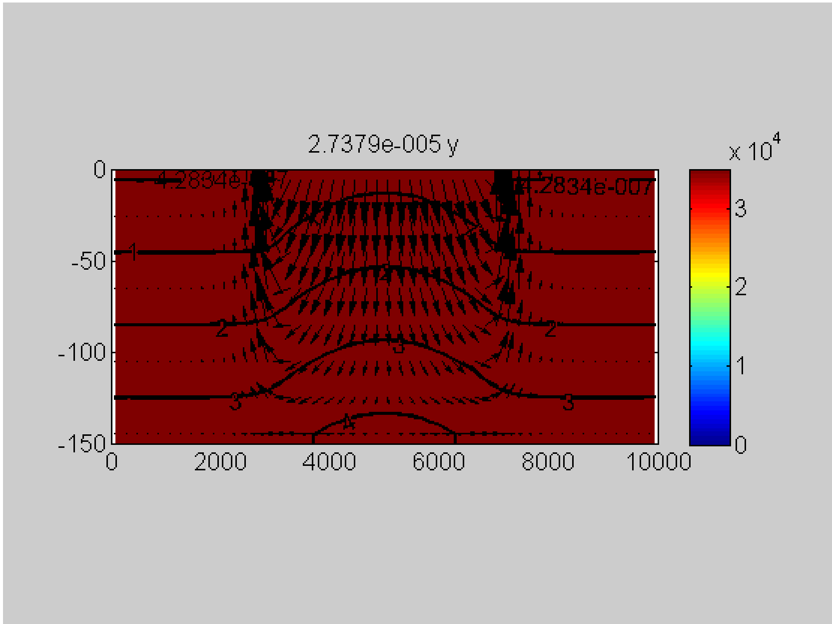
NHI fresh-salt: 2D profile freshwater head



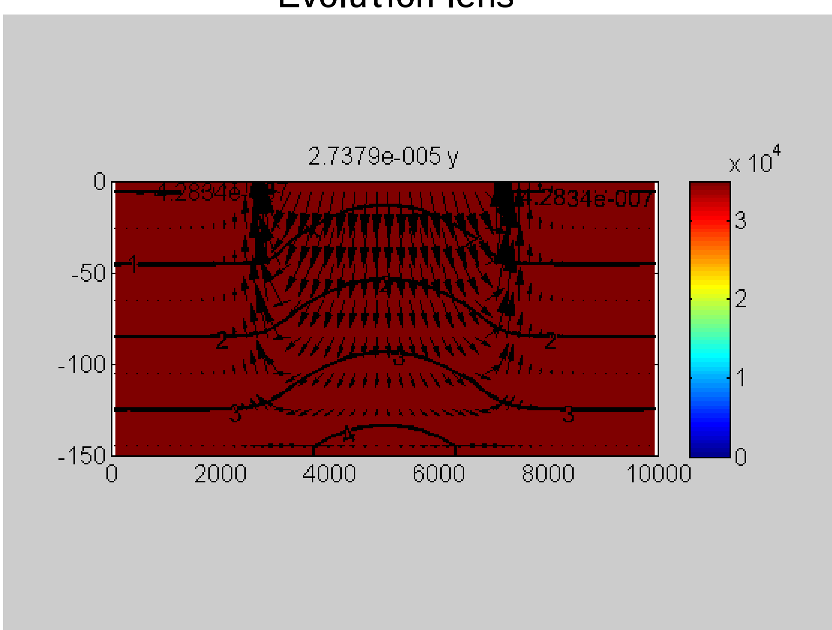
Case 2: Development of a freshwater lens



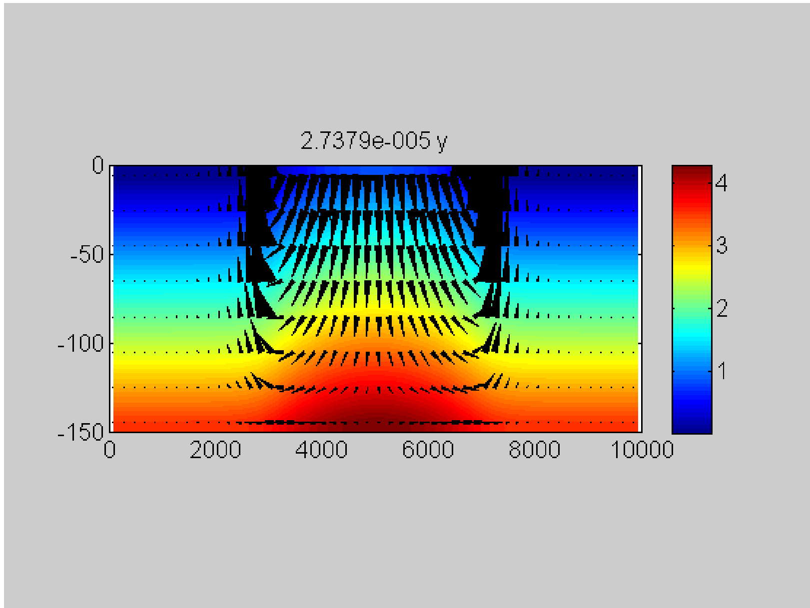
Evolution lens



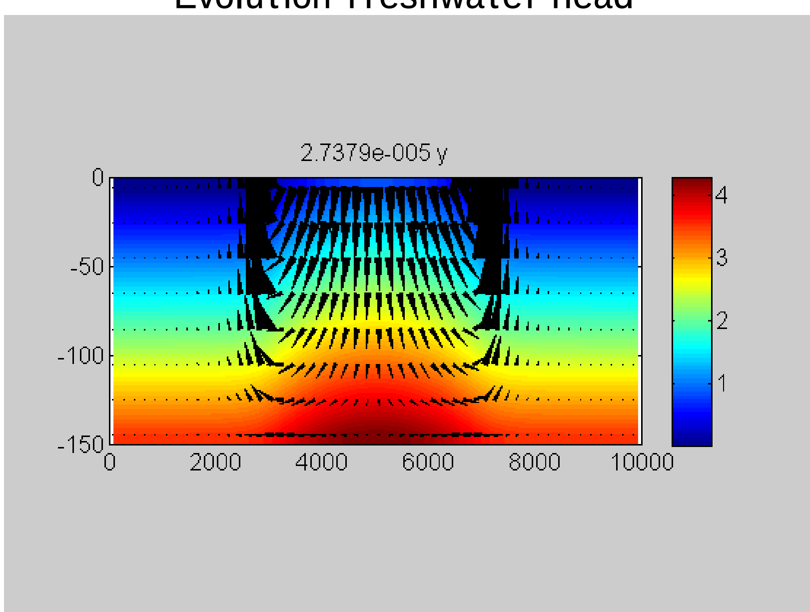
Evolution lens

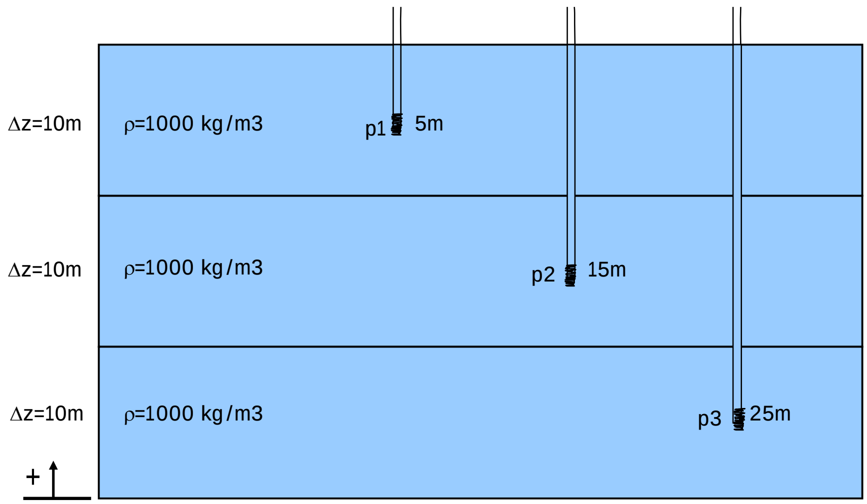


Evolution freshwater head

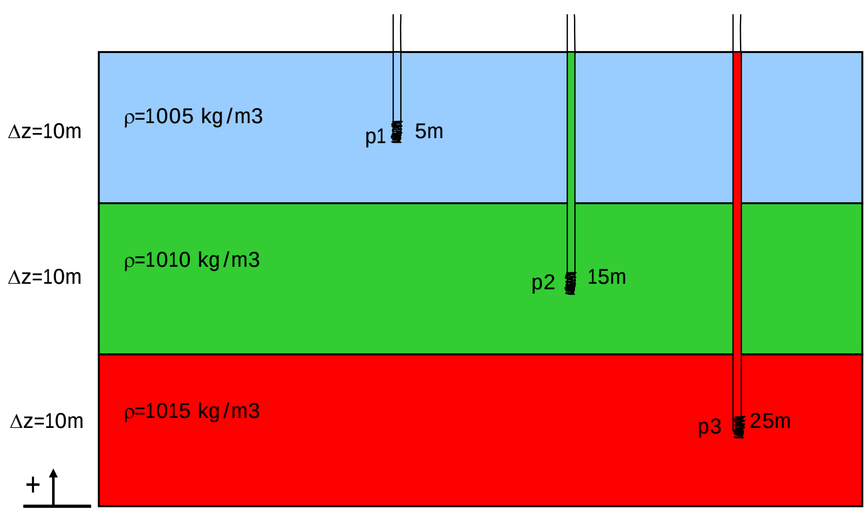


Evolution freshwater head



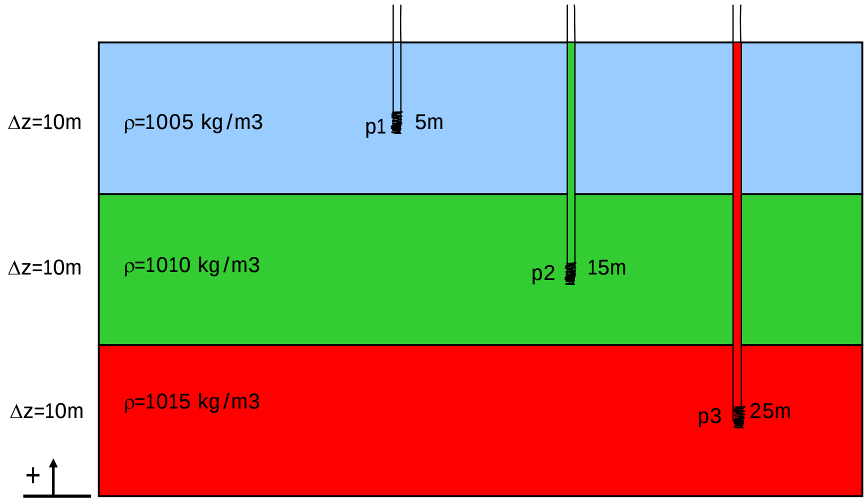


No flow



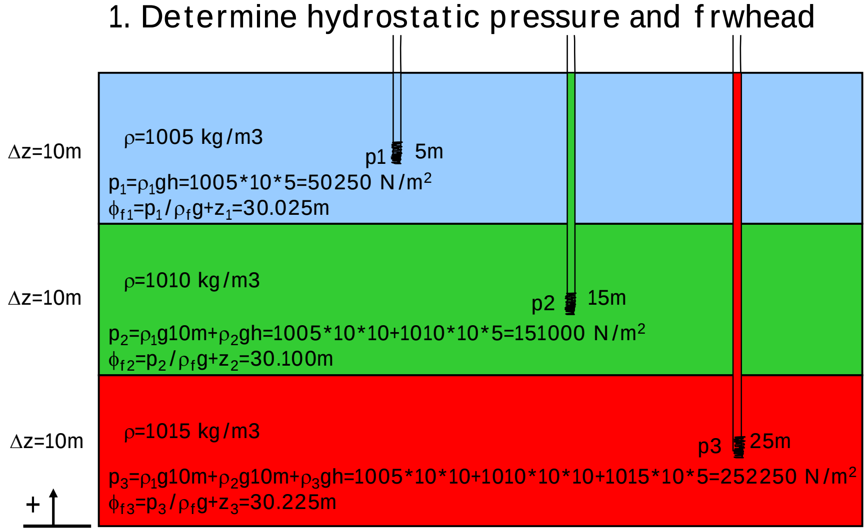
Flow or no flow? (if p≠hydrostatic than flow)

Calculate to freshwater head!



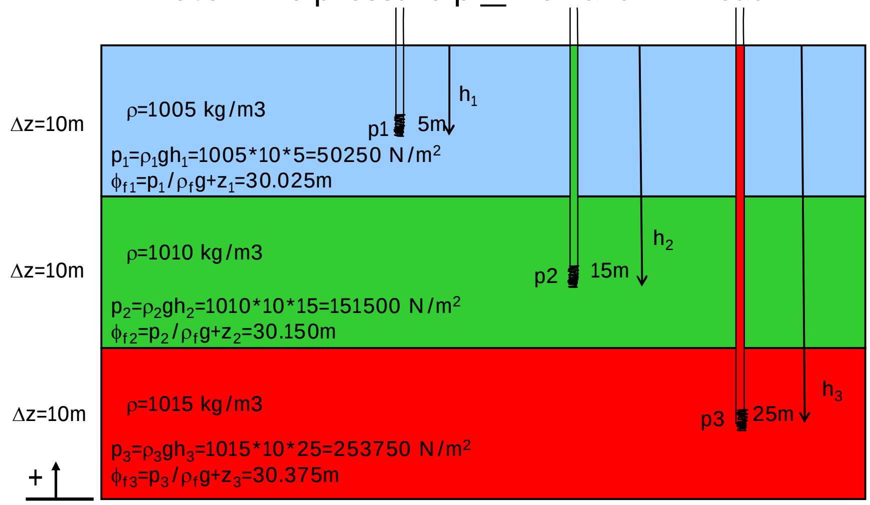
1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)

1. Determine hydrostatic pressure and frwhead



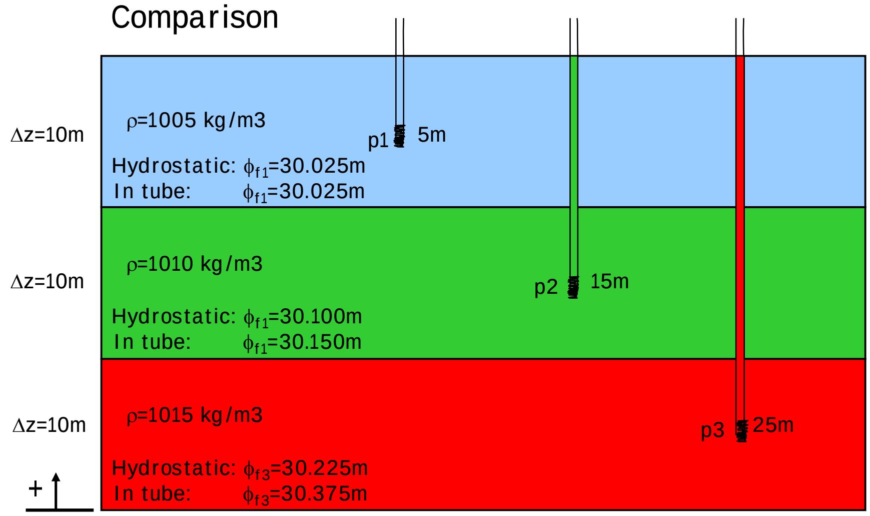
1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)

2. Determine pressure p in well and frwhead



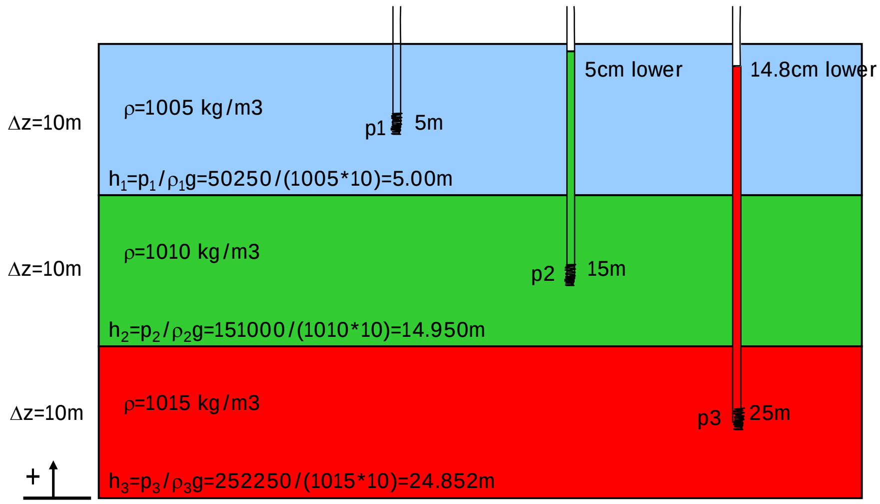
1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p in well! (and freshwater head ϕ_f)

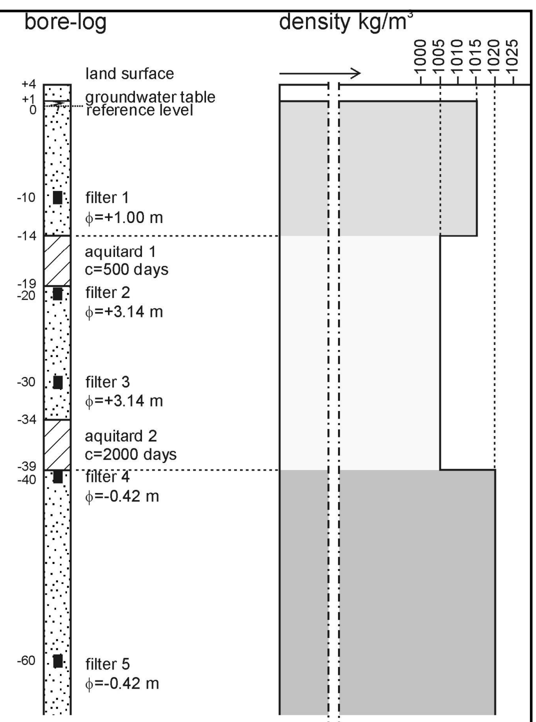
Comparison



Conclusion: freshwater head not equal, so vertical upward flow!

What would be the water level in the tube if hydrostatic?

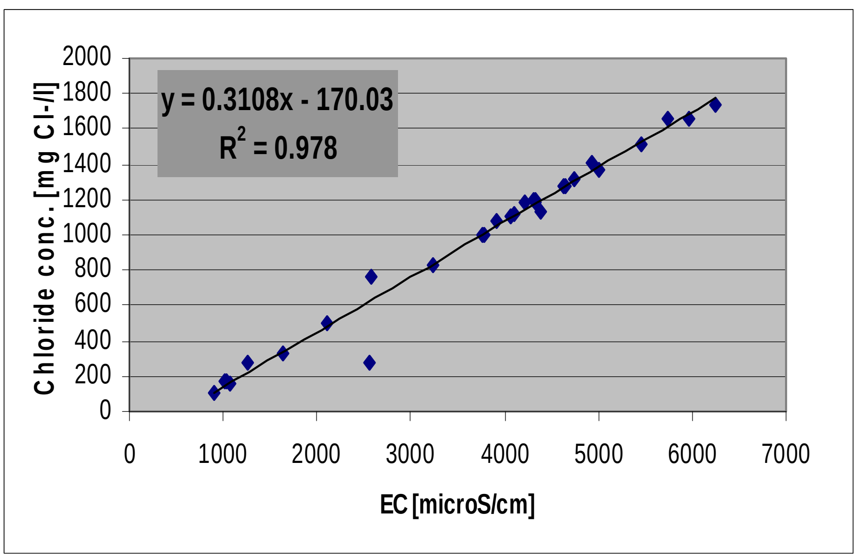




Take home message

1. In coastal area (with fresh-brackish-saline groundwater), always measure head and Electrical Conductivity (EC)
2. Convert EC to density
3. Determine freshwater head with lecture notes and ppt
4. Determine flow

Close relation between chloride concentration and Electrical Conductivity



Examples of equations of state

Knudsen (1902)

$$\rho_{(S,T)} = 1000 + 0.8054S - 0.0065(T - 4 + 0.2214S)^2$$

T<15 ºC, S<20 ppt

Linear (concentration)

$$\rho_{(C)} = \rho_f [1 + \alpha \frac{C_i}{C_s}]$$

where a=relative density difference

Linear (temperature)

$$\rho_{(T)} = \rho_f [1 - \beta (T - T')]$$

Exponential (temperature, pressure, salt)

$$\rho_{(T,p,\omega)} = \rho_f e^{-\alpha(T-T_0)+\beta(p-p_0)+\gamma\omega}$$

$$\mu = \mu_0 [1 + (1.85\omega - 4.10\omega^2 + 44.50\omega^3)]$$

Modelling

salt water intrusion /
density dependent groundwater flow

Why mathematical modelling anyway?

A model is only a schematisation of the reality!

Why mathematical modelling anyway?

+:

- cheaper than scale models
- analysis of very complex systems is possible
- a model can be used as a database
- to increase knowledge about a system (water balances)

-:

- simplification of the reality
- only a tool, no purpose on itself
- garbage in=garbage out: (field)data important
- perfect fit measurement and simulation is suspicious

Numerical modelling variable density flow

Type:

- sharp interface models
- solute transport models

State of the art:

- three-dimensional
- solute transport
- transient

Solute transport models

Combine
the groundwater flow equation
and
the advection-dispersion equation
by means of
an equation of state

Solute transport equation

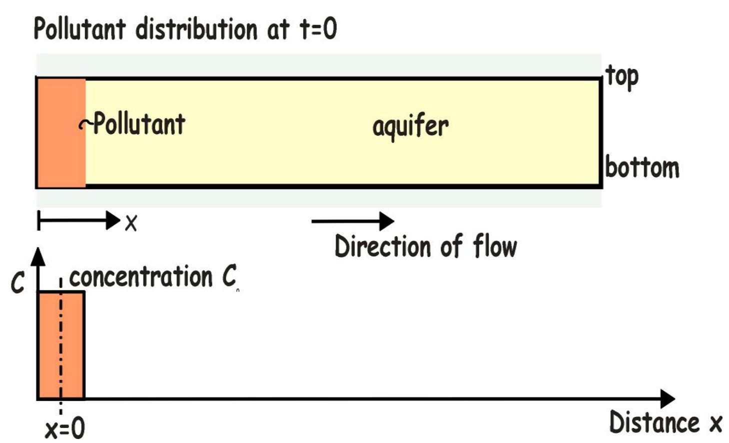
Partial differential equation (PDE):

$$R_d \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(CV_i) + \frac{(C-C)'W}{n_e} - R_d \lambda C$$

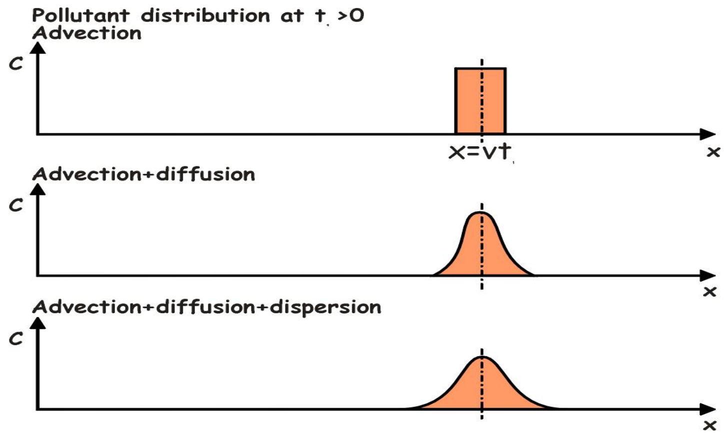
change in concentration | dispersion diffusion | advection | source/sink | decay

D_{ij}=hydrodynamic dispersion [L^2T^{-1}]
R_d=retardation factor [-]
λ=decay-term [T^{-1}]

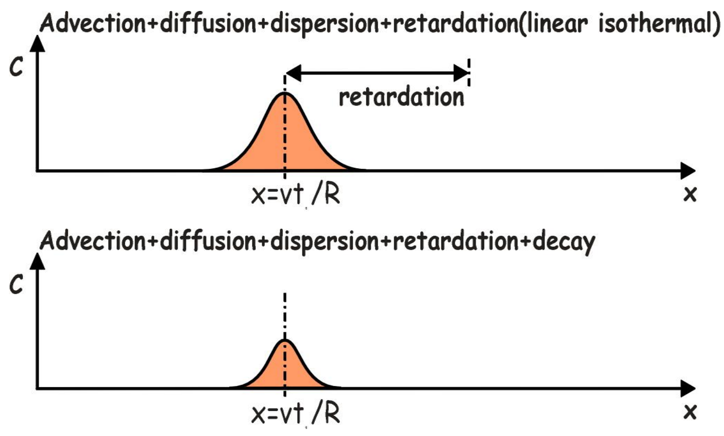
Solute transport equation: column test (I):



Solute transport equation: column test (II):



Solute transport equation: column test (III):



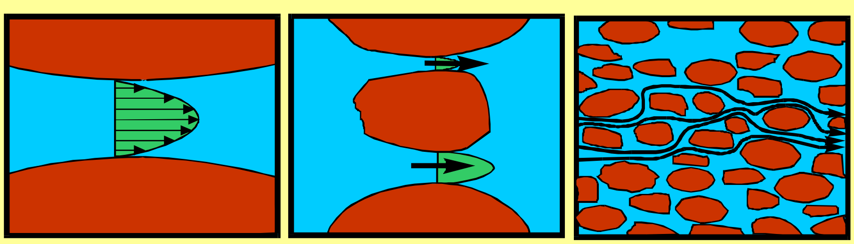
Hydrodynamic dispersion

hydrodynamic dispersion
=
mechanical dispersion+ diffusion

mechanical dispersion:
- tensor
- velocity dependant

diffusion:
- molecular process
- solutes spread due to concentration differences

Mechanical dispersion



Differences in velocity in the pore

Differences in velocity due to variation in pore-dimension

Differences in velocity due to variation in velocity direction

Solute transport equation: diffusion (I)

diffusion is a slow process: diffusion equation

only 1D-diffusion means: R_d=1, V_i=0, λ=0 and W=0

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2}$$

similarity with non-steady state groundwater flow equation

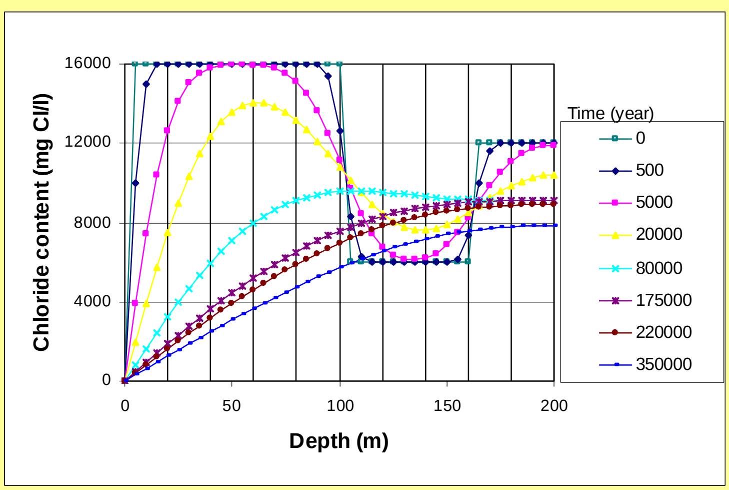
$$S\frac{\partial \phi}{\partial t} = T\frac{\partial^2 \phi}{\partial x^2} + N \qquad \frac{T\Delta t}{S\Delta x^2} < 0.5$$

$$\phi_i^{t+\Delta t} = \phi_i^t + \frac{N\Delta t}{S} + \frac{T\Delta t}{S\Delta x^2}\left(\phi_{i+1}^t - 2\phi_i^t + \phi_{i-1}^t\right)$$

$$C_i^{t+\Delta t} = C_i^t + \frac{D\Delta t}{\Delta z^2}\left(C_{i+1}^t - 2C_i^t + C_{i-1}^t\right) \qquad \frac{D\Delta t}{\Delta z^2} < 0.5$$

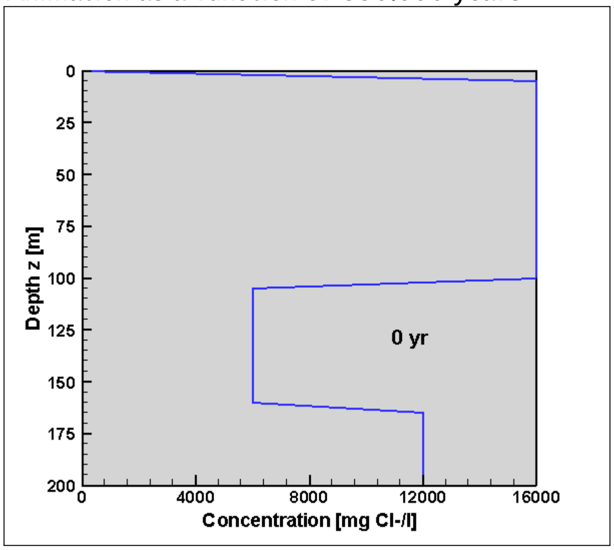
Solute transport equation: diffusion (II)

diffusion is a slow process: diffusion equation $\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2}$



Solute transport equation: diffusion (III)

Animation as a function of 350.000 years



Groundwater flow equation (MODFLOW, 1988)

Darcy

$$q_x = -\frac{\kappa_x \rho_f g}{\mu}\frac{\partial \phi_f}{\partial x}; \quad q_y = -\frac{\kappa_y \rho_f g}{\mu}\frac{\partial \phi_f}{\partial y}; \quad q_z = -\frac{\kappa_z \rho_f g}{\mu}\left(\frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f}\right)$$

Continuity

$$-\left[\frac{\partial \rho q_x}{\partial x} + \frac{\partial \rho q_y}{\partial y} + \frac{\partial \rho q_z}{\partial z}\right] = \frac{\partial n\rho}{\partial t} + W$$

buoyancy term

Freshwater head

$$\phi_f = \frac{p}{\rho_f g} + z$$

Advection-dispersion equation (MOC3D, 1996)

$$\frac{\partial C}{\partial t} = \frac{1}{nR_f}\frac{\partial}{\partial x_i}\left(nD_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{V_i}{R_f}\frac{\partial C}{\partial x_i} + \frac{\sum[W(C' - C)]}{nR_f} - \lambda C$$

Equation of state: relation density & concentration

$$\rho_{i,j,k} = \rho_f (1 + \beta C_{i,j,k})$$

Examples of equations of state

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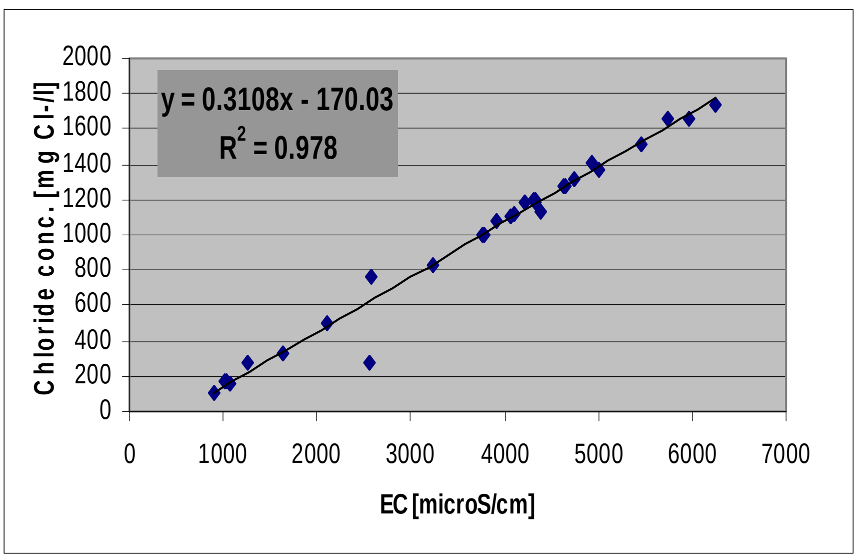
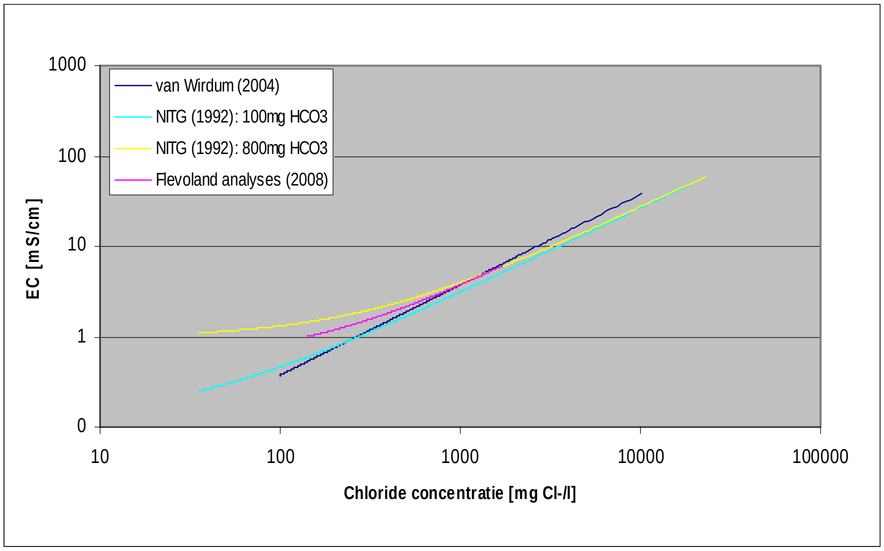
$$\rho_{(T,p,\omega)} = \rho_f e^{-\alpha(T-T_0)+\beta(p-p_0)+\gamma\omega}$$

$$\mu = \mu_0 [1 + (1.85\omega - 4.10\omega^2 + 44.50\omega^3)]$$

Close relation between chloride concentration and Electrical Conductivity

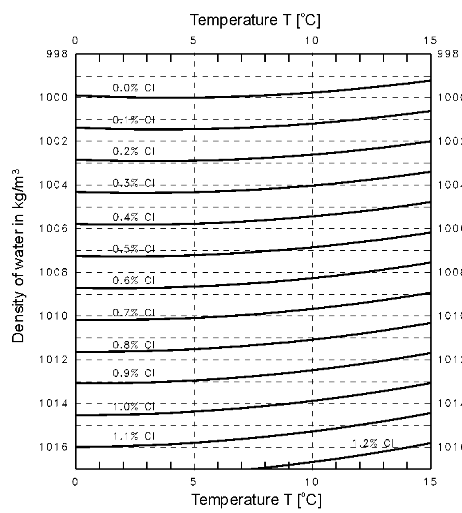


EC-Chloride



EOS

Density depends on salinity and temperature

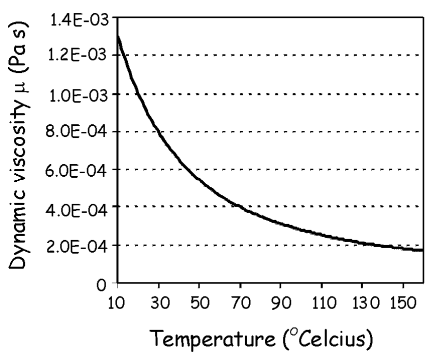


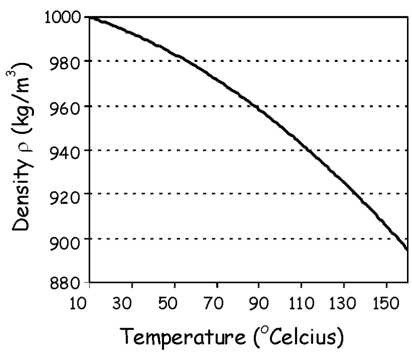
Accurate for T<15 °C and for Cl<¯1.1 %

$$\rho_{(S,T)} = 1000 + 0.8054S - 0.0065(T - 4 + 0.2214S)^2$$ Knudsen (1902)

Density and viscosity depend on temperature

(10°C-160 °C)





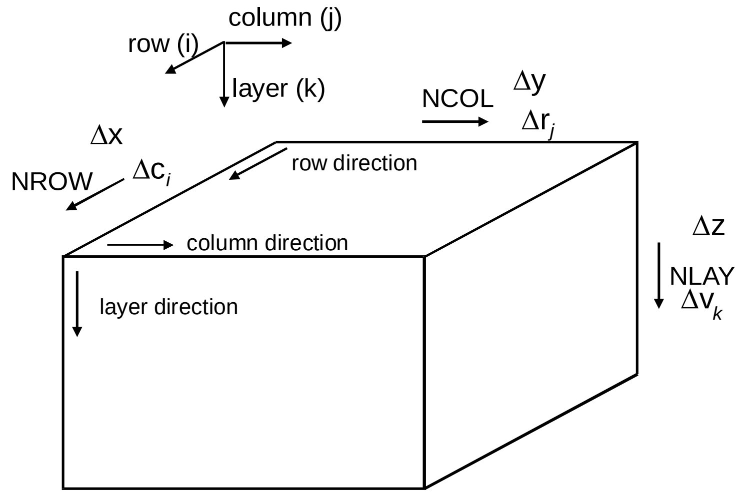
MOCDENS3D is based on MODFLOW

a modular 3D finite-difference ground-water flow model

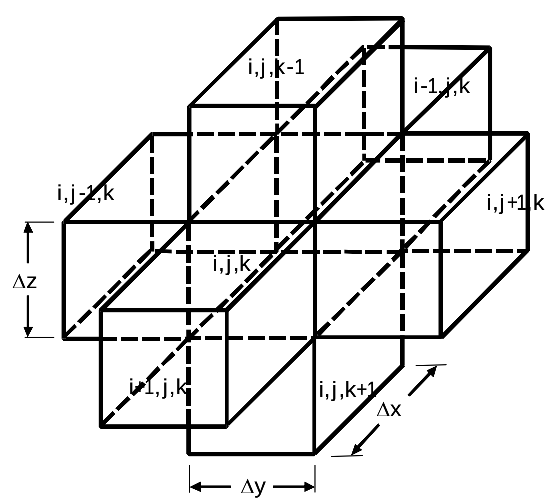
(M.G. McDonald & A.W. Harbaugh, from 1983 on)

- USGS, ‘public domain’
- non steady state
- heterogeneous porous medium
- anisotropy
- coupled to reactive solute transport
  - MOC3 (Konikow *et al*, 1996)
  - MT3D, MT3DMS (Zheng, 1990)
  - RT3D
  - PHT3D (Prommer, 2004)
- easy to use due to numerous Graphical User Interfaces (GUI’s)
  - PMWIN, GMS, Visual Modflow, Argus One, Groundwater Vistas, etc.

Nomenclature MODFLOW element [i,j,k]



MODFLOW: start with water balance of one element [i,j,k]



MODFLOW

Continuity equation (I)

In - Out = Storage

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial \phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial \phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial \phi}{\partial z}\right)-W=S_s\frac{\partial \phi}{\partial t}$$

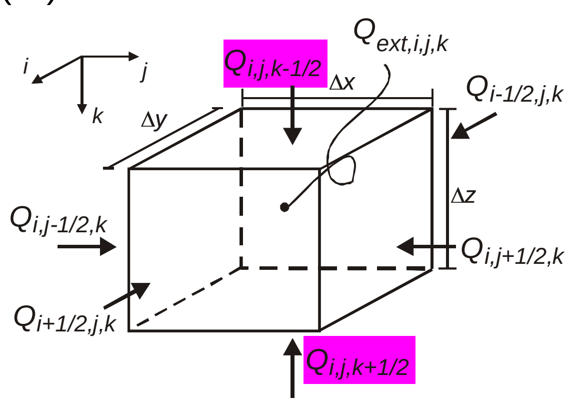
$$\sum Q_i = S_s \frac{\Delta \phi}{\Delta t}\Delta V$$

MOCDENS3D

Continuity equation (II)

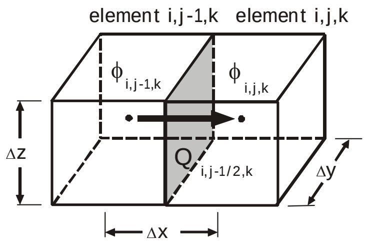
$$\sum Q_i = S_s \frac{\Delta \phi}{\Delta t}\Delta V$$

In = positive



$$Q_{i,j-1/2,k}+Q_{i,j+1/2,k}+Q_{i-1/2,j,k}+Q_{i+1/2,j,k}+Q_{i,j,k-1/2}+Q_{i,j,k+1/2}+Q_{ext,i,j,k}$$
$$=SS_{i,j,k}\frac{\phi^{t}_{i,j,k}-\phi^{t+\Delta t}_{i,j,k}}{\Delta t}\Delta V$$

Flow equation (Darcy's Law)



$$Q = surface * q = surface * k \frac{\partial \phi}{\partial x}$$

$$Q_{i,j-1/2,k} = k_{i,j-1/2,k} \, \Delta y \, \Delta z \frac{\phi_{i,j-1,k} - \phi_{i,j,k}}{\Delta x}$$

$$Q_{i,j-1/2,k} = CR_{i,j-1/2,k} \left(\phi_{i,j-1,k} - \phi_{i,j,k} \right)$$

where $CR_{i,j-1/2,k} = \frac{k_{i,j-1/2,k} \, \Delta y \, \Delta z}{\Delta x}$ is the conductance [L^2/T]

Density dependent vertical flow equation

$$q_z = -\frac{\kappa_z \rho_f g}{\mu} \left(\frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f} \right)$$

$$q_z = -k_z \left(\frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f} \right)$$

$$Q_z = surface * q_z = surface * k_z \left(\frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f} \right)$$

$$Q_{i,j,k-1/2} = k_{i,j,k-1/2} \, \Delta x \, \Delta y \left(\frac{\phi_{f,i,j,k-1} - \phi_{f,i,j,k}}{\Delta z} + BUOY_{i,j,k-1/2} \right)$$

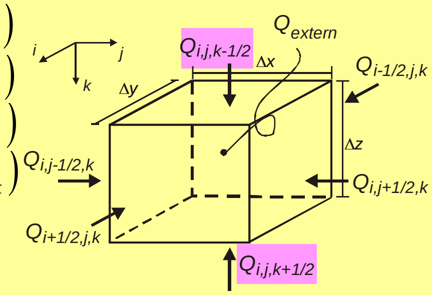
$$Q_{i,j,k-1/2} = CV_{i,j,k-1/2} \left(\phi_{f,i,j,k-1} - \phi_{f,i,j,k} + BUOY_{i,j,k-1/2} \Delta z \right)$$

where $BUOY_{i,j,k-1/2} = \left(\frac{(\rho_{i,j,k-1/2} + \rho_{i,j,k})/2 - \rho_f}{\rho_f} \right)$ =buoyancy term [-]

where $CV_{i,j,k-1/2} = \frac{k_{i,j,k-1/2} \, \Delta x \, \Delta y}{\Delta z}$ =conductance [L^2/T]

Density dependent groundwater flow equation

$$Q_{i,j-1/2,k} = CR_{i,j-1/2,k}\left(\phi_{f,i,j-1,k} - \phi_{f,i,j,k}\right)$$
$$Q_{i,j+1/2,k} = CR_{i,j+1/2,k}\left(\phi_{f,i,j+1,k} - \phi_{f,i,j,k}\right)$$
$$Q_{i-1/2,j,k} = CC_{i-1/2,j,k}\left(\phi_{f,i-1,j,k} - \phi_{f,i,j,k}\right)$$
$$Q_{i+1/2,j,k} = CC_{i+1/2,j,k}\left(\phi_{f,i+1,j,k} - \phi_{f,i,j,k}\right)$$



$$Q_{i,j,k-1/2} = CV_{i,j,k-1/2}\left(\phi_{f,i,j,k-1} - \phi_{f,i,j,k} + BUOY_{i,j,k-1/2}\Delta v_{k-1/2}\right)$$
$$Q_{i,j,k+1/2} = CV_{i,j,k+1/2}\left(\phi_{f,i,j,k+1} - \phi_{f,i,j,k} - BUOY_{i,j,k+1/2}\Delta v_{k+1/2}\right)$$

$$Q_{i,j-1/2,k} + Q_{i,j+1/2,k} + Q_{i-1/2,j,k} + Q_{i+1/2,j,k} + Q_{i,j,k-1/2} + Q_{i,j,k+1/2} + Q_{ext,i,j,k}$$
$$= SS_{i,j,k}\frac{\phi^{t}_{f,i,j,k} - \phi^{t+\Delta t}_{f,i,j,k}}{\Delta t}\Delta V$$

The term $Q_{ext,i,j,k}$

Takes into account all external sources

Rewriting the term:

$$Q_{ext,i,j,k} = P_{i,j,k}\phi^{t+\Delta t}_{i,j,k} + Q'_{i,j,k}$$

Thé variable density groundwater flow equation

$$Q_{i,j-1/2,k} + Q_{i,j+1/2,k} + Q_{i-1/2,j,k} + Q_{i+1/2,j,k} + Q_{i,j,k-1/2} + Q_{i,j,k+1/2} + Q_{ext,i,j,k} = SS_{i,j,k} \frac{\phi^{t}_{f,i,j,k} - \phi^{t+\Delta t}_{f,i,j,k}}{\Delta t} \Delta V$$

and:

$$Q_{ext,i,j,k} = P_{i,j,k} \phi^{t+\Delta t}_{f,i,j,k} + Q'_{i,j,k}$$

gives:

$$\begin{aligned} & CV_{i,j,k-1/2} \phi^{t+\Delta t}_{f,i,j,k-1} + CC_{i-1/2,j,k} \phi^{t+\Delta t}_{f,i-1,j,k} + CR_{i,j-1/2,k} \phi^{t+\Delta t}_{f,i,j-1,k} \\ & + \left(-CV_{i,j,k-1/2} - CC_{i-1/2,j,k} - CR_{i,j-1/2,k} - CR_{i,j+1/2,k} - CC_{i+1/2,j,k} - CV_{i,j,k+1/2} + HCOF_{i,j,k} \right) \phi^{t+\Delta t}_{f,i,j,k} \\ & + CR_{i,j+1/2,k} \phi^{t+\Delta t}_{f,i,j+1,k} + CC_{i+1/2,j,k} \phi^{t+\Delta t}_{f,i+1,j,k} + CV_{i,j,k+1/2} \phi^{t+\Delta t}_{f,i,j,k+1} = RHS_{i,j,k} \end{aligned}$$

with :

$$HCOF_{i,j,k} = P_{i,j,k} - SC1_{i,j,k} / (\Delta t)$$

$$\begin{aligned} RHS_{i,j,k} = & -Q'_{i,j,k} - SC1_{i,j,k} \phi^{t}_{f,i,j,k} / (\Delta t) \\ & - CV_{i,j,k-1/2} BUOY_{i,j,k-1/2} \Delta v_{k-1/2} + CV_{i,j,k+1/2} BUOY_{i,j,k+1/2} \Delta v_{k+1/2} \end{aligned}$$

$$SC1_{i,j,k} = SS_{i,j,k} \Delta V$$

Equation of state

$$BUOY_{i,j,k-1/2} = \left(\frac{(\rho_{i,j,k-1/2} + \rho_{i,j,k})/2 - \rho_f}{\rho_f} \right)$$

$$\rho_{i,j,k} = \rho_f \left(1 + \frac{\rho_s - \rho_f}{\rho_f} \frac{C_{i,j,k}}{C_s} \right)$$

or

$$\rho_{i,j,k} = \rho_f \left(1 + \beta C_{i,j,k} \right)$$

Some existing 3D codes which simulate variable density groundwater flow in porous media:

HST3D (*Kipp, '86*)
METROPOL (*Sauter, '87*)
FEFLOW (*Diersch, '94*)
MVAEM (*Strack, '95*)
D3F (*Wittum et al., '98*)
MOCDENS3D (*Oude Essink, '98*)
SWICHA (*Huyakorn et al., '87*)
SWIFT (*Ward, '91*)
FAST-C 3D (*Holzbecher, 98*)
MODFLOW+MT3D96 (*Gerven, '98*)
SEAWAT (*Guo & Bennett, 98*)
SUTRA (beta-version, Voss, '02)

Restrictions 3D salt water intrusion modelling in 2011

- the data problem:
  - -not enough hydrogeological data available
  - -e.g. the initial density distribution
  - -especially important issue in data-poor countries
- the computer problem:
  - -modelling transient 3D systems: computer only good enough at high costs
- the numerical dispersion problem:
  - -numerical dispersion is large in case of coarse grid

solution is 64 bits computer

solution is better software

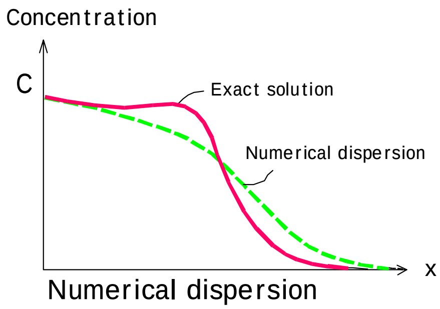
A good initial density distribution is essential

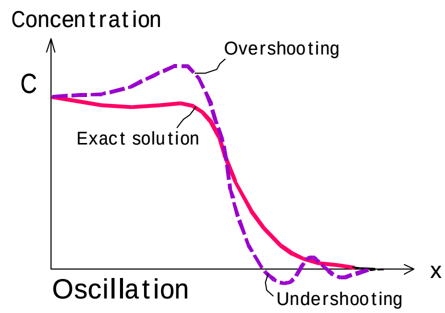
- Because groundwater and solute transport are coupled, the density influences grondwater velocities
- Numerous density measurements are necessary to get a reliable 3D density matrix

‘Procedure’ to improve initial density distribution

- Implement all chloride data
  - Analyses, Borehole, VES, Airborne techniques (HEM, SkyTem)
  - Better old then nothing
  - Better VES then nothing
- Interpolate and extrapolate
  - Sea = easy (salt)
  - Inland = fresh?
- Start with simulation (10/20/30 years) with mol.diffusion*1000 to smooth out artificial densities

Numerical dispersion and oscillation





$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} \quad C_i^{t+\Delta t} = C_i^t + \frac{D\Delta t}{\Delta z^2}\left(C_{i+1}^t - 2C_i^t + C_{i-1}^t\right) \quad \frac{D\Delta t}{\Delta z^2} < 0.5$$

Numerical dispersion problem (I)

To solve the advection-dispersion equation, standard finite difference and element techniques should consider the following spatial discretisation criterion:

Peclet number $Pe \leq 2 \text{ to } 4$

where: $Pe = \left|\frac{V\Delta x}{D_h}\right|$

V = effective velocity [L/T]
Δx = dimension grid cell [L]
D_h = hydrodynamic dispersion [L^2/T]

Numerical dispersion problem (II)

For advection dominant grondwater flow, the Peclet number can be rewritten as:

$$\Delta x \leq 2\alpha_L \text{ to } 4\alpha_L$$

where α_L = longitudinal dispersivity [L]

What does that mean?

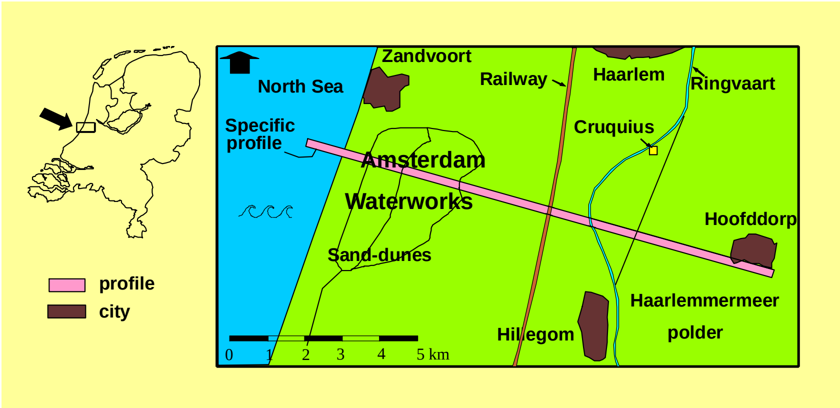
If α_L is small, then Δx should be small too!!

