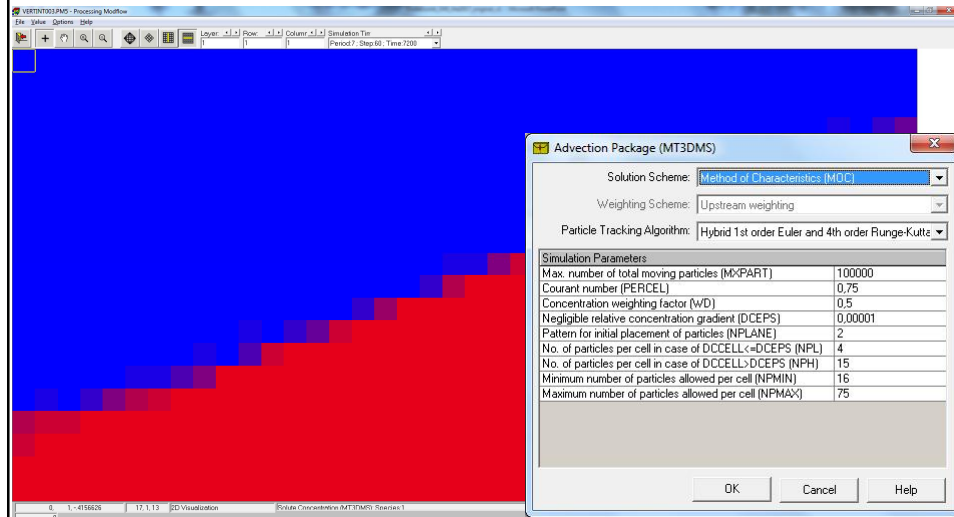
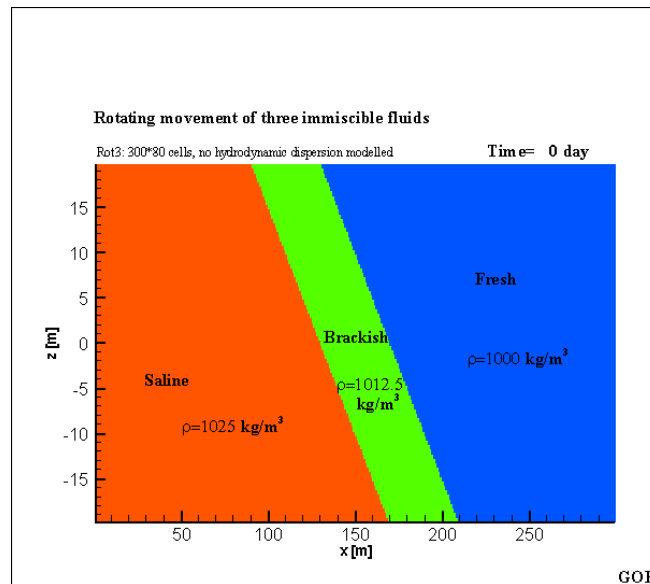


# MOC

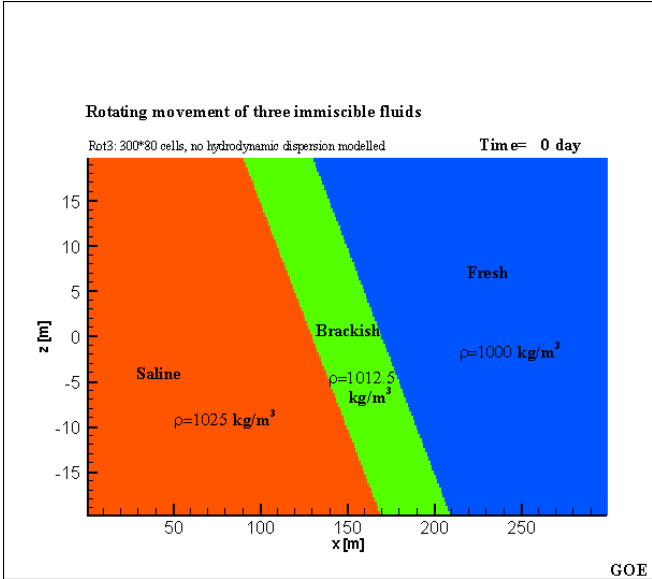


cases

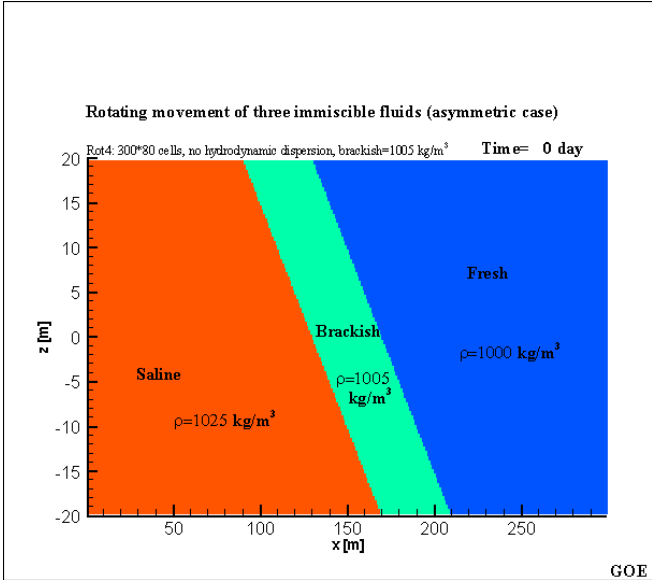
## Rotating immiscible interfaces



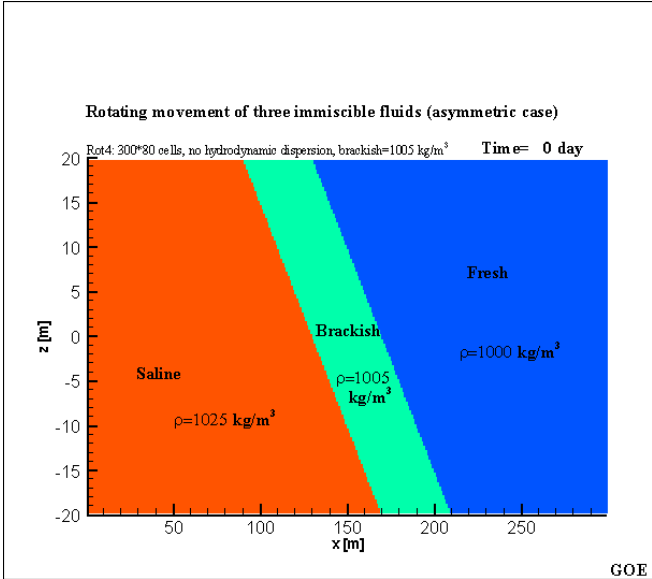
### Rotating immiscible interfaces



### Rotating immiscible interfaces (asymmetric)

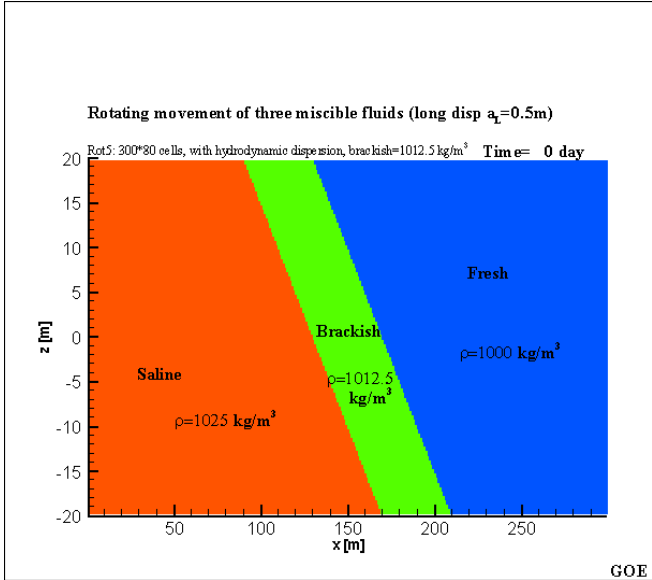


### Rotating immiscible interfaces (asymmetric)

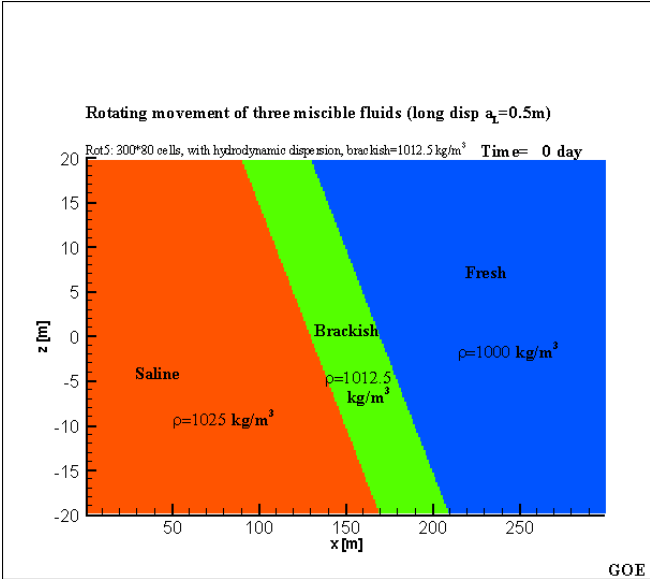


Bakker, M., Oude Essink, G.H.P. & Langevin, C. 2004. The rotating movement of three immiscible fluids. J. of Hydrology 287, 270-278

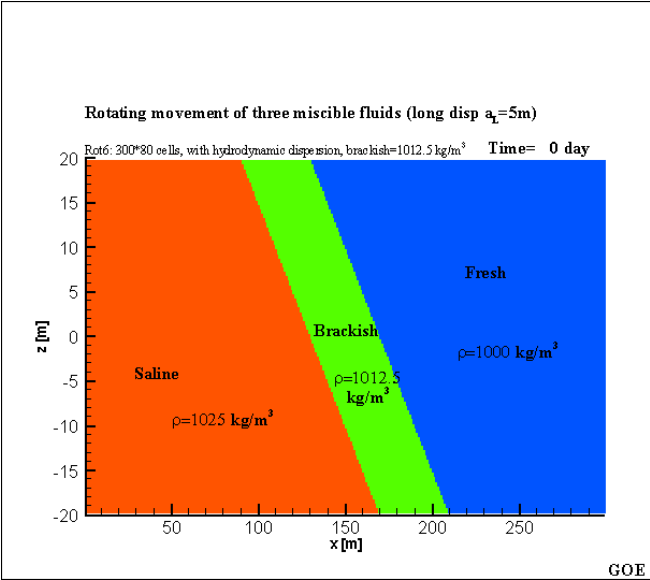
### Rotating interfaces with dispersion $\alpha_L=0.5m$



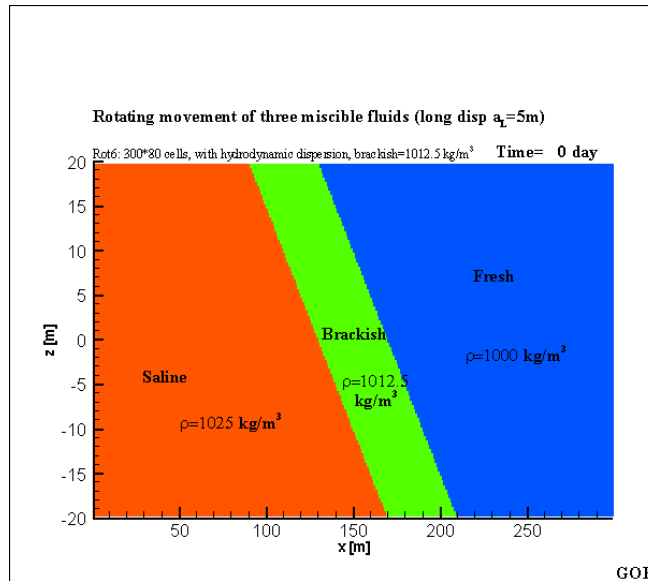
### Rotating interfaces with dispersion $\alpha_L=0.5m$



### Rotating interfaces with dispersion $\alpha_L=5m$



## Rotating interfaces with dispersion $\alpha_L=5m$



## Rotating immiscible interfaces

### Conclusion:

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

## Salt water pocket in a fresh environment

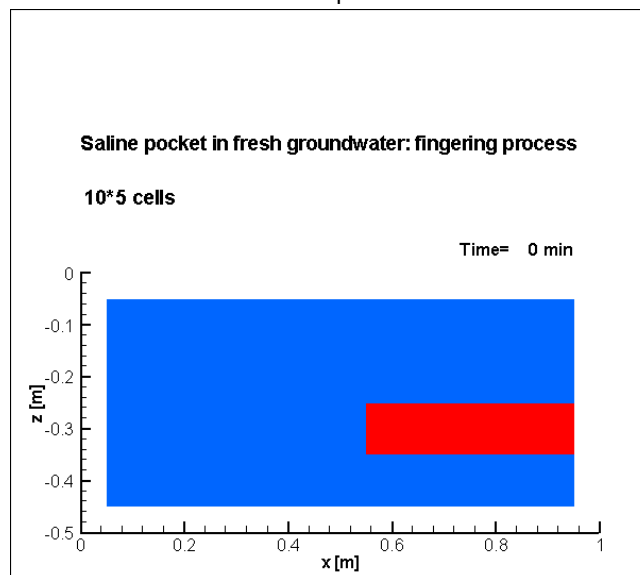
Grid convergence

Time step

## Salt water pocket in a fresh environment (I)

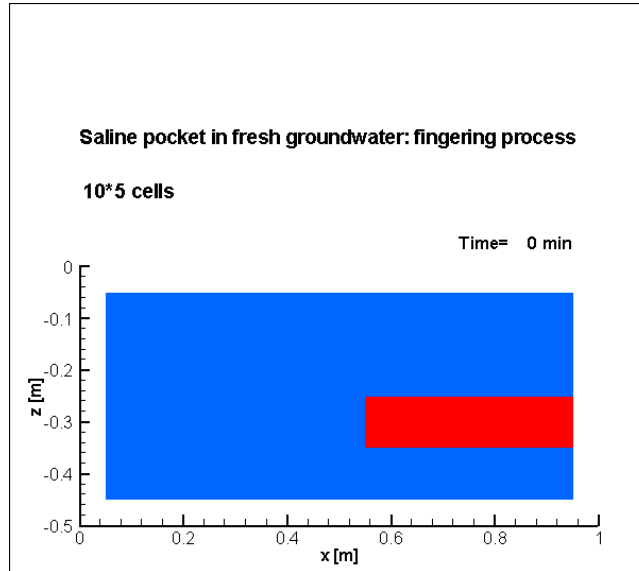
cases

Effect of discretisation on a 'salt lake problem'



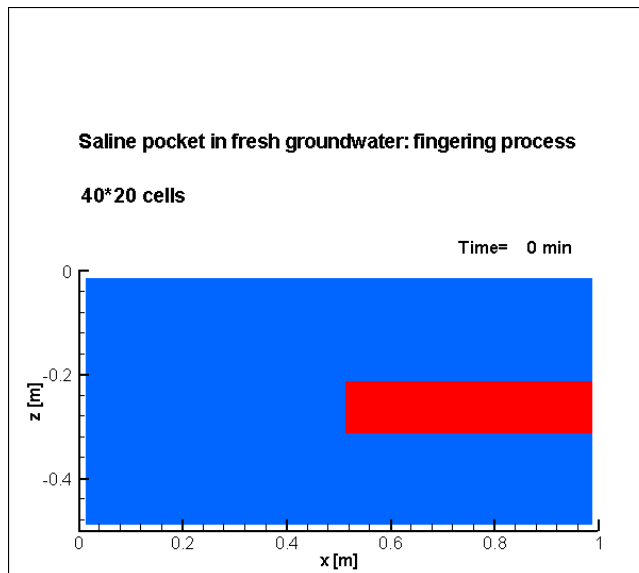
## Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



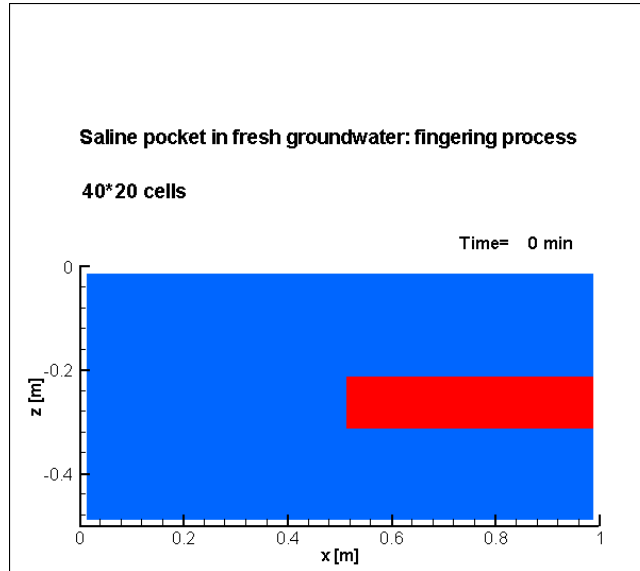
## Salt water pocket in a fresh environment (II)

Effect of discretisation



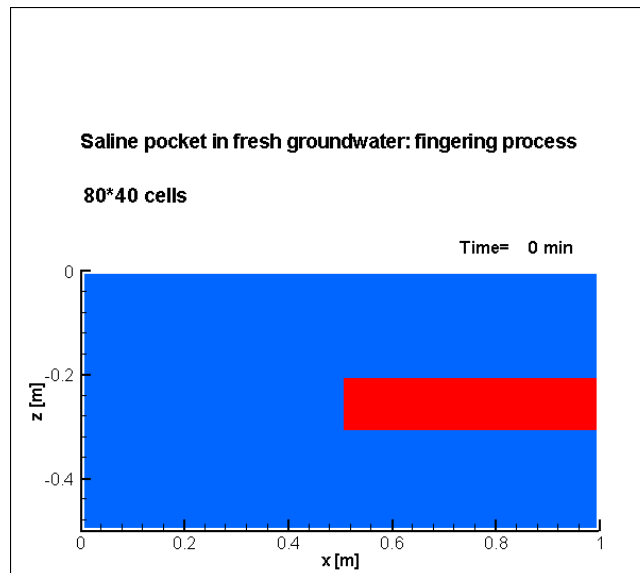
## Salt water pocket in a fresh environment (II)

Effect of discretisation



## Salt water pocket in a fresh environment (III)

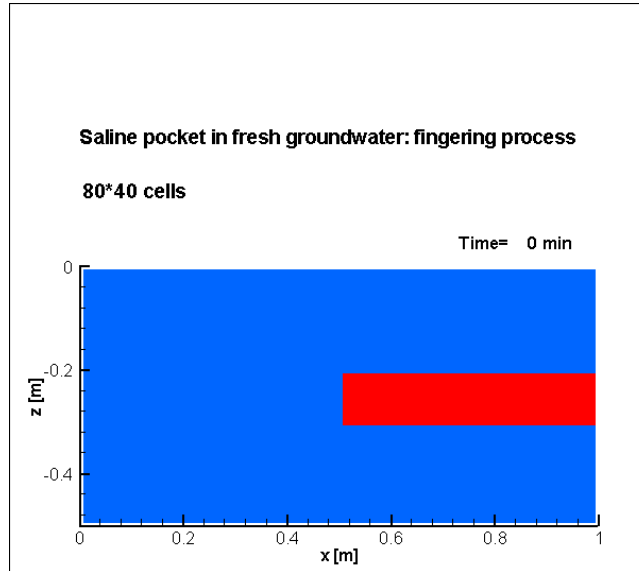
Effect of discretisation





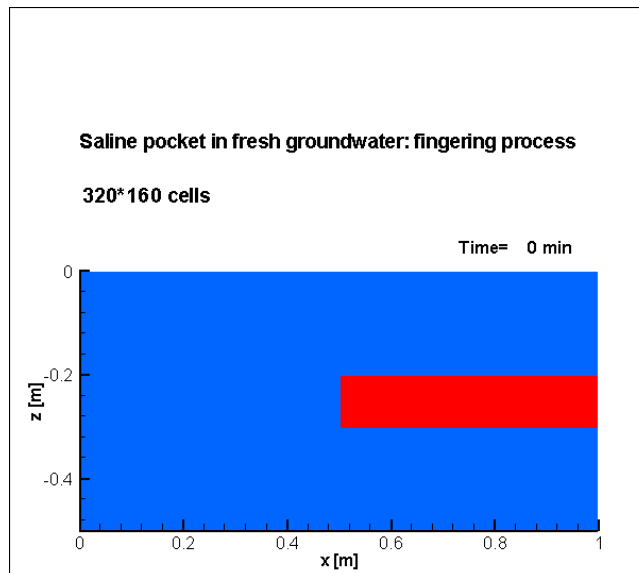
### Salt water pocket in a fresh environment (III)

Effect of discretisation



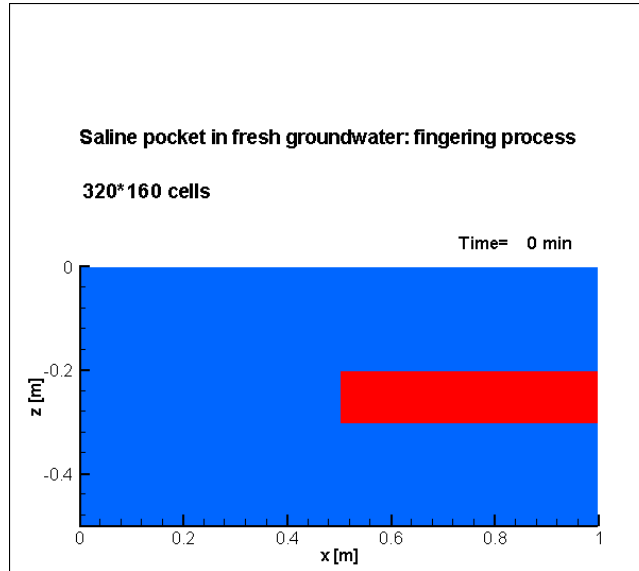
### Salt water pocket in a fresh environment (IV)

Effect of discretisation



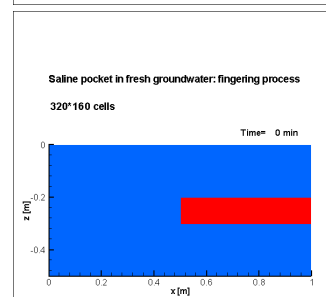
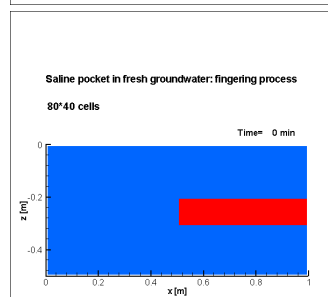
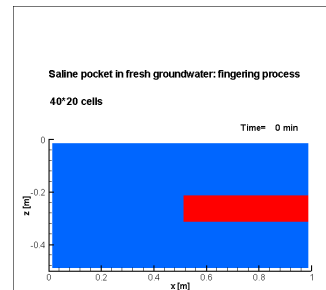
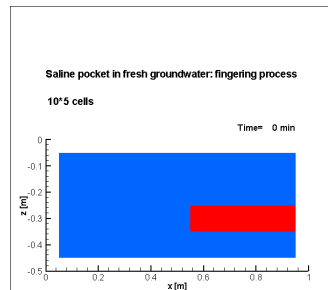
## Salt water pocket in a fresh environment (IV)

Effect of discretisation

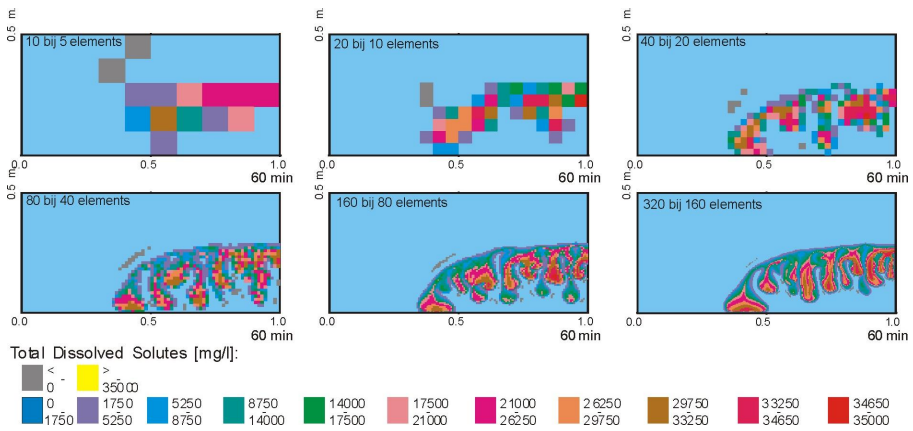


## Salt water pocket in a fresh environment (V)

Effect of discretisation

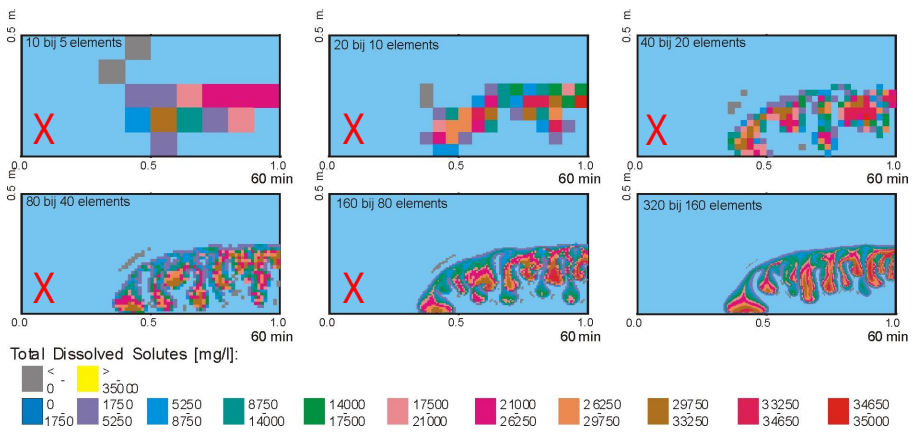


### Effect of size model cell on physical process



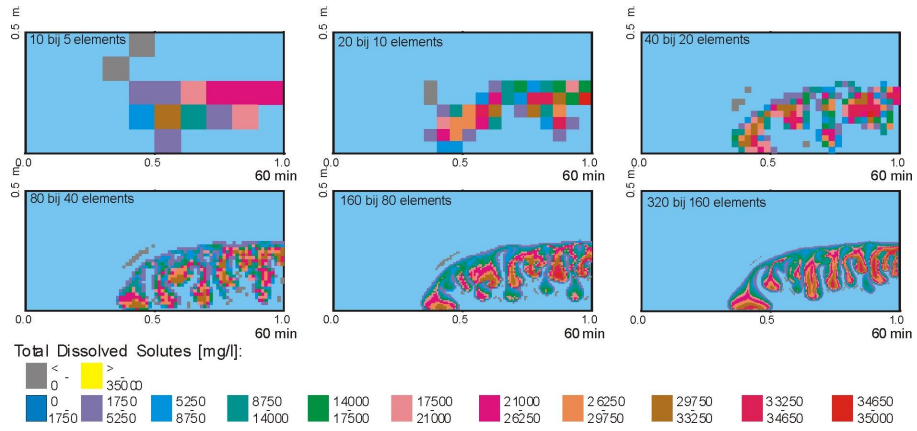
Size of cell has a large effect on modelling result!

### Effect of size model cell on physical process



X= LOUSY models for predicting exact number of salt water fingers

## Effect of size model cell on physical process



**BUT: all models are GOOD for predicting the moment of touching the base!**

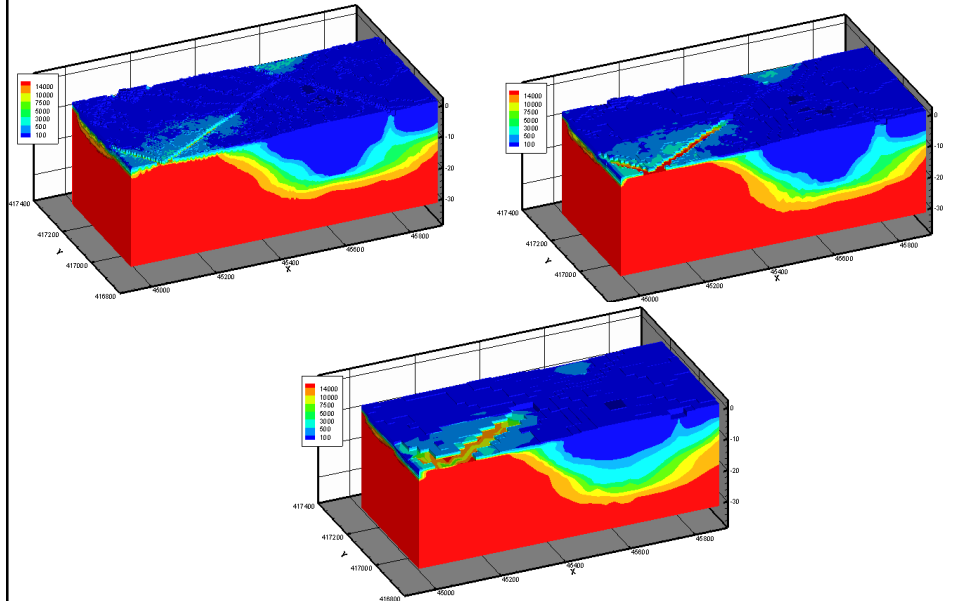
cases

## Salt water pocket in a fresh environment (VI)

### Conclusion:

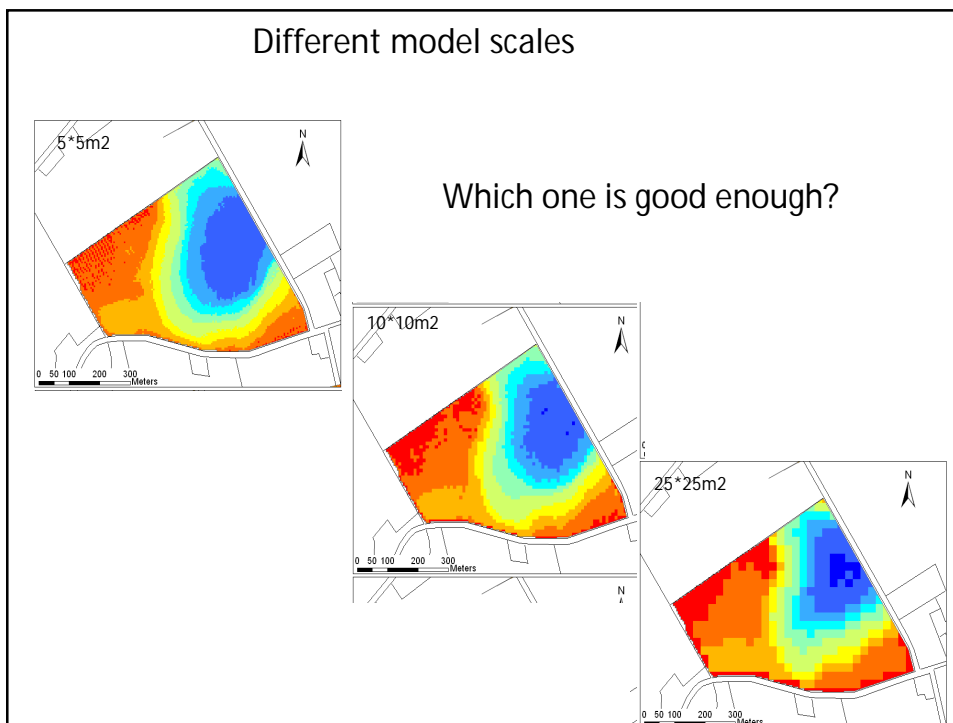
- For some physical processes, a large number of cells is necessary
- Check always grid convergence!

### Different model scales: 5, 10, 25m2

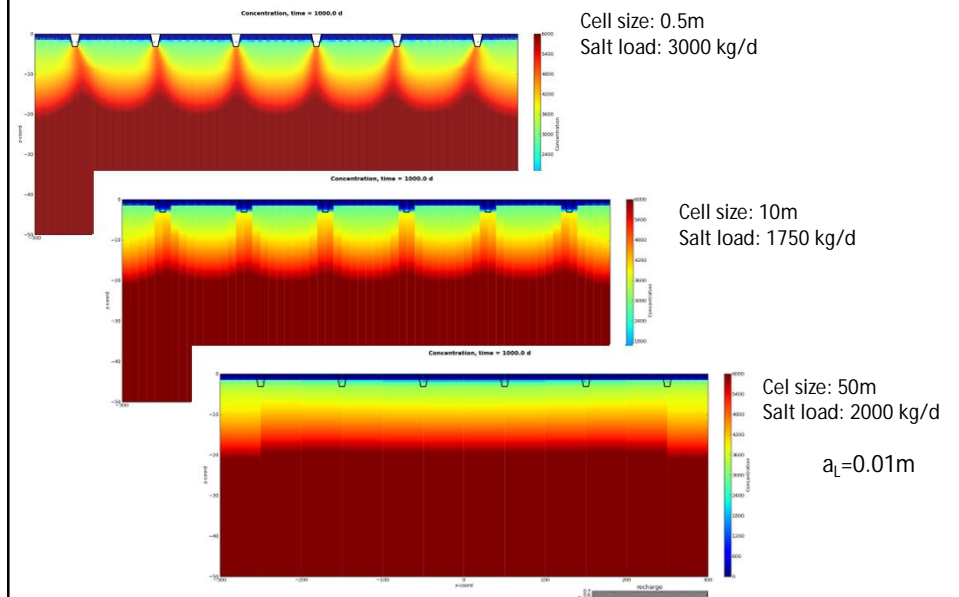


### Different model scales

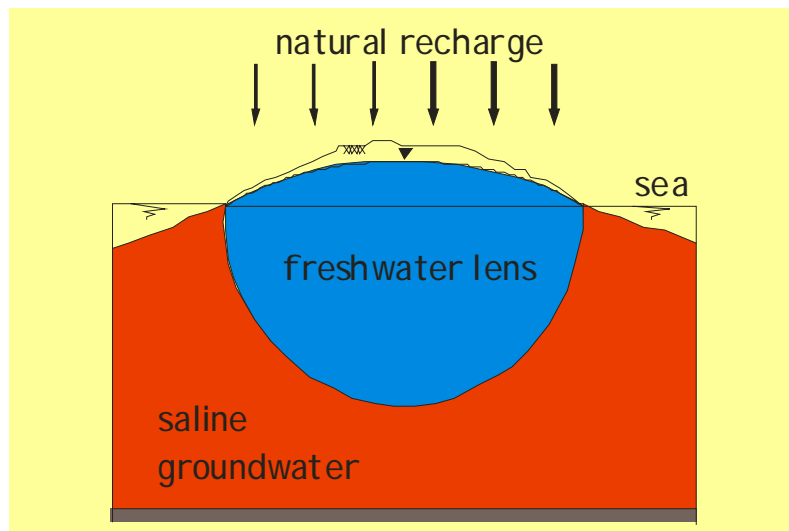
Which one is good enough?



## Upscaling issues: upconing under ditch



## Evolution of a freshwater lens



## 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

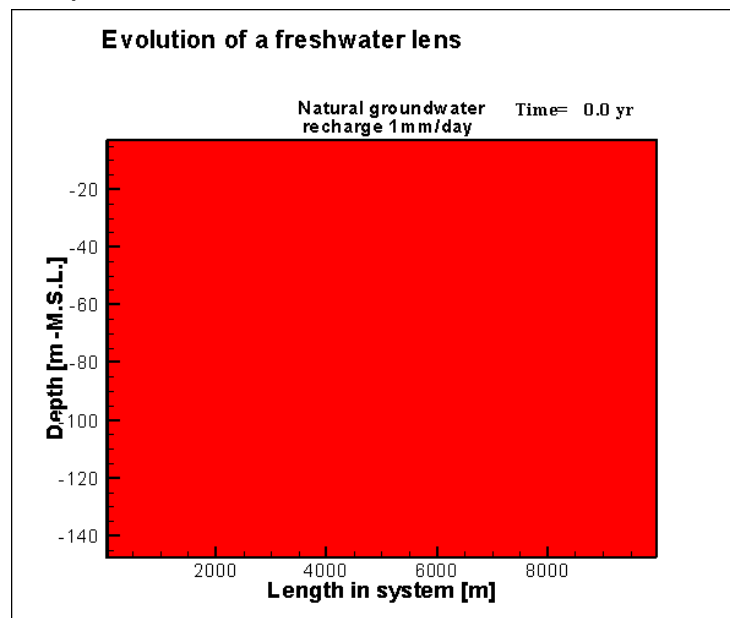
T = time period before the lens has reached 95% of its final form

In the Netherlands: T = 75-200 jaar,

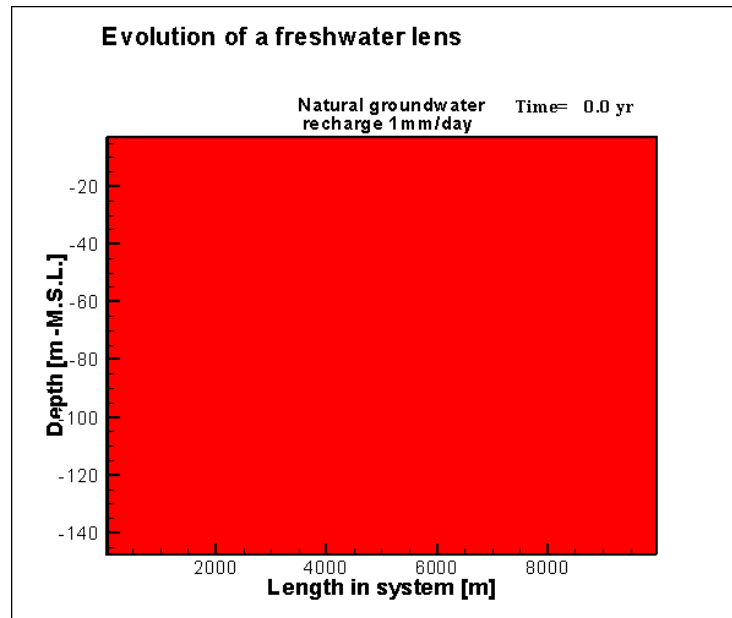
depends on:

- width dune area
- natural groundwater recharge
- hydraulic conductivity soil

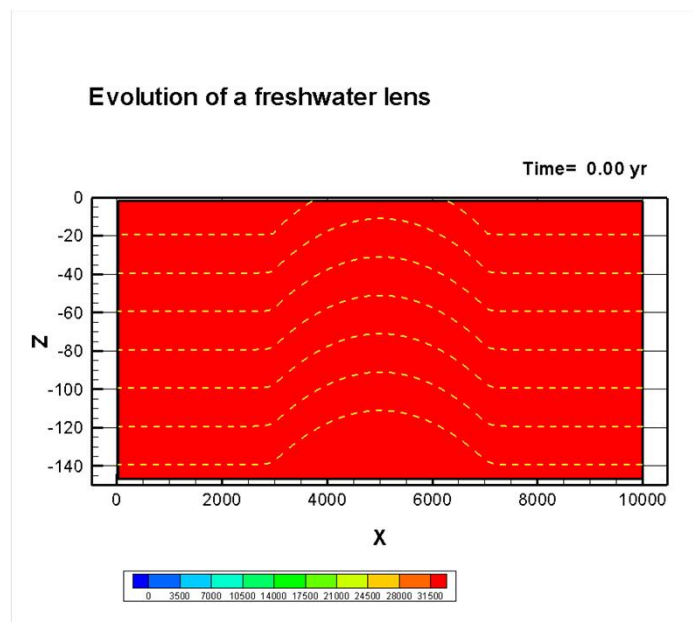
## Concept: evolution freshwater lens (not Griend!)



Concept: evolution freshwater lens (not Griend!)

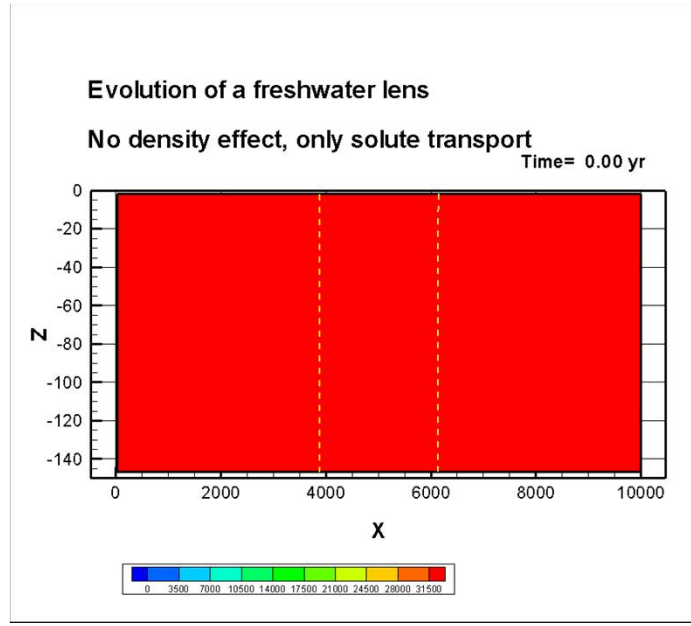


Evolution freshwater lens

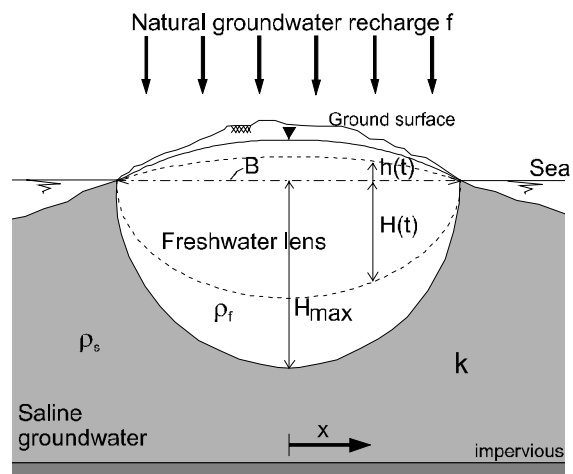




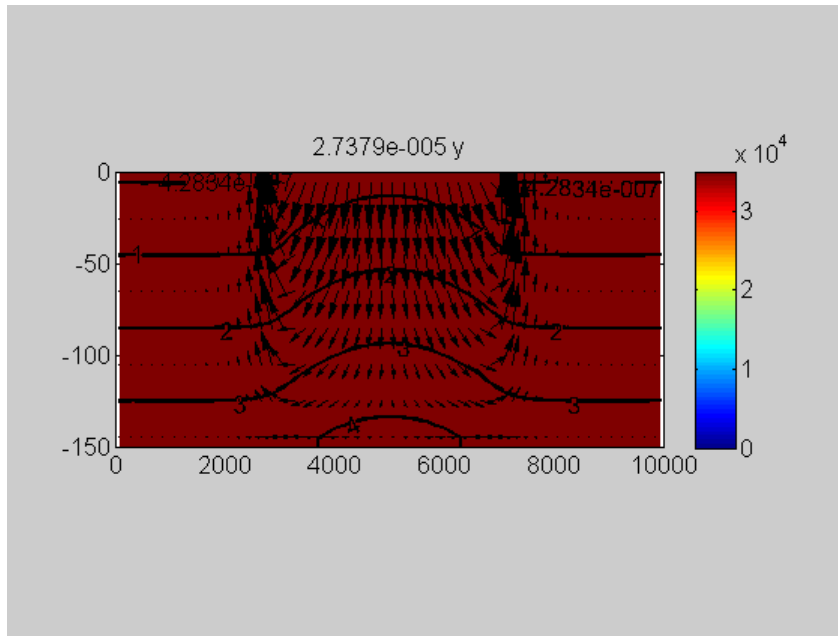
## Evolution freshwater lens: no density effects



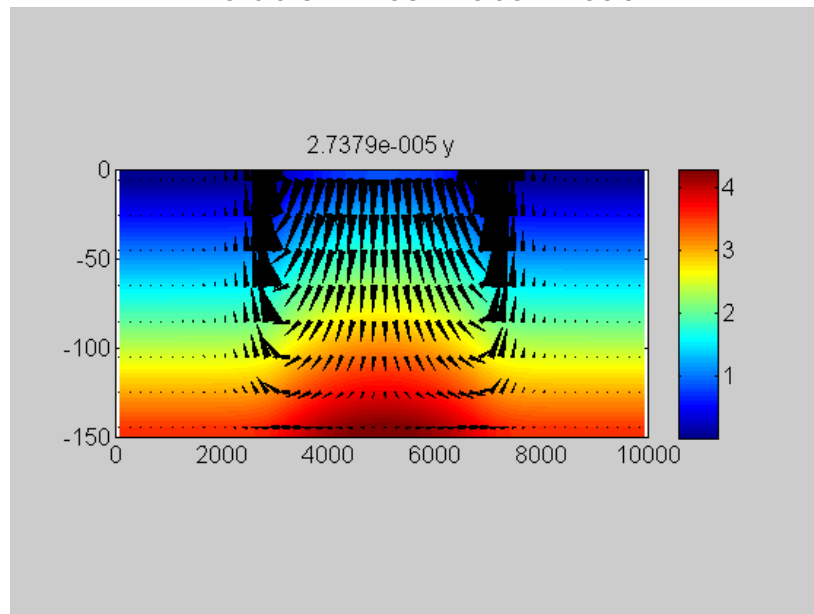
## Case 2: Development of a freshwater lens



### Evolution lens



### Evolution freshwater head



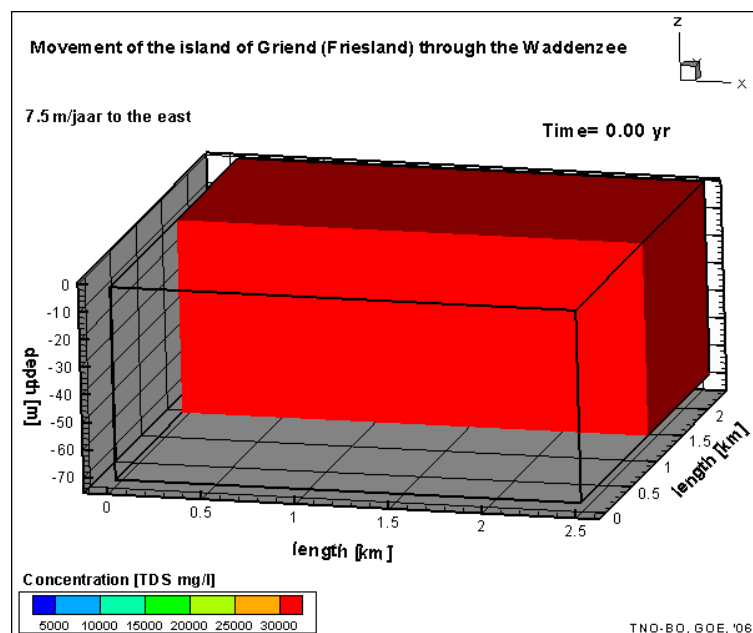
## The island of Griend

Issues:

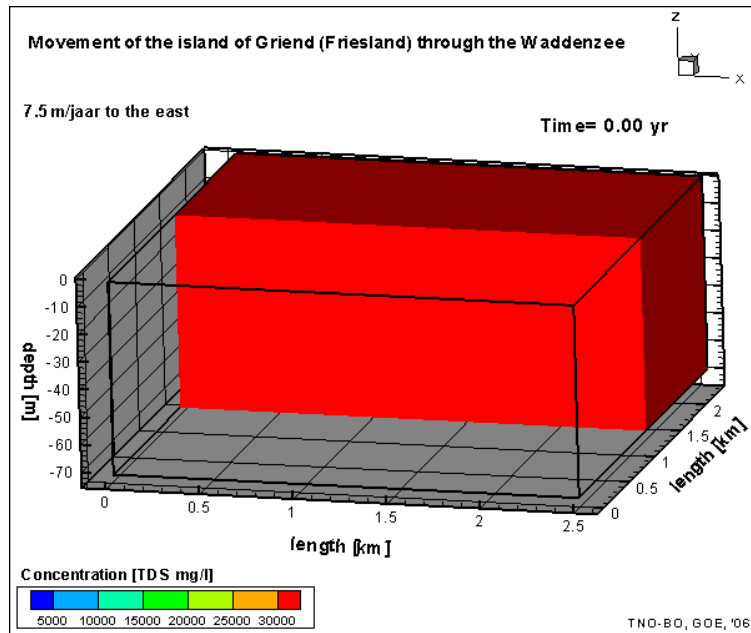
1. Small island moves ~7.5m per year to the east
2. Effect on the volume of the freshwater lens:
  - Can a lens be developed?
  - What is the thickness of the lens?