Numerical dispersion problem (III)

Now follows an transient salt water intrusion case to demonstrate why in many coastal aquifers the longitudinal dispersivity α_L [L] should be small

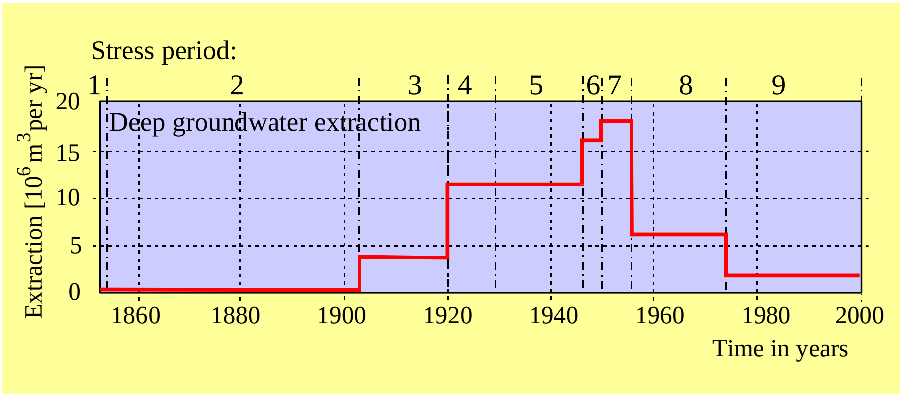
Effect of α_L on the salinisation of the aquifer (I)

Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



Effect of α_L on the salinisation of the aquifer (II)

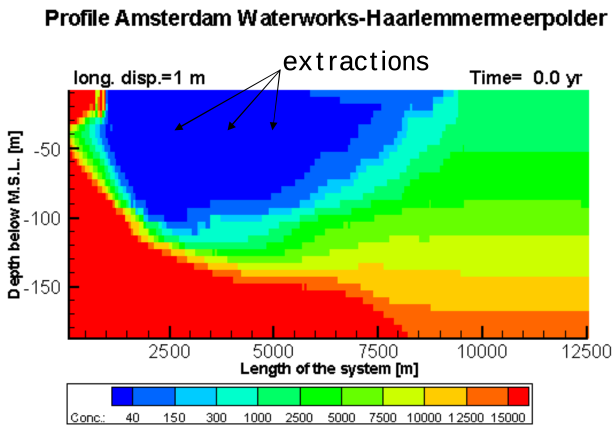
Grondwater extractions out of the middle aquifer in the sand-dune area of Amsterdam Waterworks



Effect of α_L on the salinisation of the aquifer (III)

α_L=1 m

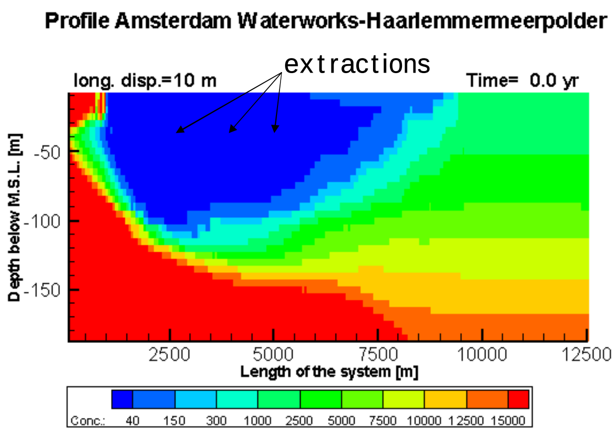
Initial situation: 154 years ago



Effect of α_L on the salinisation of the aquifer (IV)

α_L=10 m

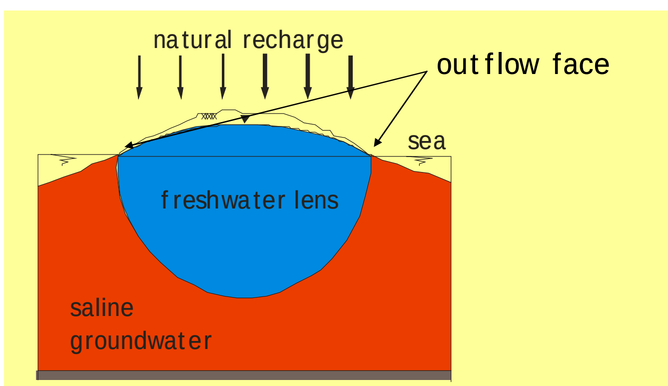
Initial situation: 154 years ago



Difficulties with variable density groundwater flow

- Initial density distribution (effects on velocity field) !
- Velocities freshwater lens at the outflow face near the sea
- Boundary conditions (especially concentration boundaries)
- Choice of element size
- Length of flow time step to recalculate groundwater flow

Outflow face at the coast is difficult to model



Flow converges and thus velocities are very high at the outflow face

This is numerically difficult to handle

A good initial density distribution is essential

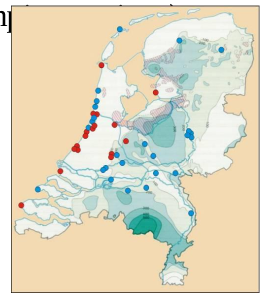
- Because groundwater and solute transport are coupled, the density influences grondwater velocities
- Numerous density measurements are necessary to get a reliable 3D density matrix

'Procedure' to improve initial density distribution

- Implement all chloride data
  - Analyses, Borehole, VES
  - Better old then nothing
  - Better VES then nothing
- Interpolate and extrapolate
  - Sea = easy (salt)
  - Inland = fresh?
- Start with simulation (10/20/30 years) with mol.diffusion*1000 to smooth out artificial densities

Monitoring salt in groundwater

- Why monitoring?
  - Mapping salt concentrations in the groundwater
  - Detection of trends (upconing near pump
  - System and process knowledge
  - Input for a groundwater model



Pumping stations with salinisation

Pumping stations closed due to salinisation

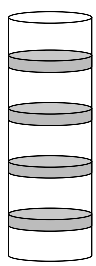
- Methods:
  1. Direct: water sample available
  2. Indirect: conductance of the subsoil

Source: V. Post, 2007

Monitoring salt in groundwater: Direct methods

Method	Advantage	Disadvantage
1. Observation well	•High accuracy •Detection trends	•Costly •Point measurement
2. Well screens in observation well	•High accuracy •Detection trends •High vertical resolution	•Costly
3. Sediment sample (extraction milliliters of water)	•High accuracy •High vertical resolution	•Very costly and time consuming

Direct methods 1 and 2



Source: V. Post, 2007

Monitoring salt in groundwater: Indirect methods

Indirect methods measure the **conductance** of:

1. **The groundwater**
   - High conductance: saline groundwater
   - Low conductance: fresh groundwater

AND

2. **The soil**
   - High conductance: clay, sand
   - Low conductance: coarse sand, gravel

Hence information about the lithology (sand, clay etc) is needed!

Source: V. Post, 2007

Monitoring salt in groundwater: Indirect methods

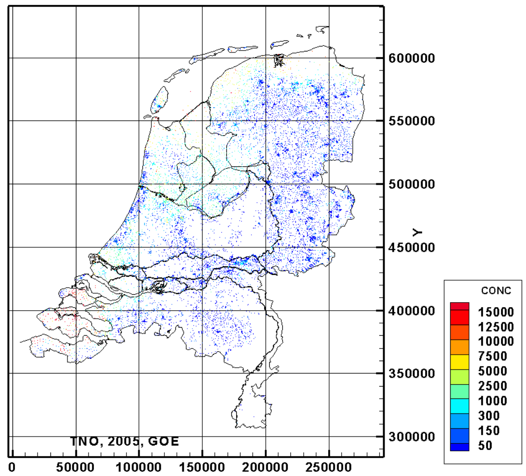
Method	**Advantages**	**Disadvantages**
1. Electrical conductance measurements	•High resolution (3D) •Depth ~200 m	•Time consuming
2. Electromagnetic measurements	•Fast	•Limited vertical resolution •Sensitive for underground conductors (pipes)
3. Satellites	•Suitable for large areas	•Small vertical resolution •Low accuracy

Source: V. Post, 2007

Method used at Deltares

Combination of:
- Direct measurements
- Electrical conductance measurements
  - Surface (VES)
  - Borehole

Number of measurements bottom Holocene top layer : direct methods and Vertical Electric Soundings (VES)



Source: Oude Essink et al (2005)

Electrical conductance measurements

1. Measuring:
   - **Inside a borehole**
   - From surface level
   - From the air

Source: TNO

Source: V. Post, 2007

Electrical conductance measurements

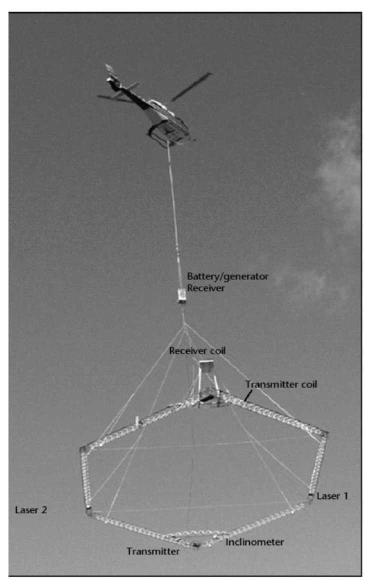
1. Measuring:
   - Inside a borehole
   - **From surface level (depth ~ 200 m)**
   - From the air

Source: Vitens

Source: V. Post, 2007

Electrical conductance measurements

1. Measuring:
   - Inside a borehole
   - From surface level
   - **From the air**



Source: V. Post, 2007

Monitoring salt in groundwater: Indirect methods

- Electrical conductance measurements

$\rho_s = F^* \rho_w$

ρ_s = resistance subsoil & groundwater
ρ_w = resistance groundwater
F = formation factor

Lithology	**F**
Gravel with sand	7
Coarse sand	5
Sand with silt	2 - 3
Clay	*1-3**
peat	*1**

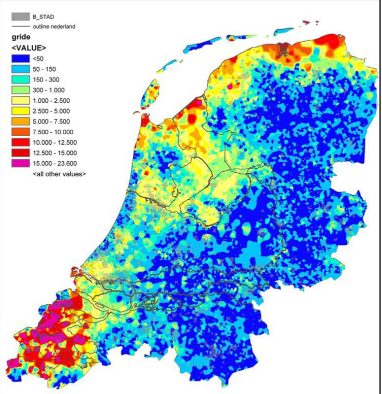
→ *F varies with the resistance of the groundwater* (Clay, peat)

If the lithology is known AND the measurement is in an aquifer
→ ρ_w can be calculated

VES measurements are used in combination with borehole logging

Source: Oude Essink, 2005

Result: chloride concentration bottom Holocene toplayer



Source: Oude Essink, 2005

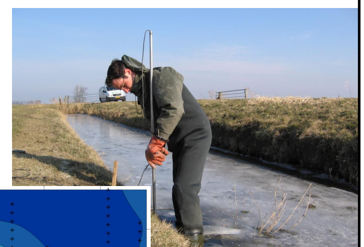
- Software Geological Survey of the Netherlands (TNO) is used to determine the salt concentration of the groundwater in the measurements
- Inter- and extrapolation is used to make a continuous field
- 2D Result is an combination of:
  1. Direct measurements (3500)
  2. Electrical conductance in boreholes (2000)
  3. Vertical Electric Sounding (VES) measurements (10.000)

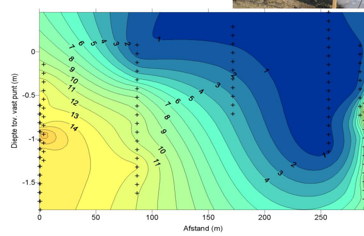
Example: Assessing effect of climate change on salt water intrusion

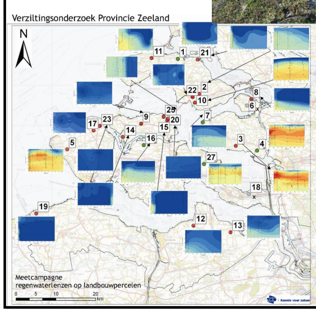
Source: Oude Essink, 2009

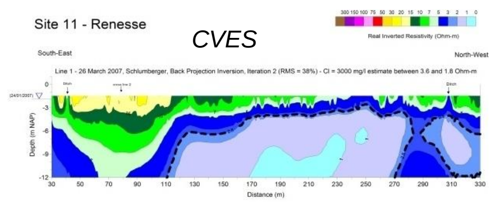
Monitoring:
- piezometric head and solute concentration
- TEC probes, CVES
- online

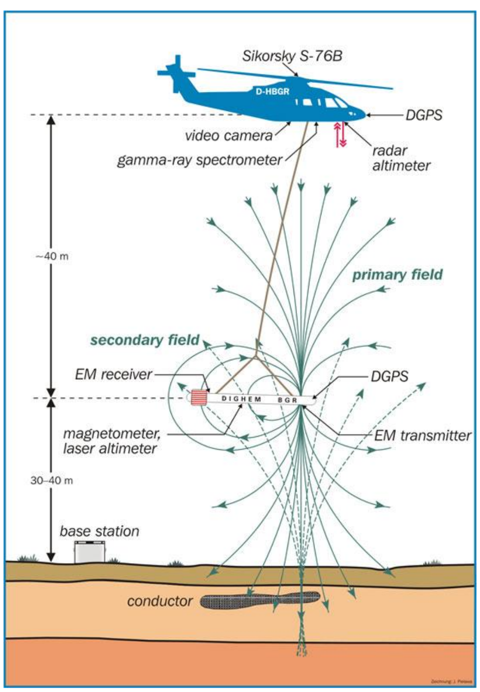
TEC probe



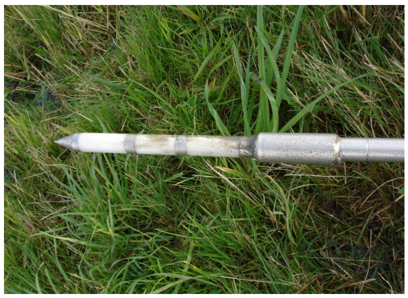


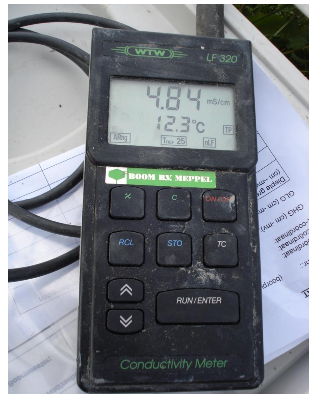






T-EC probe





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WETTERSKIP FRYSLÂN

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TEC fieldwork

Altitude measurements

CLIWAT
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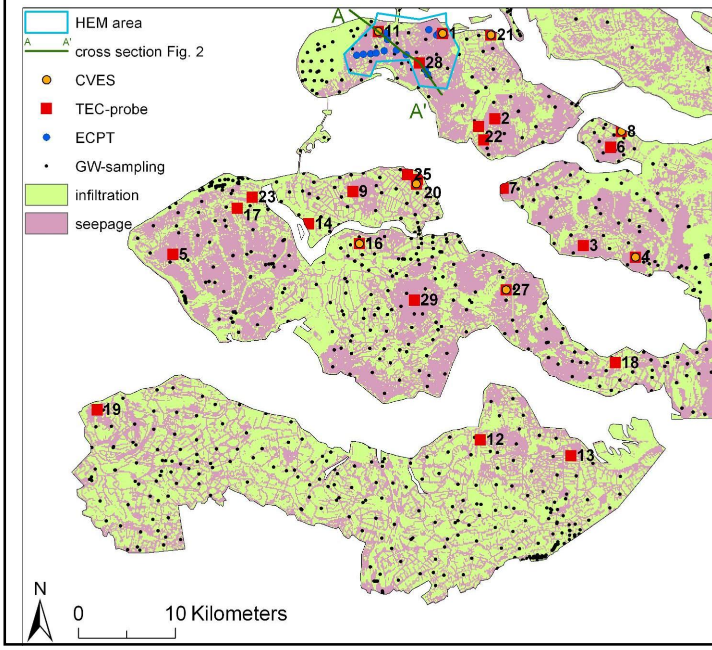
Monitoring network



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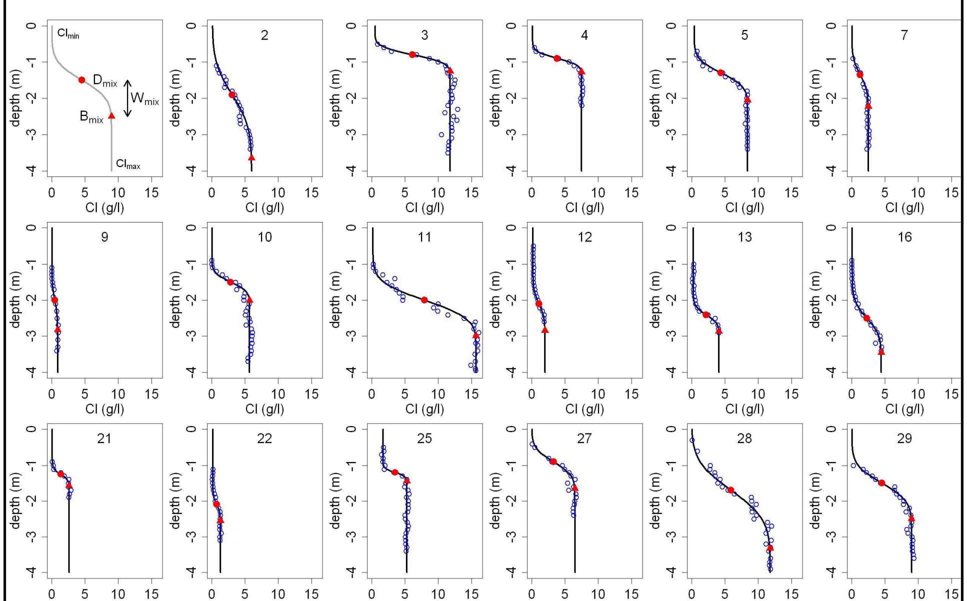
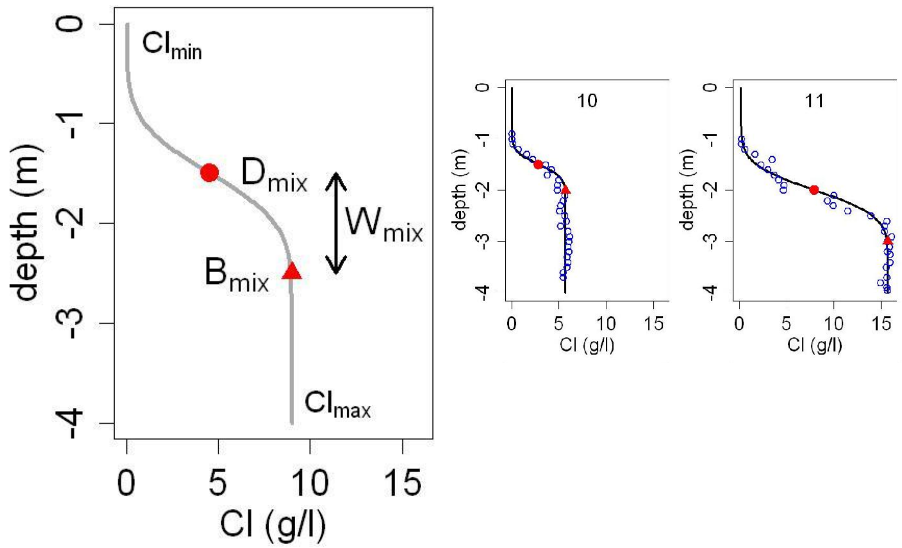
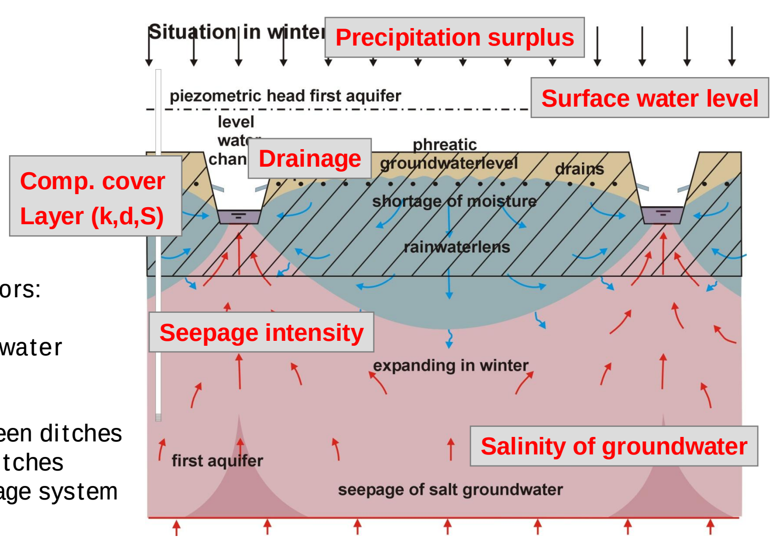
TEC-probe results



Lens characteristics



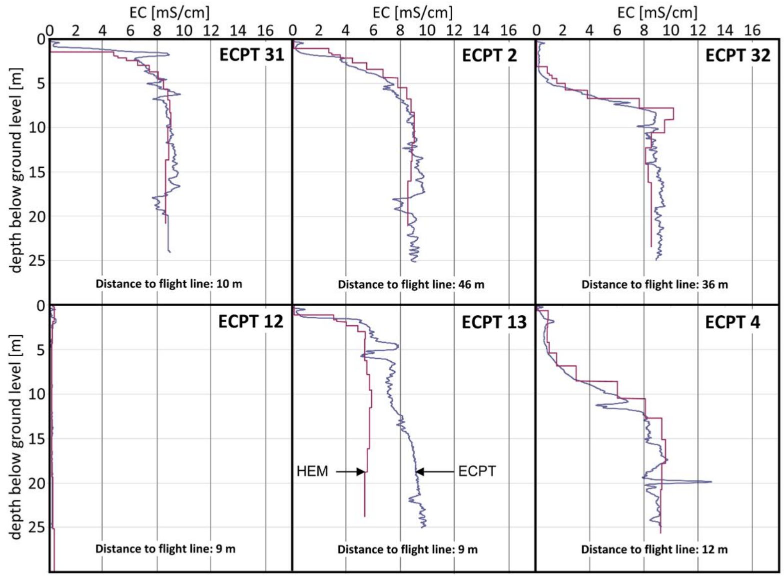
Factors controlling fresh-salt interface



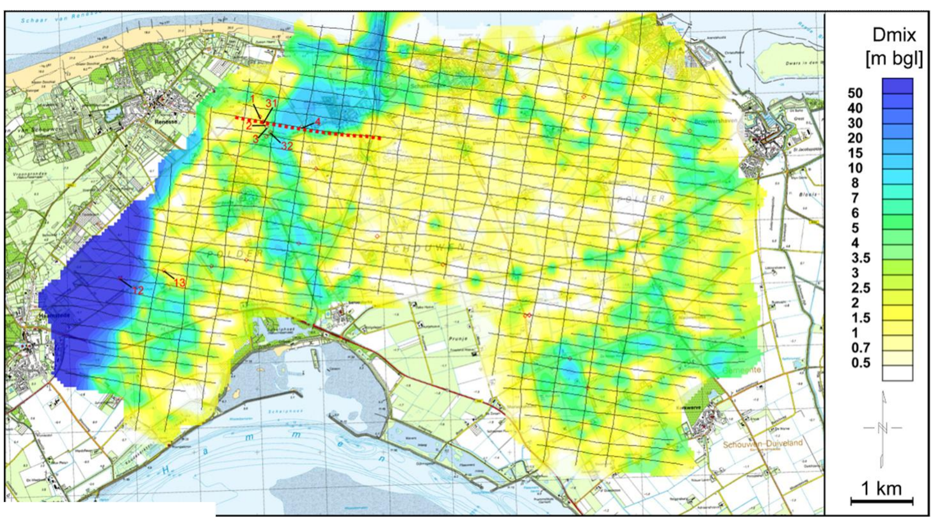
Important factors:

- natural groundwater recharge
- geology
- distance between ditches
- water levele ditches
- capacity drainage system

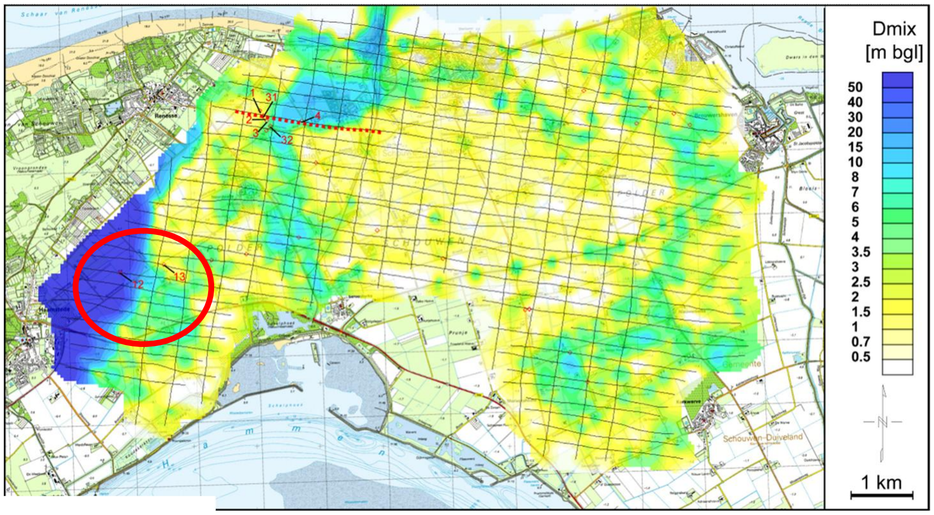
Comparison HEM – ECPT



Rainwater lens thickness (D_{mix}= average position mixing zone) mapped with HEM



Rainwater lens thickness (Dmix= average position mixing zone) mapped with HEM



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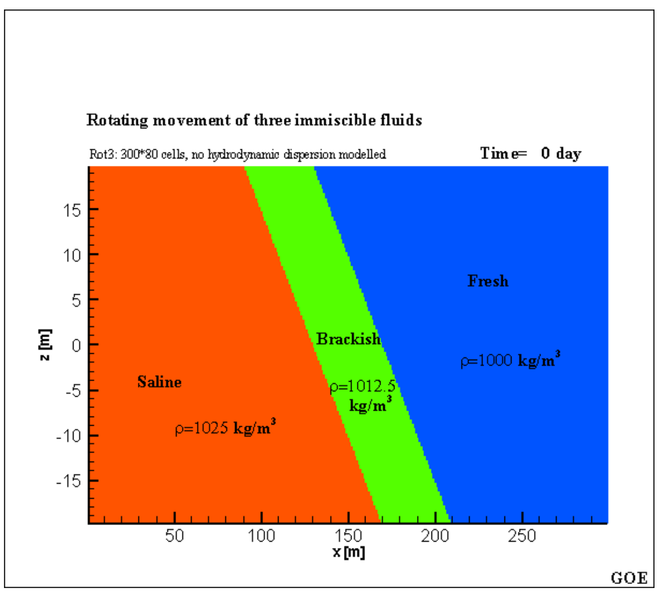
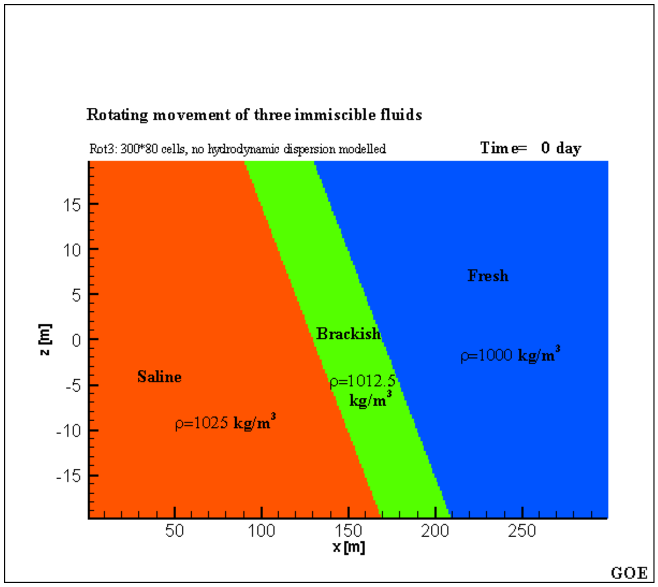
Examples of variable-density groundwater flow

- Rotating immiscible interface
- Henry's problem
- Evolution freshwater lens
- Hydrocoin
- Salt water pocket
- Broad 14 Basin, North Sea
- Heat transport: Elder and Rayleigh=4000
- 5 Dutch 3D cases
- Freshwater lenses
- Effect of Tsunami on groundwater resources

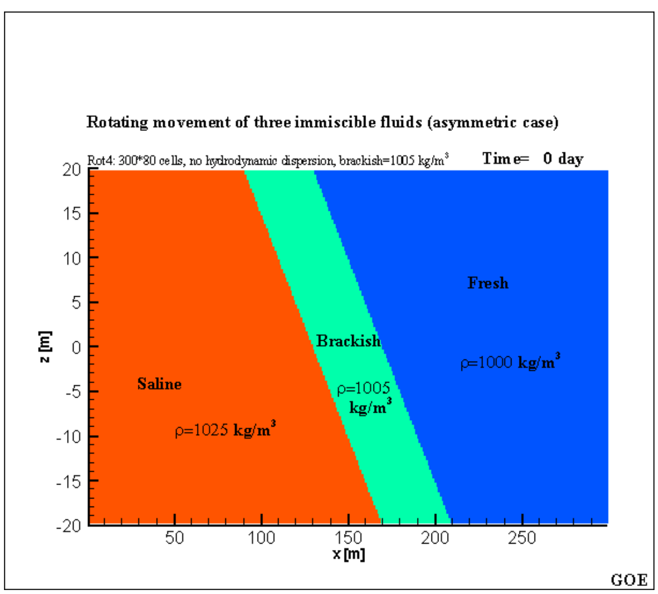
Rotating immiscible interfaces



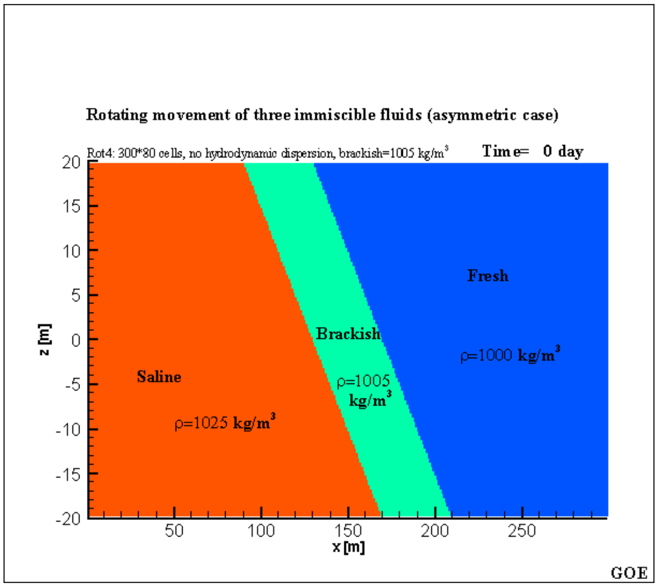
Rotating immiscible interfaces



Rotating immiscible interfaces (asymmetric)

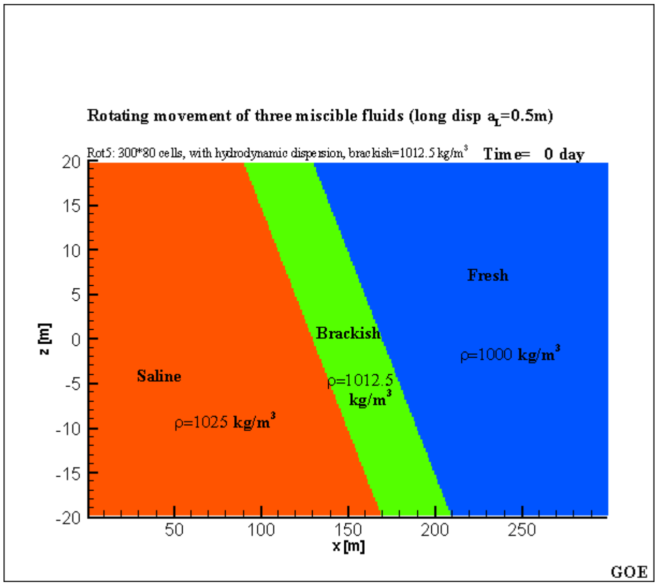


Rotating immiscible interfaces (asymmetric)

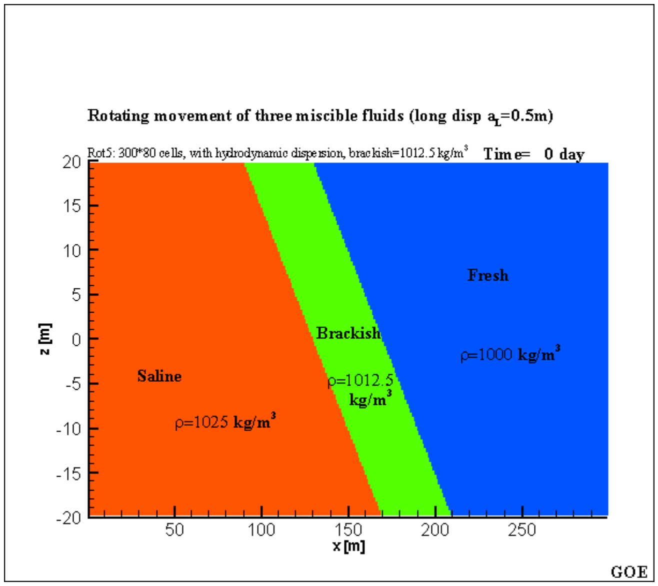


Bakker, M., Oude Essink, G.H.P. & Langevin, C. 2004. The rotating movement of three immiscible fluids, J. of Hydrology 287, 270-278

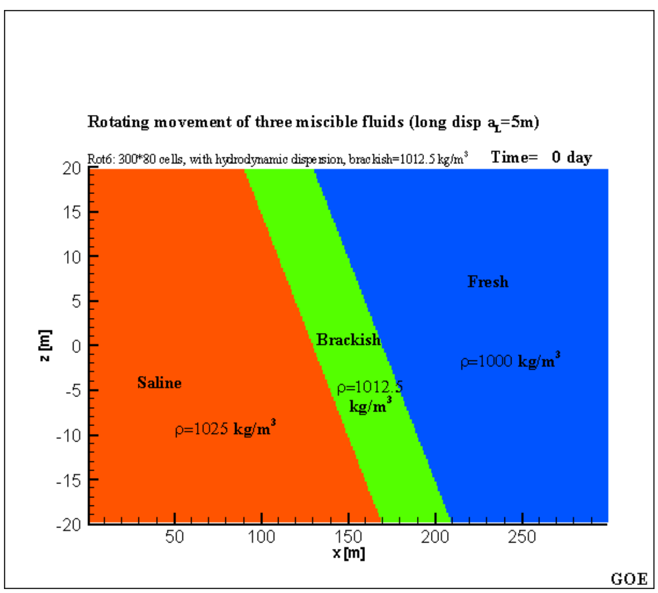
Rotating interfaces with dispersion α_L=0.5m



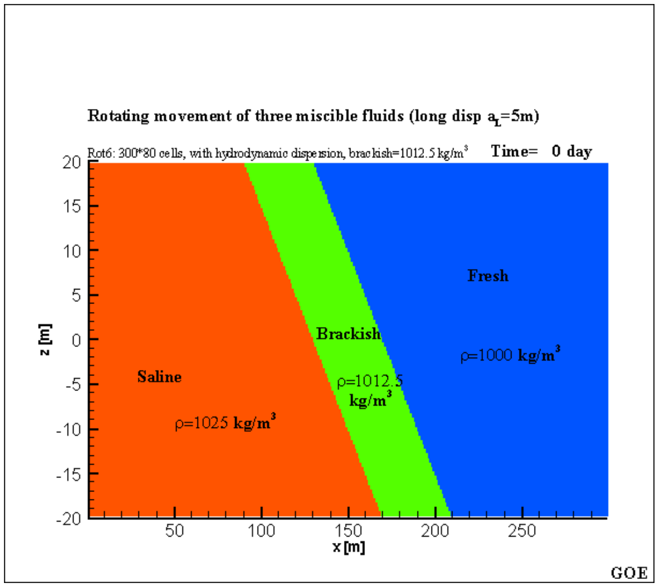
Rotating interfaces with dispersion α_L=0.5m



Rotating interfaces with dispersion α_L=5m



Rotating interfaces with dispersion α_L=5m

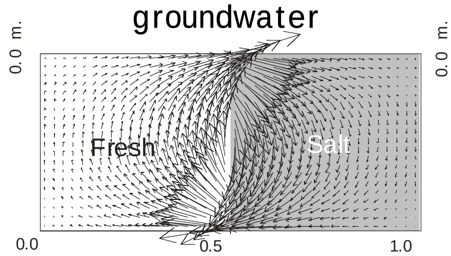


Rotating immiscible interfaces

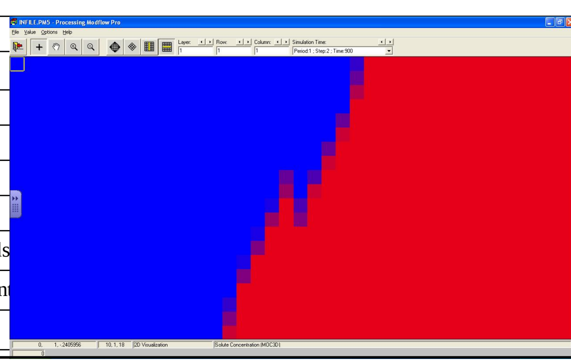
Conclusion:

To check the variable-density component of your code, this immiscible interface benchmark can be used.

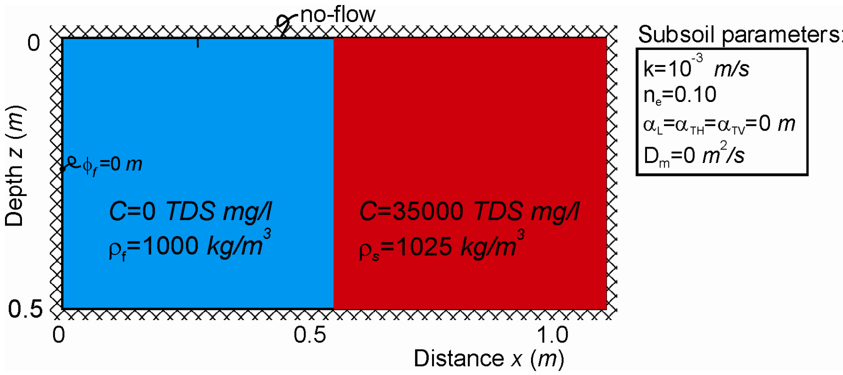
Case 1: Vertical interface between fresh and saline groundwater



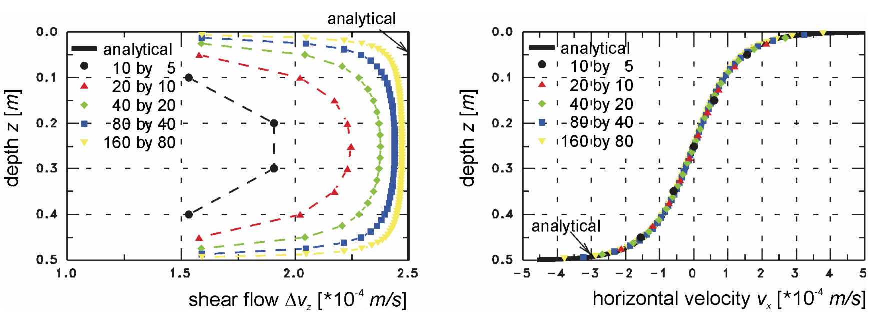
Parameters	
Layers	$^{-3}$ m/s
Rows	10^{-5} m/s
Columns	
Δx	
Δy	
Δz	
Stress periods	
Initial concen	
bouyancy	



Vertical interface



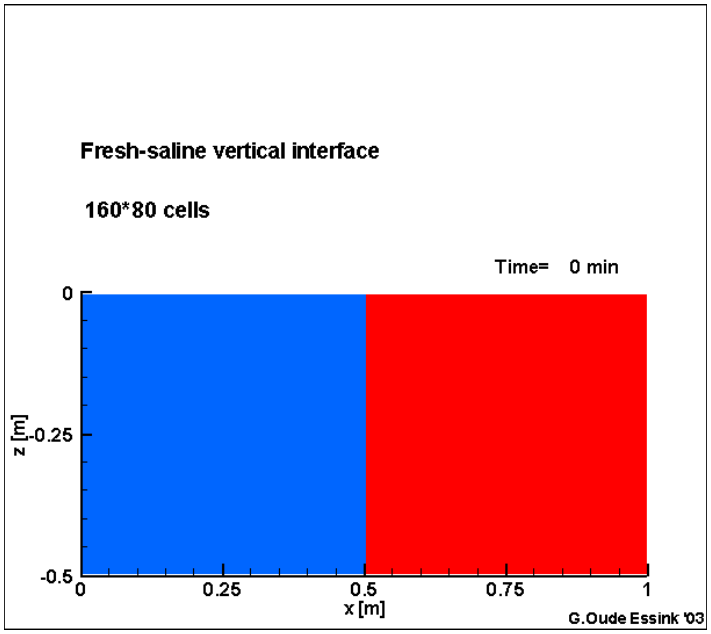
Effect of the number of cells on the shear flow at the interface at t=0



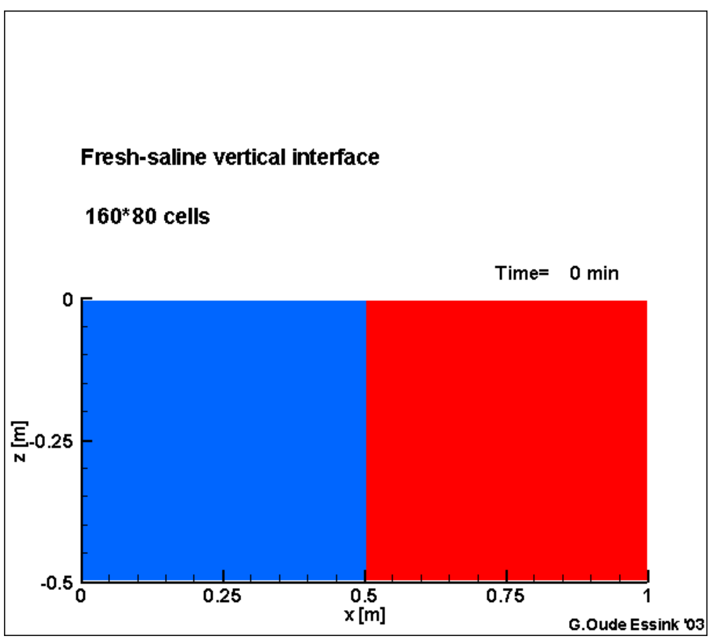
$$\Delta v_z = \frac{k}{n_e}\left(\frac{\rho_s - \rho_f}{\rho_f}\right)$$

$$v_x = \frac{k}{n_e}\left(\frac{\rho_s - \rho_f}{\rho_f}\right)\frac{1}{\pi}\ln\tan\left(\frac{\pi z}{2D}\right)$$

Vertical interface



Vertical interface



Salt water pocket in a fresh environment

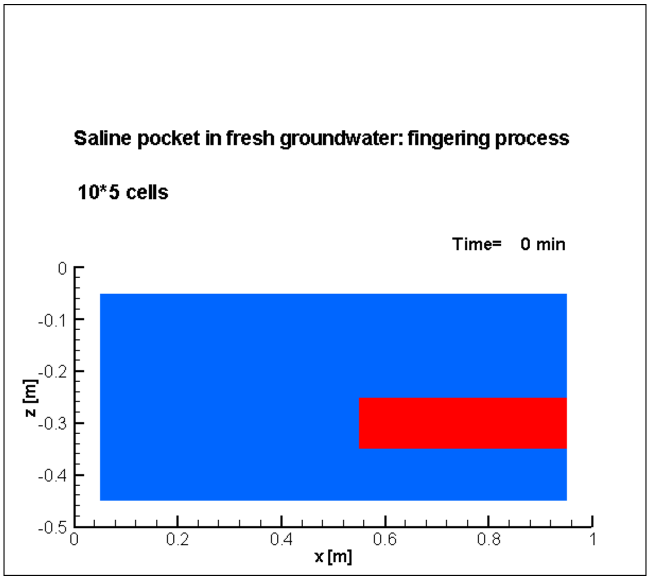
Grid convergence

Time step

cases

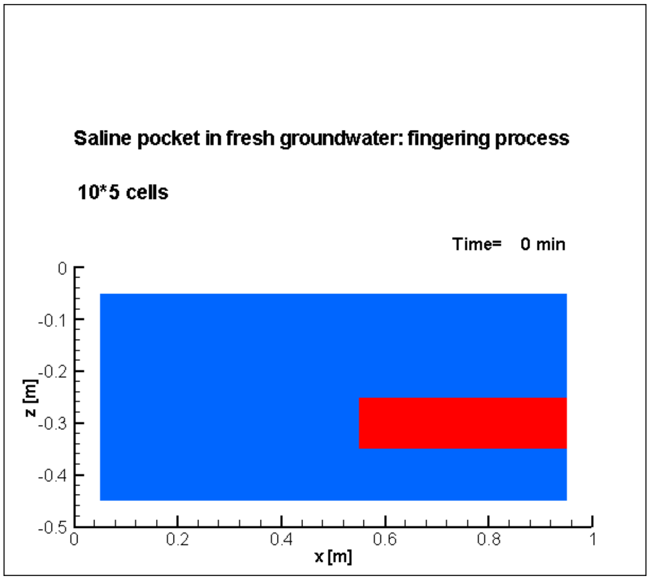
Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



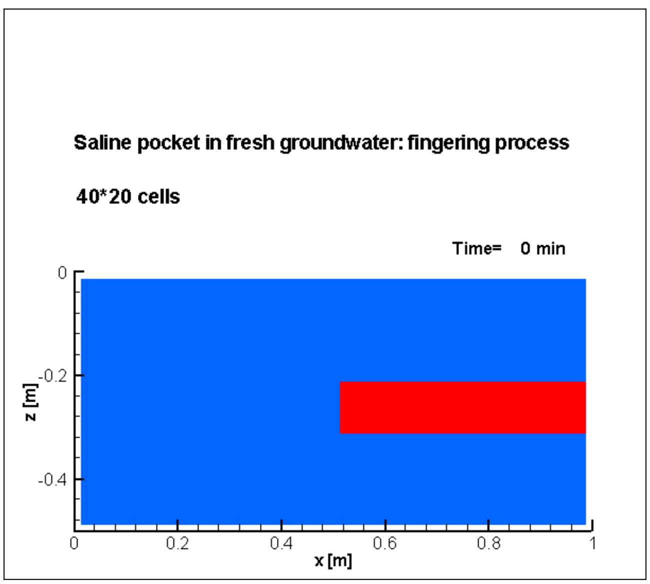
Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



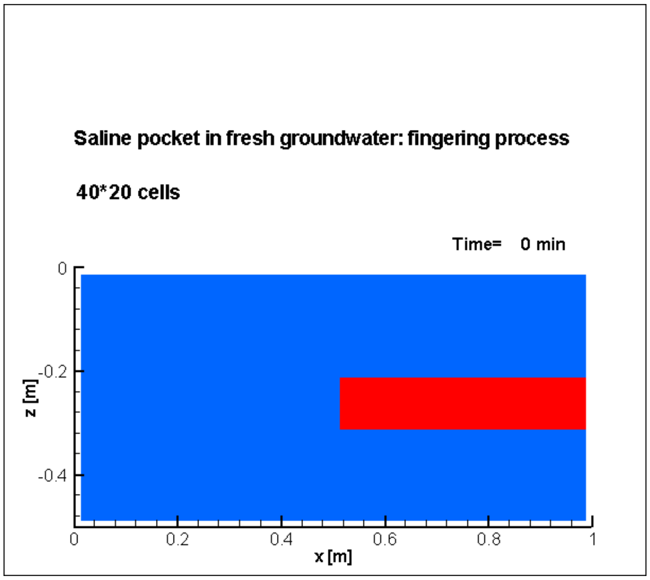
Salt water pocket in a fresh environment (II)

Effect of discretisation



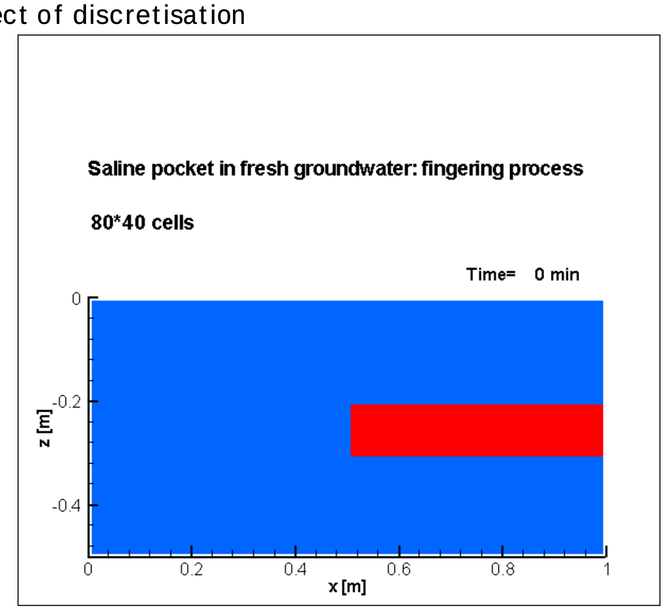
Salt water pocket in a fresh environment (II)

Effect of discretisation



Salt water pocket in a fresh environment (III)

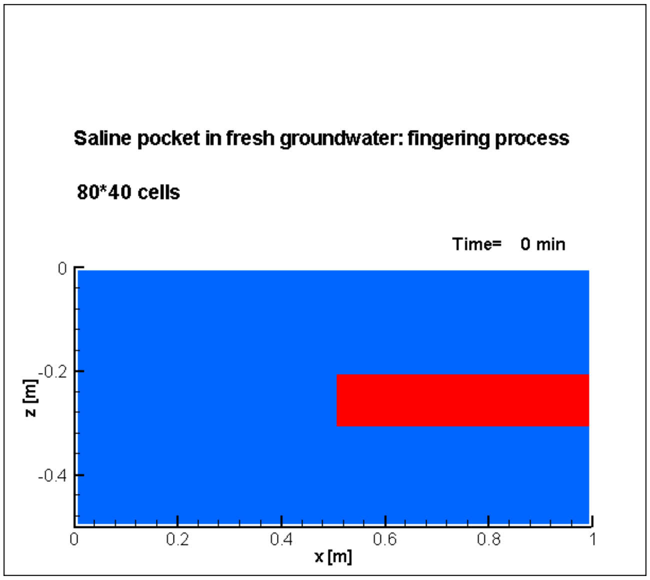
Effect of discretisation



cases

Salt water pocket in a fresh environment (III)

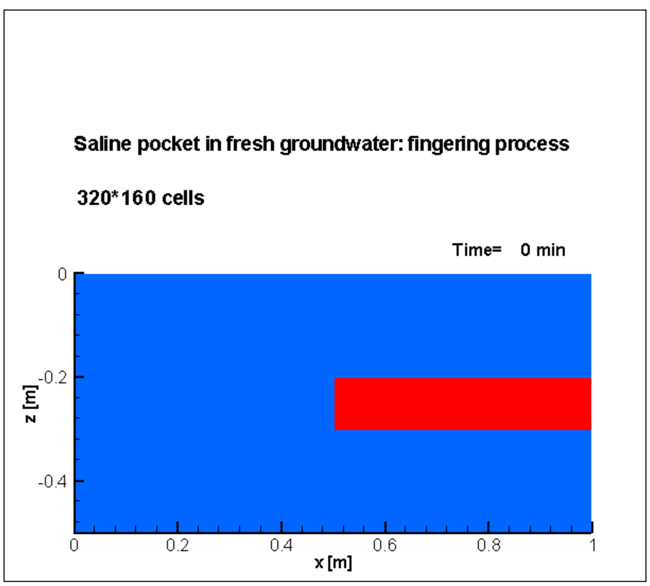
Effect of discretisation



cases

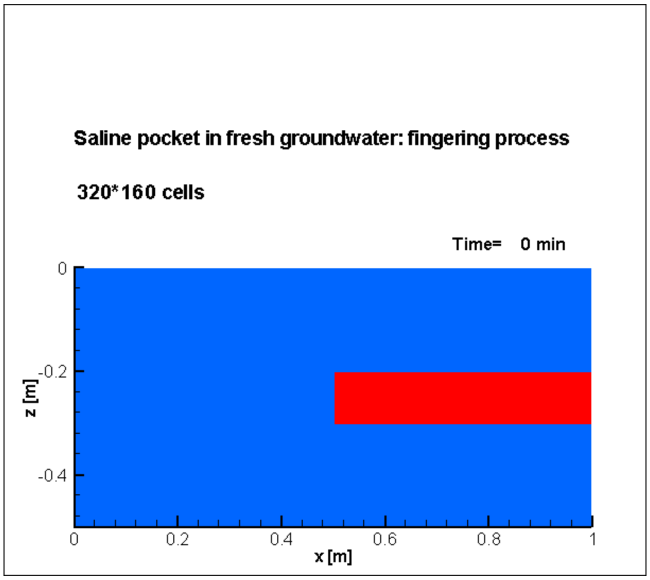
Salt water pocket in a fresh environment (IV)

Effect of discretisation



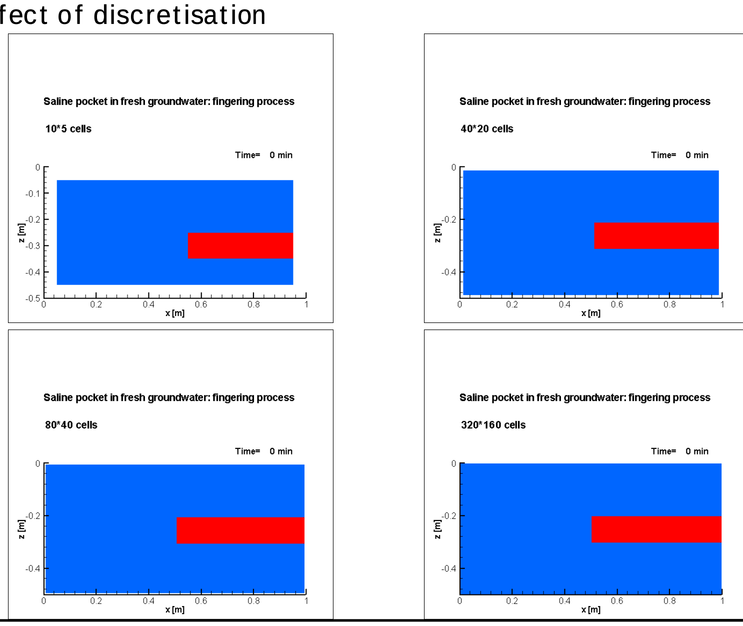
Salt water pocket in a fresh environment (IV)

Effect of discretisation



Salt water pocket in a fresh environment (V)

Effect of discretisation

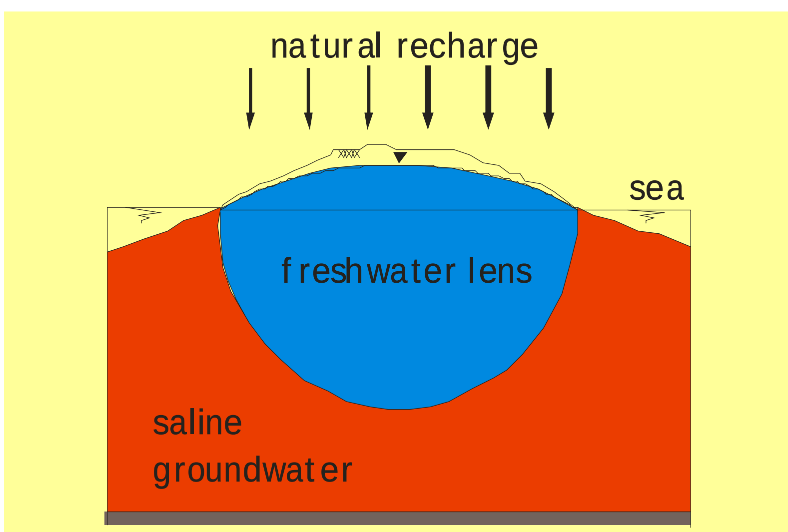


Salt water pocket in a fresh environment (VI)

Conclusion:

- For some physical processes, a large number of cells is necessary
- Check always grid convergence!

Evolution of a freshwater lens



cases

Question:

How long does it take before the volume of a freshwater lens is filled?:

a. 5 years
b. 25 years
c. 100 years
d. 500 years

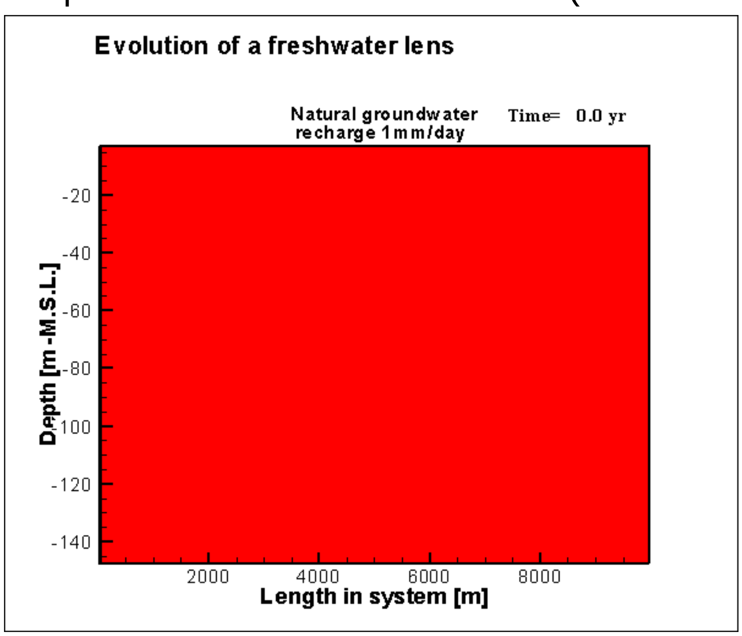
T **= specific time scale**

T **= time period before the lens has reached 95% of its final form**

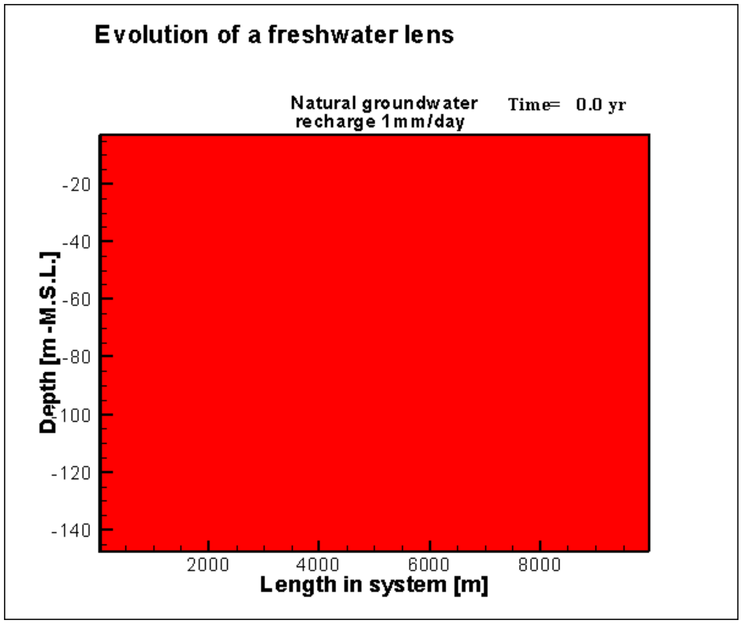
In the Netherlands: T = 75-200 jaar,

depends on:
• width dune area
• natural groundwater recharge
• hydraulic conductivity soil

Concept: evolution freshwater lens (not Griend!)



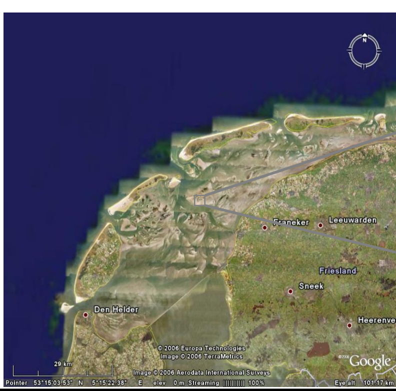
Concept: evolution freshwater lens (not Griend!)



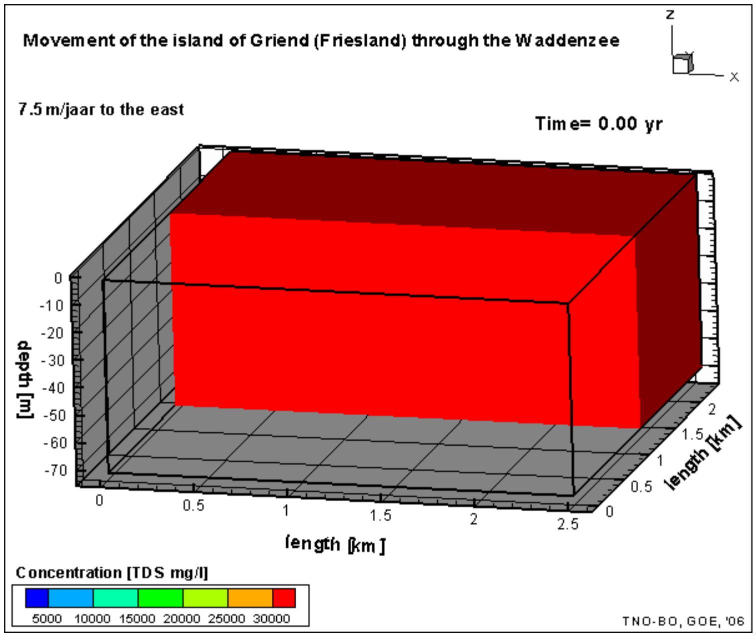
The island of Griend

Issues:

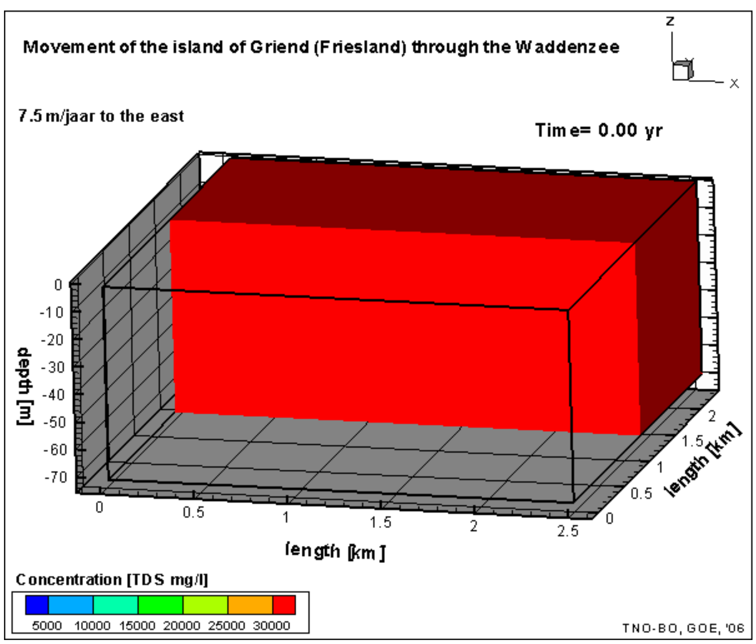
1. Small island moves ~7.5m per year to the east
2. Effect on the volume of the freshwater lens:
   - Can a lens be developed?
   - What is the thickness of the lens?



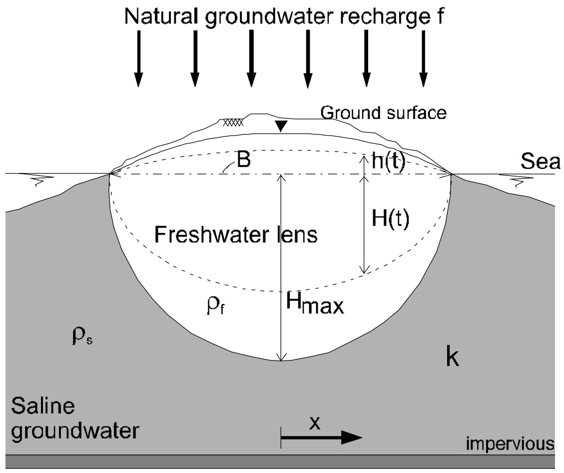
Movement of De Griend and creation of the lens



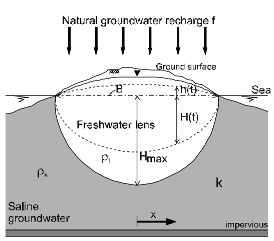
Movement of De Griend and creation of the lens



Case 2: Development of a freshwater lens

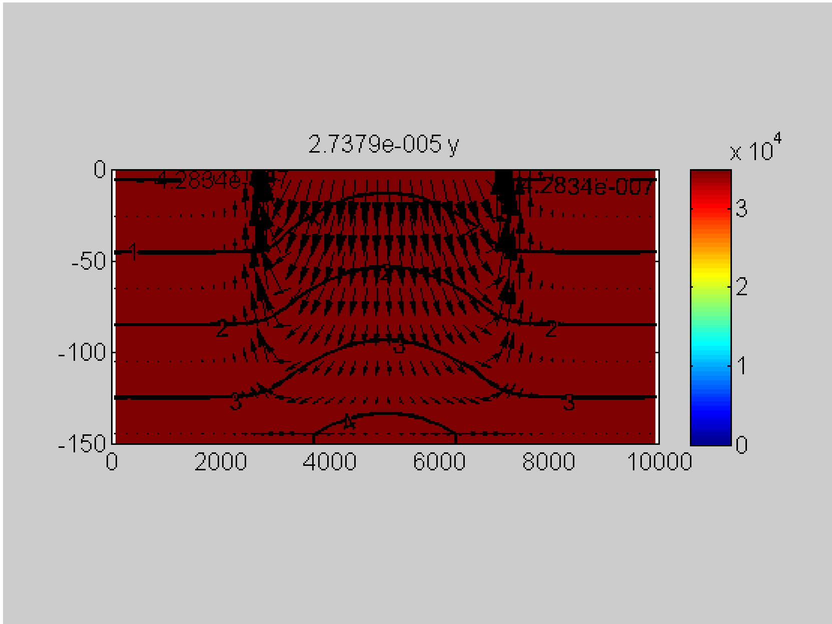


Case 2: Development of a freshwater lens

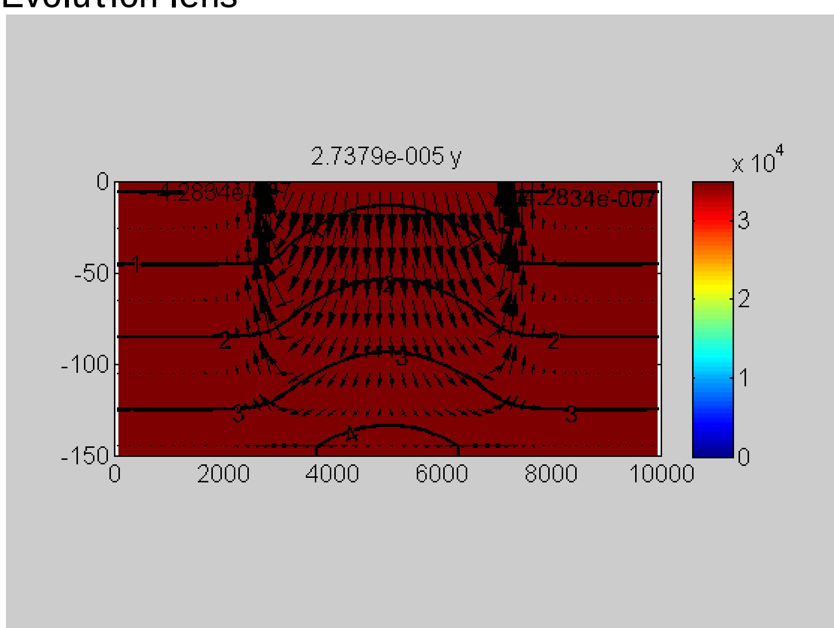


Parameters			
Layers	15	K_{hor}	20 m/d
Rows	1	T	200 m/d
Columns	100	Anisotropy K_{hor}/K_{ver}	10
Δx	100 m	ne	0.35
Δy	10 m	αL	0 m
Δz	10 m	αT	0 m
Stress periods	10	recharge	360 mm/y
Initial concentration	35000 mg/l	Recharge concentration	0 mg/l
bouyancy	0.025		

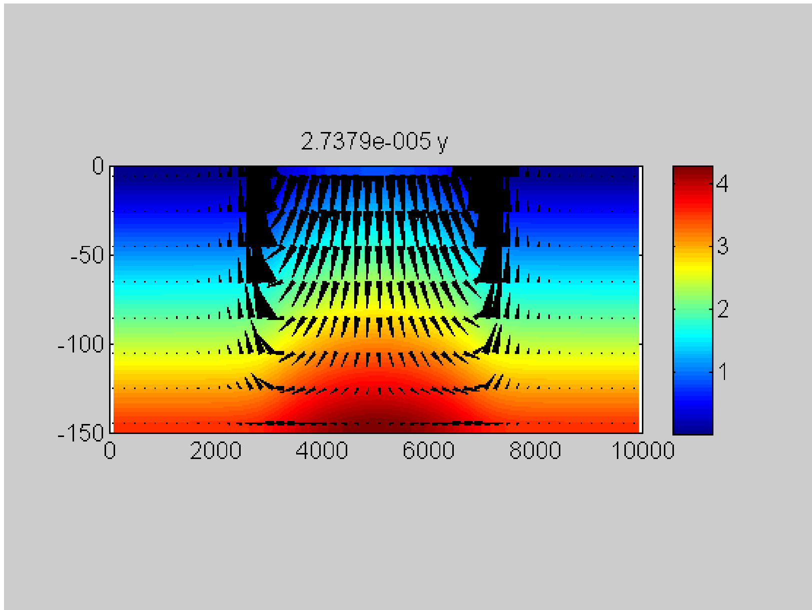
Evolution lens



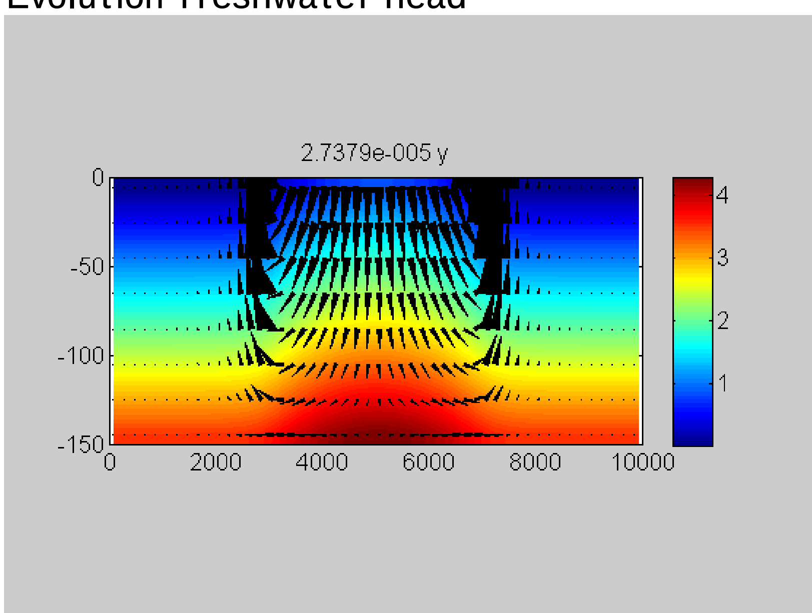
Evolution lens



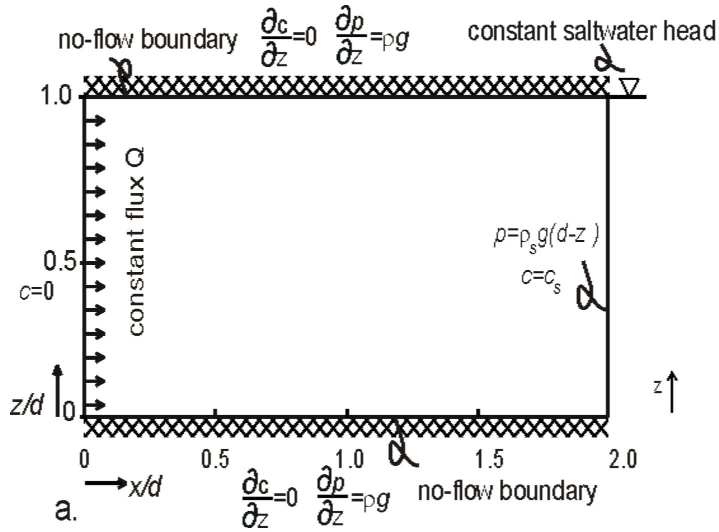
Evolution freshwater head



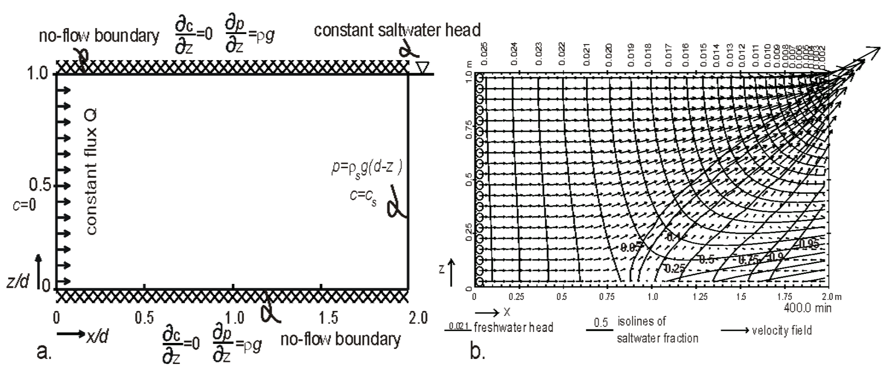
Evolution freshwater head



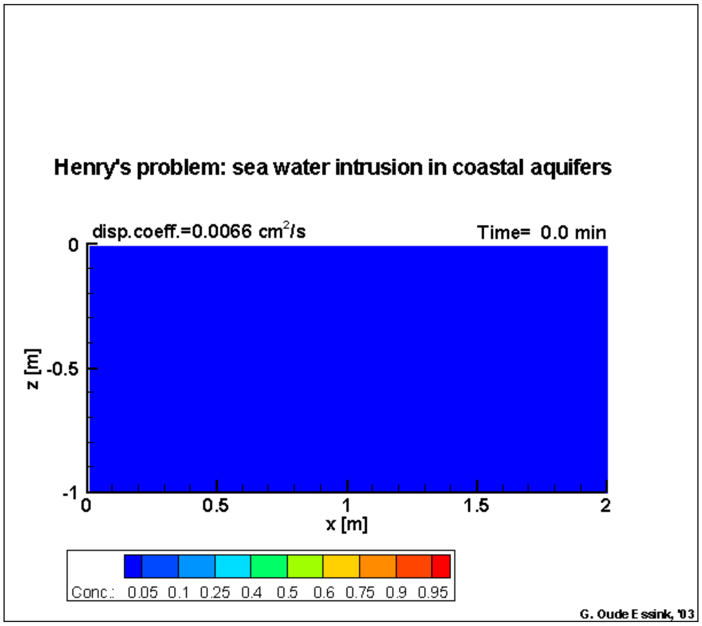
Henry's problem (1964)



Henry's problem



Henry's problem

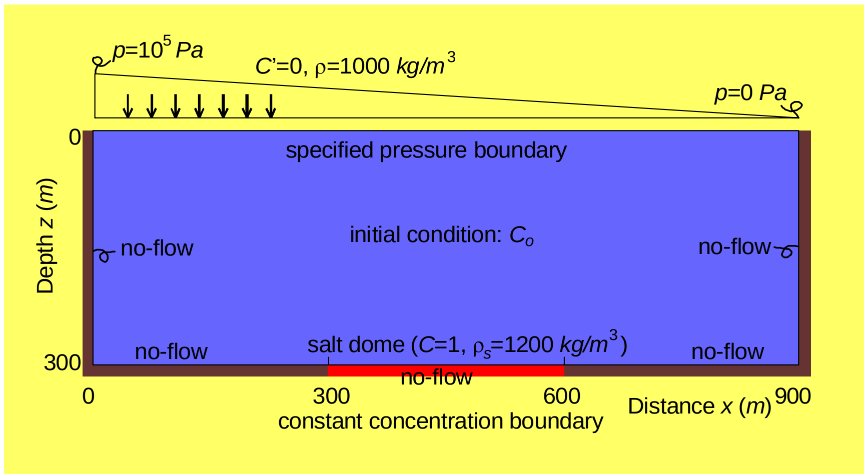


Henry's problem

Don't use the Henry problem as a variable-density benchmark, because even with a constant density model, the results are more or less the same!

Hydrocoin:

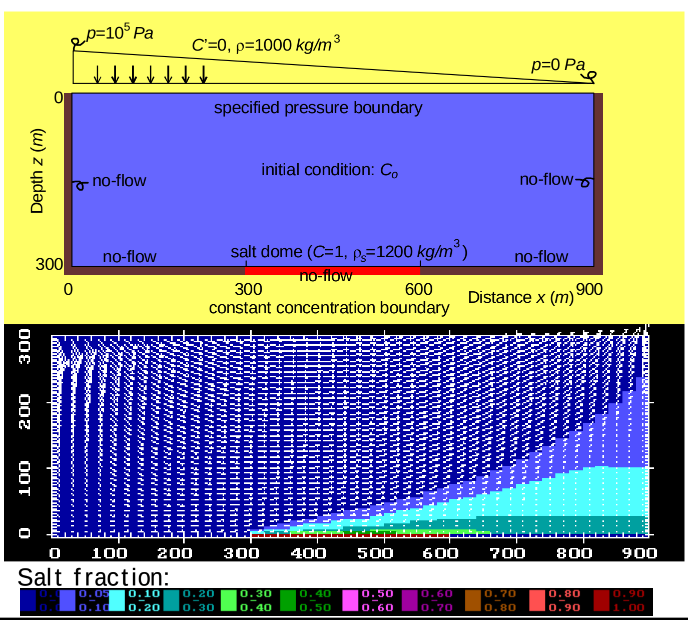
disposal of high-level nuclear waste
groundwater movement near salt domes
Gorleben salt dome, Germany



cases

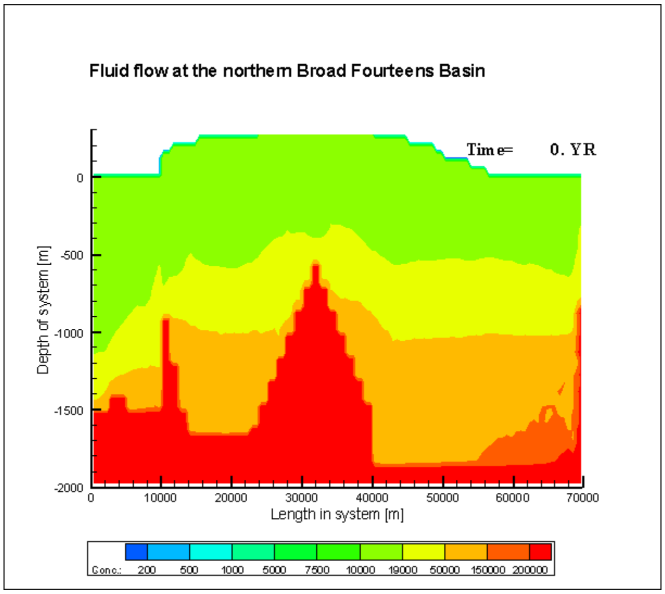
Hydrocoin:

groundwater movement near salt domes



Broad 14 Basin, North Sea

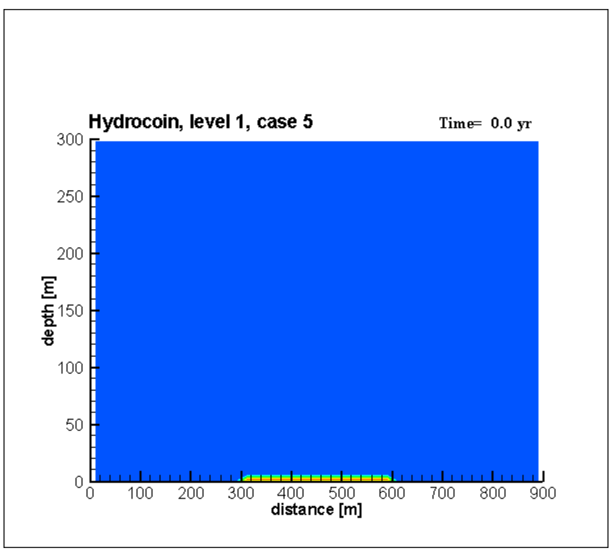
Geofluids'03, with L. Bouw



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

Hydrocoin: effect of boundary condition (I)

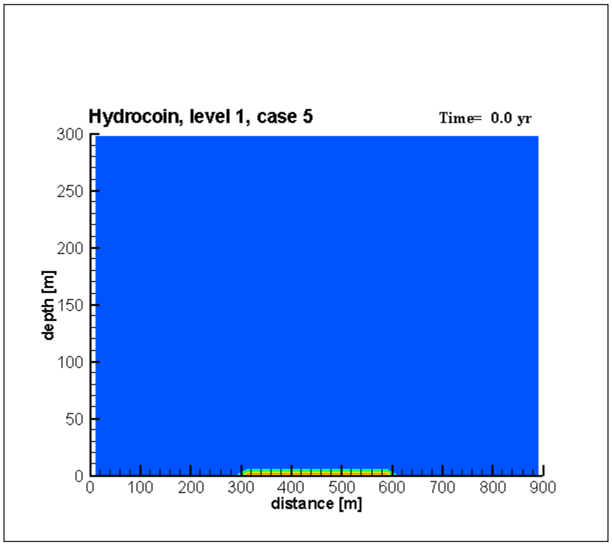
supply of brine through advection and hydrodynamic dispersion



recirculation type

Hydrocoin: effect of boundary condition (I)

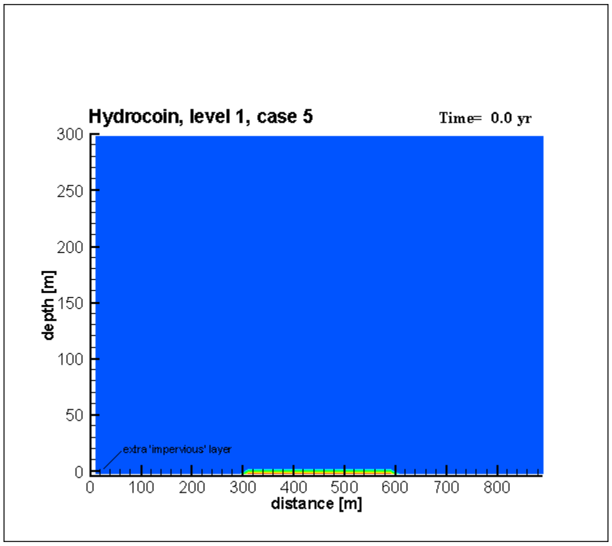
supply of brine through advection and hydrodynamic dispersion



recirculation type

Hydrocoin: effect of boundary condition (II)

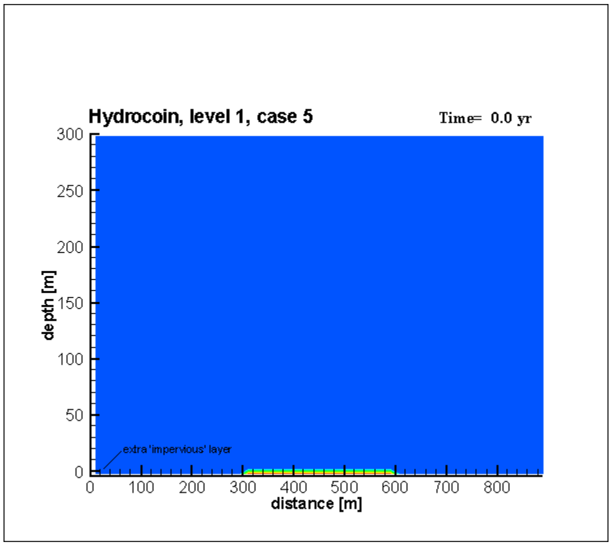
supply of brine through only hydrodynamic dispersion



swept-forward type

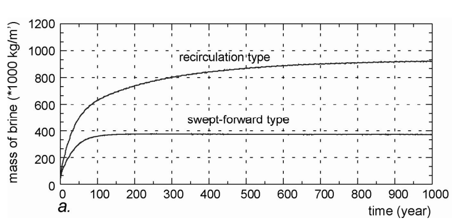
Hydrocoin: effect of boundary condition (II)

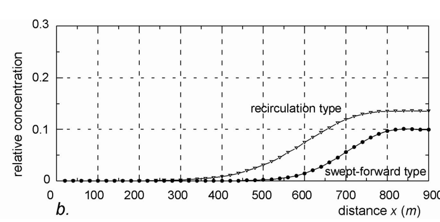
supply of brine through only hydrodynamic dispersion



swept-forward type

Hydrocoin: difference recirculation vs swept forward



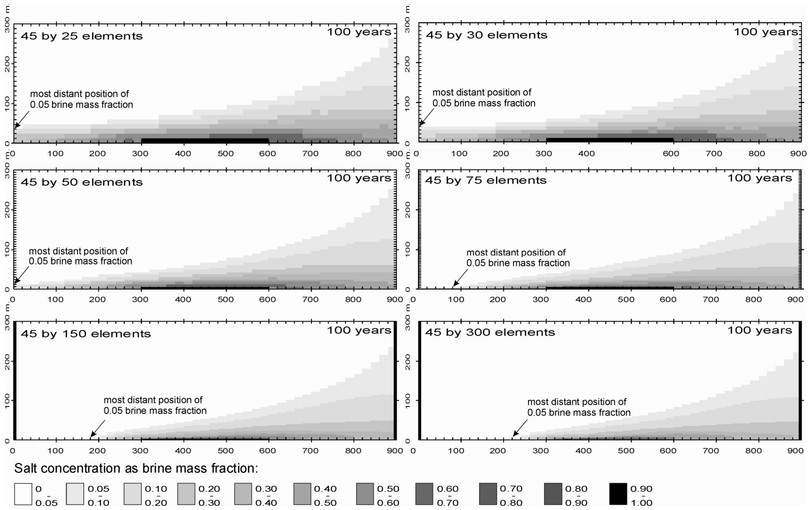


total mass of brine

brine conc at depth=200m

Lecture notes, p. 86-91

Hydrocoin: effect of vertical grid size

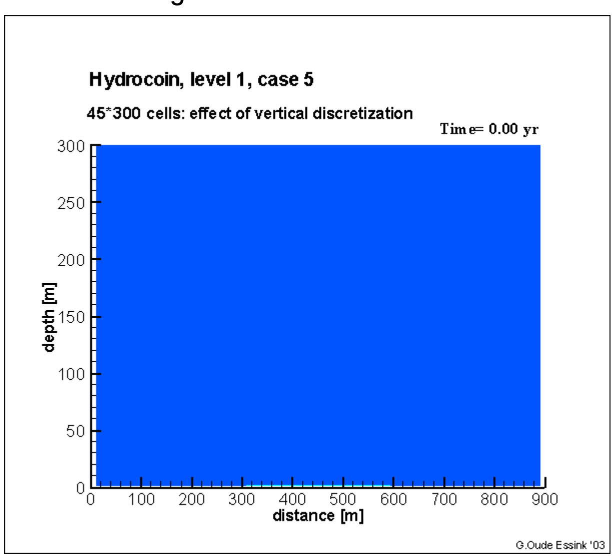


Recirculation type

cases

Hydrocoin: effect of vertical discretization (III)

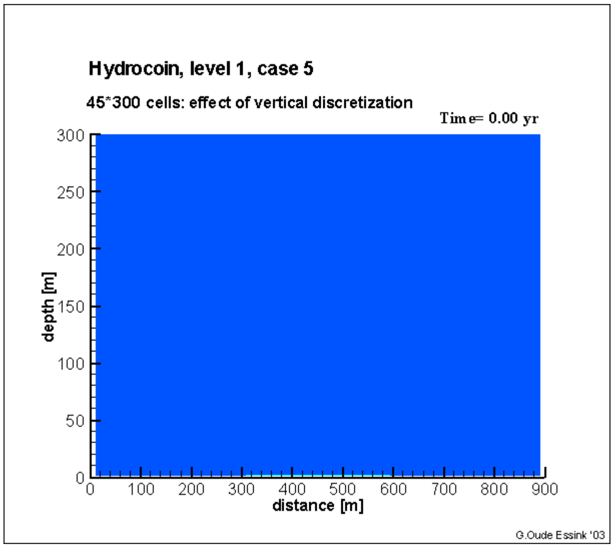
more vertical cells give better solution



like the swept-forward type

Hydrocoin: effect of vertical discretization (III)

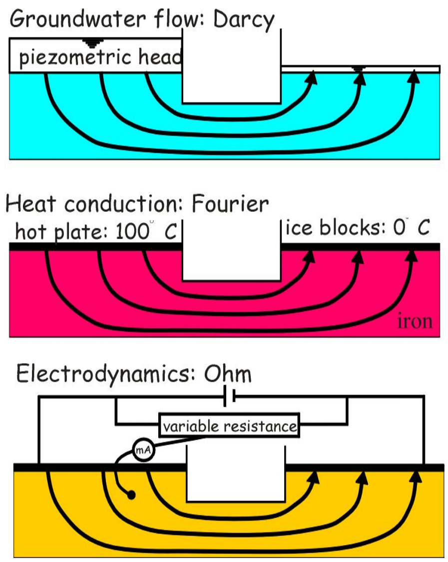
more vertical cells give better solution



like the swept-forward type

Analogy physical processes

Heat transport (analogy with solute transport)



$$q = -k \frac{\partial \phi}{\partial x}$$

$$h = -\lambda \frac{\partial T}{\partial x}$$

$$i = -\sigma \frac{\partial V}{\partial x}$$

Conduction and convection of heat

$$h = -\lambda_e \frac{\partial T}{\partial x} + n_e \rho c_f VT$$

heat flux | conduction (Fourier) | convection (fluid flow)

thermal conductivity [Joule/(ms °C)]

$$\lambda_e = n_e \lambda_{fluid} + (1 - n_e)\lambda_{solid}$$

continuity equation

$$-\frac{\partial h}{\partial x} = \rho' c' \frac{\partial T}{\partial t}$$

specific heat capacity [Joule/(kg °C)]

$$\rho' c' = n_e \rho c_{fluid} + (1 - n_e)\rho_{solid} c_{solid}$$

Analogy solute and heat transport

Solute: advection-dispersion equation

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i}(CV_i) + \frac{(C - C)'W}{n_e}$$

Heat: convection-conduction equation

$$\rho' c' \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(\Lambda_{ij} \frac{\partial T}{\partial x_j} \right) - \rho c_f \frac{\partial T q_i}{\partial x_i} + \Gamma$$

Analogy heat and solute transport

Heat transport

Convection-conduction equation

$$\rho' c' \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(\Lambda_{ij} \frac{\partial T}{\partial x_j} \right) - \rho c_f \frac{\partial T q_i}{\partial x_i} + \Gamma$$

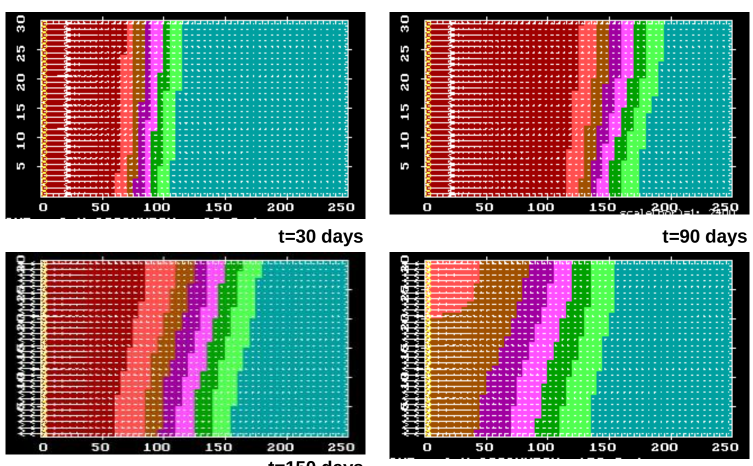
Equation of state: relation density & temperature

$$\rho_{\mathrm{i,j,k}} = \rho_f (1 - \alpha_f T_{i,j,k})$$

Analogy between solute and heat transport

Solute	Heat
C	T
R_d	$1 + \frac{(1-n_e)\rho_s c_s}{n_e \rho c_f}$
D_m	$\frac{n_e \lambda_e + (1-n_e)\lambda_s}{n_e \rho c_f}$
λ	0

Energy storage in geothermal reservoirs



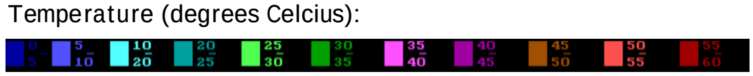
t=30 days

t=90 days

t=150 days

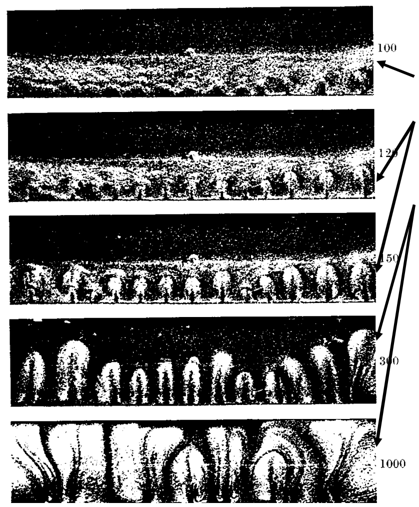
t=210 days

Temperature (degrees Celcius):



Elder problem (I)

It is originally a heat transport problem



Phases:

1. Stable growth diffusive boundary layer
2. Development flow cells embedded in boundary layer
3. Emergence of disturbances that grow into fingers

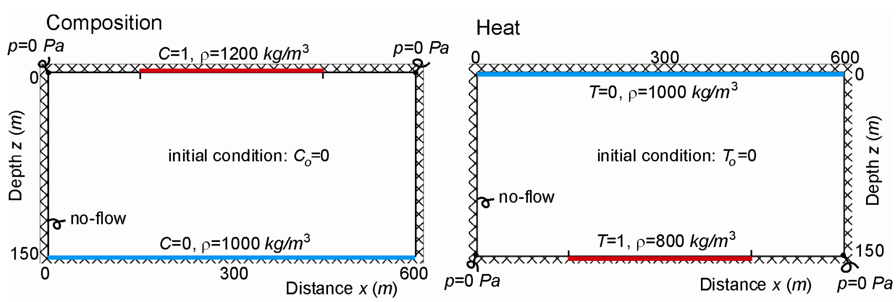
Convection of heat occurs when:

Rayleigh number > $4\pi^2$

Elder, J. Fluid Mech. 32, 69-96, 1968

Elder problem (II)

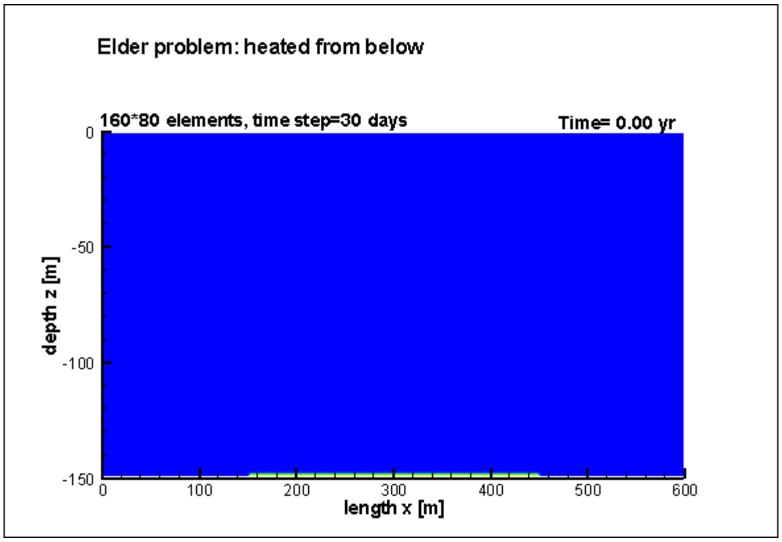
Anology composition and heat



Lecture notes, p. 91-96

Elder problem (III)

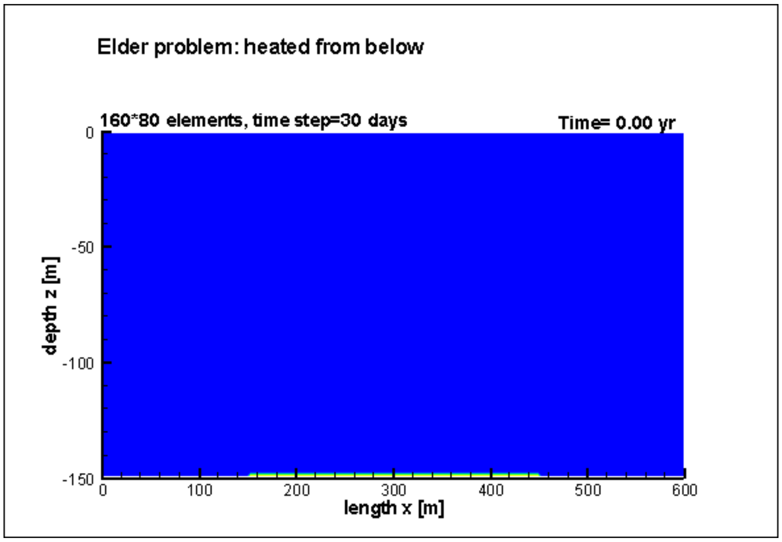
Development of convection cells (Rayleigh number=400)



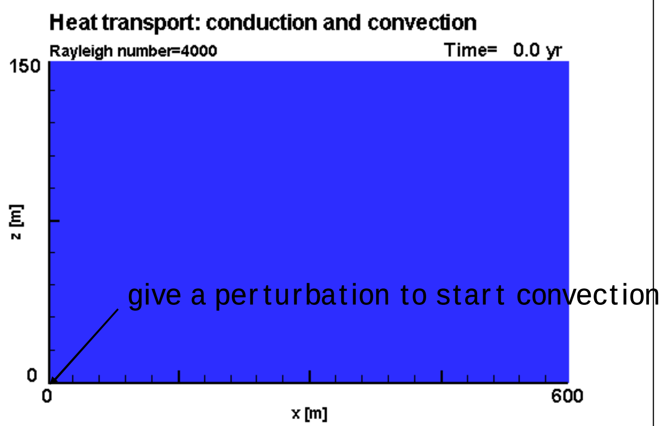
cases

Elder problem (III)

Development of convection cells (Rayleigh number=400)



Heat transport (Rayleigh number=4000)



Impact of the 26-12-04 Tsunami on groundwater systems

Sri Lanka
Some days after December 26th, 2004

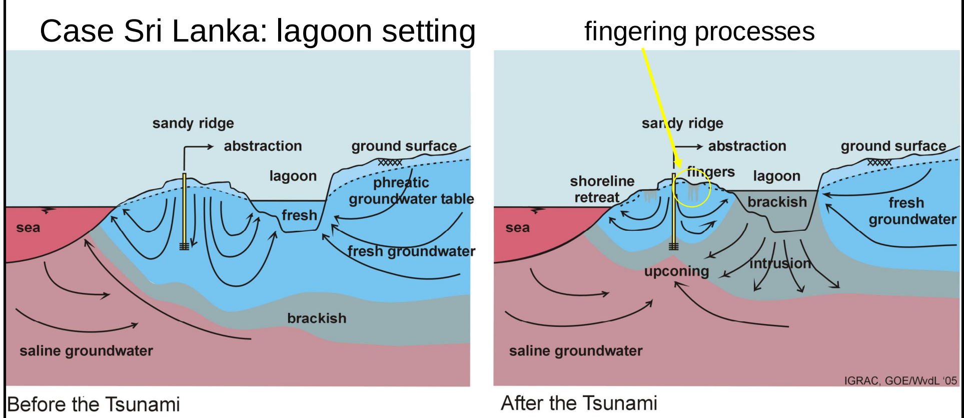
Impact of the 26-12-04 Tsunami on groundwater systems

Impression of relevant salinisation processes by conceptual models of salt water intrusion in coastal aquifers:

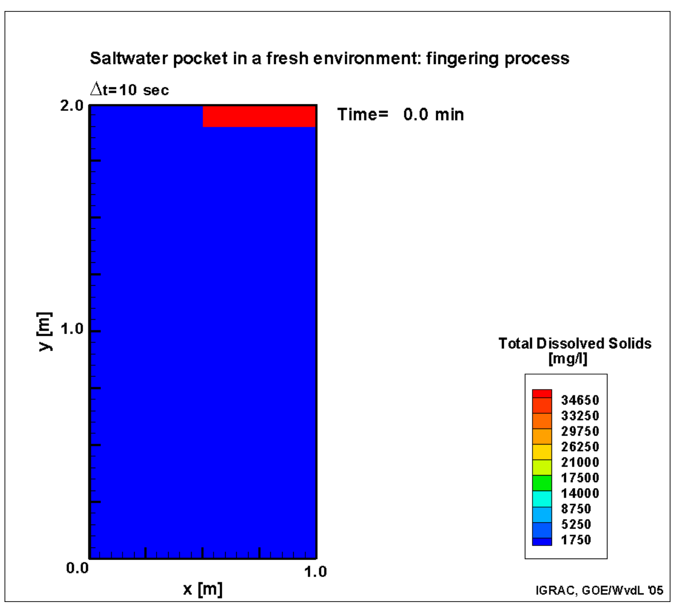
1. Fingering processes in the subsoil
2. Evolution of a freshwater lens after flooding by sea water
3. Freshwater lens in a coastal aquifer with a brackish lagoon

Next step:
quantifying processes in real situations, using topographic and hydrogeological data, and ending up with vulnerability maps

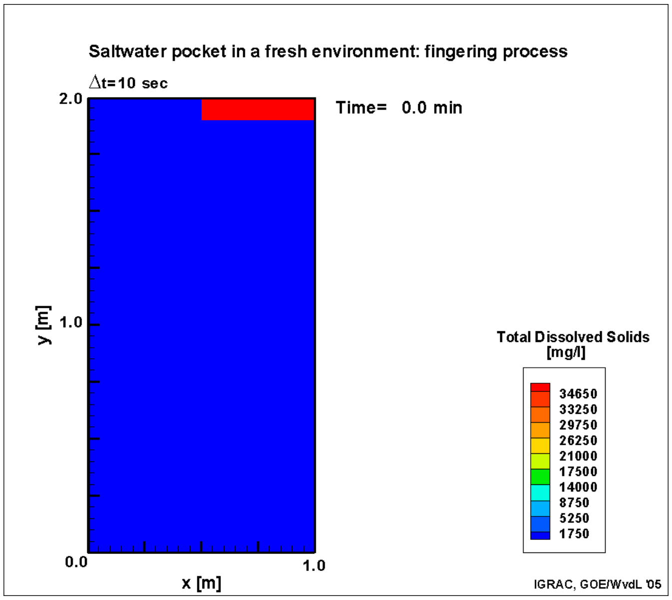
Concept 1: Fingering processes in the subsoil



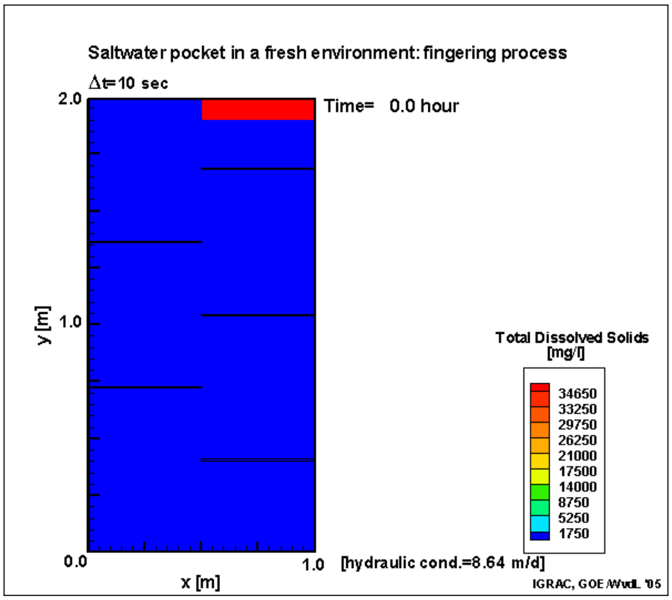
Concept 1: Fingering processes in the subsoil



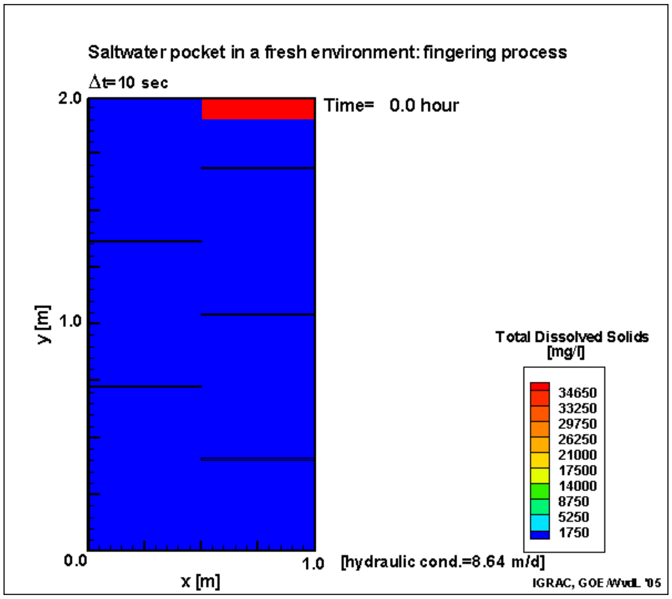
Concept 1: Fingering processes in the subsoil



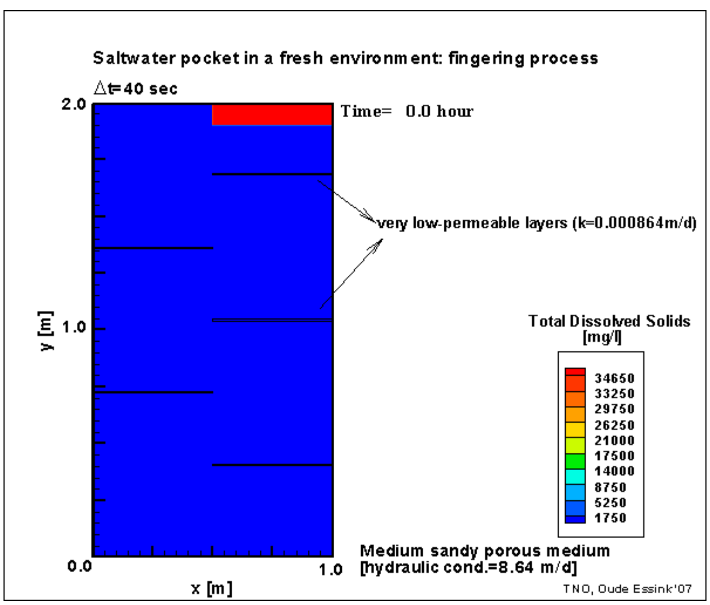
Concept 1: Fingering processes in the subsoil



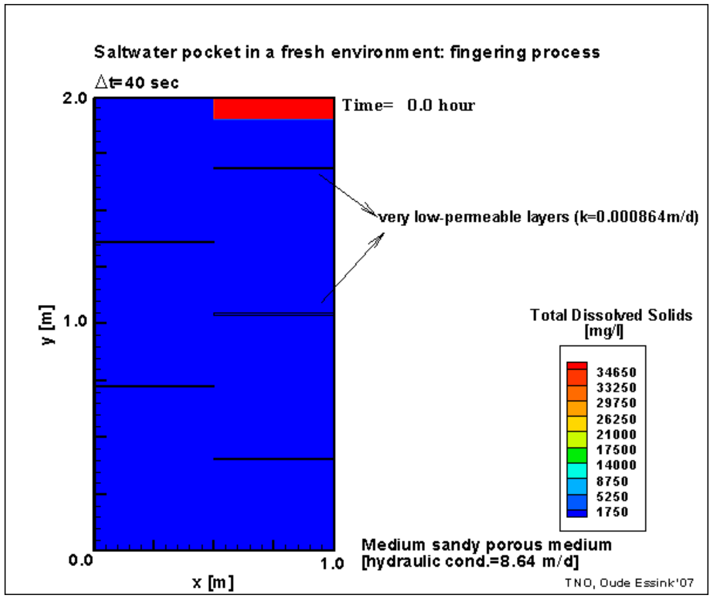
Concept 1: Fingering processes in the subsoil



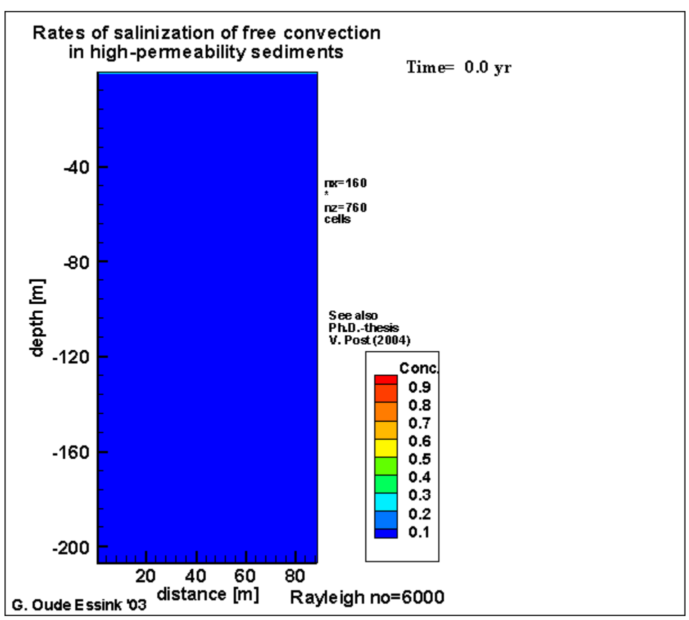
Concept 1: Fingering processes in the subsoil