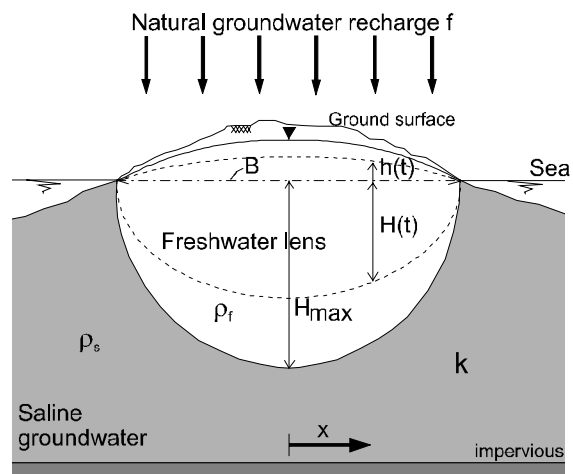
## Movement of De Griend and creation of the lens



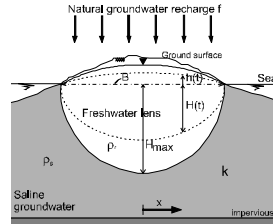
## Movement of De Griend and creation of the lens



## Case 2: Development of a freshwater lens



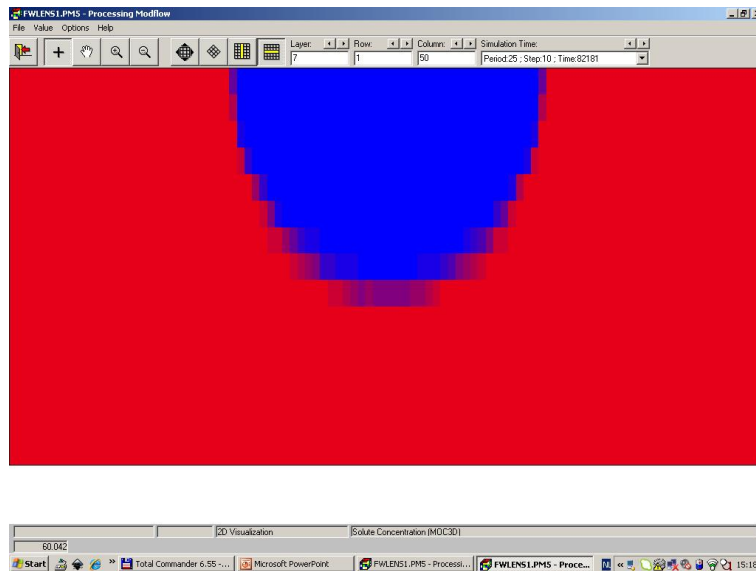
## Case 2: Development of a freshwater lens



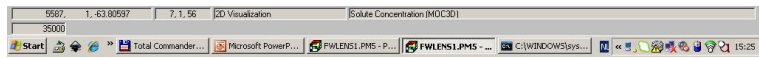
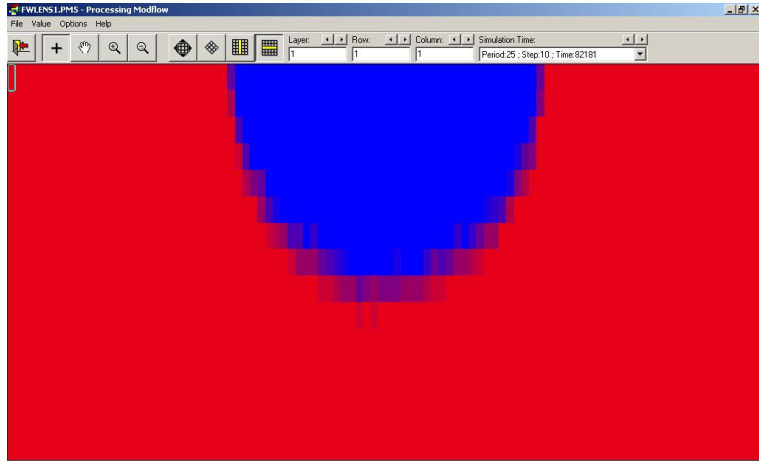
### Parameters

Layers	15	$K_{hor}$	20 m/d
Rows	1	T	200 m/d
Columns	100	Anisotropy $K_{hor}/K_{ver}$	10
$\Delta x$	100 m	ne	0.35
$\Delta y$	10 m	$\alpha L$	0 m
$\Delta z$	10 m	$\alpha T$	0 m
Stress periods	10	recharge	360 mm/y
Initial concentration	35000 mg/l	Recharge concentration	0 mg/l
bouyancy	0.025		

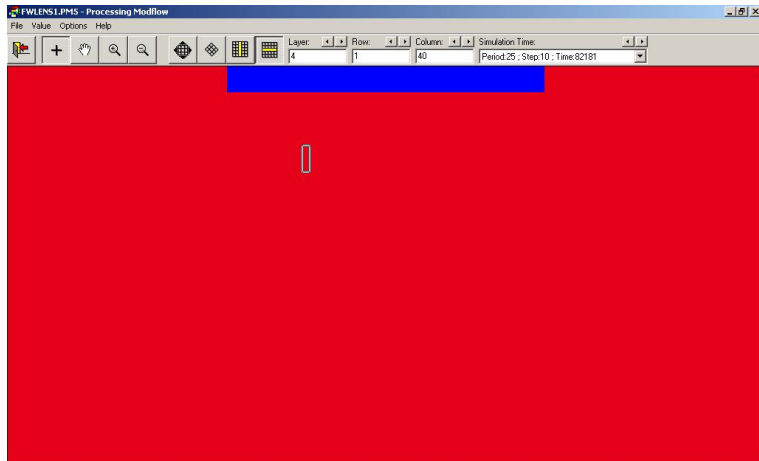
## MOC3D, no disp, 16part



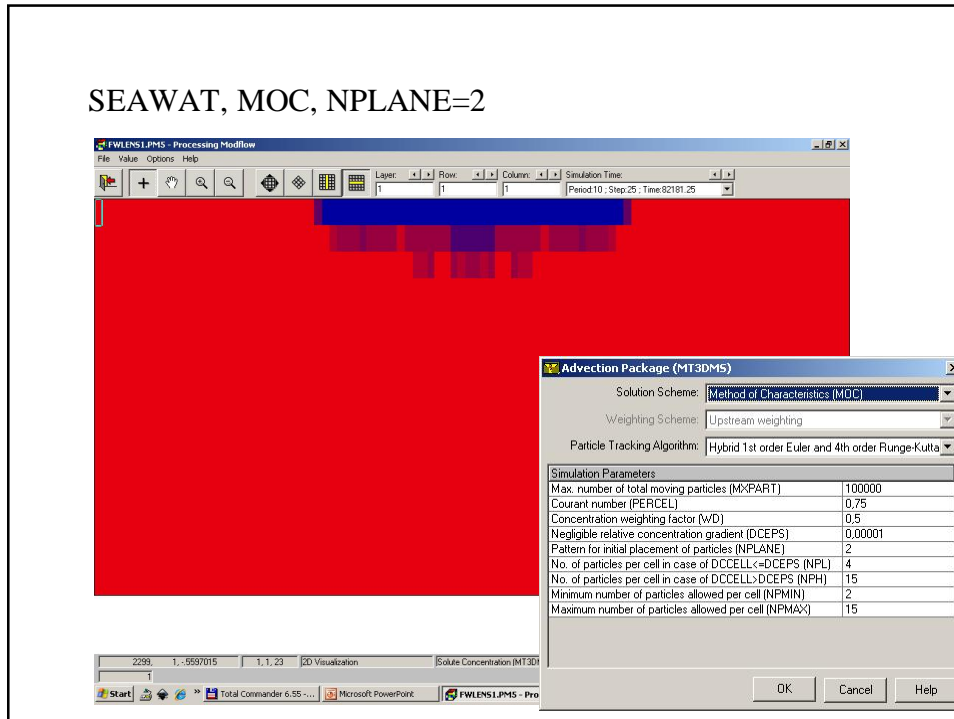
### MOCDENS3D, no disp, 4part



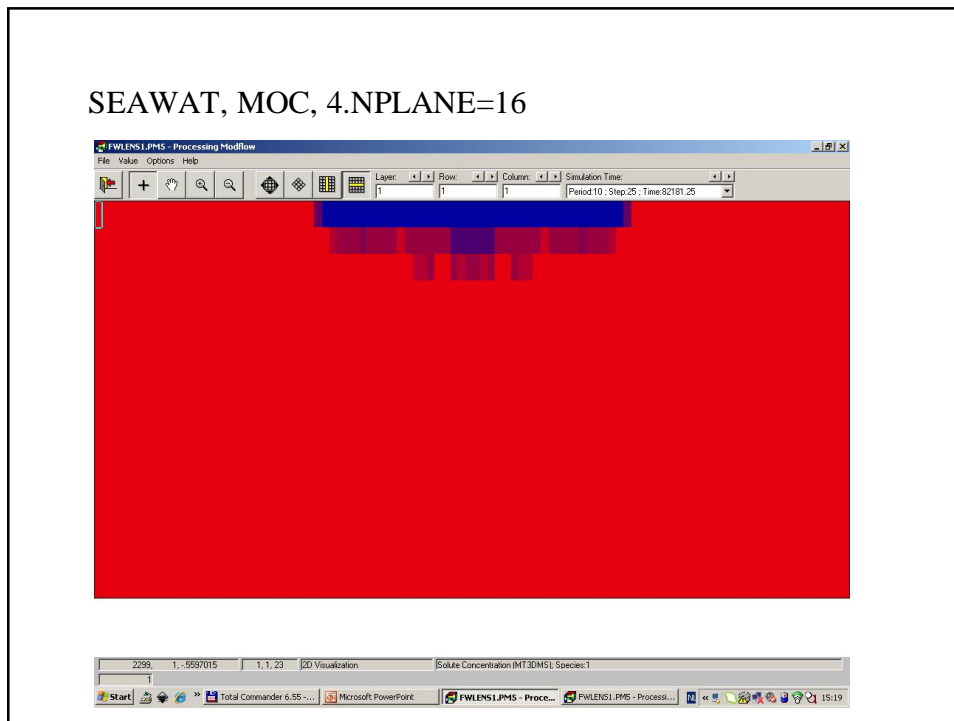
### MOCDENS3D, no disp, 1part



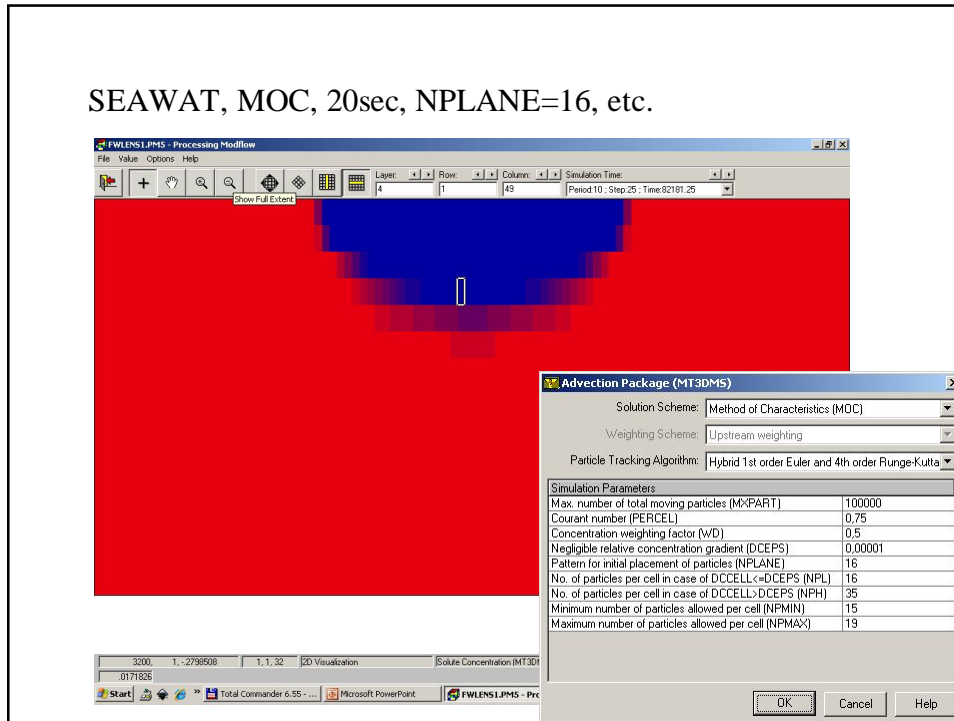
## SEAWAT, MOC, NPLANE=2



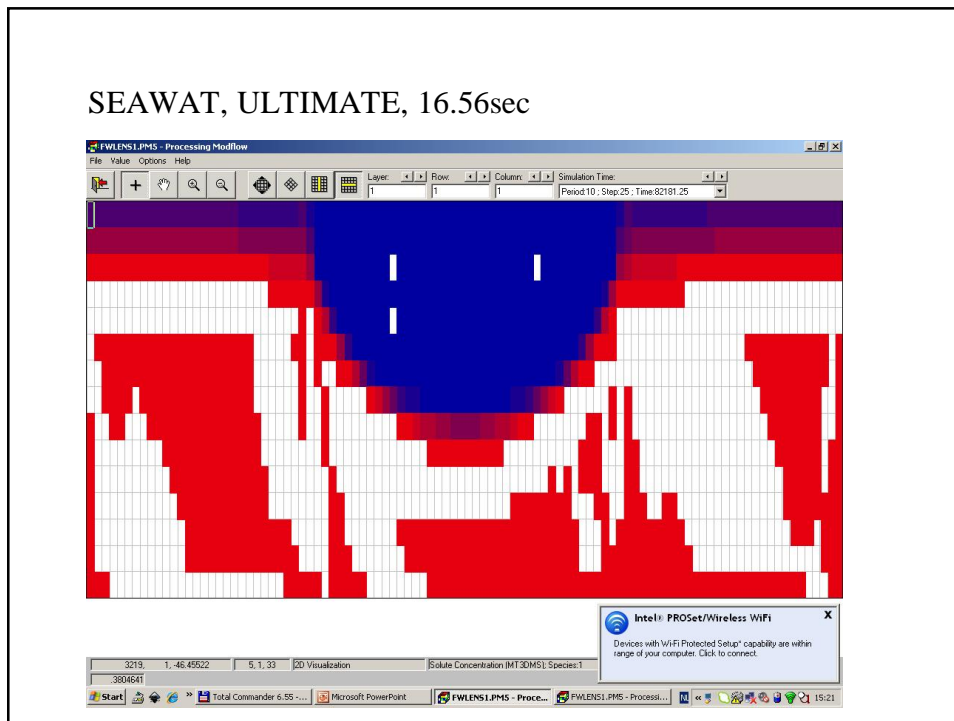
## SEAWAT, MOC, 4.NPLANE=16



## SEAWAT, MOC, 20sec, NPLANE=16, etc.

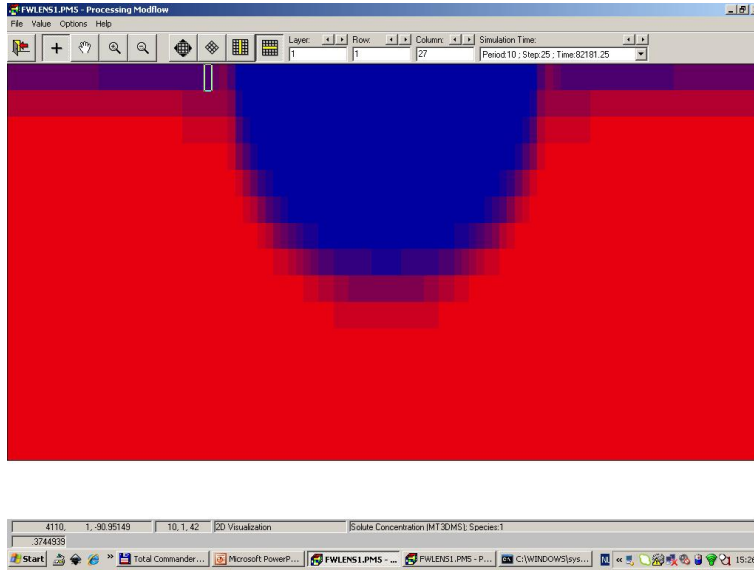


## SEAWAT, ULTIMATE, 16.56sec

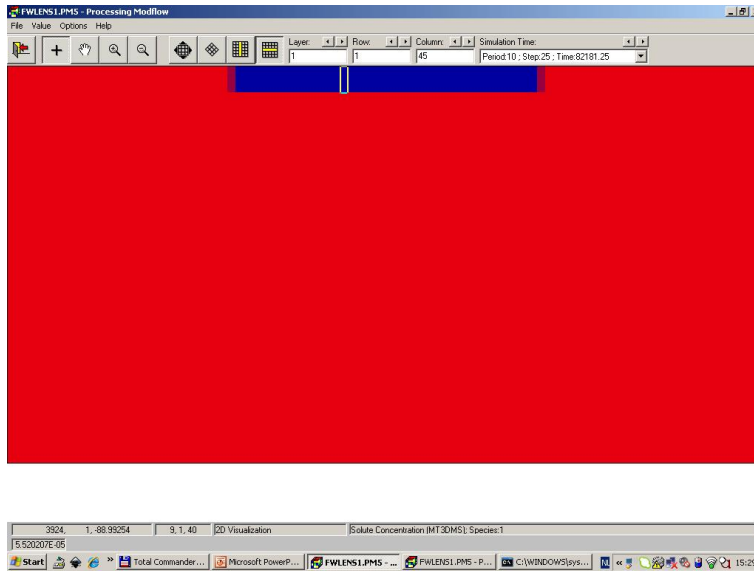




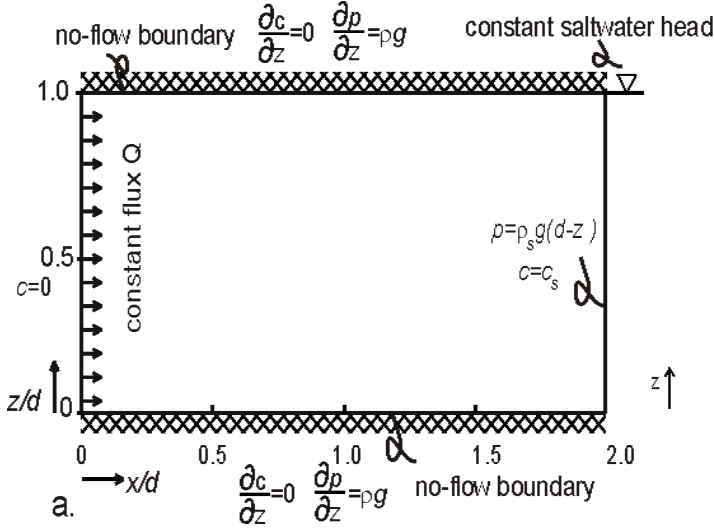
## SEAWAT, MMOC, 8.5sec



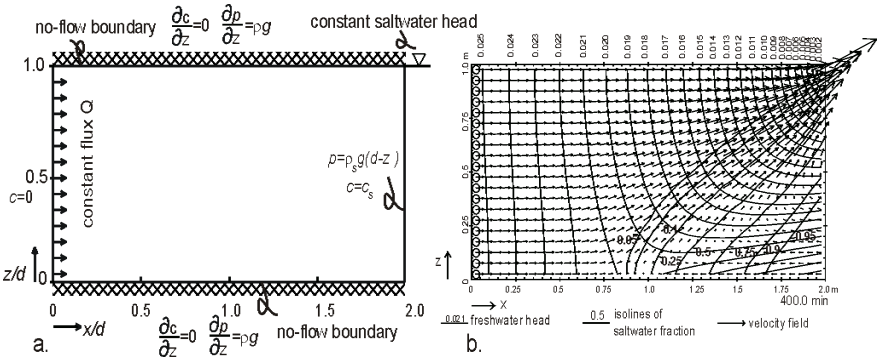
## SEAWAT, HMOC, 6.8sec



### Henry's problem (1964)

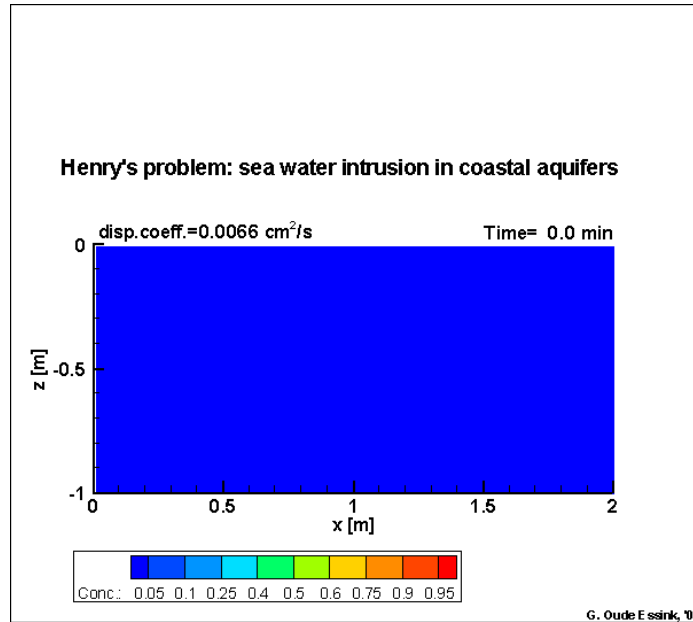


### Henry's problem



## Henry's problem

cases



## Henry's problem

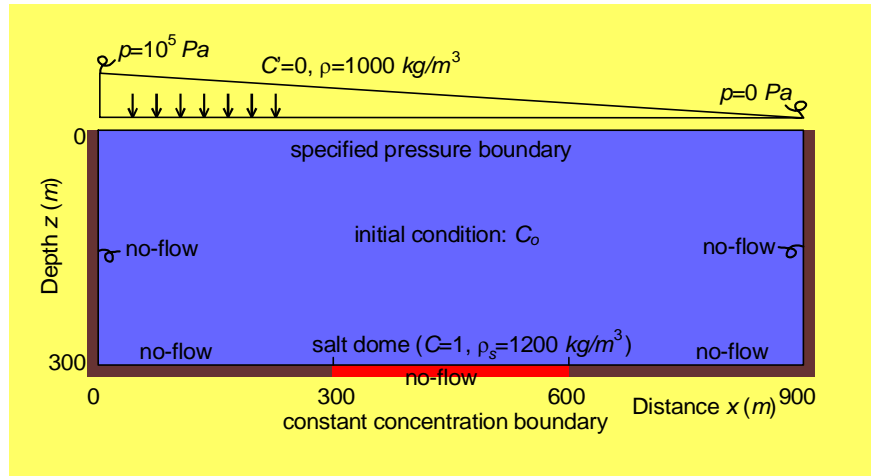
cases

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:

cases

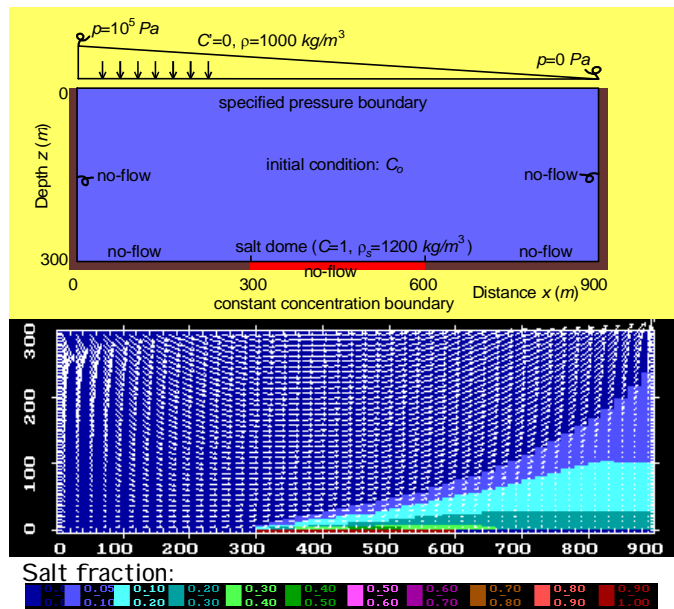
disposal of high-level nuclear waste  
groundwater movement near salt domes  
Gorleben salt dome, Germany



## Hydrocoin:

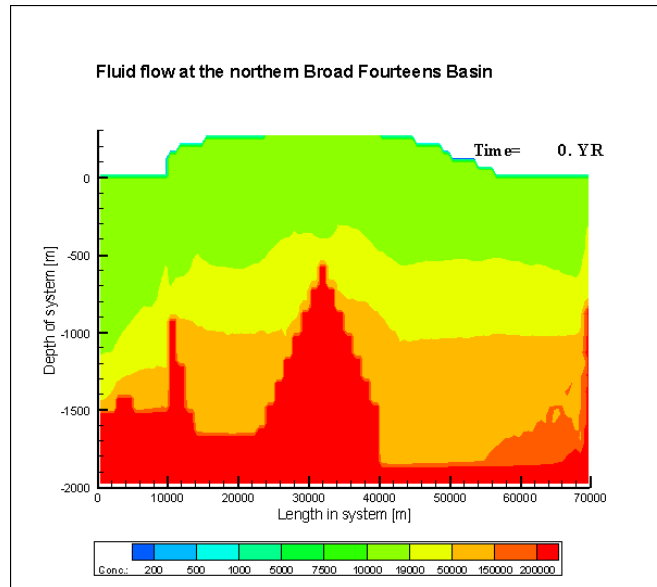
cases

groundwater movement near salt domes



### Broad 14 Basin, North Sea

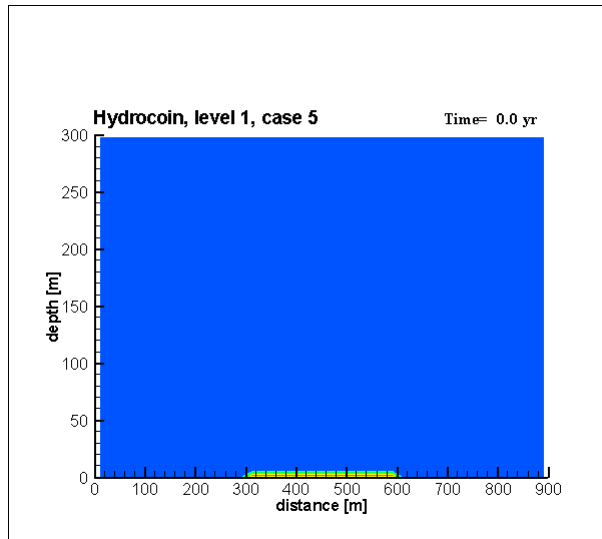
Geofluids'03, with L. Bouw



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)

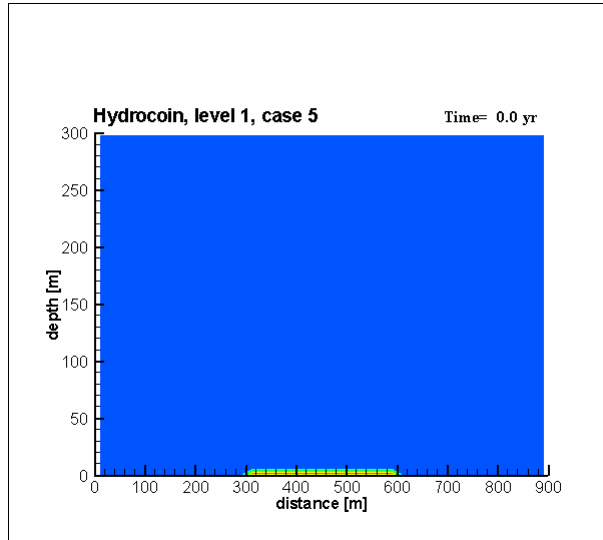
supply of brine through advection and hydrodynamic dispersion



*recirculation type*

Hydrocoin: effect of boundary condition (I)  
supply of brine through advection and hydrodynamic dispersion

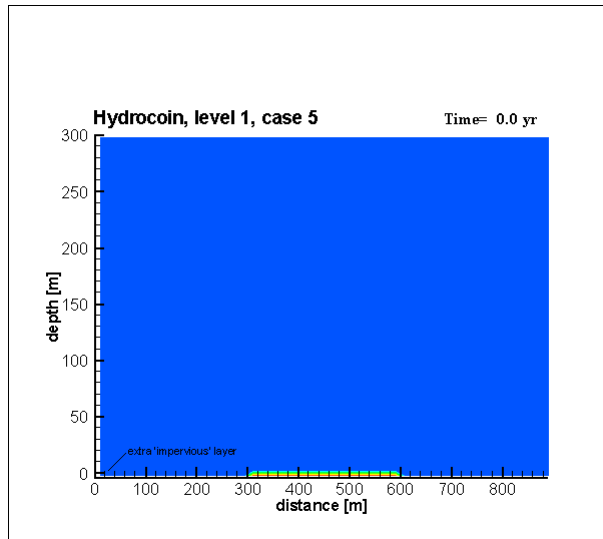
cases



*recirculation type*

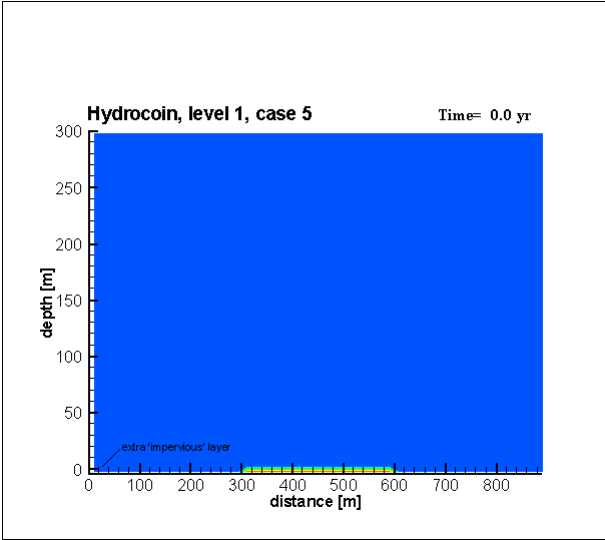
Hydrocoin: effect of boundary condition (II)  
supply of brine through only hydrodynamic dispersion

cases



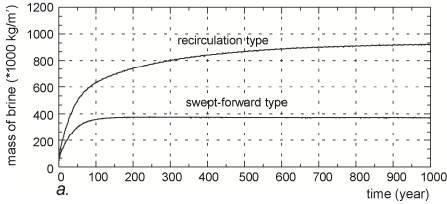
*swept-forward type*

### Hydrocoin: effect of boundary condition (II) supply of brine through only hydrodynamic dispersion

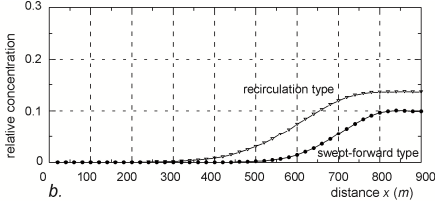


swept-forward type

### Hydrocoin: difference recirculation vs swept forward

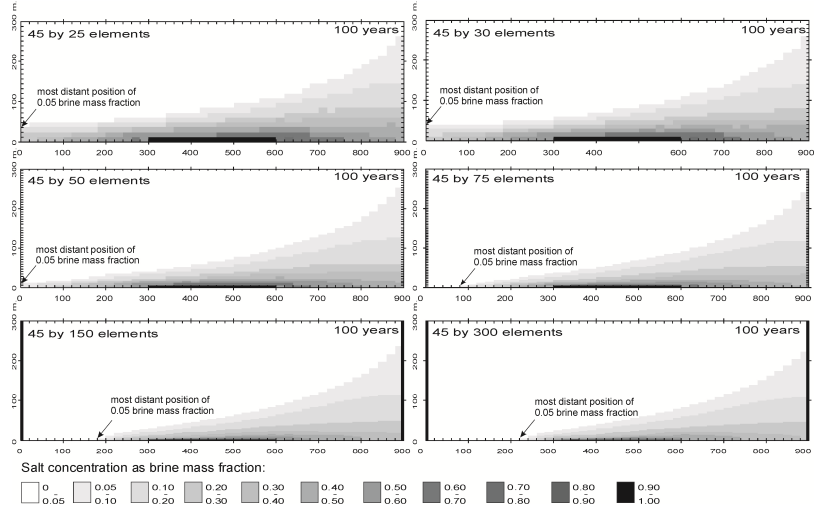


total mass of brine



brine conc at depth=200m

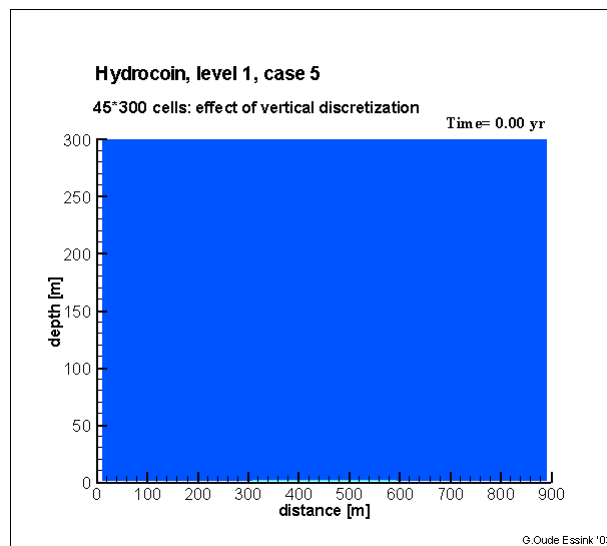
## Hydrocoin: effect of vertical grid size



Recirculation type

## Hydrocoin: effect of vertical discretization (III) <sup>cases</sup>

more vertical cells give better solution

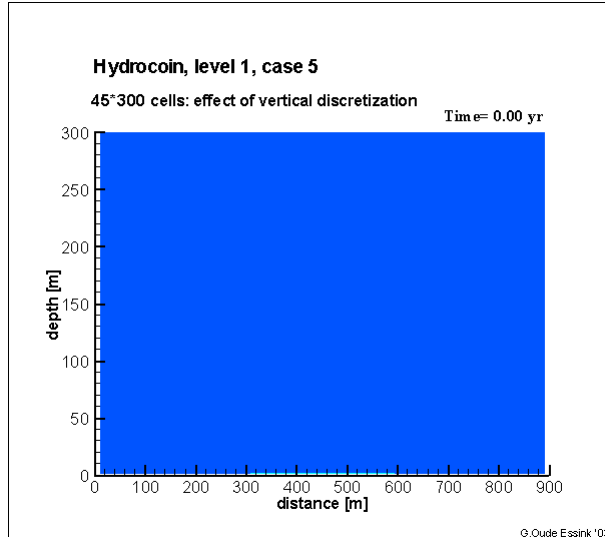


like the swept-forward type



## Hydrocoin: effect of vertical discretization (III)

more vertical cells give better solution

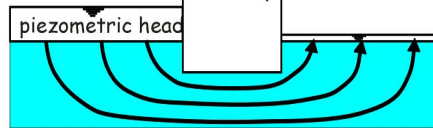


*like the swept-forward type*

## Analogy physical processes

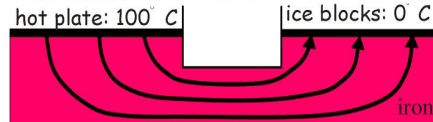
Heat transport (analogy with solute transport)

Groundwater flow: Darcy



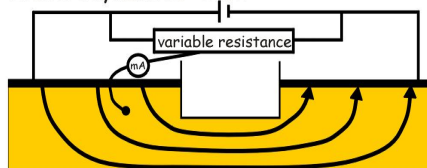
$$q = -k \frac{\partial \phi}{\partial x}$$

Heat conduction: Fourier



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

Electrodynamics: Ohm



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

## Conduction and convection of heat

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

thermal conductivity [Joule/(ms<sup>0</sup> C)]  
 $\lambda_e = n_e \lambda_{fluid} + (1 - n_e) \lambda_{solid}$

heat flux    conduction (Fourier)    convection (fluid flow)

continuity equation

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

specific heat capacity [Joule/(kg<sup>0</sup> C)]  
 $\rho' c' = n_e \rho c_{fluid} + (1 - n_e) \rho_{solid} c_{solid}$

## Analogy solute and heat transport

Solute: advection-dispersion equation

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

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

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

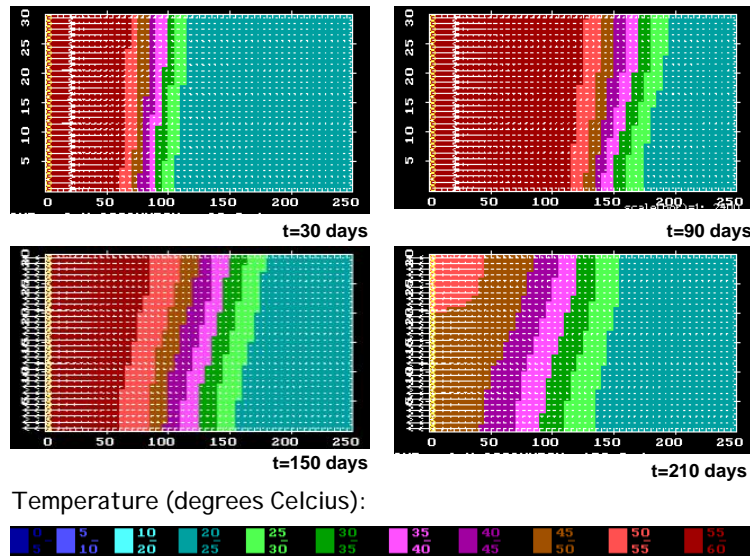
Equation of state: relation density & temperature

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

Analogy between solute and heat transport

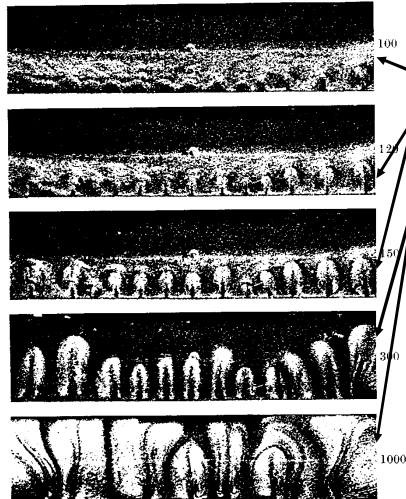
Solute	Heat
$C$	$T$
$R_d$	$1 + \frac{(1-n_e)\rho_s c_s}{n_e \rho c_f}$
$D_m$	$\frac{n_e \lambda_e + (1-n_e)\lambda_s}{n_e \rho c_f}$
$\lambda$	0

## Energy storage in geothermal reservoirs



## 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

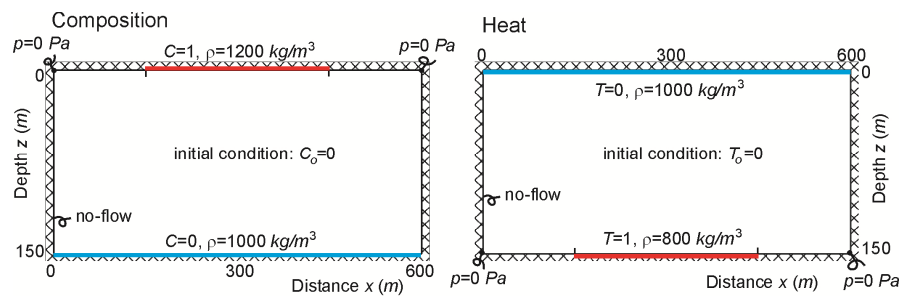
Convection of heat occurs when:

$$\text{Rayleigh number} > 4\pi^2$$

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

## Elder problem (II)

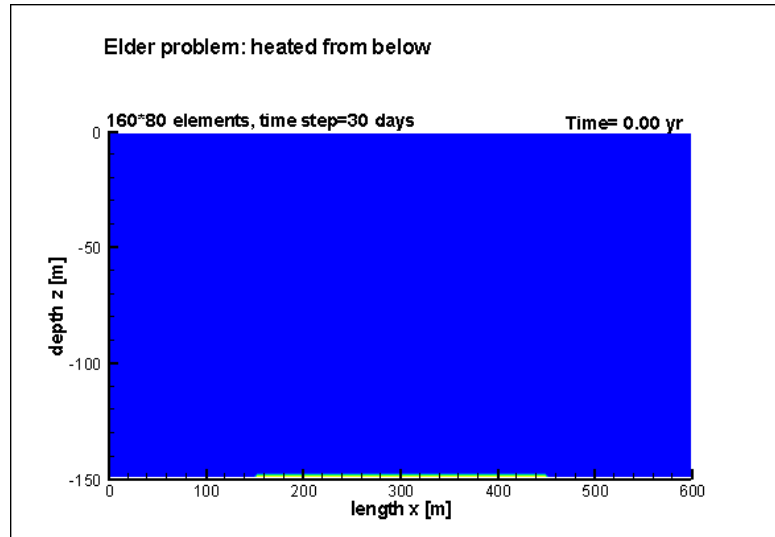
Analogy composition and heat



Lecture notes, p. 91-96

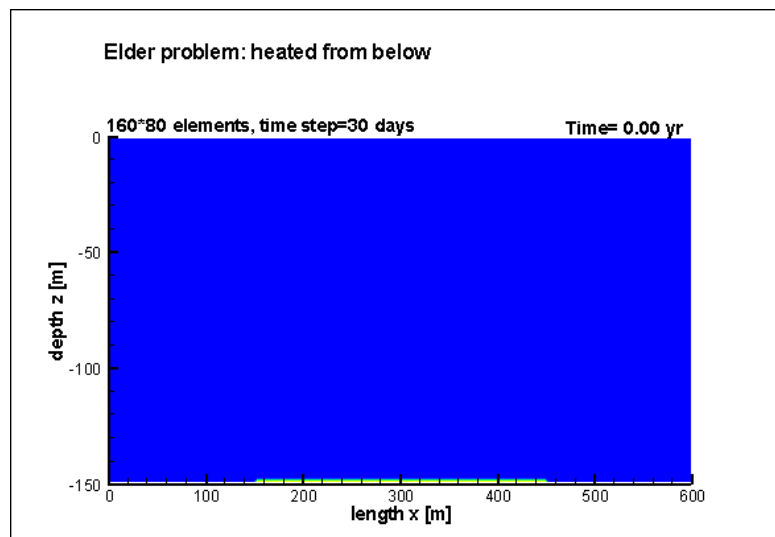
### Elder problem (III)

Development of convection cells (Rayleigh number=400)

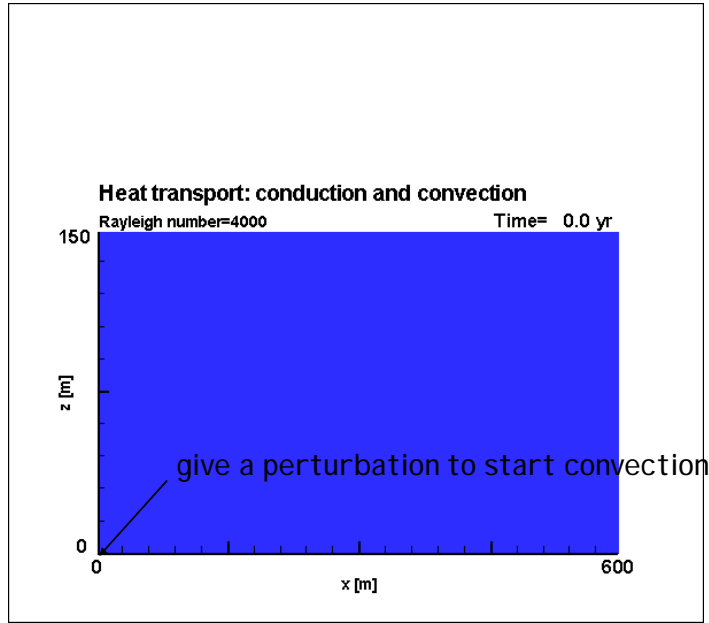


### Elder problem (III)

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 26<sup>th</sup>, 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:

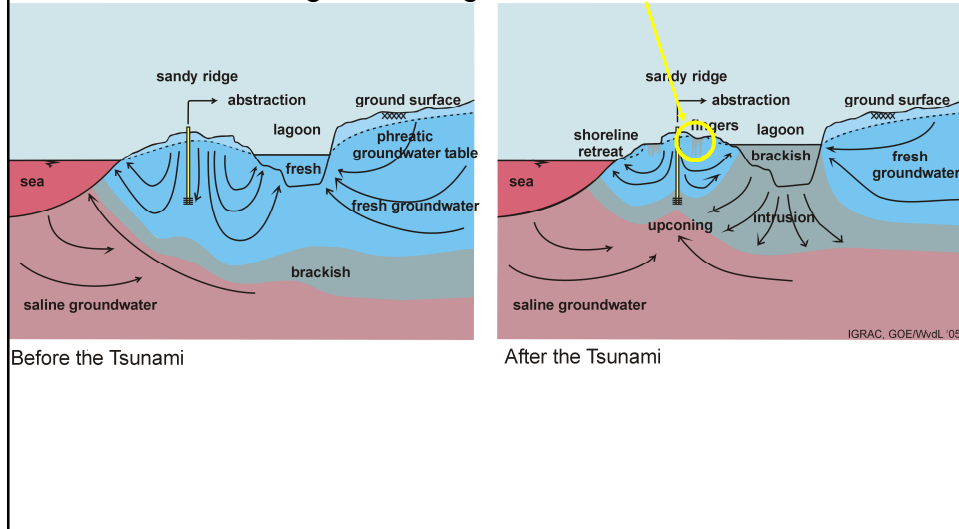
1. Fingering processes in the subsoil
2. Evolution of a freshwater lens after flooding by sea water
3. Freshwater lens in a coastal aquifer with a brackish lagoon

Next step:

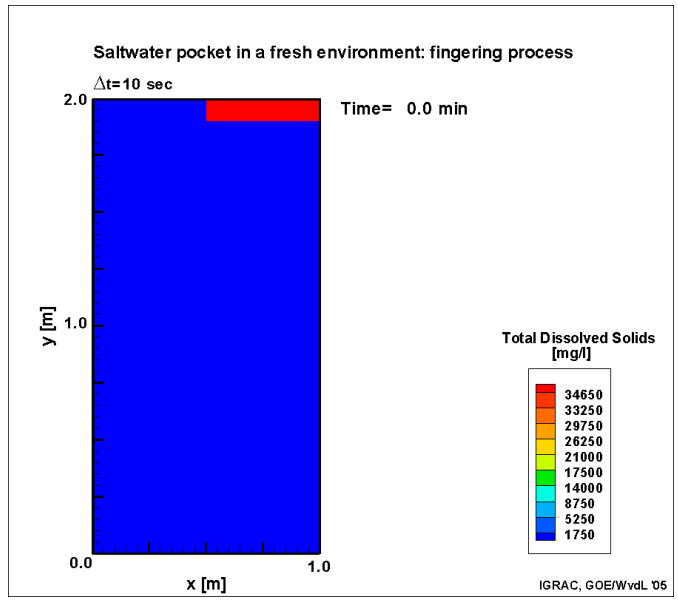
quantifying processes in real situations, using topographic and hydrogeological data, and ending up with vulnerability maps

### Concept 1: Fingering processes in the subsoil

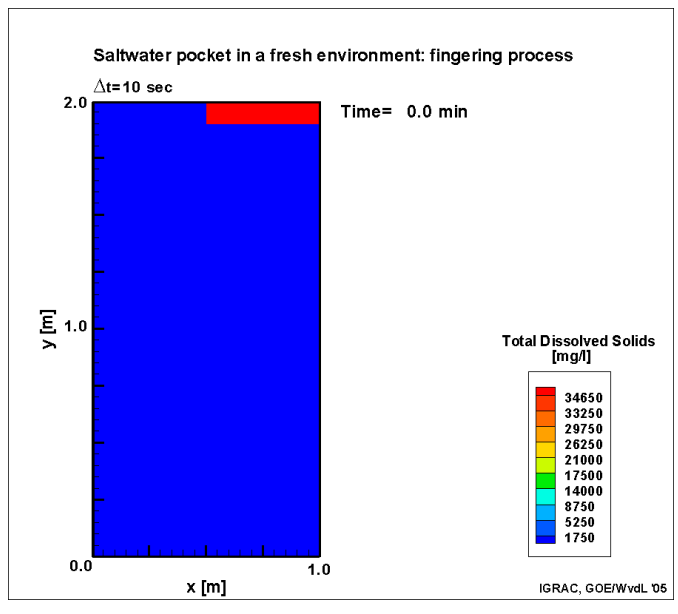
#### Case Sri Lanka: lagoon setting



# Concept 1: Fingering processes in the subsoil

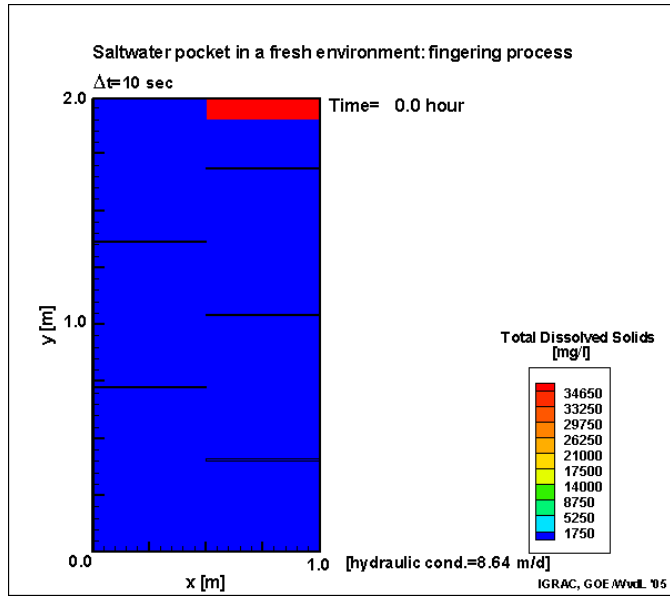


# Concept 1: Fingering processes in the subsoil

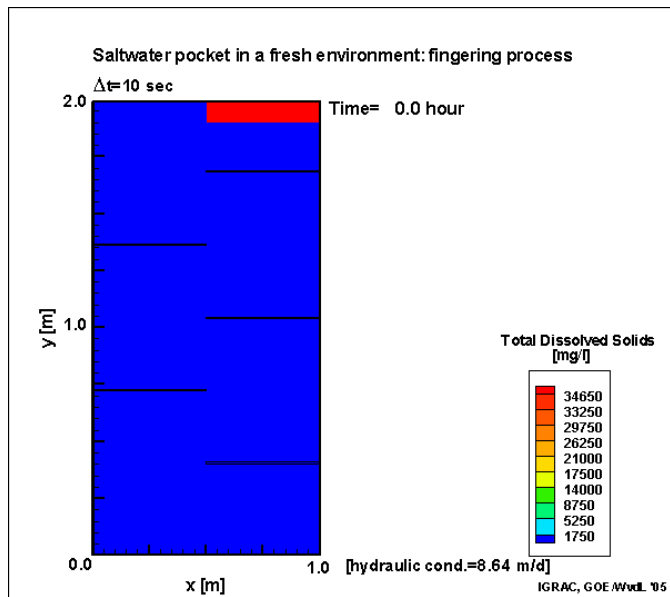




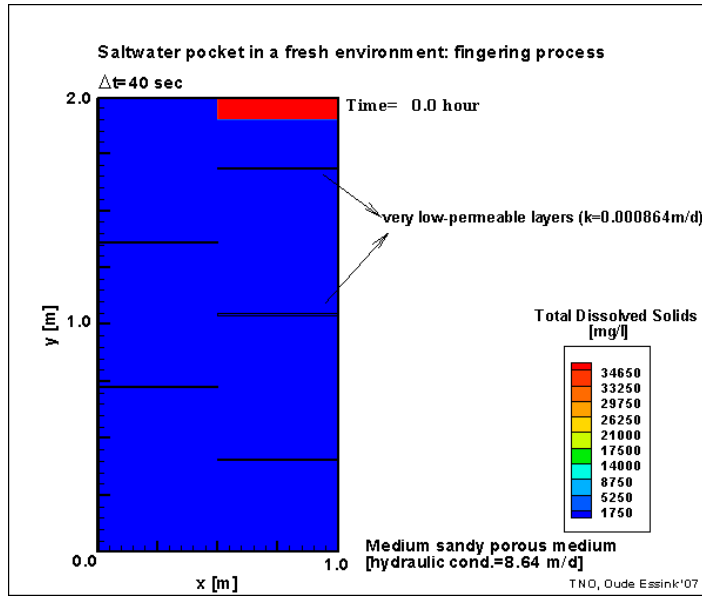
# Concept 1: Fingering processes in the subsoil



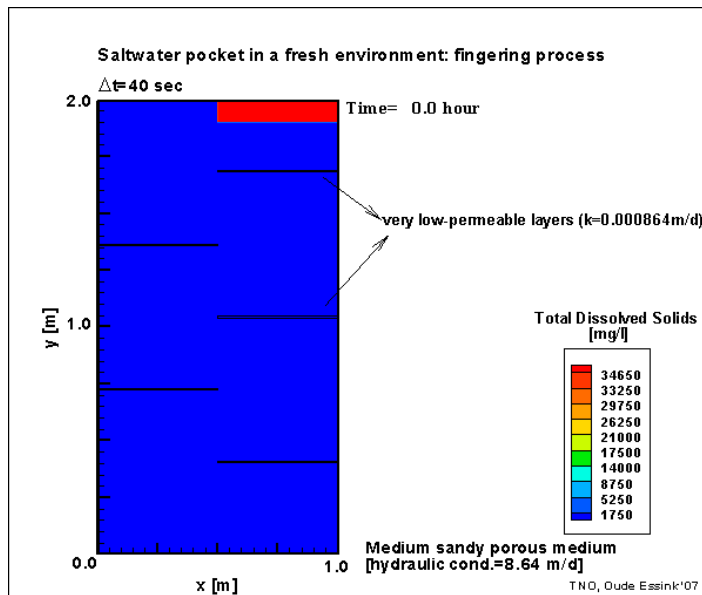
# Concept 1: Fingering processes in the subsoil



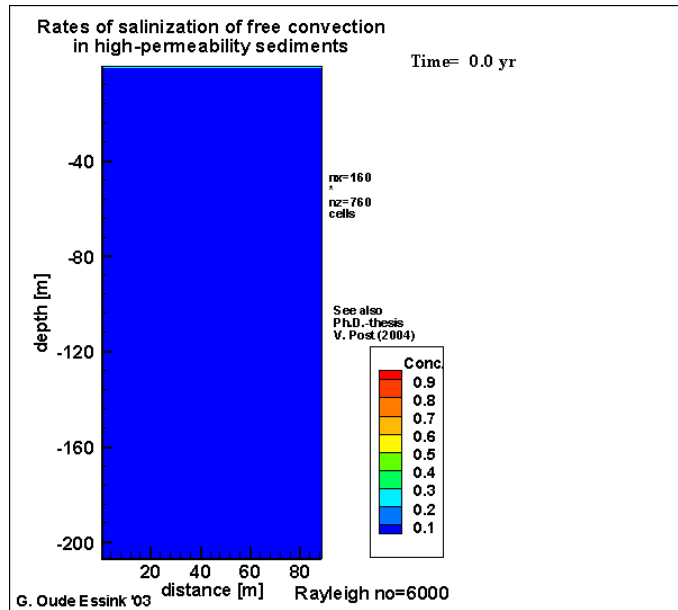
# Concept 1: Fingering processes in the subsoil



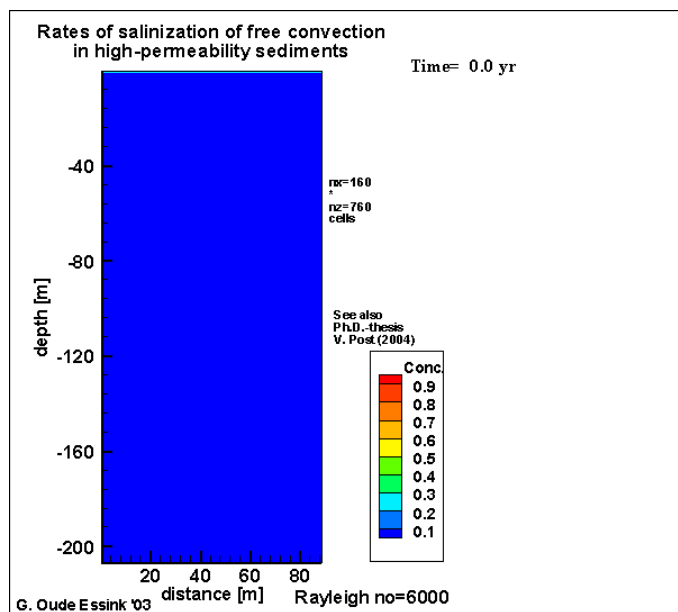
# Concept 1: Fingering processes in the subsoil



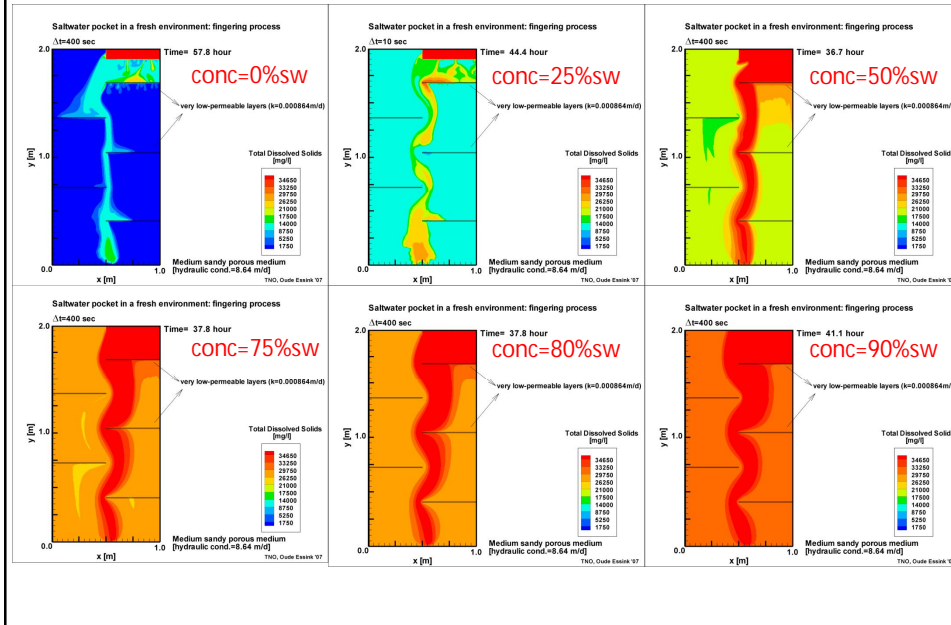
## Concept 1: Fingering processes in the subsoil



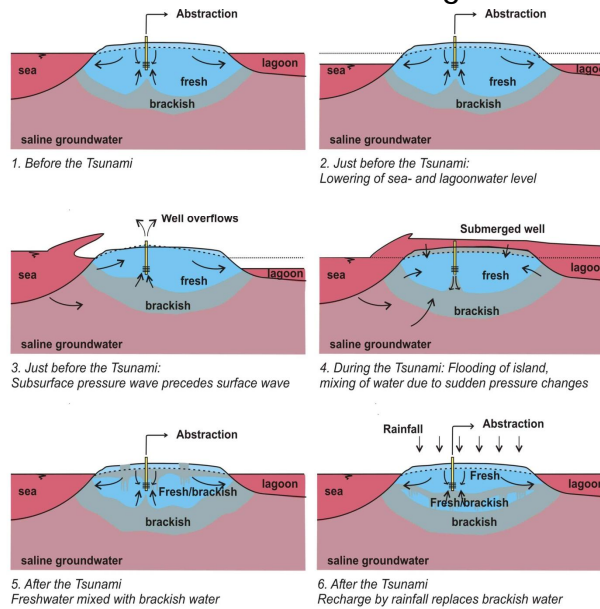
## Concept 1: Fingering processes in the subsoil



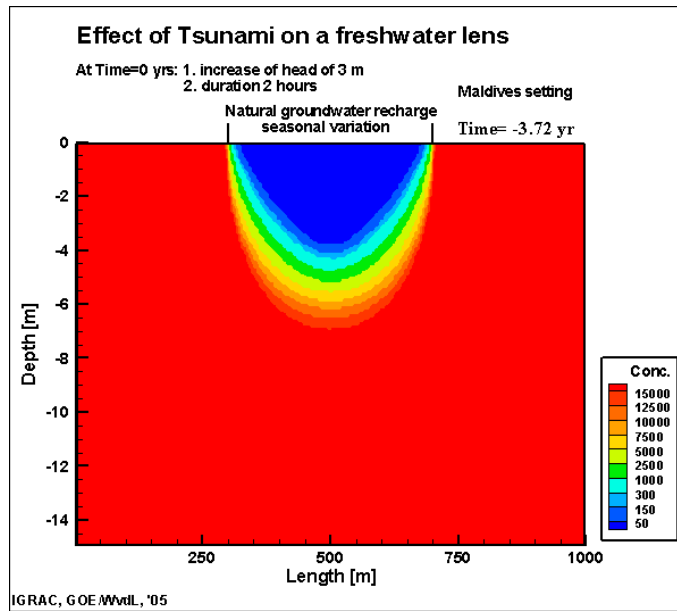
# Fingering processes in the subsol



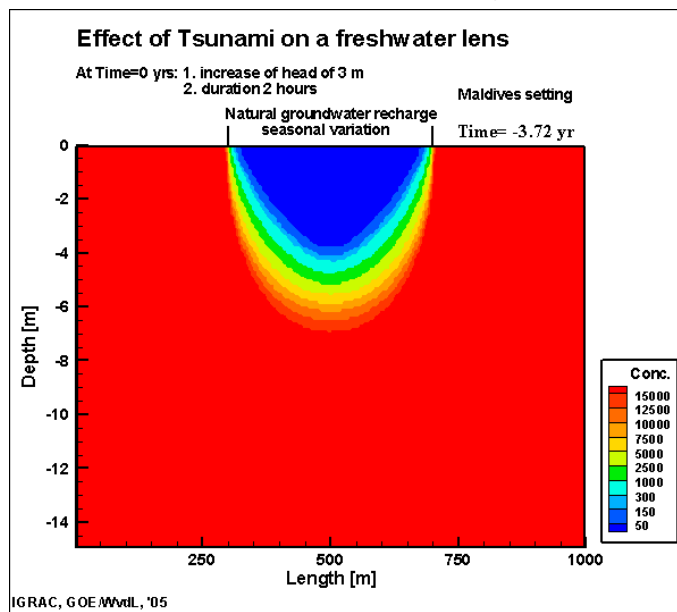
## Concept 2: Evolution of a freshwater lens after flooding