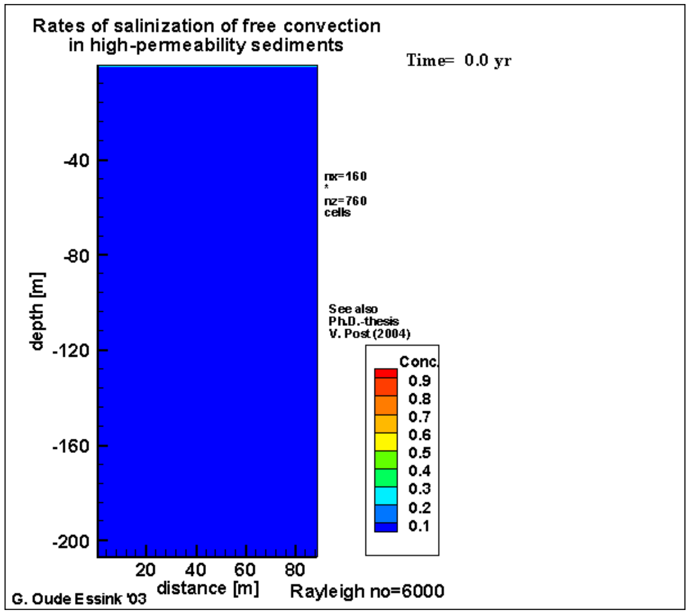
Concept 1: Fingering processes in the subsoil



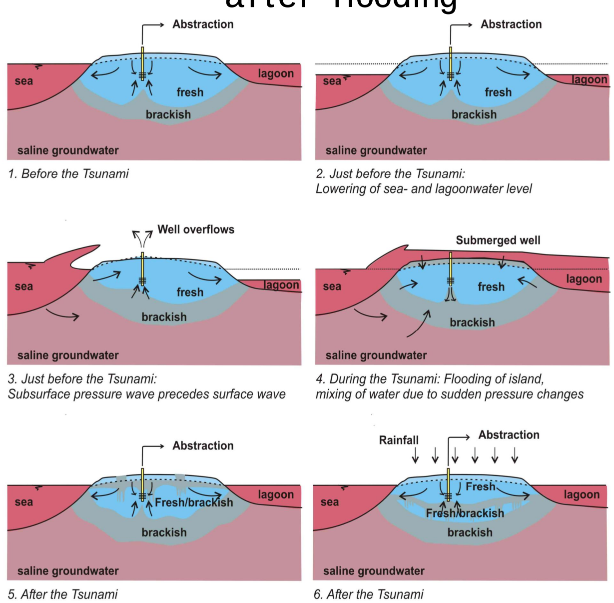
Concept 1: Fingering processes in the subsoil



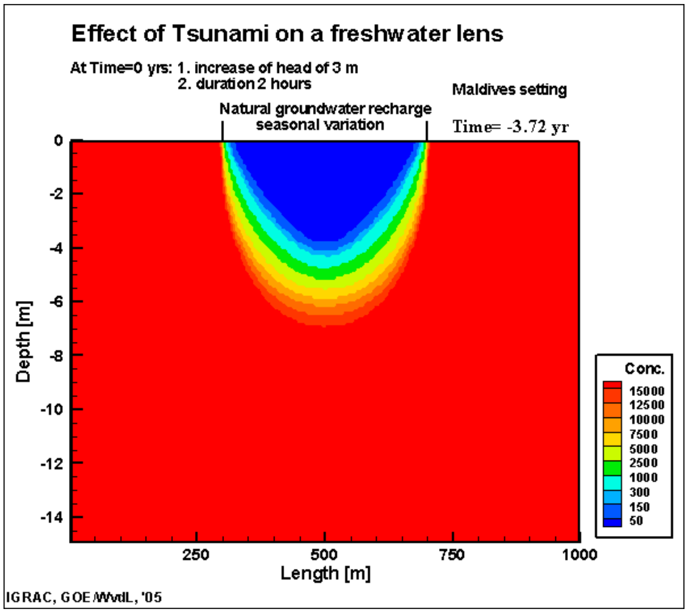
Concept 1: Fingering processes in the subsoil



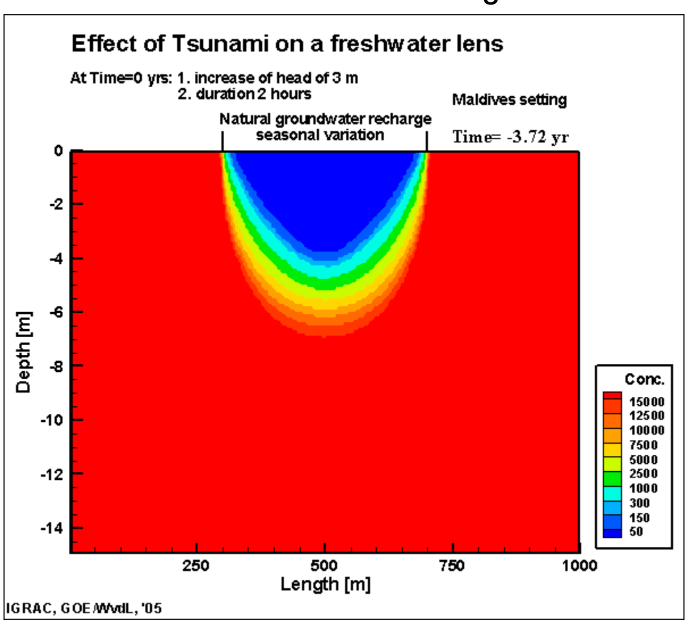
Concept 2: Evolution of a freshwater lens after flooding



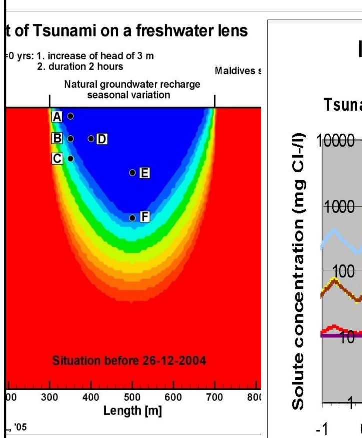
Concept 2: Evolution of a freshwater lens after flooding

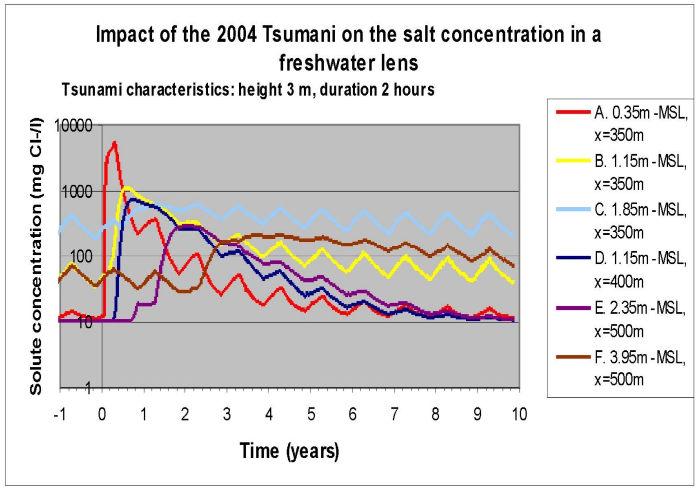


Concept 2: Evolution of a freshwater lens after flooding



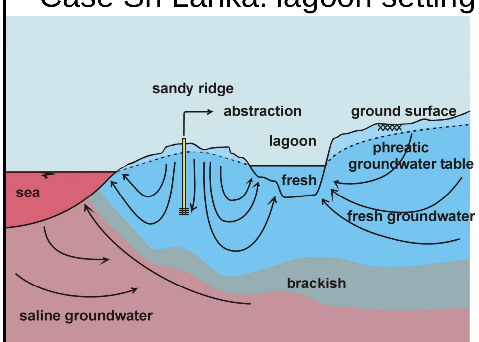
Concept 2: Evolution of a freshwater lens after flooding



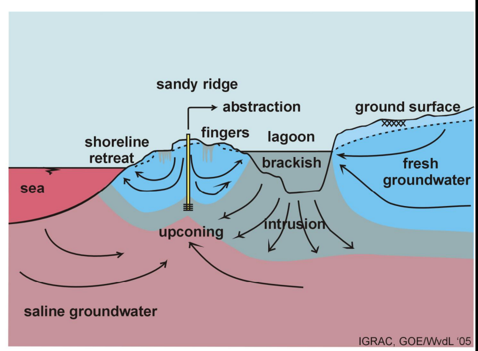


Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

Case Sri Lanka: lagoon setting

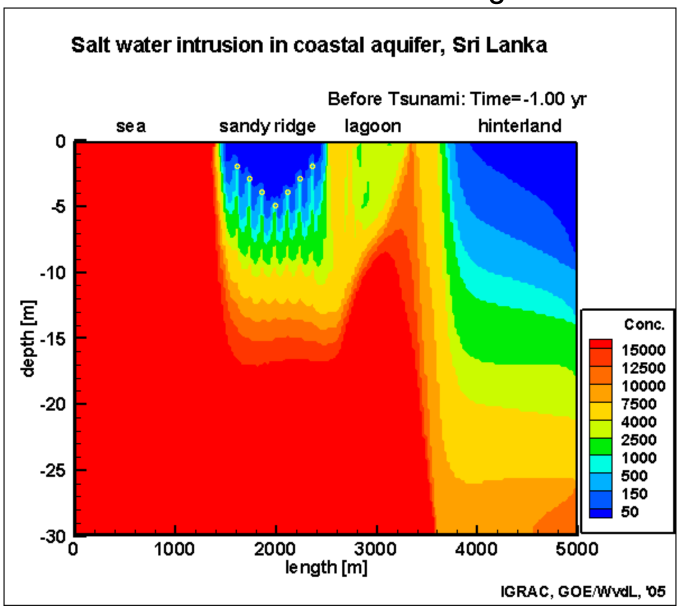


Before the Tsunami

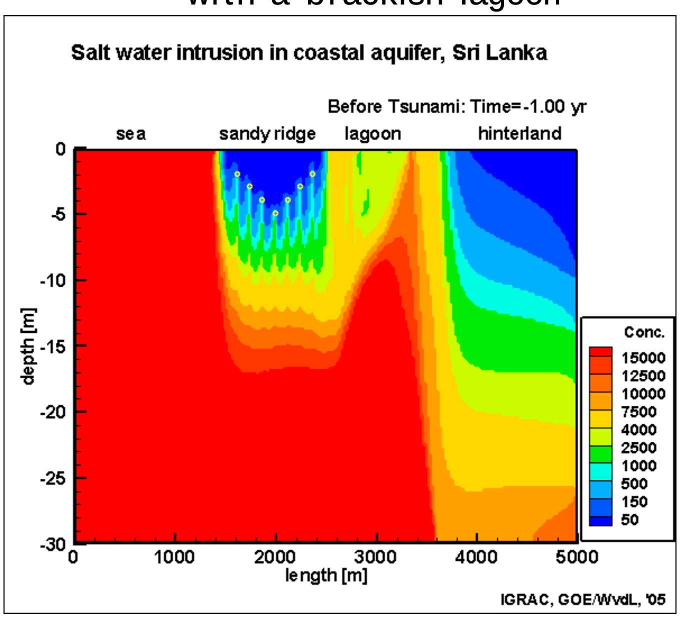


After the Tsunami

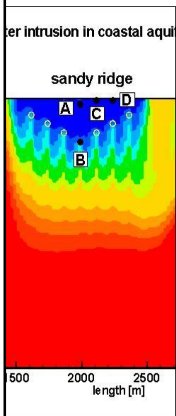
Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

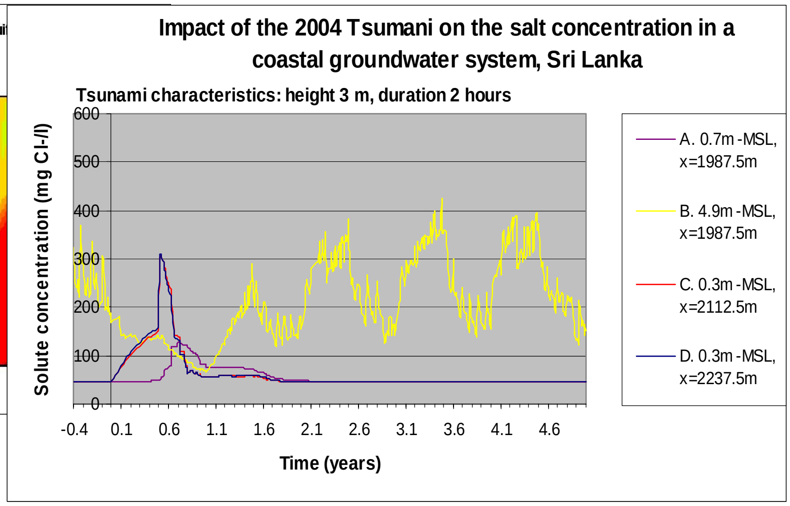


Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon



Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon



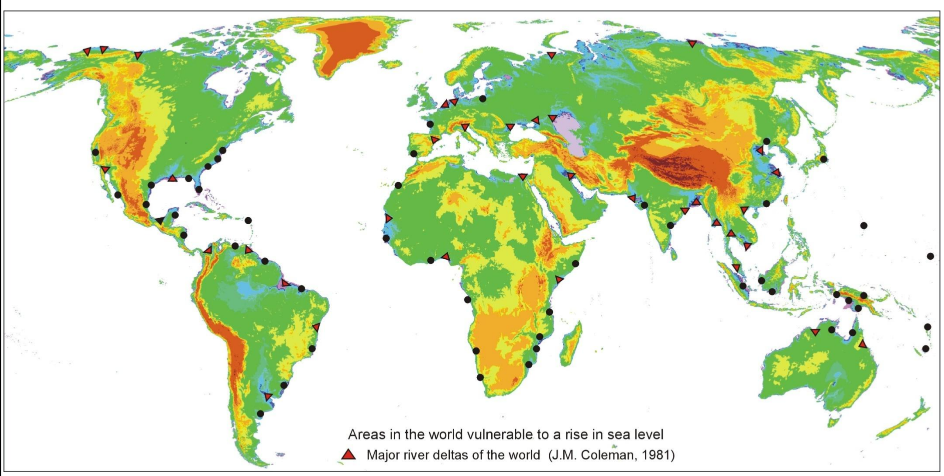


Effect sea level rise

Effects of sea level rise on groundwater resources in deltaic areas

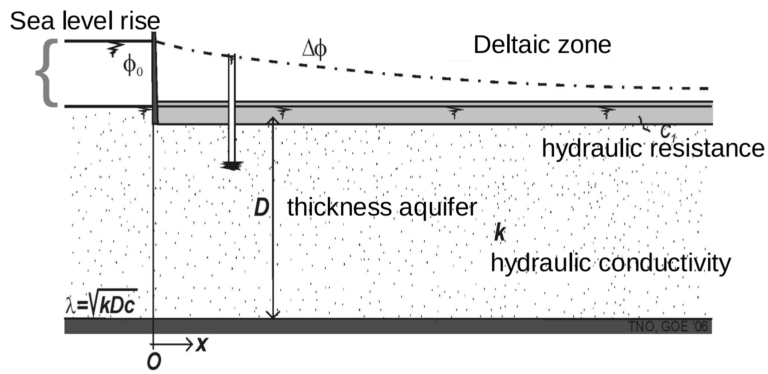
1. Increase of salt water intrusion
2. Increase of upconing under groundwater extraction wells
3. Increase of piezometric head
4. Increase of seepage and salt load to the surface water system
5. Risk of instable Holocene aquitards
6. [Decrease of fresh groundwater reservoirs due to decrease in natural groundwater recharge]

Effects of sea level rise on groundwater resources in deltaic areas



Digital Elevation Model (DEM)

Effect of sea level rise:
Analytical approach for zone of influence in deltaic areas



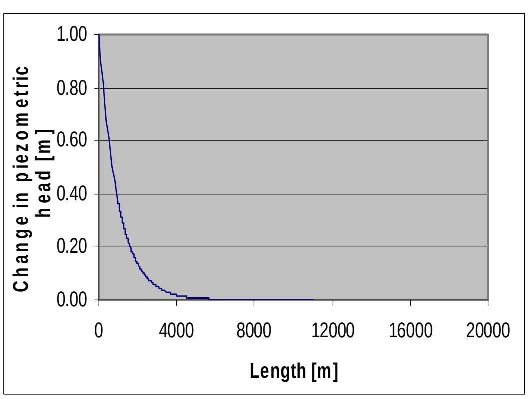
$$\Delta\phi(x) = \phi_0 e^{-x/\lambda}$$

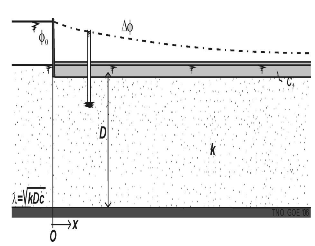
$$\lambda = \sqrt{kDc}$$

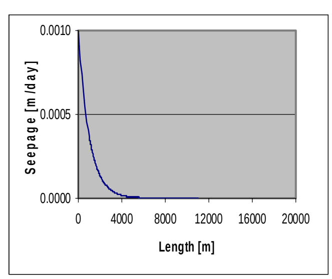
- Zone of influence is equal to sqrt(kDc)
- At x=3λ, only 5% of sea level rise is detactable

Effect of sea level rise:
Case 1 with Dutch subsoil parameters

kD = 1000 m²/day
c = 1000 day
λ = 1000 m



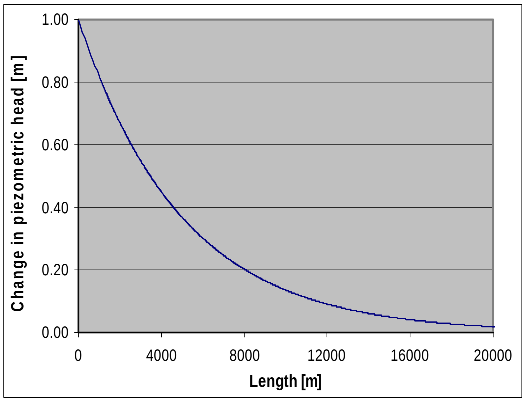


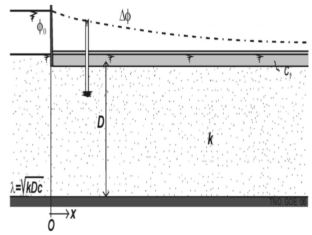


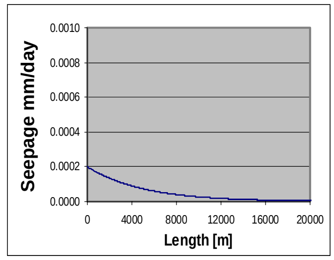
Effect of sea level rise:

Case 2 with Dutch subsoil parameters

kD = 5000 m2/day
c = 5000 day
λ = 5000 m

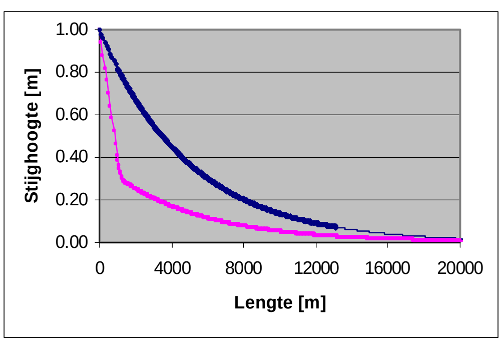


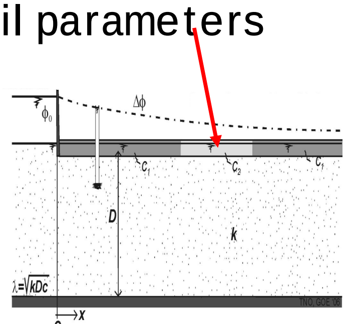


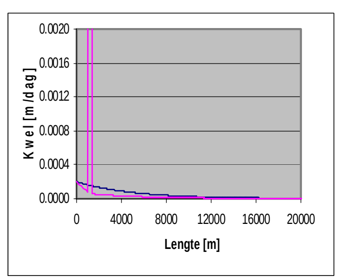


Case 3 with Dutch subsoil parameters

kD = 5000 m2/dag
c1 = 5000 dag, c2 = 50 dag

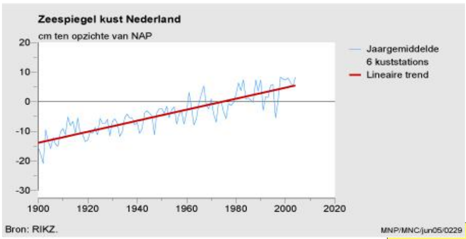


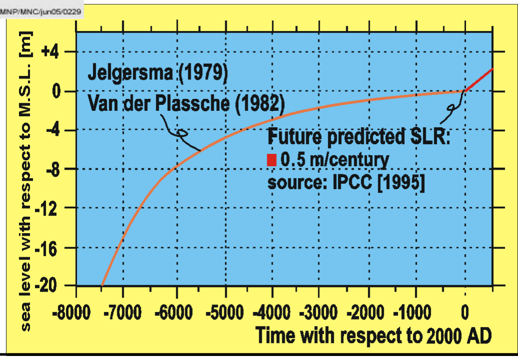




Climate change is HOT!

Past and future sea level rise in the Netherlands



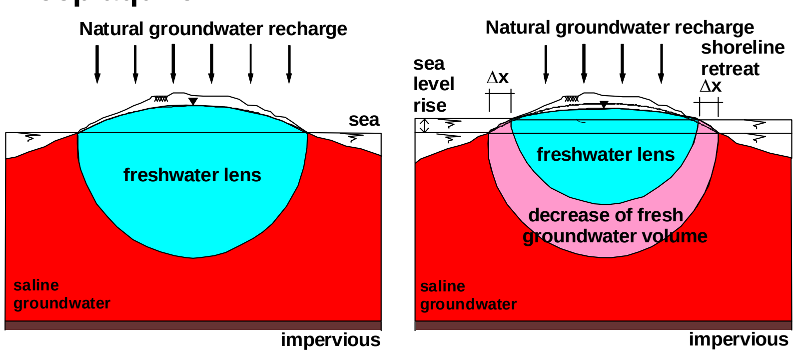


Implementing new KNMI06 climate scenarios

2100		G	G+	W	W+	C	C+
Worldwide temperature rise in 2050		**+1°C**	**+1°C**	**+2°C**	**+2°C**	**+3°C**	**+3°C**
Worldwide temperature rise in 2100		**+2°C**	**+2°C**	**+4°C**	**+4°C**	**+6°C**	**+6°C**
Change in airstream pattern Western Europa		**no**	**yes**	**no**	**yes**	**no**	**yes**
Winter	**Average temperature**	**+1,8°C**	**+2,3°C**	**+3,6°C**	**+4,6°C**	**+5,4°C**	**+6,9°C**
	Coldest winter day each year	**+2,1°C**	**+2,9°C**	**+4,2°C**	**+5,8°C**	**+6,3°C**	**+7,8°C**
	Average precipitation	7%	14%	14%	28%	21%	42%
Summer	**Average temperature**	**+1,7°C**	**+2,8°C**	**+3,4°C**	**+5,6°C**	**+5,1°C**	**+8,4°C**
	Hottest summer day each year	**+2,1°C**	**+3,8°C**	**+4,2°C**	**+7,6°C**	**+6,3°C**	**+11,4°C**
	Average precipitation	6%	-19%	12%	-38%	18%	-57%
Sea level rise	Absolute rise (cm)	35-60	35-60	40-85	40-85	45-110	45-110

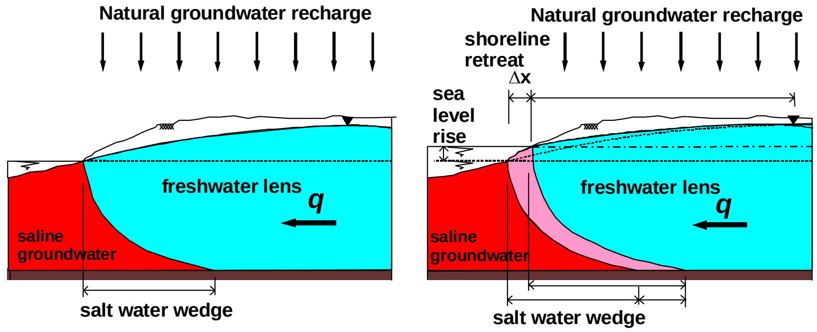
Effect of a relative sea level rise (1):

Deep aquifer



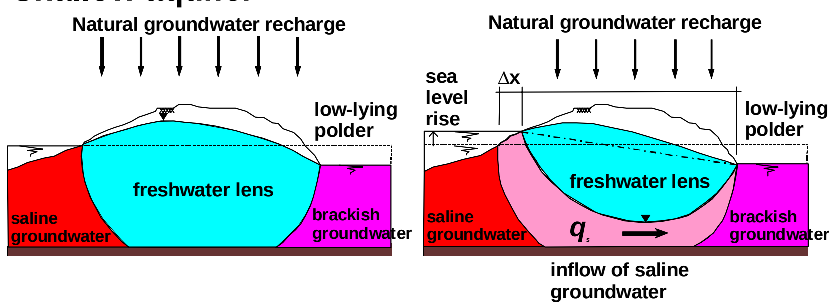
Effect of a relative sea level rise (2):

Shallow aquifer



Effect of a relative sea level rise (3):

Shallow aquifer



Salt water intrusion in the Netherlands

Case study: The Netherlands

The Dutch coastal zone is already theathened by sea level rise and land subsidence for many centuries

Intensive water management system

Coping with salt water intrusion problems since 1950's

The ‘low-lying’ lands: Netherlands

The facts:

- a deltaic area with 3 rivers: Meuse, Scheldt & Rhine
- 25% of land surface is lying below mean sea level
- 65 % would be flooded regularly if there were no dunes and dikes
- 8 million people would be endangered

The Great Flooding in february 1953

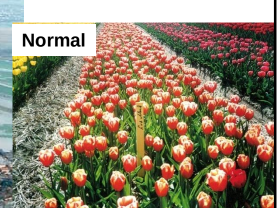
Combination of high tide and heavy storm:

-1853 casualties
-2000 km^2 flooded

Infrastructure to protect our low-lying land from flooding

River flooding in 1995

Combination of heavy rains upstream the catchment
& short retention time



Dike collapse 2003

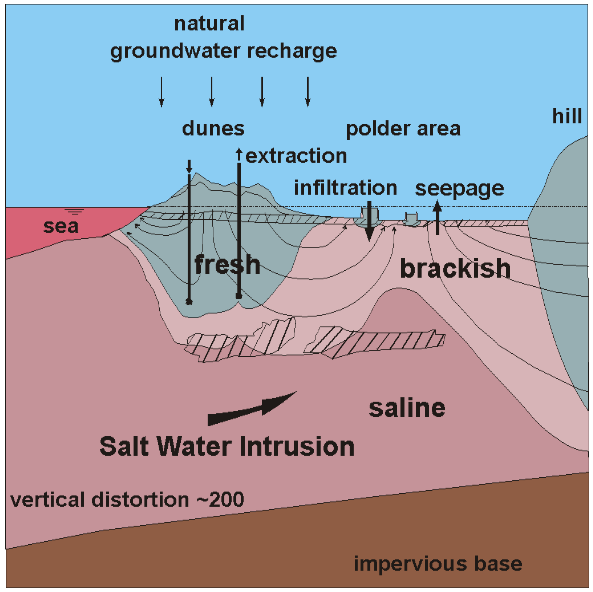
Combination of peat dike instability and very dry summer

Estimated water management costs 'to keep our feet dry'

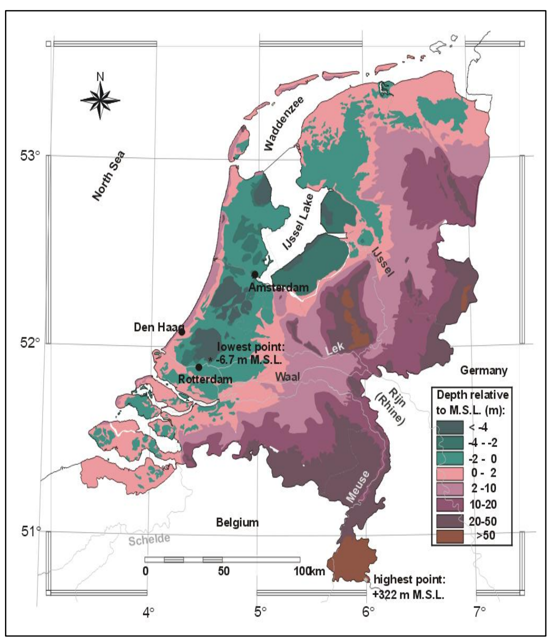
Costs up till 2050 in billion euros:

rivers: upper part	5.7
rivers: lower part	5.6
low-lands	1.7
coastal zone	8.0
infrastructure	3.5
purchase of ground	2.0
	-----+
	26.5 billion euros

Salt water intrusion in the Netherlands



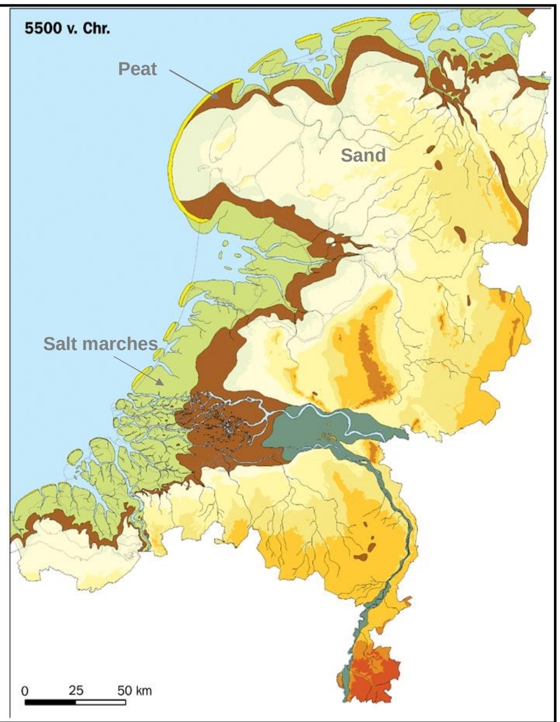
Present ground surface in the Netherlands



The Holocene transgressions

Major impact on present regional brackish groundwater systems

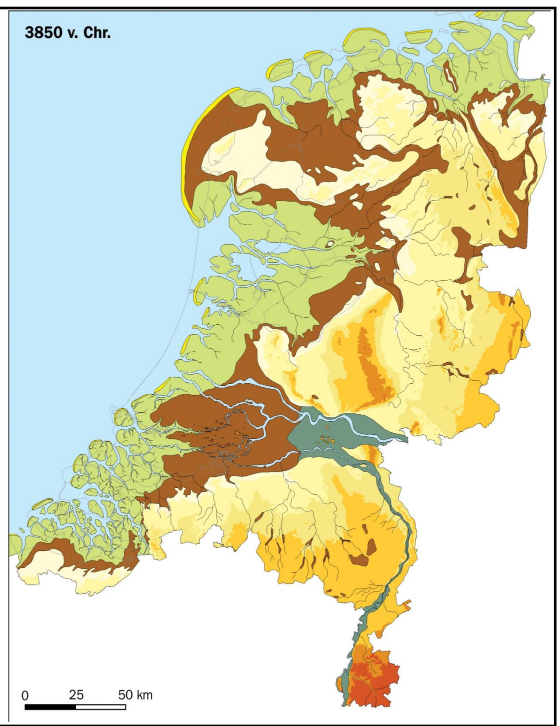
7500 BP



The Holocene transgressions

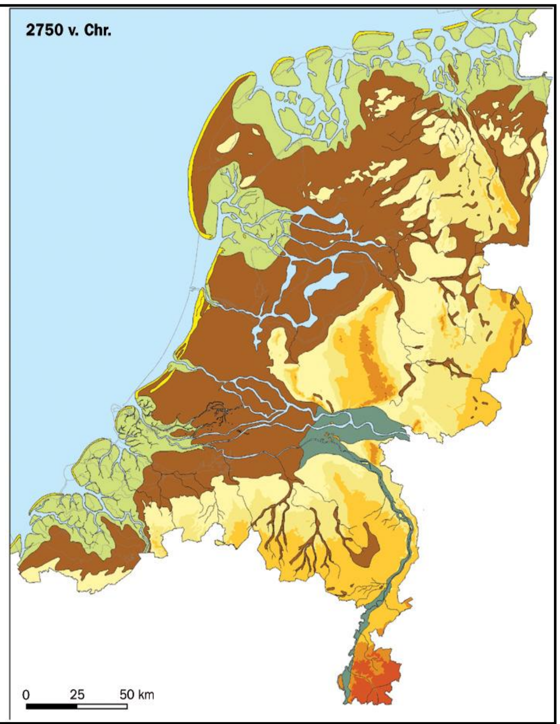
Maximum transgression

5850 BP



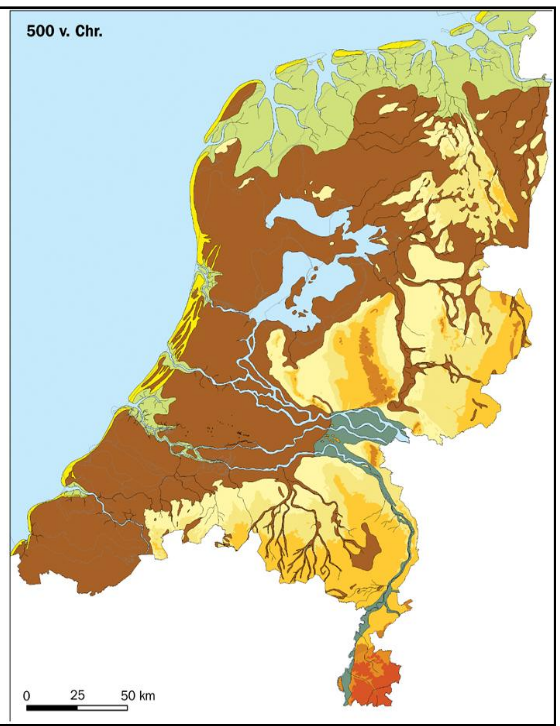
The Holocene transgressions

4750 BP



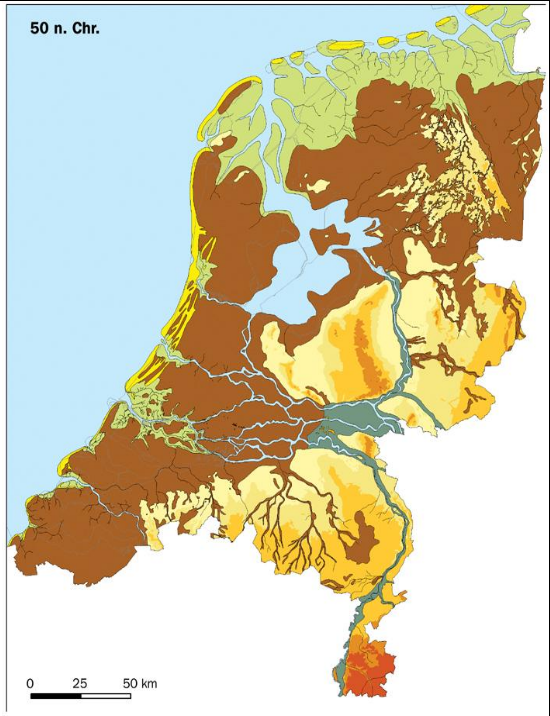
The Holocene transgressions

2500 BP



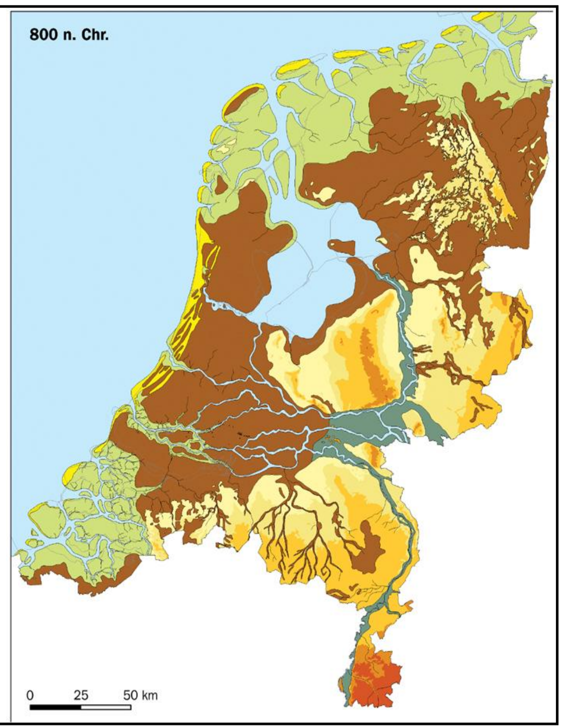
The Holocene transgressions

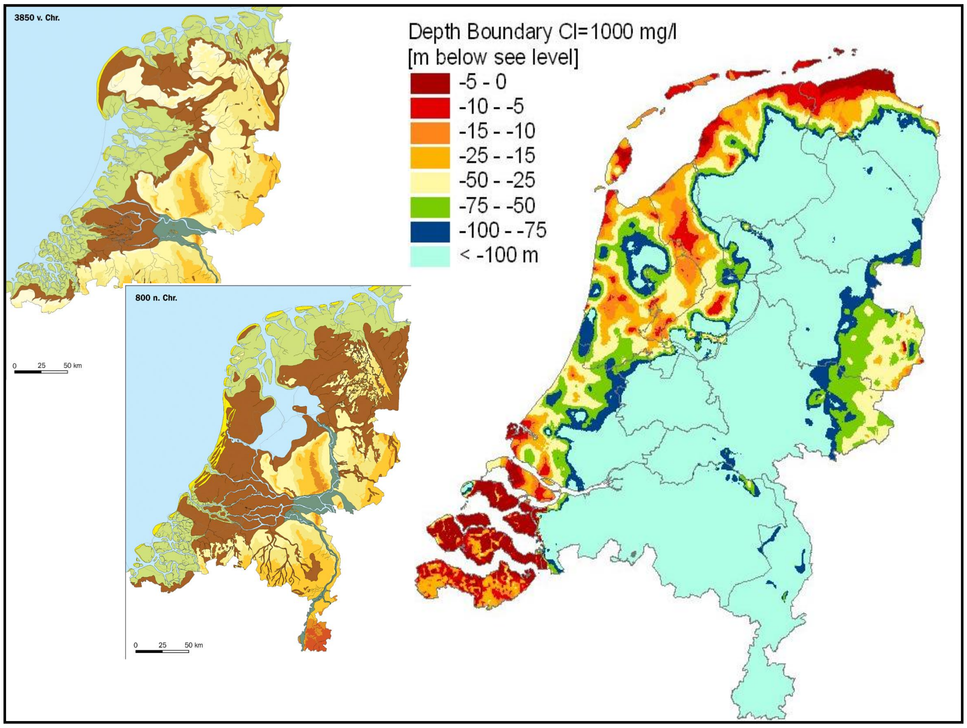
50 AD (Roman time)



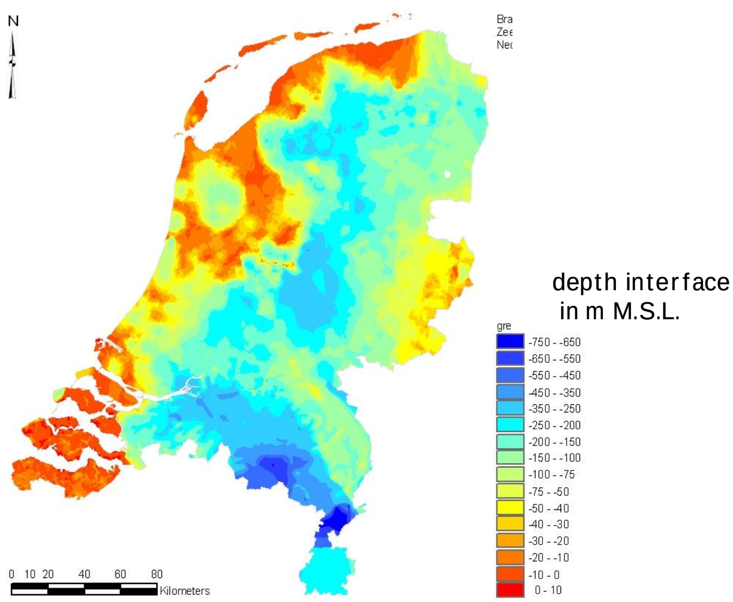
The Holocene transgressions

800 AD

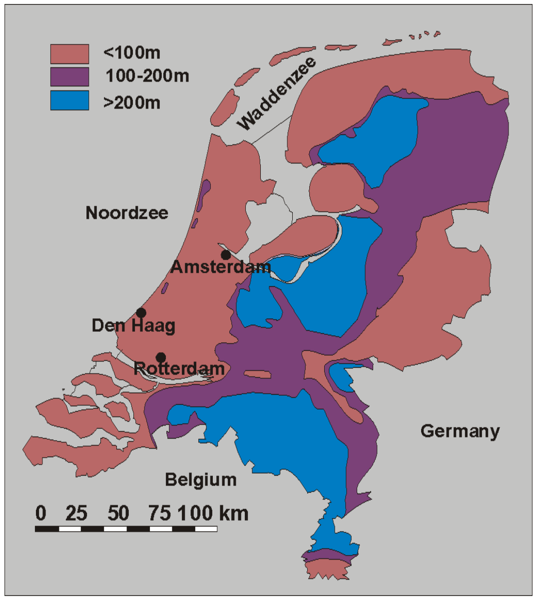




Fresh-Salt interface



Depth saline-fresh interface (150 mg Cl^-/l)



Salinisation of the Dutch subsurface

Physical transport processes:

- advective: e.g. trans- and regressions
- dispersive: mixing with marine deposits
- diffusive: e.g. IJsselmeer lake
- chemical: solution, precipitation, ion-exchange

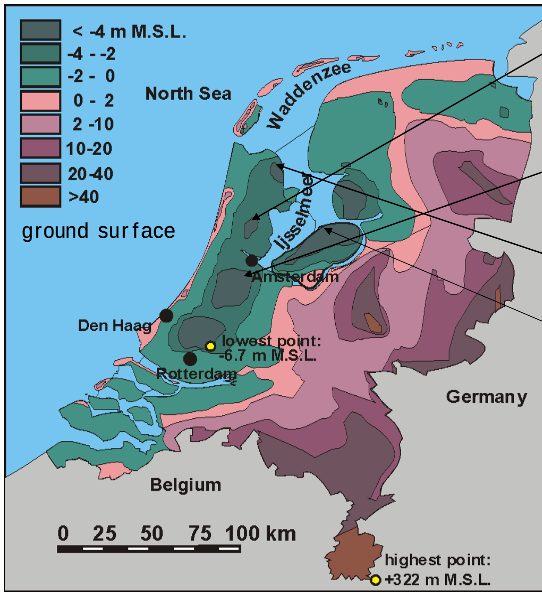
Anthropogenic causes:

- land subsidence
- polder level lowering
- groundwater extractions

Future developments (climate change):

- sea level rise
- changes in recharge

Abrupt land subsidence



position polders:

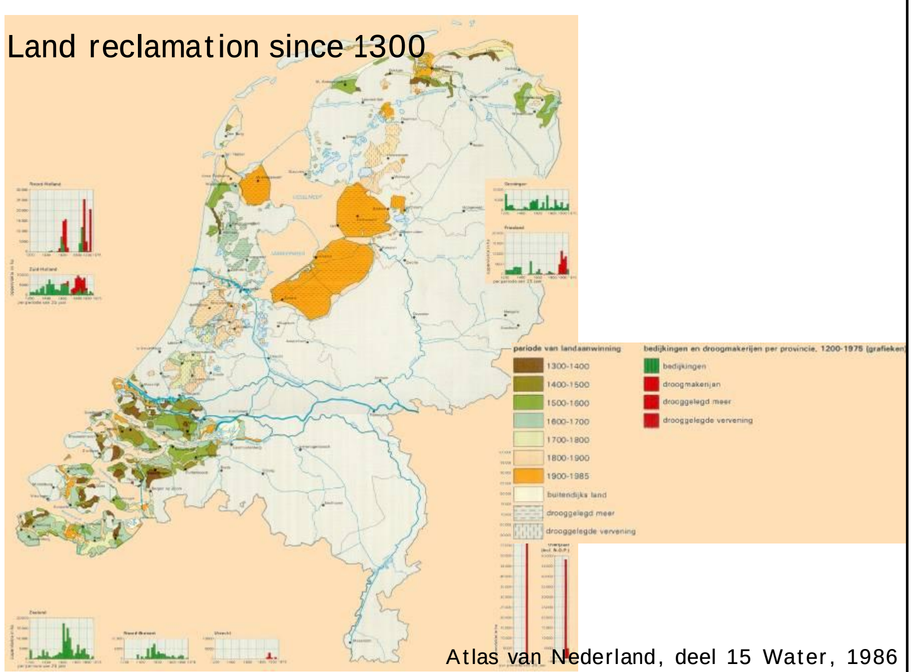
Beemster 1608-1612
Wormer 1625-1626
Schermer 1633-1635
Purmer 1618-1622

Haarlemmermeer polder 1850-1852

Wieringermeer polder ~1930

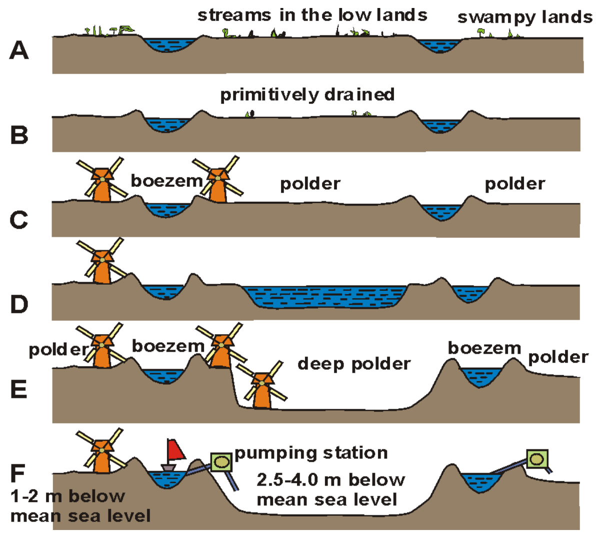
Flevo polders 1950-60s

Land reclamation since 1300

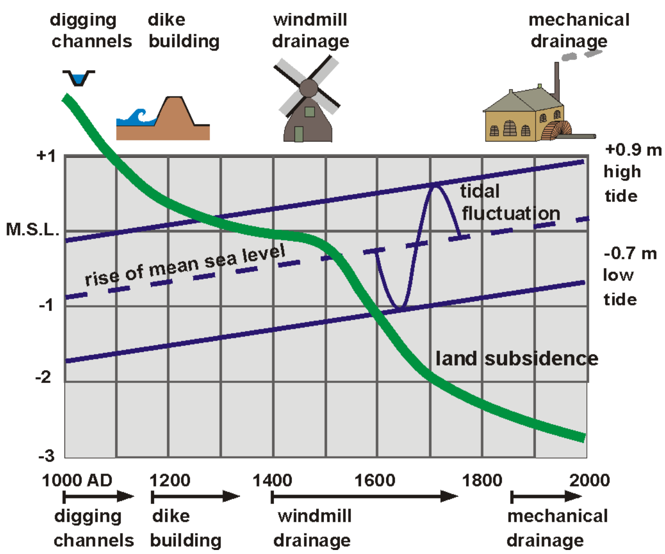


Atlas van Nederland, deel 15 Water, 1986

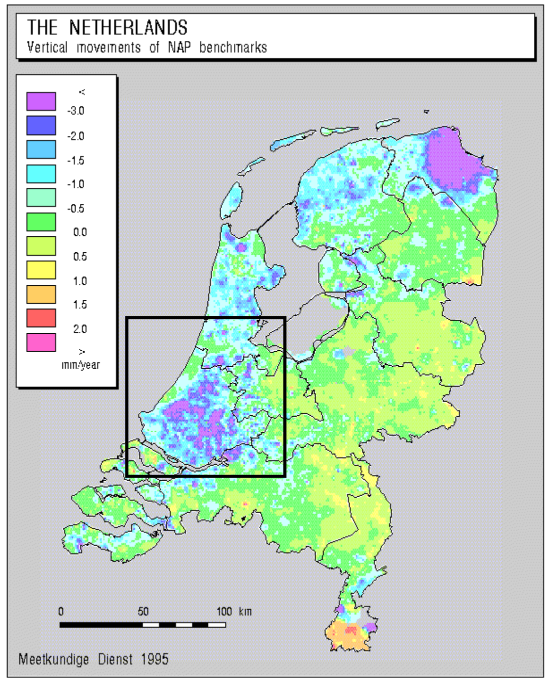
Development of the Dutch polder area



Historic lowering of the ground surface in Holland



Land subsidence related to M.S.L.