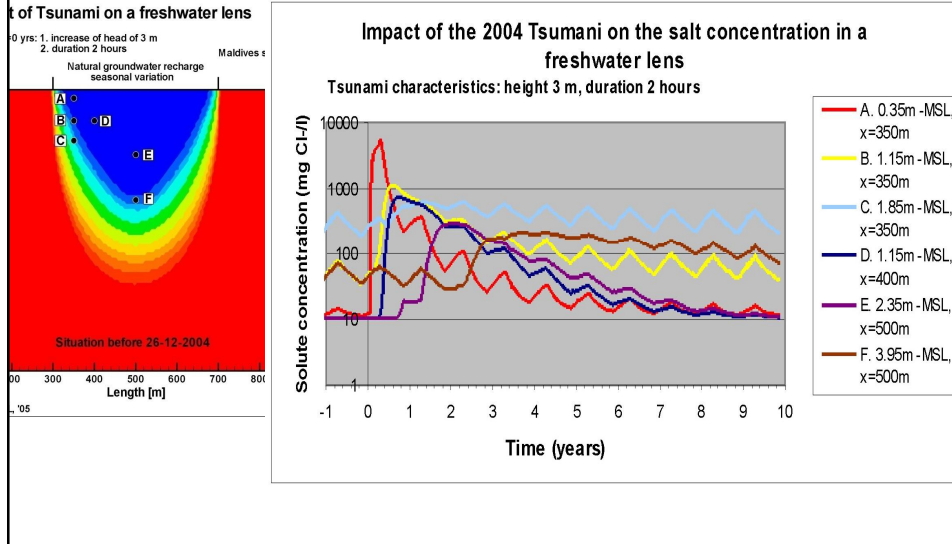
## Concept 2: Evolution of a freshwater lens after flooding



## Concept 2: Evolution of a freshwater lens after flooding

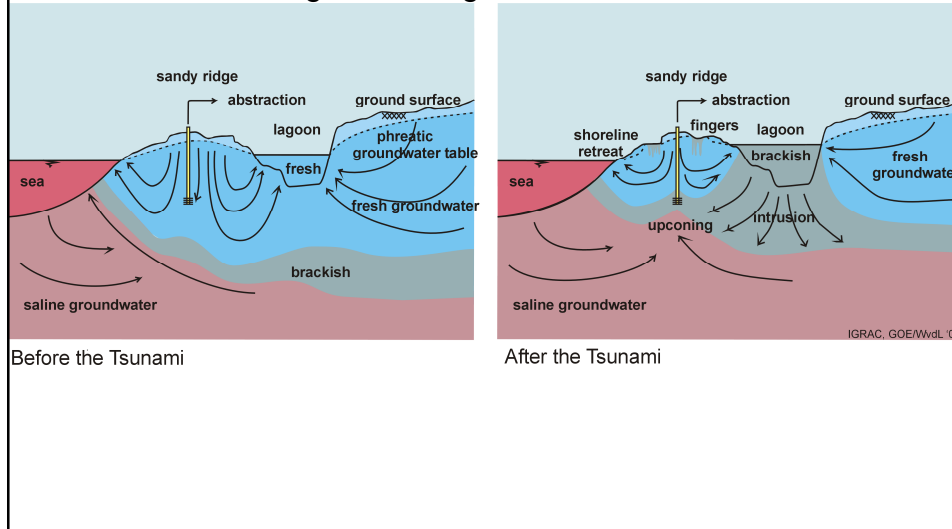


## Concept 2: Evolution of a freshwater lens after flooding

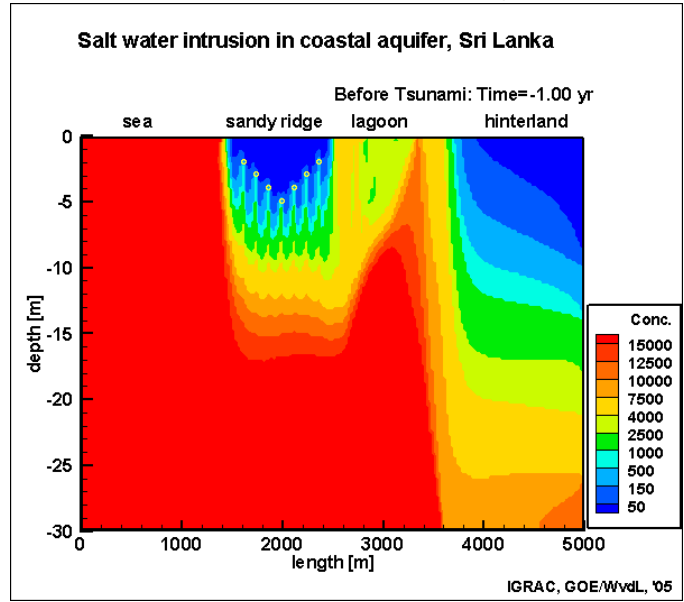


## Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

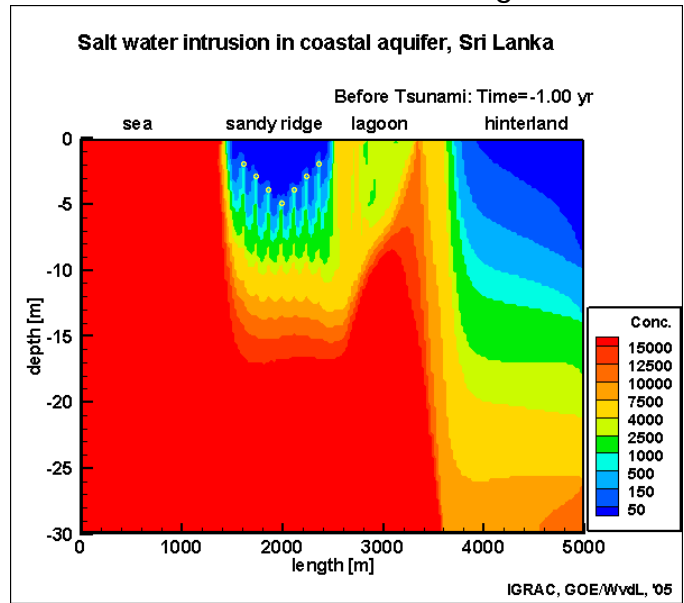
### Case Sri Lanka: lagoon setting



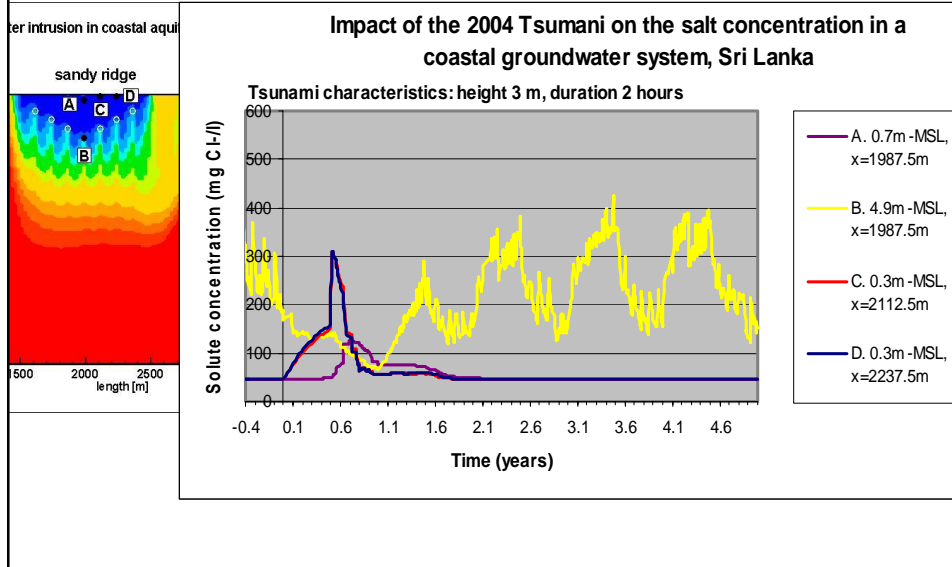
### Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon



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



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



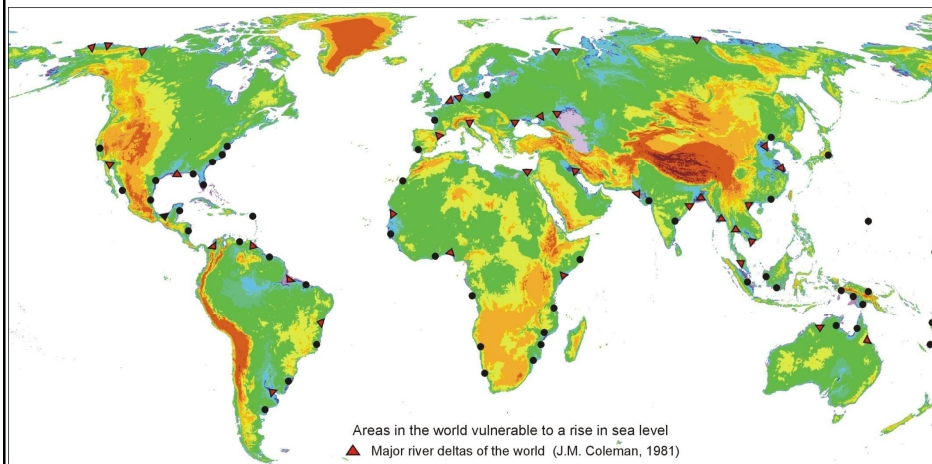
Effect sea level rise



## Effects of sea level rise on groundwater resources in deltaic areas

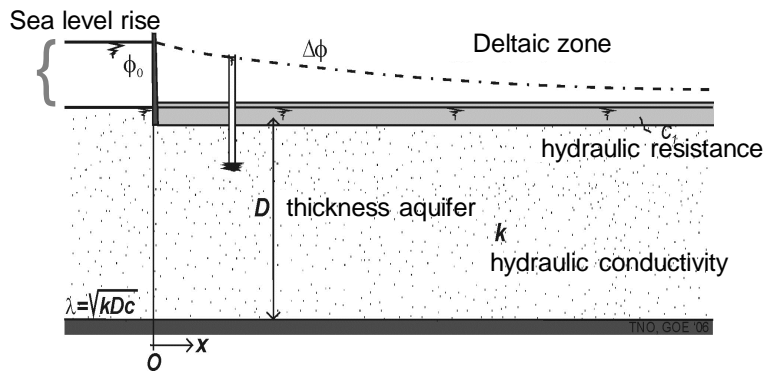
1. Increase of salt water intrusion
2. Increase of upconing under groundwater extraction wells
3. Increase of piezometric head
4. Increase of seepage and salt load to the surface water system
5. Risk of instable Holocene aquitards
6. [Decrease of fresh groundwater reservoirs due to decrease in natural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



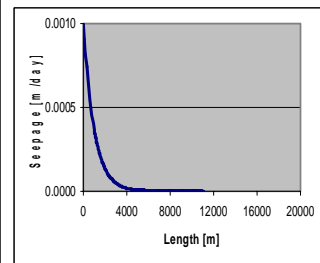
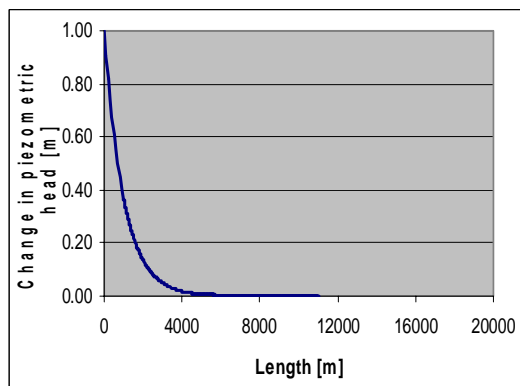
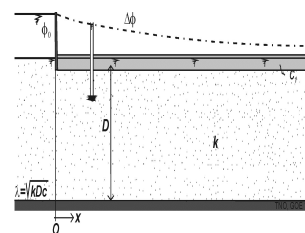
$$\Delta\phi(x) = \phi_0 e^{-x/\lambda}$$

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

- Zone of influence is equal to  $\sqrt{kDc}$
- At  $x=3\lambda$ , only 5% of sea level rise is detectable

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

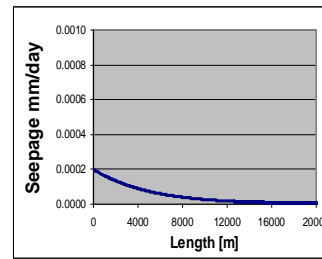
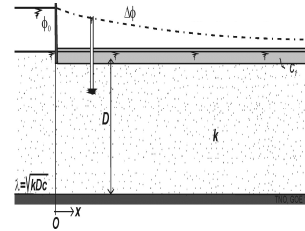
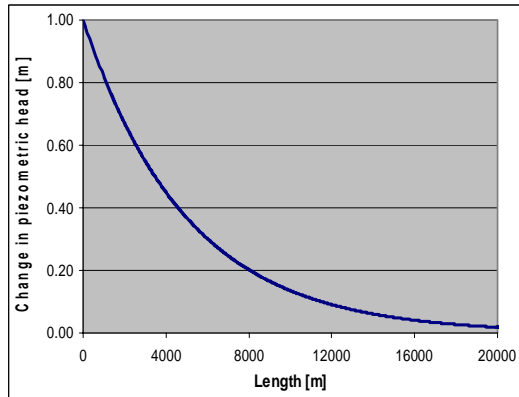
**$kD = 1000 \text{ m}^2/\text{day}$**   
 **$c = 1000 \text{ day}$**   
 **$\lambda = 1000 \text{ m}$**



### Effect of sea level rise:

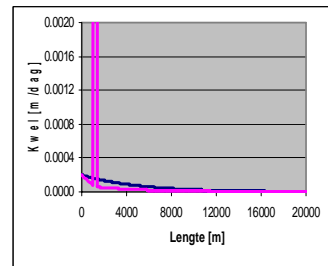
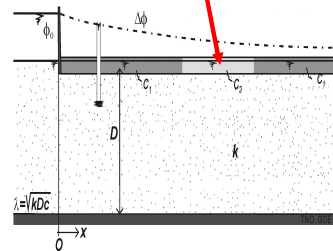
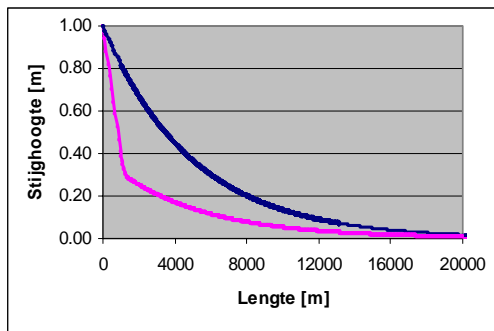
#### Case 2 with Dutch subsoil parameters

**$kD = 5000 \text{ m}^2/\text{day}$**   
 **$c = 5000 \text{ day}$**   
 **$\lambda = 5000 \text{ m}$**



#### Case 3 with Dutch subsoil parameters

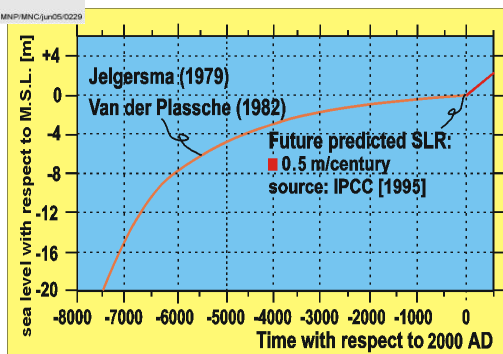
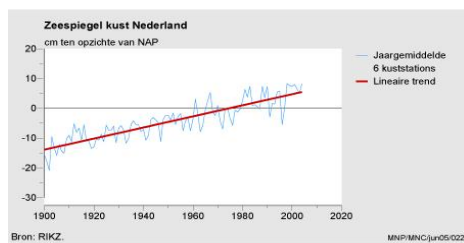
**$kD = 5000 \text{ m}^2/\text{dag}$**   
 **$c_1 = 5000 \text{ dag}$ ,  $c_2 = 50 \text{ dag}$**



# Climate change is HOT!



## Past and future sea level rise in the Netherlands

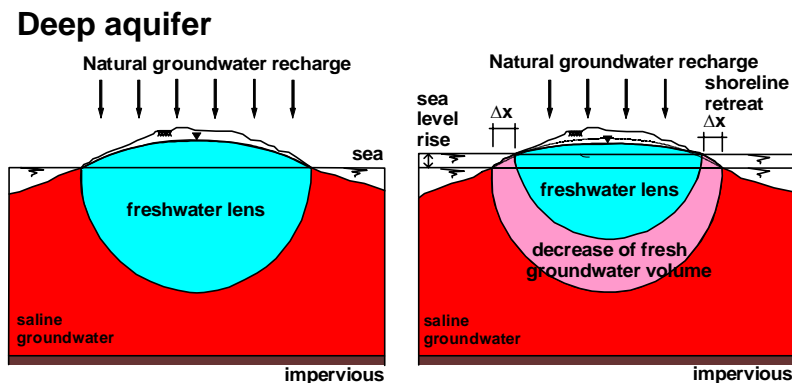


## Implementing new KNMI 06 climate scenarios

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 Europe		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

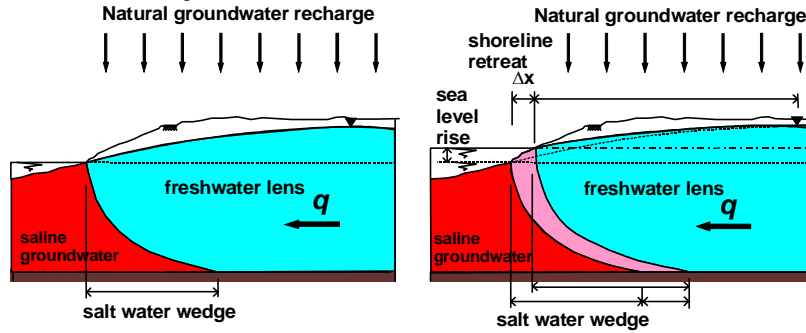
Introduction

Effect of a relative sea level rise (1):



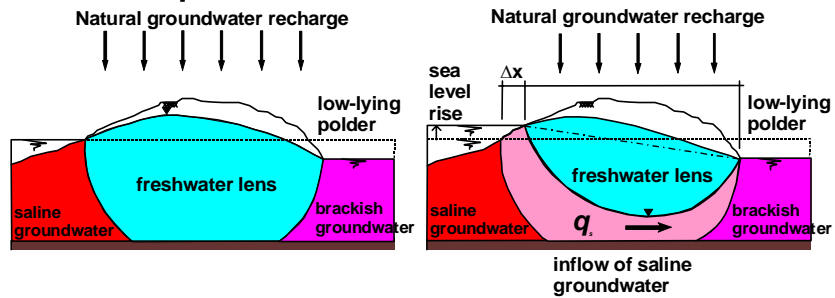
Effect of a relative sea level rise (2):

Shallow aquifer

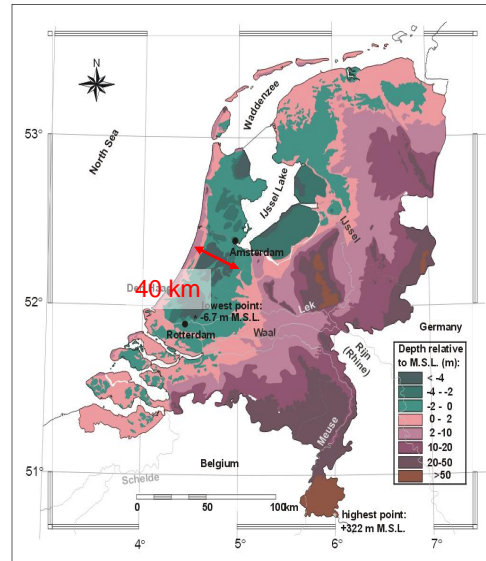


Effect of a relative sea level rise (3):

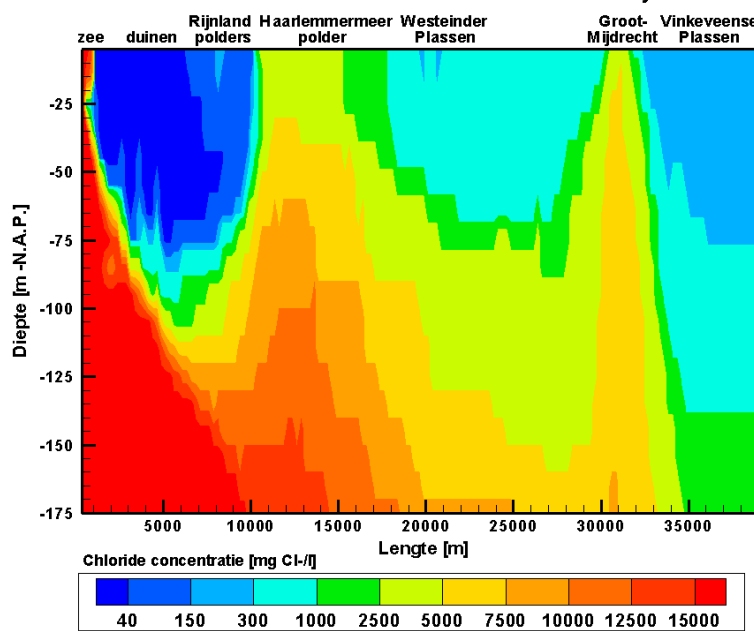
Shallow aquifer

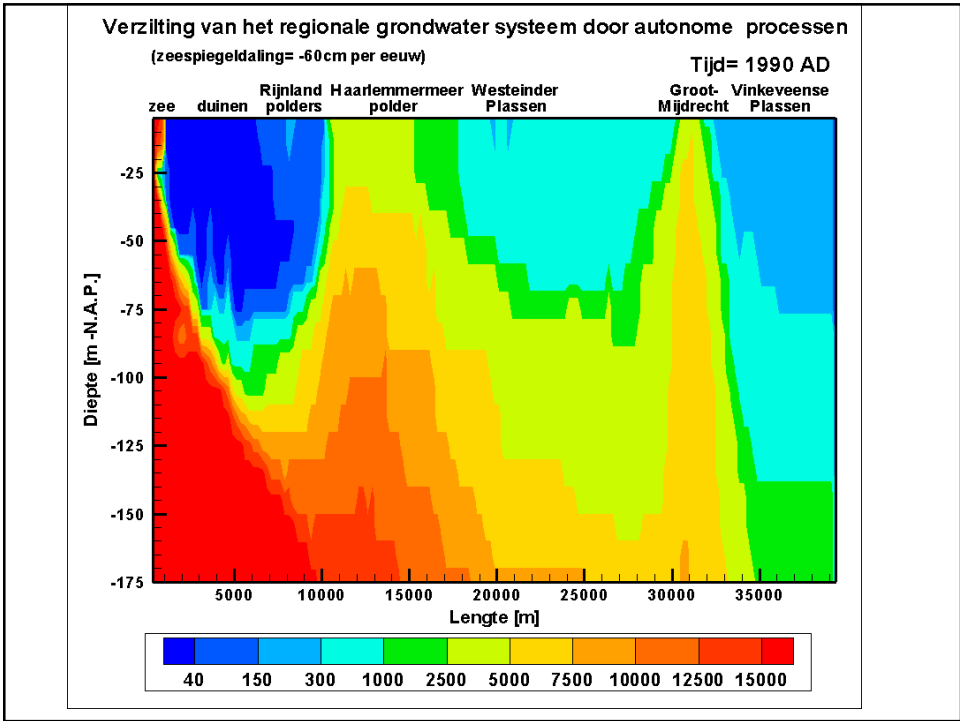
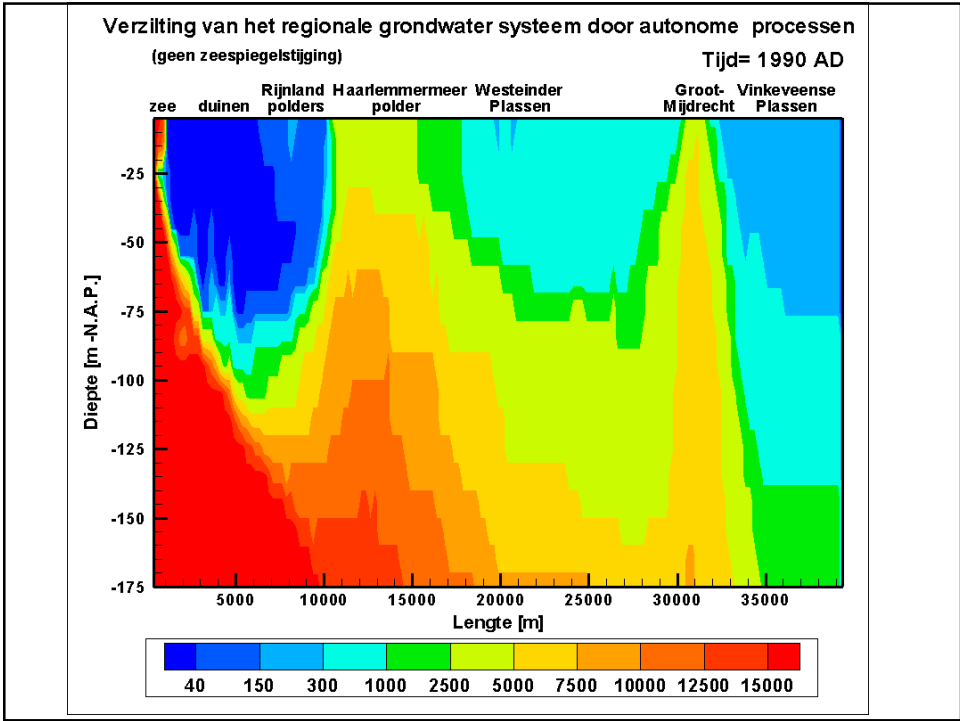


## 2D Profile and effect sea level rise

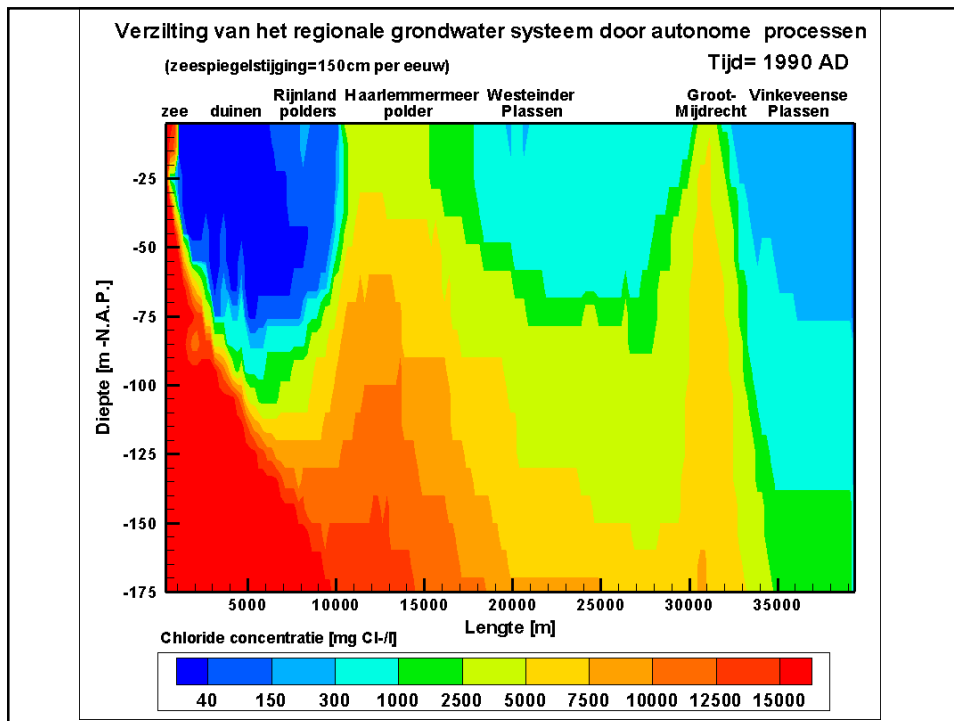
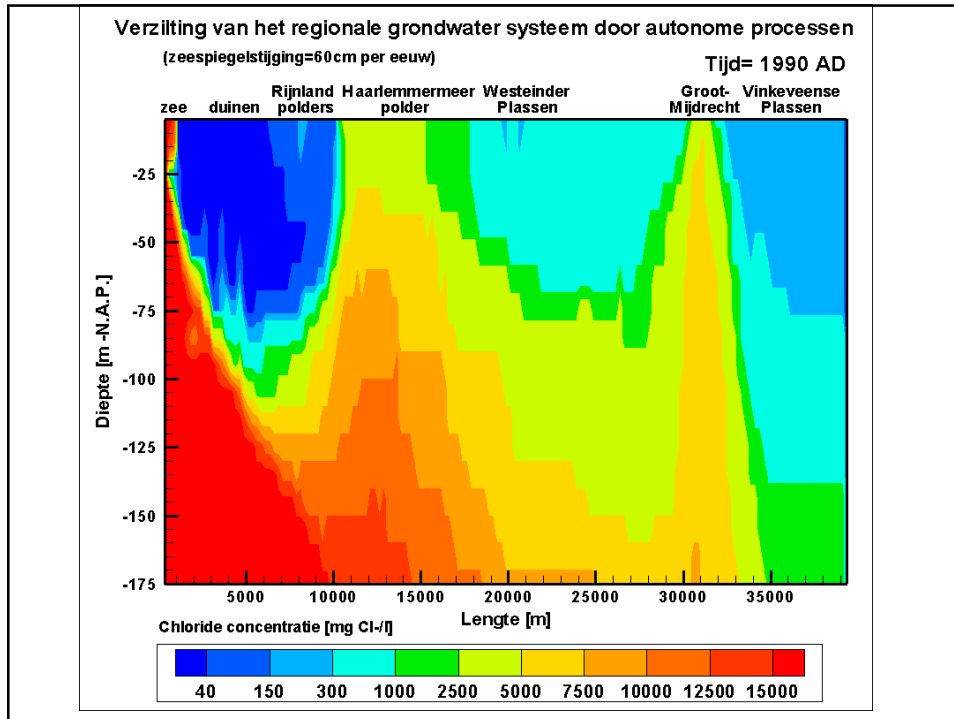


### Verziltig van het regionale grondwater systeem door autonome processen (geen zeespiegelstijging) Tijd= 1990 AD



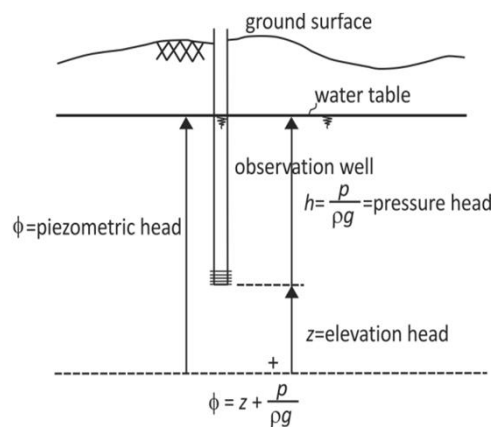






# Point water head and Freshwater head $\phi_f$

## Piezometric head $\phi$



$$\phi = \frac{p}{\rho g} + z$$

$$p = \rho g (\phi - z)$$

## Freshwater head $\phi_f$

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

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 $\phi_f$

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

$$\phi_f = h_f + z$$

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

e.g.:  
 $\rho_s = 1025 \text{ kg/m}^3$   
 $h = 10 \text{ m}$   
 $\phi_f = 10.25 \text{ m}$

Special case: hydrostatic pressure:  $q_z=0$

$$q_z = -\frac{\kappa_z \rho_f g}{\mu} \left( \frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f} \right) \quad \text{no vertical flow}$$

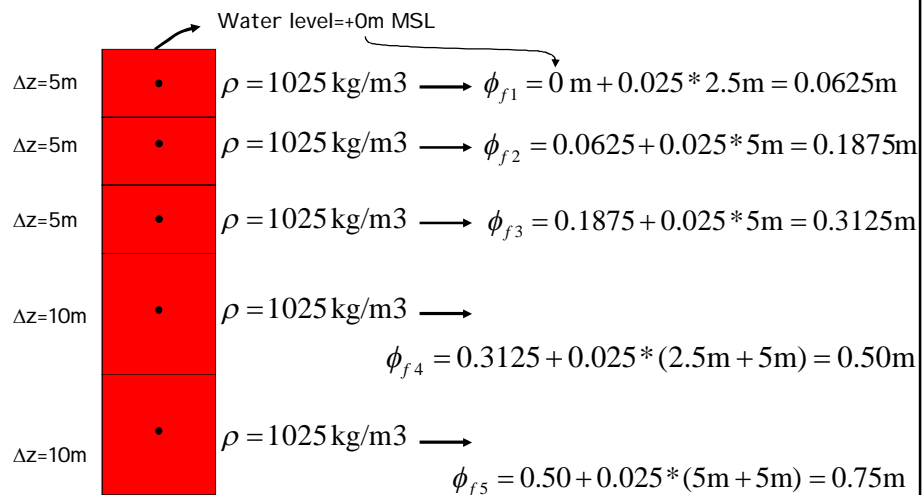
$$0 = \left( \frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f} \right)$$

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

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

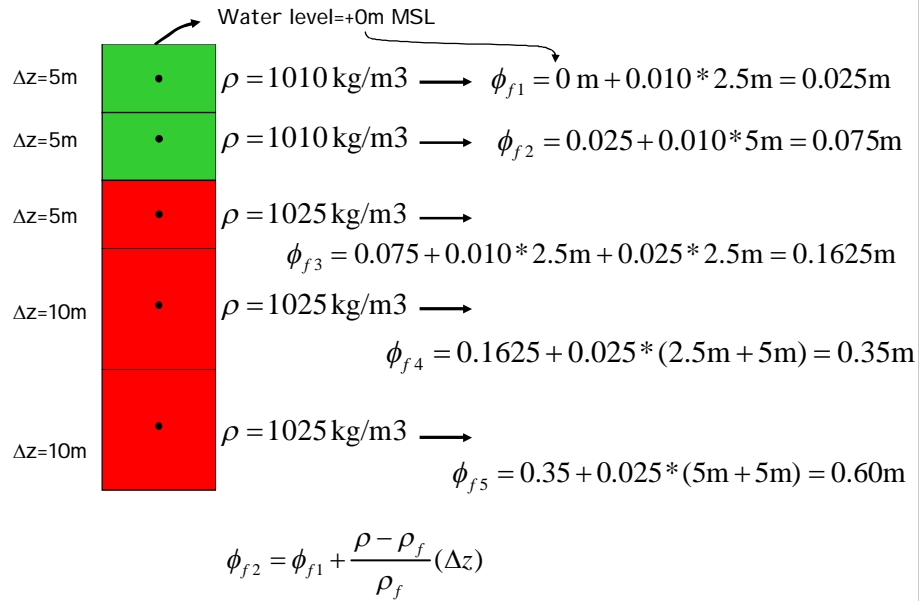
$$\downarrow + \quad \phi_{f2} = \phi_{f1} + \frac{\rho - \rho_f}{\rho_f} (\Delta z)$$

Hydrostatic boundary condition at the sea

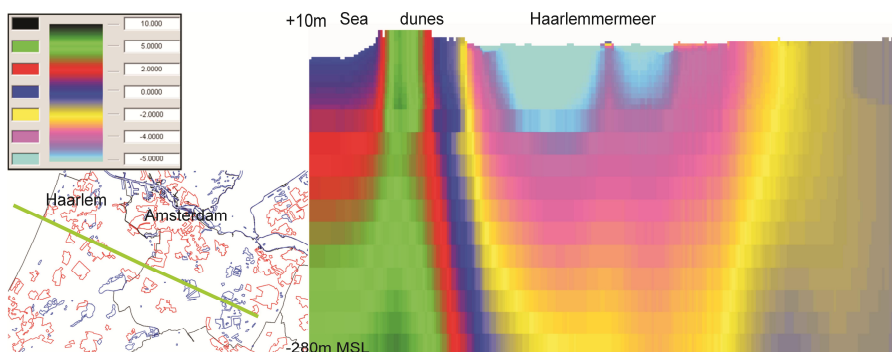


$$\phi_{f2} = \phi_{f1} + \frac{\rho - \rho_f}{\rho_f} (\Delta z)$$

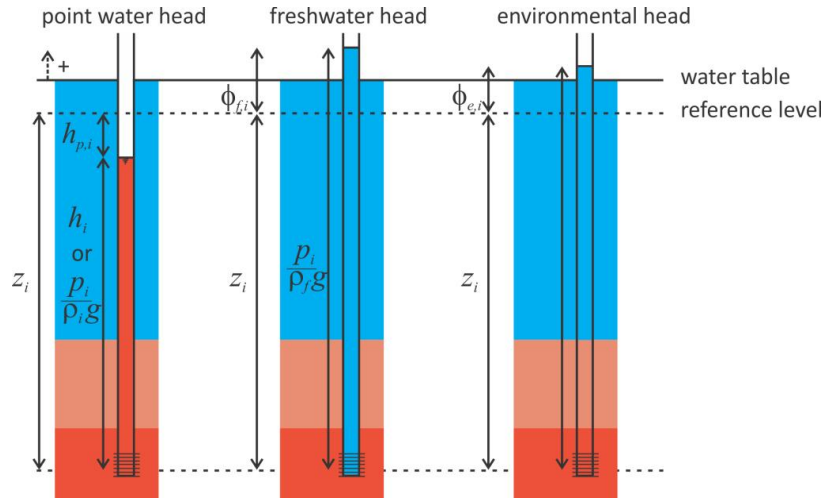
## Hydrostatic boundary condition at the sea



## Example 2D profile NHI model freshwater head $\phi_f$



Which one is useful?



Post, Kooi and Simmons, 2007, Ground Water

Point water head

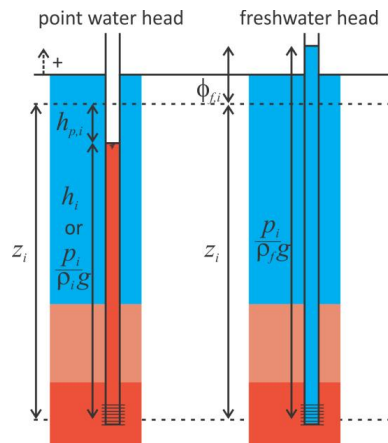
$$h_{p,i} = z_i + h_i \leftrightarrow h_i = h_{p,i} - z_i$$

$$h_i = \frac{p_i}{\rho_i g} \leftrightarrow p_i = h_i \rho_i g$$

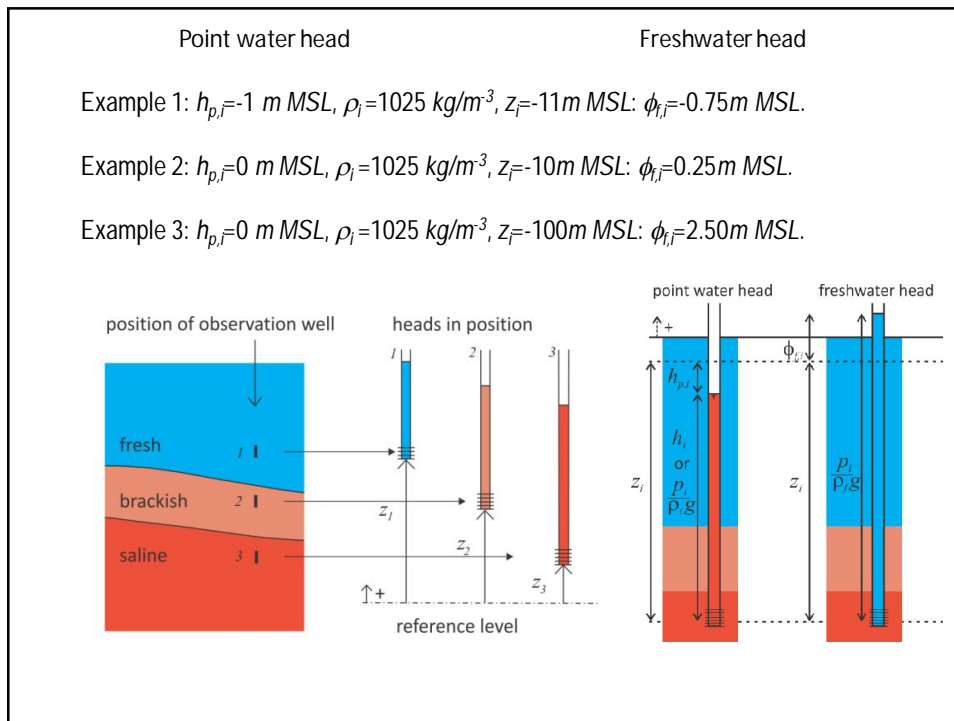
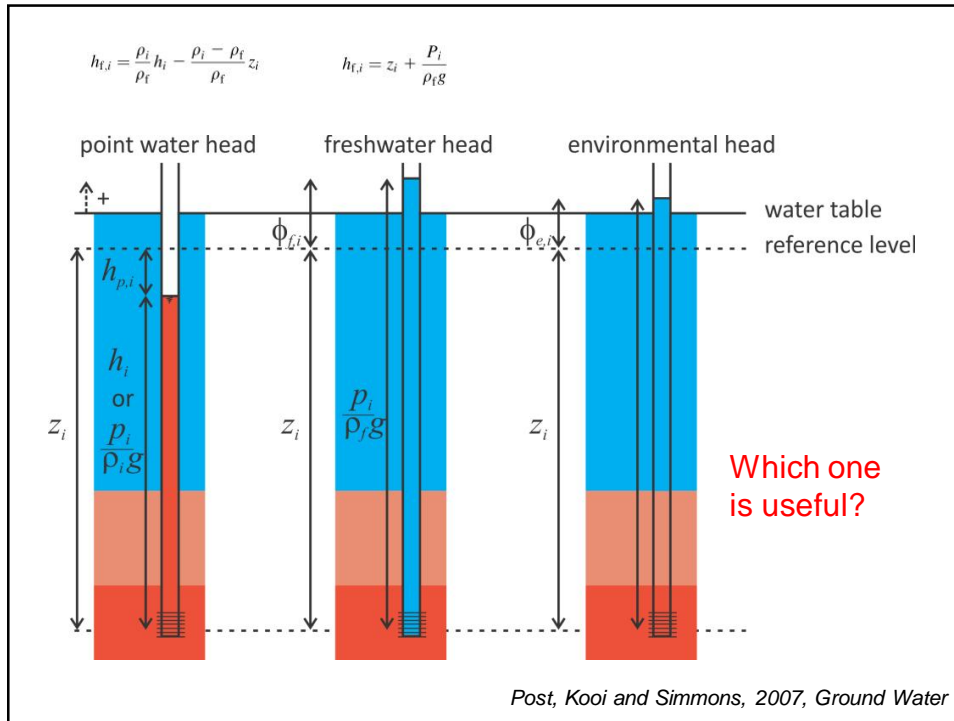
Freshwater head

$$\phi_{f,i} = z_i + \frac{p_i}{\rho_f g} \leftrightarrow \phi_{f,i} = z_i + \frac{h_i \rho_i}{\rho_f}$$

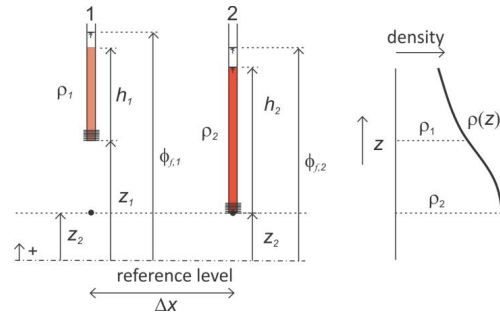
$$\phi_{f,i} = \frac{\rho_i}{\rho_f} h_{p,i} - \frac{\rho_i - \rho_f}{\rho_f} z_i$$



Post, Kooi and Simmons, 2007, Ground Water



### Freshwater head $\phi_f$ : horizontal flow?

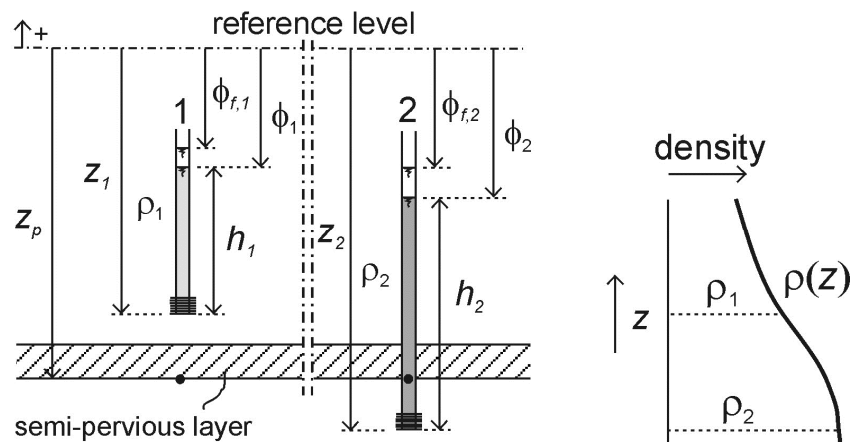


$$p_1^{at\ z=z_2} = \rho_1 g h_1 + \int_{z_2}^{z_1} \rho(z) g dz \quad \phi_{f,1}^{at\ z=z_2} = z_2 + \frac{\rho_1}{\rho_f} h_1 + \frac{1}{\rho_f g} \int_{z_2}^{z_1} \rho(z) g dz$$

$$p_2^{at\ z=z_2} = \rho_2 g h_2 \quad \phi_{f,2}^{at\ z=z_2} = z_2 + \frac{\rho_2}{\rho_f} h_2$$

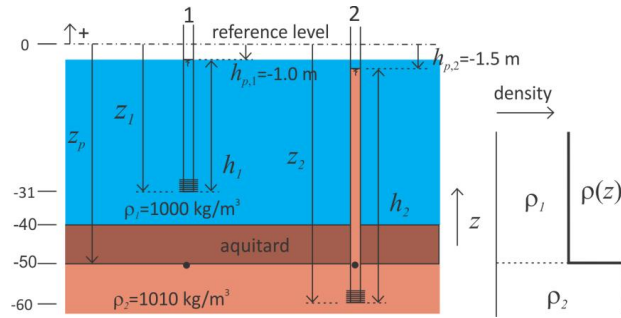
$$q^{at\ z=z_2} \cong -k_x \frac{\phi_{f,2}^{at\ z=z_2} - \phi_{f,1}^{at\ z=z_2}}{\Delta x}$$

### Freshwater head $\phi_f$ : vertical flow?



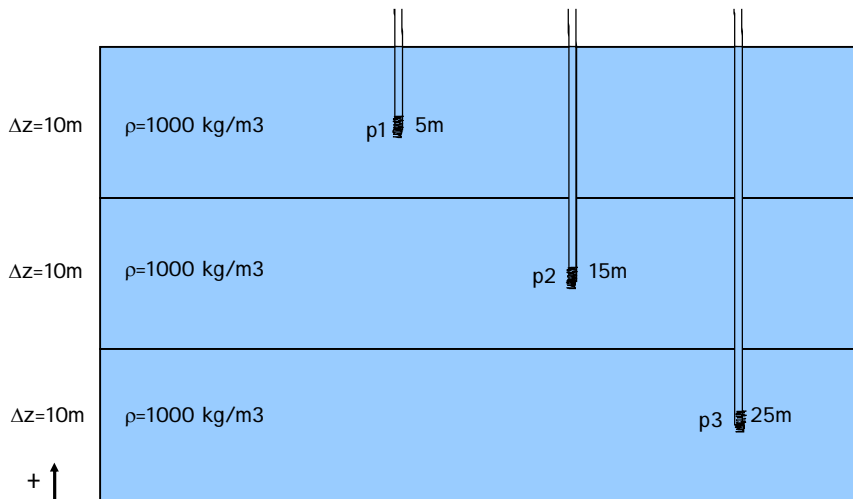


### Freshwater head $\phi_f$

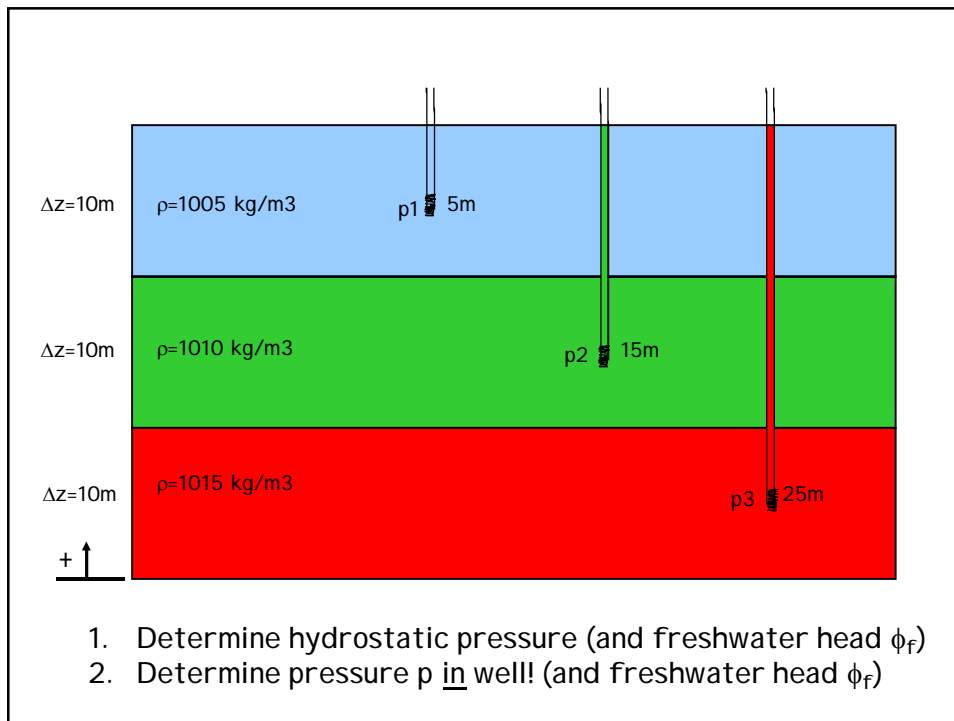
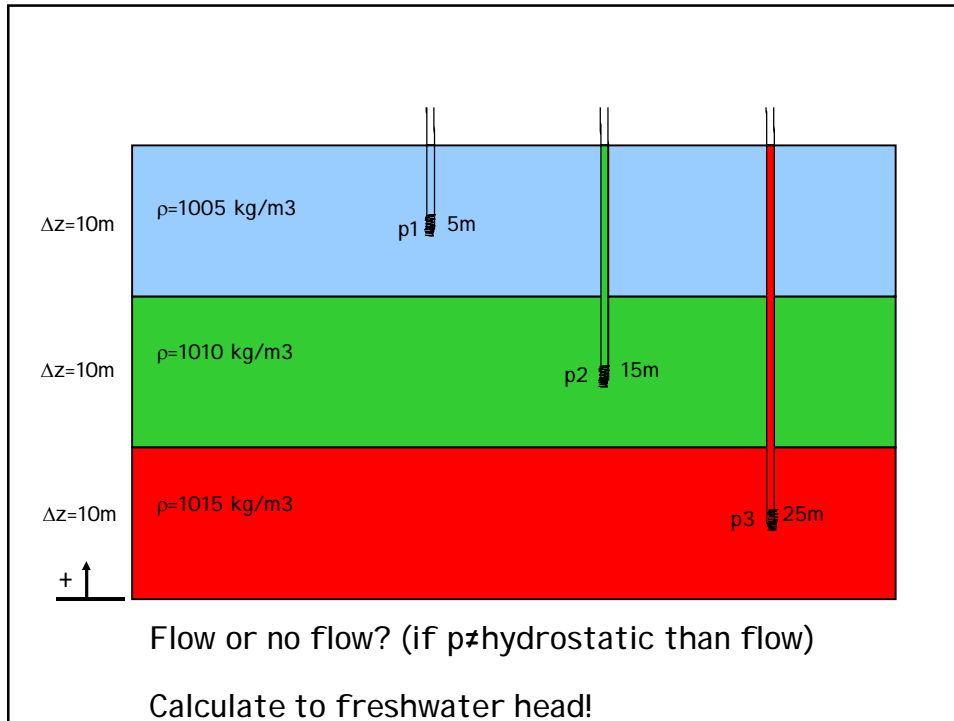


$$\phi_{f,1}^{z=-50} = -50 + \frac{1000}{1000}30 + \frac{1}{1000g} \int_{-50}^{-31} 1000g dz = -50 + 30 + 19 = -1.0$$

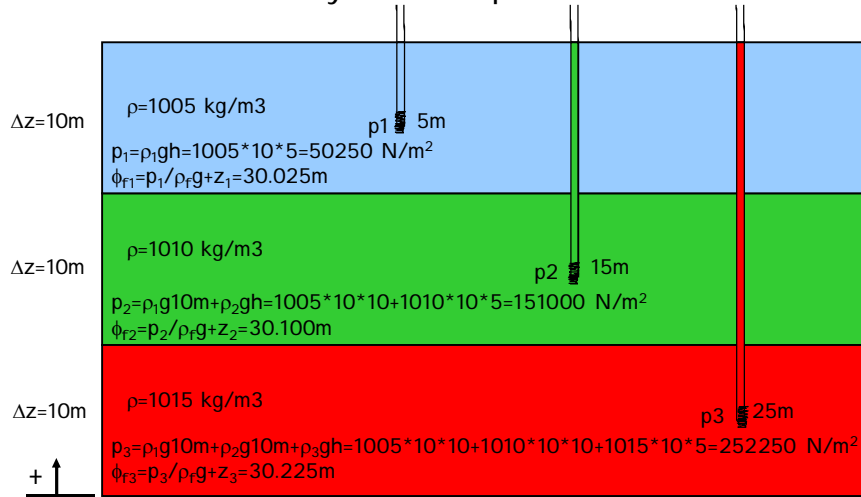
$$\phi_{f,2}^{z=-50} = -50 + \frac{1010}{1000}58.5 - \frac{1}{1000g} \int_{-50}^{-60} 1010g dz = -50 + 59.085 - 1.01(-50 + 60) = -1.015$$



No flow

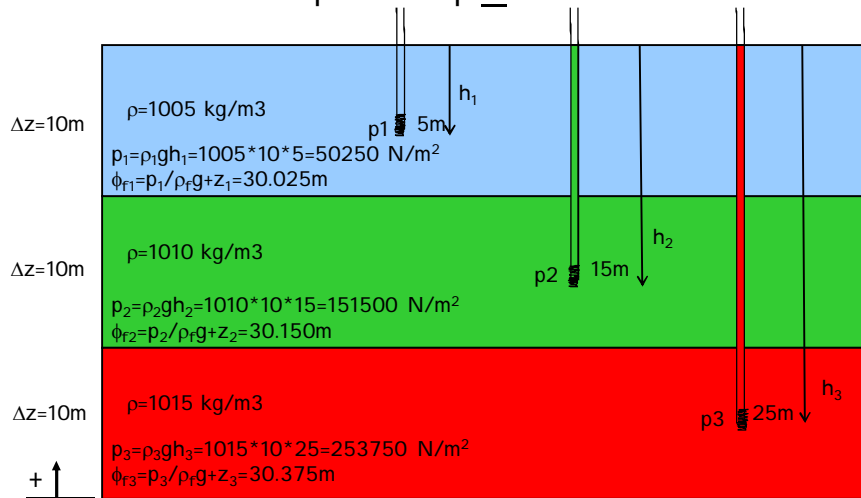


### 1. Determine hydrostatic pressure and frwhead

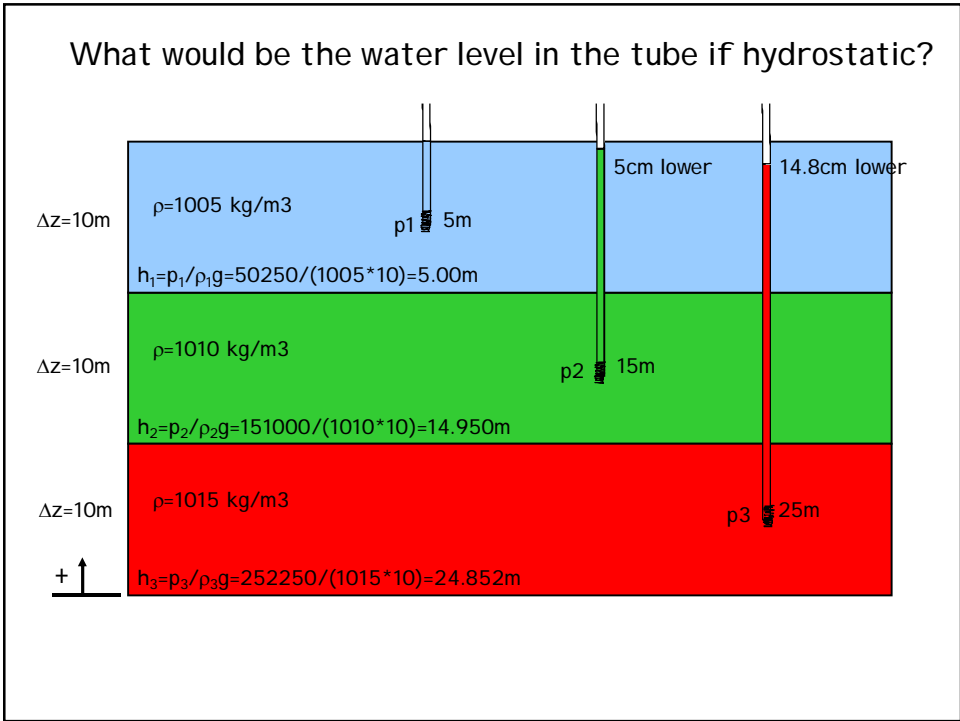
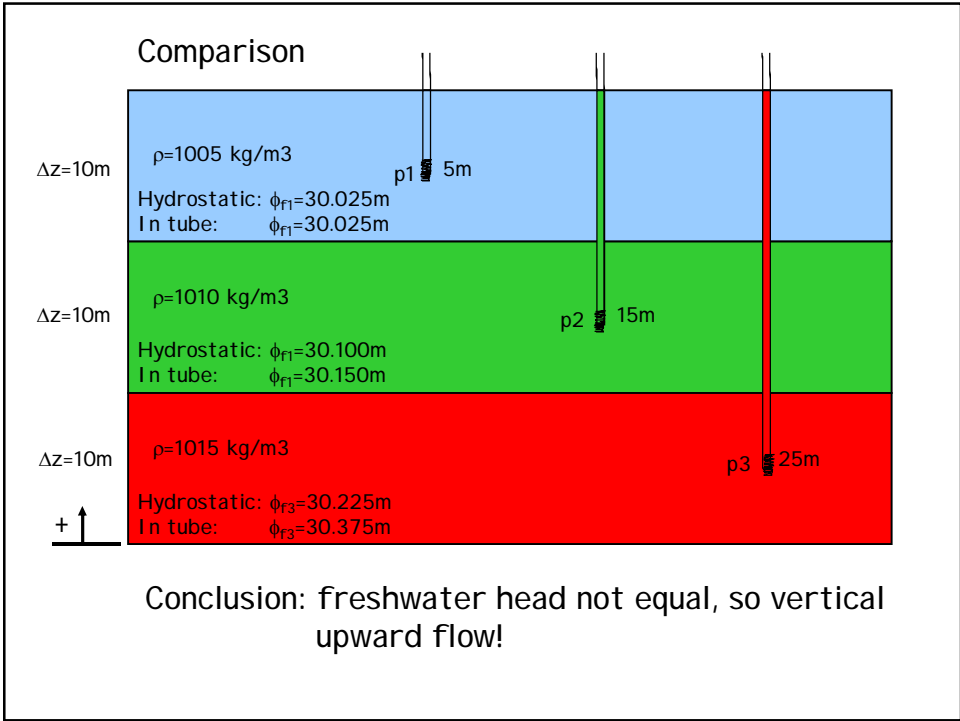


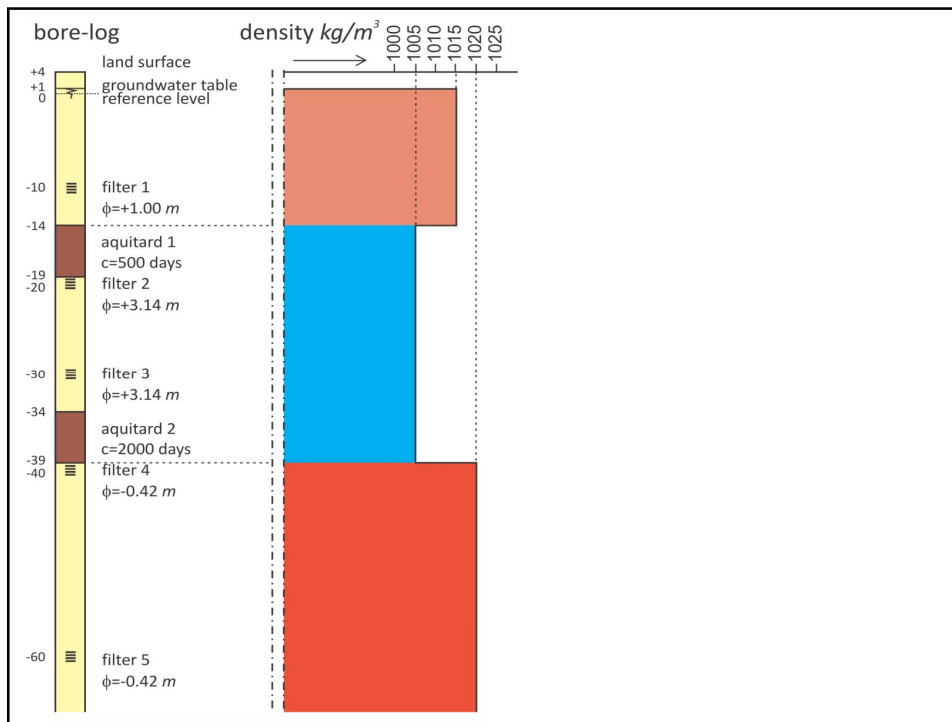
1. Determine hydrostatic pressure (and freshwater head  $\phi_f$ )
2. Determine pressure  $p$  in well! (and freshwater head  $\phi_f$ )

### 2. Determine pressure $p$ in well and frwhead



1. Determine hydrostatic pressure (and freshwater head  $\phi_f$ )
2. Determine pressure  $p$  in well! (and freshwater head  $\phi_f$ )



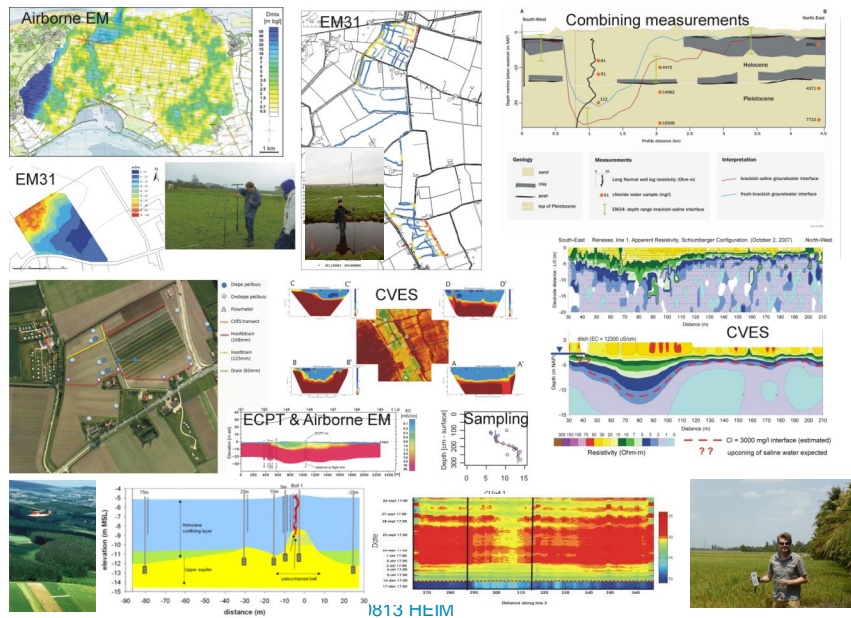


## Take home message

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

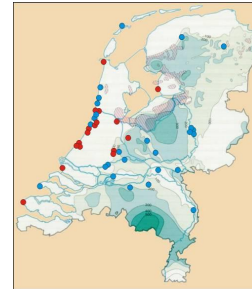
# Monitoring

## Different (fresh-salt) monitoring techniques



# Monitoring salt in groundwater

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

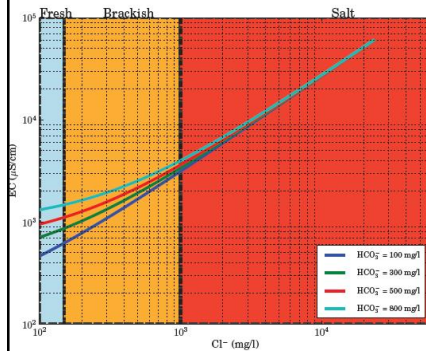


- Pumping stations with salinisation
- Pumping stations closed due to salinisation

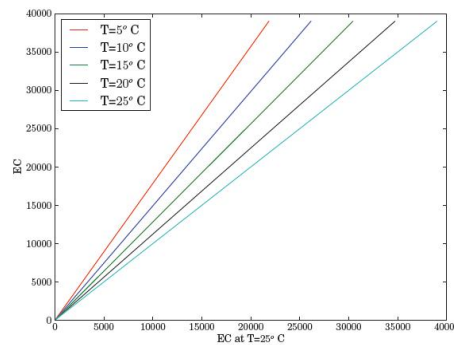
- Methods:
  1. Direct: water sample available
  2. Indirect: conductance of the subsoil

Source: V. Post, 2007

## EC and Chloride



EC-Cl at different  $\text{HCO}_3^-$  concentrations.

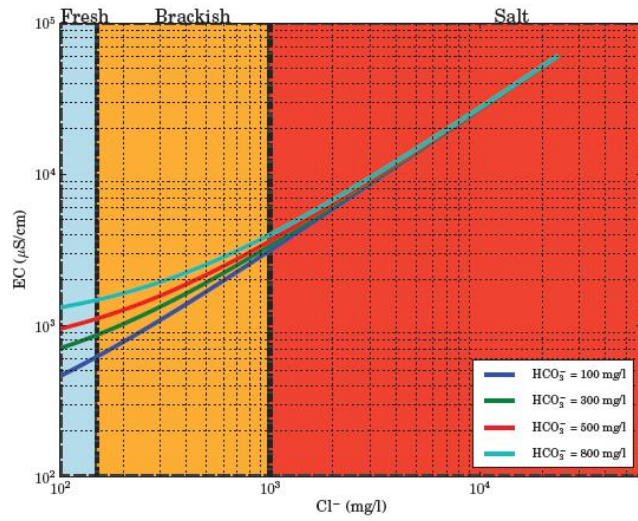


(b) EC and temperature standardized EC.

P. Pauw, 2009

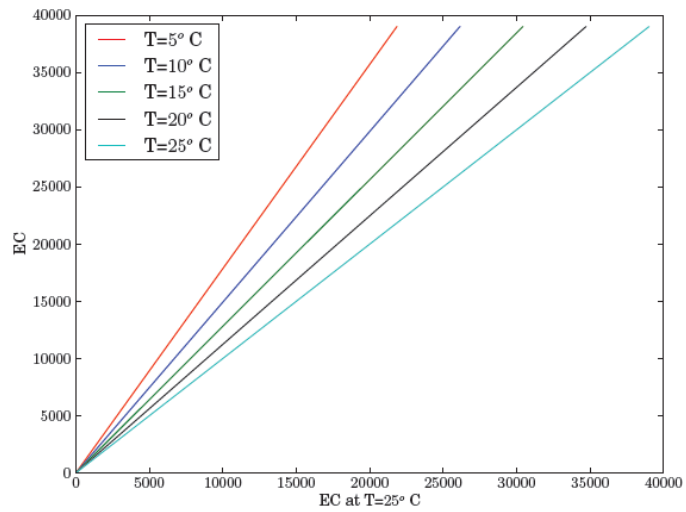
20120622 SWIM22

## EC and Chloride



20120<sup>6</sup> EC-Cl at different  $\text{HCO}_3^-$  concentrations.

## EC and Chloride



2<sup>1</sup> (b) EC and temperature standardized EC.



## Airborne measurements

Measuring system	Physical parameter	Geology/terrain information
radar	EM traveltime	Terrain elevation
Infrared photography	Infrared radiation	Surface temperature
Time domain EM Frequency domain EM	Electr. resistivity from induced EM fields	Lithology Water salinity
Magnetic gradiometer	Magnetic field (variations)	Lithology (magnetite) Artefacts Steel/Iron objects
Spectral gamma	Radiation (gamma)	Soil type Surface lithology Recent disturbance

Source: Koos Groen

## Surface measurements

Measuring system	Physical parameter	Geology/terrain information
Ground penetrating radar	EM traveltime, dielectric constant,	Lithology Soil moisture
ERT	Electr. resistivity	Lithology Water salinity
Time domain EM Frequency domain EM	Electr. resistivity	Lithology Water salinity
Magnetometer (total field, gradiometer)	Magnetic field (variations) magnetic susceptibility	Lithology (magnetite) Artefacts Steel/Iron objects (UXO)
Spectral gamma	Radiation (gamma)	Soil type Surface lithology Recent disturbance

Source: Koos Groen

# Cone Penetration Tests

Measuring system	Physical parameter	Geology/terrain information
mechanical CPT	Cone resistance Friction resistance	Lithology Geotechnical parameters
Electrical conductivity	Electrical formation conductivity	Water salinity
Continuous water pressure	Water pressure	Lithology Piezometric head
Water pressure dissipation in clay layers	Water pressure in time	Permeability clays
BAT sampling in CPT casing		Water chemistry
ROST, MIP		Contamination of hydrocarbons (high concentration)
Camera sonde	Visual view	Lithology, contamination, gas

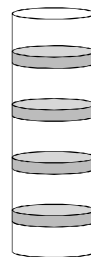
Source: Koos Groen

## Monitoring salt in groundwater: Direct methods

Method	Advantage	Disadvantage
1. Observation well	<ul style="list-style-type: none"> <li>•High accuracy</li> <li>•Detection trends</li> </ul>	<ul style="list-style-type: none"> <li>•Costly</li> <li>•Point measurement</li> </ul>
2. Well screens in observation well	<ul style="list-style-type: none"> <li>•High accuracy</li> <li>•Detection trends</li> <li>•High vertical resolution</li> </ul>	<ul style="list-style-type: none"> <li>•Costly</li> </ul>
3. Sediment sample (extraction milliliters of water)	<ul style="list-style-type: none"> <li>•High accuracy</li> <li>•High vertical resolution</li> </ul>	<ul style="list-style-type: none"> <li>•Very costly and time consuming</li> </ul>



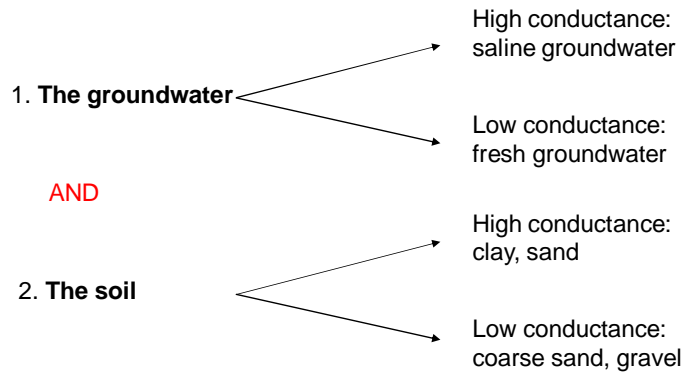
Direct methods 1 and 2



Source: V. Post, 2007

## Monitoring salt in groundwater: Indirect methods

Indirect methods measure the **conductance** of:



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	<ul style="list-style-type: none"> <li>•High resolution (3D)</li> <li>•Depth ~200 m</li> </ul>	<ul style="list-style-type: none"> <li>•Time consuming</li> </ul>
2. Electromagnetic measurements	<ul style="list-style-type: none"> <li>•Fast</li> </ul>	<ul style="list-style-type: none"> <li>•Limited vertical resolution</li> <li>•Sensitive for underground conductors (pipes)</li> </ul>
3. Satellites	<ul style="list-style-type: none"> <li>•Suitable for large areas</li> </ul>	<ul style="list-style-type: none"> <li>•Small vertical resolution</li> <li>•Low accuracy</li> </ul>

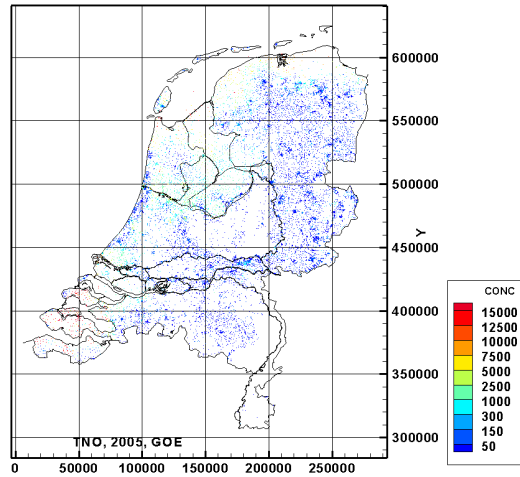
Source: V. Post, 2007

## Method used at Deltares

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

Combination of:

- Direct measurements
- Electrical conductance measurements
  - Surface (VES)
  - Borehole



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: V. Post, 2007

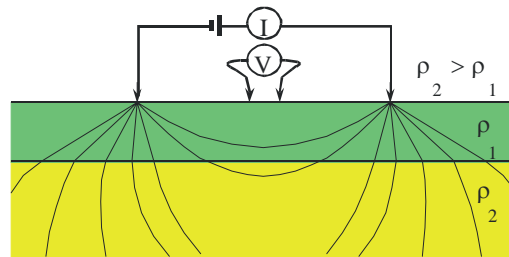
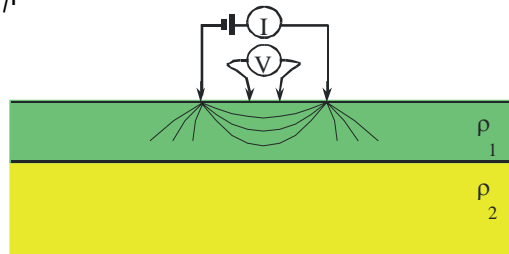


Source: Vitens

### Principle geo-elektrical measurement

I: currentelektrode, V: potentialelektrodes, Ra: appearant elektrical resistiuivity

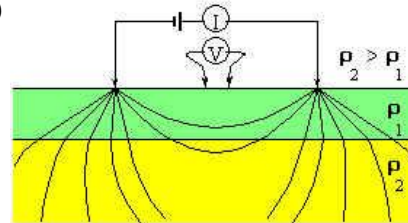
$$R_a = \text{constant} \cdot V/I$$



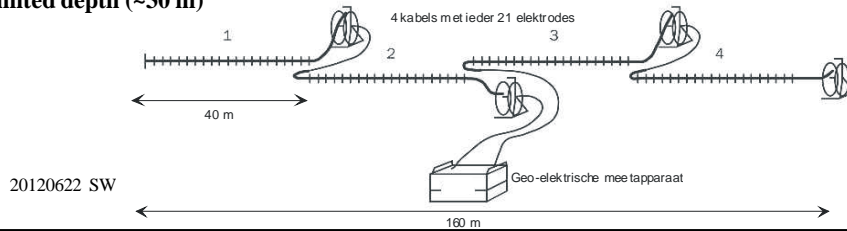
20120622 SWIM22

## Types geo-electrical measurements

- I Vertical Electrical Sounding (VES)
- 4 elektrodes at surface
- 1D elektrical resistivity profile
- Labor intense
- Accurate, great depths
- Deep hydrogeology



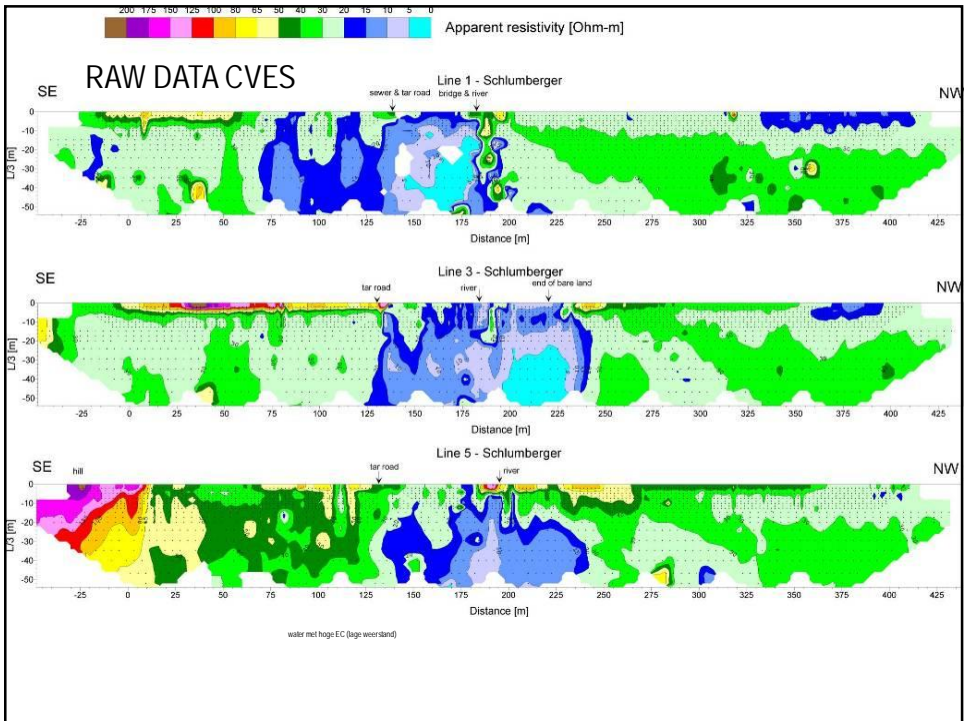
- II Continue Vertical Elektrical Sounding (CVES)
- >80 elektrodes at surface
- 2D elektrical resistivity subsurface
- Limited depth (~30 m)

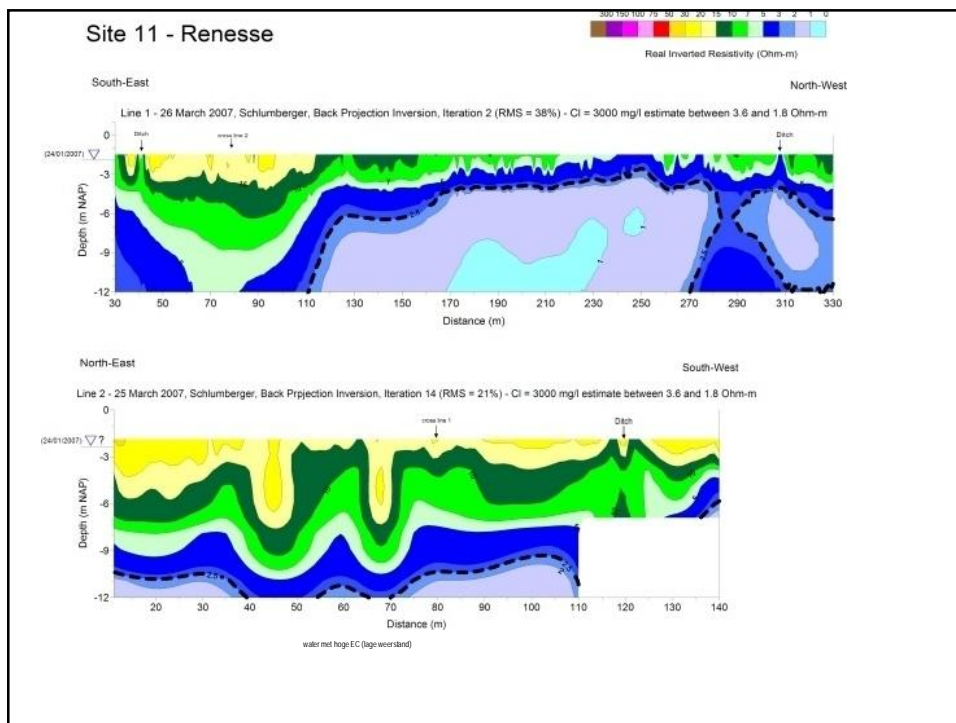
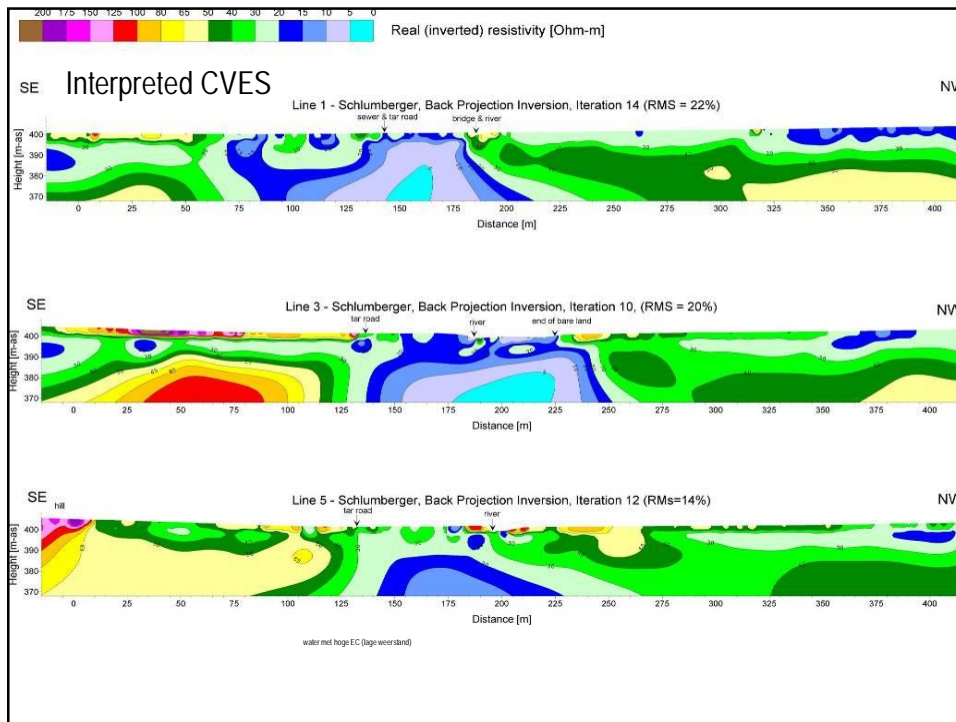


VES measurement end 1950s/begin 1960s



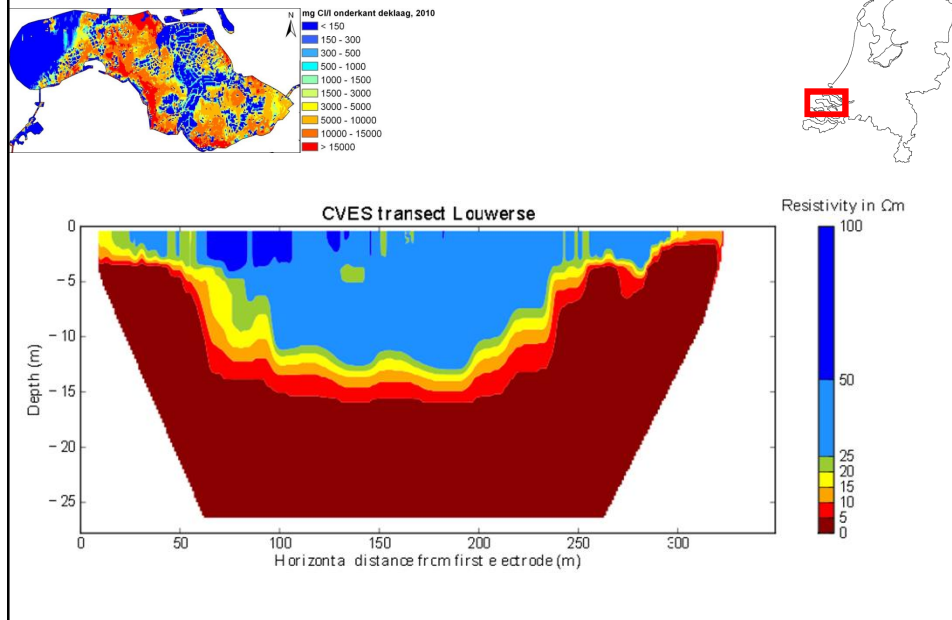
CVES  
measurements 2010s







## Possible measures for sandy creeks



## Monitoring salt in groundwater: Indirect methods

- Electrical conductance measurements

$$\rho_s = F \cdot \rho_w$$

$\rho_s$  = resistance subsoil & groundwater

$\rho_w$  = resistance groundwater

F = formation factor

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

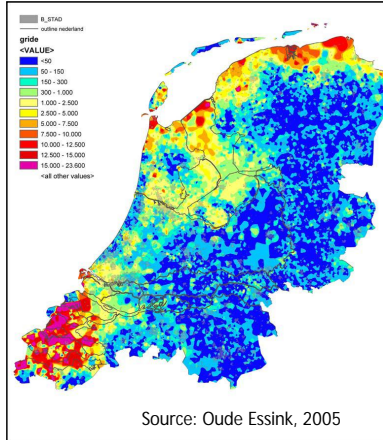
*F varies with the resistance of the groundwater*

If the lithology is known AND the measurement is in an aquifer  
 $\rightarrow \rho_w$  can be calculated

VES measurements are used in combination with borehole logging

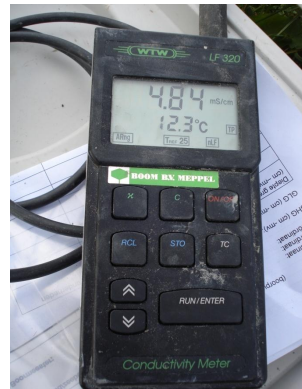
Source: Oude Essink, 2005

## Result: chloride concentration bottom Holocene toplayer



- 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 a combination of:
  1. Direct measurements (3500)
  2. Electrical conductance in boreholes (2000)
  3. Vertical Electric Sounding (VES) measurements (10.000)

## T-EC probe

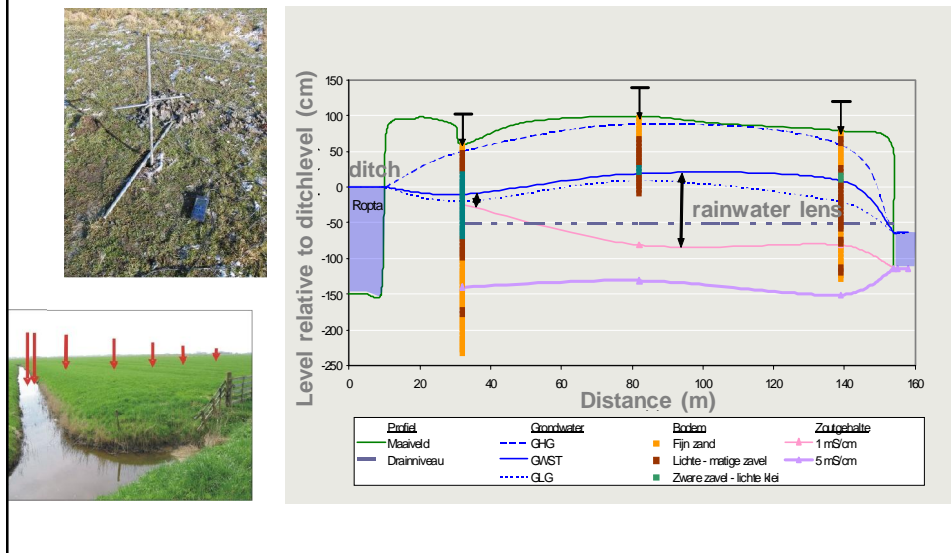


# T EC fieldwork

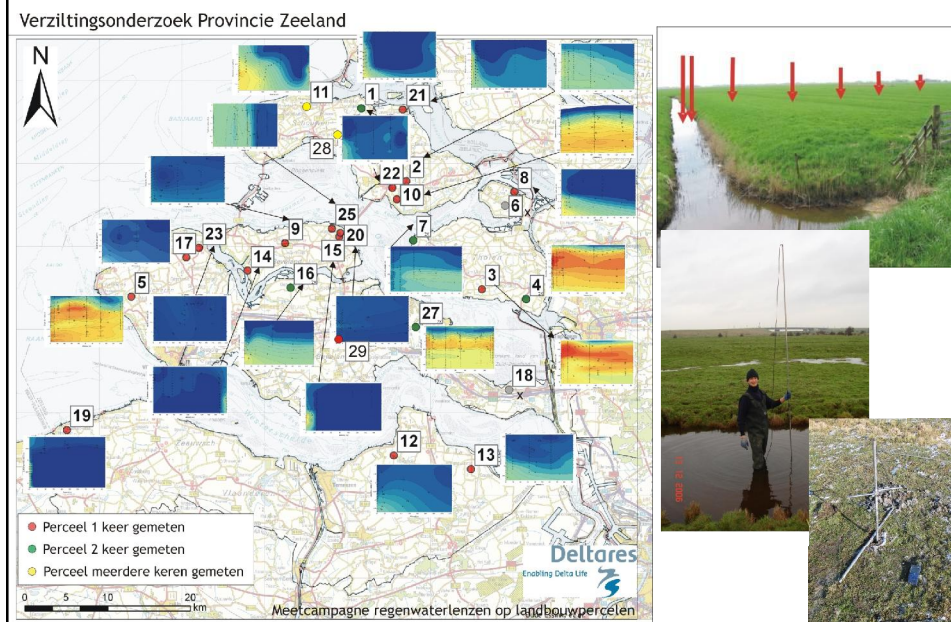
## Altitude measurements



## Use field measurements to understand the process



## TEC-probe Monitoring campaign 2005-2009

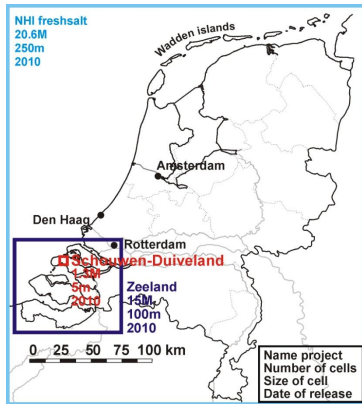


# CliWat [www.cliwat.eu](http://www.cliwat.eu)

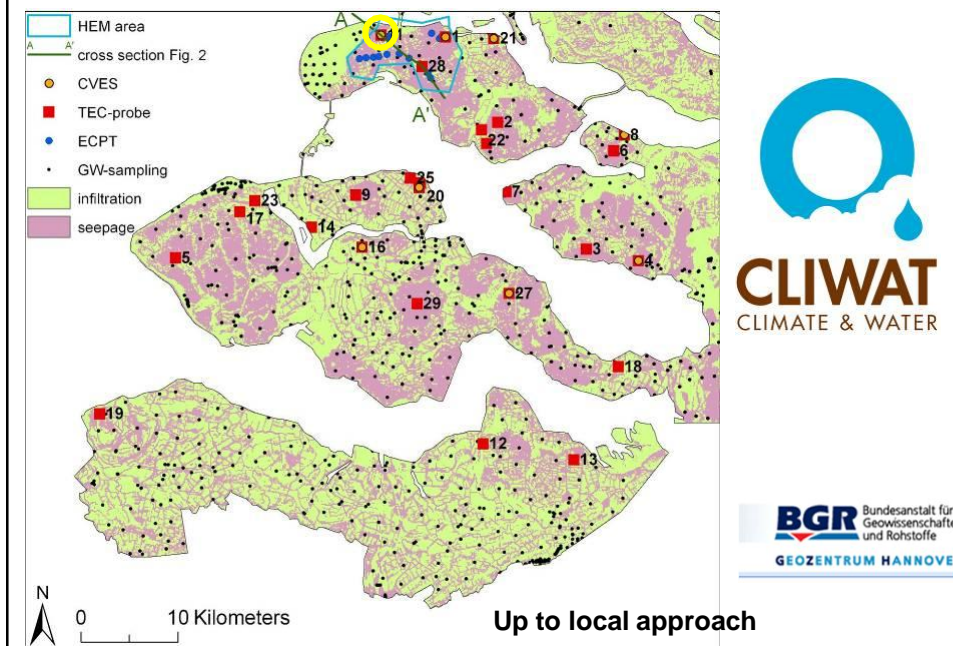
- Transnational project in the North Sea Region
- Main objectives:
  - to evaluate the physical and chemical impacts of climate change on groundwater and surface water systems
  - to provide data for adaptive and sustainable water management and infrastructure.
- Different innovative monitoring techniques (Helicopter EM, CVES, CPT, TEC-probe) are used to map the salinization status of the coastal groundwater system.



## Description local area



# Monitoring network in our Pilot Area Zeeland



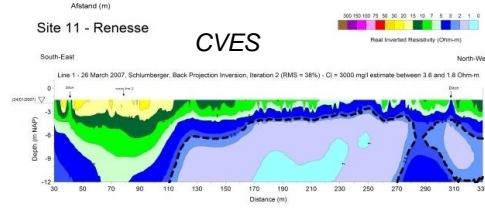
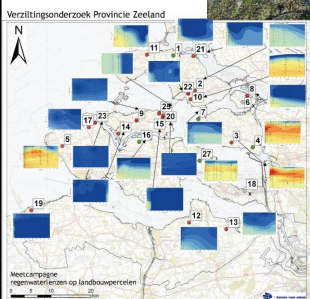
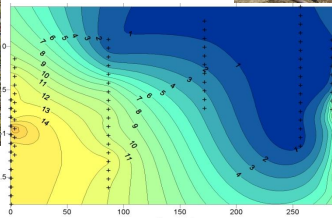
## Example: Assessing effect of climate change on salt water intrusion

### Monitoring:

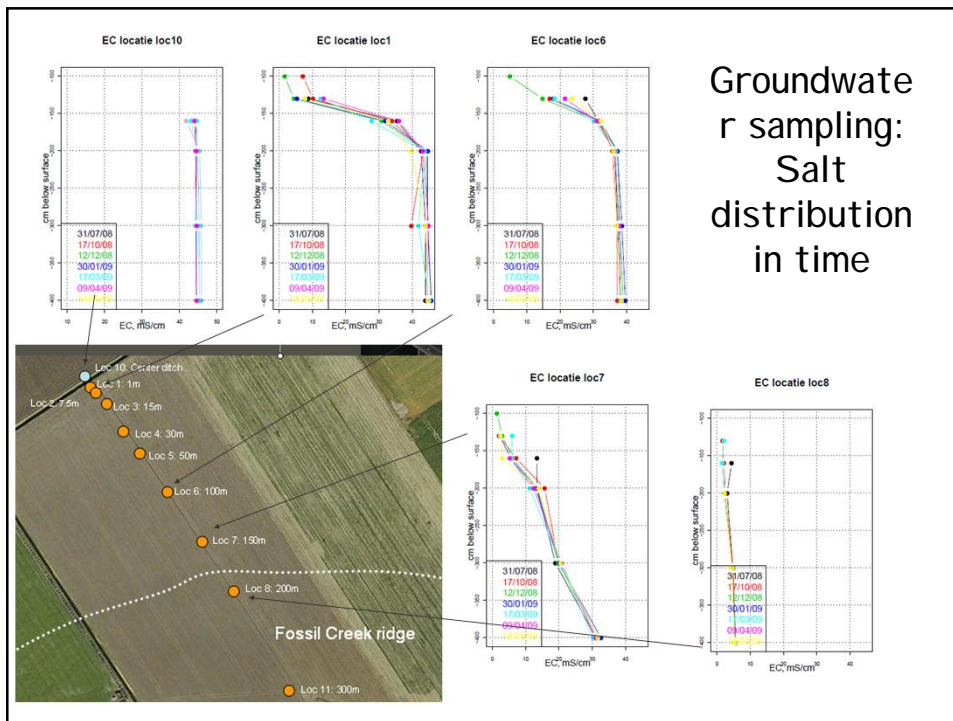
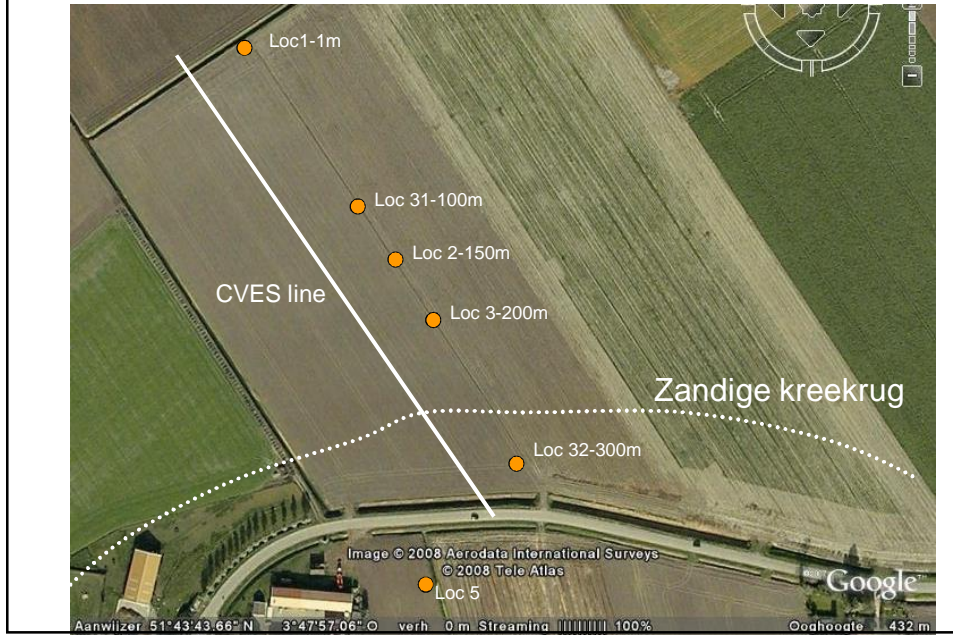
Source: Oude Essink, 2009

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

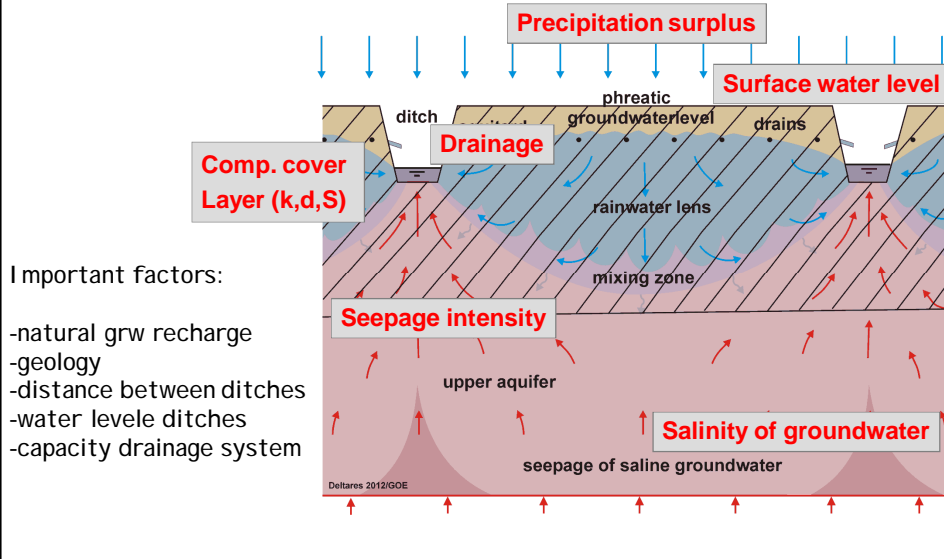
TEC probe



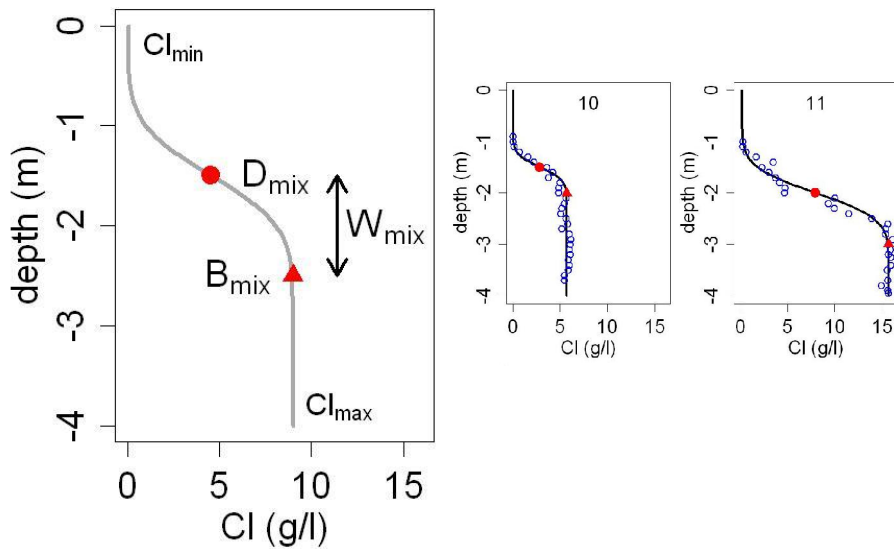
# Site 11: from infiltration to seepage



## Factors controlling fresh-salt interface

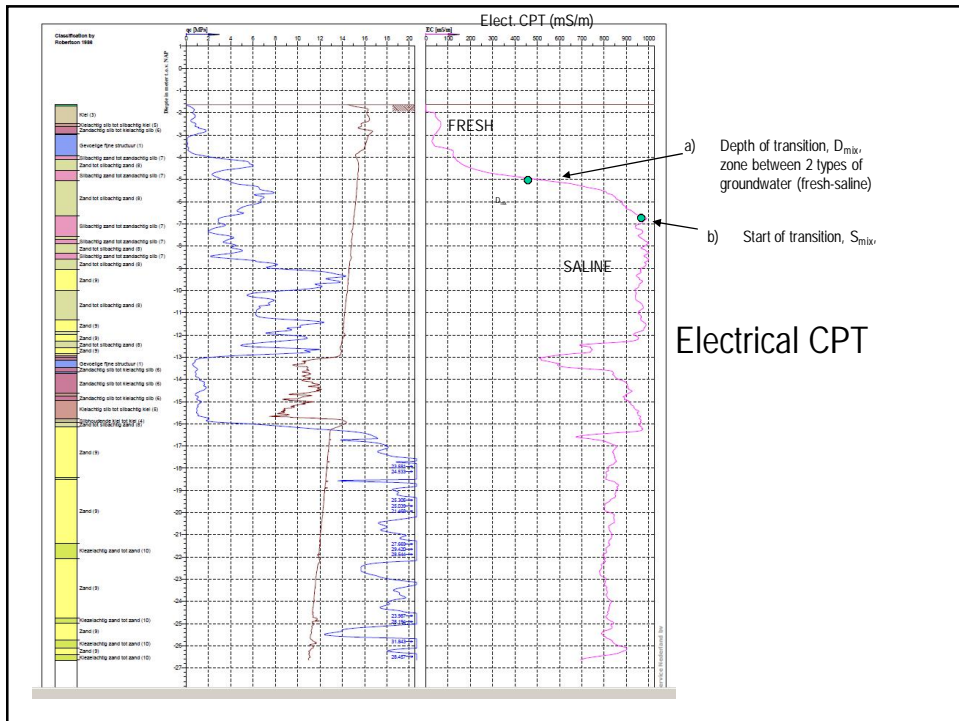
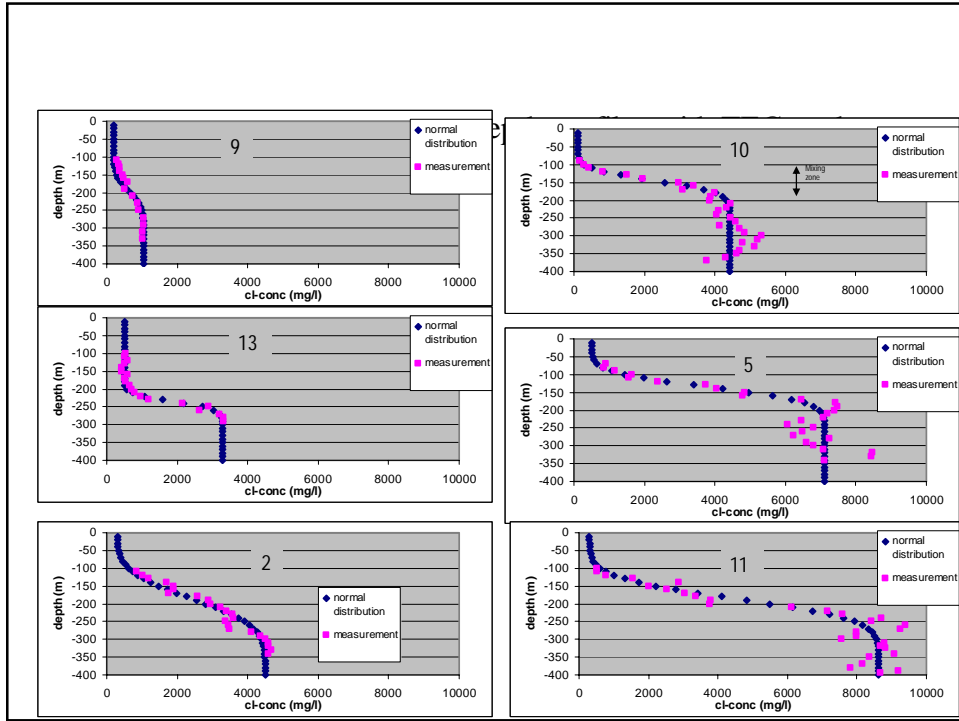


## Lens characteristics

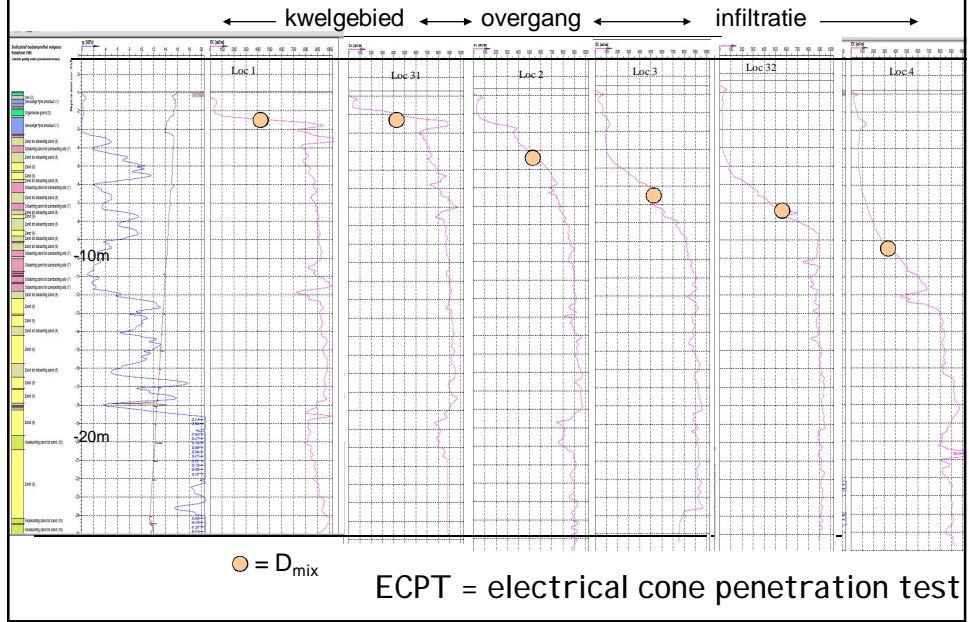


Louw, P.G.B., de, Eeman, S., Siemon, B., Voortman, B.R., Gunnink, J., Baaren, E.S., van and G.H.P. Oude Essink, Shallow rainwater lenses in deltaic areas with saline seepage, *Hydrol. Earth Syst. Sci. Discuss.*, 8, 7657-7707, 2011.