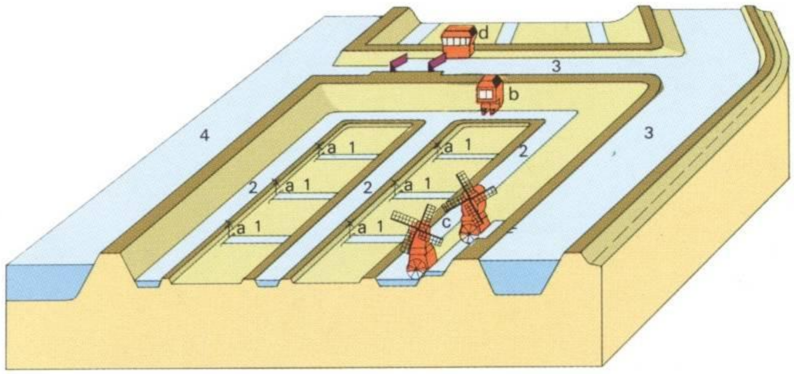
Land subsidence

up to 1 m per century

The polder system

A land below the sea with an excess of water needs..

a sophisticated drainage system



The polder system

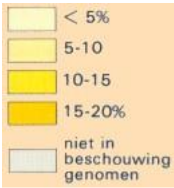
Many agricultural plots with different water levels throughout the season

The polder system

The polder system

Bulb farms at the landside of the sand dunes

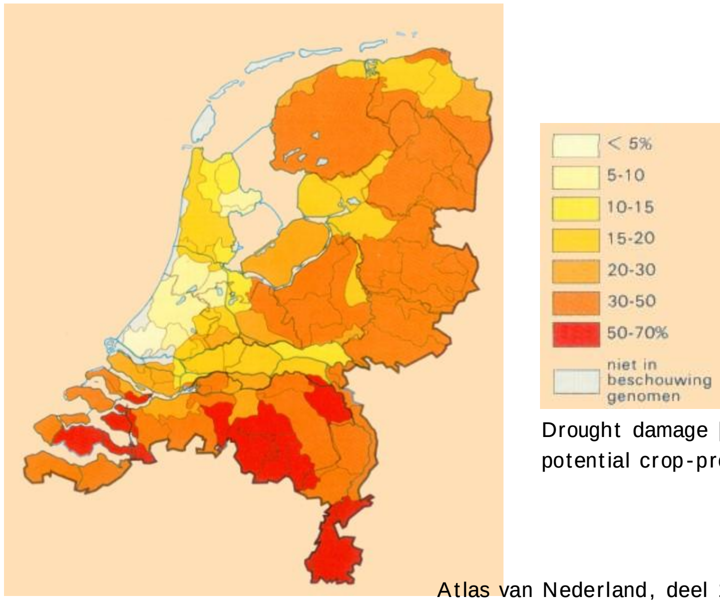
Salt damage in 1976 (very dry year)



Salt damage [percentage] in potential crop-production

Atlas van Nederland, deel 15 Water, 1986

Drought damage in 1976 (very dry year)



Drought damage [percentage] in potential crop-production

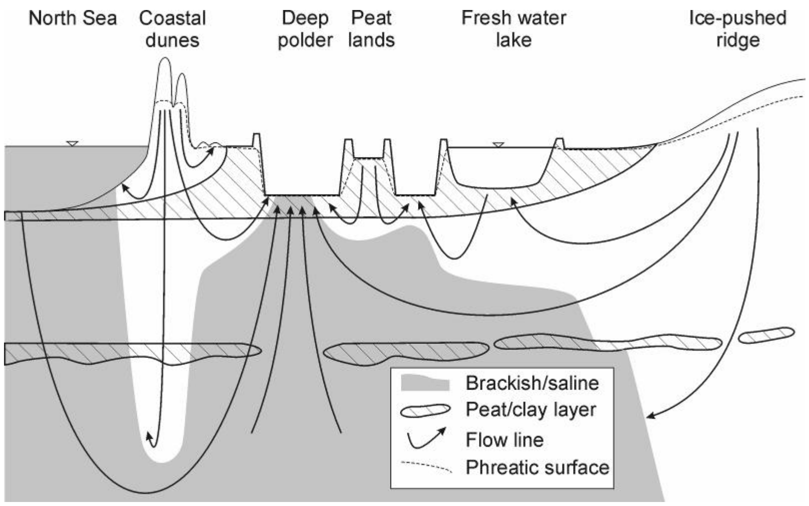
Atlas van Nederland, deel 15 Water, 1986

'Wetting' damage

Normal situation

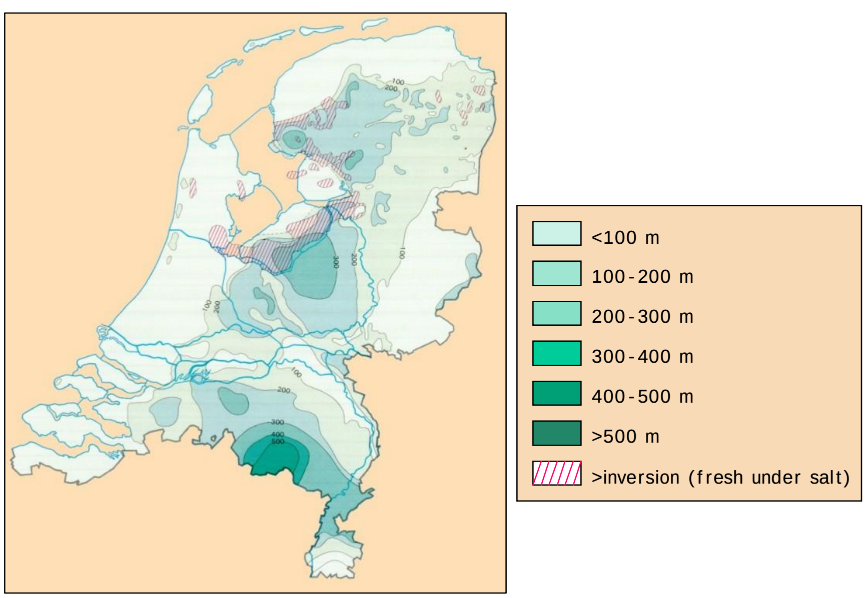
Crop damage due to a reduction in groundwater extraction in the dune area

Now focus on groundwater…



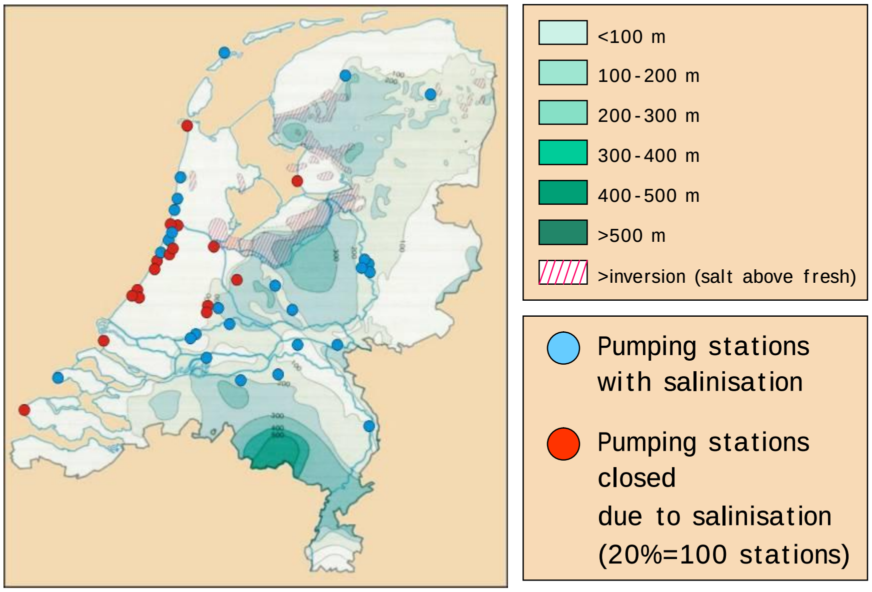
Present situation

Fresh-salt interface (150 mg Cl⁻/l)



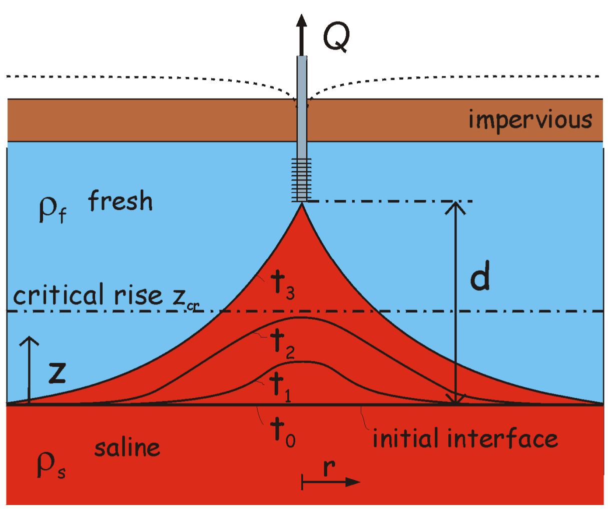
Impacts

Availability of fresh groundwater

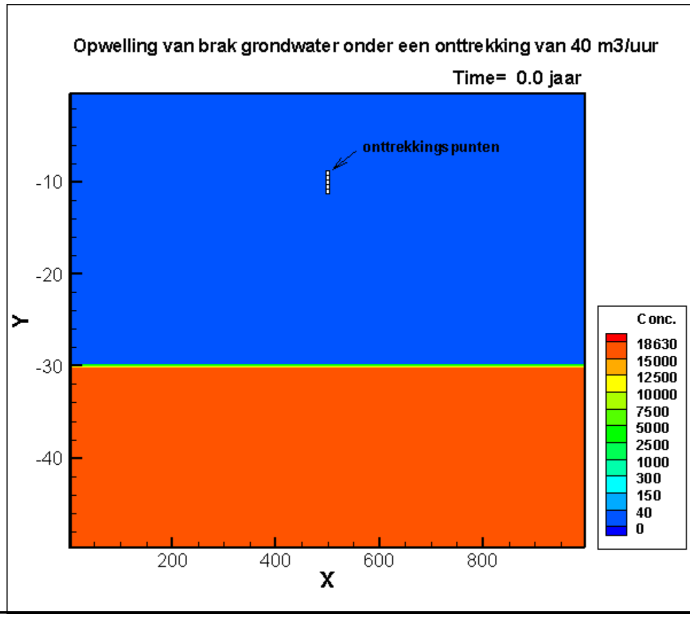


Threats

Upconing of saline groundwater under extraction well



Upconing of salt under an extraction



Threats to water management due to climate change:

Short term threats:

- -flooding
- -dike collapse
- -drought

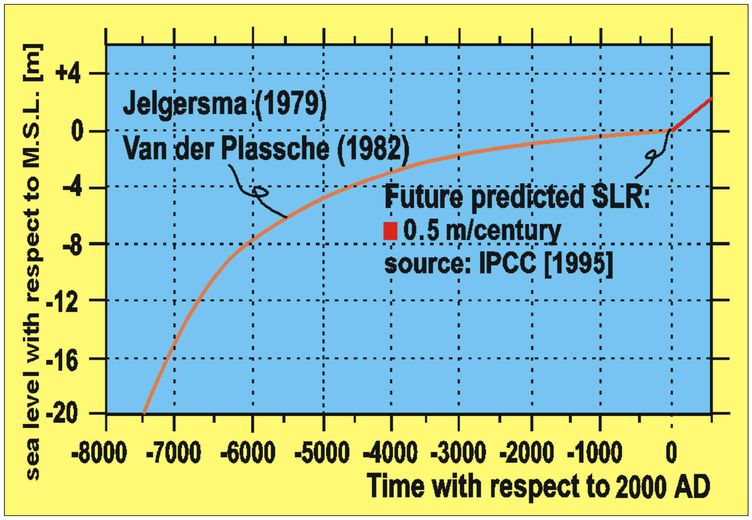
asks for operational water management

Long term threats:

- -salt water intrusion
- -land subsidence
- -smaller fresh groundwater resources

asks for strategic water management

Past and future sea level rise in the Netherlands

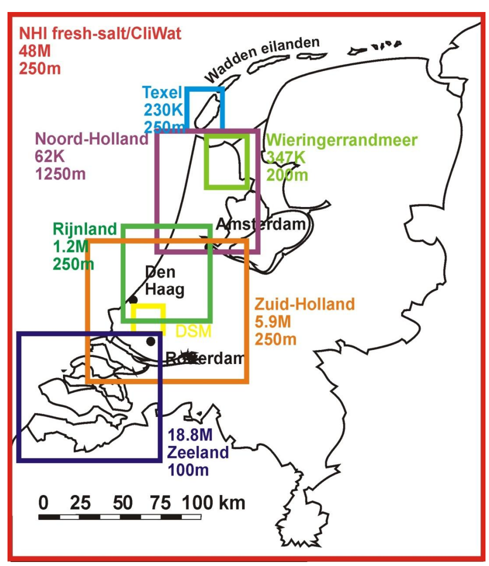


Numerical variable density models at Deltares

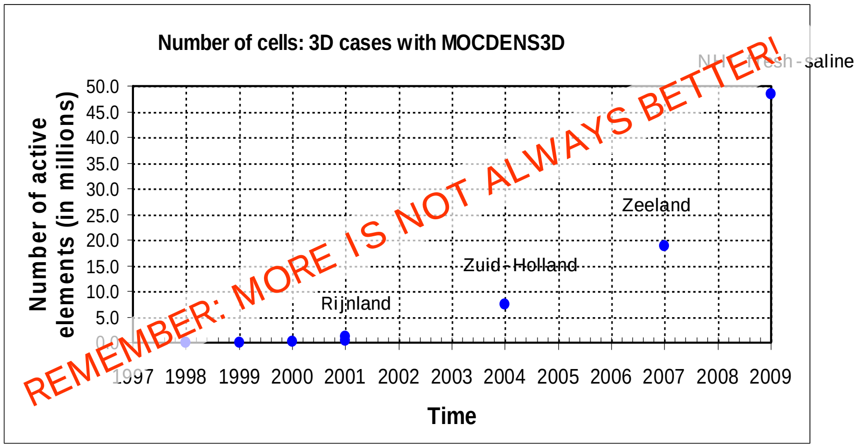
Characteristics:
- variable-density groundwater
- fresh, brackish and saline
- 3D, non-steady
- coupled solute transport

Code (MODFLOW family):
MOCDENS3D
SEAWAT

Assessing effects:
- autonomous salinisation
- sea level rise
- changing recharge pattern
- land subsidence
- changing extraction rates
- adaption measures

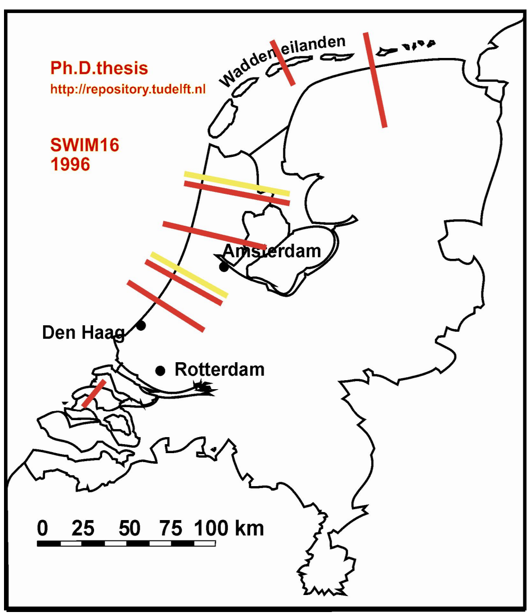


'DO NOT DO THIS AT HOME!' (DATA PROBLEM)



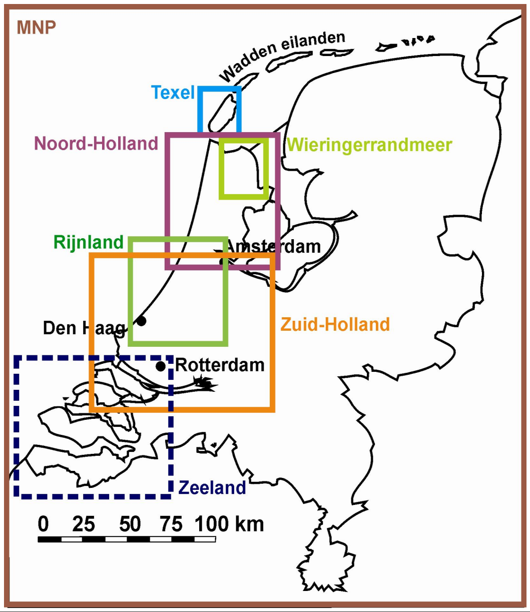
Modelling effect sea level rise on salt water intrusion

2D models



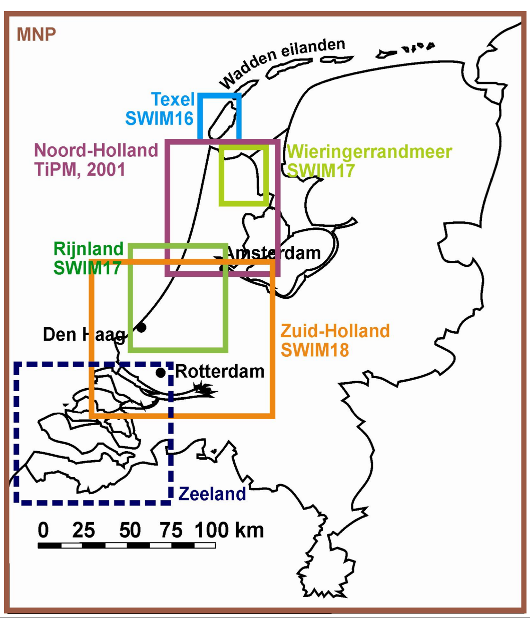
Modelling effect sea level rise on salt water intrusion

3D models



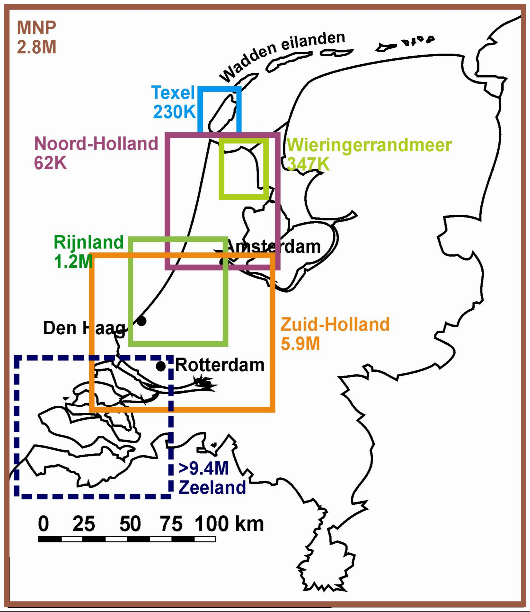
Modelling effect sea level rise on salt water intrusion

3D models
SWIM



Modelling effect sea level rise on salt water intrusion

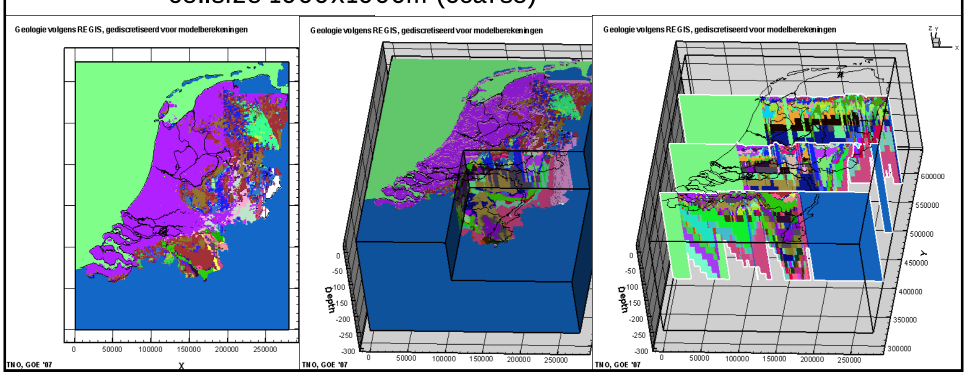
3D models number cells



Recent model study for the whole Netherlands on the effect of sea level rise of water management (1)

Using the national subsoil parametrisation

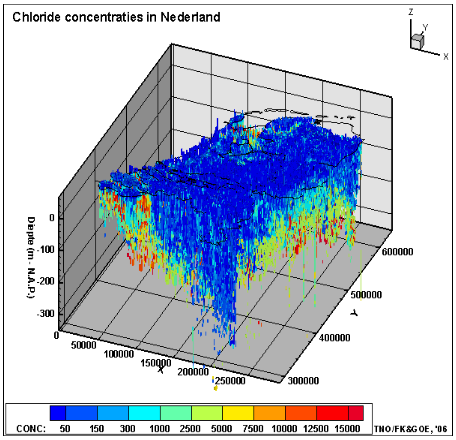
- REGIS V2
- Top geological system from +10m up to -280m M.S.L.
- 31 modellayers with thicknesses: 2*5m; 10*2m; 8*5m en 11*20m
- cellsize 1000x1000m (coarse)

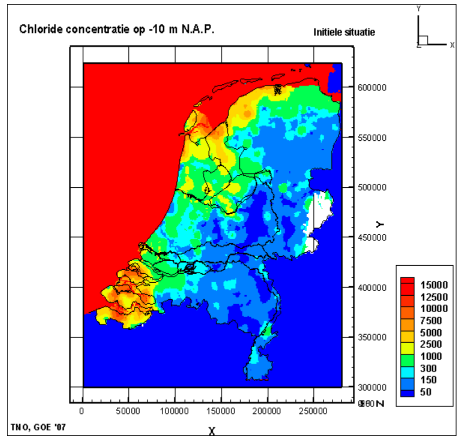


Recent model study for the whole Netherlands on the effect of sea level rise of water management (2)

Using the national 3D salt concentration in groundwater

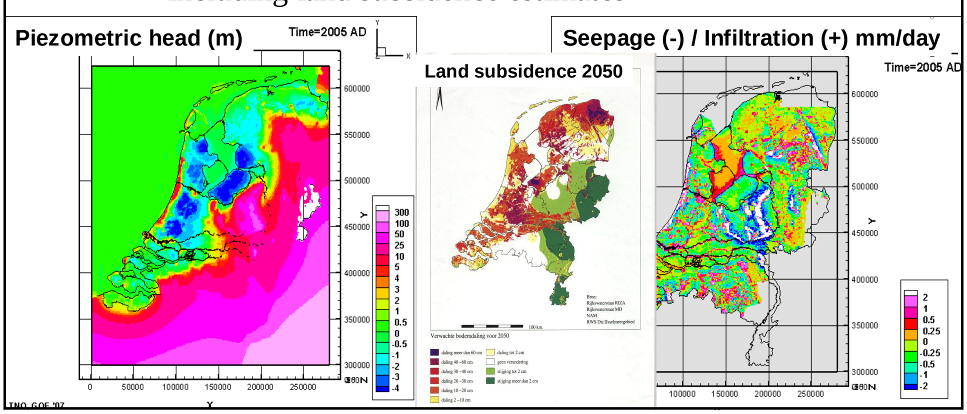
Zoet-Zout REGIS: ~65000 measuring points (analyses, VES, Borehole)



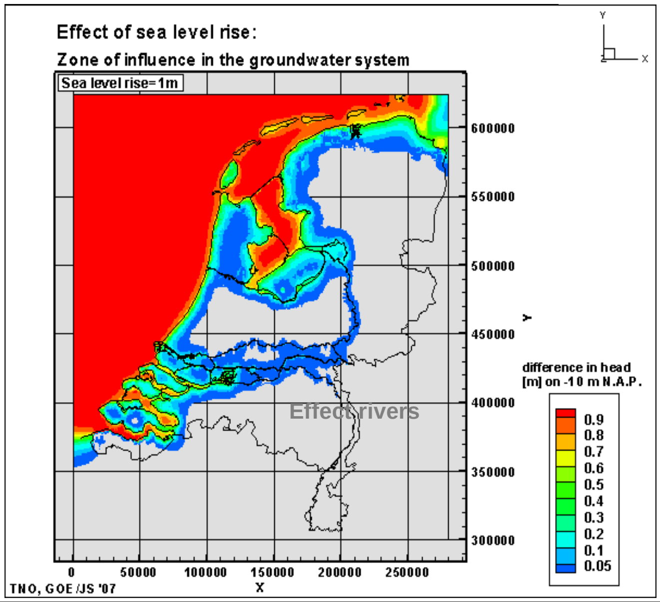


Recent model study for the whole Netherlands on the effect of sea level rise of water management (3)

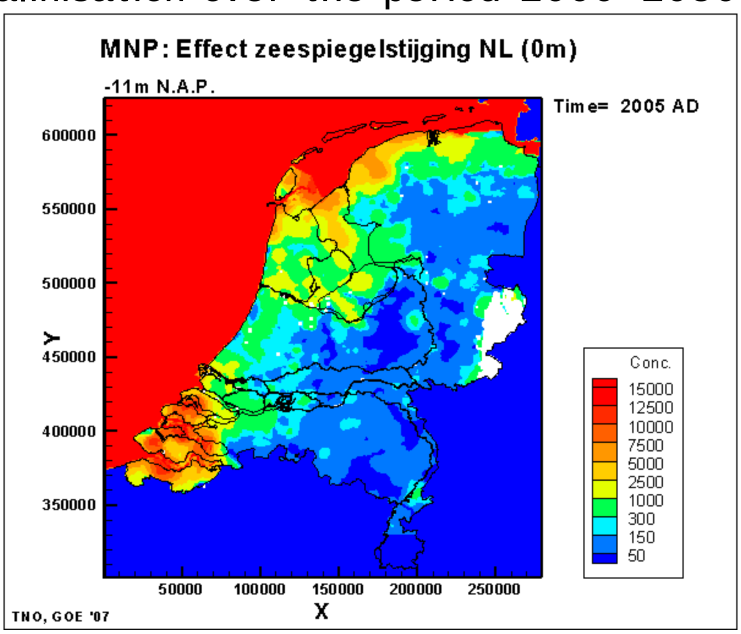
- Variable-density 3D groundwater flow model and coupled solute transport
  - 10 scenario's, including extreme sea level rise
  - including land subsidence estimates



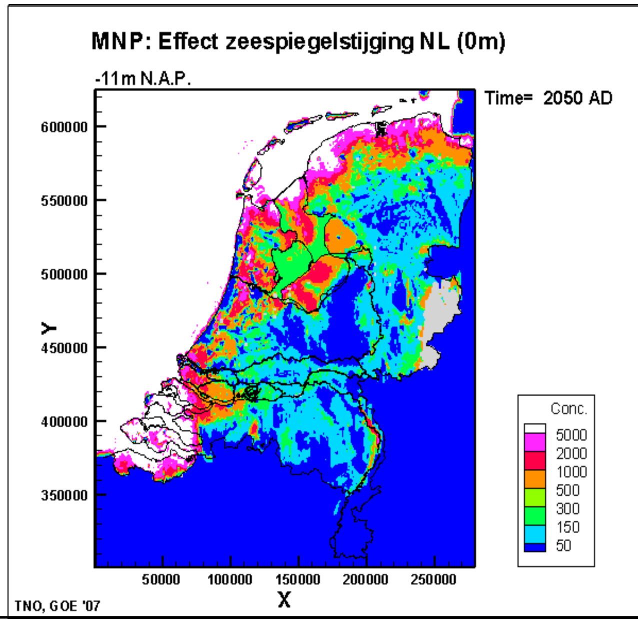
Results: zone of influence 1m sea level rise



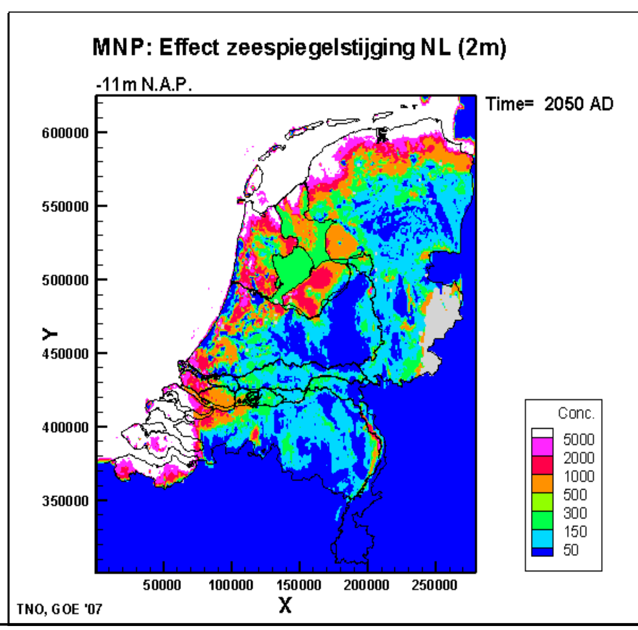
Salinisation over the period 2000-2050



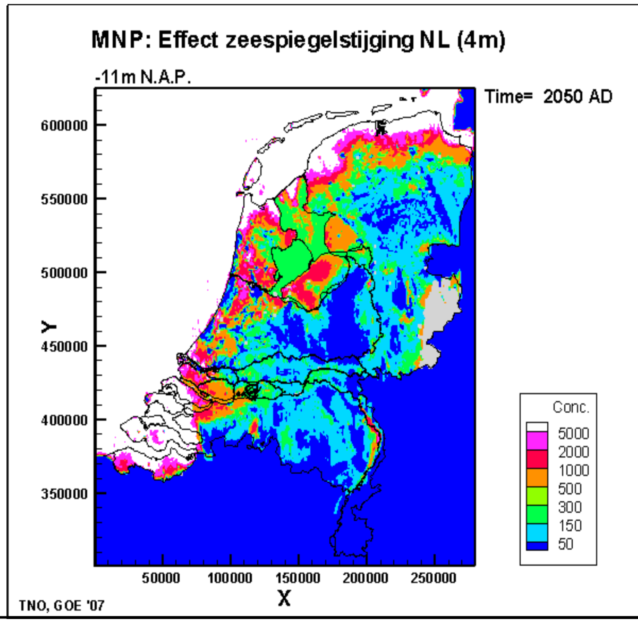
Salinisation subsoil at 0m sea level rise in 2050



Salinisation subsoil at 2m sea level rise in 2050

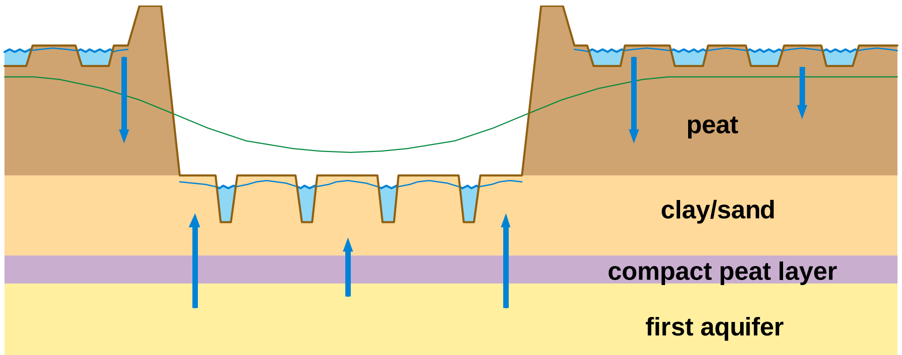


Salinisation subsoil at 4m sea level rise in 2050

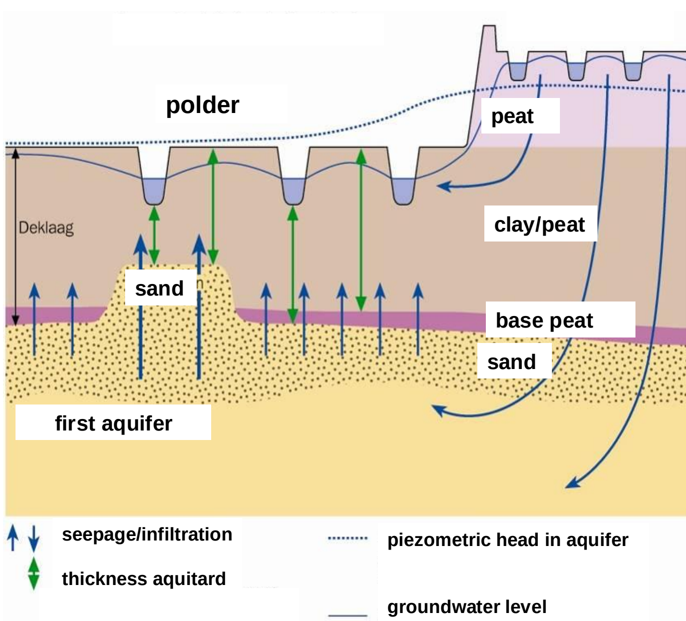


Salty wells

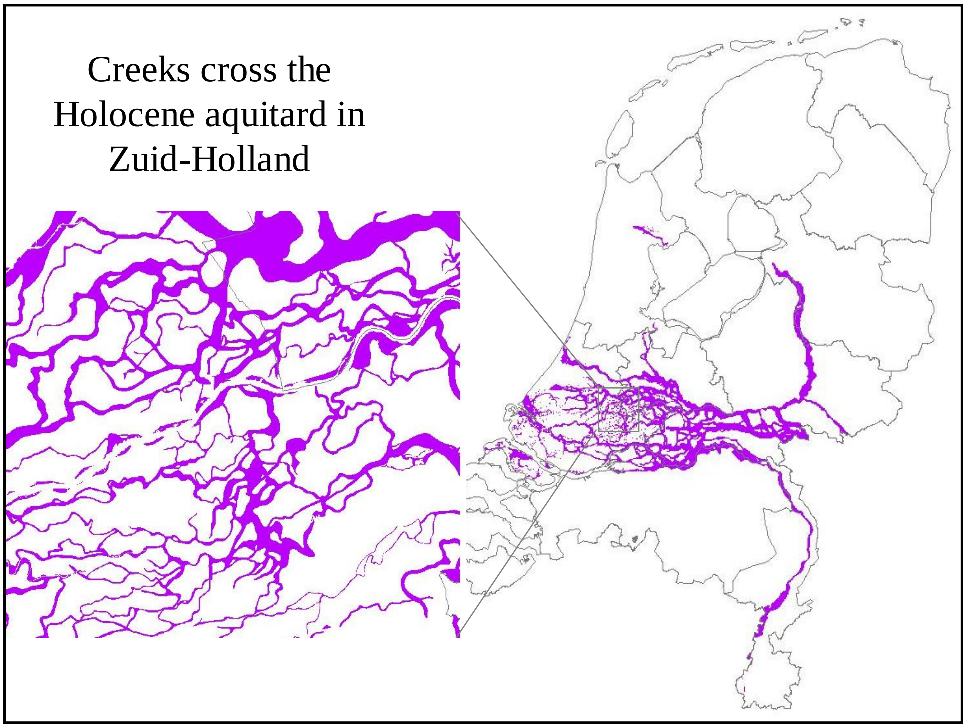
Seepage and infiltration situation around deep polders

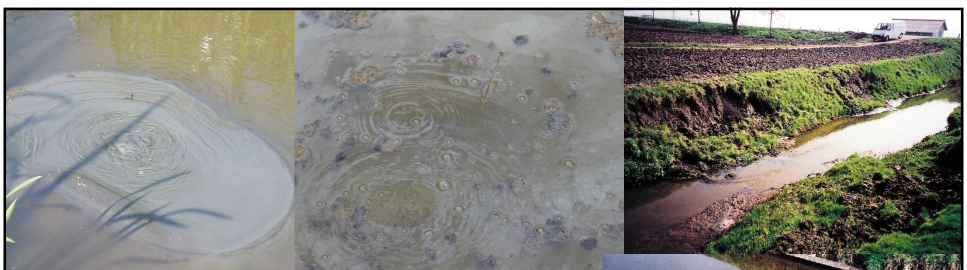


Risk of instable Holocene aquitards (1)



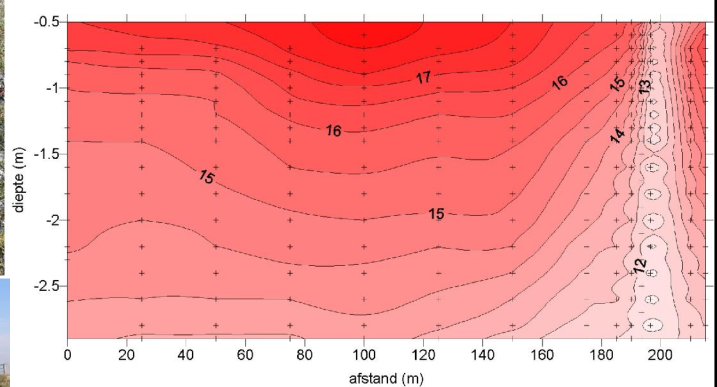
Creeks cross the Holocene aquitard in Zuid-Holland



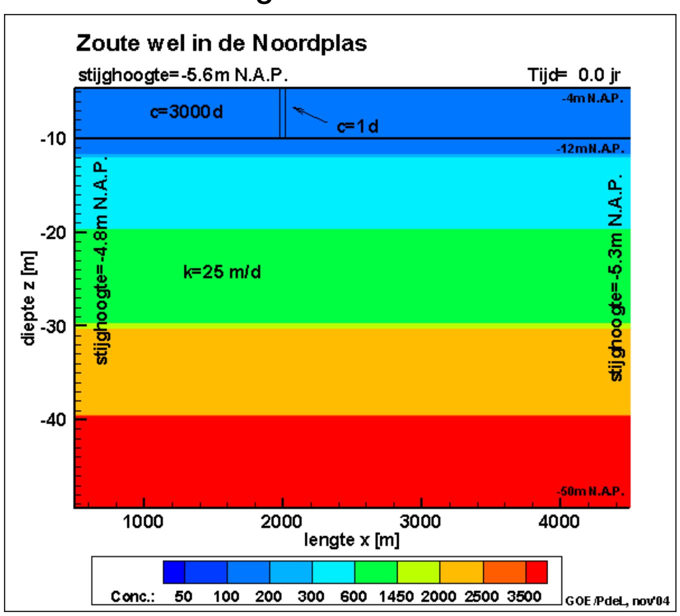


'*Wells*' (weak spots in Holocene layer)

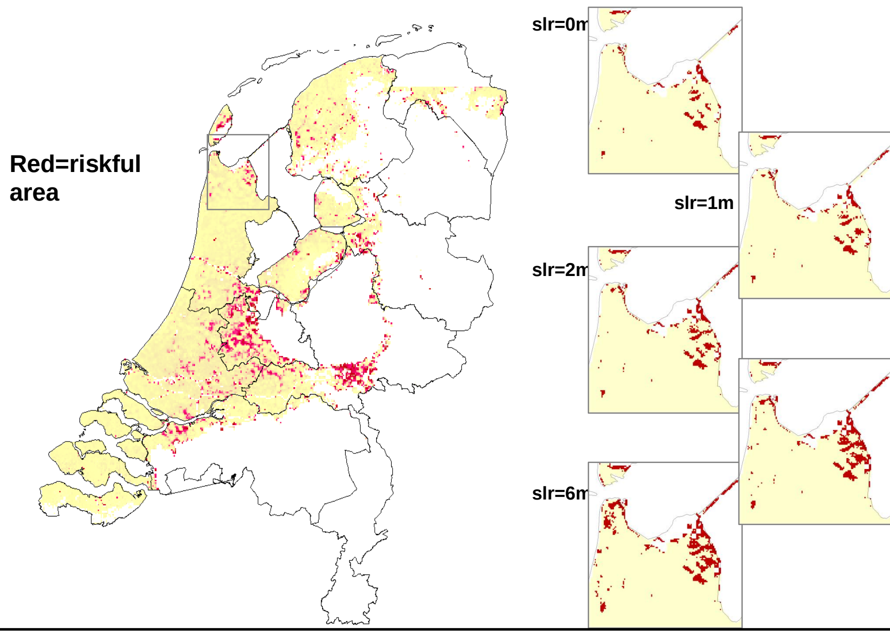
Temperature measurements



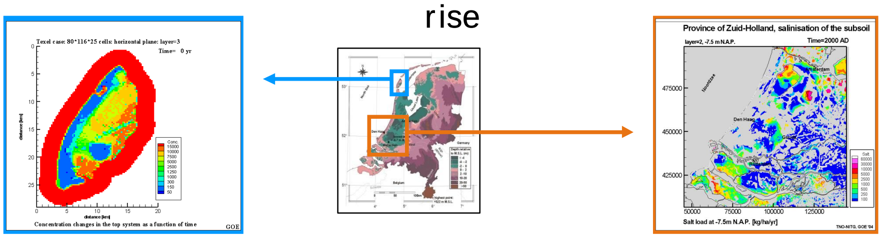
Simulation of salt groundwater towards *wells*



Risk of instable Holocene aquitards (2)



Quantification hydrogeological impacts of sea level rise



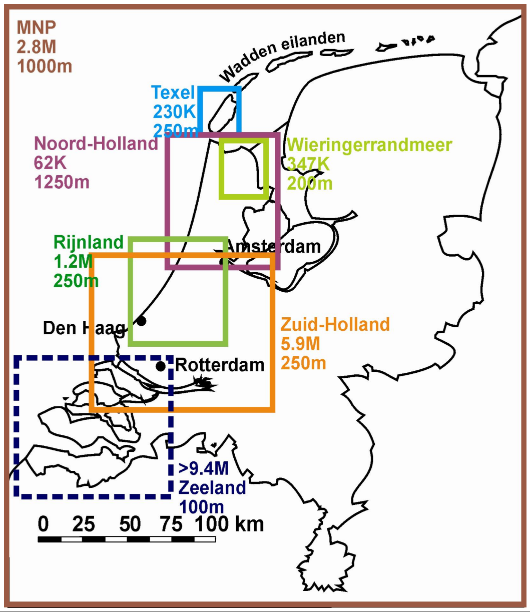
Situation at 2100 AD with sea level rise of 0.5m/century,

Including land subsidence at Zuid-Holland (max 1.0m/century)

	Texel	Zuid-Holland
Increase seepage (%)	+22	+4
Increase salt load (%)	+46	+34
Hinge area: from infiltration to seepage (% land surface)	+3	+5

Modelling effect sea level rise on salt water intrusion

3D models
number cells
grid size



Characteristics 3D Cases (I): geometry & subsoil

Case	Kop van Noord-Holland	Texel	Wieringer-meerpolder	Rijnland
total land surface [km^2]	2150	130	200	1100
L_x*L_y modelled area [km]	65*51	20*29	23*27	52*60
depth system [m –N.A.P]	290	302	385	190
aquifer hydr.cond. [m/d]	5-70	5-30	15-40	12-70
aquitard hydr.cond. [m/d]	0.12-0.001	0.01-1	0.012-0.056	2.5E-4-0.8
porosity	0.35	0.3	0.25	0.25
anisotropy [k_z/k_x]	0.4	0.4	0.25	0.1
long. dispersivity α_L [m]**	2	2	2	1
# head&conc. observations	not applicable*	111	95	1632
characteristics head calibration	not applicable*	$\|\Delta\phi\|$=0.24 m σ=0.77 m	$\|\Delta\phi\|$=0.34 m σ=0.21 m	$\|\Delta\phi\|$=0.60 m σ=0.77 m

* calibration with seepage & salt load in polders

**molecular diffusion=10^{-9} m^2/s; trans. disp.=1/10 long. disp.

Characteristics 3D Cases (II): model parameters

Case	Kop van Noord-Holland	Texel	Wieringer-meerpolder	Rijnland (=391 EM RAM)
horizontal cell size [m]	1250*1250	250*250	200*200	250*250
vertical cell size [m]	10	1.5 to 20	2 to 70	5 to 10
total # active cells	~40.000	~126.000	~312.000	~1.200.000
# cells	41*52*29	80*116*23	116*136*22	209*241*24
# particles per cell	27	8	8	8
total time [yr]	1000	500	50	500

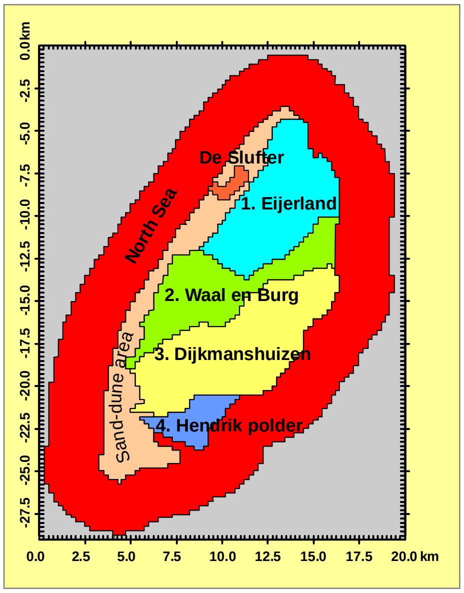
convergence head criterion= $10^{-5}/10^{-4}$ m

flow time step Δt=1 year

Model of the island of Texel

Texel

Characteristics of the island of Texel (I)



- Tourist island in summer time
- Land surface: 130 km^2
- Polder areas:
  1. Eijerland
  2. Waal en Burg
  3. Dijkmanshuizen
  4. Hendrik polder

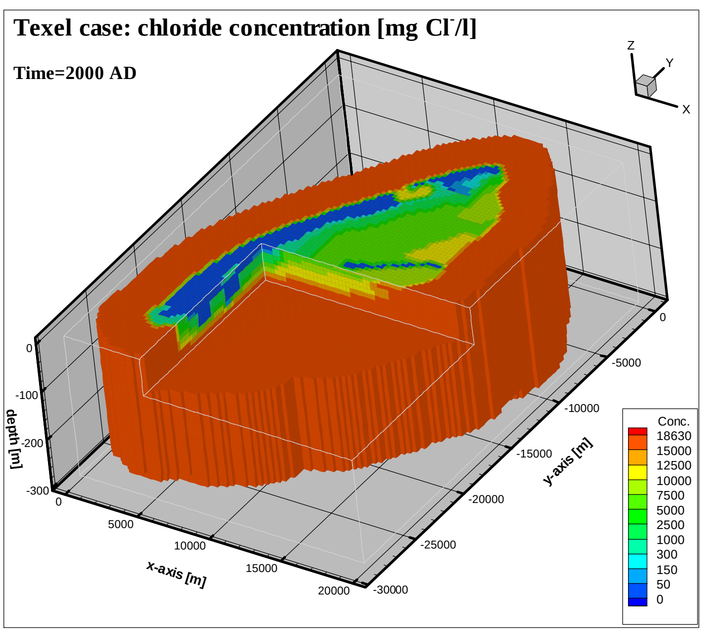
Sand-dune area at western side

'De Slufter' is a tidal salt-marsh

North Sea surrounds the island

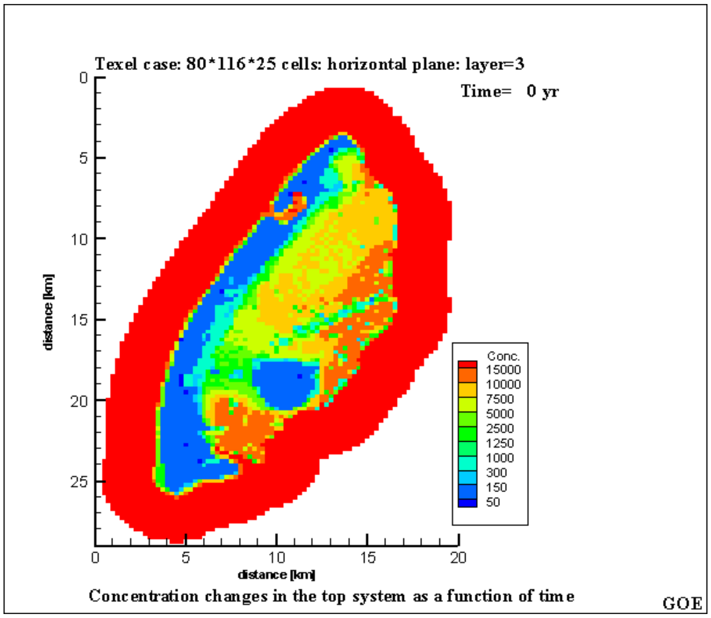
Texel

Texel: present 3D chloride distribution



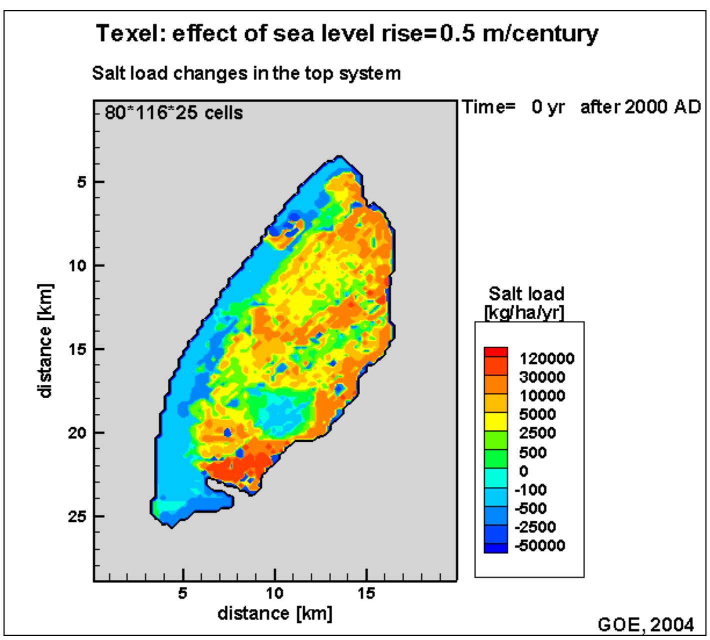
Texel

Texel: reference case=autonomous development



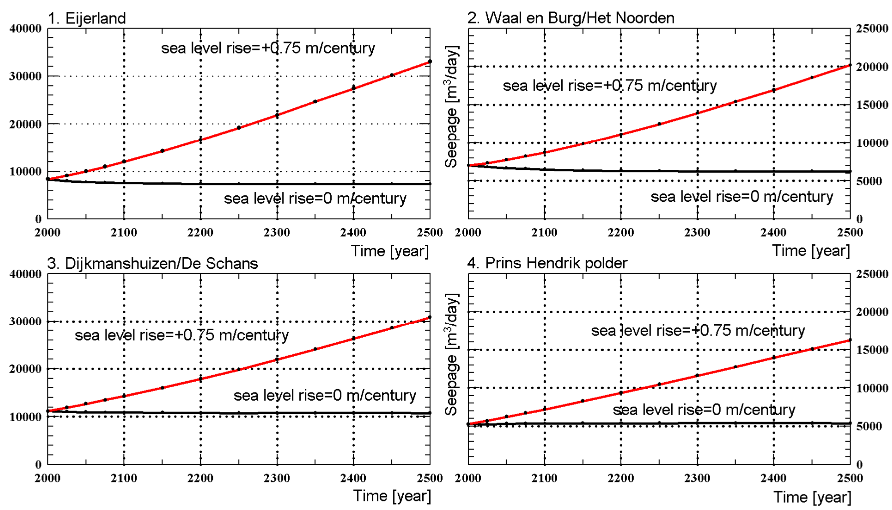
Texel

Texel: effect of sea level rise on salt load



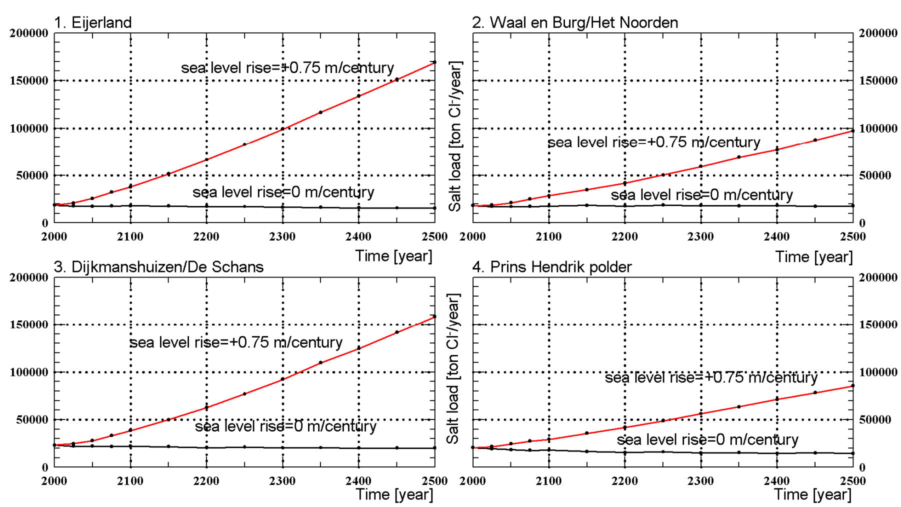
Texel

Texel: change in seepage of the four polders



Texel

Texel: change in salt load of the four polders



Model of the Province of Zuid-Holland

Case study: Province of Zuid-Holland

European water framework directive

“in 2015, state of all groundwaters and surface waters must be good“

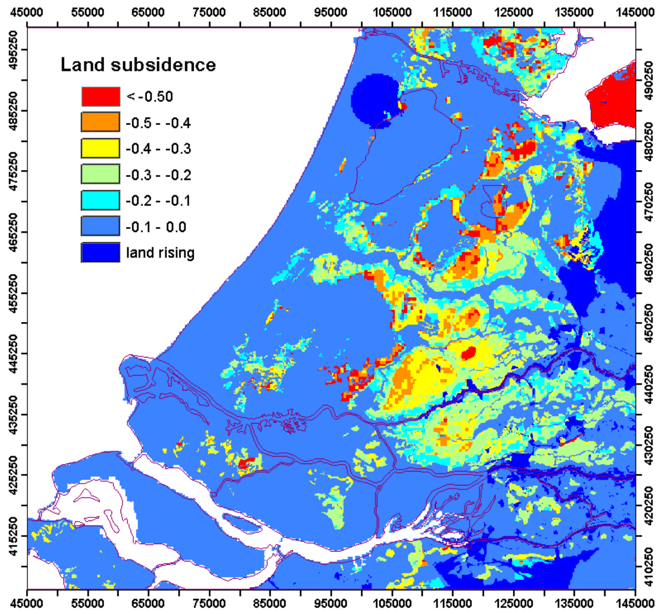
Identification of all fresh groundwater bodies in the province

How fast is the salinisation process?

More seepage, more salt load?