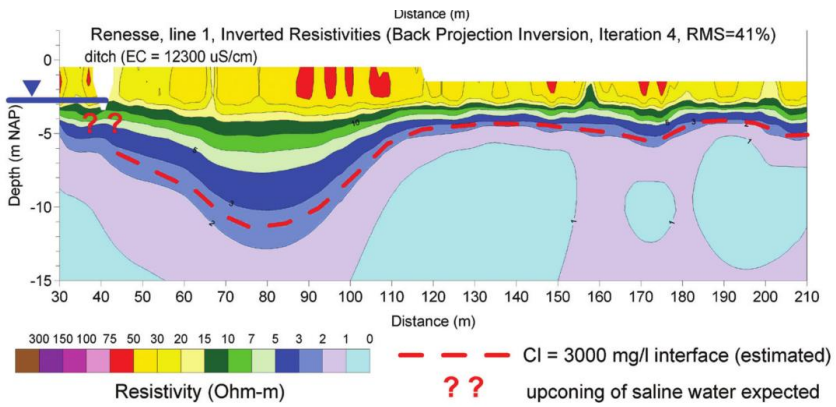


# Results from ECPT's (soundings)

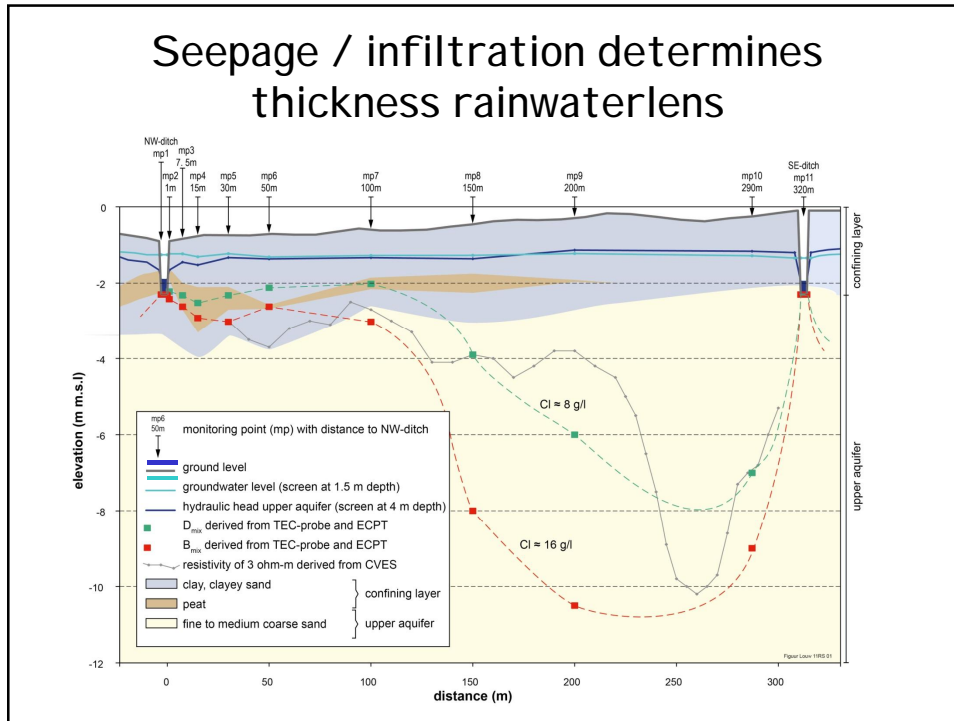


# CVES

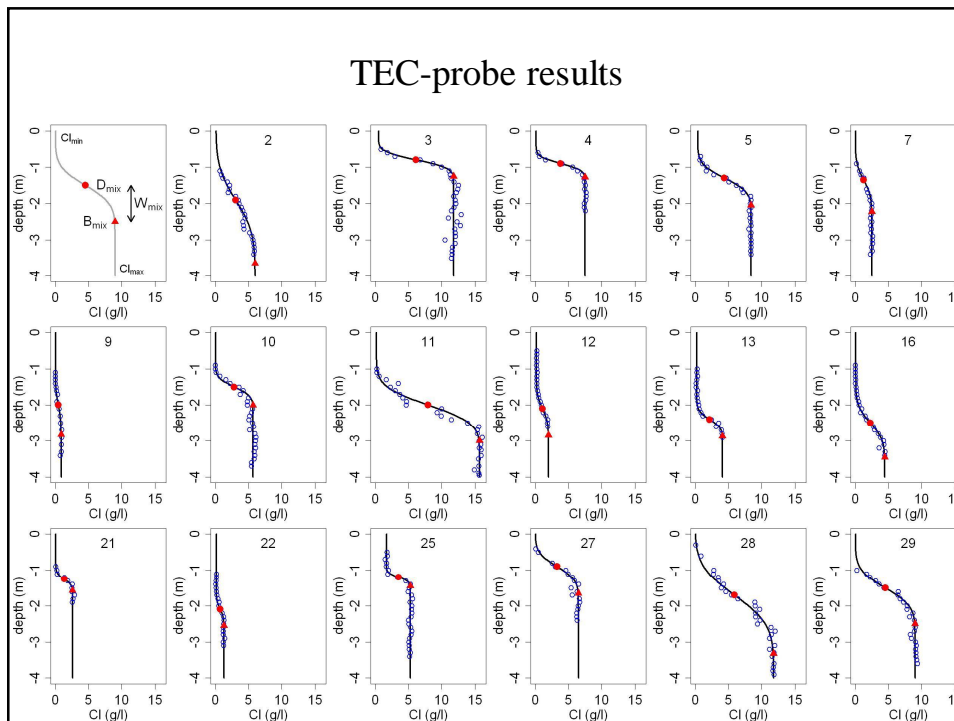
CVES: continuous vertical electrical sounding



## Seepage / infiltration determines thickness rainwater lens



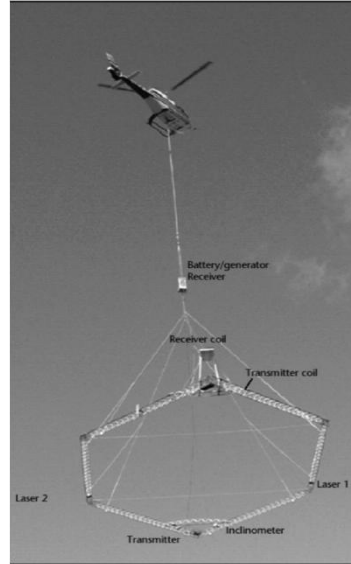
## TEC-probe results



## Electrical conductance measurements



10 juni 2013



## From bulk to groundwater resistivity

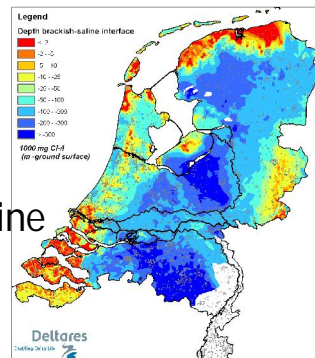
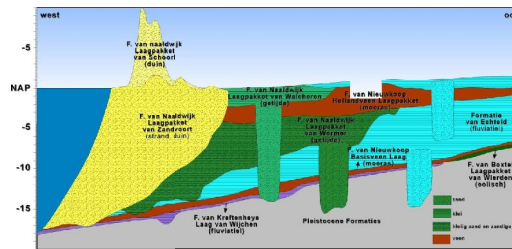


EC<sup>bulk</sup>

EC lithology

EC groundwater  
→ fresh-brackish-saline

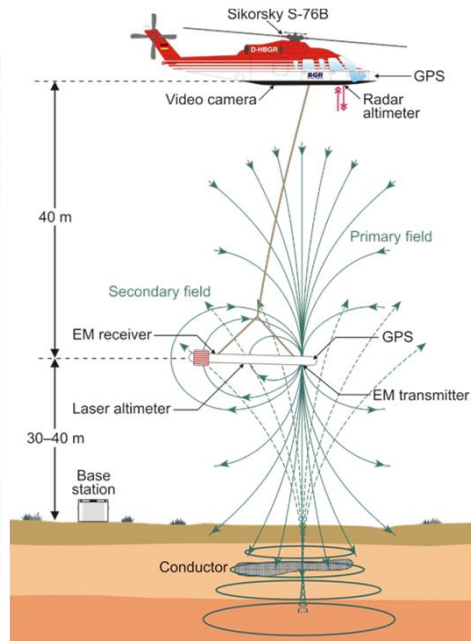
EC = Electrical Conductivity = conductivity



## BGR helicopter-borne geophysical system

### Airborne geophysical survey system

Helicopter:	Sikorsky S-76B
Helicopter equipment:	GPS-Navigation GPS-Tracking Radar and barometric altimeters Video camera
Standard equipment:	Electromagnetic system Magnetometer Laser altimeter Gamma-ray spectrometer
Optional equipment:	Laser scanner Pulse radar <i>Stepped frequency</i> - Radar Gravimeter Differential GPS Photogrammetric camera Infrared camera
Base station equipment:	Magnetic total field sensor Air pressure sensor Differential GPS
Survey speed:	130 – 160 km/h
Sampling distance:	~ 4 and 40 m
Line separation	50 – 2000 m



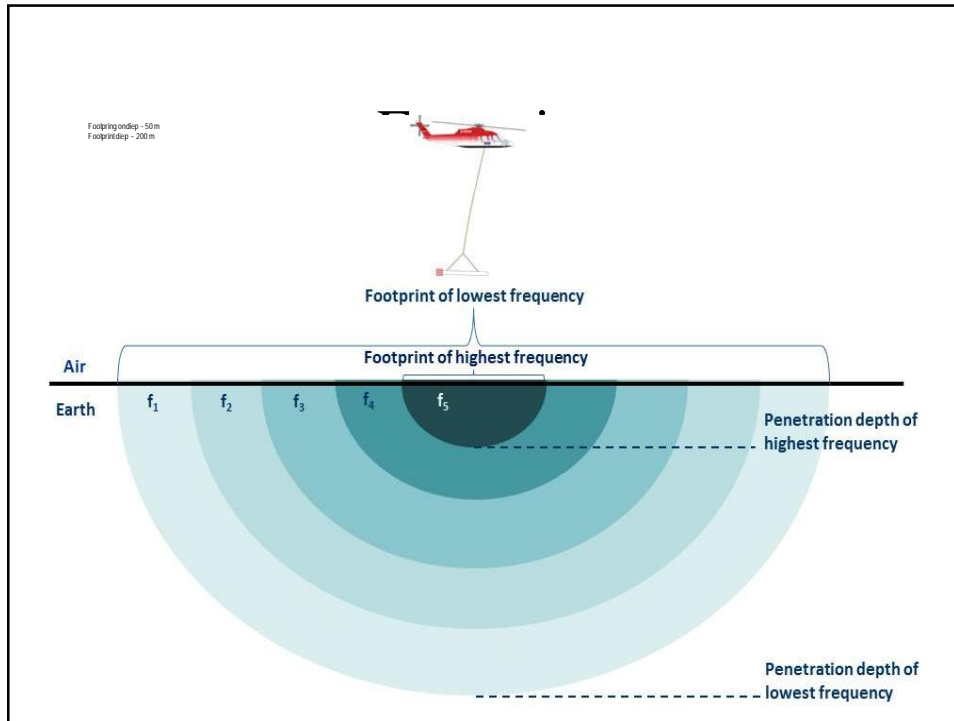
Meeting in Utrecht Feb. 25th 2014

## BGR helicopter-borne geophysical system

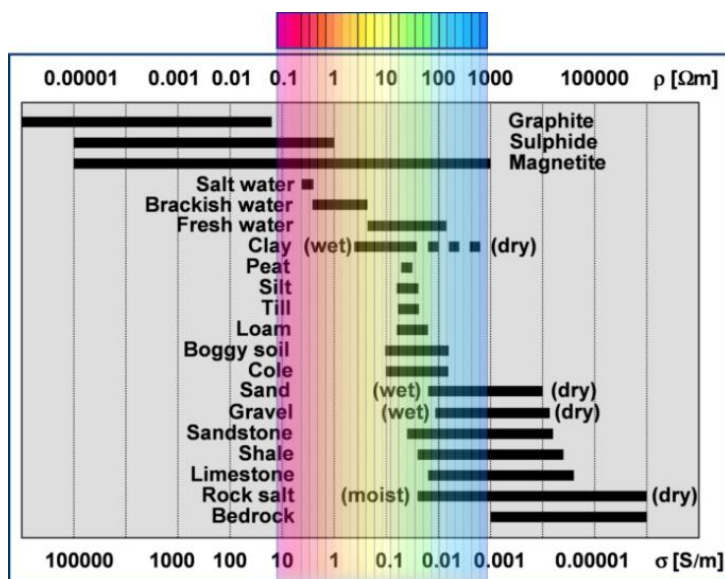
### Recent six-frequency HEM system

Type:	RESOLVE – Digital system Modified BKS36a DSP and BKS60 DSP systems	
Length:	~ 10 m	
Weight:	~ 400 kg incl. cable (80 kg)	
Manufacturer:	Fugro Airborne Systems, Canada	
Frequency [Hz]	Coil separation[m]	Geometry
387	7.94	horizontal coplanar
1820	7.93	horizontal coplanar
5500	9.06	vertical coaxial
8225	7.93	horizontal coplanar
41550	7.91	horizontal coplanar
133200	7.92	horizontal coplanar

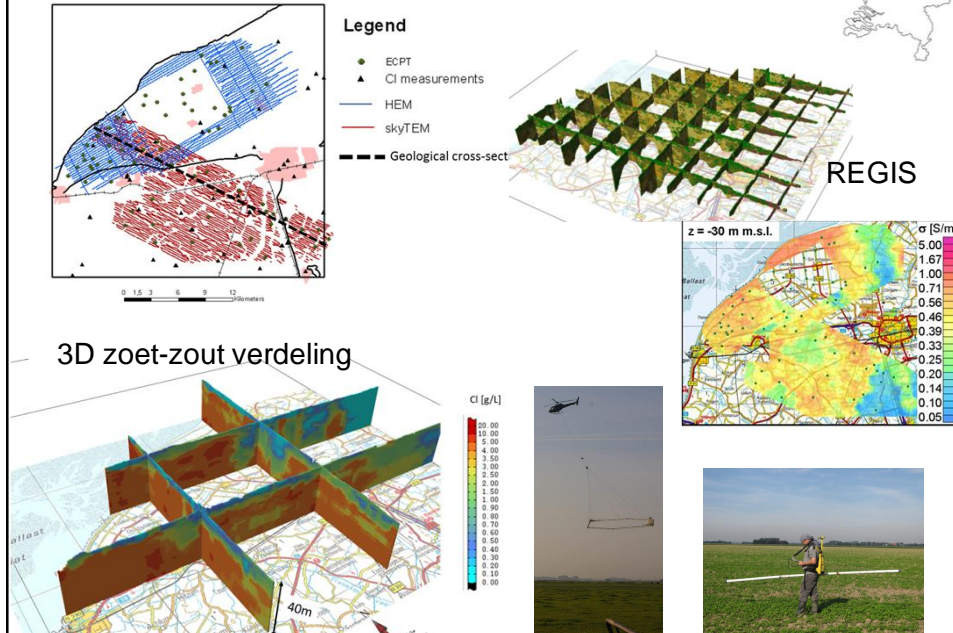




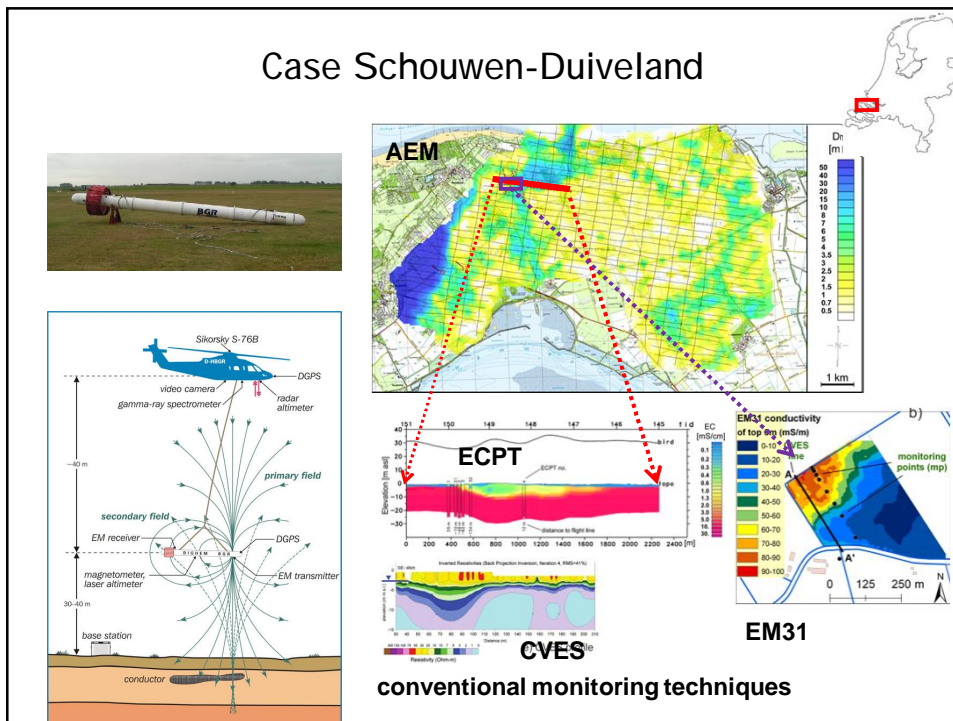
## Typical resistivities / conductivities

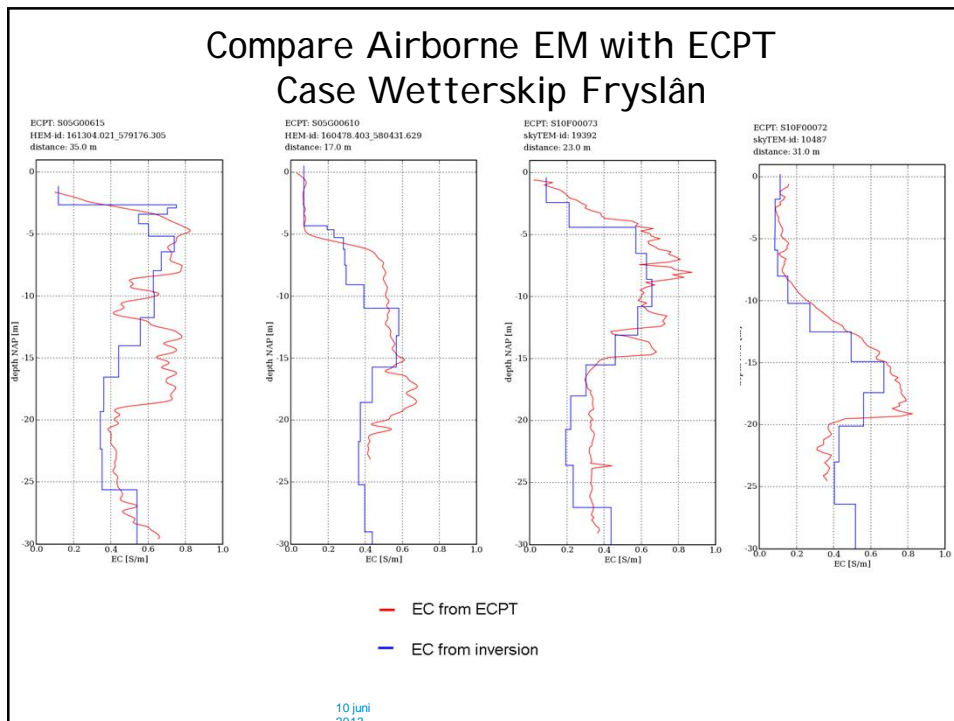
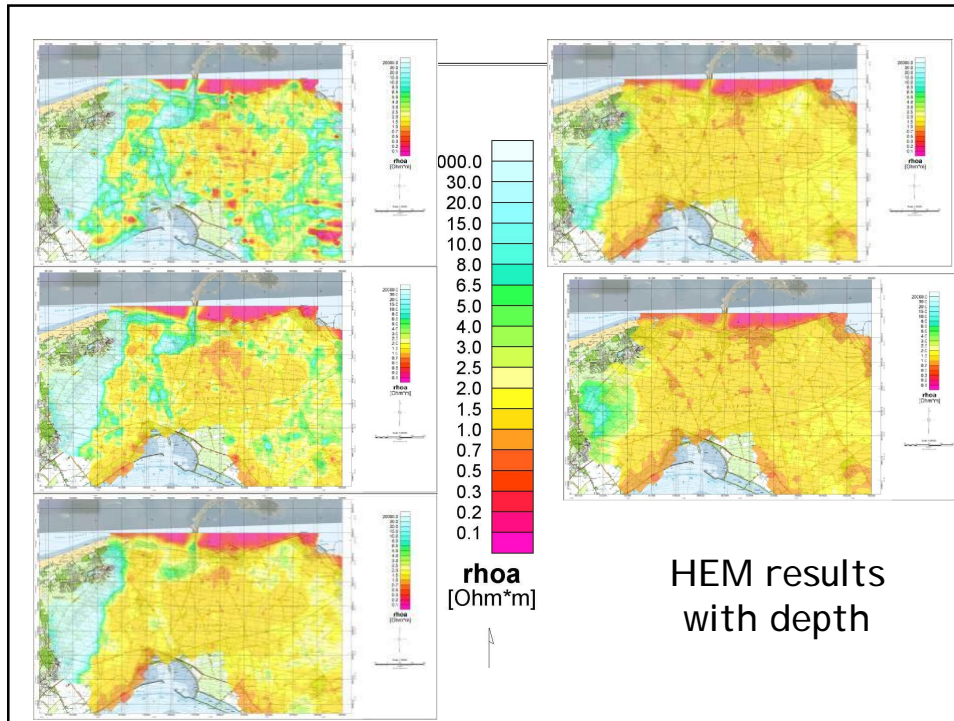


## Case Wetterskip Fryslân



## Case Schouwen-Duiveland





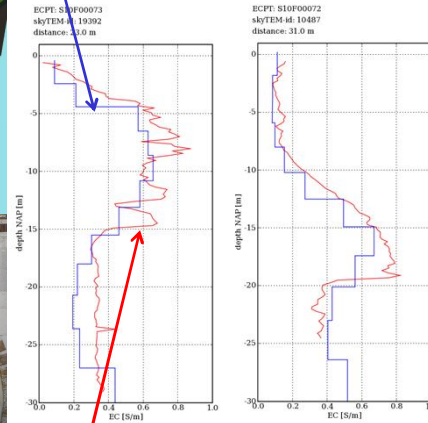


# 3D characterising fresh-saline groundwater



How much samples in 1 week on 900km<sup>2</sup>?

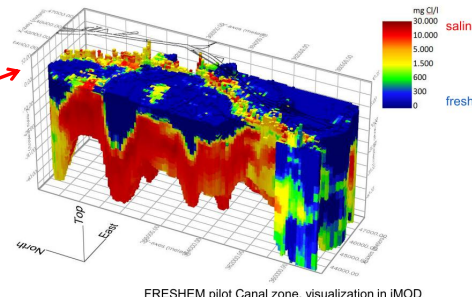
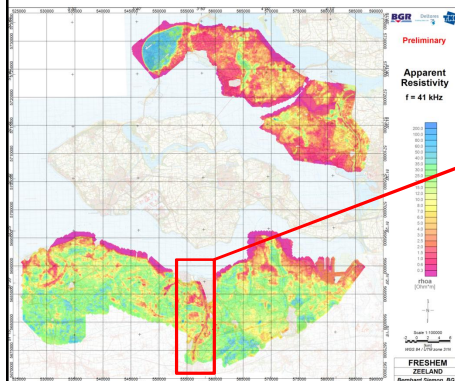
**AEM: 80000 data points**



**In-situ: >100 data points**

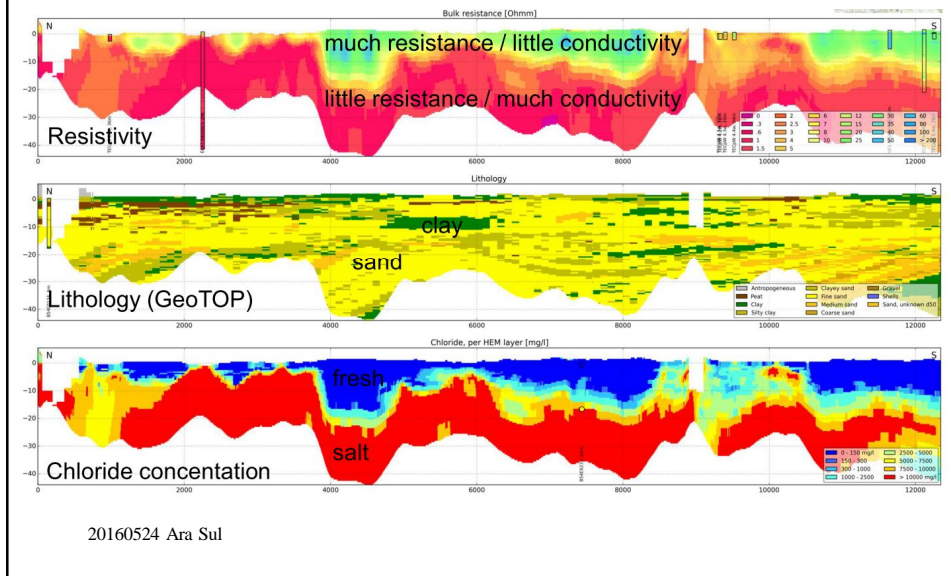
# 3D Characterisation of the subsoil

Airborne EM surveys:  
much cheaper, faster, 3D,  
and as equal accurate as  
conventional geophysical methods

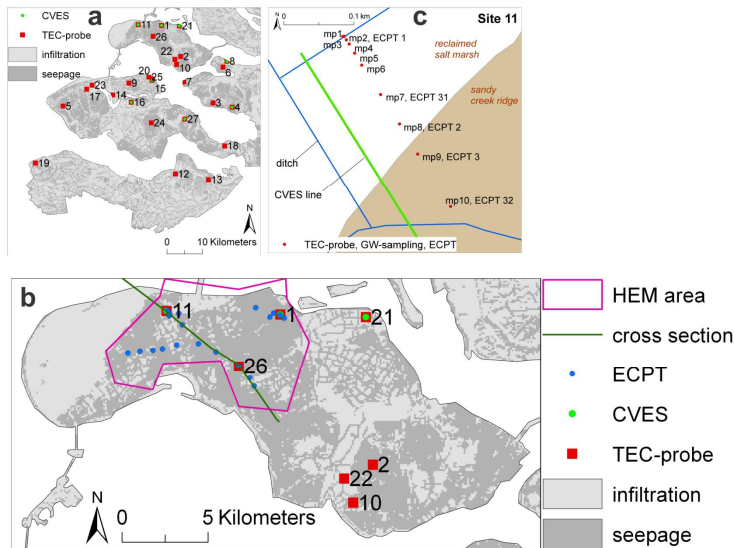


FRESHEM pilot Canal zone, visualization in iMOD

# Example NL, Zeeland, project FRESHEM



## Combining monitoring techniques



10 juni 2013

# Helicopter-EM data for mapping fresh-saline groundwater

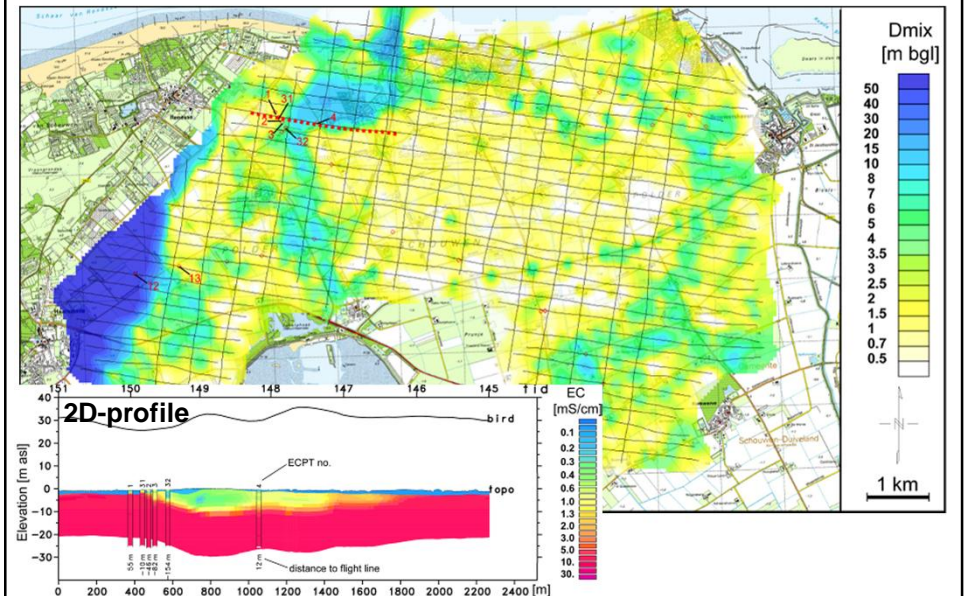
HEM

- dunes
- reclaimed salt marches
- creek deposits

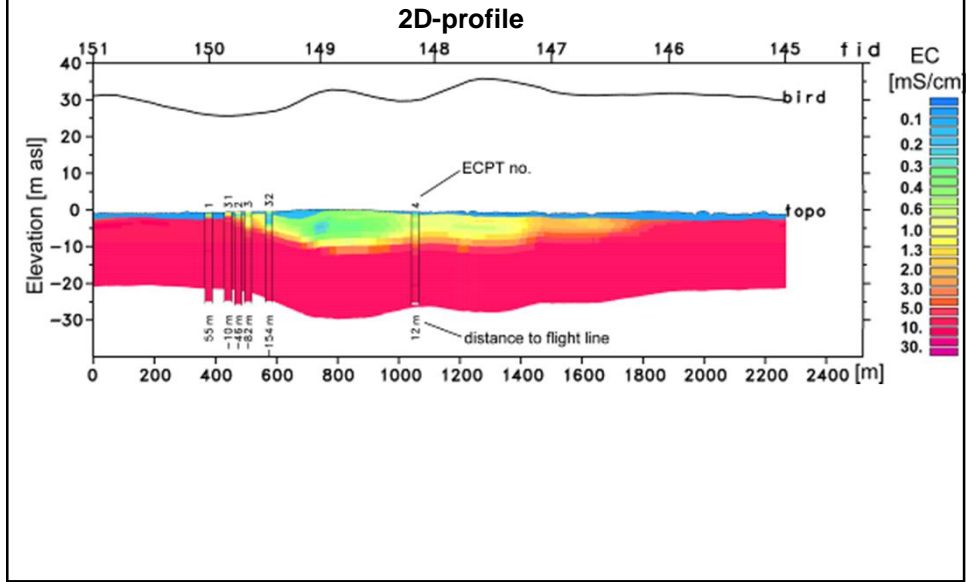
Interreg IV-B

**CLIWAT**  
CLIMATE & WATER

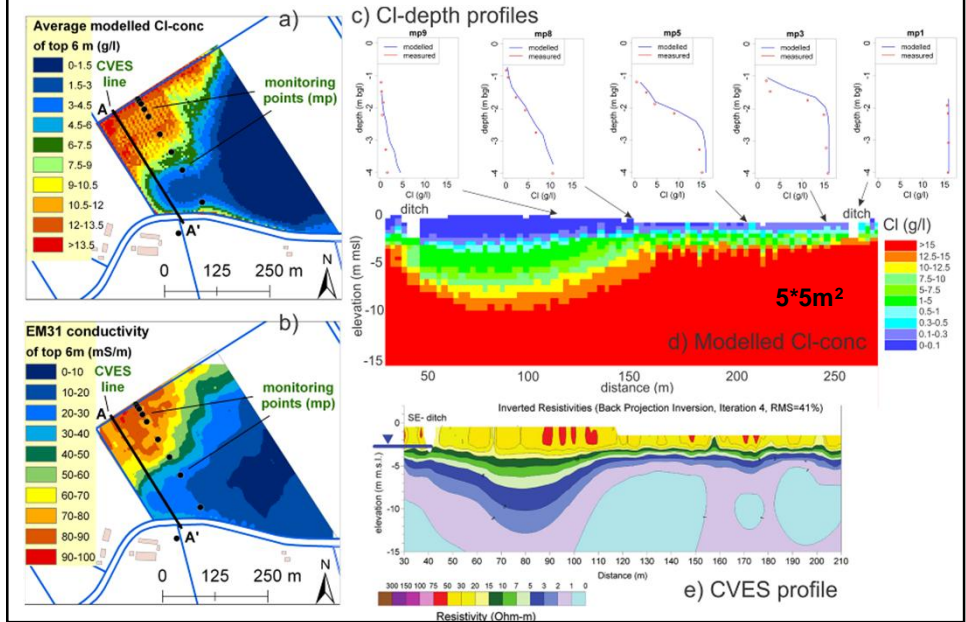
# Thickness rainwater lens ( $D_{mix}$ ) by HEM



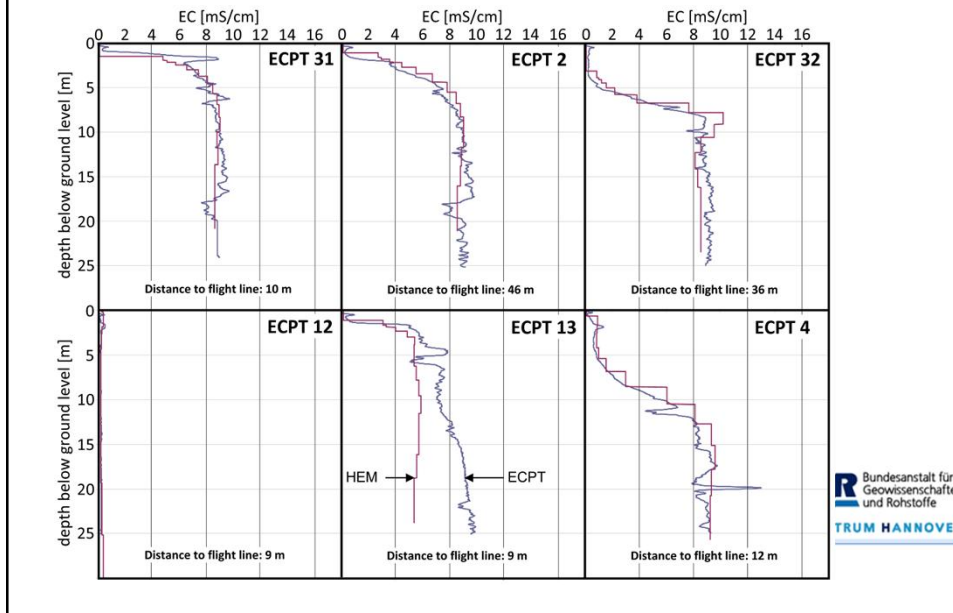
# Thickness rainwater lens ( $D_{mix}$ ) by HEM



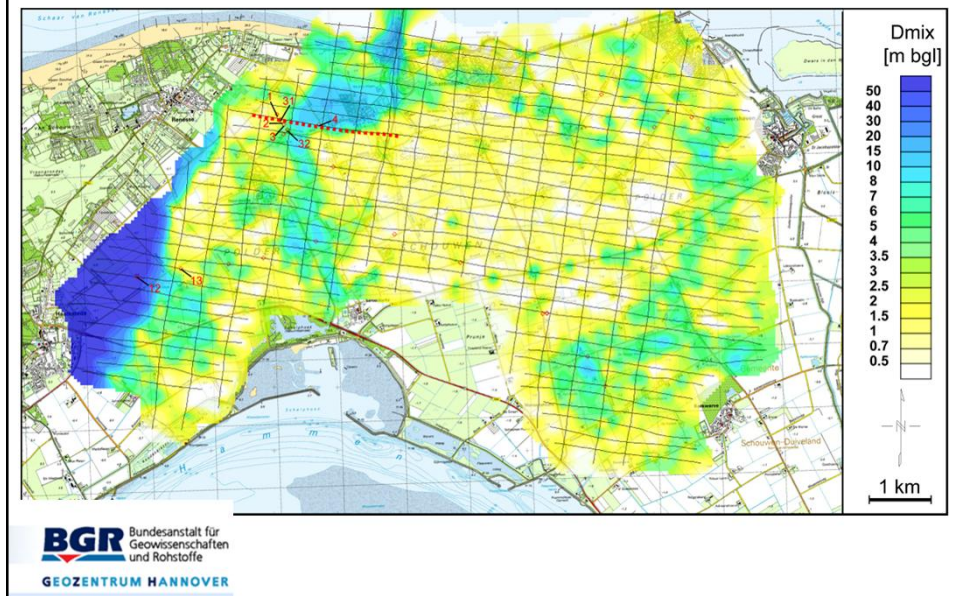
# Comparison monitoring data with model results



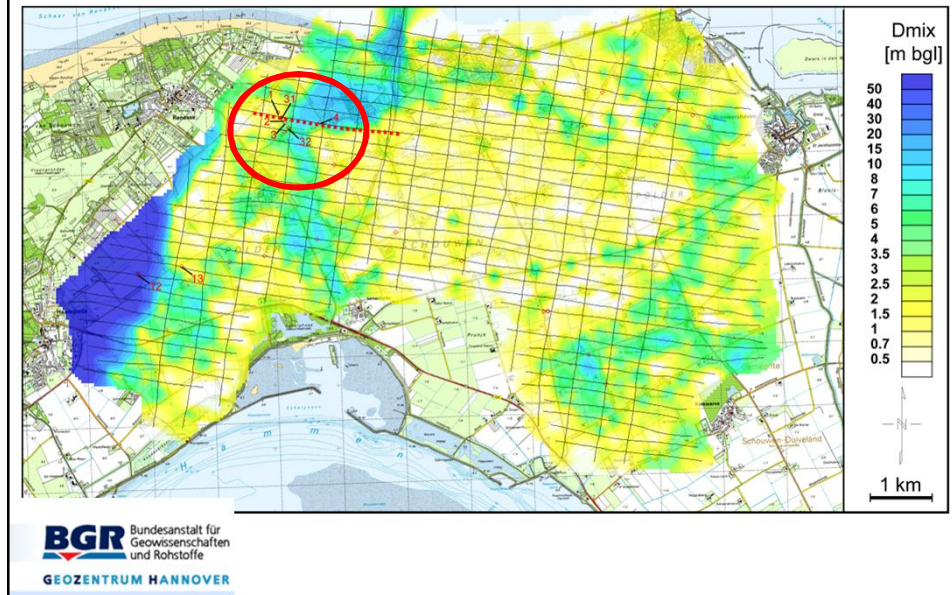
## Comparison HEM - ECPT



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



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



## Local 3D model of the agricultural plot

### Modelling:

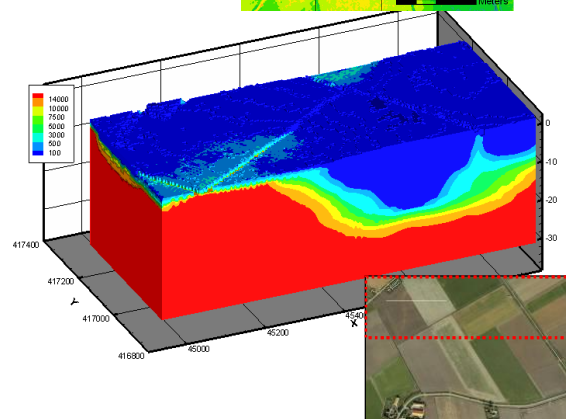
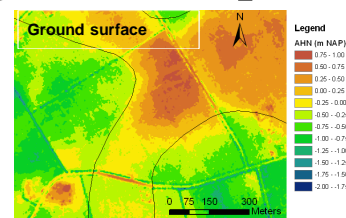
- variable-density
- 3D, non-steady
- groundwater flow & coupled solute transport
- model cell size:  $5 \times 5 \text{ m}^2$

### Code:

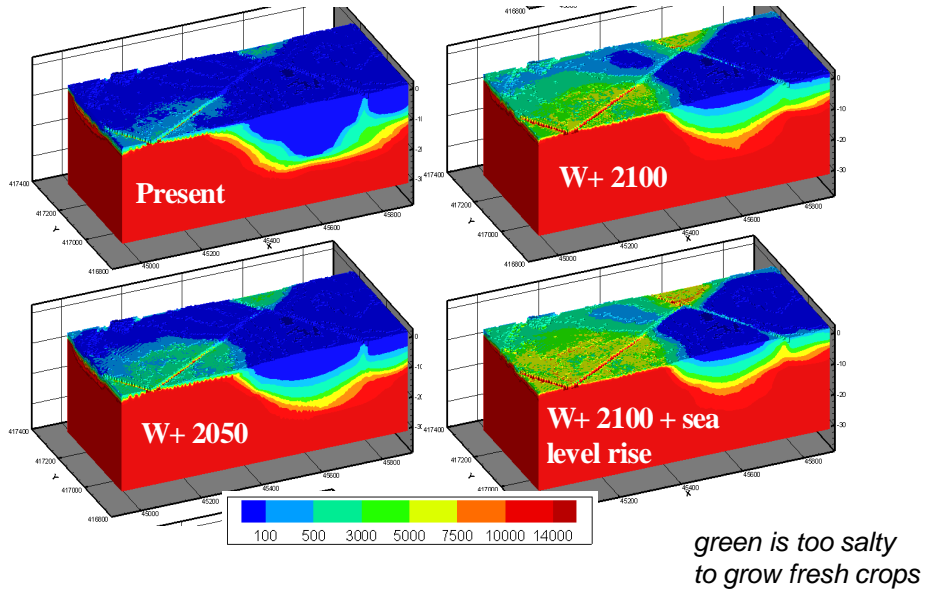
MOCDENS3D

### Assessing effects:

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



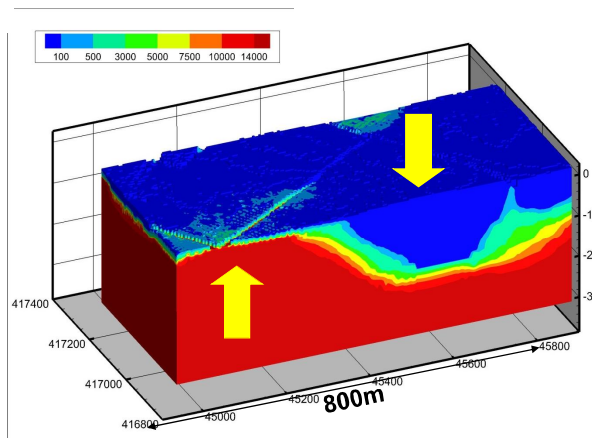
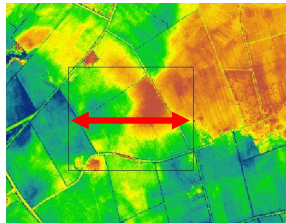
## Local approach: simulated Cl-conc. with different CC-scenarios



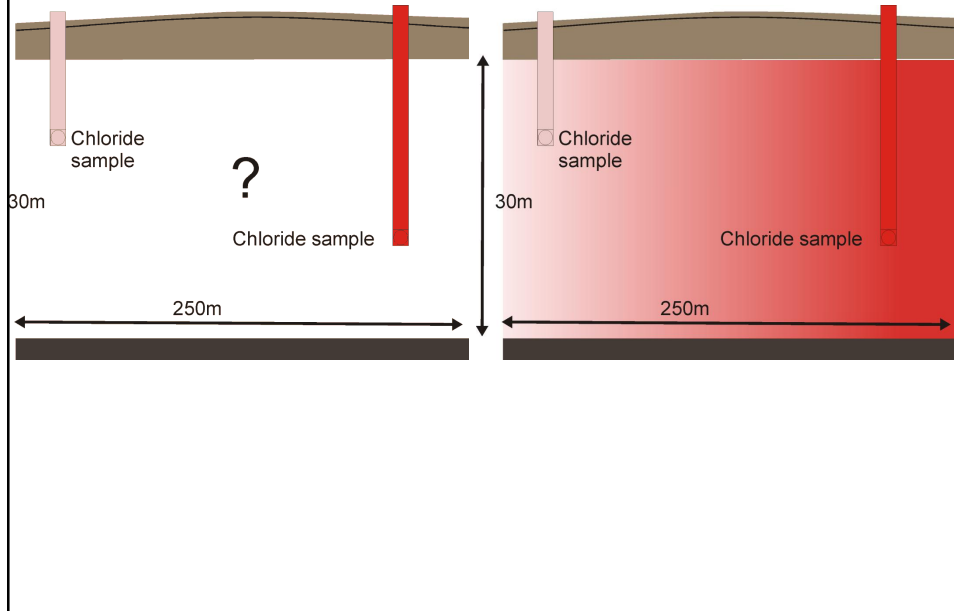
## Use variable-density groundwater flow modelling

### Why a model?

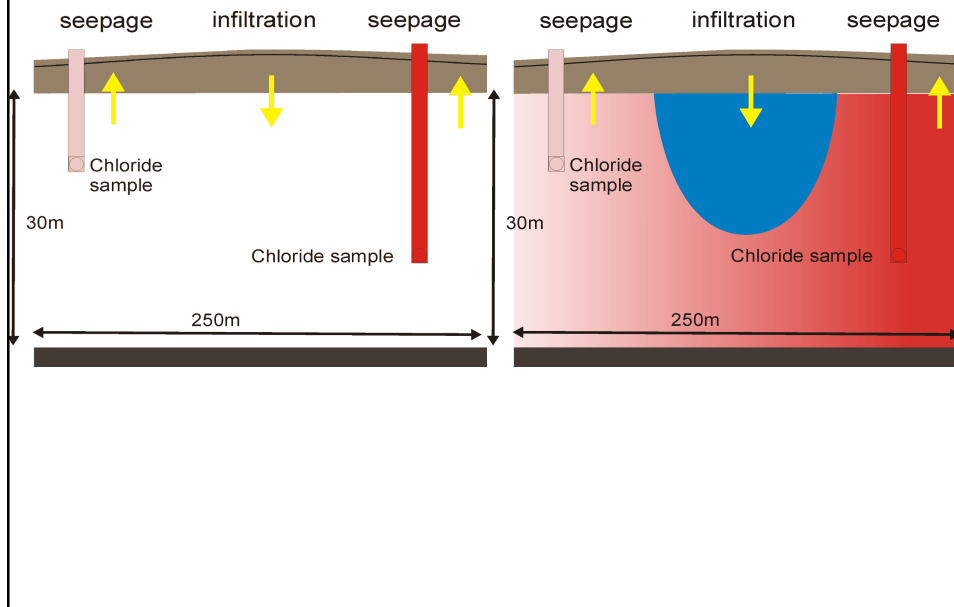
- variation in ground surface directly affects fresh-saline distribution



### Interpolation chloride



### Using flow model for better interpolate chloride

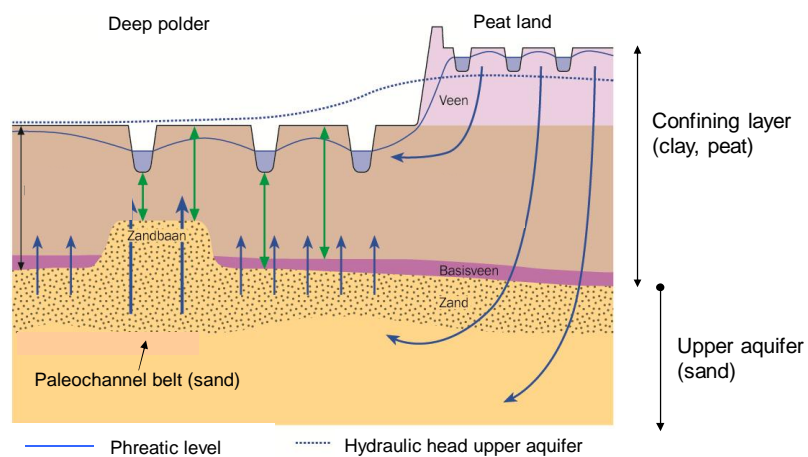


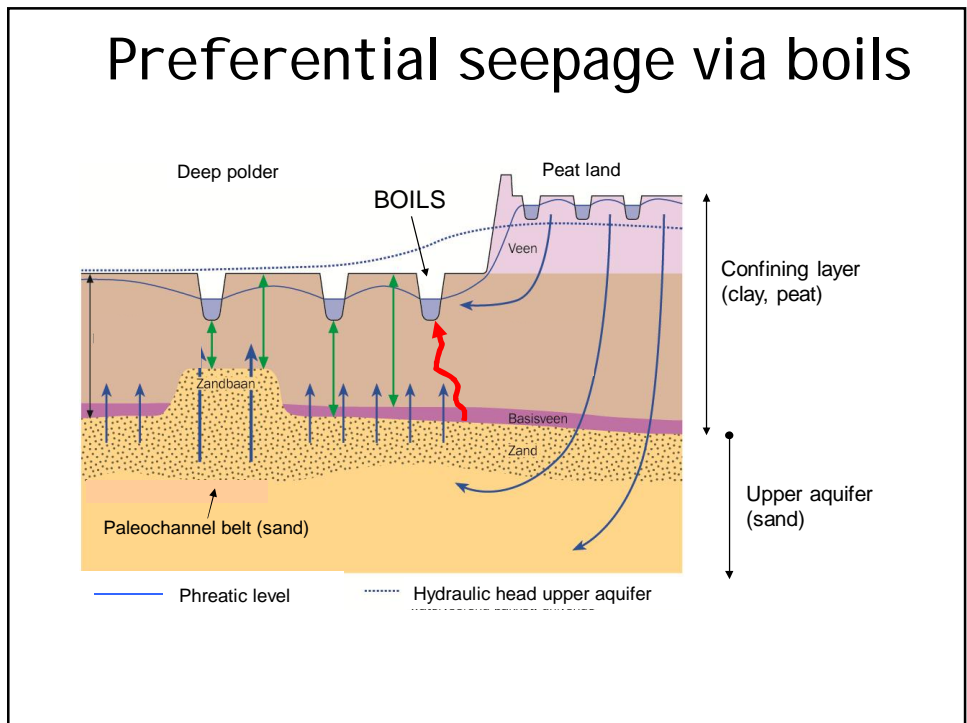
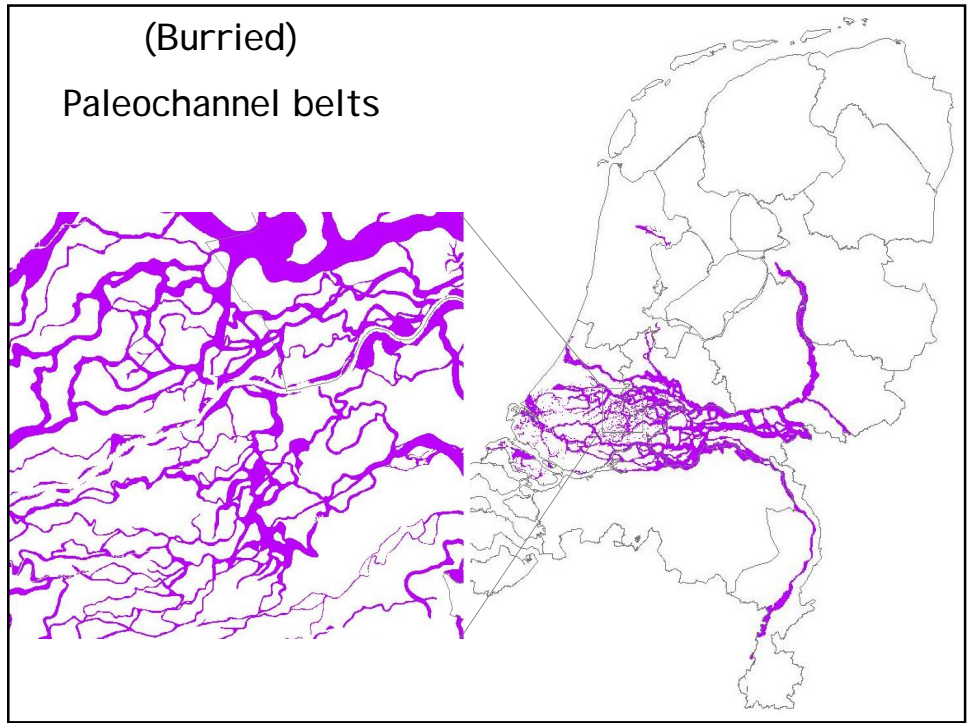


# Salty boils

Louw, P.G.B., de, Oude Essink, G.H.P., Stuyfzand, P.J., Zee, van der, S.E.A.T.M., 2010, Upward groundwater flow in boils as the dominant mechanism of salinization in deep polders, The Netherlands, J. Hydrol. 394, 494-506.

## Upward groundwater seepage in a deep polder and paleochannel belts as preferential flow paths

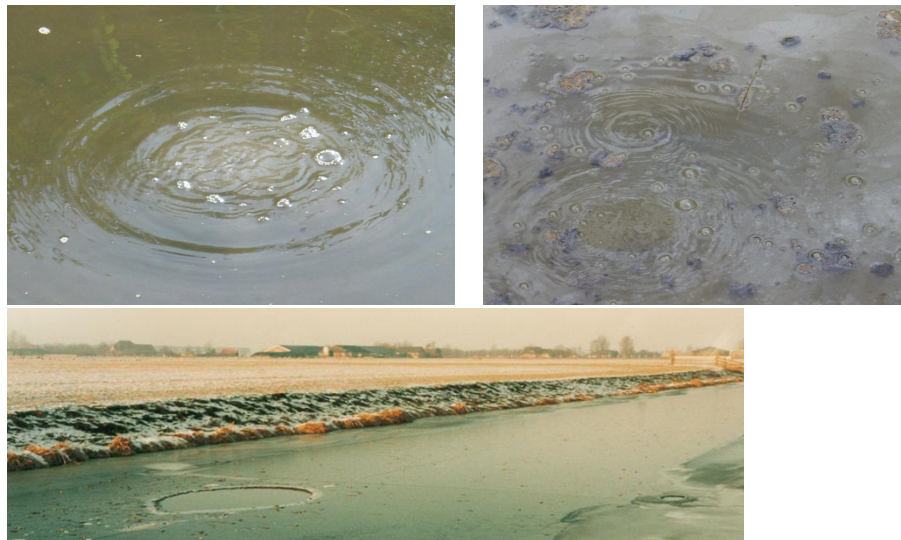




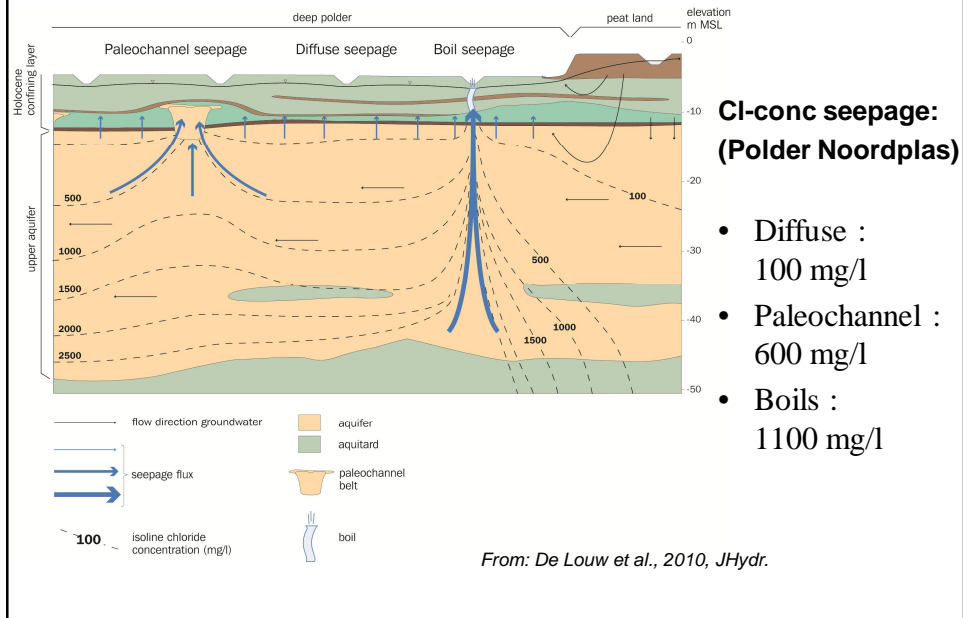
## Preferential saline seepage via boils



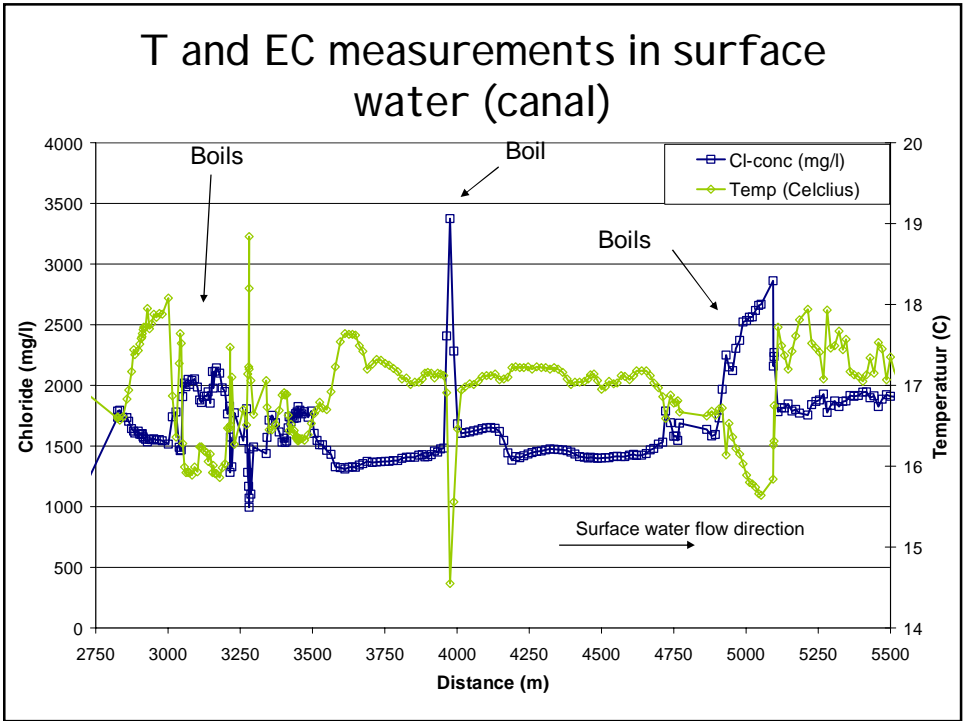
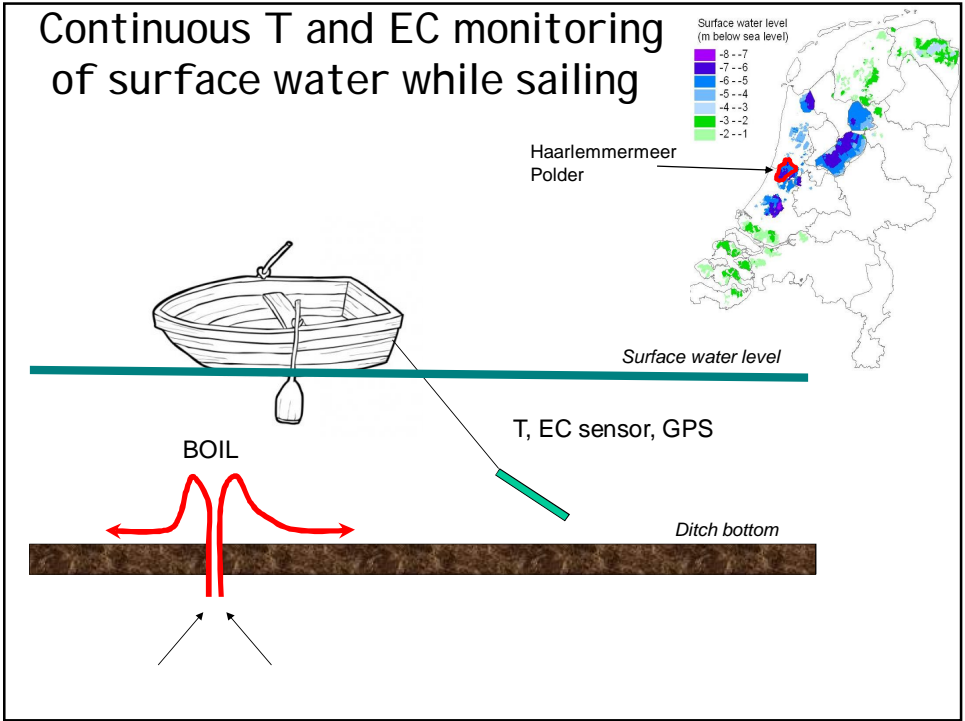
## Preferential saline seepage via boils

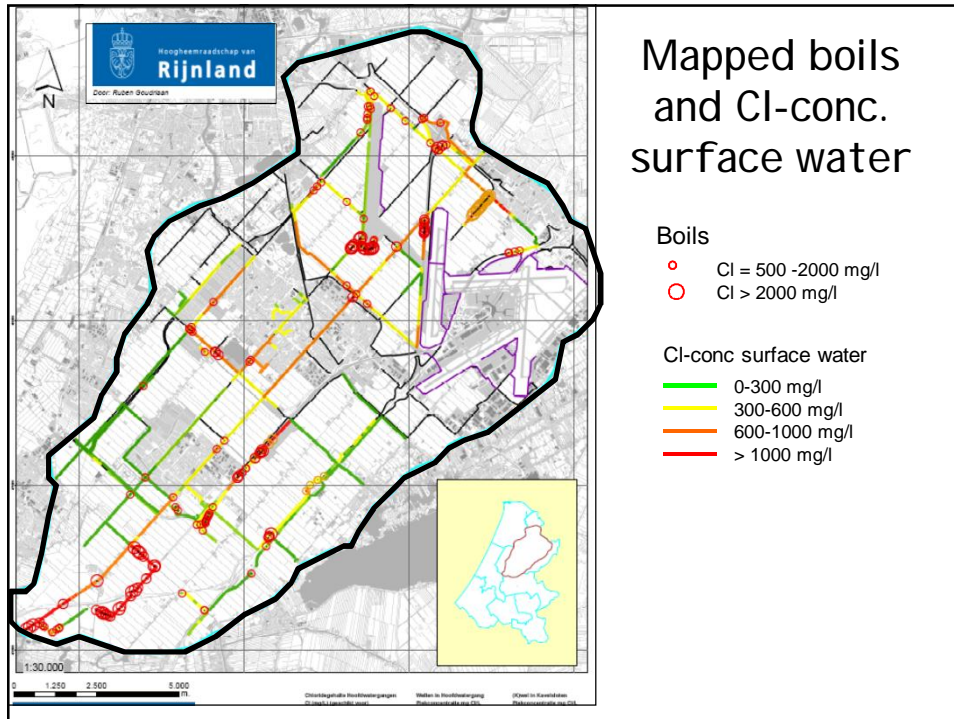


## Three types of upward groundwater seepage







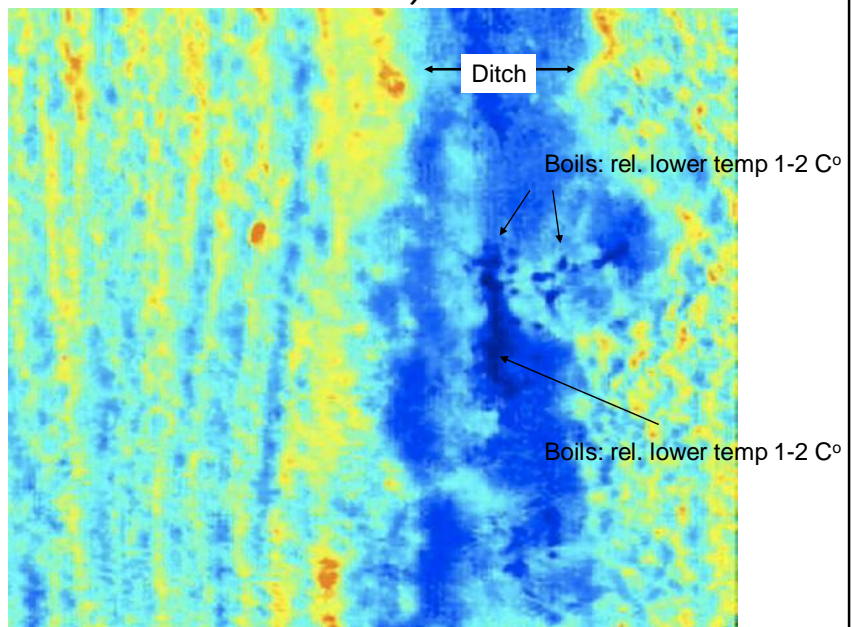


### LARS technology (TNO Industry): Thermal Infra-red

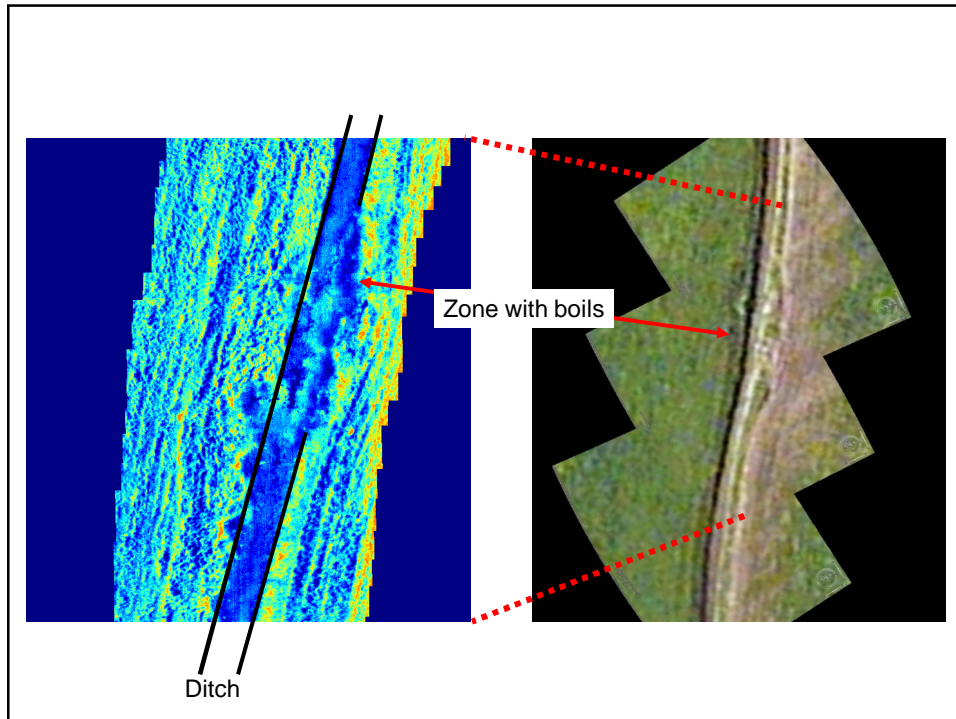
- Altitude: 0-150 m
- Temp-detection using Thermal Infra Red sensors (only surface !)



Thermal infra-red results (blue is cold, red is warm)



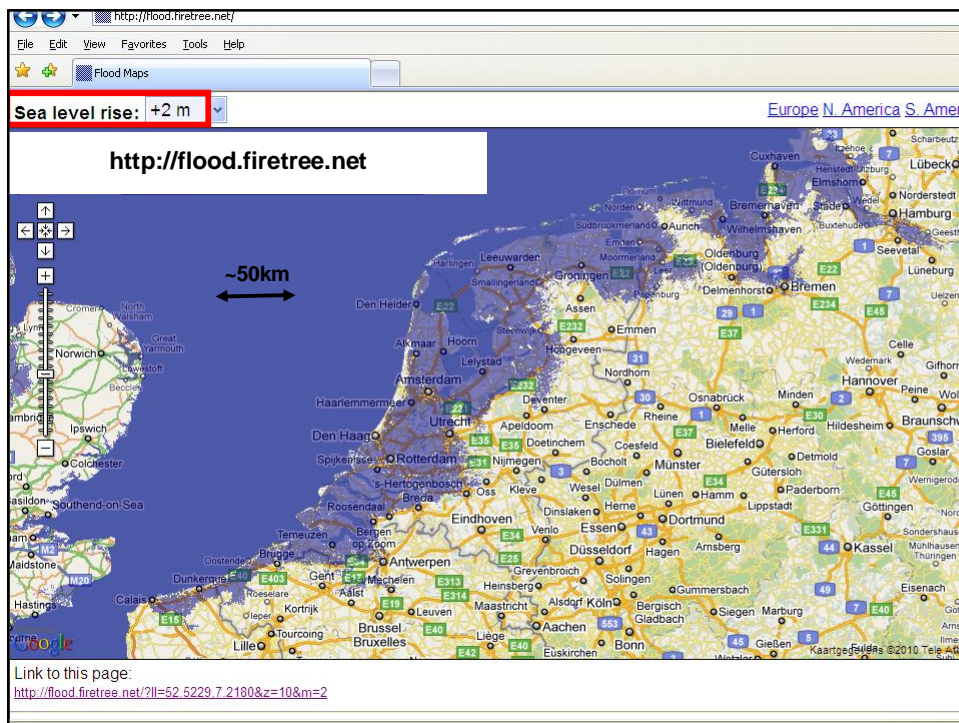




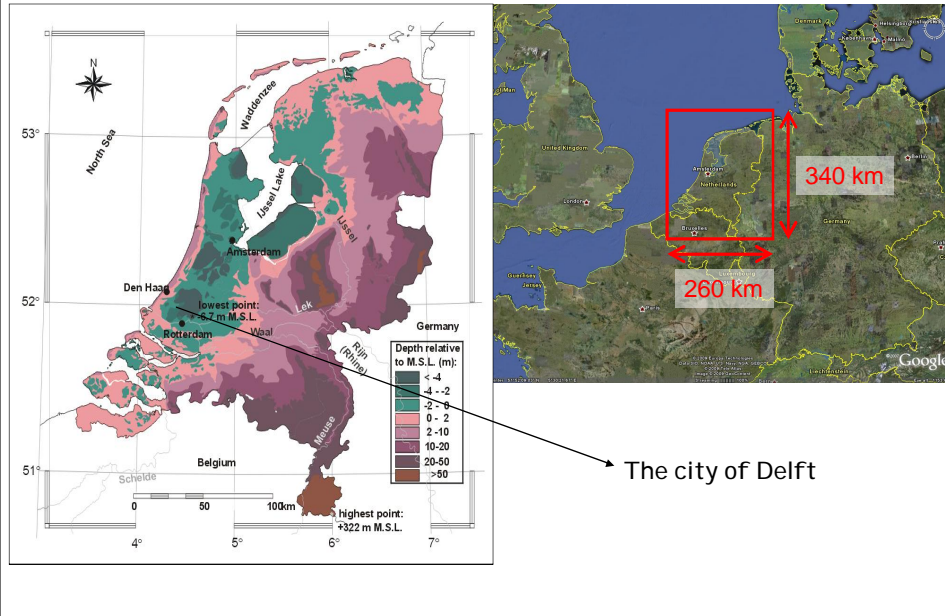
To get an idea about the possible future effects of sea level  
rise and climate change in your delta ...

*evaluate of the past water management in the Dutch delta*

## Salt water intrusion in the Netherlands



## The 'low-lying' lands: Netherlands



## Case study: The Netherlands

The Dutch coastal zone is already threatened 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<sup>2</sup> 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



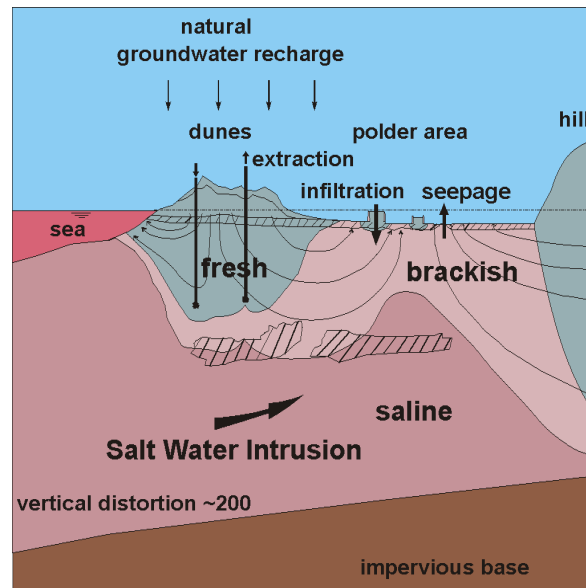
## Estimated water management costs 'to keep our feet dry'

Costs up till 2050 in billion euros:

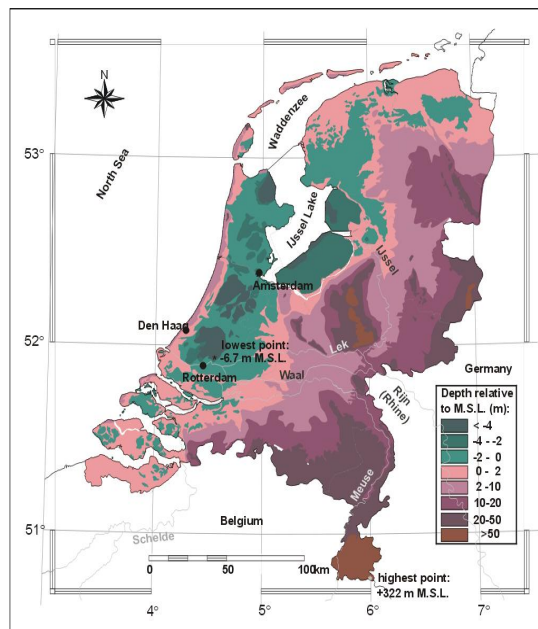
ivers: upper part	5.7
ivers: lower part	5.6
low-lands	1.7
coastal zone	8.0
infrastructure	3.5
purchase of ground	2.0
	-----+
	26.5 billion euros

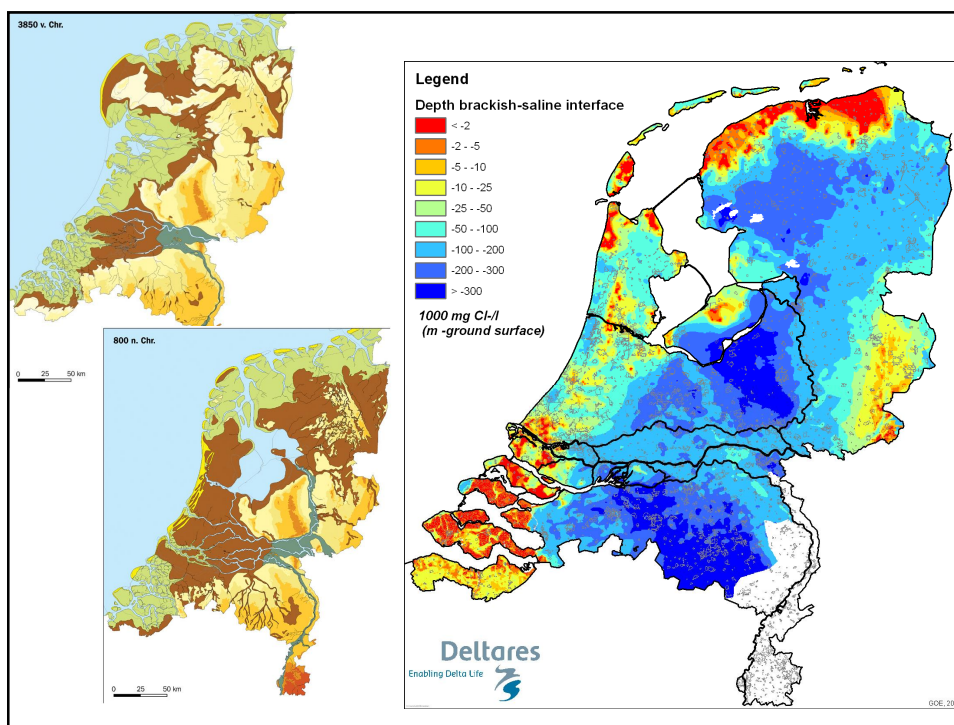
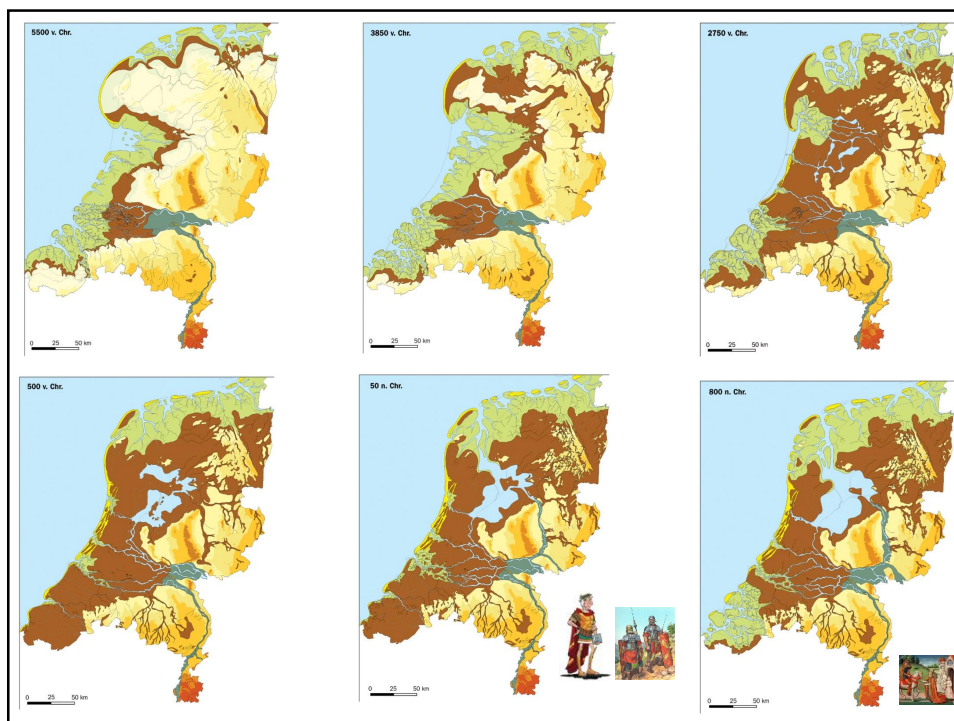
Dutch setting

## Salt water intrusion in the Netherlands

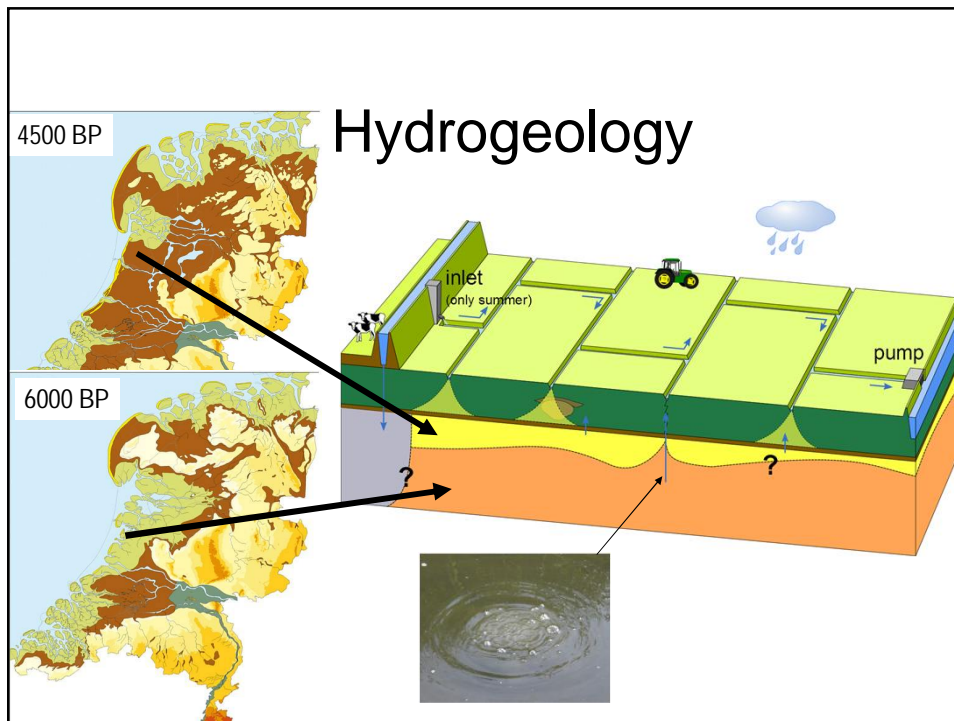
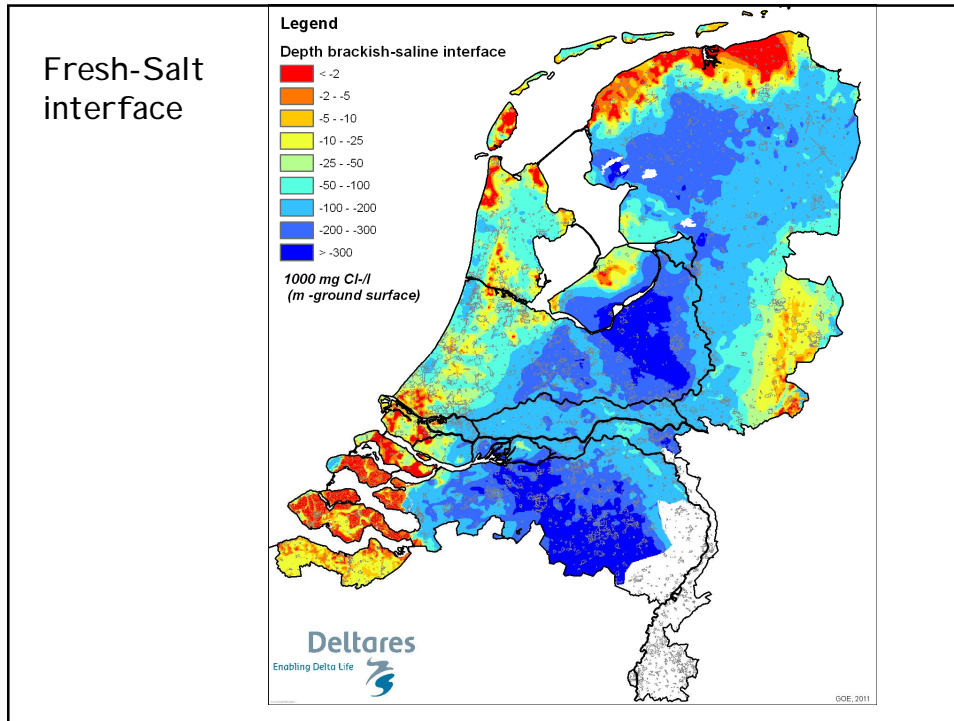


## Present ground surface in the Netherlands









## 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

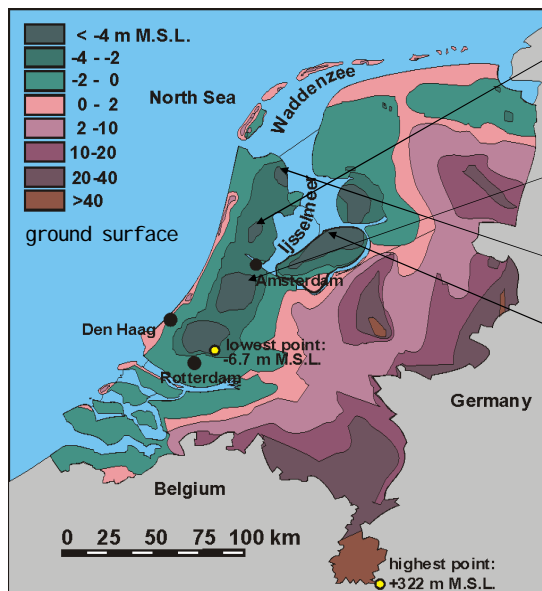
### Anthropogenic causes:

- land subsidence
- polder level lowering
- groundwater extractions

### Future developments (climate change):

- sea level rise
- changes in recharge

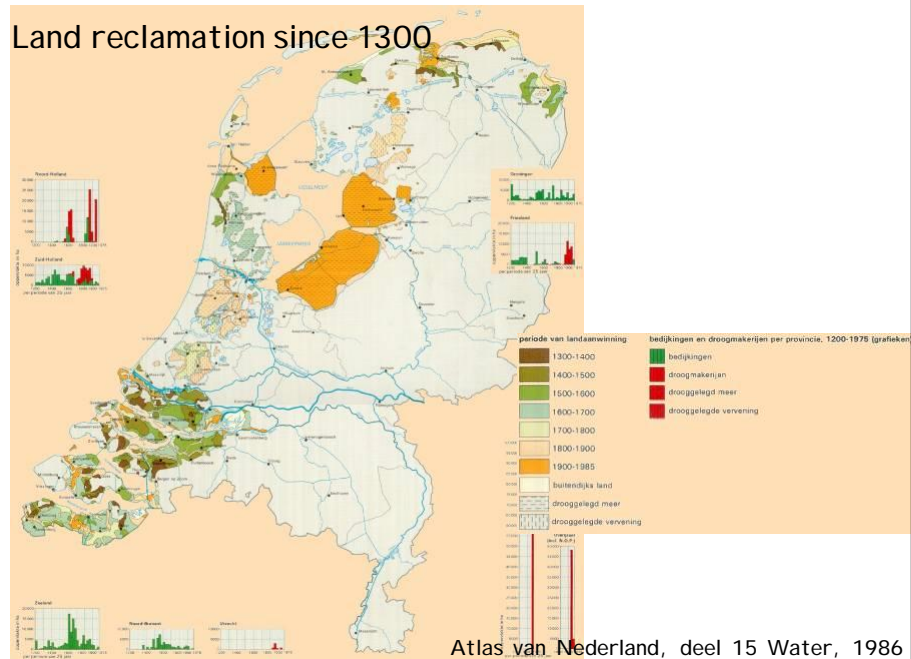
## Abrupt land subsidence



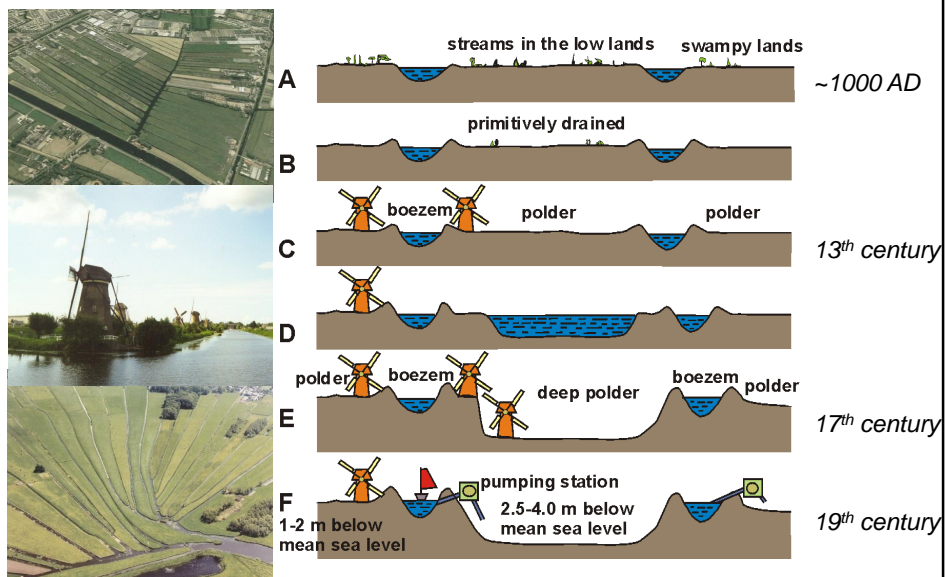
### position polders:

- 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



## Development of the Dutch 'Polder' Landscape

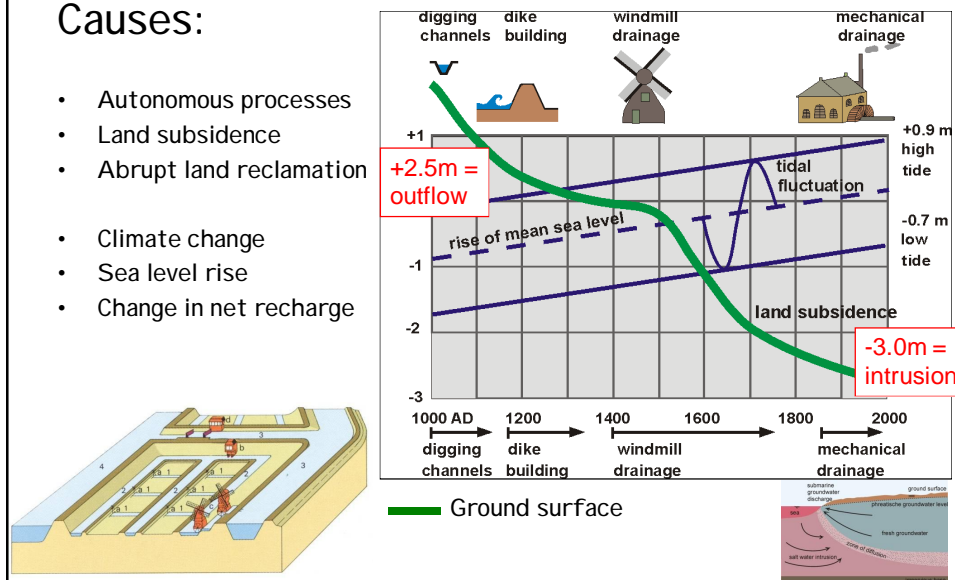


# From fresh water outflow to salt water inflow

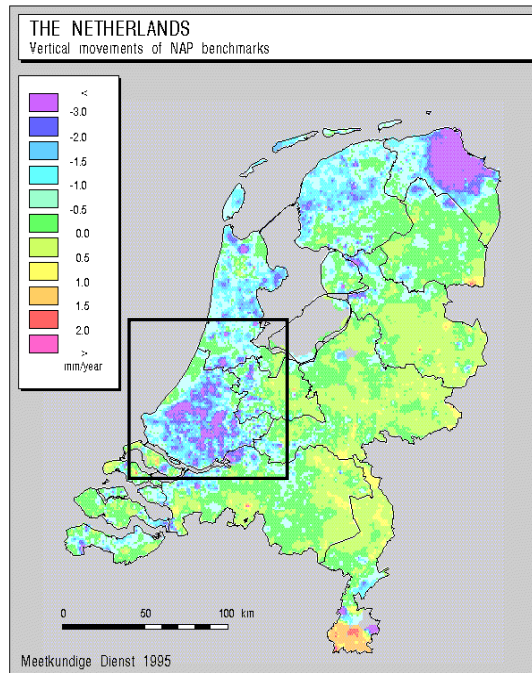
## Causes:

- Autonomous processes
- Land subsidence
- Abrupt land reclamation
- Climate change
- Sea level rise
- Change in net recharge

## Historical subsidence of the ground surface in Holland



## Land subsidence related to M.S.L.



## Land subsidence



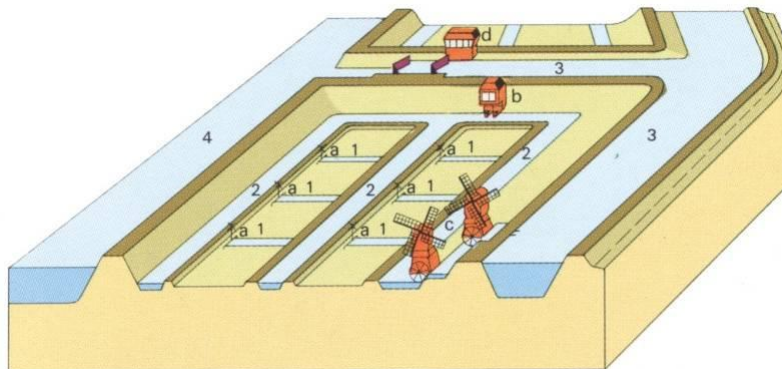
up to 1 m per century



## 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



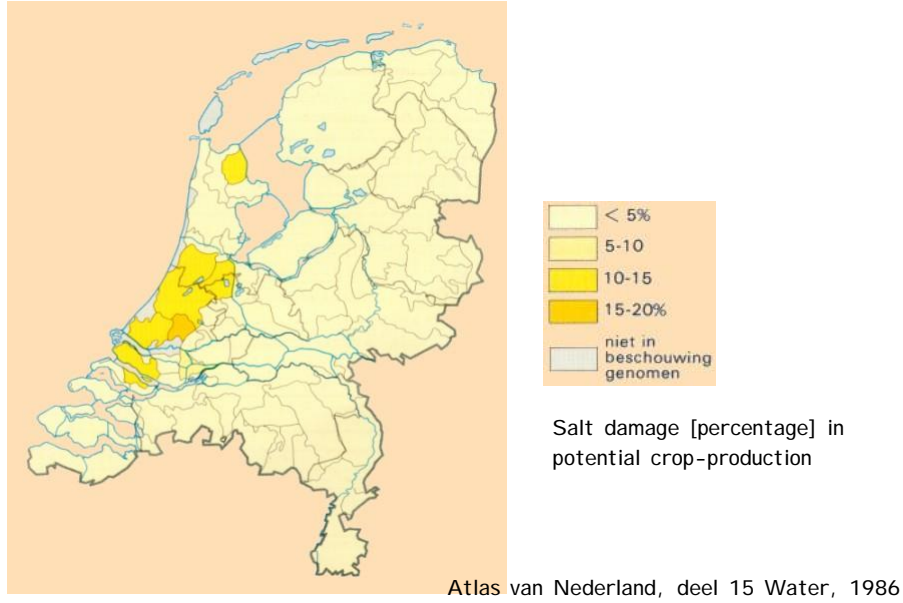
## The polder system



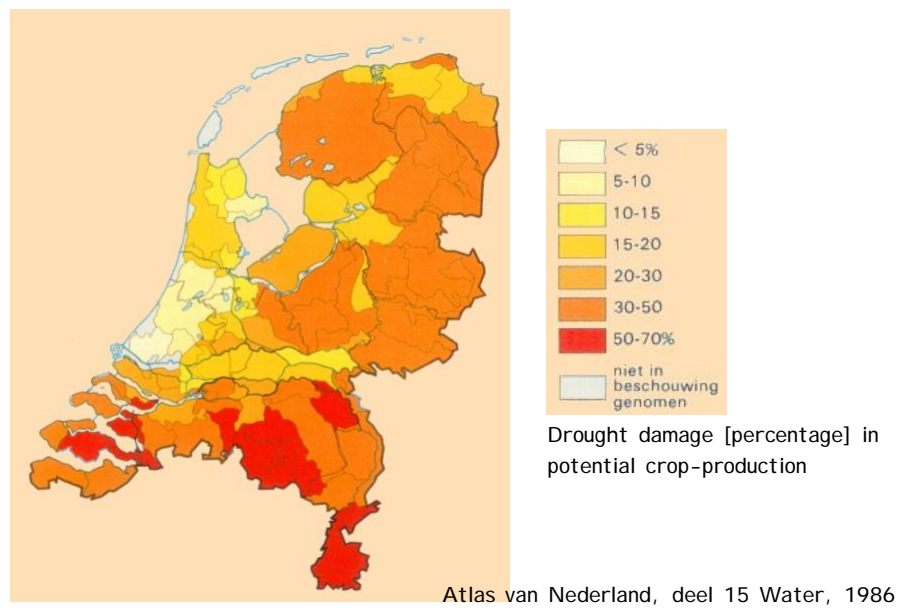
## Bulb farms at the landside of the sand dunes



### Salt damage in 1976 (very dry year)



### Drought damage in 1976 (very dry year)





### 'Wetting' damage

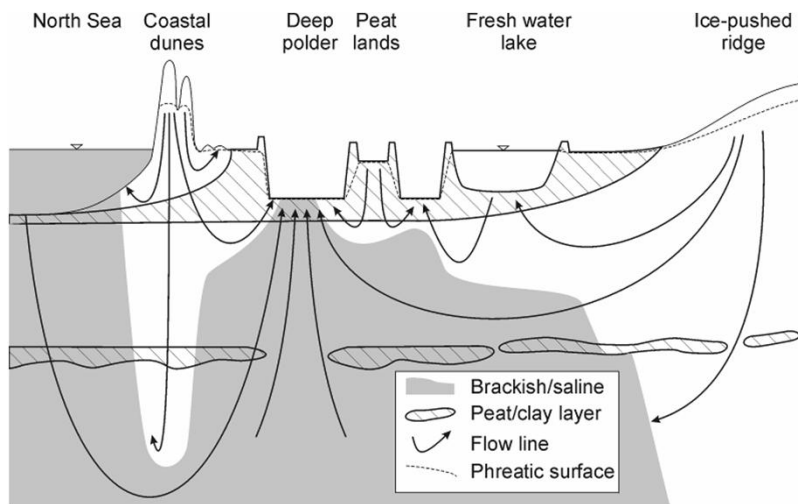


Normal situation



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

### Now focus on groundwater...



## Threats to water management due to climate change:

Short term threats:

- flooding
- dike collapse
- drought

*asks for operational water management*

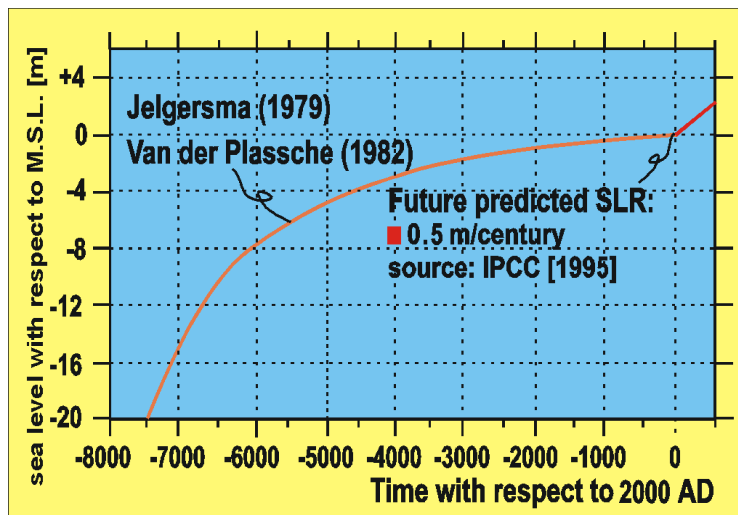
Long term threats:

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

*asks for strategic water management*

Dutch setting

### Past and future sea level rise in the Netherlands



## Numerical variable density models at Deltares

### Characteristics:

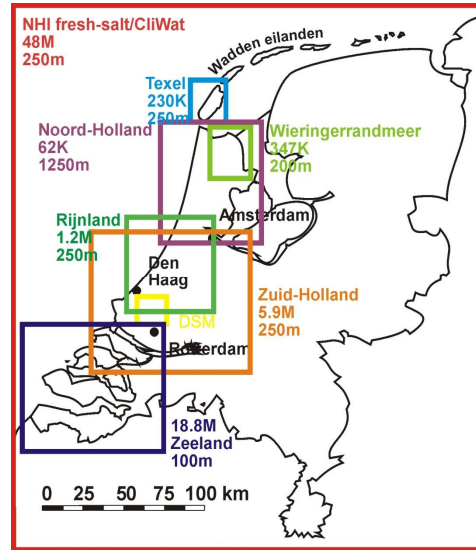
- variable-density groundwater
- fresh, brackish and saline
- 3D, non-steady
- coupled solute transport

### Code (MODFLOW family):

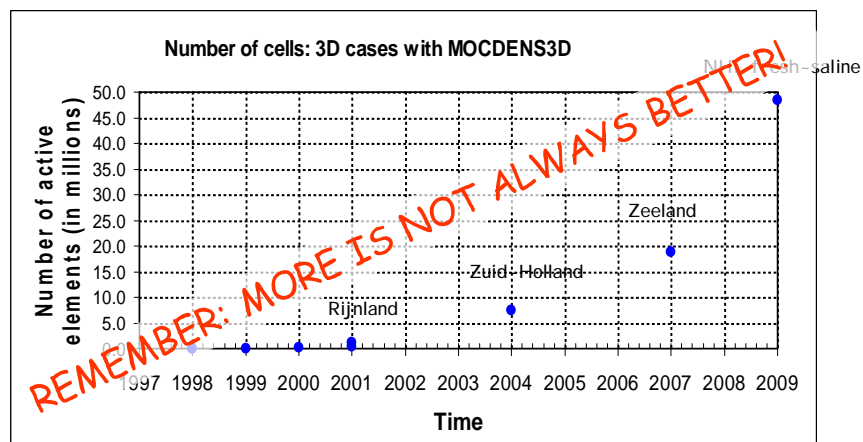
MOCDENS3D  
SEAWAT

### Assessing effects:

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

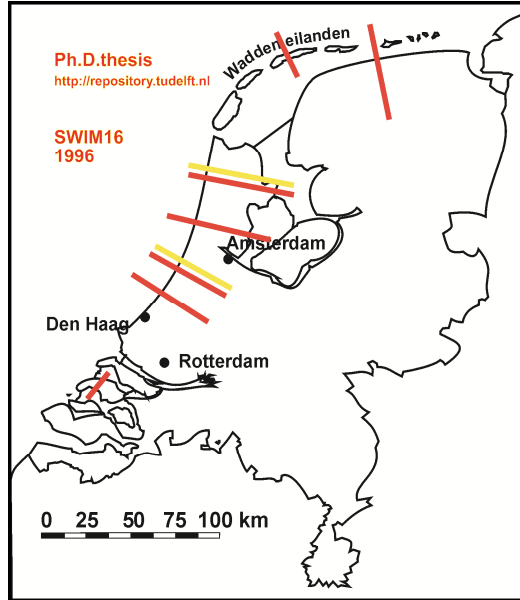


## 'DO NOT DO THIS AT HOME!' (DATA PROBLEM)



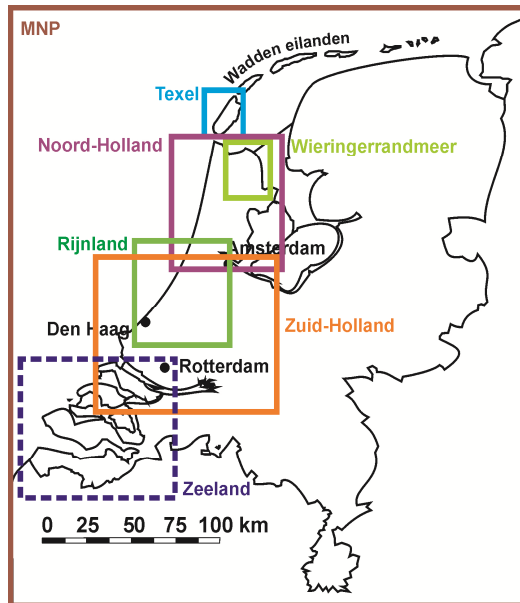
## Modelling effect sea level rise on salt water intrusion

### 2D models



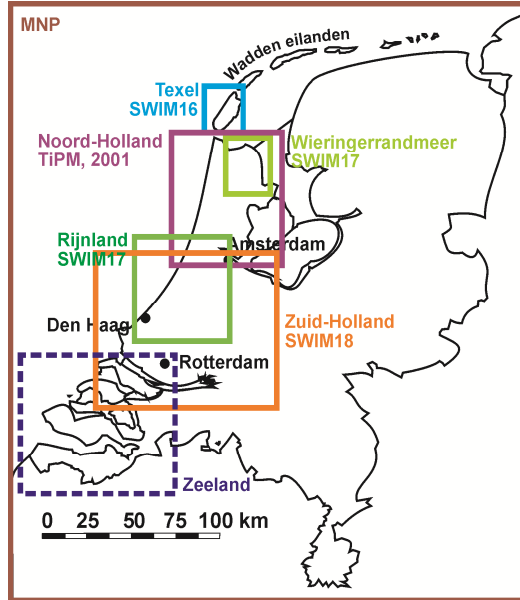
## Modelling effect sea level rise on salt water intrusion

### 3D models



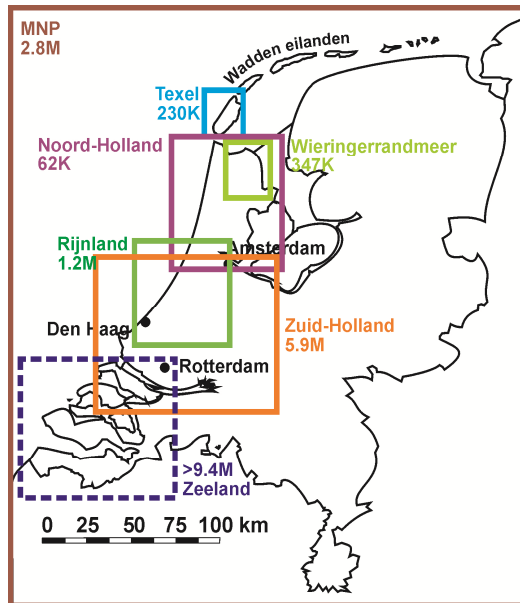
## Modelling effect sea level rise on salt water intrusion

3D models  
SWIM



## Modelling effect sea level rise on salt water intrusion

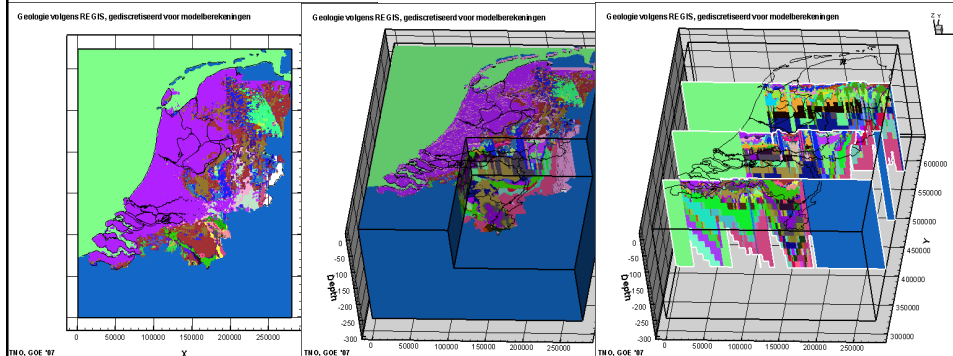
3D models  
number cells



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

Using the national subsoil parametrisation

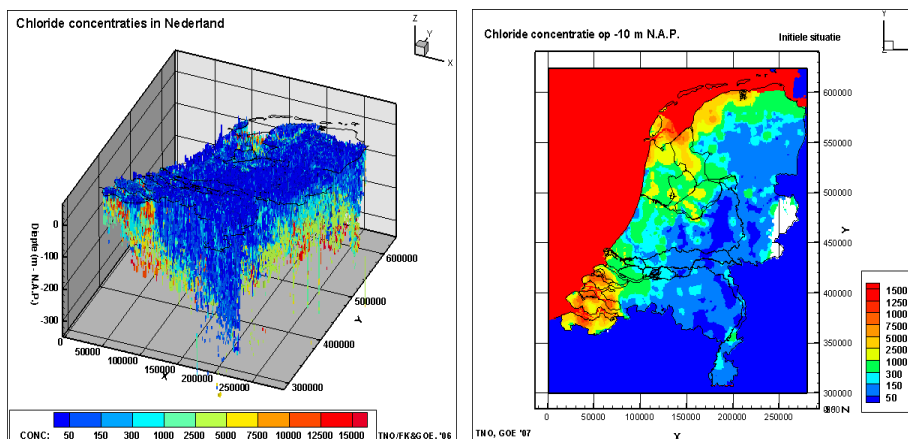
- REGIS V2
- Top geological system from +10m up to -280m M.S.L.
- 31 modellayers with thicknesses: 2\*5m; 10\*2m; 8\*5m en 11\*20m
- cellsize 1000x1000m (coarse)



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

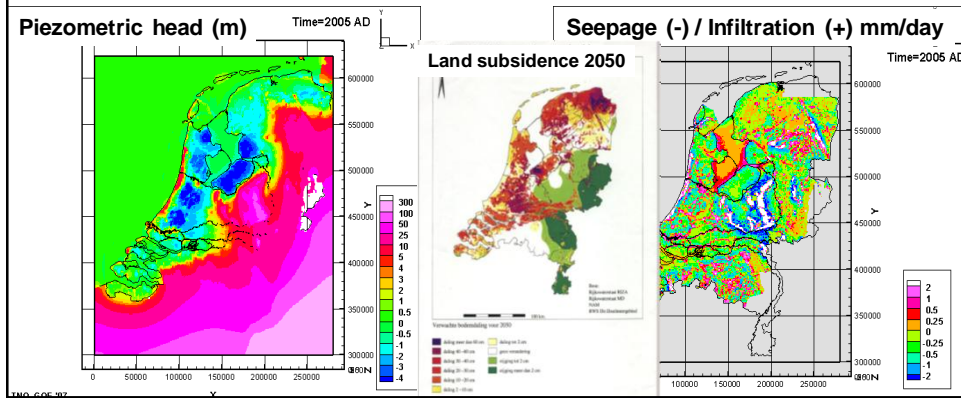
Using the national 3D salt concentration in groundwater

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

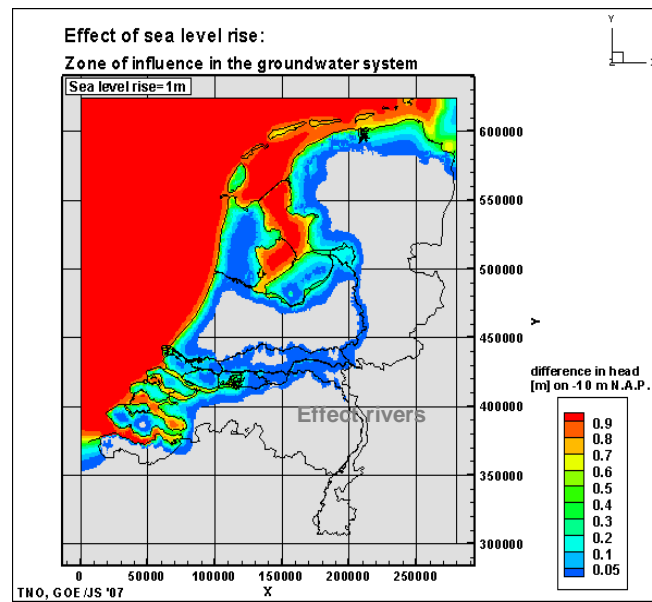


## Recent model study for the whole Netherlands on the effect of sea level rise of water management (3)

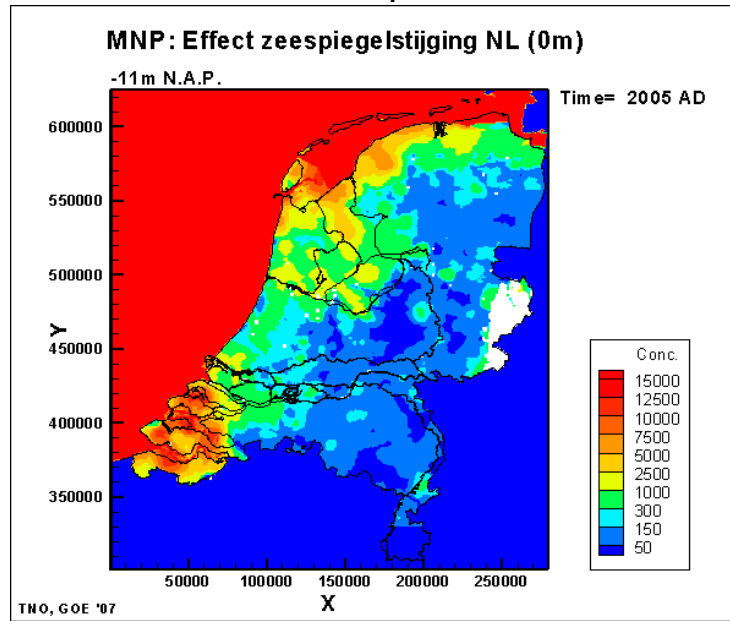
- Variable-density 3D groundwater flow model and coupled solute transport
  - 10 scenario's, including extreme sea level rise
  - including land subsidence estimates



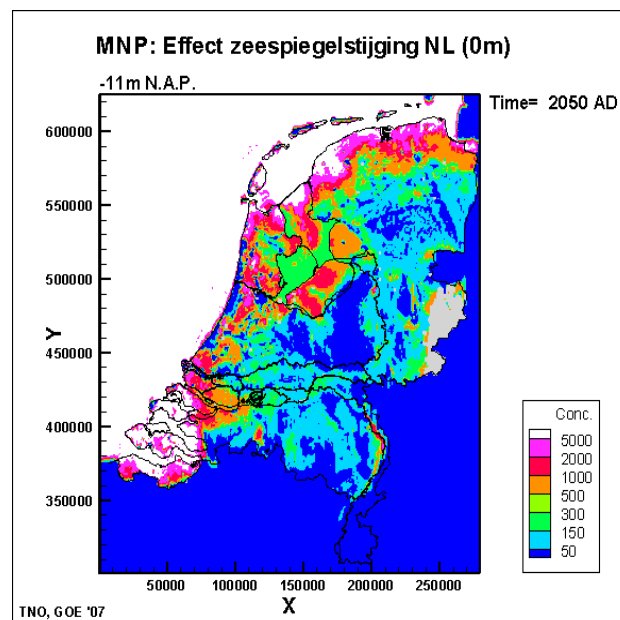
## Results: zone of influence 1m sea level rise