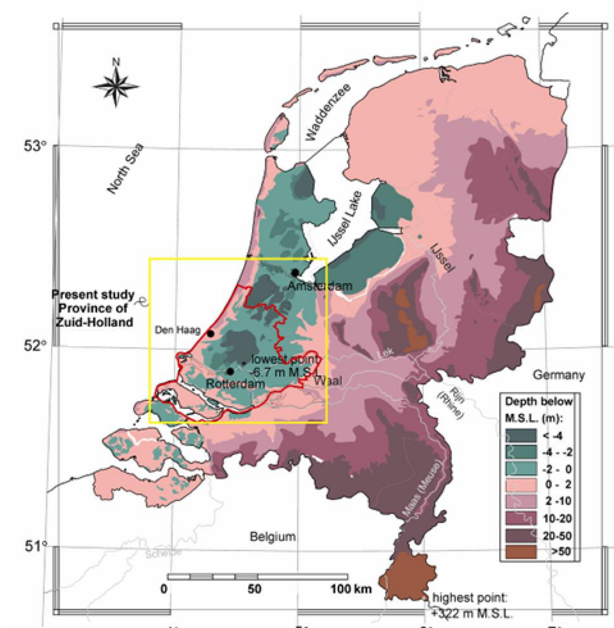
Land subsidence

2050



Source: RIZA

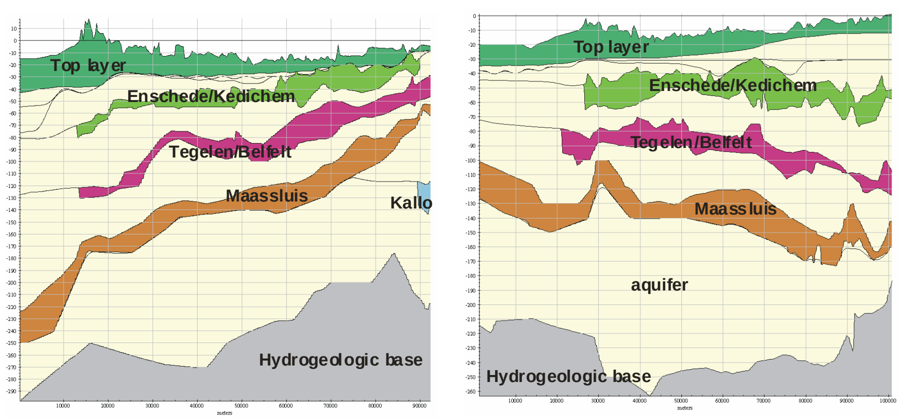
Location of the Province of Zuid-Holland



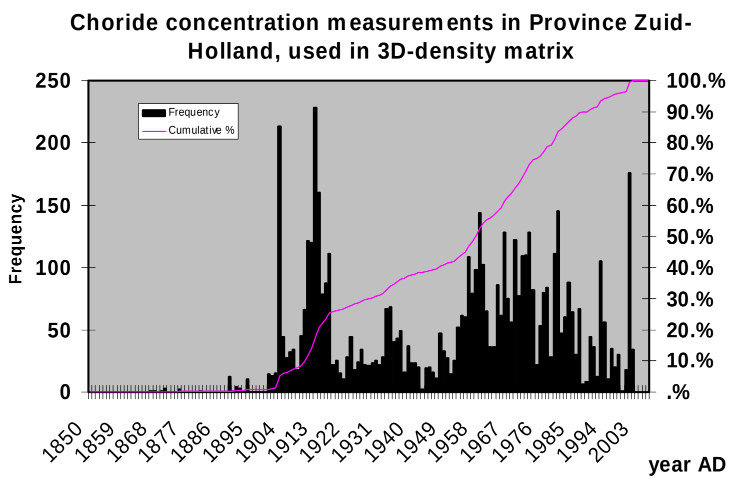
Numerical model description

- variable-density groundwater flow
- coupled solute transport
- MOCDENS3D
- area: 100km * 92.5km * 300m depth
- 400 *370 cells, 40 layers
- ~4 million active cells
- uses most accurate Dutch 3D subsurface schematization available
- 9 aquifers and aquitards
- uses 5772 chloride concentration measurements

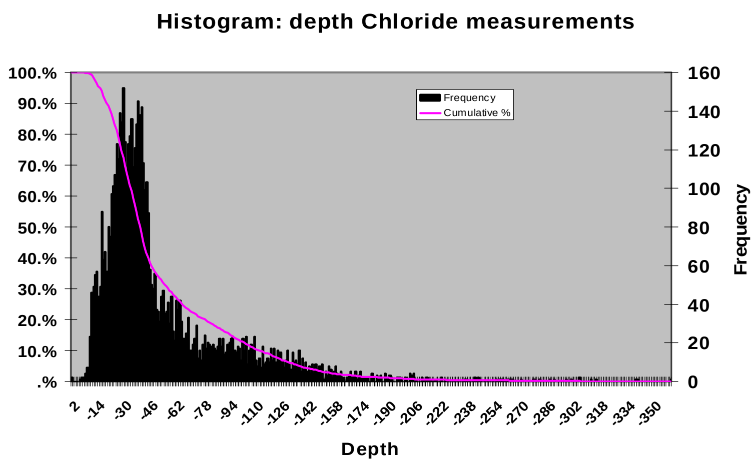
Position and name of aquitards



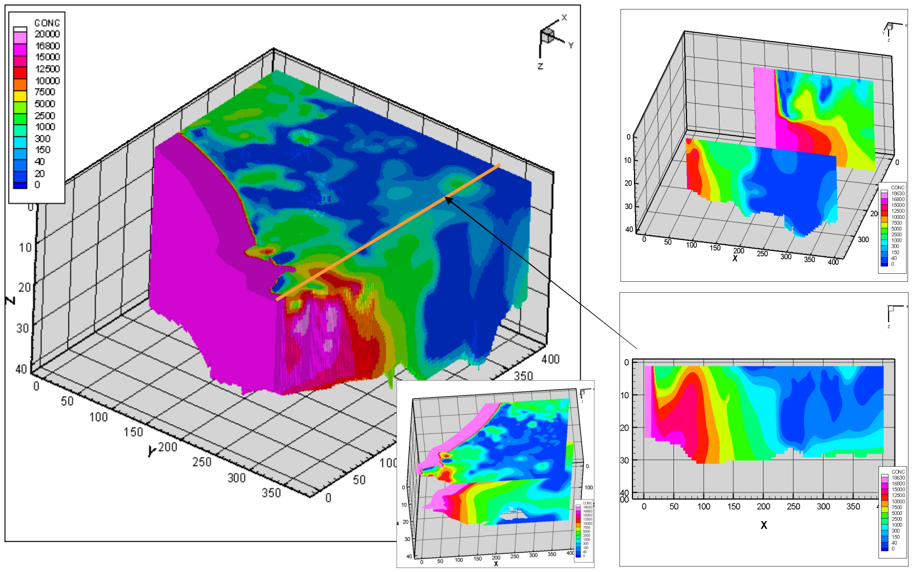
3D interpolation of chloride-concentration



3D interpolation of chloride-concentration



Initial chloride distribution

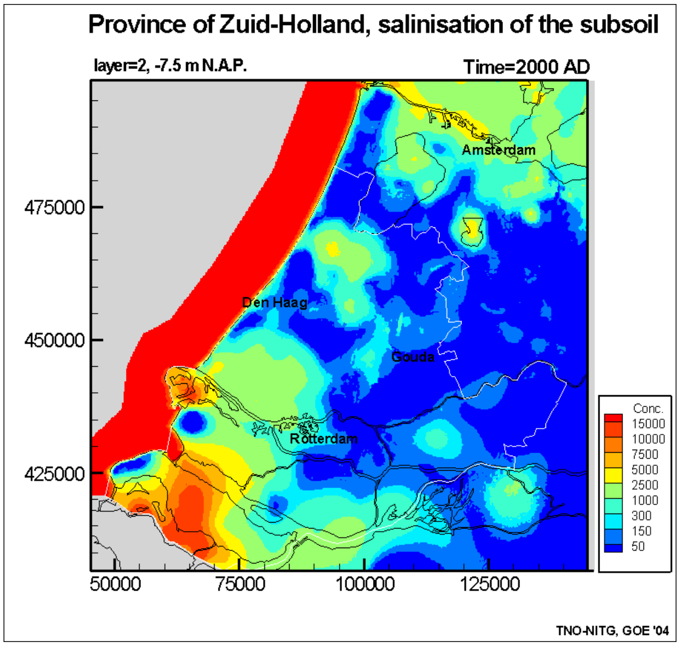


Present freshwater volume

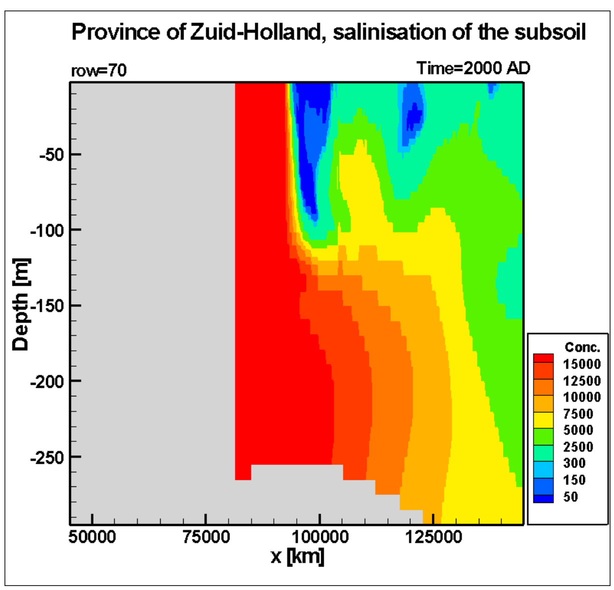
27 billion m^3

36% fresh, 14% brackish, 50% saline

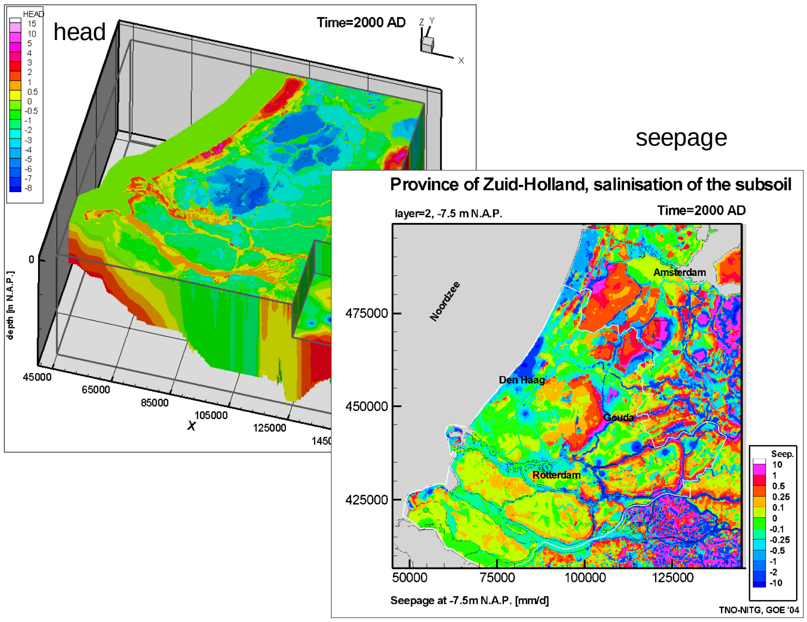
Results: Chloride conc. in 200 yrs



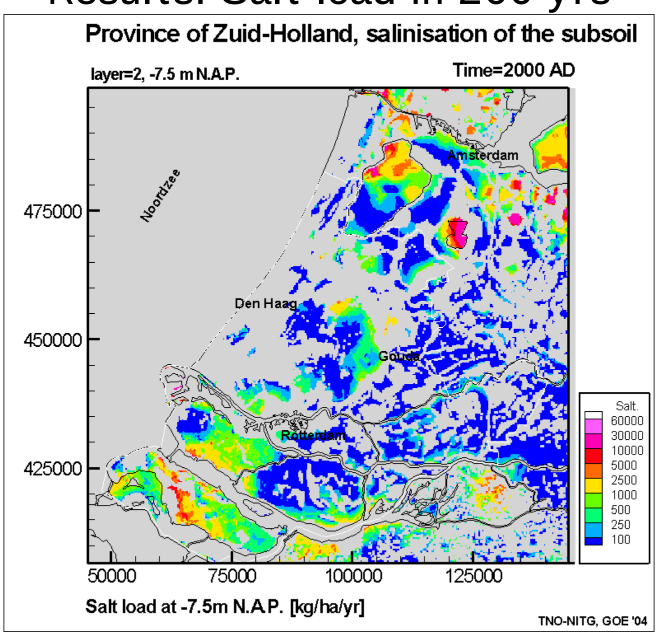
Results: Chloride conc. in 200 yrs



Results: freshwater head and seepage at 2000 AD



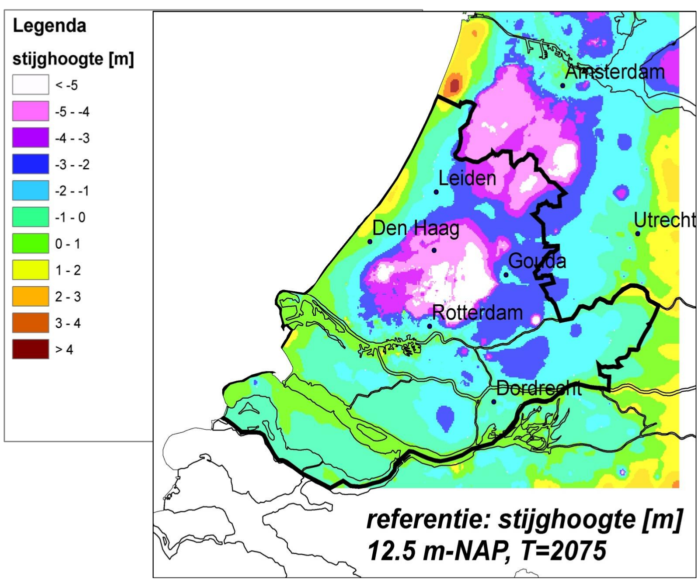
Results: Salt load in 200 yrs



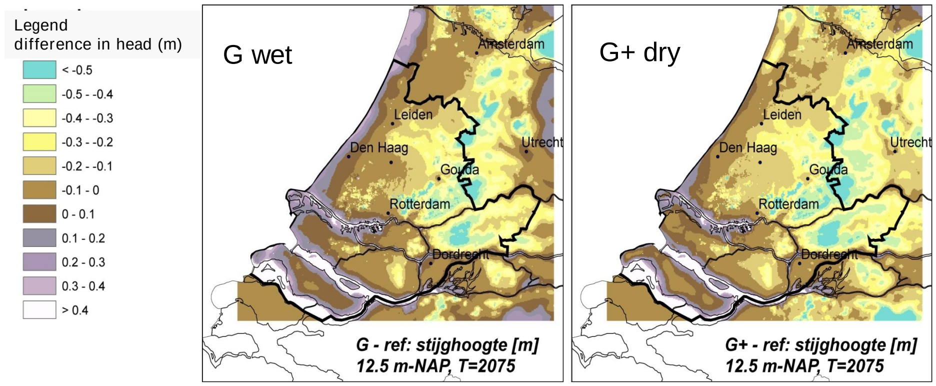
Effect sea level rise, change in natural groundwater recharge and land subsidence on freshwater head in aquifer

Some regional modelling results

Freshwater head at -12.5 M.S.L.



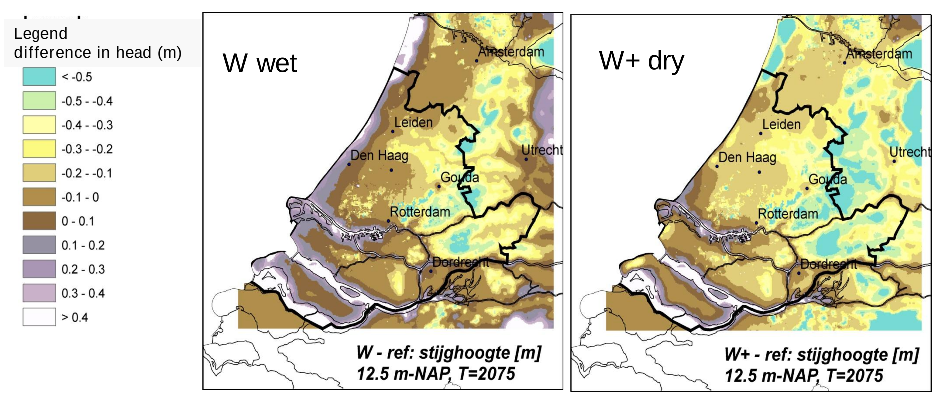
Difference in freshwater head on op -12.5 N.A.P.: G scenarios



Sea level rise is 60 cm

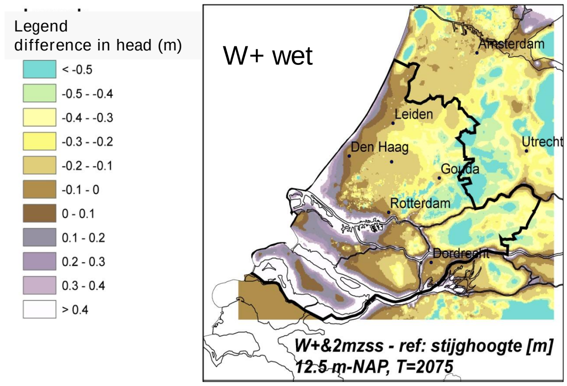
Including change in natural groundwater recharge

Difference in freshwater headon op -12.5 N.A.P.: W scenarios



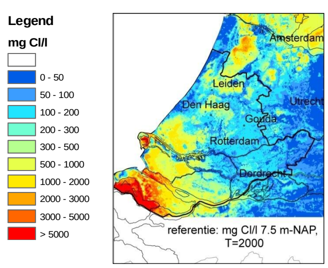
Sea level rise is 85 cm

Difference in freshwater headon op -12.5 N.A.P.: W scenarios



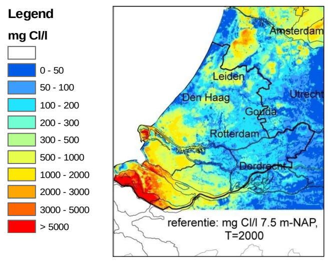
Sea level rise is 200 cm

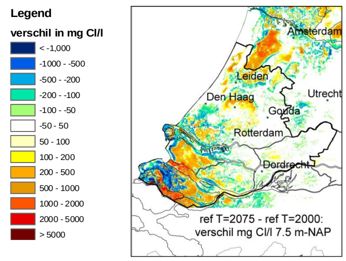
Salinisation/freshening Netherlands?: Present situation



modelstudy

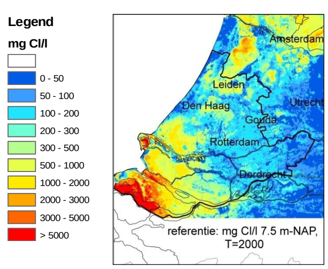
Salinisation/freshening Netherlands?: Autonomous processes

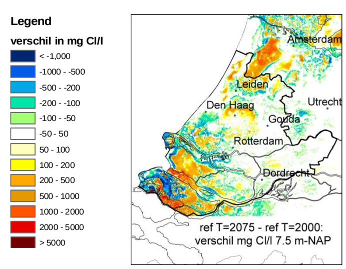


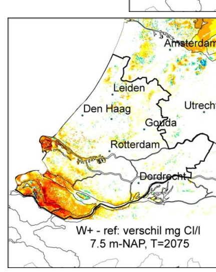


modelstudy

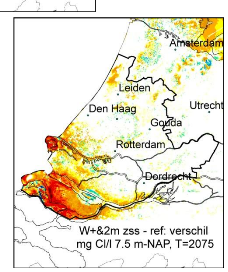
Salinisation/freshening Netherlands?: climate change







85 cm sea level rise

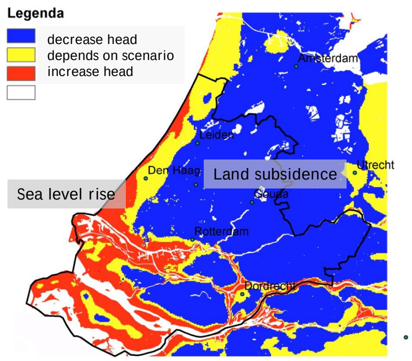


200 cm sea level rise

modelstudy

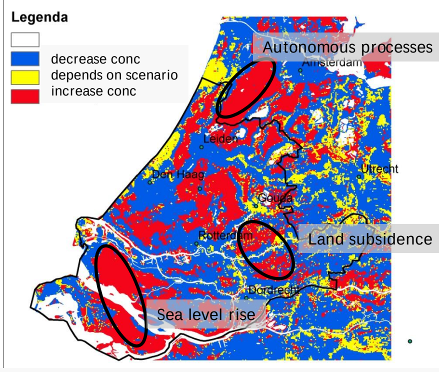
Effect climate scenarios in 2075 on

freshwater head



Increase or decrease head for all climate scenarios G, G+, W, W+

salinisation



Increase or decrease concentration for all climate scenarios G, G+, W, W+

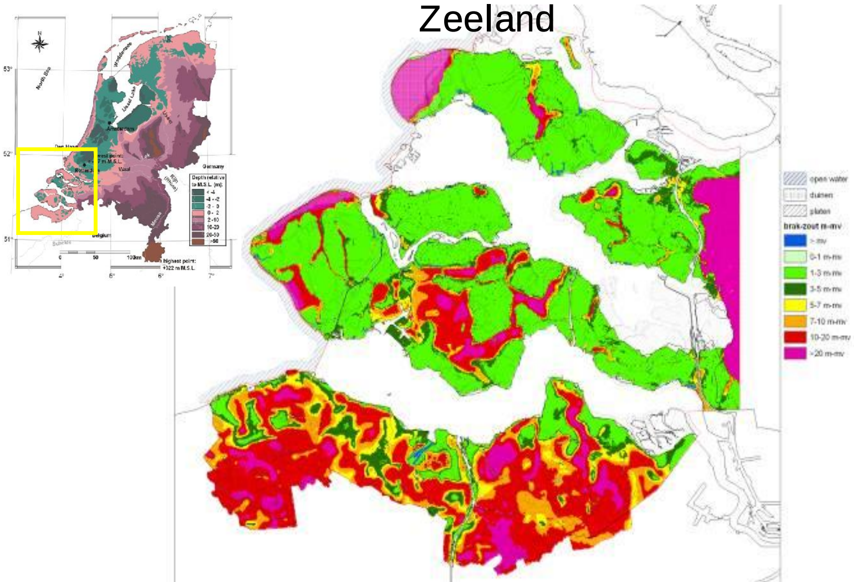
Modelstudie PZH

Rainwater lenses in an agricultural setting

Shallow dynamic freshwater bodies flowing upon brackish-saline groundwater

- density dependent
- dynamics: seasonal & long-year

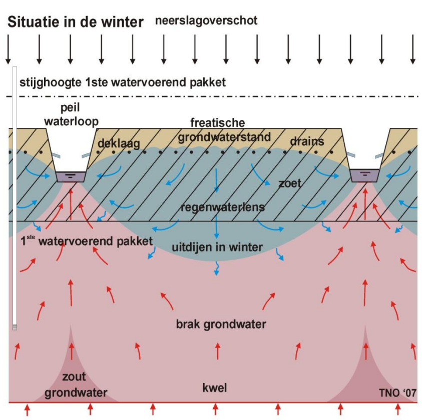
Salinisation of the phreatic groundwater in Zeeland



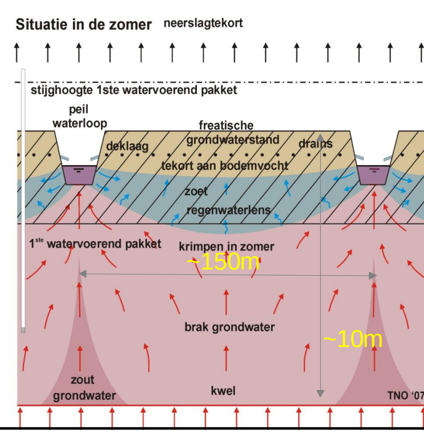
Position of brackish-saline interface

Salinisation of the phreatic groundwater in Zeeland

Dynamic rainwater lenses floating on saline groundwater



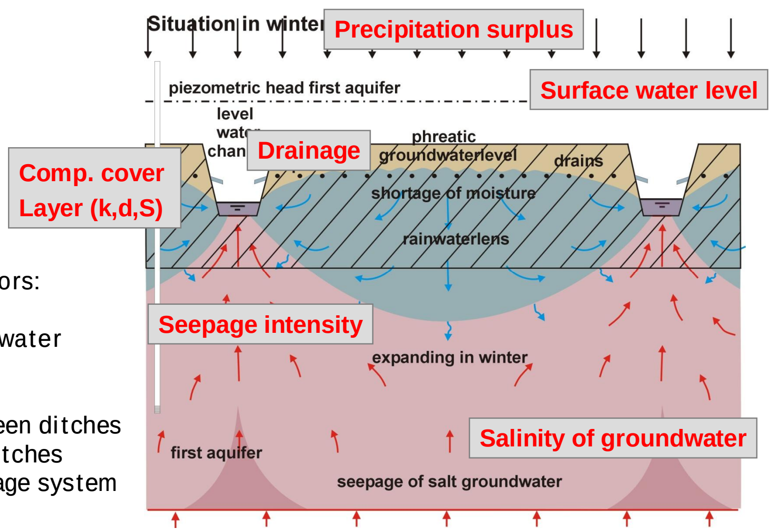
thickness rainwater lens varies due to the dynamics in seasonal and long-year natural groundwater recharge



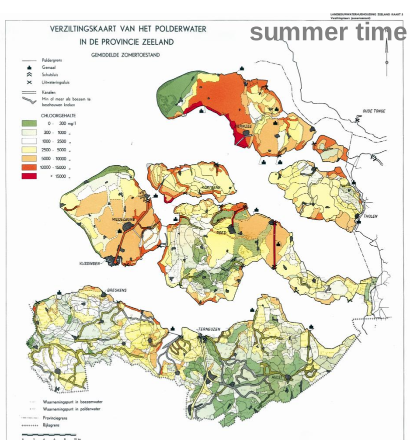
Factors controlling fresh-salt interface

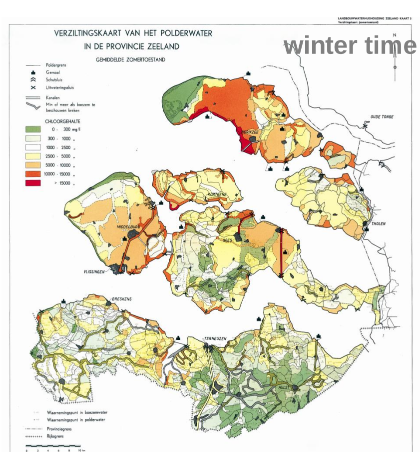
Important factors:

-natural groundwater
 recharge
-geology
-distance between ditches
-water levele ditches
-capacity drainage system

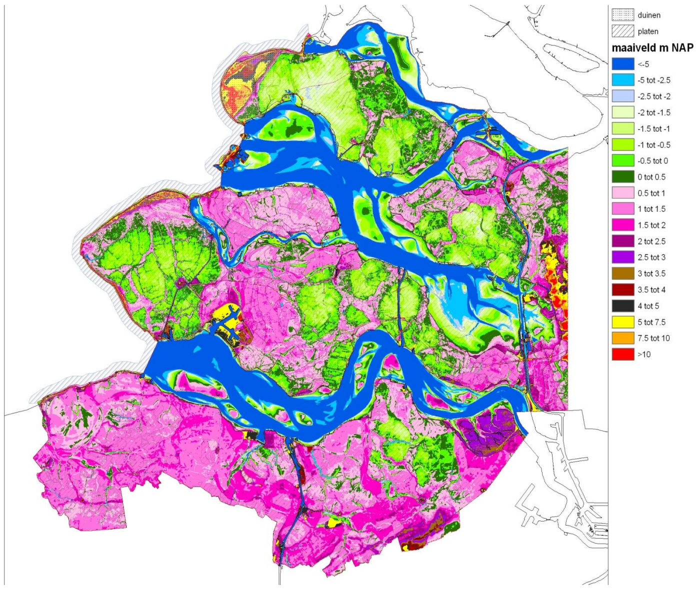


Salinisation surface water

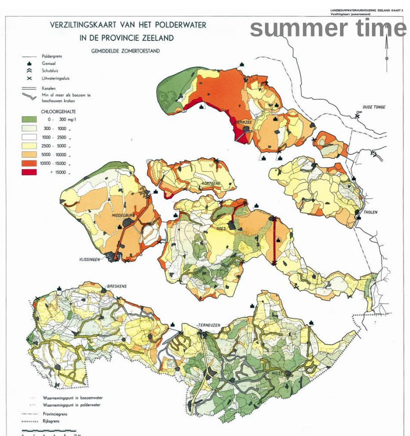


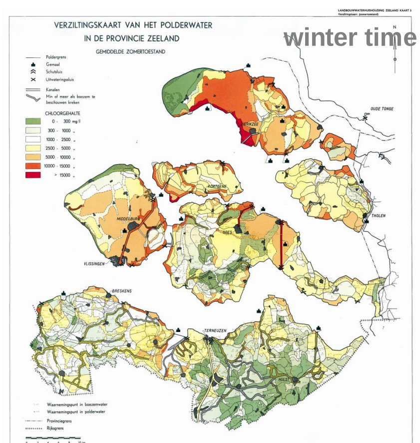


Position of the ground surface



Salinisation surface water





Problem definition dynamic freshwater lenses

Salt in the agricultural plots originates from:

- surface water system (irrigation water)
- groundwater system (salt load to the root zone)

The salinisation will increase due to:

- sea level rise
- climate change
- water level management

How to tackle the problem?

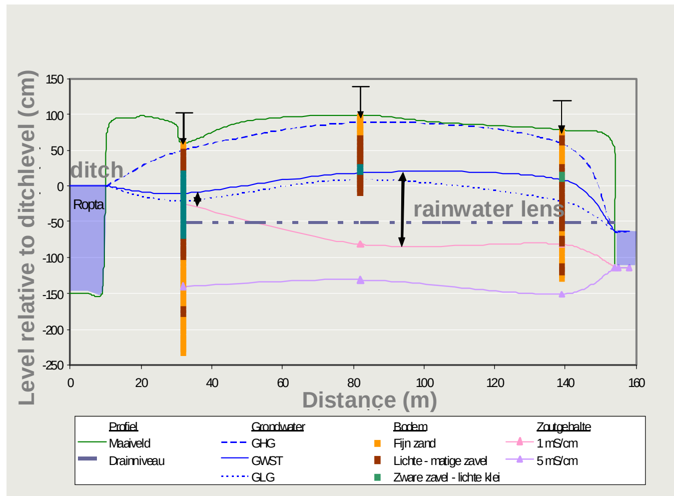
Field measurements at parcels

- fresh-brackish-salt interface at local scale using T-EC-probe and later CVES and ERT
- groundwater level and quality
- surface water level and quality

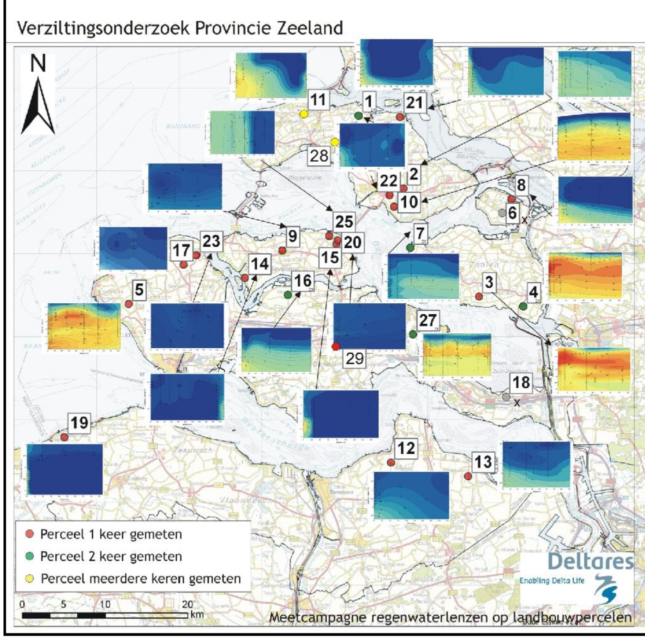
Modelling

- density dependent groundwater flow
- two different scales:
  - regional scale: transect perpendicular at coast
  - local scale: parcel between two ditches

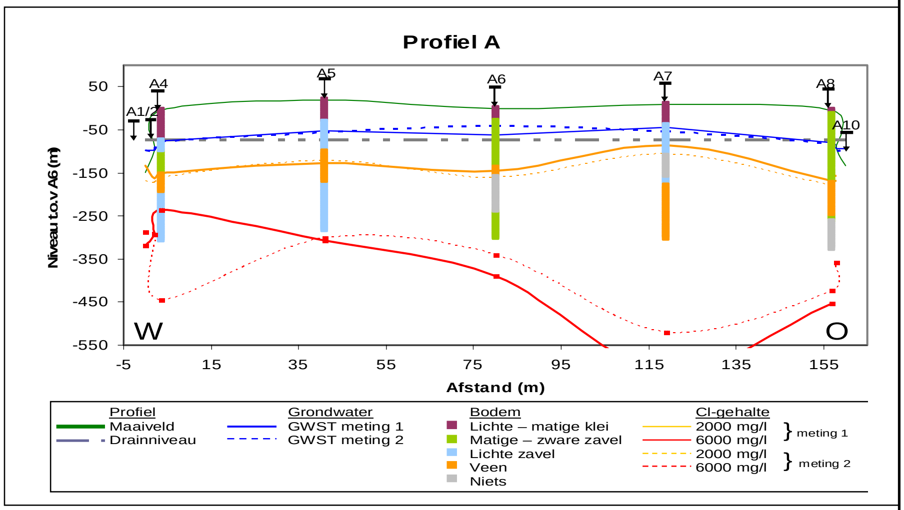
Use field measurements to understand the process



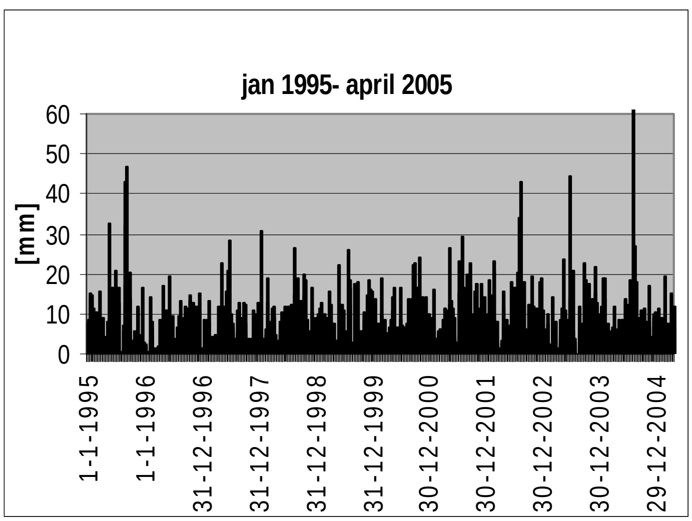
TEC-probe Monitoring campaign 2005-2009



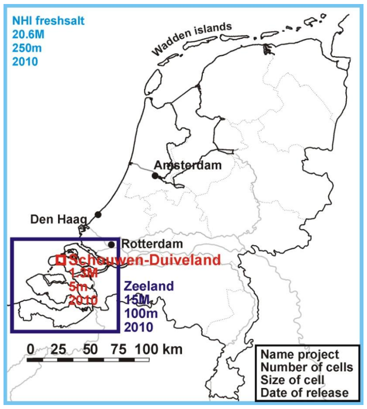
Measuring and monitoring thickness freshwater lens with a T-EC probe

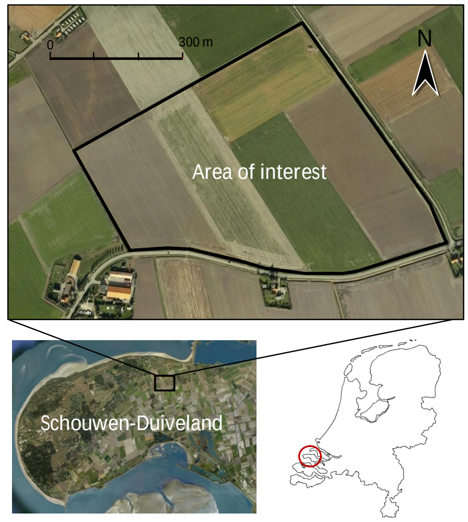


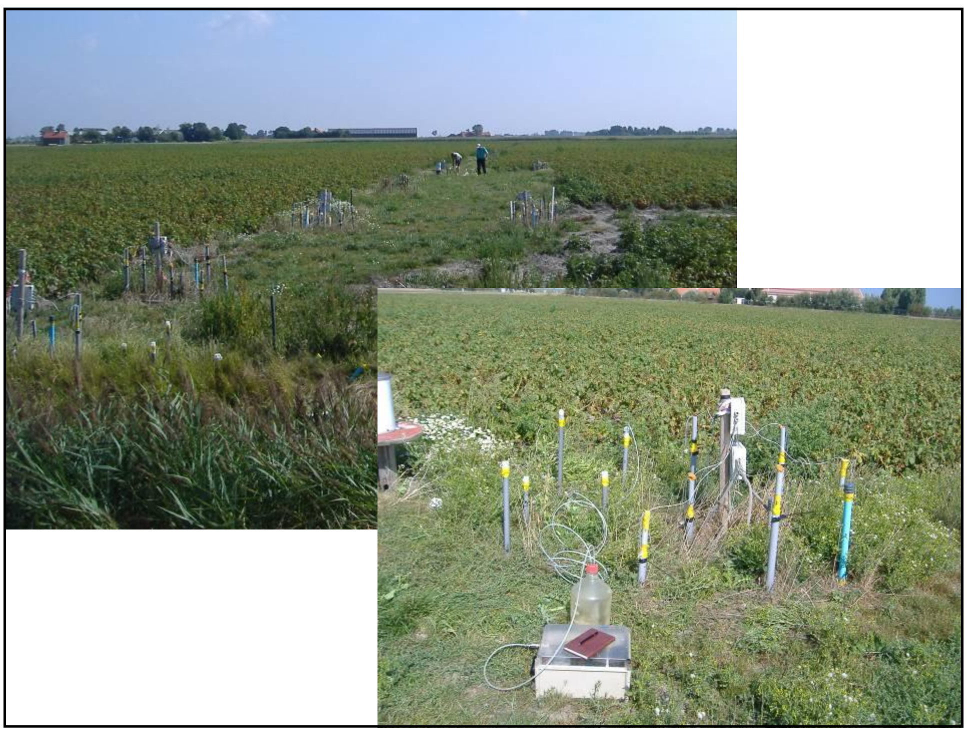
Real recharge data used

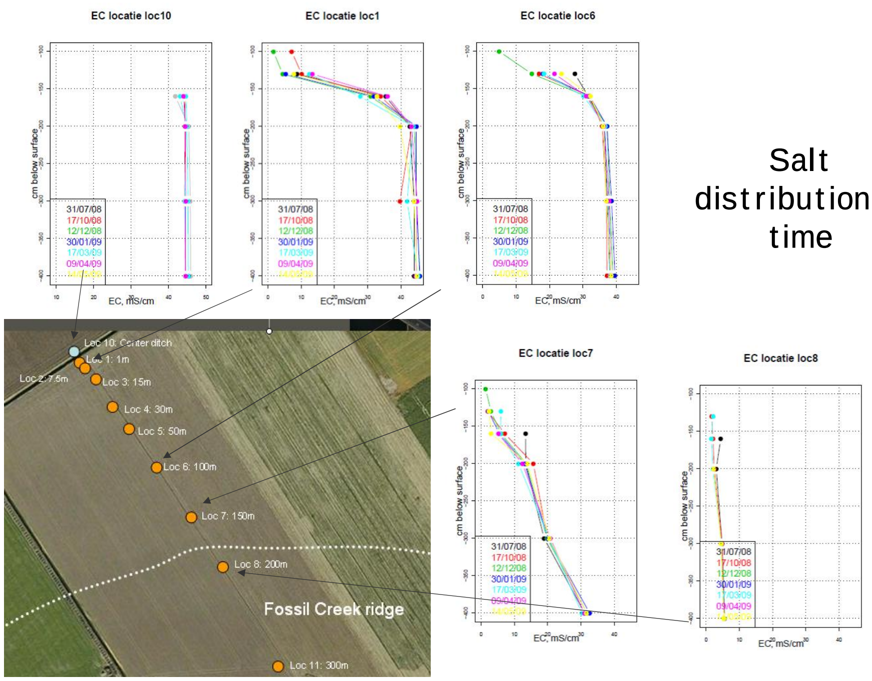


Description local area





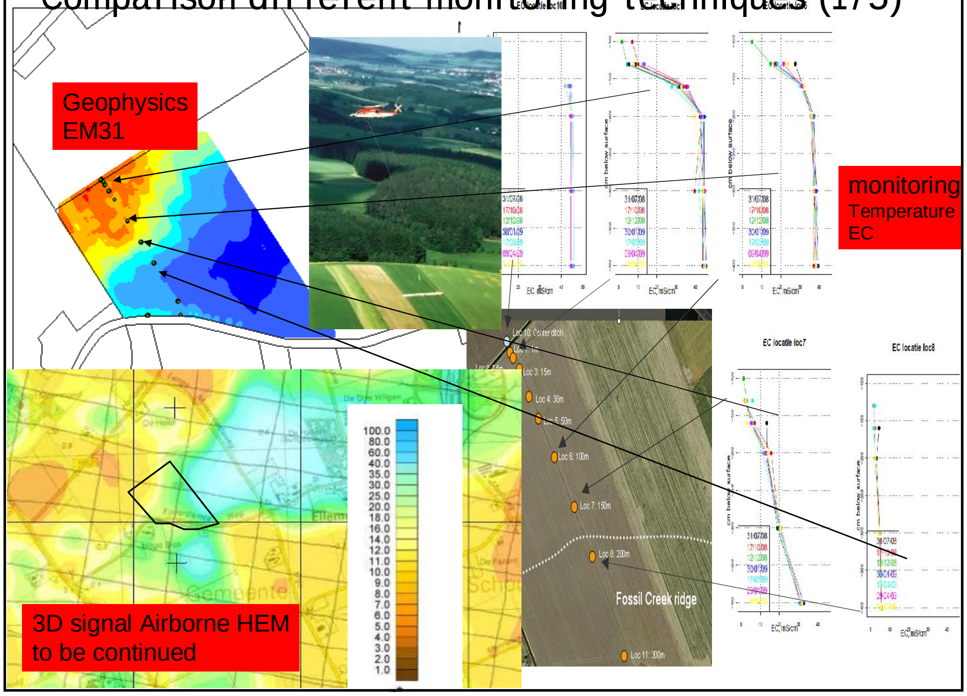




Salt distribution in time

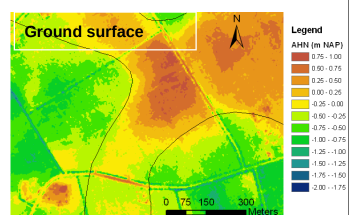
- TEC
- sampling
- EM31
- CVES
- HEM
- ECPT
- Numerical models (2D and 3D)

Comparison different monitoring techniques (1/5)

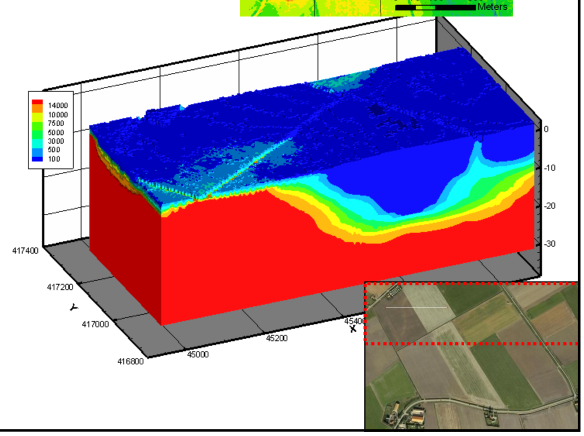


Local 3D model of the agricultural plot

Modelling:
- variable-density
- 3D, non-steady
- groundwater flow & coupled solute transport
- model cell size: 5*5m^2

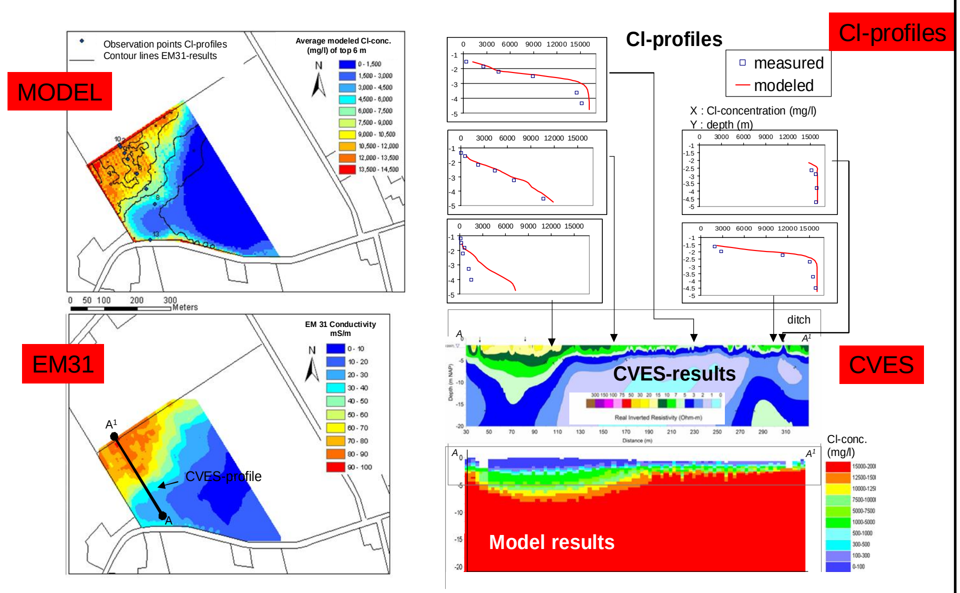


Code:
MOCDENS3D

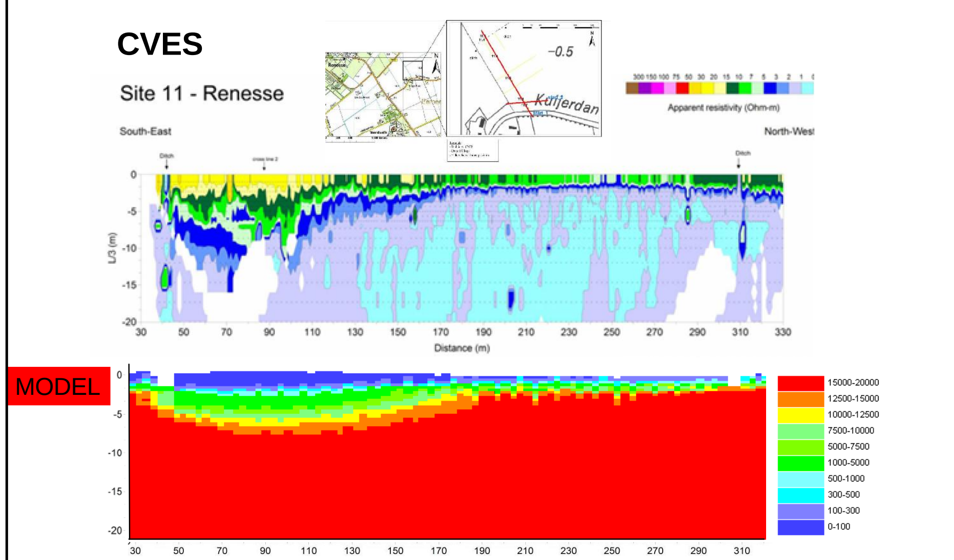


Assessing effects:
- autonomous salinisation
- sea level rise
- changing recharge pattern
- (adaption measures)

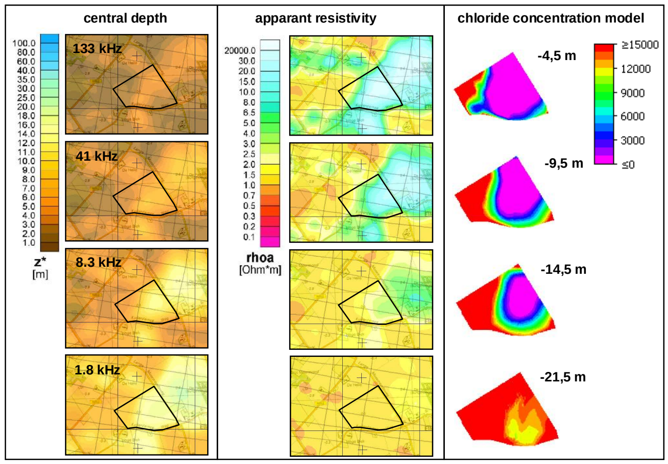
Comparison model with EM31, CVES, profiles



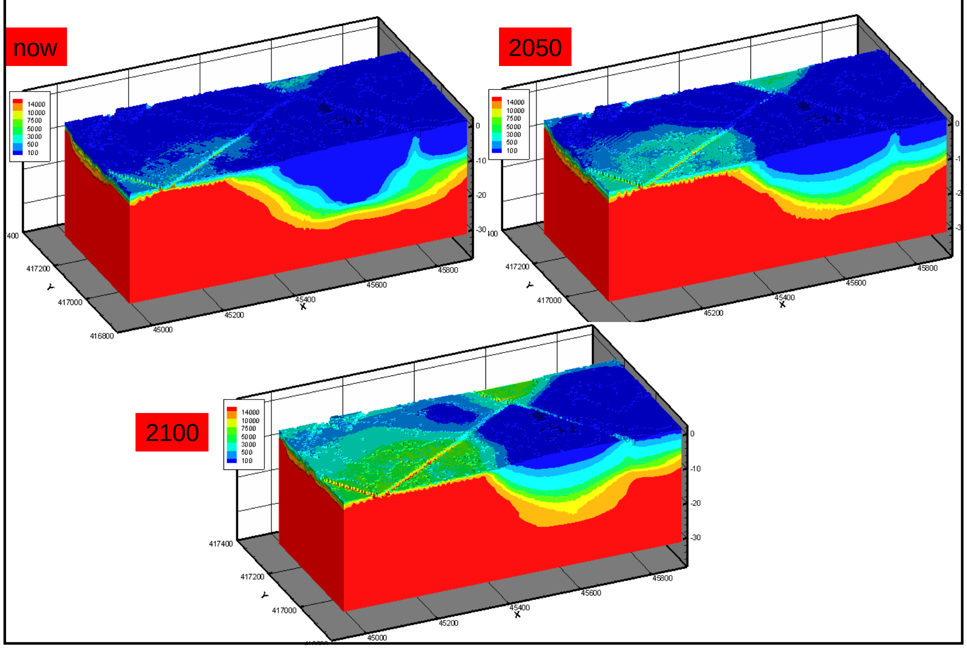
Comparison 3D model and CVES



HEM data



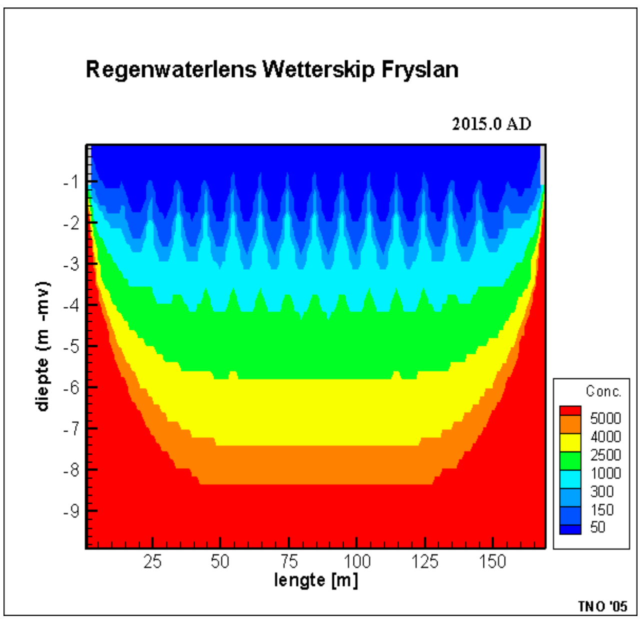
Climate change scenario (dry): model result



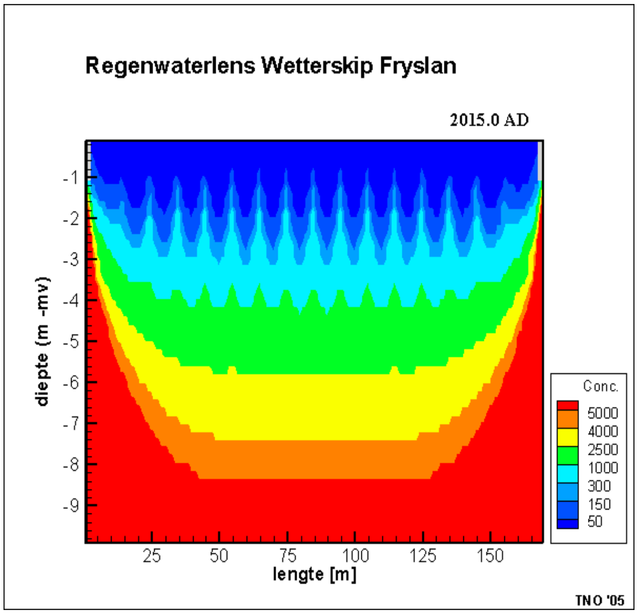
To be continued…

- Implementing more realisations of 3D geology and initial 3D fresh-saline
  - Analyse the differences
- Running climate change scenarios (on national and regional level)
  - Effect on surface water (salt load)
  - Effect on root zone (rainwater lenses)
  - Effect on freshwater volumes (drinking water)
- Compare model results of different scales and give recommendations

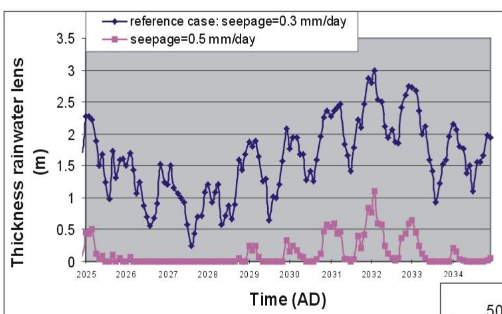
Model the dynamics of fresh-brackish-salt interface



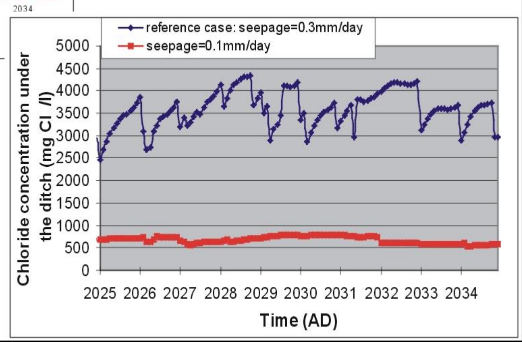
Model the dynamics of fresh-brackish-salt interface



Thickness of the lens and salt load to surface water varies



depends on seepage



Conclusions (salinisation Dutch aquifers):

- Salinisation in the Netherlands is a non-stationary process
- Three physical processes threaten the Dutch aquifers:
  - autonomous development
  - land subsidence
  - sea level rise
- Increase in seepage and salt load can be severe during the coming 50/100 years
- Modelling techniques are available to assess possible effects

Recommendations (salinisation Dutch aquifers):

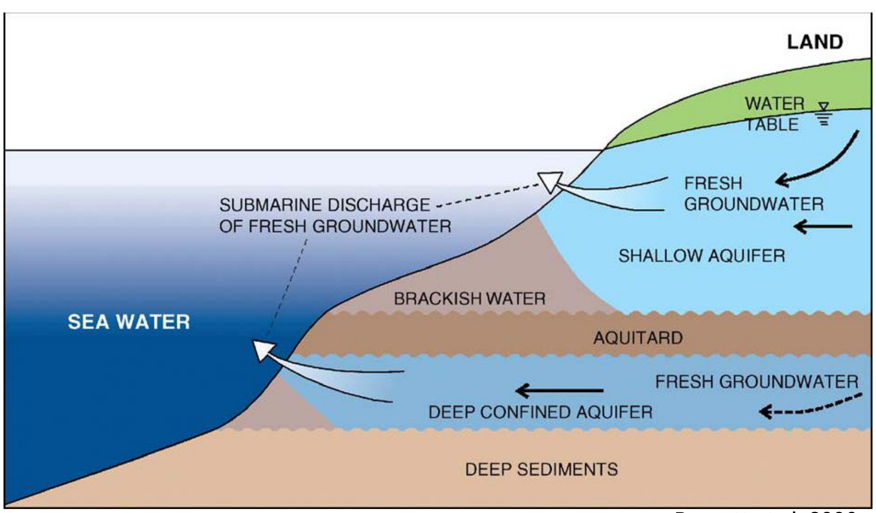
- Number of quality measurements should be increased
- Feasibility study is necessary to implement potential technical measures to compensate salt water intrusion

International

- Philippines (submarie groundwater discharge)
- Gujarat, India (evaluation anti-swi measures)
- Maldives (effect dec 2004 Tsunami)

What is Submarine Groundwater Discharge (SGD)?

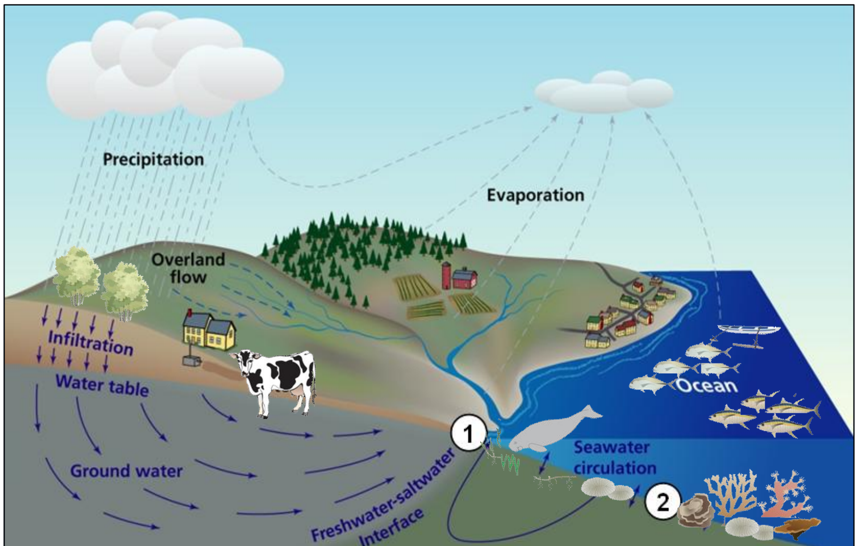
any flow of water out across the sea floor



Burnett et al, 2006

Why study SGD?