## Salinisation over the period 2000-2050

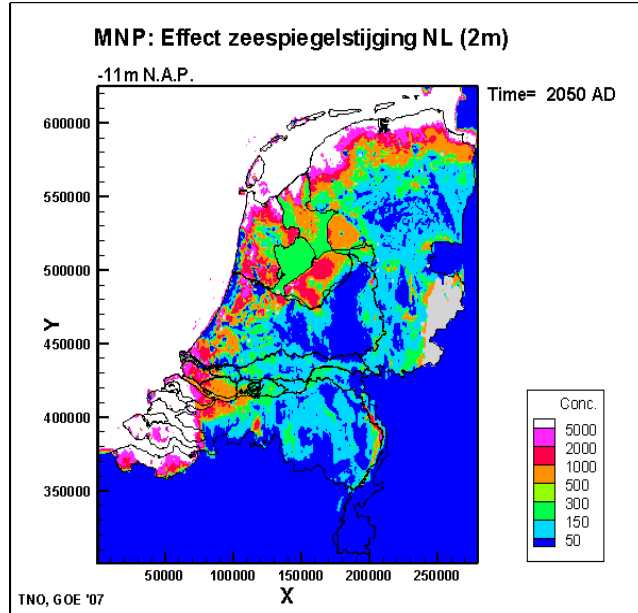


## Salinisation subsoil at 0m sea level rise in 2050

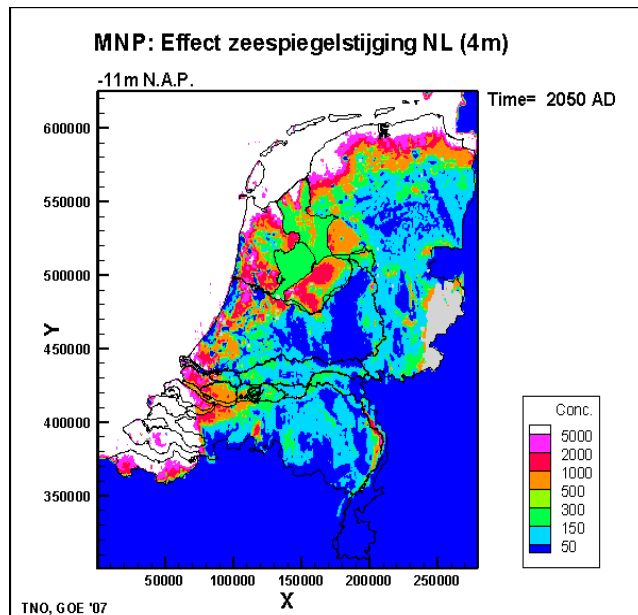




## Salinisation subsoil at 2m sea level rise in 2050

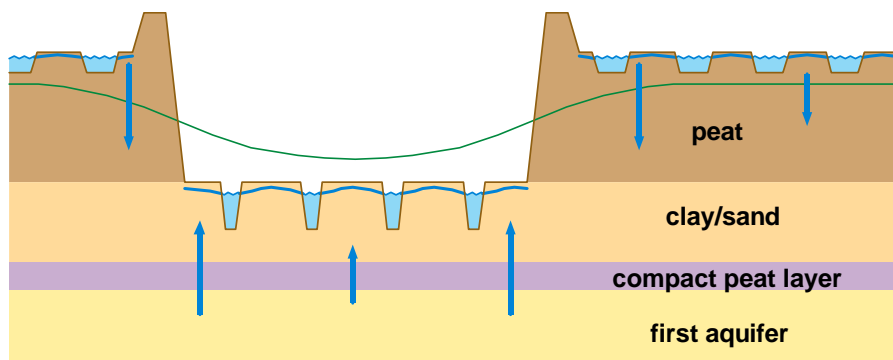


## Salinisation subsoil at 4m sea level rise in 2050

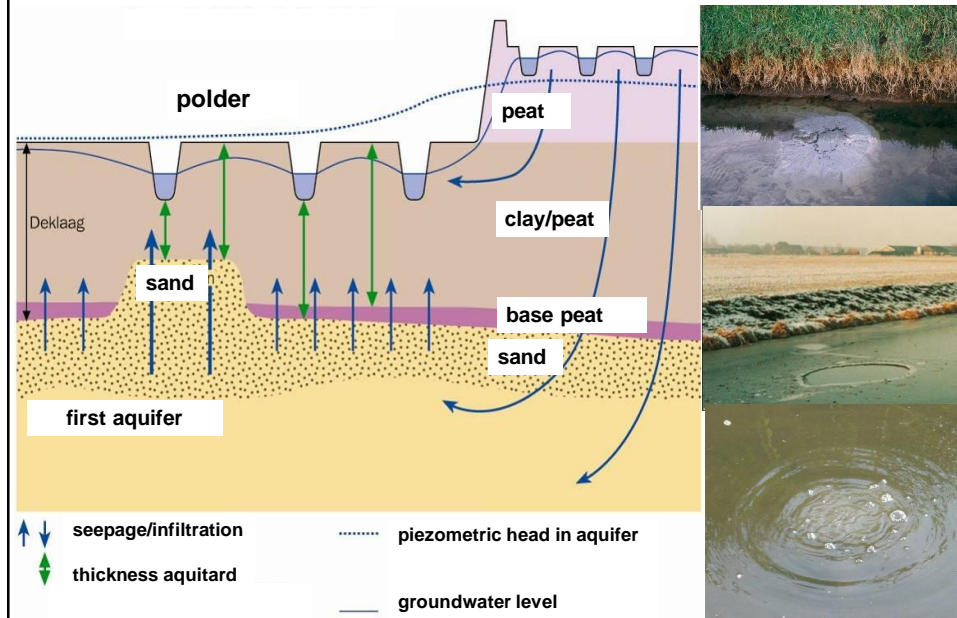


# Salty wells

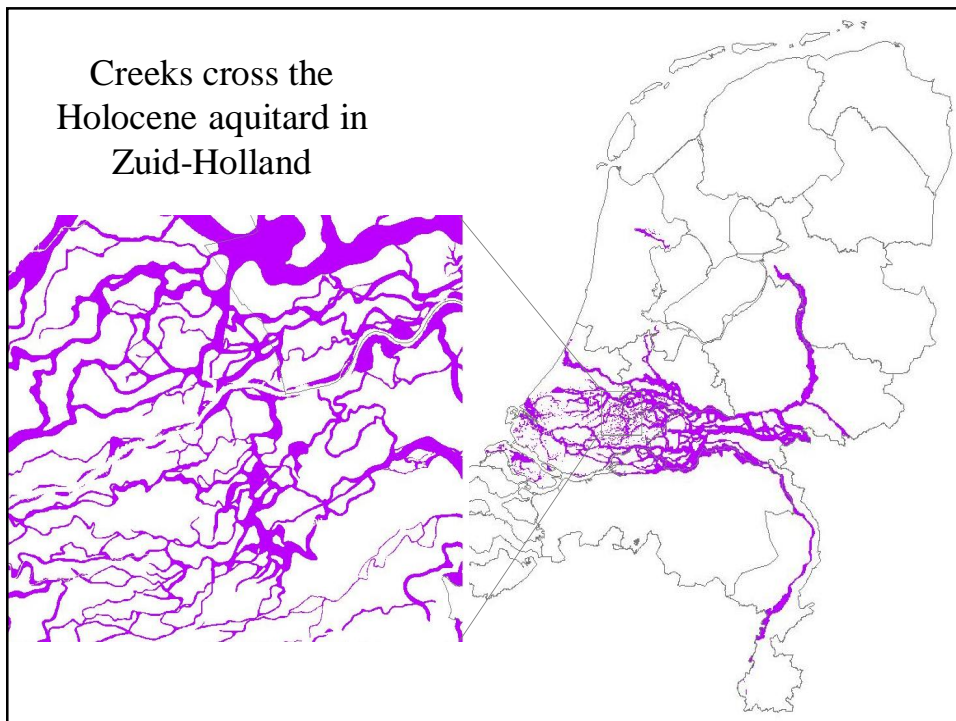
Seepage and infiltration situation around deep polders

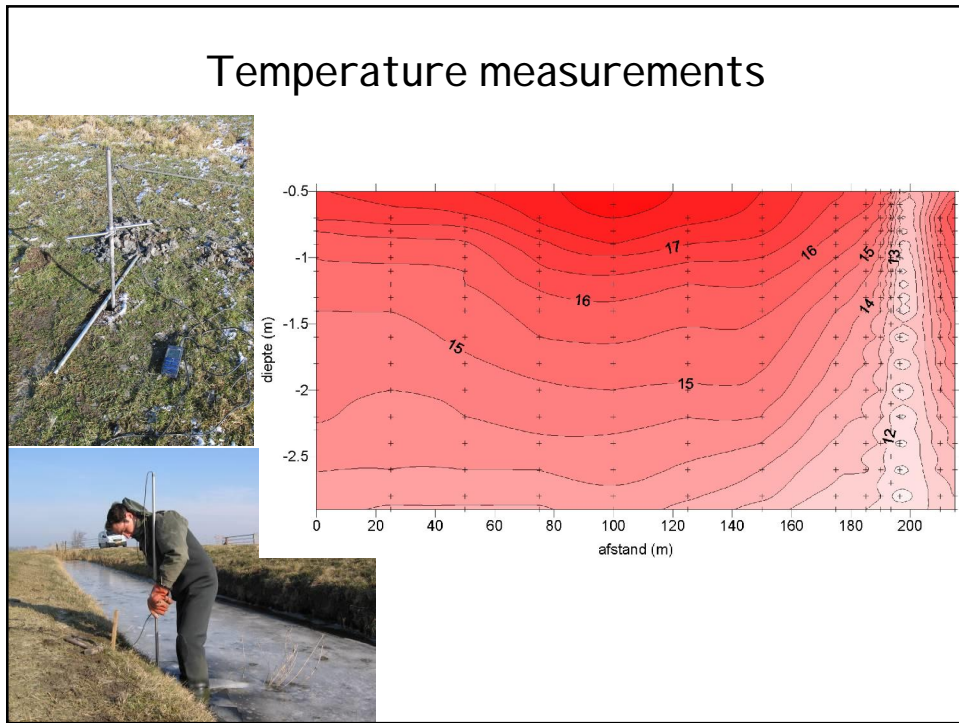


## Risk of instable Holocene aquitards (1)

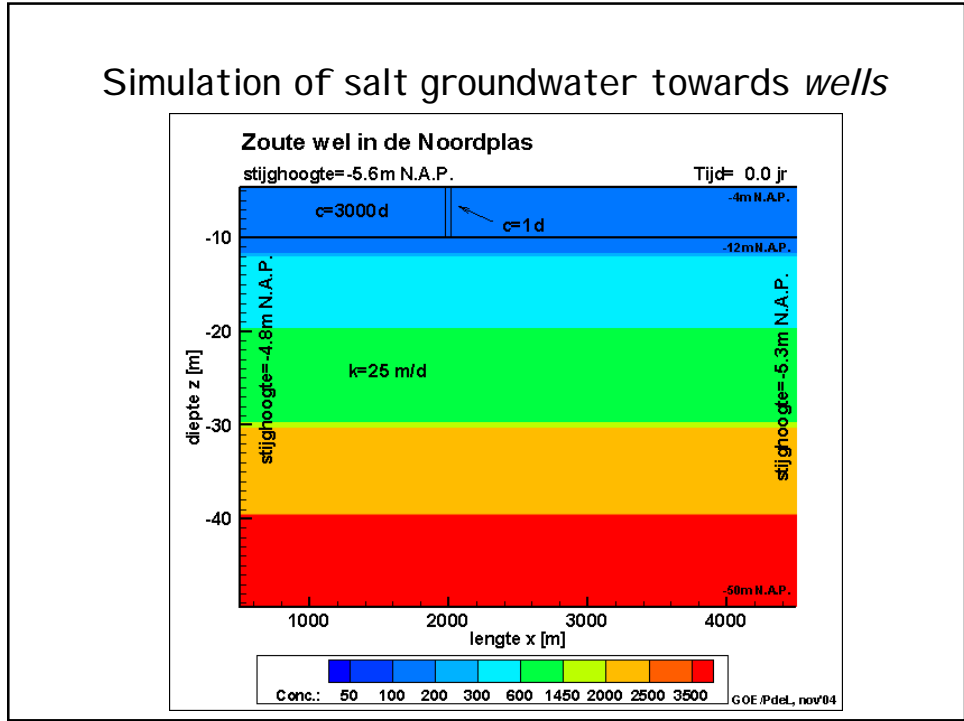


## Creeks cross the Holocene aquitard in Zuid-Holland

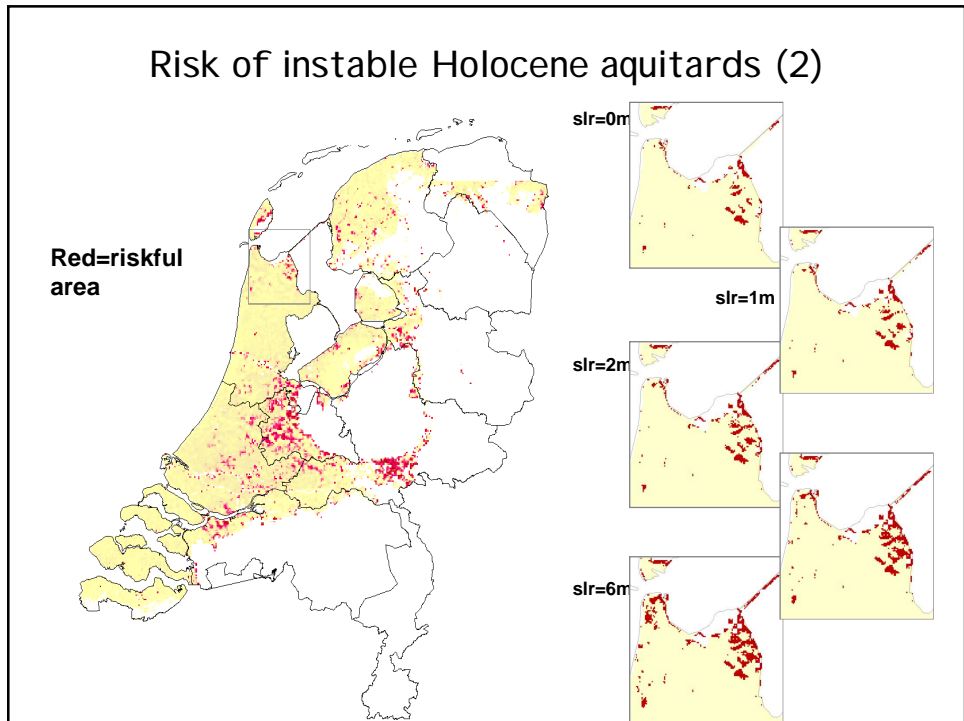




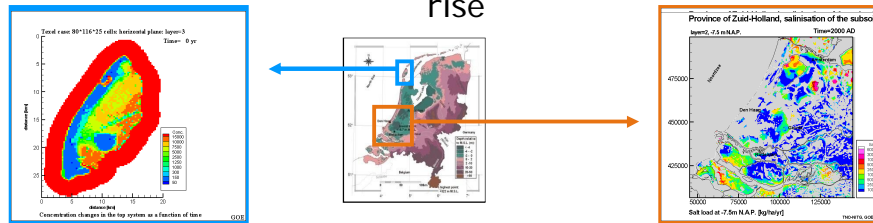
## Simulation of salt groundwater towards wells



## Risk of instable Holocene aquitards (2)



## Quantification hydrogeological impacts of sea level rise

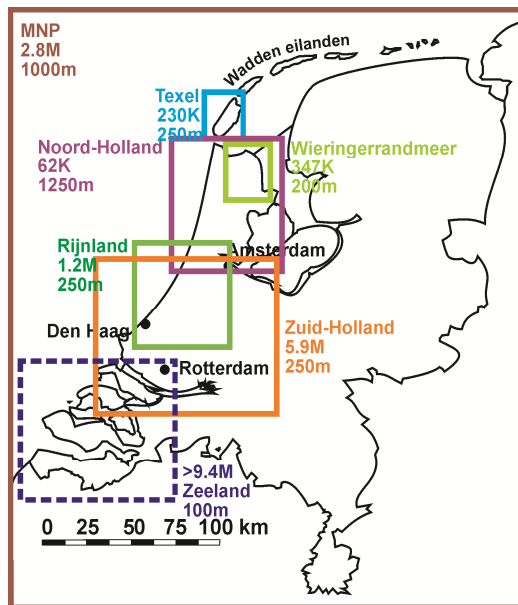


Situation at 2100 AD with sea level rise of 0.5m/century,  
Including land subsidence at Zuid-Holland (max 1.0m/century)

	<u>Texel</u>	<u>Zuid-Holland</u>
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 &amp; subsoil

Case	Kop van Noord-Holland	Texel	Wieringer-meerpolder	Rijnland
total land surface [km <sup>2</sup> ]	2150	130	200	1100
L <sub>x</sub> *L <sub>y</sub> 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 <sub>z</sub> /k <sub>x</sub> ]	0.4	0.4	0.25	0.1
long. dispersivity α <sub>L</sub> [m]**	2	2	2	1
# head&conc. observations	not applicable*	111	95	1632
characteristics head calibration	not applicable*	Δφ =0.24 m σ=0.77 m	Δφ =0.34 m σ=0.21 m	Δφ =0.60 m σ=0.77 m

\* calibration with seepage & salt load in polders

\*\*molecular diffusion=10<sup>-9</sup> m<sup>2</sup>/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

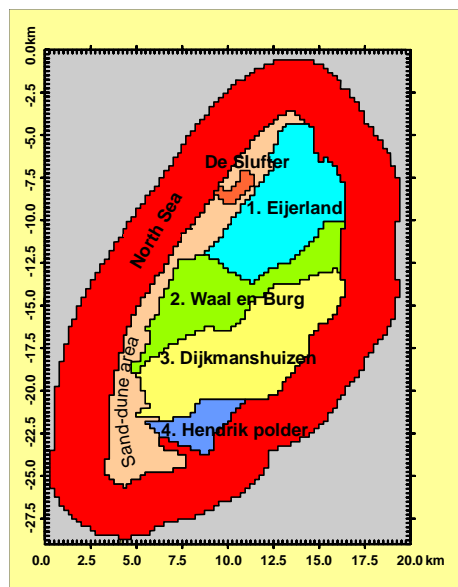
convergence head criterion= 10<sup>-5</sup>/10<sup>-4</sup> m

flow time step Δt=1 year

## Model of the island of Texel

### Characteristics of the island of Texel (I)

Texel



- Tourist island in summer time

- Land surface: 130 km<sup>2</sup>

- Polder areas:

- 1. Eijerland
- 2. Waal en Burg
- 3. Dijkmanshuizen
- 4. Hendrik polder

- Sand-dune area at western side

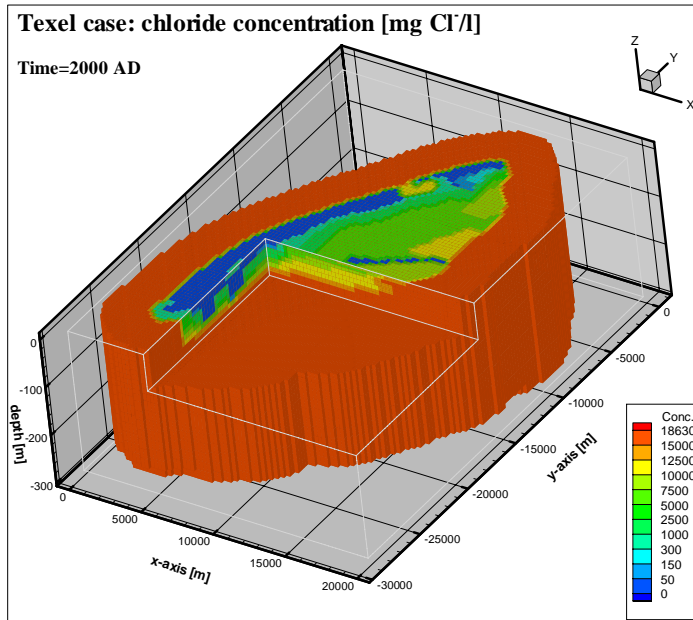
- 'De Slufter' is a tidal salt-marsh

- North Sea surrounds the island



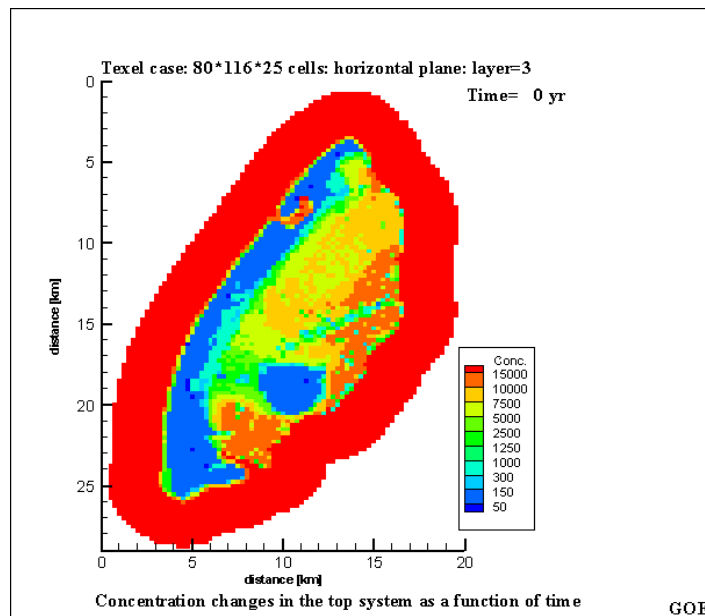
# Texel: present 3D chloride distribution

Texel



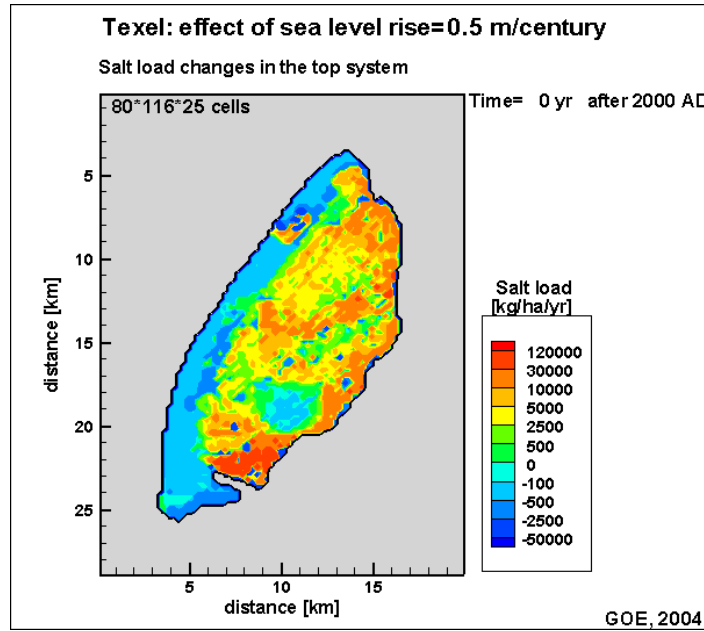
# Texel: reference case=autonomous development

Texel



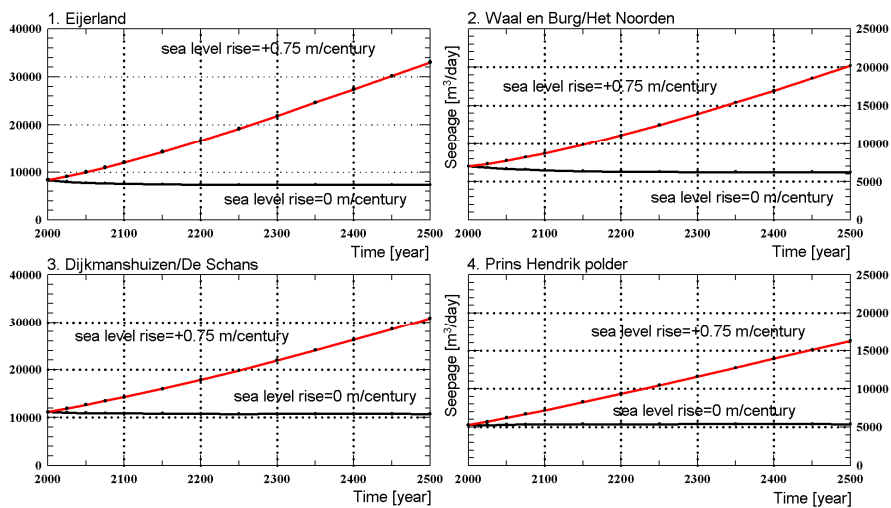
# Texel: effect of sea level rise on salt load

Texel

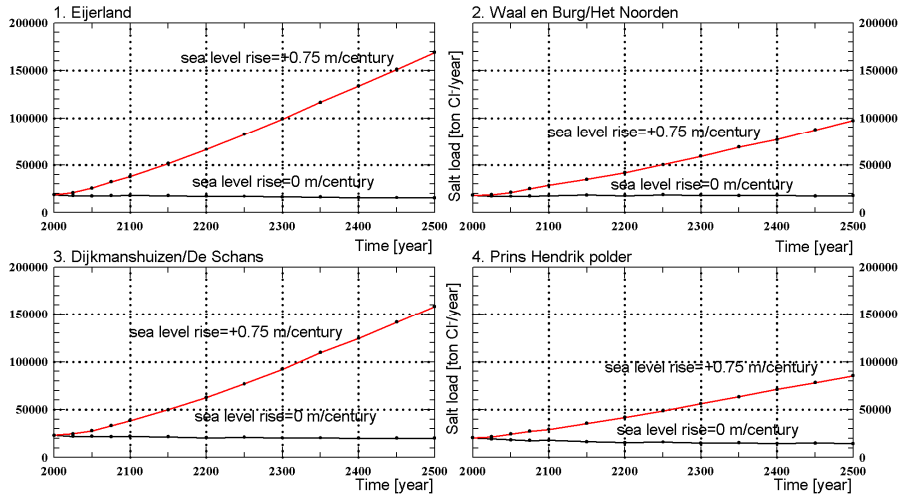


# Texel: change in seepage of the four polders

Texel



### Texel: change in salt load of the four polders



Model of the Province of Zuid-Holland

## Case study: Province of Zuid-Holland

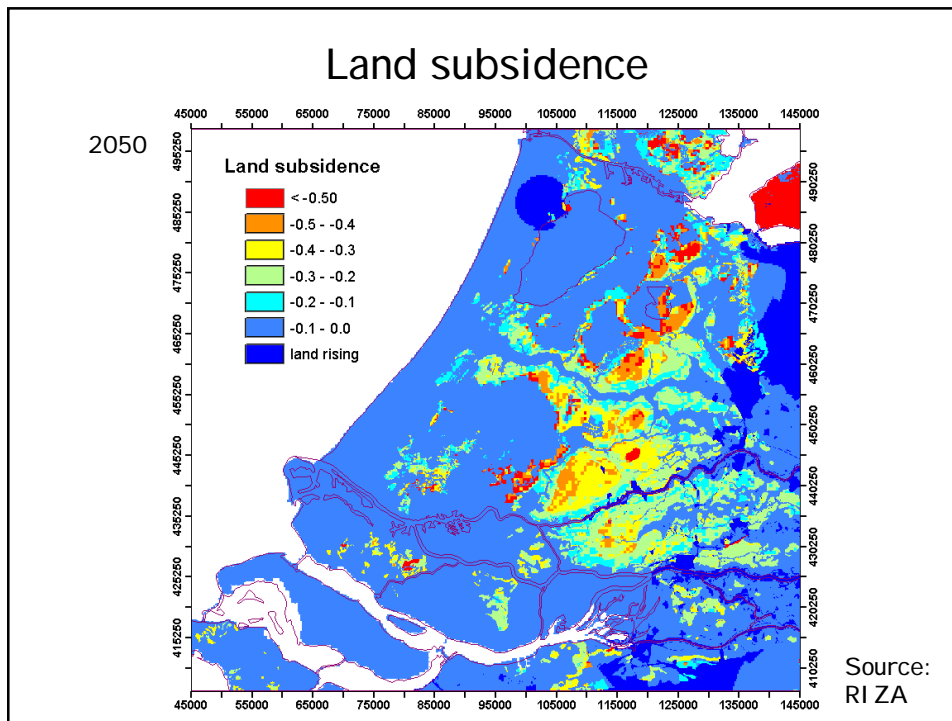
European water framework directive

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

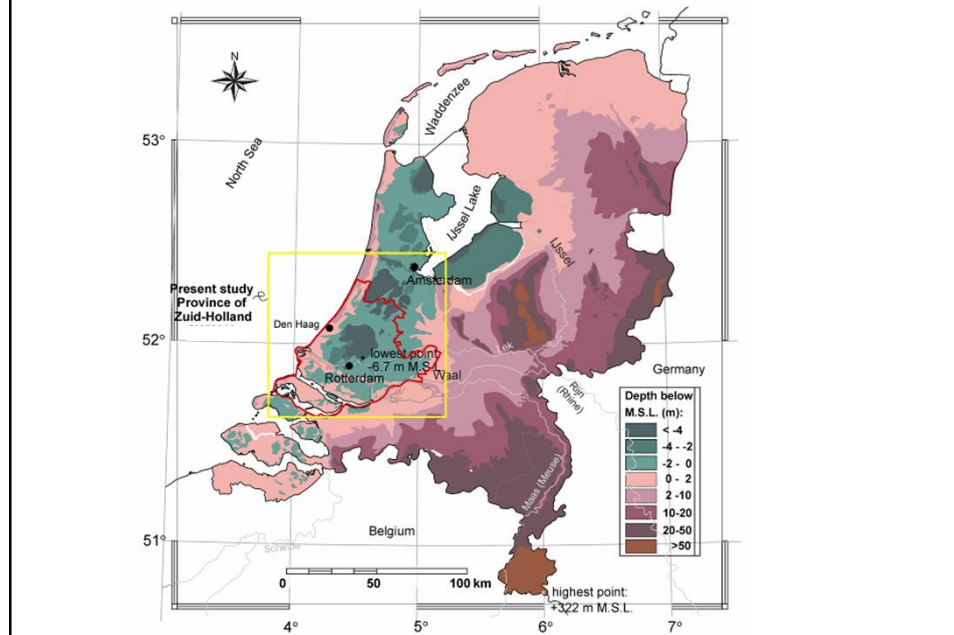
Identification of all fresh groundwater bodies in the province

How fast is the salinisation process?

More seepage, more salt load?



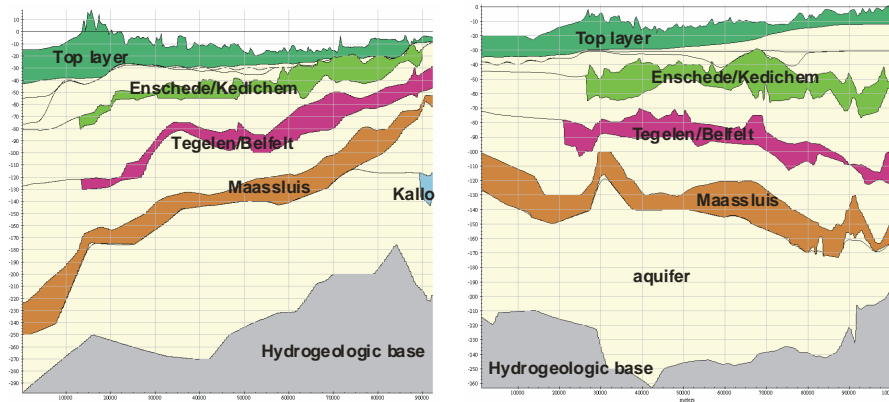
## Location of the Province of Zuid-Holland



## Numerical model description

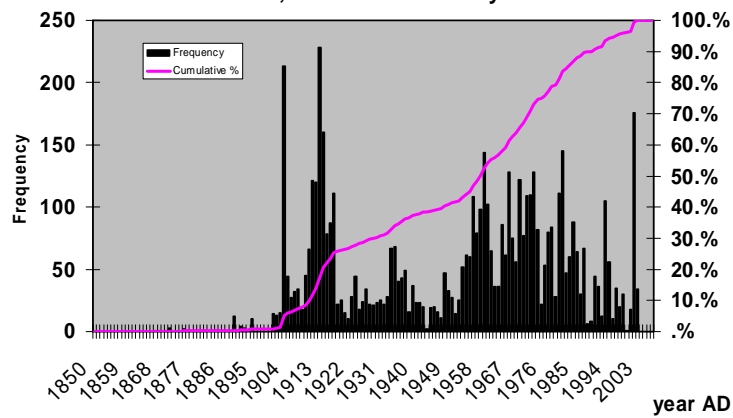
- variable-density groundwater flow
- coupled solute transport
- MOCDENS3D
- area: 100km \* 92.5km \* 300m depth
- 400 \* 370 cells, 40 layers
- ~4 million active cells
- uses most accurate Dutch 3D subsurface schematization available
- 9 aquifers and aquitards
- uses 5772 chloride concentration measurements

## Position and name of aquitards



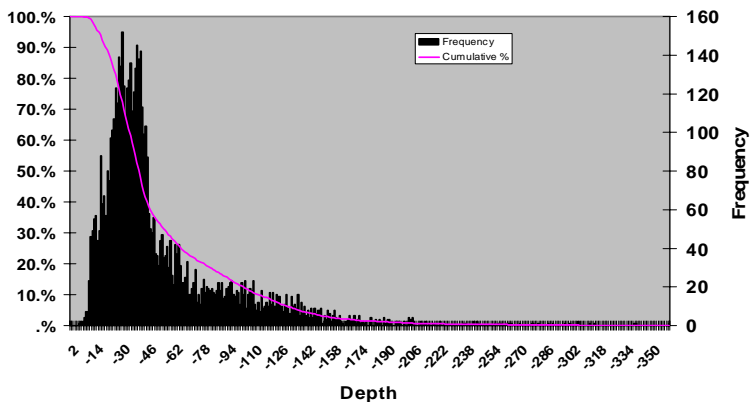
## 3D interpolation of chloride-concentration

Chloride concentration measurements in Province Zuid-Holland, used in 3D-density matrix

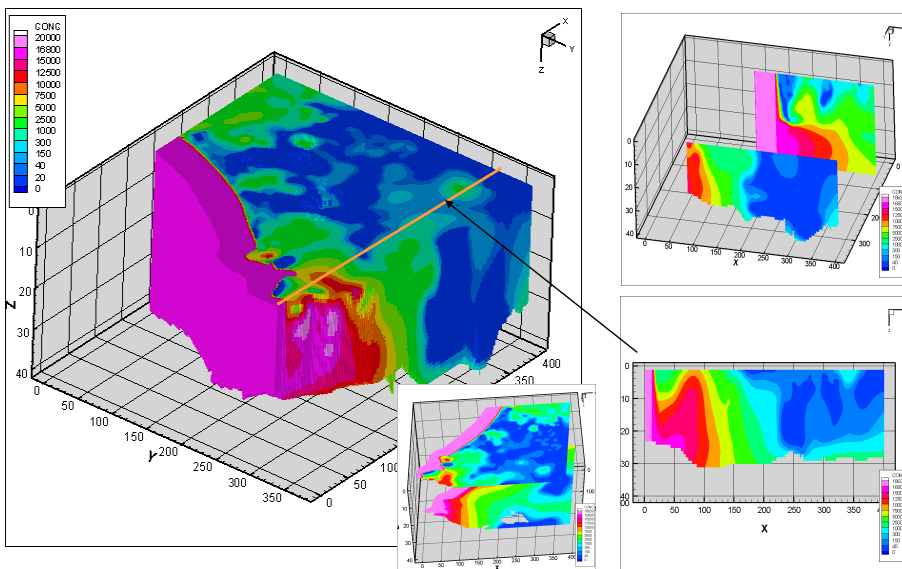


# 3D interpolation of chloride-concentration

## Histogram: depth Chloride measurements



# Initial chloride distribution

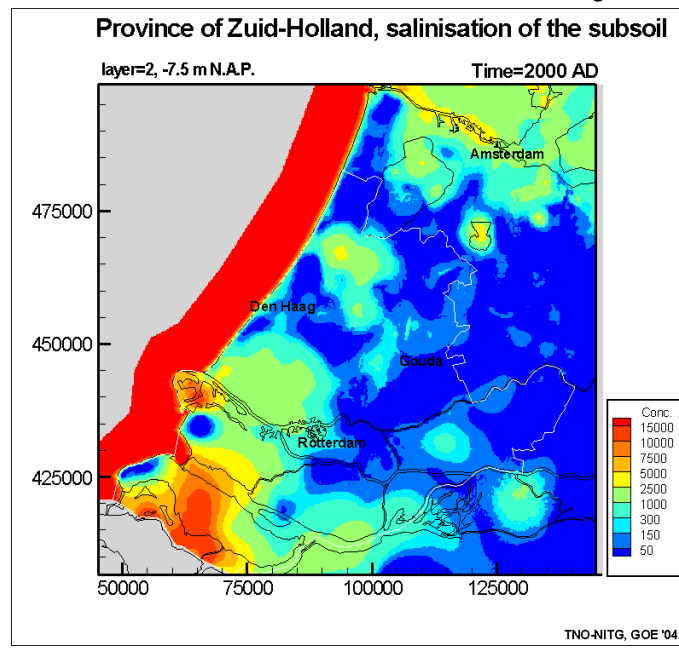


## Present freshwater volume

27 billion m<sup>3</sup>

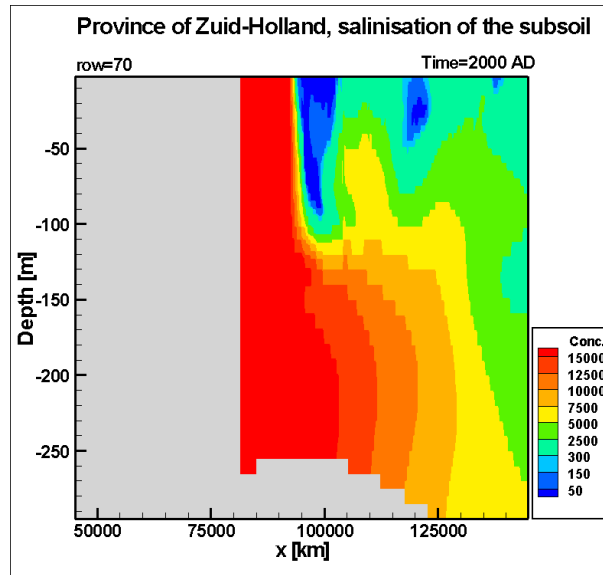
36% fresh, 14% brackish, 50% saline

## Results: Chloride conc. in 200 yrs

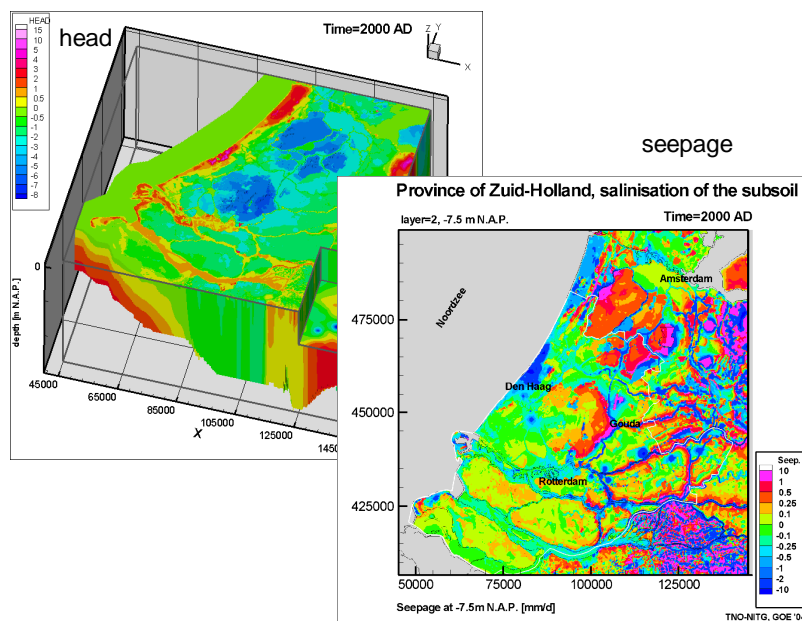




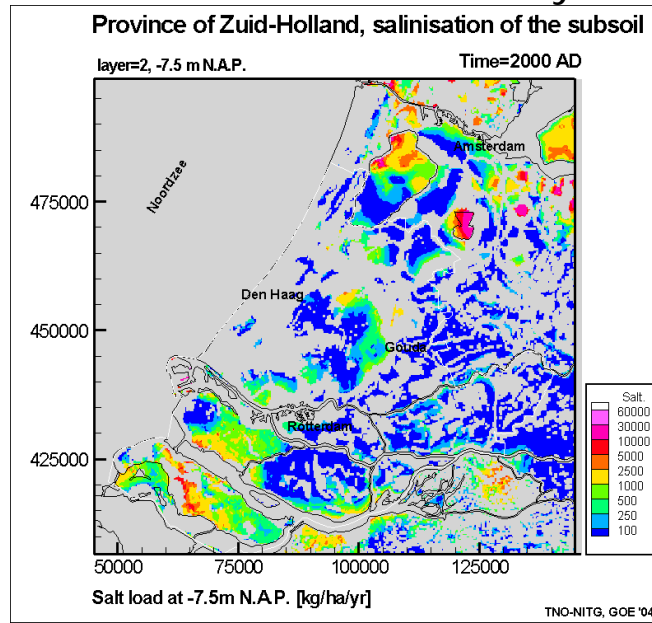
## Results: Chloride conc. in 200 yrs



## Results: freshwater head and seepage at 2000 AD



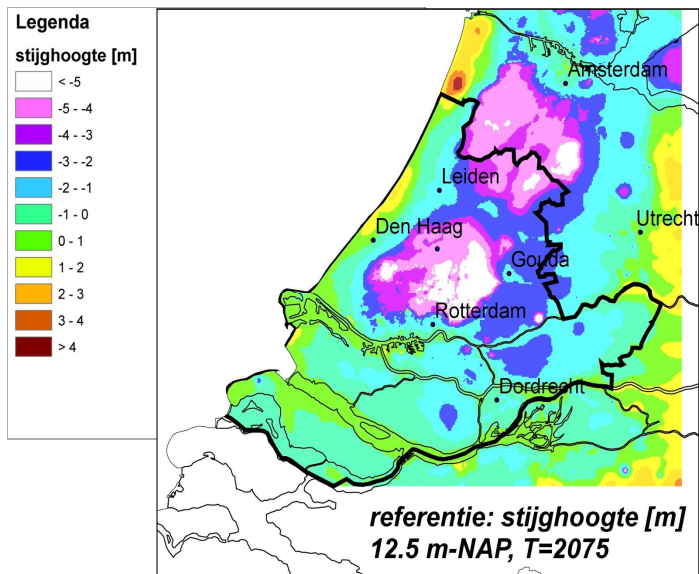
## Results: Salt load in 200 yrs



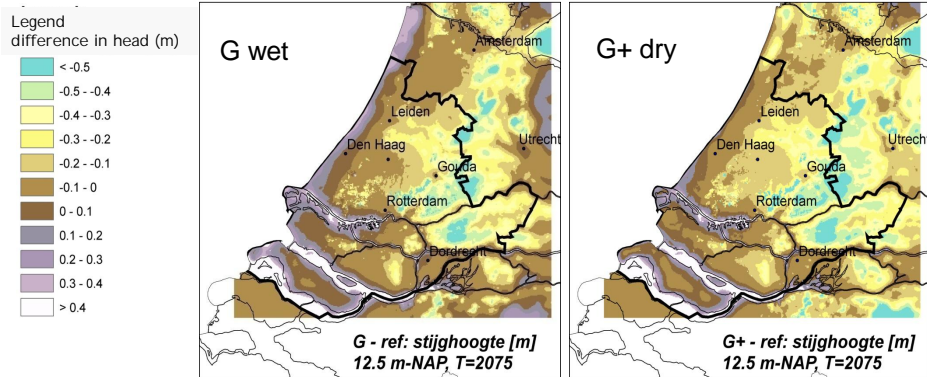
Effect sea level rise, change in natural groundwater recharge and land subsidence on freshwater head in aquifer

Some regional modelling results

### Freshwater head at -12.5 M.S.L.



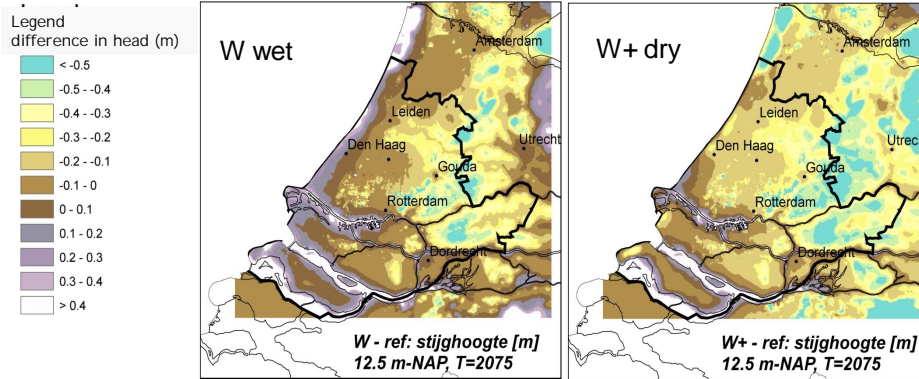
### Difference in freshwater head on op -12.5 N.A.P.: G scenarios



Sea level rise is 60 cm

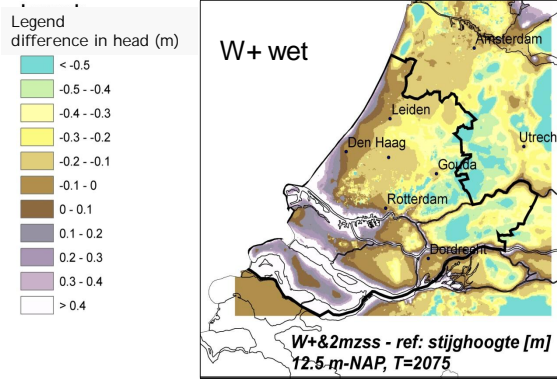
Including change in natural groundwater recharge

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



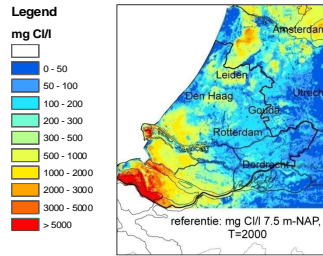
Sea level rise is 85 cm

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



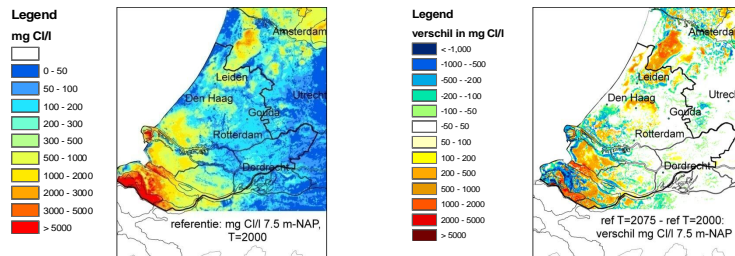
Sea level rise is 200 cm

## Salinisation/freshening Netherlands?: Present situation



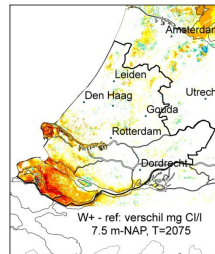
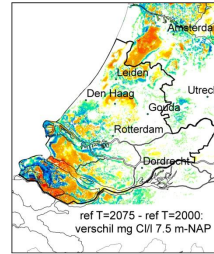
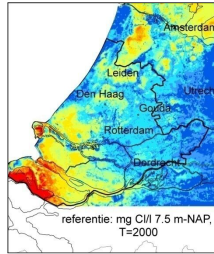
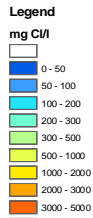
modelstudy

## Salinisation/freshening Netherlands?: Autonomous processes

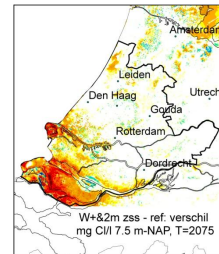


modelstudy

## Salinisation/freshening Netherlands?: climate change



85 cm sea level rise



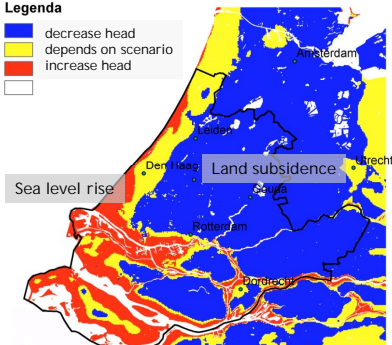
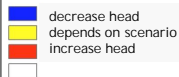
200 cm sea level rise

modelstudy

## Effect climate scenarios in 2075 on

### freshwater head

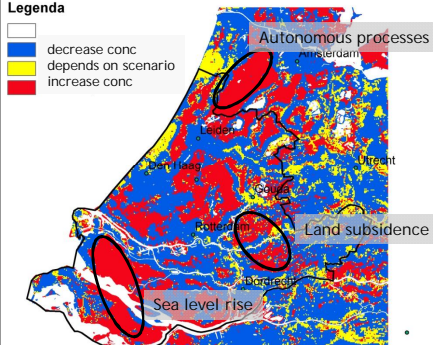
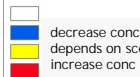
**Legenda**



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

### salinisation

**Legenda**



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

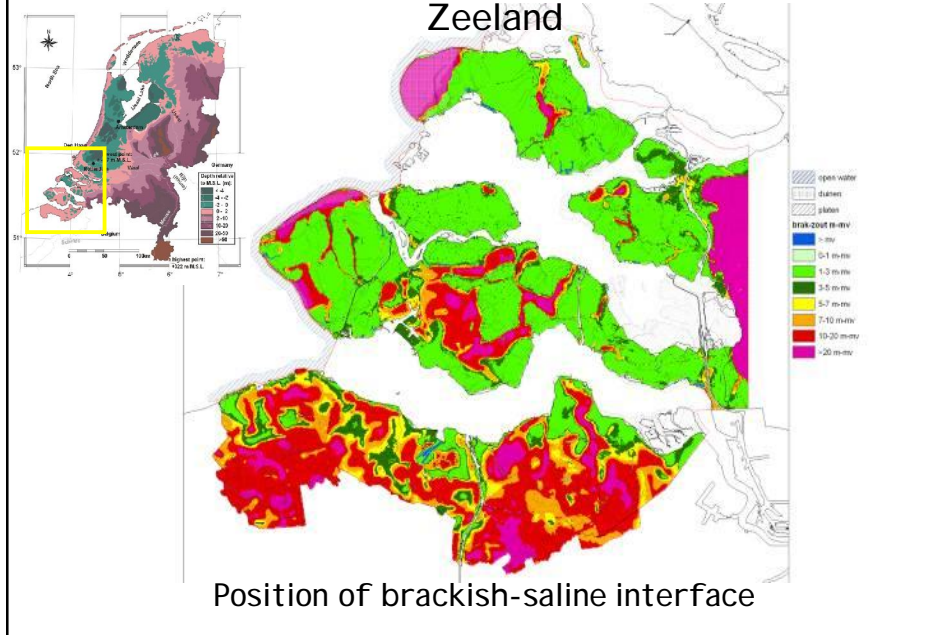
Modelstudie PZH

## Rainwater lenses in an agricultural setting

Shallow dynamic freshwater bodies flowing upon brackish-saline groundwater

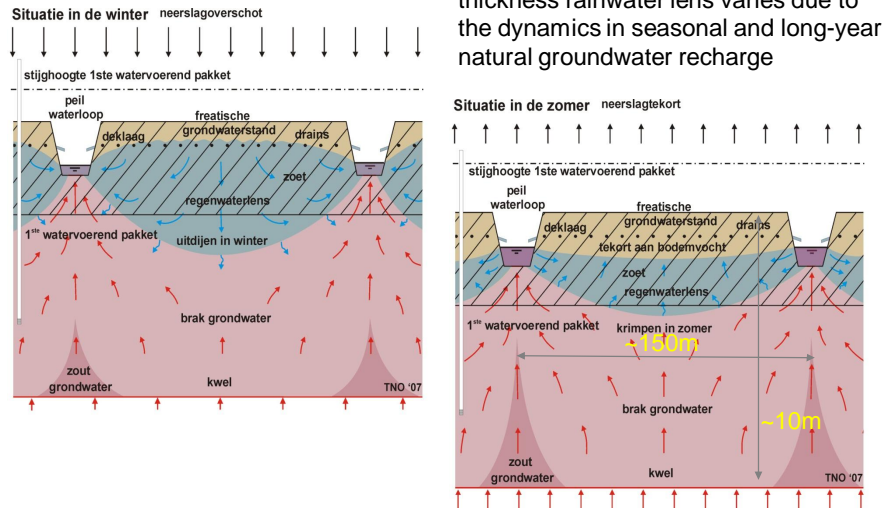
- density dependent
- dynamics: seasonal & long-year

## Salinisation of the phreatic groundwater in Zeeland

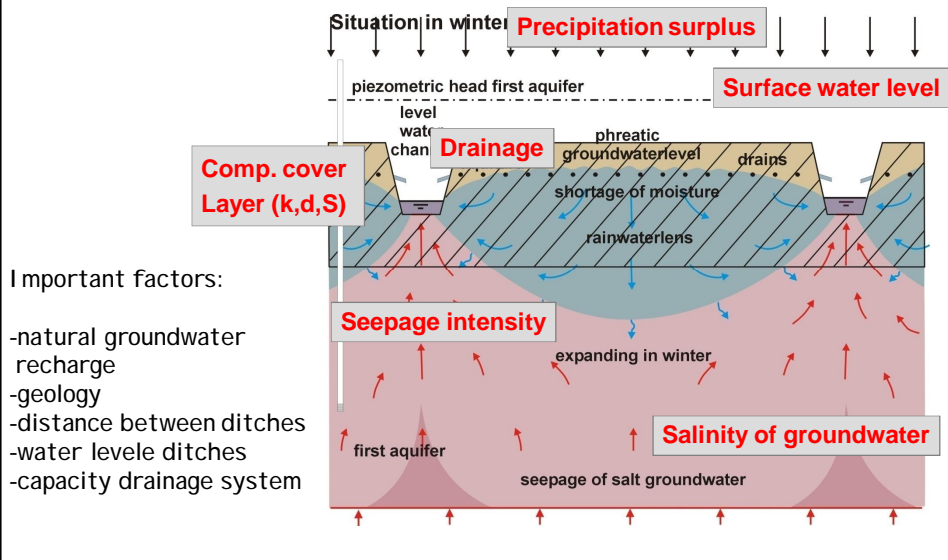


# Salinisation of the phreatic groundwater in Zeeland

Dynamic rainwater lenses floating on saline groundwater

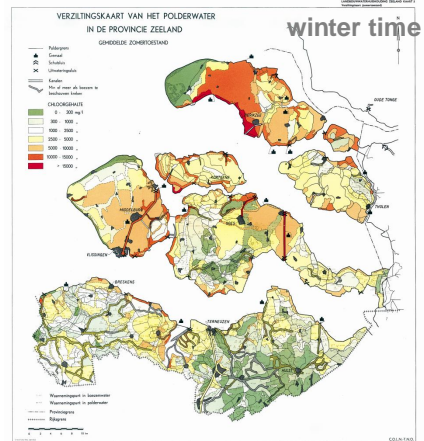
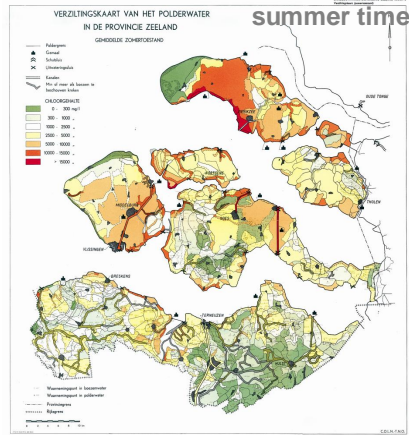