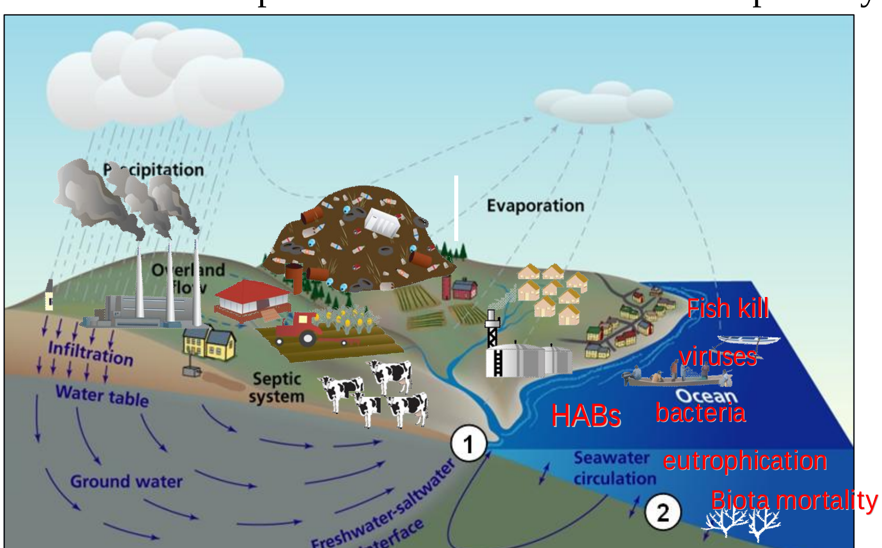
Nutrients are transported from land to sea via SGD pathway



Symbols: IAN.umces.edu

Why study SGD?

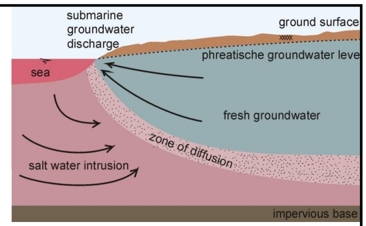
Nutrients are transported from land to sea via SGD pathway

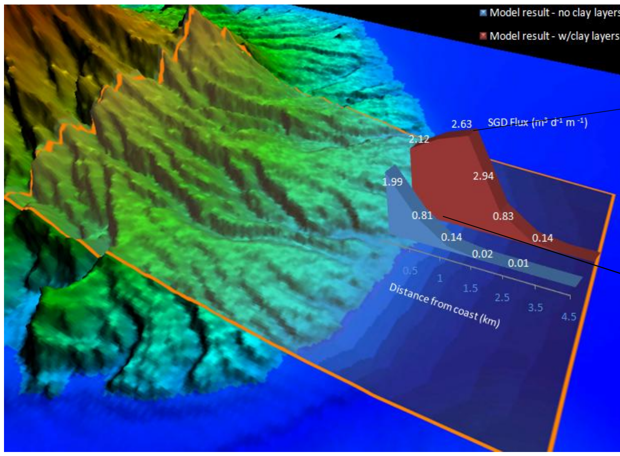


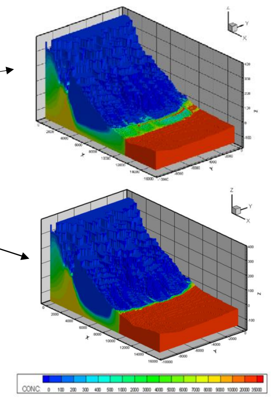
Symbols: IAN.umces.edu

Philippines

Submarine Groundwater Discharge

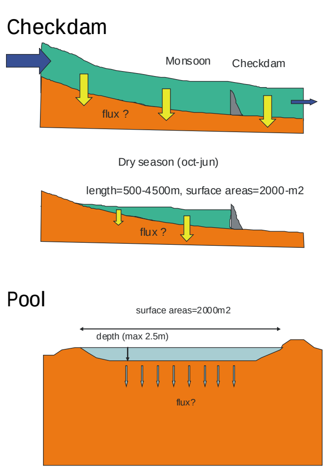


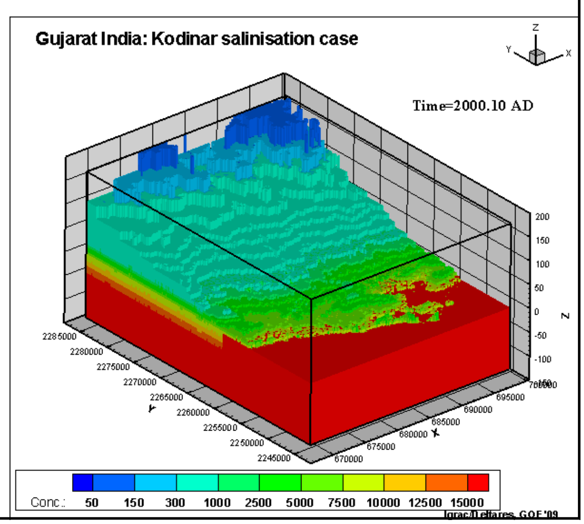


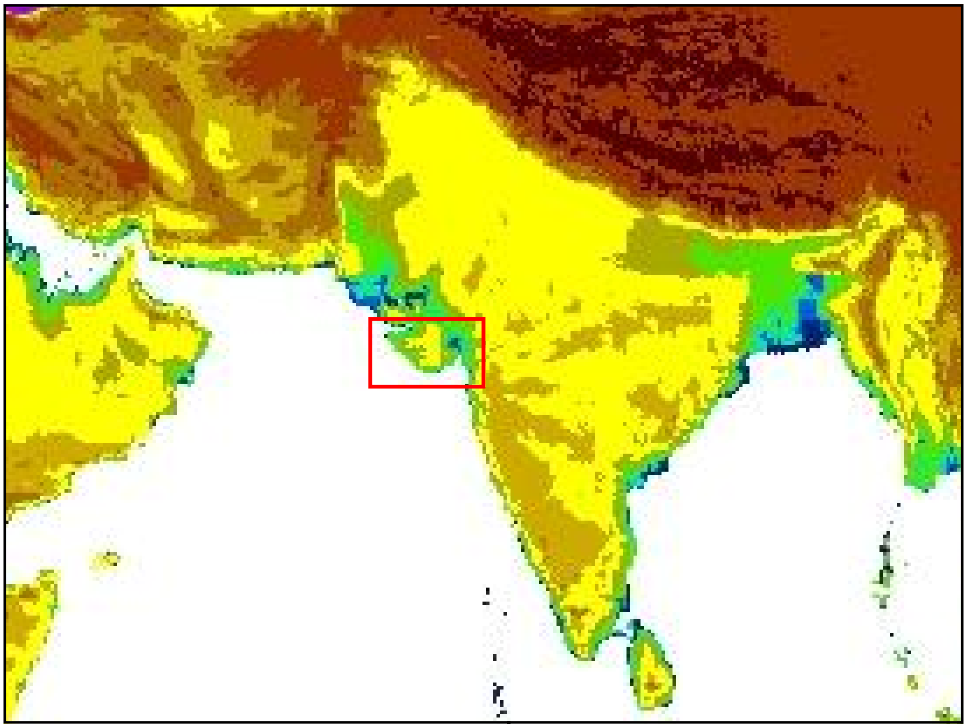


Gujarat, India

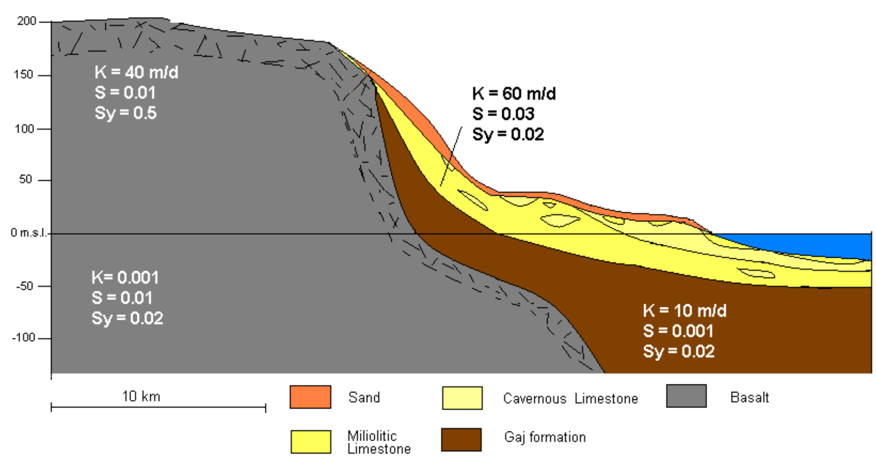
Learning from the Salinity Ingress Prevention Measures in the Coastal Area of Gujarat



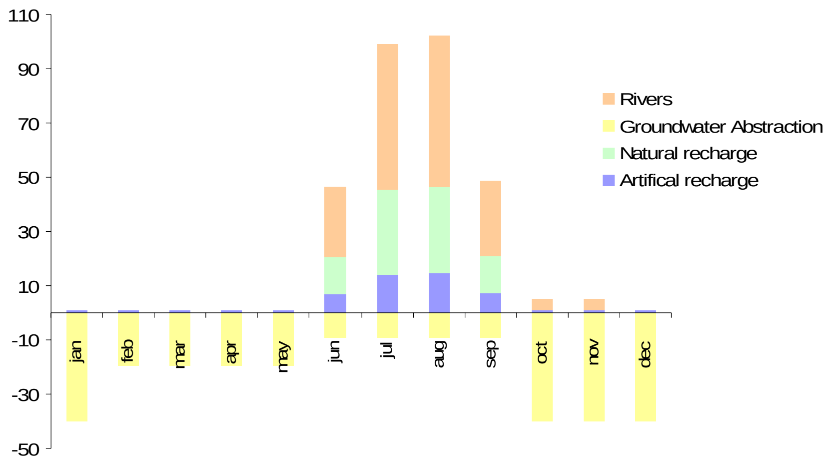




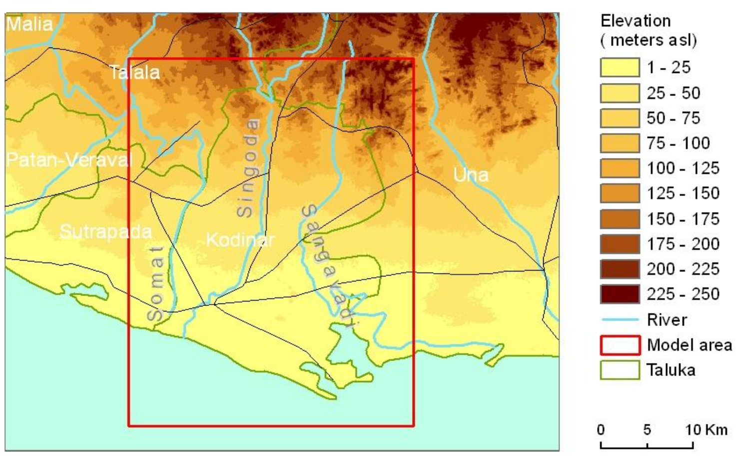
Hydrogeology, 2D profile



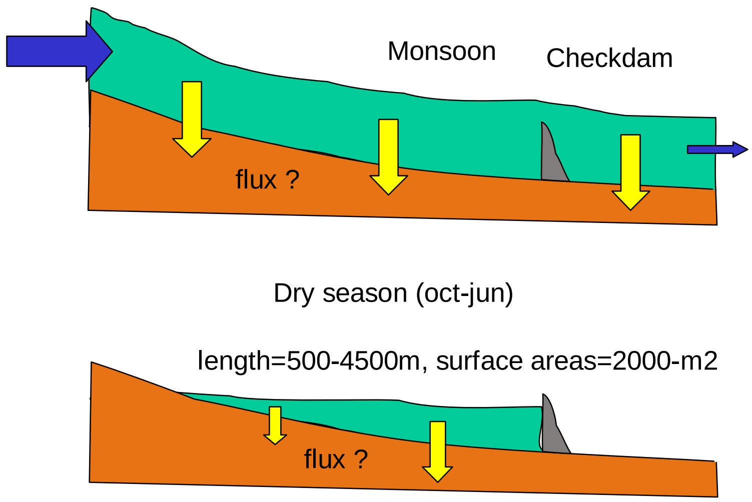
Waterbalance



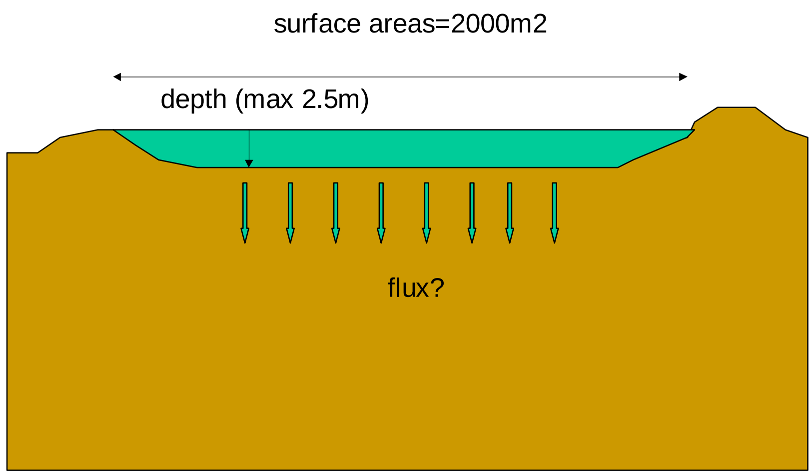
Topography, elevation



Concept Checkdam

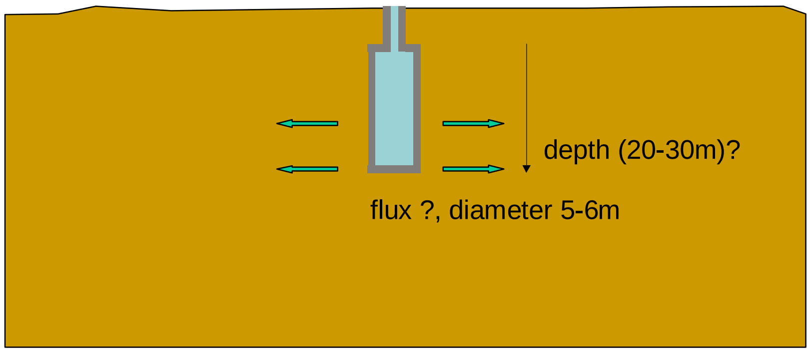


Concept Pond

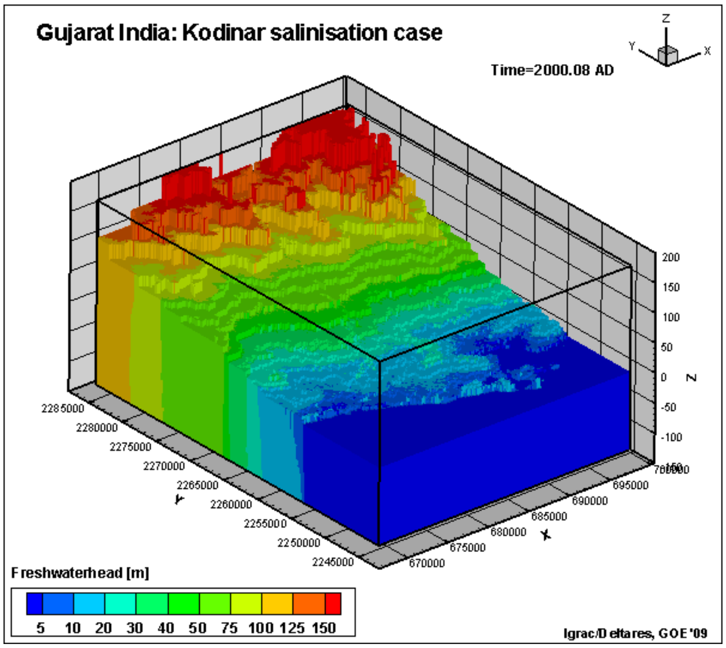


Concept Percolation tank

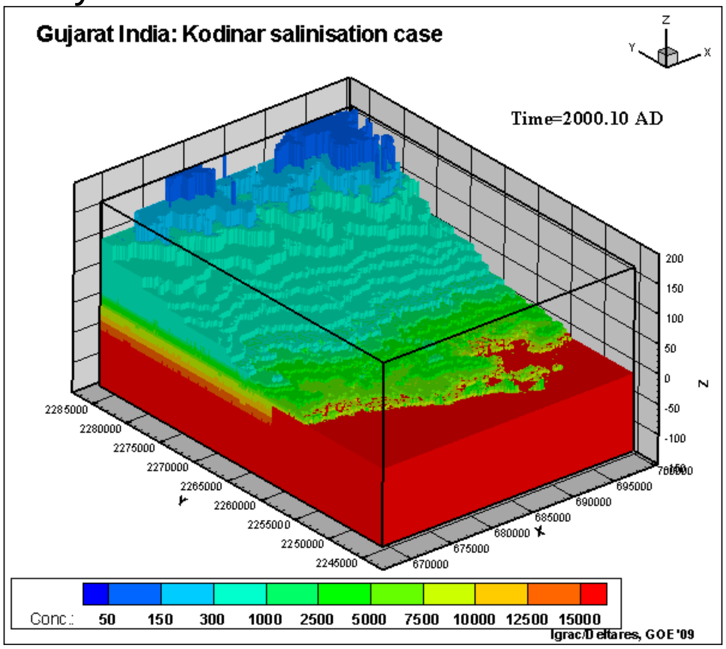
number of wells per village: ?



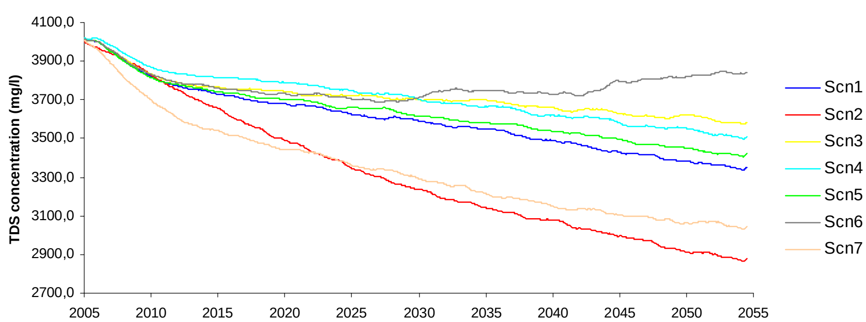
Freshwater head



Salinity



Average TDS concentration



Scn1. Reference case
Scn2. Reference case without artificial recharge
Scn3. Business as usual – increase in population, increase in abstraction
Scn4. Business to the max (agricultural production and increase abstraction in summer)
Scn5. Reference case plus industrial zone development (increase of industr. abstraction)
Scn6. Drought scenario – climate change, sea level rise
Scn7. Reference case plus water saving measures

Conclusions (modelling of variable-density flow)

- Don't use the Henry problem to test your variable-density code
- Use enough cells to model the Hydrocoin and Elder problem

For modelling 3D systems:

- Remember the Peclet discretisation limitation for cell sizes (unless you're using the method of characteristics!)
- Longitudinal dispersivity should not be too large (e.g. <10m)
- It's important to derive a very accurate density distribution (as that significantly effects the velocity field!)
- Watch out for numerical problems at the outflow face to the sea

Challenges for the future

- Improve the 3D density matrix, e.g. by more types of measurements
- Implement effect of climate change and sea level rise on coastal aquifers
- Optimalisation of (ground)water management in coastal aquifers by using 3D variable-density flow models
- Improve calibration of 3D models by using transient data of solute concentrations
- Incorporate reactive multicomponent solute transport

Leading in research on groundwater in the coastal zone

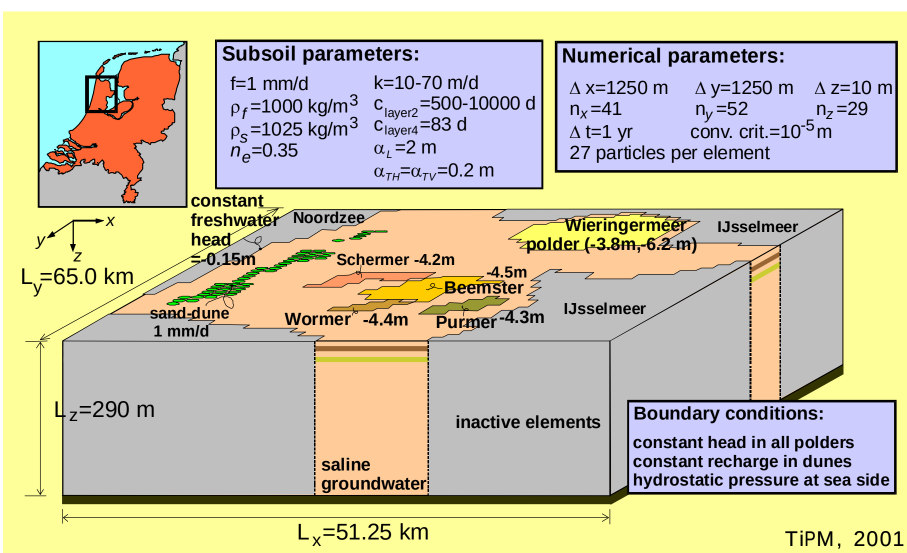
- 15 years experience in variable-density dependent groundwater flow and coupled solute transport in the coastal zone
- Incorporating monitoring campaigns results in numerical modeling tools
- Initiating (inter)national research on new fresh-saline phenomenae: salty seepage boils and thin freshwater lenses in saline environments
- Broad knowledge on creating 3D initial chloride distribution, based on geostatistics and geophysical data (analyses, VES, borehole measurements)
- Quantifying effects of climate change and sea level rise on fresh groundwater resources
- Developing adaptive and mitigative measurements to stop salinization of the coastal groundwater system (e.g. fresh keeper, coastal collectors, freshwater storage underground)

Model of the Kop van Noord-Holland,

The Netherlands

Oude Essink, G. H. P. 2001. Saltwater intrusion in 3D large-scale aquifers: a Dutch case. Phys. & Chem. of the Earth 26(4): 337-344.

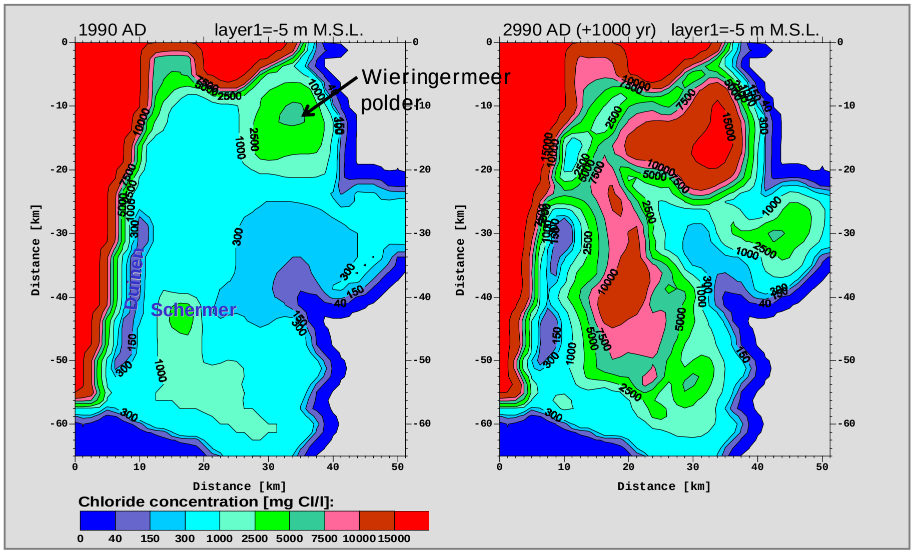
Characteristics of the Kop van Noord-Holland (I)



Kop van Noord-Holland (II)

Reference case=autonomous development

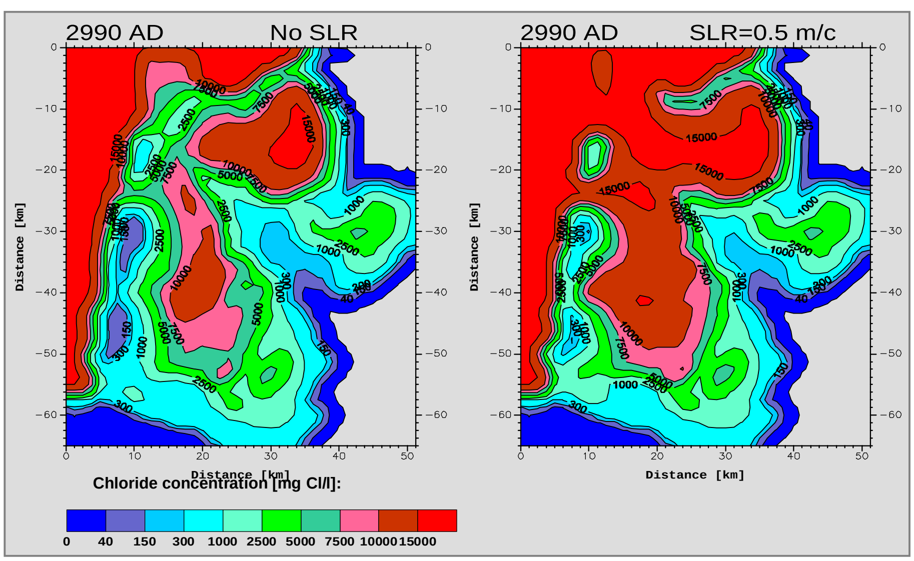
Change in concentration in the top system during 1000 years



Kop van Noord-Holland (III)

Sea level rise case=0.50 m/century

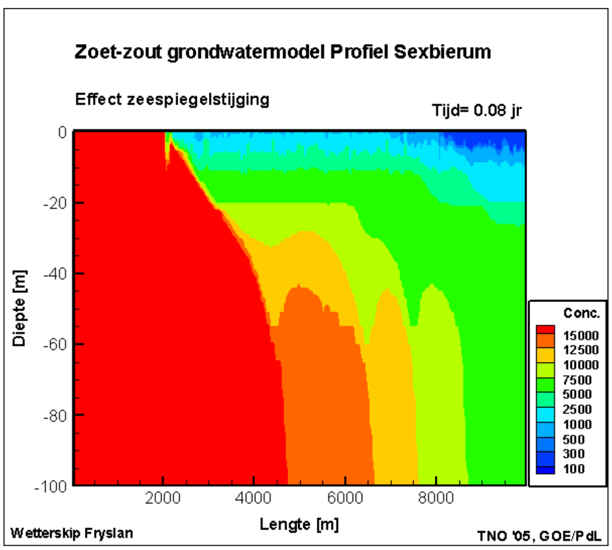
Change in concentration in the top system during 1000 years



Model of the Wetterskip of Fryslan

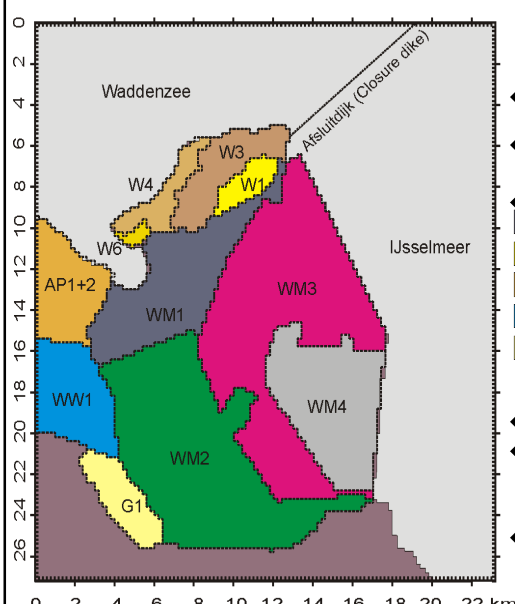
Wetterskip Fryslan

- Zoutverdeling – Huidige en toekomstige situatie (+30jaar)
- Effect zeespiegelstijging en bodemdaling door zoutwinning



Model of the Wieringermeer polder

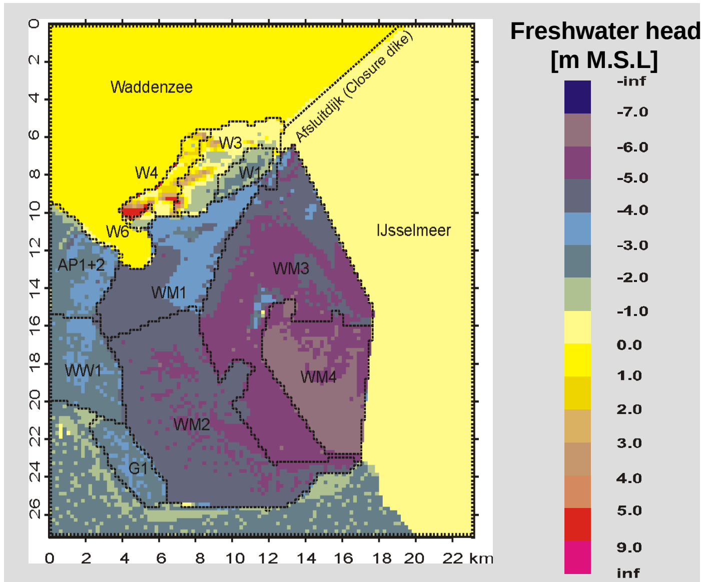
Characteristics of the Wieringermeer polder



- Land surface polder: ~200 km^2
- Reclaimed from the sea in the 1930's
- Geometrical units:
  - WM1-WM4 Wieringermeer polder
  - W1-W6 Wieringen
  - AP1+2 Anna Palowna polder
  - WW1 Wieringerwaard
  - G1 Groet polder
- Waddenzee: tidal salt marsh/innersea
- IJsselmeer freshwater lake (before 1932 innersea)
- 11 polder units in studied area

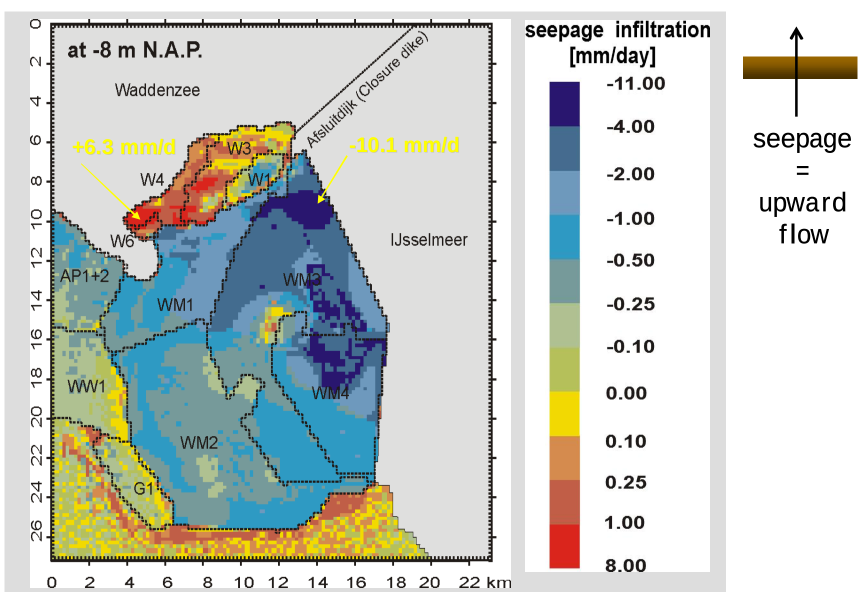
Wieringermeer

Present phreatic water level

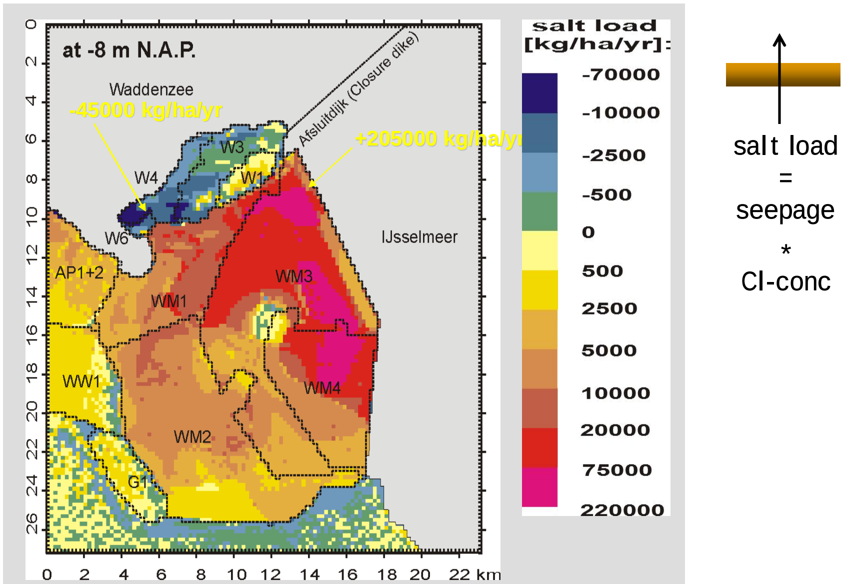


Wieringermeer

Calculated present seepage and infiltration

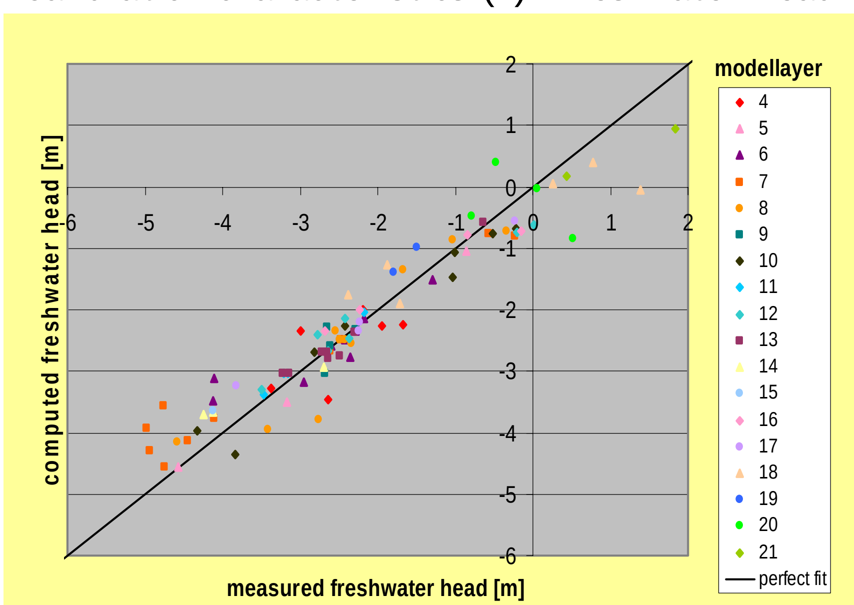


Calculated present salt load

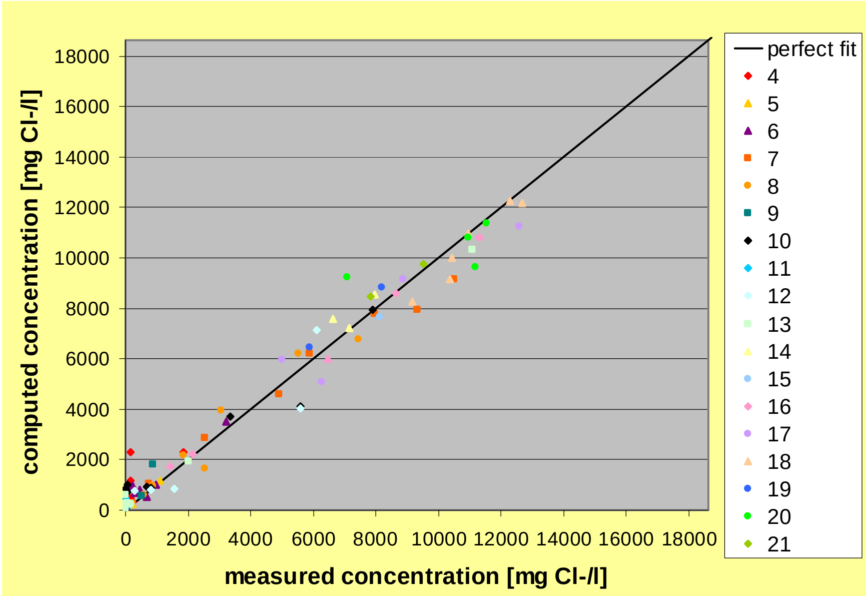


Wieringermeer

Calibration characteristics (I): freshwater head



Calibration characteristics (II): concentration



Two future scenarios (during 50 years):

I Reference case
- -present mean sea level
- -autonomous development

II Sea level rise case
- -relative sea level rise of 0.75 m/century

Interest is focused on:

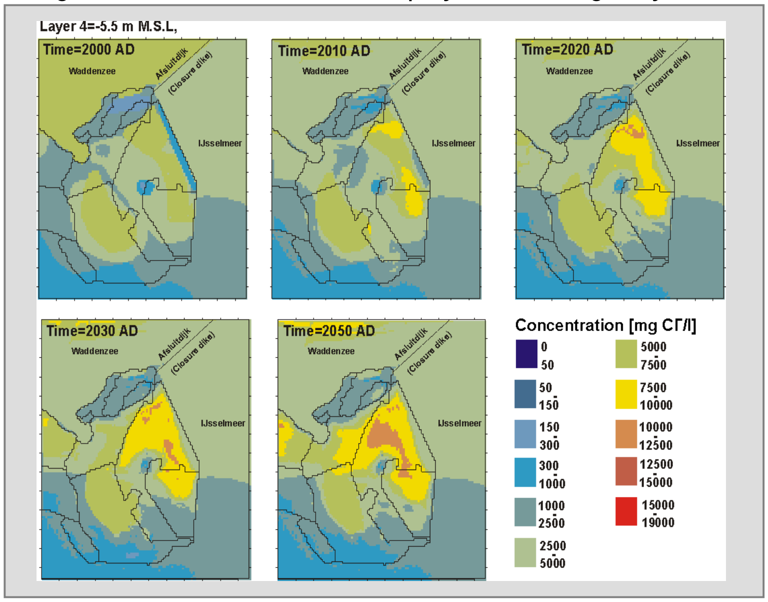
A. Change in concentration in top layer

B. Change in seepage in the polder

C. Change in salt load in the polder

Wieringermeer: reference case

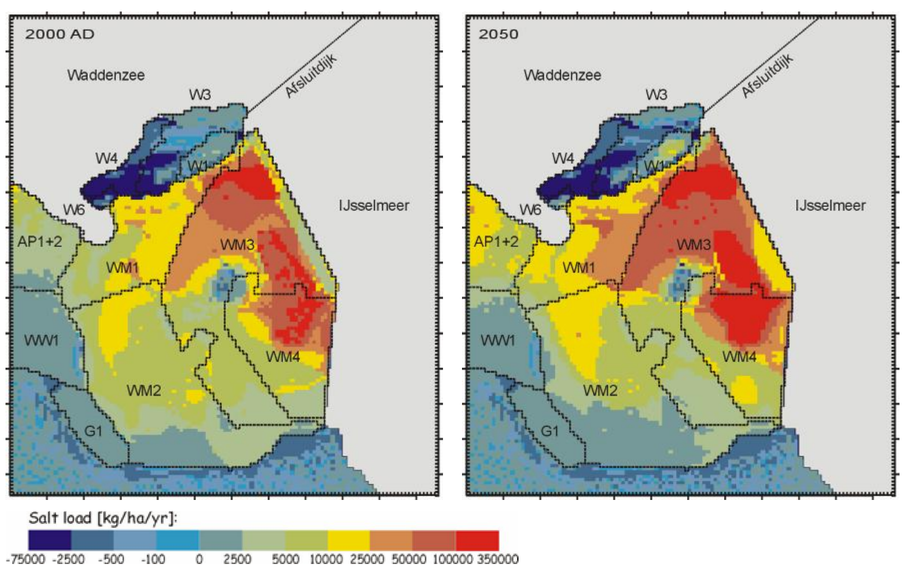
Change in concentration in the top system during 50 years



Wieringermeer

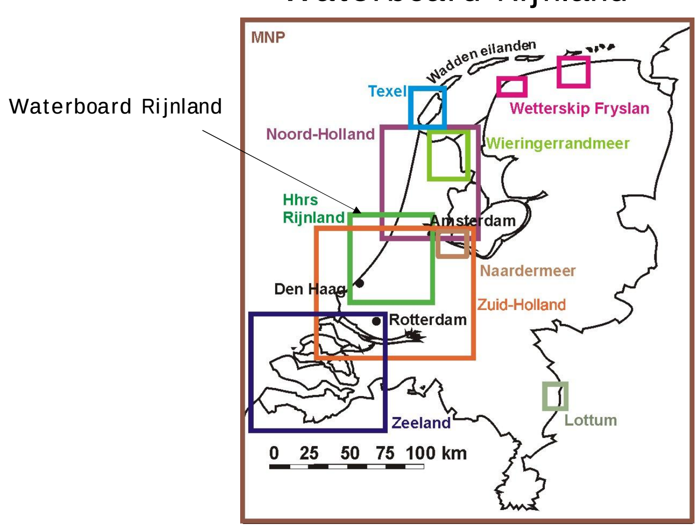
Wieringermeer: reference case

Change in salt load in the top system during 50 years

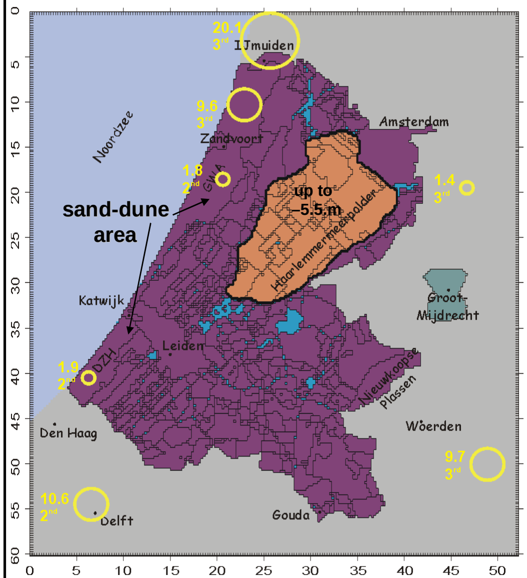


Model of the Waterboard Rijnland

3D Case: effect measurements
Waterboard Rijnland



Characteristics of the Waterboard Rijnland



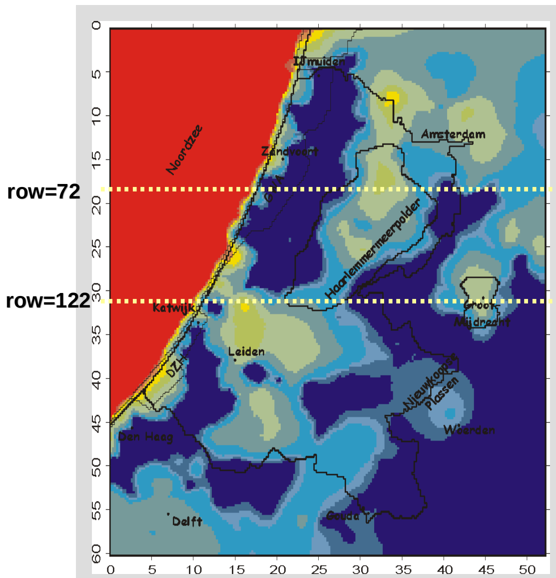
- Land surface: ~1100 km²
- Geometrical units:
  1. Waterboard of Rijnland
  2. Haarlemmermeerpolder
  3. Open Water
  4. Sea
  5. Remaining land
  6. Polder Groot-Mijdrecht
- 550 polder units in Water Board

=position of extraction

9.6 =rate of extraction [10^6 m^3/yr]

3rd =aquifer from which water is extracted

Present chloride concentration in the top layer



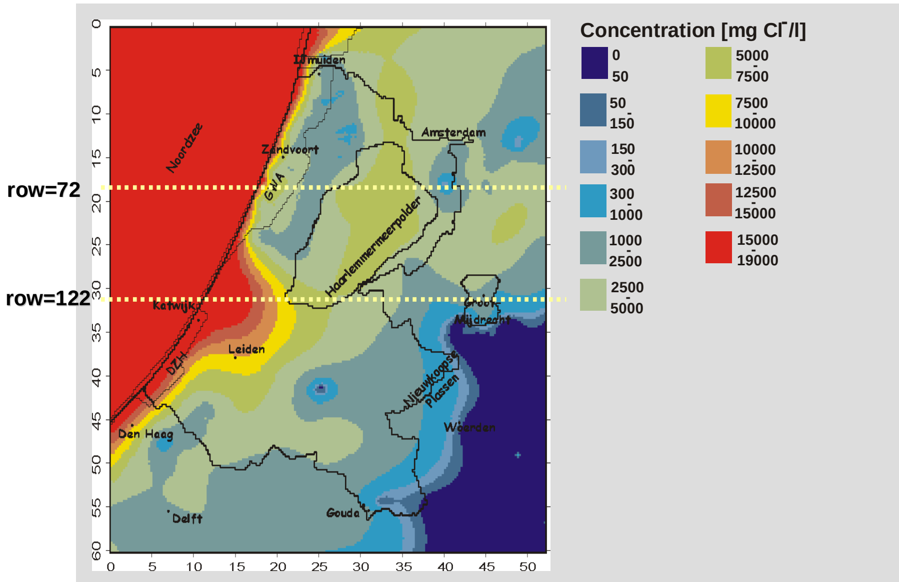
Concentration [mg Cl⁻/l]

0 - 50	5000 - 7500
50 - 150	7500 - 10000
150 - 300	10000 - 12500
300 - 1000	12500 - 15000
1000 - 2500	15000 - 19000
2500 - 5000	

Based on 6921 density points in the system, deduced from the National Groundwater Model NAGROM

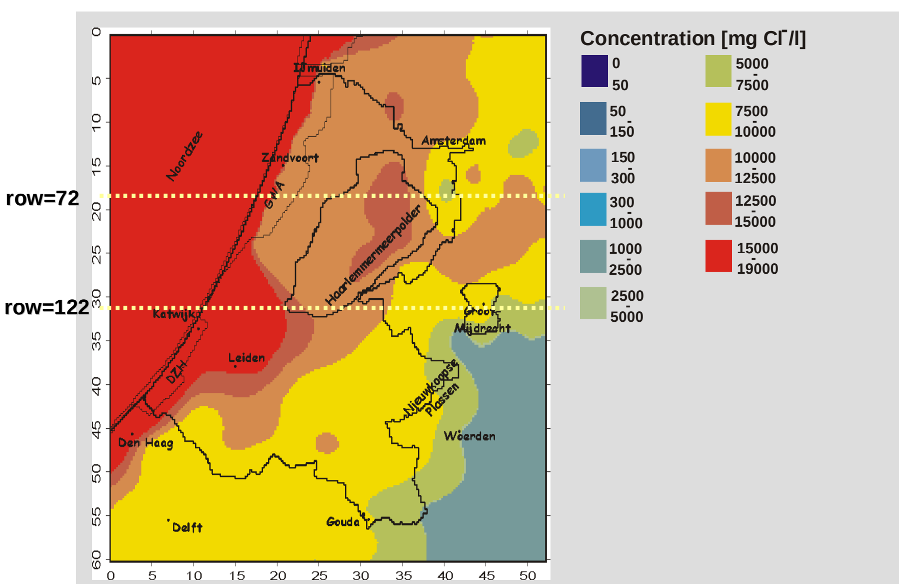
Rijnland

Present chloride concentration at –95 m N.A.P.



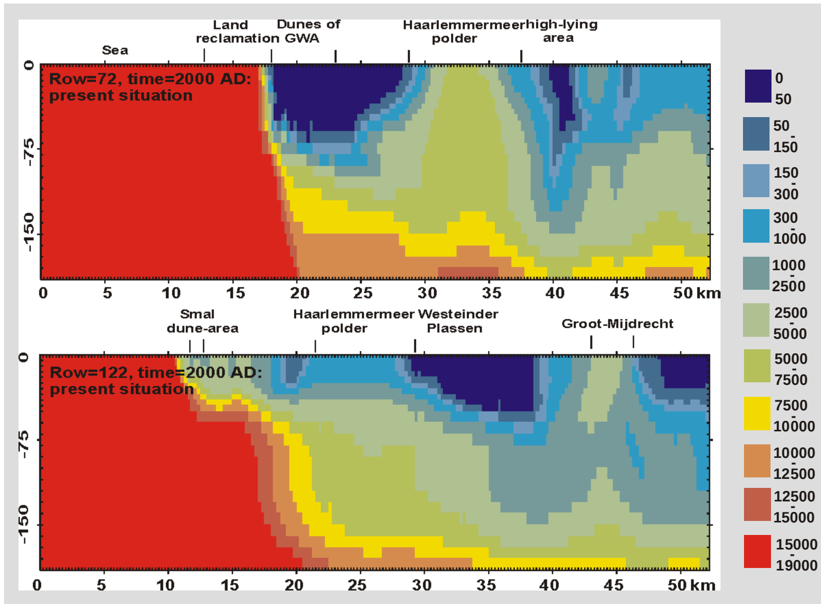
Rijnland

Present chloride concentration at –175 m N.A.P.



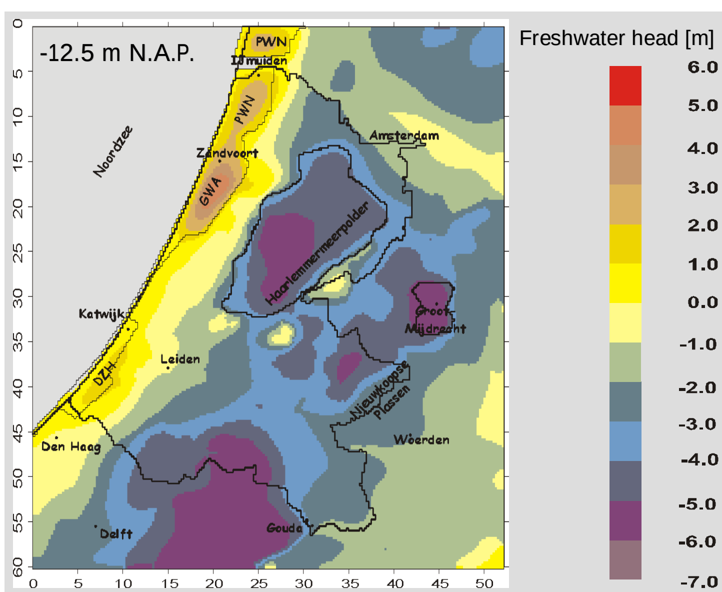
Rijnland

Present chloride concentration in row 72 and 122



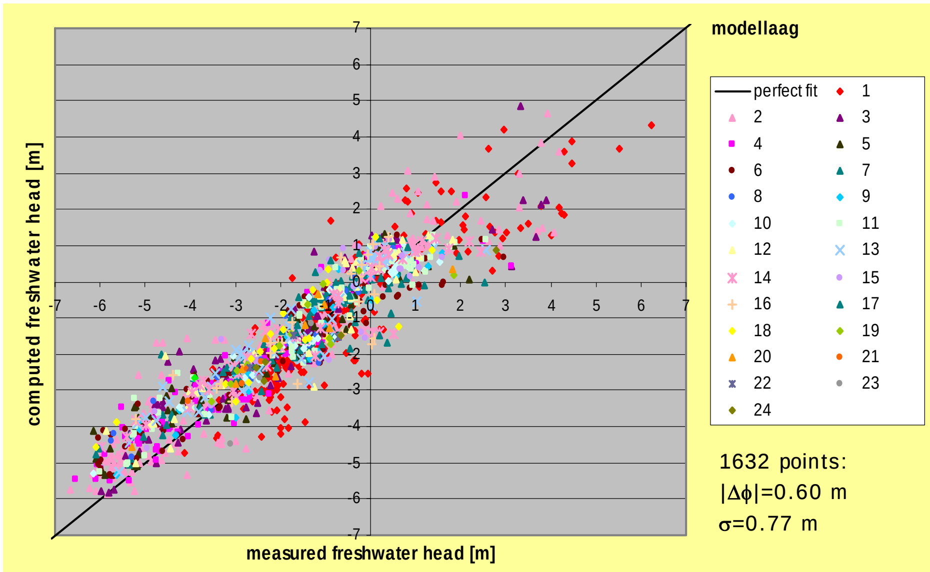
Rijnland

Computed present phreatic water level



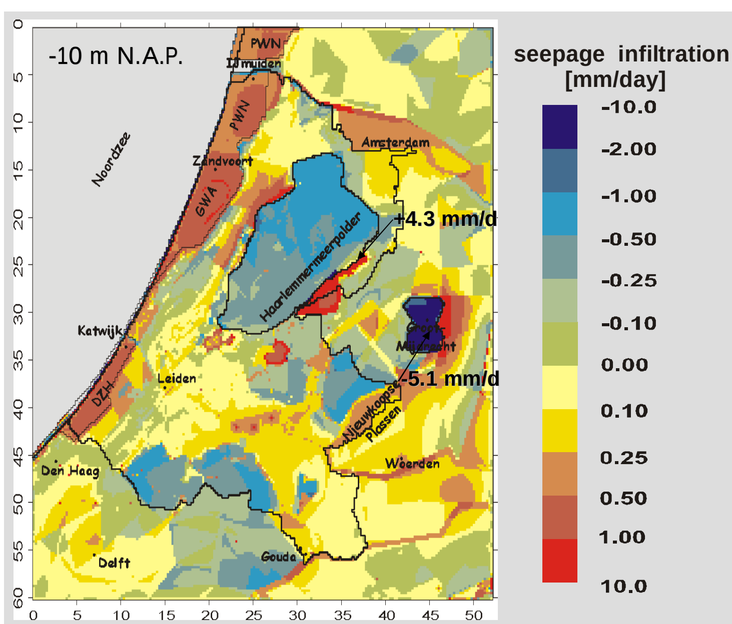
Rijnland

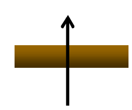
Calibration characteristics: head



Rijnland

Calculated present seepage and infiltration





seepage
=
upward
flow

Some values:

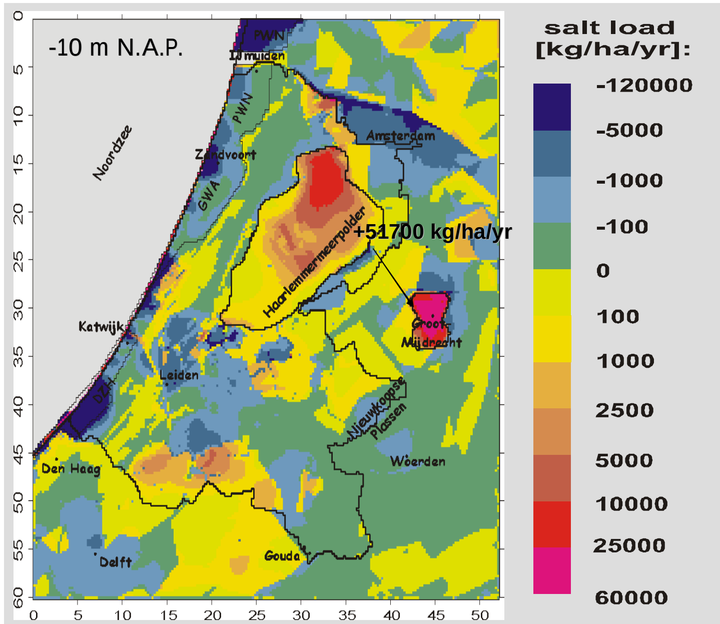
Haarlem. polder:
-0.51 mm/d

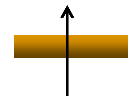
Groot-Mijdrecht:
-2.85 mm/d

GWA:
~+0.59 mm/d

DZH:
~+0.62 mm/d

Calculated present salt load





salt load
=
seepage
*
Cl-conc

Some values:

Haarlem. polder:
62900 ton Cl/jr

Groot-Mijdrecht:
47100 ton Cl/jr

Four future scenarios (during 500 years):

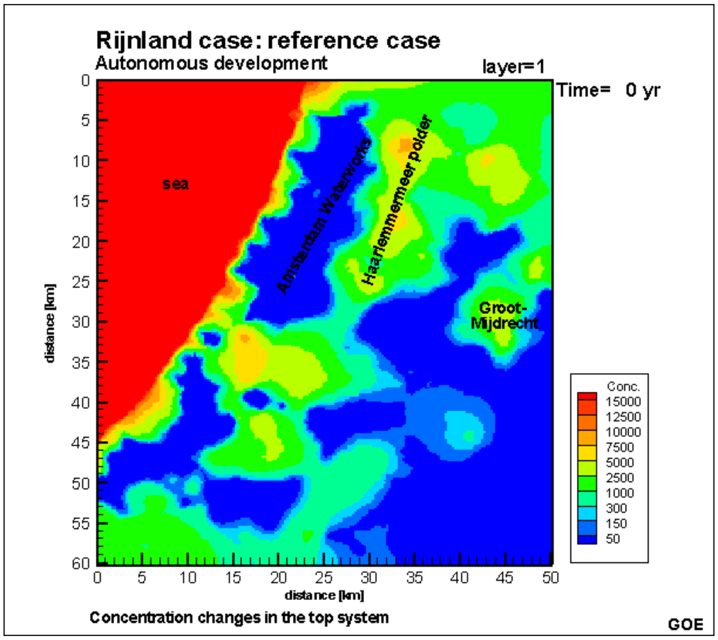
I. Reference case
- to determine autonomous salt water intrusion

II. Climate change case:
- sea level rise of 0.9 m/century
- increase of natural recharge in dunes with 6%
- decrease of groundwater extraction in some sand-dunes
- land subsidence in polder area: 0.3 and 1.0 m/century

III. Compensating measures

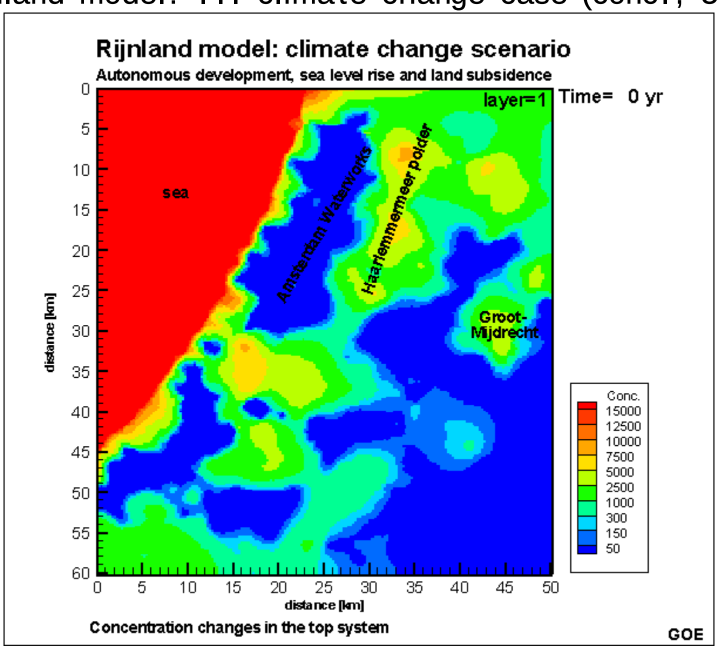
Rijnland

Rijnland model: I. reference case (conc., 500 yr)

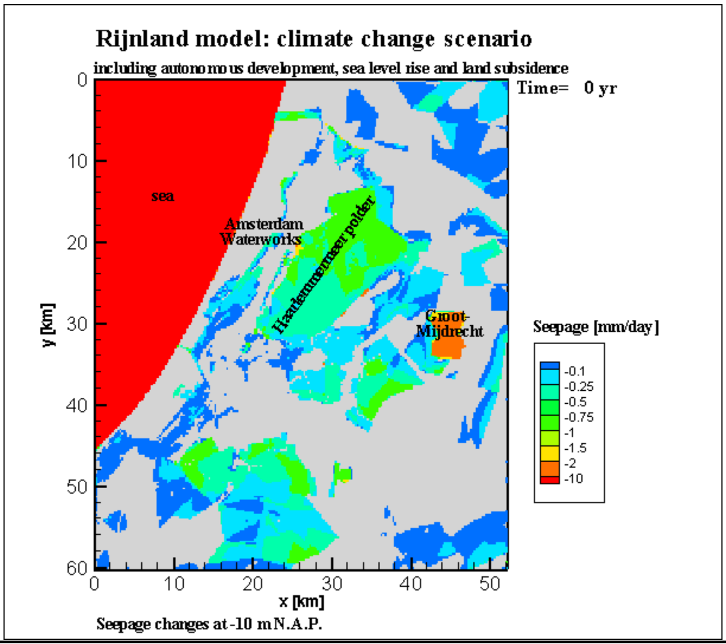


Rijnland

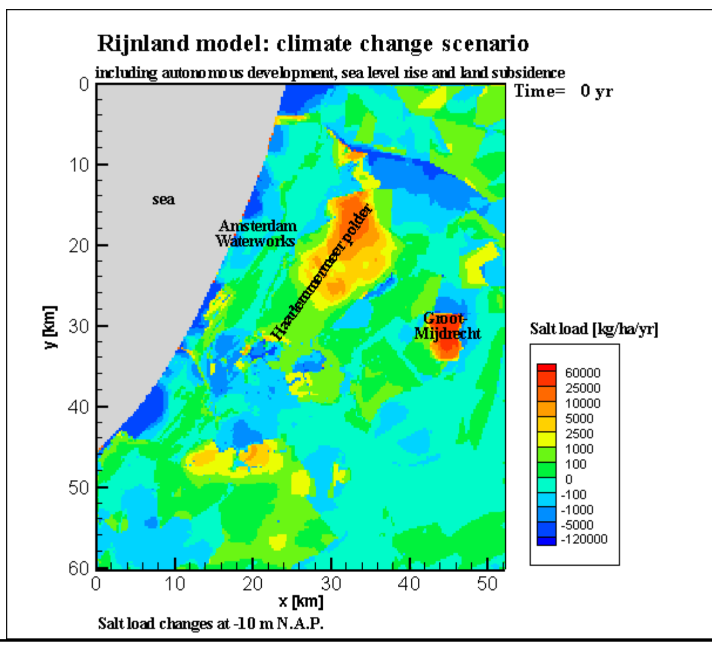
Rijnland model: II. climate change case (conc., 500 yr)



Rijnland model : II. climate change case (seepage, 500 yr)



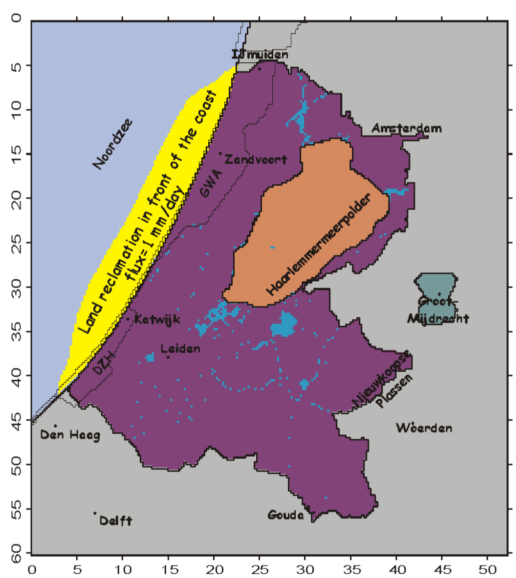
Rijnland model: II. climate change case (salt load, 500 yr)



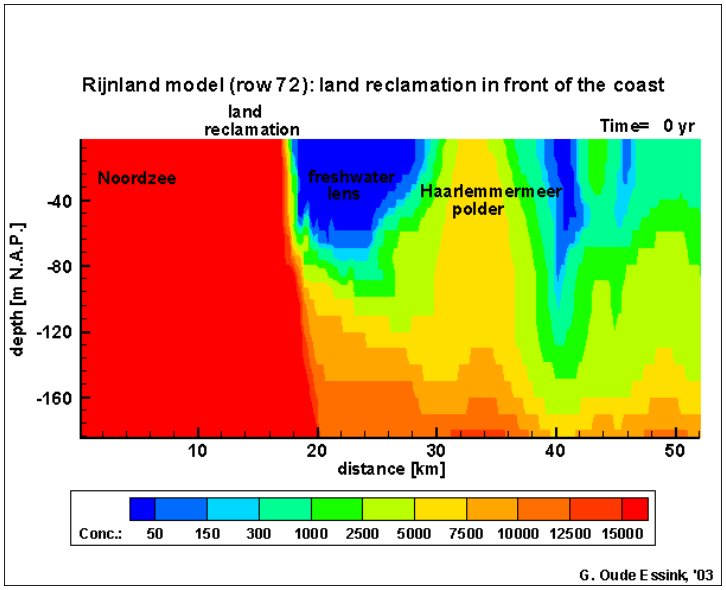
Possible measures to compensate salt water intrusion

1. Land reclamation in front of the coast
2. Inundation of low-lying polders
3. Extraction of saline/brackish groundwater
4. Infiltration of fresh surface water
5. Creating physical barriers

1. Rijnland model: land reclamation case



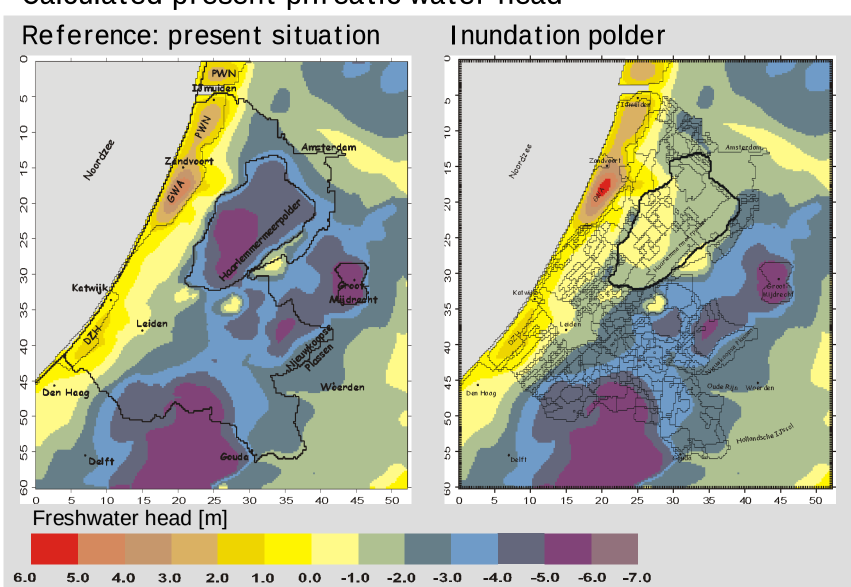
1. Land reclamation in front of the coast



Rijnland

2. Rijnland model: Inundation Haarlemmermeerpolder

Calculated present phreatic water head

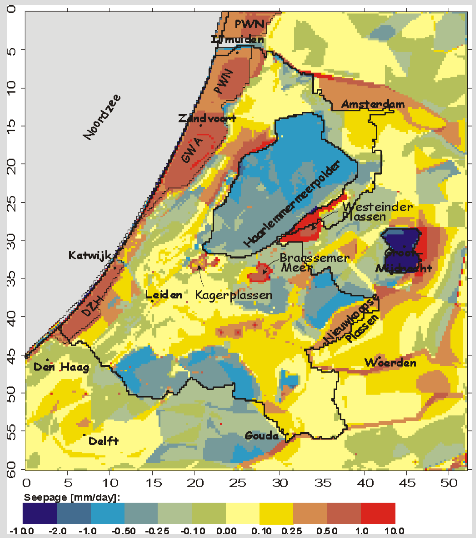


Rijnland

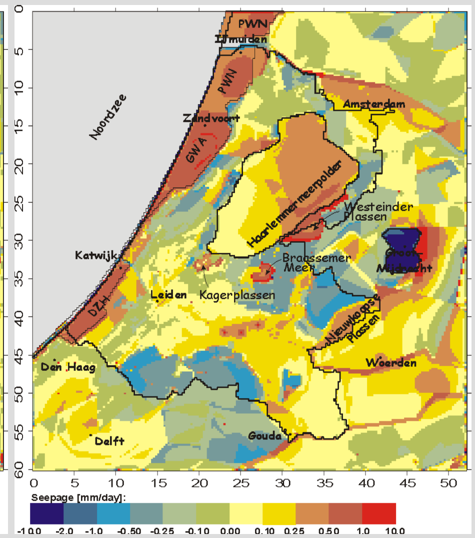
2. Rijnland model : Inundation Haarlemmermeerpolder

Calculated seepage and infiltration on –10 m M.S.L.

Reference: present situation



Inundation polder

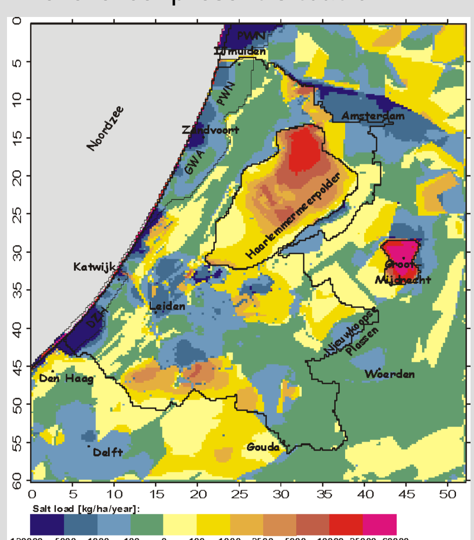


Rijnland

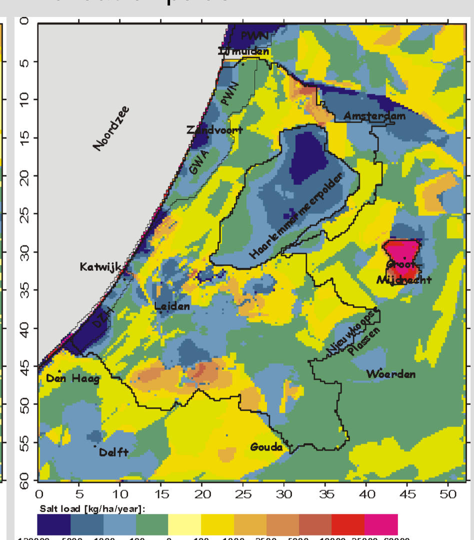
2. Rijnland model: Inundation Haarlemmermeerpolder

Calculated salt load on –10 m M.S.L.

Reference: present situation

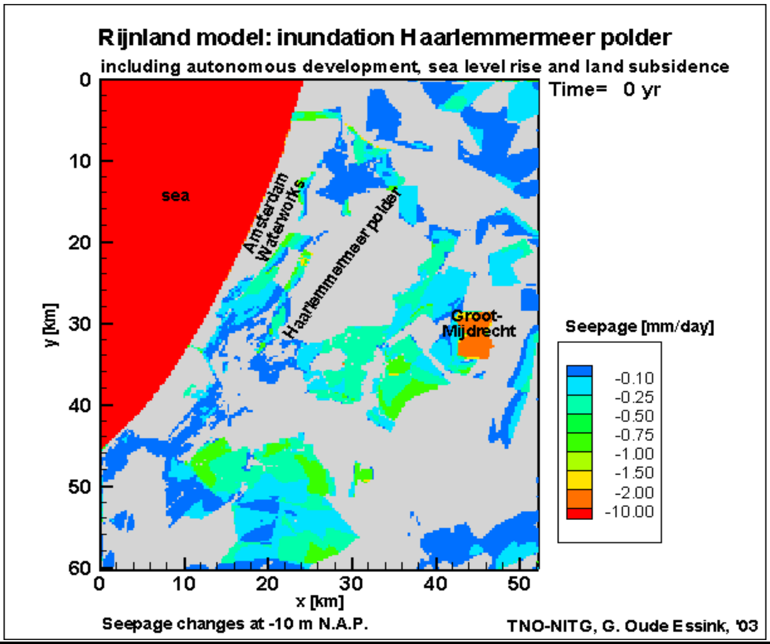


Inundation polder



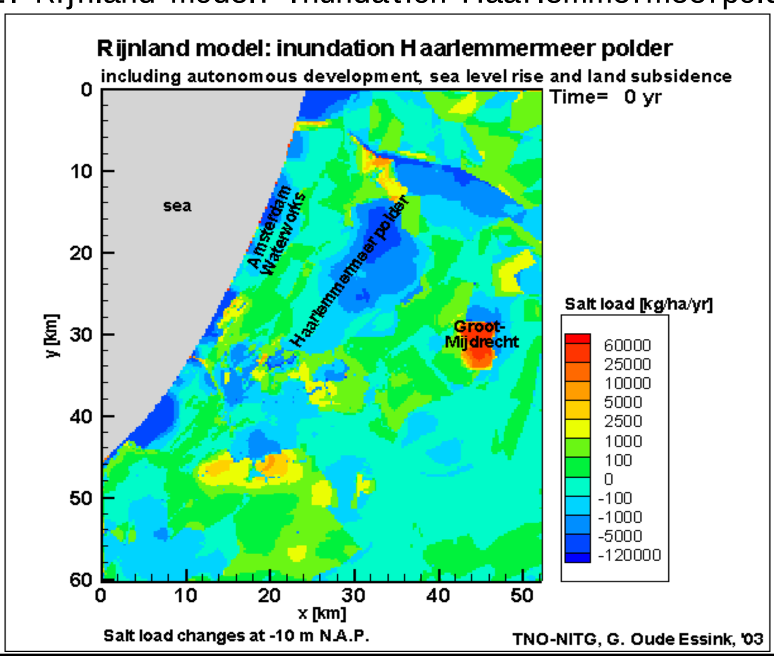
Rijnland

2. Rijnland model: Inundation Haarlemmermeerpolder

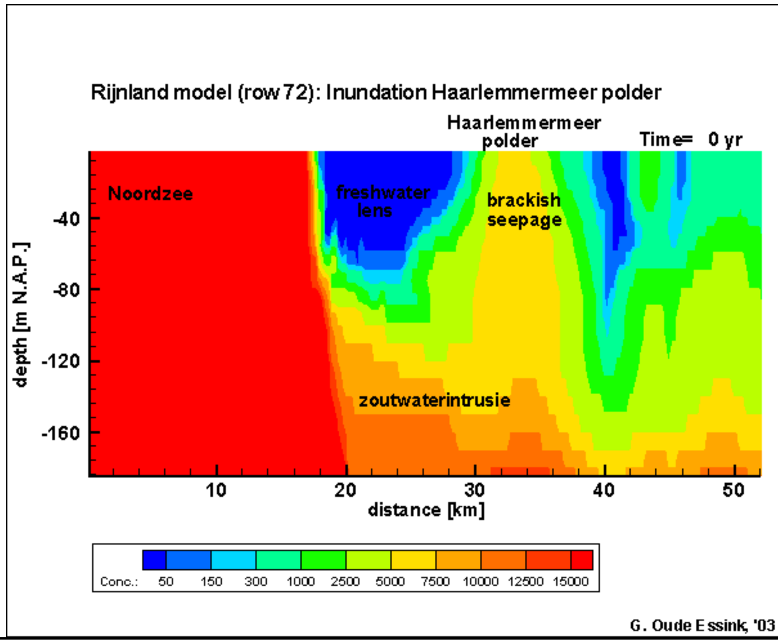


Rijnland

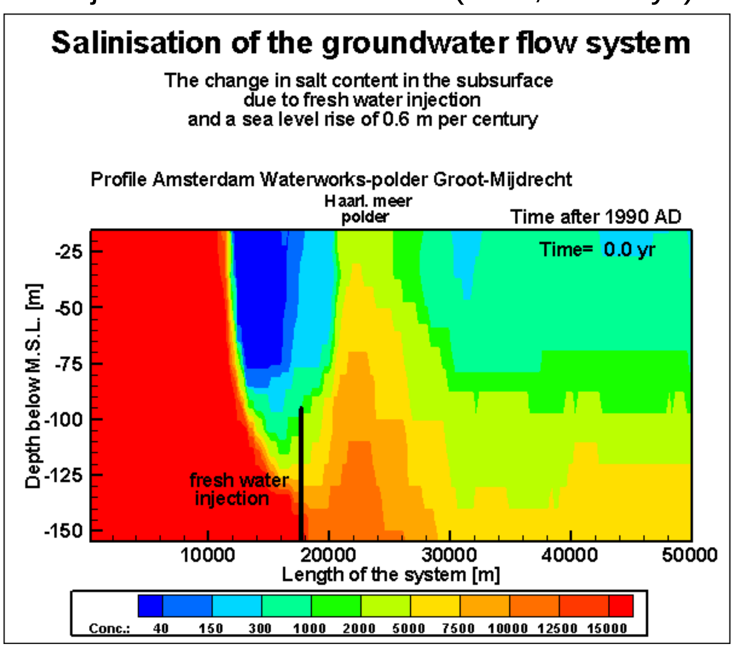
2. Rijnland model: Inundation Haarlemmermeerpolder



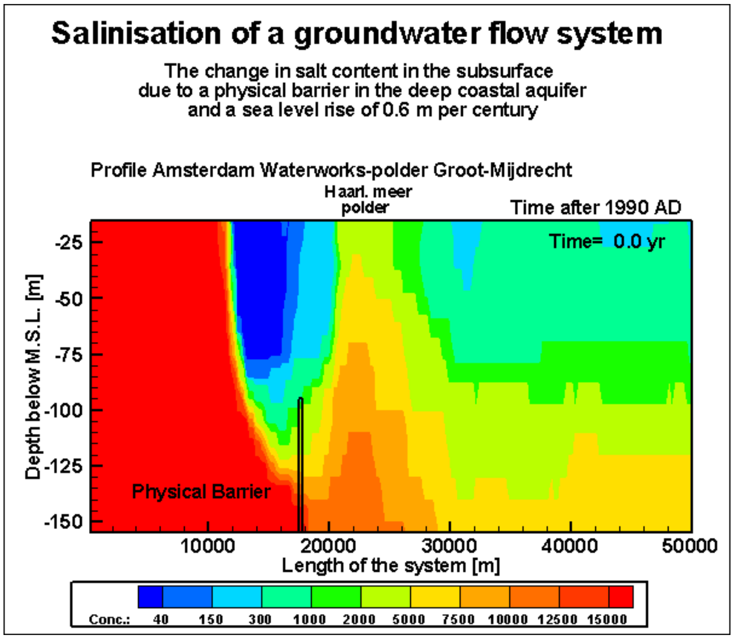
2. Rijnland model: Inundation Haarl.polder (conc, 500 jr)



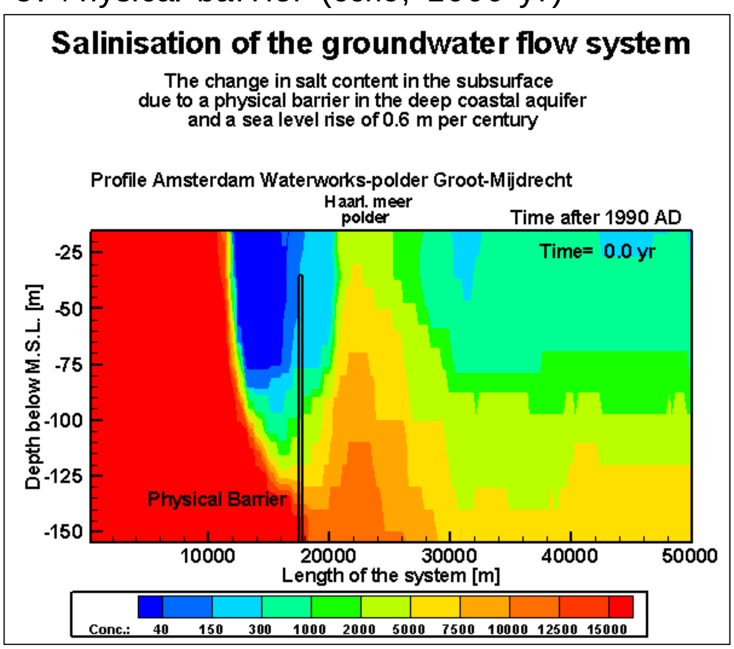
4. Injection of fresh water (conc, 1000 yr)



5. Physical barrier (conc, 1000 yr)



5. Physical barrier (conc, 1000 yr)



MOCDENS3D

MOCDENS3D is similar to SEAWAT

MOCDENS3D
non-steady 3D variable-density groundwater flow

- Genesis present salt-fresh distribution
- Upconing of saline groundwater under extraction wells
- Effects of land subsidence and climate change on groundwater systems

MOCDENS3D

MOCDENS3D = MOC3D (*Konikow et al.*, 1996)
but adapted for density differences

- density dependent groundwater flow
  - motion: Darcy
  - continuity: mass balance
- solute transport
  - advection
  - hydrodynamic dispersion: mixing of solutes
- fresh, brackish and saline groundwater
- relation between density & concentration

Solving the solute transport equetion

MOC particle tracking

Characteristics MOCDENS3D:

- integration of MODFLOW and MOC3D
- finite difference method for groundwater flow
- method of characteristics (particle tracking) for solute transport
- transient flow of groundwater

Advantage MOCDENS3D:

- no numerical problems if grid Peclet numbers are high
- large-scale geometries with limited number of elements are no problem

Method of Characteristics (MOC)

Solve the advection-dispersion equation (ADE) with the Method of Characteristics

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(CV_i) + \frac{(C - C)'W}{n_e}$$

Lagrangian approach:

Splitting up the advection part and the dispersion/source part:

- advection by means of a particle tracking technique
- dispersion/source by means of the finite difference method

Length flow time step

NOT EQUAL TO SOLUTE TIME STEP !

Stability criteria for solute transport equation (I)

1. Neumann criterion:

$$\frac{D_{xx}\Delta t_s}{\Delta x^2} + \frac{D_{yy}\Delta t_s}{\Delta y^2} + \frac{D_{zz}\Delta t_s}{\Delta z^2} \leq 0.5$$

$$\Delta t_s \leq \frac{0.5}{\frac{D_{xx}}{\Delta x^2} + \frac{D_{yy}}{\Delta y^2} + \frac{D_{zz}}{\Delta z^2}}$$

Stability criteria for solute transport equation (II)

2. Mixing criterion:

$$\Delta t_s \leq \frac{n_e b^k_{i,j,k}}{Q'_{i,j,k}}$$

Change in concentration in element is not allowed to be larger than the difference between the present concentration in the element and the concentration in the source

Stability criteria for solute transport equation (III)

3. Courant criterion:

$$0<\xi<=\sim 1$$

$$\Delta t_s \le \frac{\xi \Delta x}{V_{x,\max}} \qquad \Delta t_s \le \frac{\xi \Delta y}{V_{y,\max}} \qquad \Delta t_s \le \frac{\xi \Delta z}{V_{z,\max}}$$

Advantage of the MOC approach by splitting up the advection-dispersion equation

It is difficult to solve the whole advection-dispersion equation in one step, because the so-called Peclet-number is high in most groundwater flow/solute transport problems.

The Peclet number stands for the ratio between advection and dispersion

Procedure of MOC: advective transport by particle tracking

- Place a number of particles in each element
- Determine the effective velocity of each particle by (bi)linear interpolation of the velocity field which is derived from MODFLOW
- Move particles during one solute time step Δt_{solute}
- Average values of all particles in an element to one node value
- Calculate the change in concentration in all nodes due to advective transport
- Add this result to dispersive/source changes of solute transport

Steps in MOC-procedure

1. Determine concentration gradients at old timestep k-1
2. Move particles to model advective transport
3. Concentration of particles to concentration in element node
4. Determine concentration gradients on new timestep k*
5. Determine concentration in element node after advective, dispersive/source transport on timestep k

Konikow and Bredehoeft, 1978

Causes of errors in MOC-procedure

1. Concentration gradients

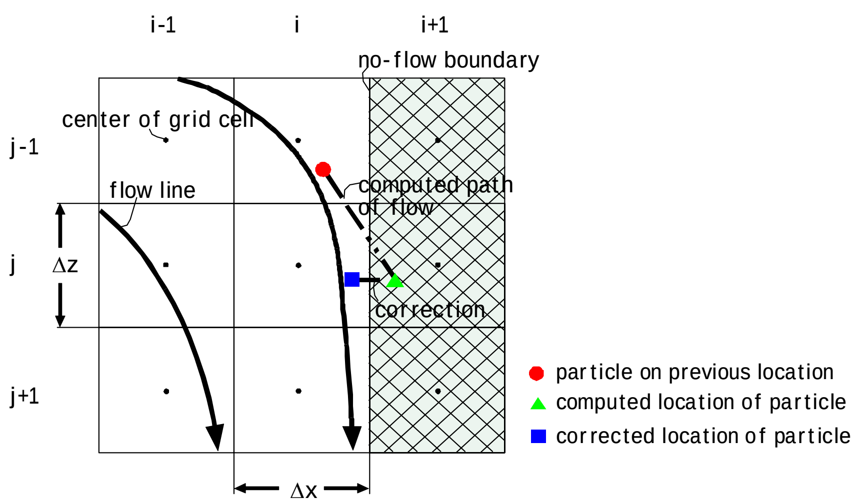
2. Average from particles to node element, and visa versa

3. Concentration of sources/sinks to entire element

4. Empty elements

5. No-flow boundary: reflection in boundary

Reflection in boundary



MOC3D

Stability criteria (III)

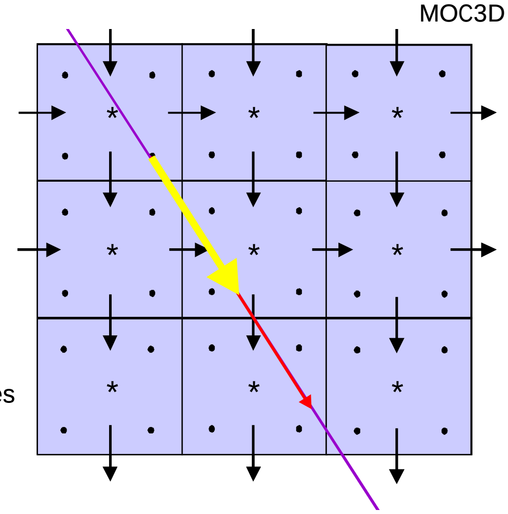
3. Courant criterium

* Node element

• Particle

Velocity direction

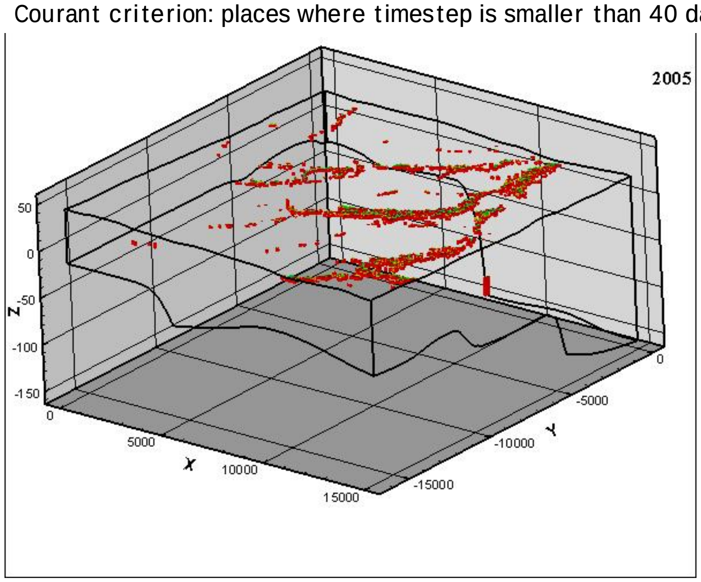
Movement particles



$0<\xi<=\sim 1$

$$\Delta t_s \le \frac{\xi \Delta x}{V_{x,\max}} \qquad \Delta t_s \le \frac{\xi \Delta y}{V_{y,\max}} \qquad \Delta t_s \le \frac{\xi \Delta z}{V_{z,\max}}$$

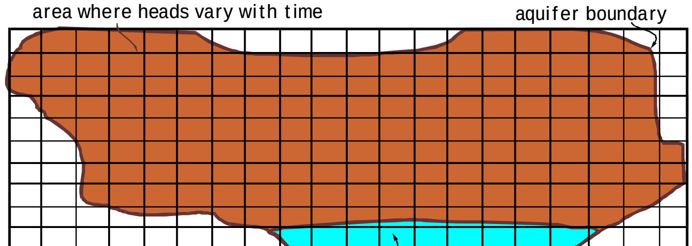
Courant criterion: places where timestep is smaller than 40 days



MODFLOW

Boundary conditions in MODFLOW (I)

Example of a system with three types of boundary conditions



Numeric model

0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0
0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	0

Boundary conditions in MODFLOW (II)

For a constant head condition: IBOUND<0
For a no flow condition: IBOUND=0
For a variable head: IBOUND>0

Packages in MODFLOW

1. Well package
2. River package
3. Recharge package
4. Drain package
5. Evaporation package
6. General head package

1. Well package

$$Q_{well} = Q_{i,j,k}$$

Example: an extraction of 10 m^3 per day should be inserted in an element as:

$$Q_{ext,i,j,k} = P_{i,j,k}\phi_{i,j,k}^{t+\Delta t} + Q'_{i,j,k}$$

$$Q_{ext,i,j,k} = -10$$ (in = positive)

$$Q'_{i,j,k} = -10$$

WEL

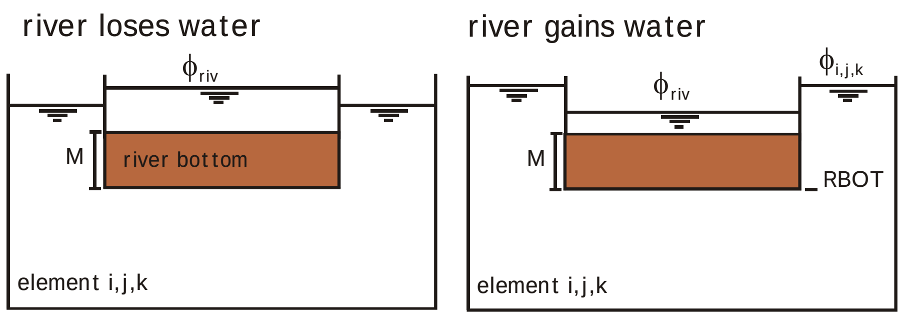
```
      2503          0    AUXILIARY CON  CBCALLOCATE MXWELL,IWELBD
      2503                ITMP (NWELLS)
       1       1       1    1.360       0.0
       1       1       2    1.360       0.0
       1       1       3    1.360       0.0
       1       1       4    1.360       0.0
       1       1       5    1.360       0.0
       1       1       6    1.360       0.0
       1       1       7    1.360       0.0
.
.
.
Number of Wells for this stress period
      -1
      -1
      -1
```

GHB

```
         5           0     AUXILIARY CONC CBCALLOCATE MXGHB,IGHBBD
         5                 ITMP (NGHB)
        1       3       1   5.000    10.0    100.0
        1       3       2   5.000    10.0    100.0
        1       3       3   5.000    10.0    100.0
        1       3       4   5.000    10.0    100.0
        1       3       5   5.000    10.0    100.0
.
.
.
number of ghb cells
      -1
         5                 ITMP (NGHB)
        1       3       1   2.500    10.0    100.0
        1       3       2   2.500    10.0    100.0
        1       3       3   2.500    10.0    100.0
        1       3       4   2.500    10.0    100.0
.
.
.
number of ghb cells
        1       3       5   2.500    10.0    100.0
      -1
```

MODFLOW

2. River package (I)



$$Q_{riv} = KLW\left(\frac{\phi_{riv} - \phi_{i,j,k}}{M}\right)$$

$$Q_{riv} = \frac{KLW}{M}\left(\phi_{riv} - \phi_{i,j,k}\right) \Leftrightarrow Q_{riv} = C_{riv}\left(\phi_{riv} - \phi_{i,j,k}\right)$$

2. River package (II)

$$Q_{riv} = C_{riv}\left(\phi_{riv} - \phi_{i,j,k}\right)$$

Example: the river conductance C_{riv} is 20 m^2/day and the rivel level=3 m, than this package should be inserted in an element as:

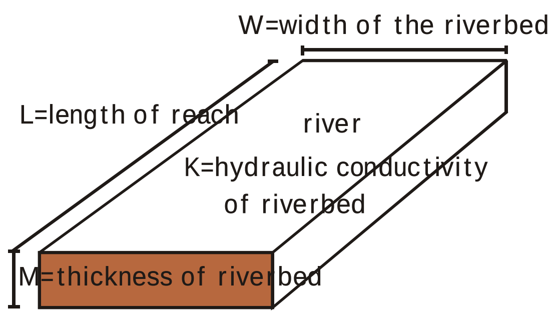
$$Q_{ext,i,j,k} = P_{i,j,k}\phi_{i,j,k}^{t+\Delta t} + Q'_{i,j,k}$$

$$Q_{ext,i,j,k} = 20\left(3 - \phi_{i,j,k}\right)$$

$$Q'_{i,j,k} = 60 \quad \text{and} \quad P_{i,j,k} = -20$$

2. River package (III)

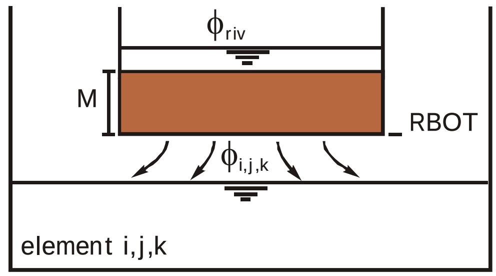
Determine the conductance of the river in one element:



where $C_{riv} = \dfrac{KLW}{M}$ is the conductance [L^2/T] of the river

2. River package (IV)

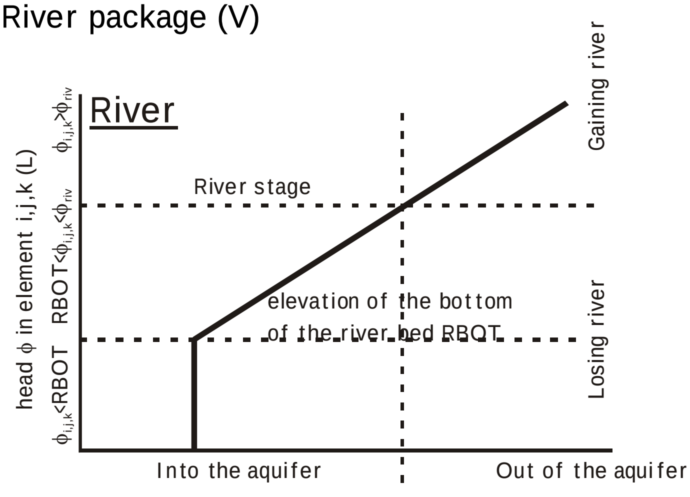
Leakage to the groundwater system



Special case:

if $\phi_{i,j,k}$<RBOT, then $Q_{riv} = C_{riv}(\phi_{riv} - RBOT)$

2. River package (V)



RIV

```
        5          0    AUXILIARY CONC CBCALLOCATE MXRIV,IWELBD
        5               ITMP (NRIVERS)
       1       3       1      2.00     10.00     -2.00    100.00
       1       3       2      2.00     10.00     -2.00    100.00
       1       3       3      2.00     10.00     -2.00    100.00
       1       3       4      2.00     10.00     -2.00    100.00
       1       3       5      2.00     10.00     -2.00    100.00
.
.
.
number of river cells
      -1
        5               ITMP (NRIVERS)
       1       3       1      2.00     10.00     -2.00    100.00
       1       3       2      2.00     10.00     -2.00    100.00
       1       3       3      2.00     10.00     -2.00    100.00
       1       3       4      2.00     10.00     -2.00    100.00
       1       3       5      2.00     10.00     -2.00    100.00
.
.
number of river cells
      -1
```

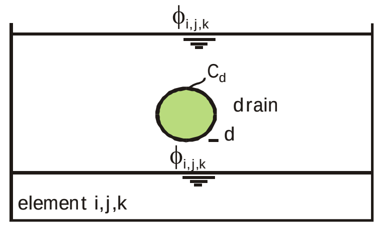

3. Recharge package

$$Q_{rec} = I\Delta x\Delta y$$

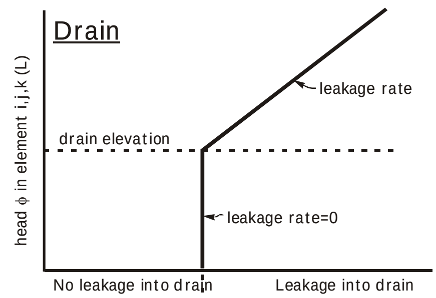
4. Drain package

$$Q_{drn} = C_{drn}\left(\phi_{i,j,k} - d\right)$$

Special case: →



if $\phi_{i,j,k} < d$ than $Q_{drn} = 0$

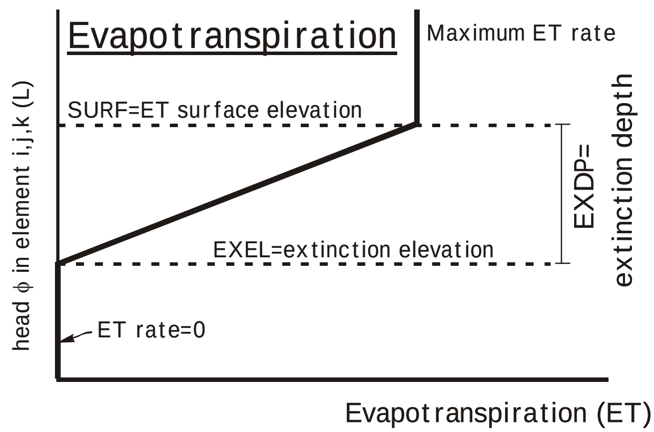


Leakage into a drain

DRN

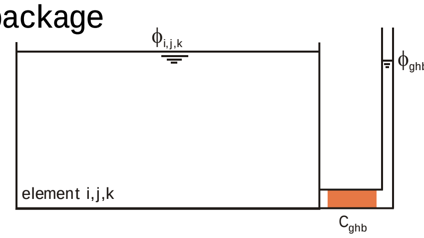
```
         5          0    AUXILIARY CONC CBCALLOCATE MXDRAIN,IDRNBD
         5               ITMP (NDRAIN)
        1       3       1  -1.000    10.0    100.0
        1       3       2  -1.000    10.0    100.0
        1       3       3  -1.000    10.0    100.0
        1       3       4  -1.000    10.0    100.0
        1       3       5  -1.000    10.0    100.0
 .
 .
 .
number of drainage cells
       -1
         5               ITMP (NDRAIN)
        1       3       1  -1.000    10.0    100.0
        1       3       2  -1.000    10.0    100.0
        1       3       3  -1.000    10.0    100.0
        1       3       4  -1.000    10.0    100.0
        1       3       5  -1.000    10.0    100.0
 .
 .
 .
number of drainage cells
       -1
```

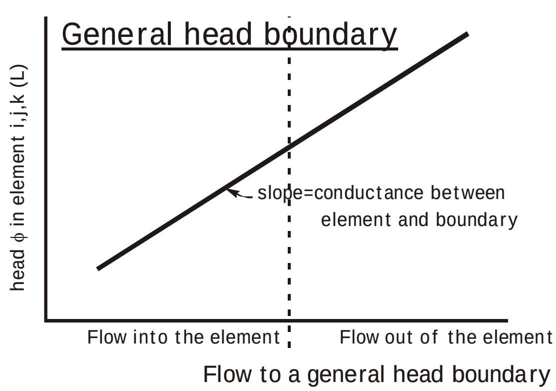
5. Evapotranspiration package

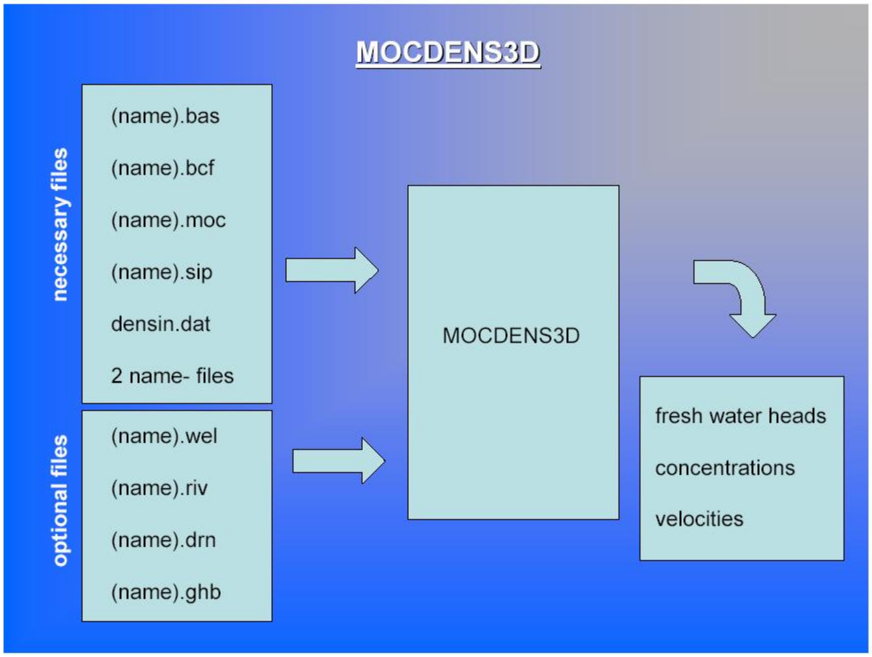


6. General head boundary package

$$Q_{ghb} = C_{ghb}\left(\phi_{ghb} - \phi_{i,j,k}\right)$$







1 (name).bas-file
2 (name).bcf-file
3 (name).moc-file
4 (name).wel-file
5 (name).riv-file
6 (name).drn-file
7 (name).ghb-file
8 (name).sip-file
9 densin.dat-file
10 (name).nam-files

INFILE.NAM

```
List  16 flow.out
BAS   95 test.bas
BCF   11 test.bcf
SIP   19 test.sip
WEL   66 test.wel
CONC  33 test_moc.nam
```

TEST_MOC.NAM

```
clst    94 test.out
moc     96 test.moc
oba     45 test.oba
data    44 test.obs
```

BAS

```
basic grid example
      NLAY      NROW      NCOL      NPER    ITMUNI
         4        50        50         4         4
FREE
         0         1      ; IAPART,ISTRT
        95         1(50I2)                          3   ; IBOUND 1
-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1 … NCOL
.
.
.
NROW
Repeated for every layer
    9999.00                                      ; HNOFLO
        95         1(50F7.2)                1   ; HEAD 1
4.50   4.50   4.50   4.50   … NCOL
.
.
.
NROW
Repeated for every layer
 100.00        10         1     PERLEN, NSTP,TSMULTI
 100.00        10         1     PERLEN, NSTP,TSMULTI
 100.00        10         1     PERLEN, NSTP,TSMULTI
 100.00        10         1     PERLEN, NSTP,TSMULTI
```

BCF

```
              1         0 0.0 0 0.0 0 0   ISS,IBCFBD     BCF Input
0 0 0 0  LAYCON
         0         1 TRPY
         0     20.0 DELR
         0     20.0 DELC
         0   10.000 TRAN 1
         0    0.0020 VERT/THCK 1
         0    0.500 TRAN 2
         0    0.0020 VERT/THCK 2
         0   15.000 TRAN 3
         0    0.0300 VERT/THCK 3
         0   25.000 TRAN 4
```

BCF

```
              1         0 0.0 0 0.0 0 0   ISS,IBCFBD     BCF Input
0 0 0 0  LAYCON
         0         1 TRPY
         0     20.0 DELR
         0     20.0 DELC
        11       1.0  (50F6.2)                      1    ; TRAN 1
 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 … NCOL
.
.
.
NROW
        11       1.0  (50F7.4)                      1    ; VERT/THCK 1
 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 … NCOL
.
.
.
NROW
Repeated for every layer
```

BCF

```
              0         0 0.0 0 0.0 0 0   ISS,IBCFBD     BCF Input
0 0 0 0  LAYCON
         0         1 TRPY
         0     20.0 DELR
         0     20.0 DELC
         0 0.002000 SF 1
         0   10.000 TRAN 1
         0    0.0020 VERT/THCK 1
         0 0.005000 SF 2
         0    0.500 TRAN 2
         0    0.0020 VERT/THCK 2
         0 0.000100 SF 3
         0   15.000 TRAN 3
         0    0.0300 VERT/THCK 3
         0 0.000100 SF 4
         0   25.000 TRAN 4
```

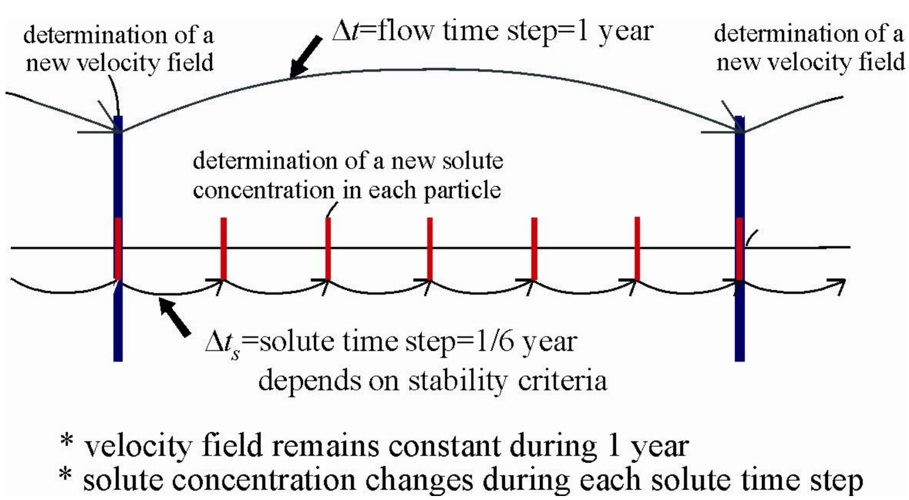
BCF

```
               0         0 0.0 0 0.0 0 0   ISS,IBCFBD     BCF Input
0 0 0 0  LAYCON
         0         1 TRPY
         0     20.0 DELR
         0     20.0 DELC
        11 1.000000  (50F9.6)                      1    ; SF 1
 0.002000 0.002000 0.002000 0.002000 0.002000 0.002000 0.002000 0.002000 … NCOL
.
.
.
NROW
        11       1.0  (50F6.2)                      1    ; TRAN 1
 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 … NCOL
.
.
.
NROW
        11       1.0  (50F7.4)                      1    ; VERT/THCK 1
 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 0.0020 … NCOL
.
.
.
NROW
Repeated for every layer
```

Time indication MODFLOW

ITMUNI=1: seconde
ITMUNI=2: minute
ITMUNI=3: hour
ITMUNI=4: day
ITMUNI=5: year

Flow time step and solute time step



MOC (1/2)

```
moc basic grid example

       1       4       1       50       1      50 ISLAY1  ISLAY2  ISROW1 ISROW2
       0       0       0 NODISP  DECAY   DIFFUSION
       0       8 NPMAX   NPTPND
     0.6    0.05       2 CELDIS  FZERO   INTRPL
       0       3       0       8        0       8      -1 NPNTCL  ICONFM … IVELFM
  -9999 CNOFLOW
        96       1.0(50F9.2)                      1    ; CONC  1
     0.00     0.00     0.00     0.00     0.00     0.00     0.00 … NCOL
.
.
.
NROW
Repeated for every layer
       1 NZONES
        -1       0.0
         0         1                              ; IGENPT 1
         0         1                              ; IGENPT 2
         0         1                              ; IGENPT 3
         0         1                              ; IGENPT 4
         0      0.50                              ; ALONG
         0     0.050                              ; ATRANH
         0     0.005                              ; ATRANV
         0     1.000                               RF1
         0       5.0                               THICK 1
         0      0.38                               POR 1
         0       5.0                               THICK 2
```

MOC (2/2)

```
Repeated for every layer
       1 NZONES
        -1       0.0
         0         1                              ; IGENPT 1
         0         1                              ; IGENPT 2
         0         1                              ; IGENPT 3
         0         1                              ; IGENPT 4
         0      0.50                              ; ALONG
         0     0.050                              ; ATRANH
         0     0.005                              ; ATRANV
         0     1.000                               RF1
         0       5.0                               THICK 1
         0      0.38                               POR 1
         0       5.0                               THICK 2
         0      0.38                               POR 2
         0       5.0                               THICK 3
         0      0.38                               POR 3
         0       5.0                               THICK 4
         0      0.38                               POR 4
```

DENSIN.DAT

```
  30000.0     0.020    CONCD    DVCONC
    0.0    32.5     175     500    1000    2700    CONC.COLORS FOR FILM-OPTION
   5000    7500   10000   15000   20000   27000    CONC.COLORS FOR FILM-OPTION
```