## Factors controlling fresh-salt interface

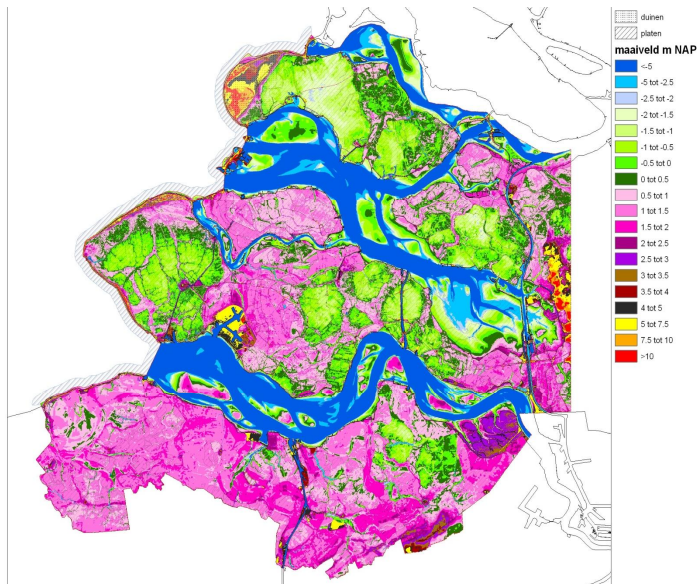




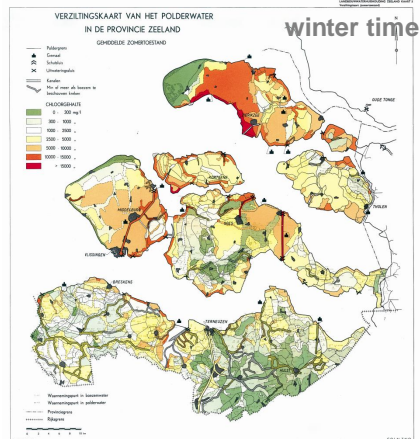
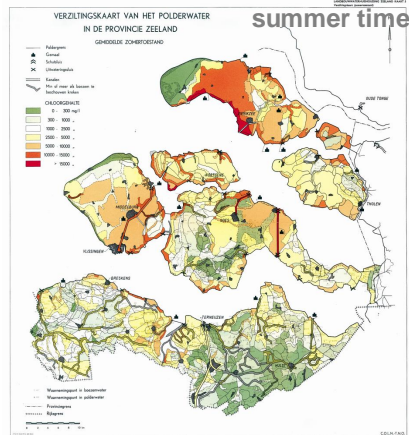
# Salinisation surface water



# 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?

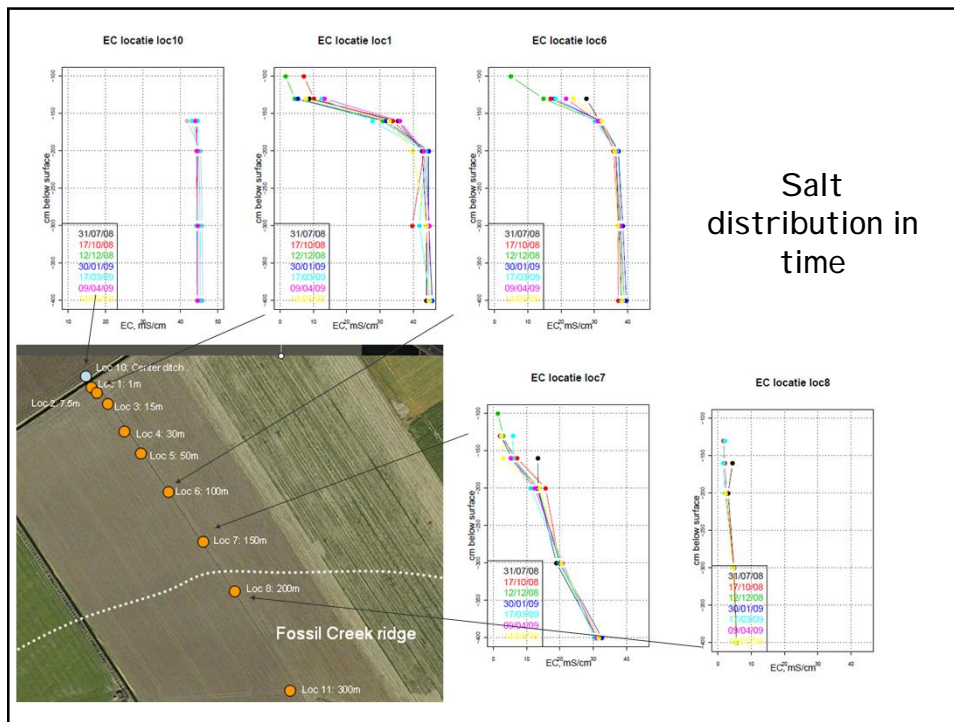
### Field measurements at parcels

- 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

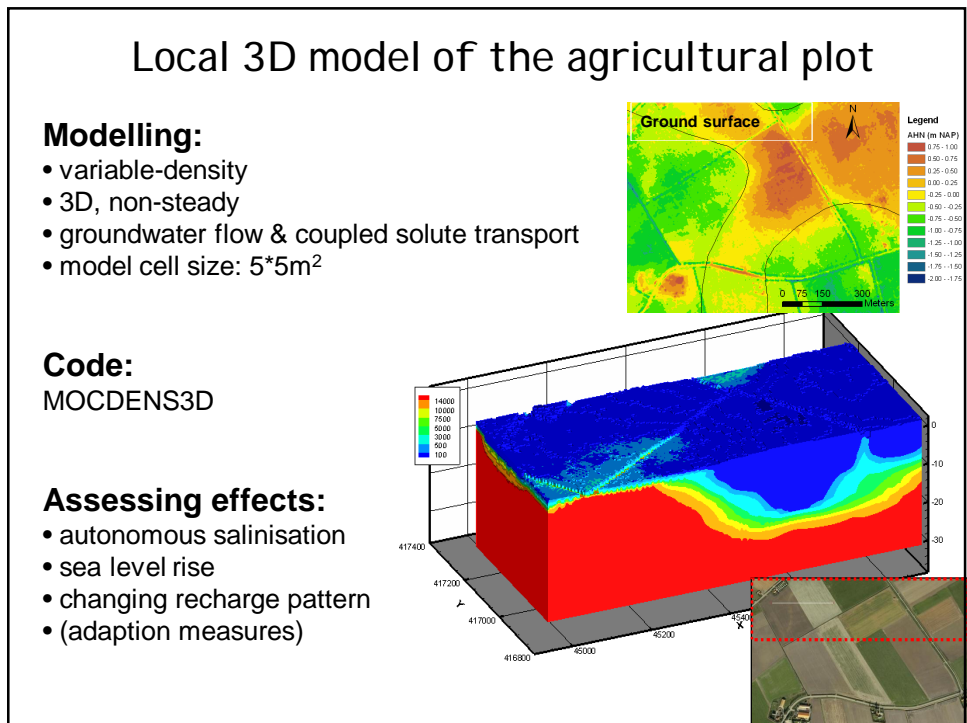
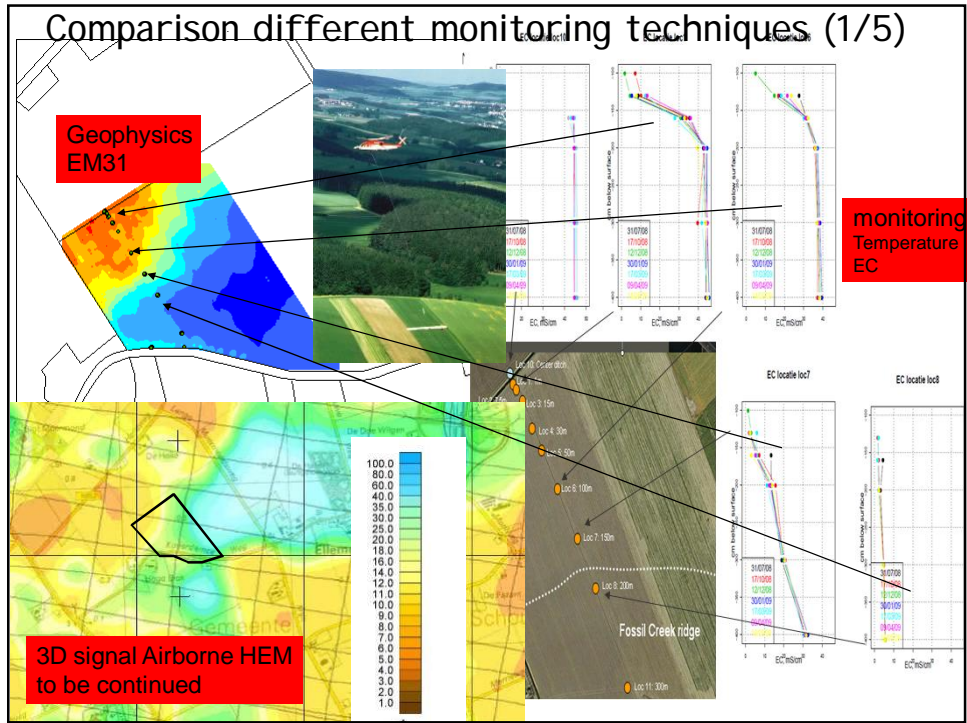
### Modelling

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

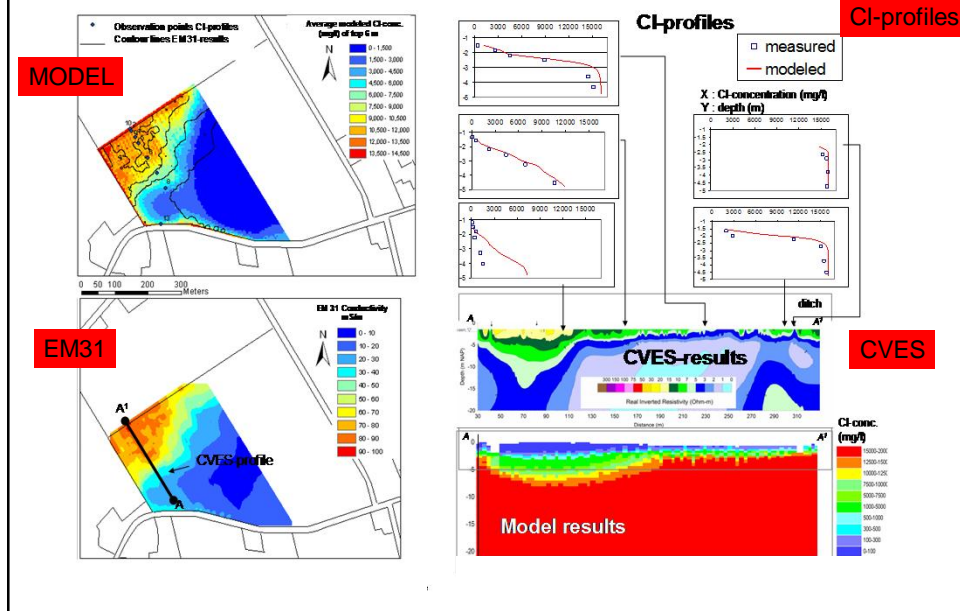




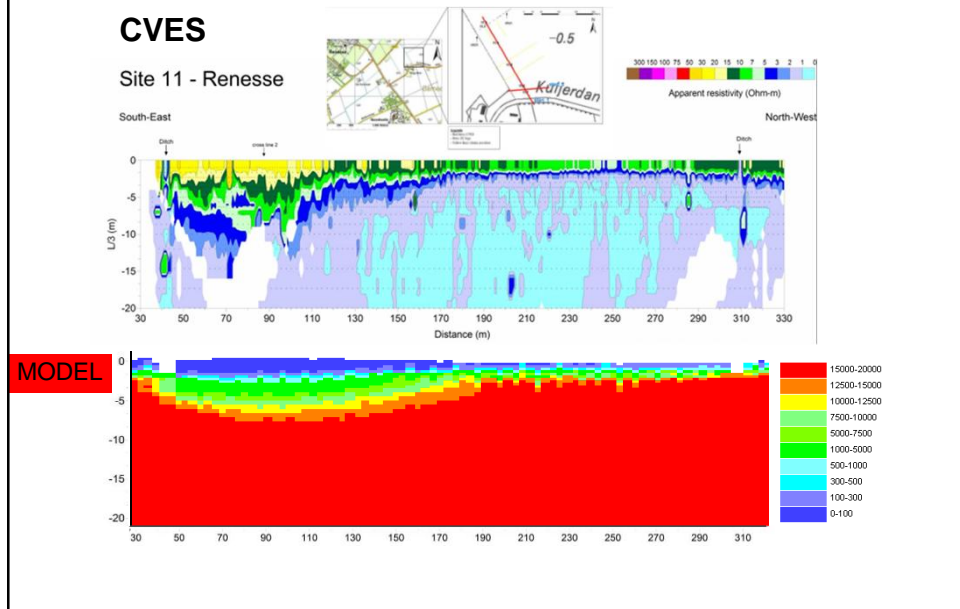
- TEC
- sampling
- EM31
- CVES
- HEM
- ECPT
- Numerical models (2D and 3D)



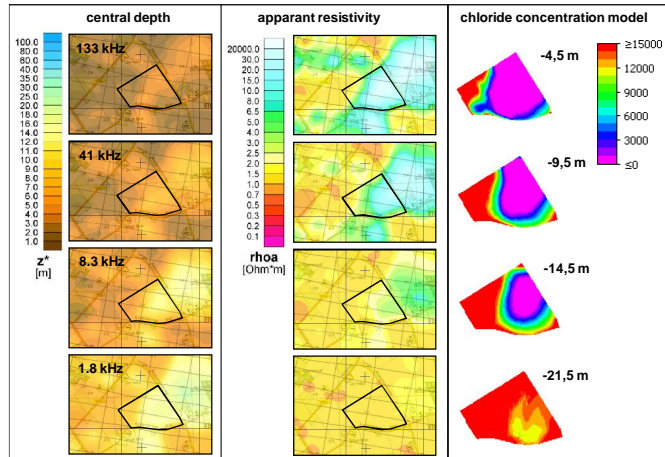
## Comparison model with EM31, CVES, profiles



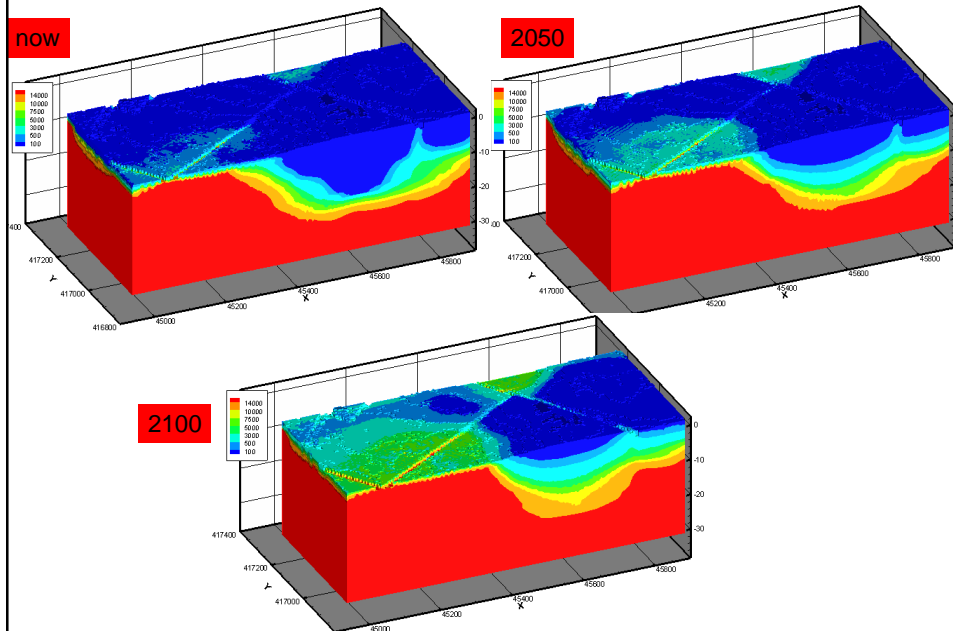
## Comparison 3D model and CVES



# HEM data



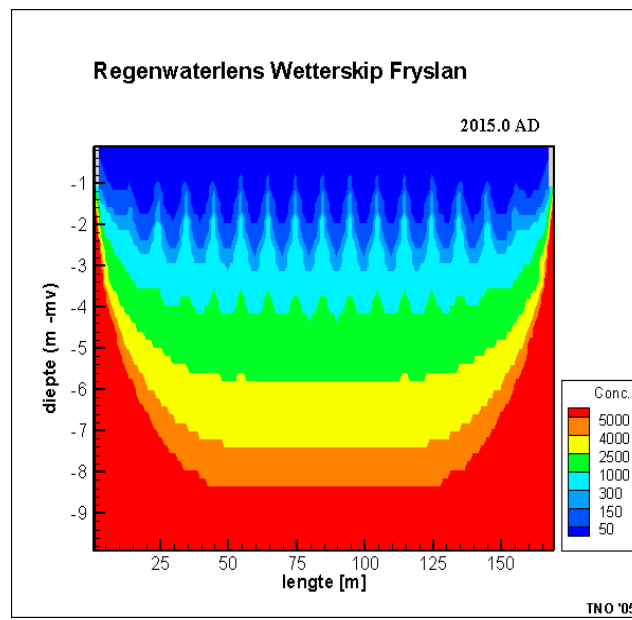
# Climate change scenario (dry): model result



## To be continued...

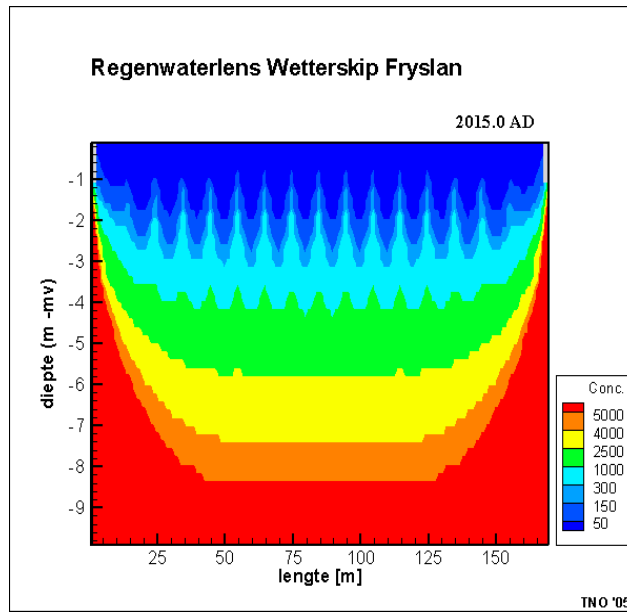
- Implementing more realisations of 3D geology and initial 3D fresh-saline
  - Analyse the differences
- Running climate change scenarios (on national and regional level)
  - Effect on surface water (salt load)
  - Effect on root zone (rainwater lenses)
  - Effect on freshwater volumes (drinking water)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

## Model the dynamics of fresh-brackish-salt interface

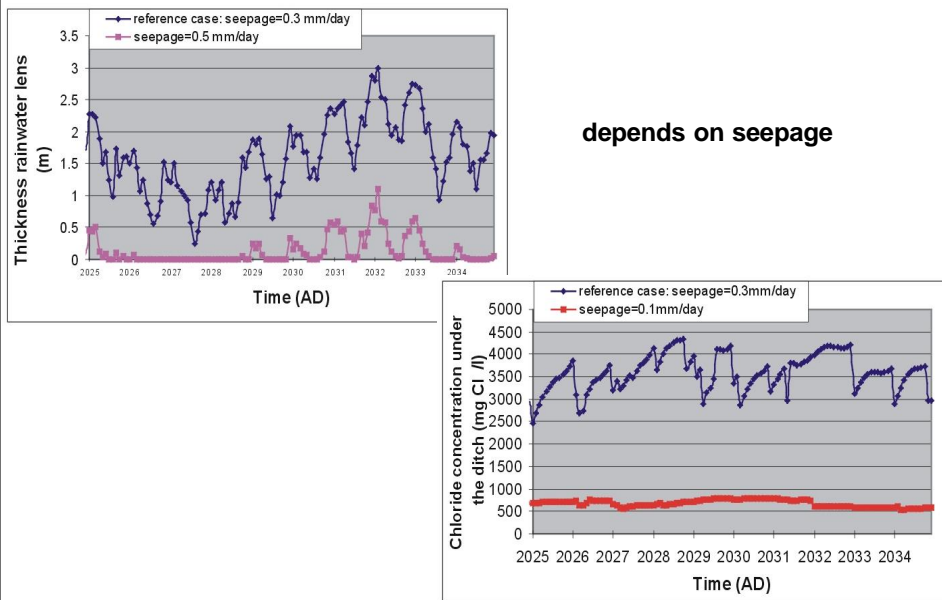




## Model the dynamics of fresh-brackish-salt interface



## Thickness of the lens and salt load to surface water varies



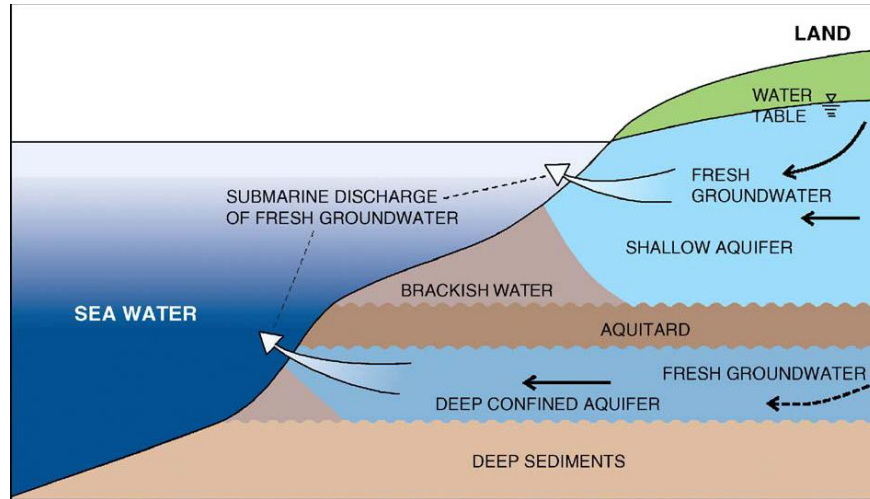
### Conclusions (salinisation Dutch aquifers):

- 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):

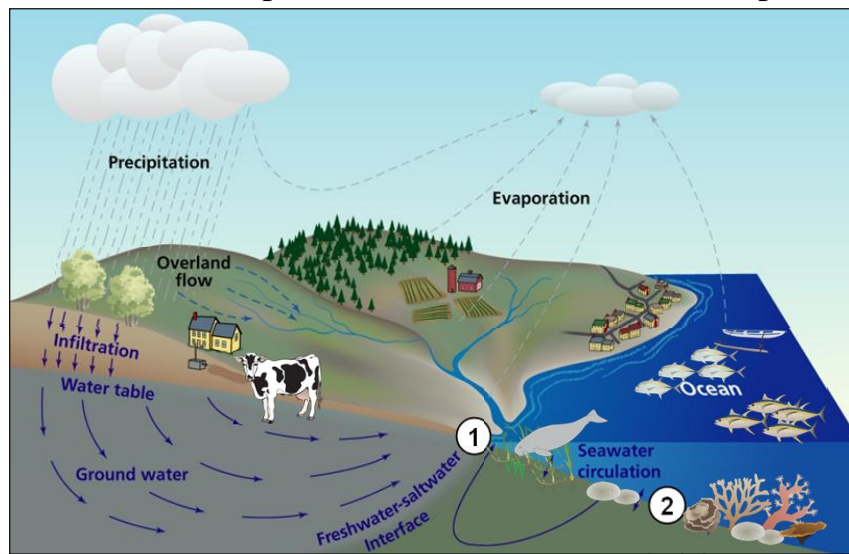
- Number of quality measurements should be increased
- Feasibility study is necessary to implement potential technical measures to compensate salt water intrusion

What is Submarine Groundwater Discharge (SGD)?  
*any flow of water out across the sea floor*



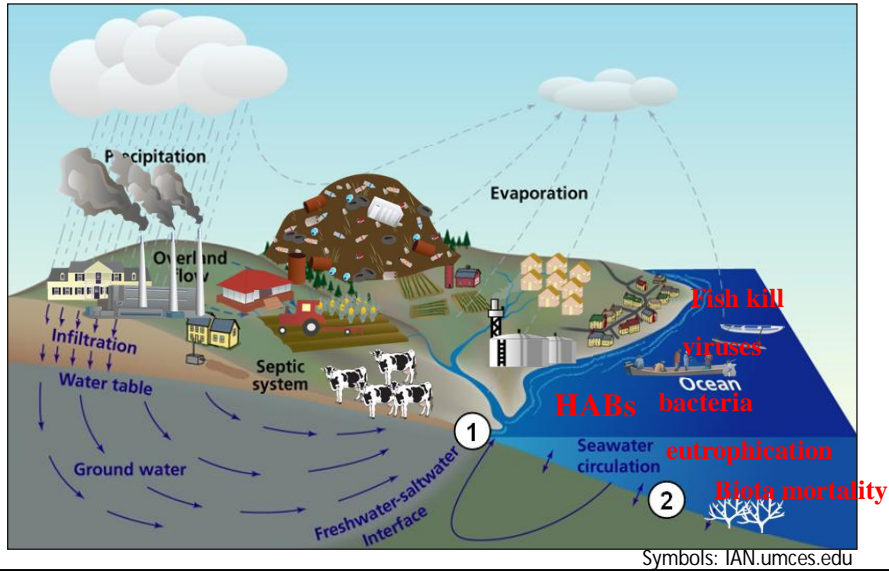
Why study SGD?

Nutrients are transported from land to sea via SGD pathway



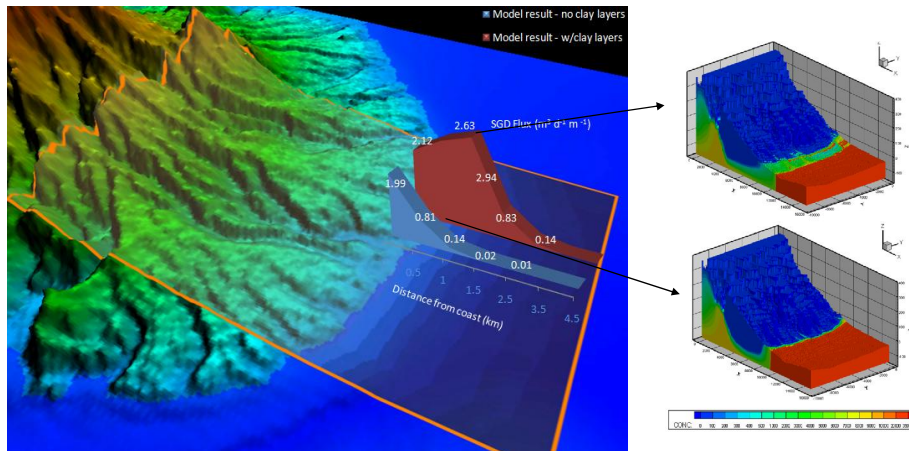
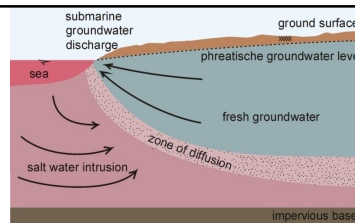
# Why study SGD?

Nutrients are transported from land to sea via SGD pathway



## Philippines

Submarine Groundwater Discharge



## 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

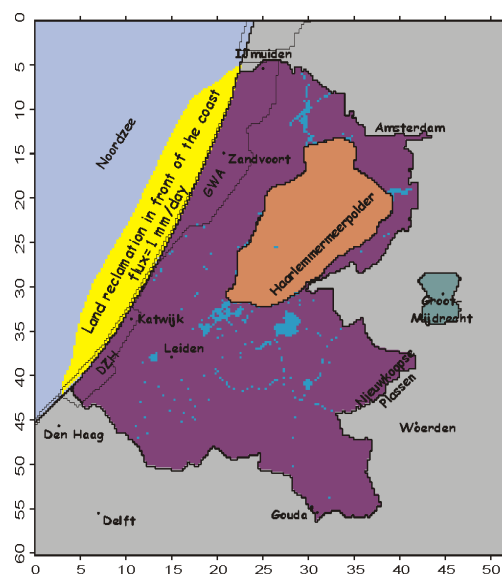
## Challenges for the future

- Improve the 3D density matrix, e.g. by more types of measurements
- Implement effect of climate change and sea level rise on coastal aquifers
- Optimisation 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

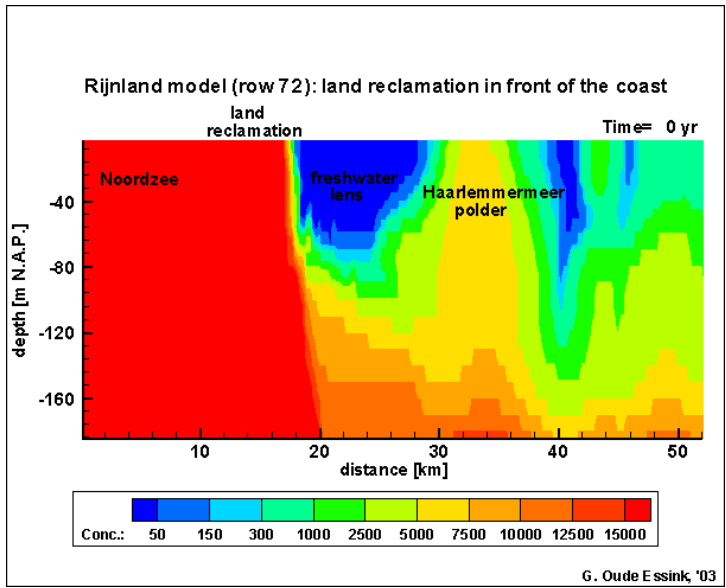
## Possible measures to compensate salt water intrusion

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



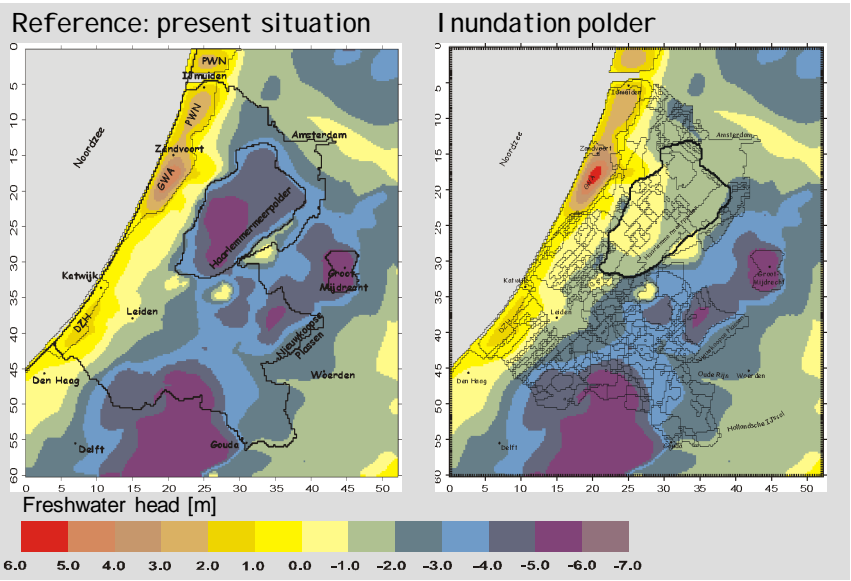
# 1. Land reclamation in front of the coast



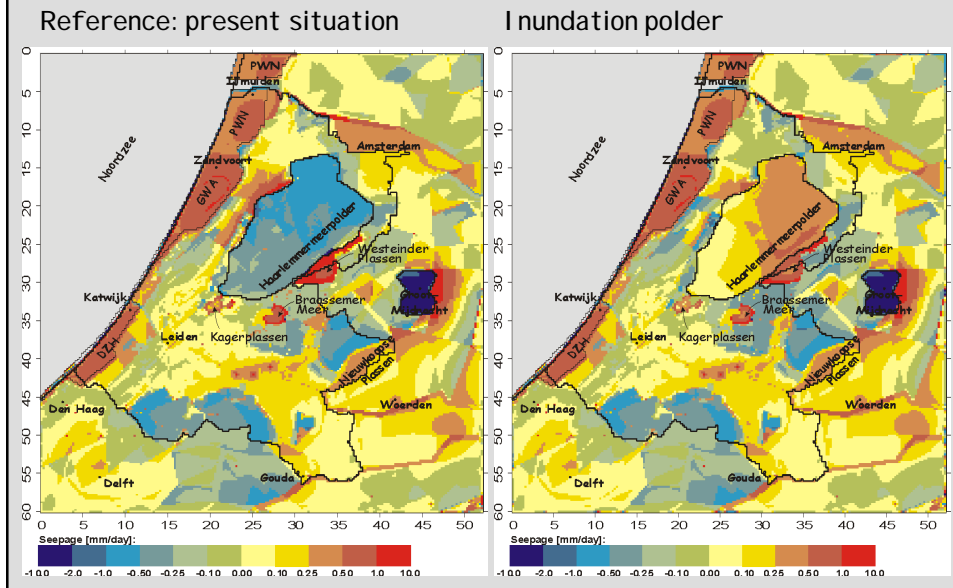
# 2. Rijnland model: Inundation Haarlemmermeerpolder

Rijnland

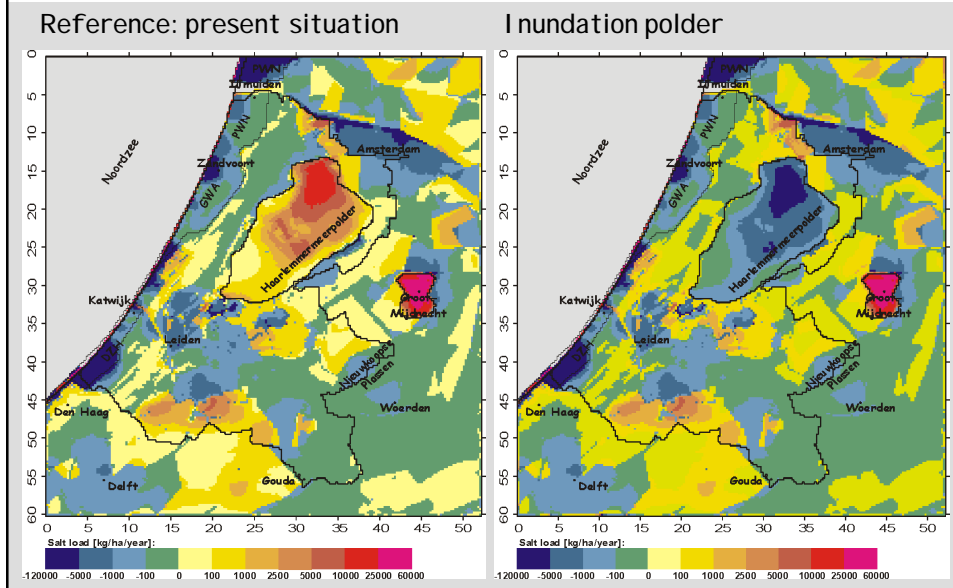
Calculated present phreatic water head



## 2. Rijnland model : I nundation Haarlemmermeerpolder Calculated seepage and infiltration on -10 m M.S.L.

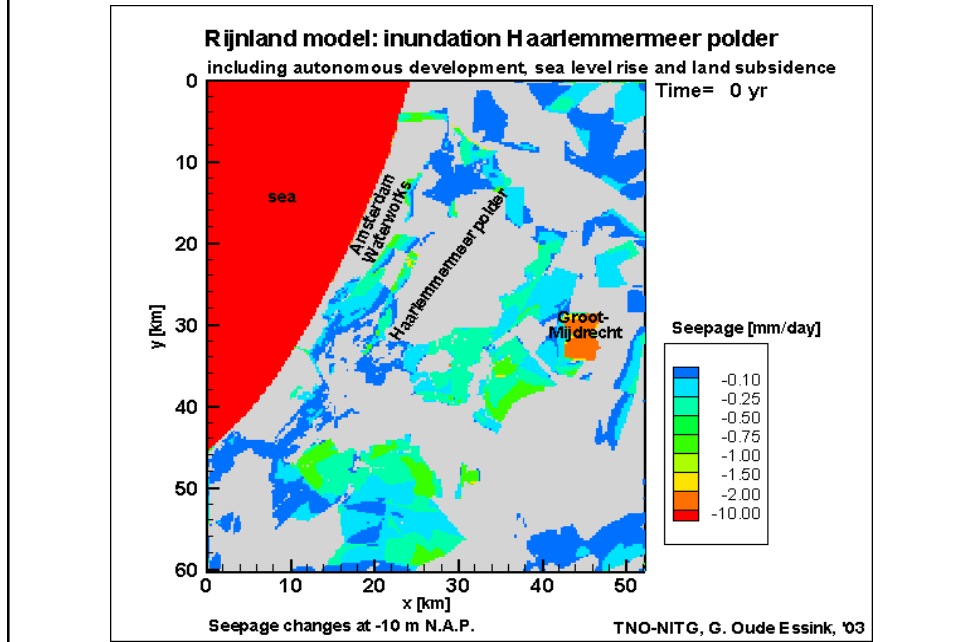


## 2. Rijnland model: I nundation Haarlemmermeerpolder Calculated salt load on -10 m M.S.L.

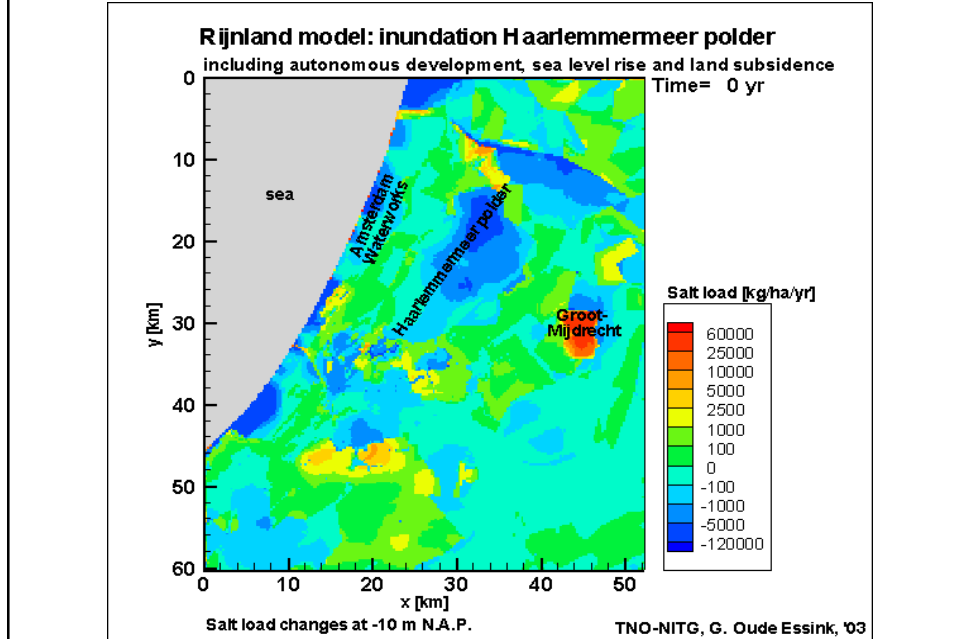




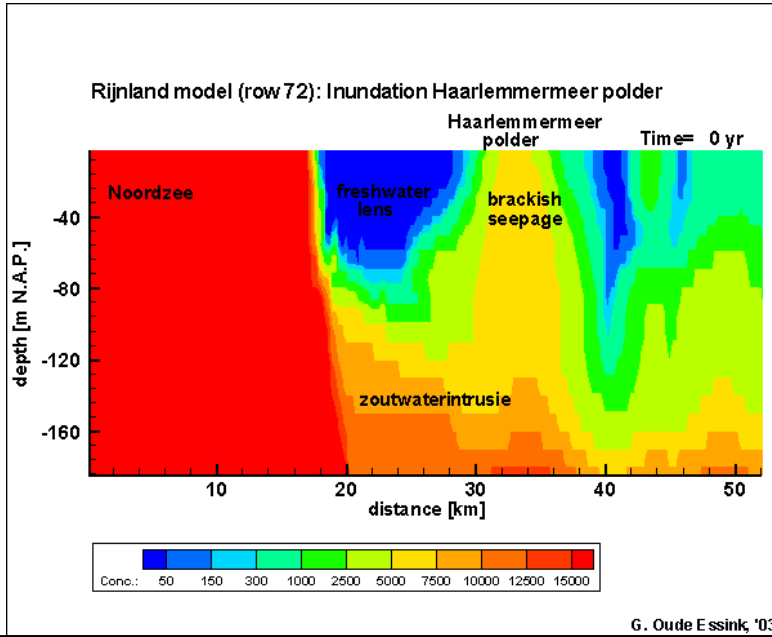
## 2. Rijnland model: Inundation Haarlemmermeerpolder



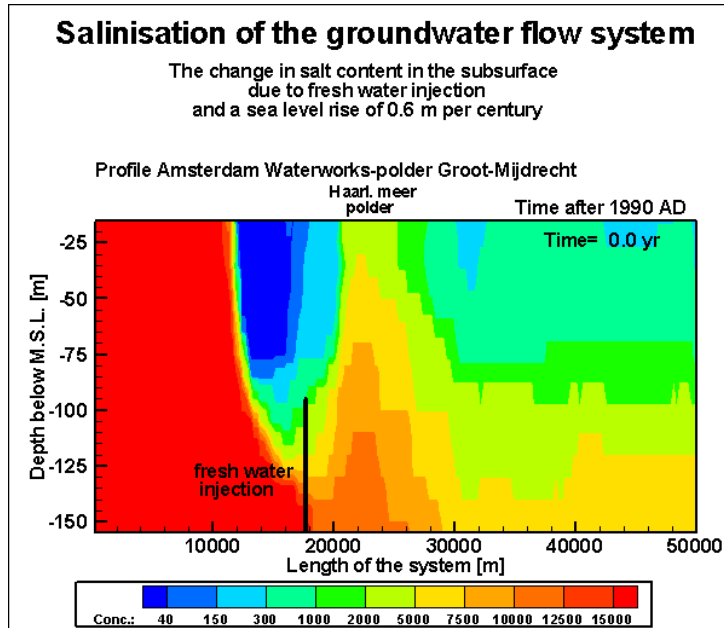
## 2. Rijnland model: Inundation Haarlemmermeerpolder



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



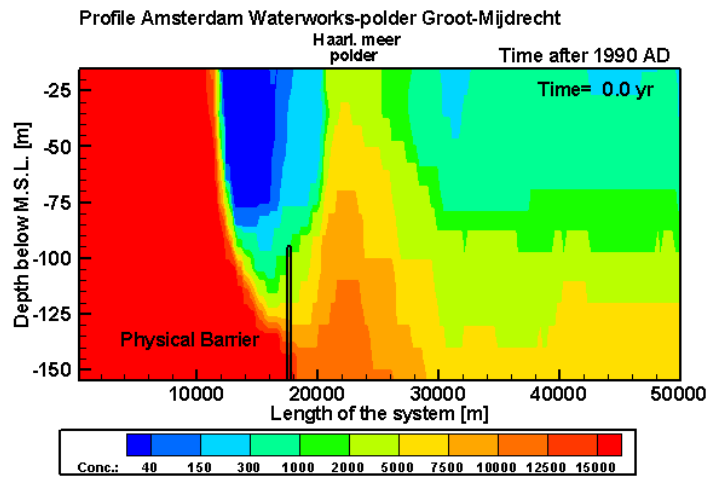
4. Injection of fresh water (conc, 1000 yr)



## 5. Physical barrier (conc, 1000 yr)

### Salinisation of a groundwater flow system

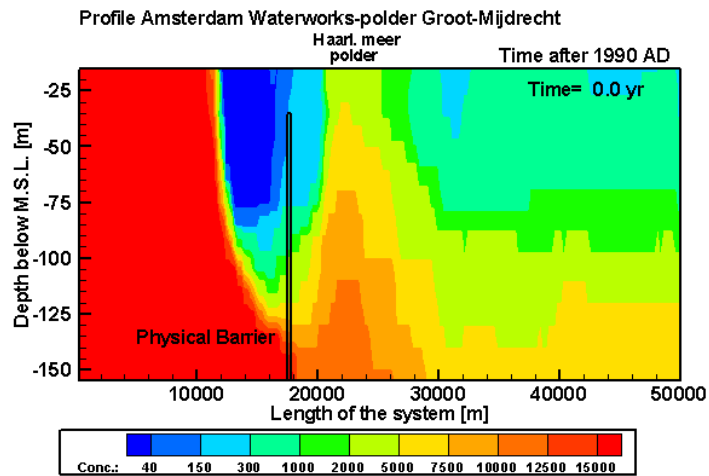
The change in salt content in the subsurface due to a physical barrier in the deep coastal aquifer and a sea level rise of 0.6 m per century

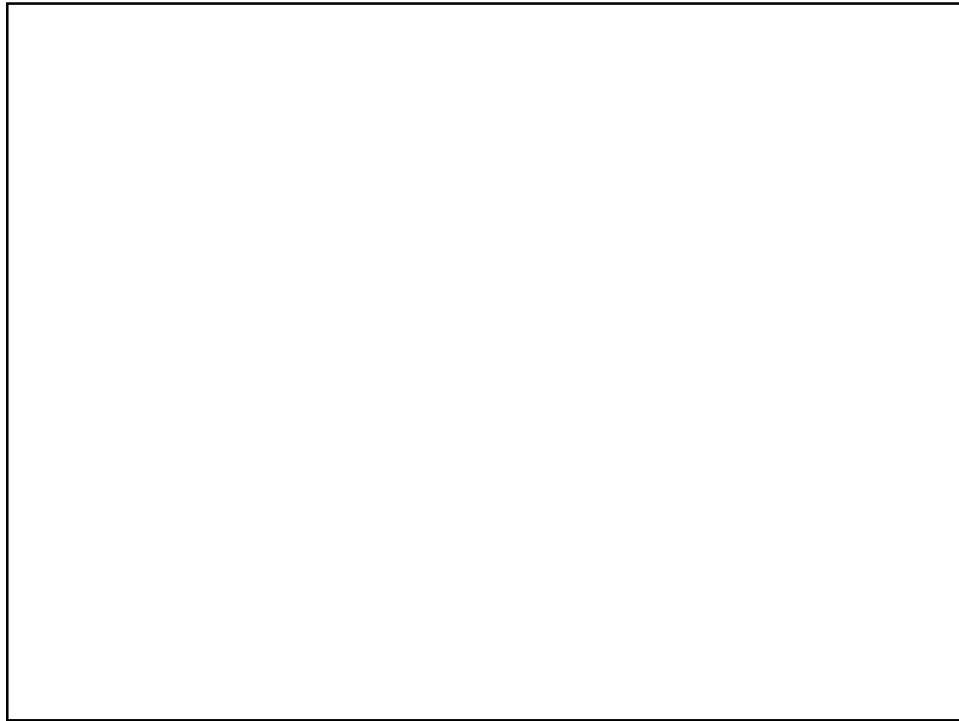


## 5. Physical barrier (conc, 1000 yr)

### Salinisation of the groundwater flow system

The change in salt content in the subsurface due to a physical barrier in the deep coastal aquifer and a sea level rise of 0.6 m per century





modelling

## 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):

$$R_d \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left( D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (C V_i) + \frac{(C - C^*) W}{n_e} - R_d \lambda C$$

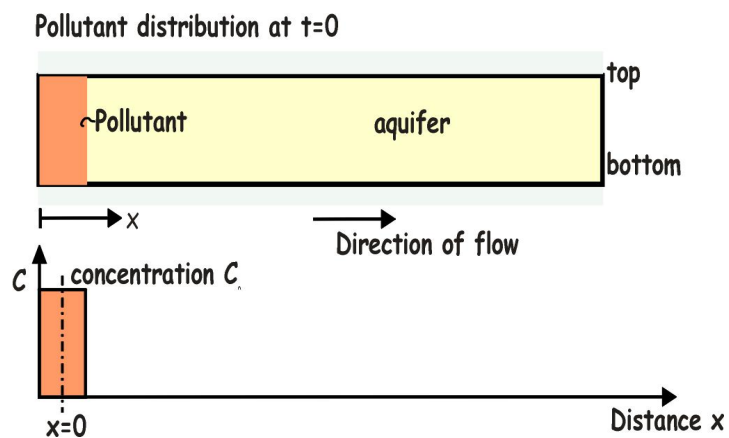
change in concentration    dispersion    advection    source/sink    decay  
in concentration    diffusion

$D_{ij}$  = hydrodynamic dispersion [ $L^2 T^{-1}$ ]

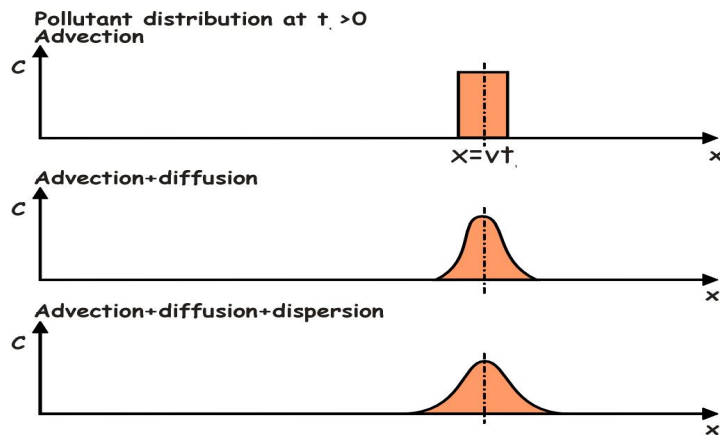
$R_d$  = retardation factor [-]

$\lambda$  = decay-term [ $T^{-1}$ ]

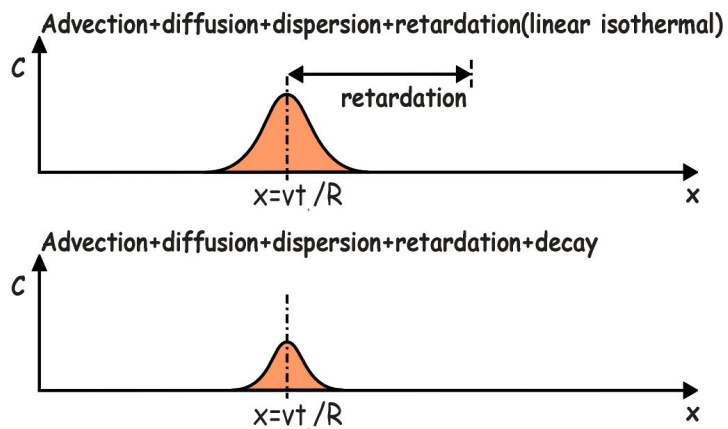
## Solute transport equation: column test (I):



## Solute transport equation: column test (II):



## Solute transport equation: column test (III):



## Hydrodynamic dispersion

$$\text{hydrodynamic dispersion} = \text{mechanical dispersion} + \text{diffusion}$$

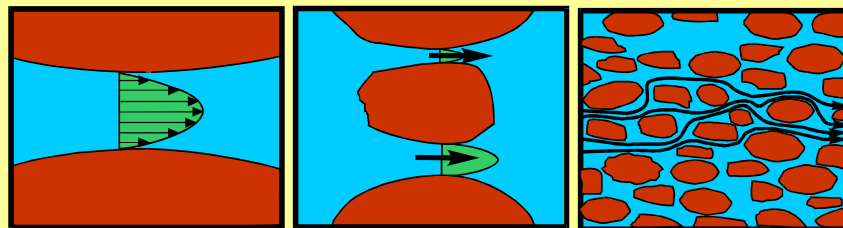
mechanical dispersion:

tensor  
velocity dependant

diffusion:

molecular process  
solute 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:  $R_f=1$ ,  $V_f=0$ ,  $\lambda=0$  and  $W=0$ 

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

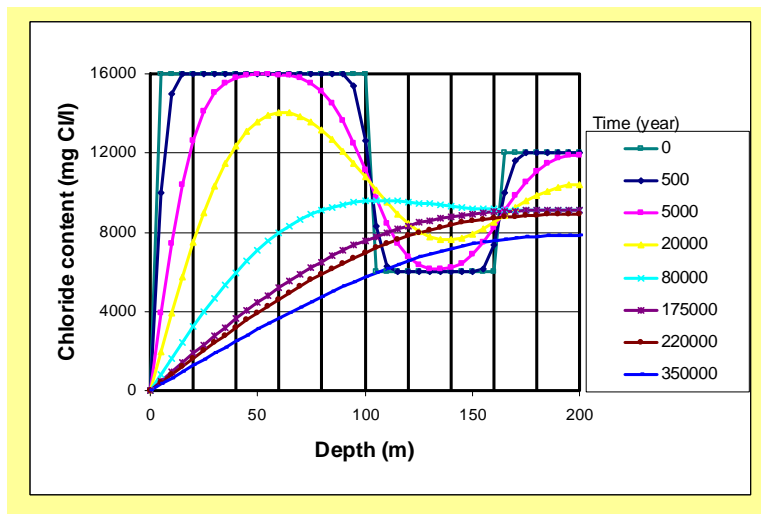
similarity with non-steady state groundwater flow equation

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

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

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

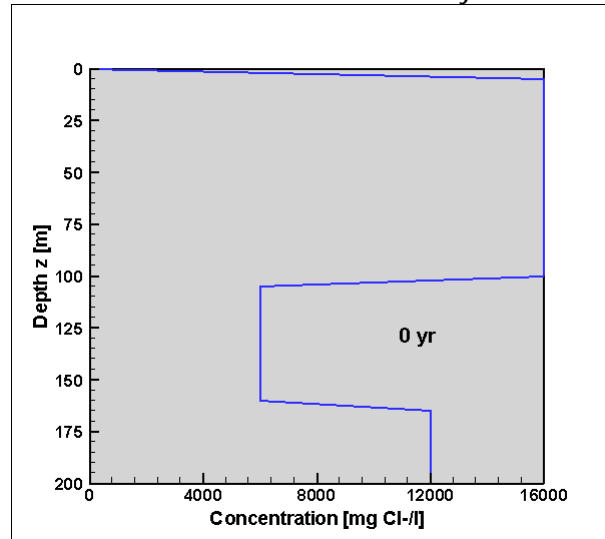
## Solute transport equation: diffusion (II)

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

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

Freshwater head

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

↑  
buoyancy  
term

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 &amp; concentration

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

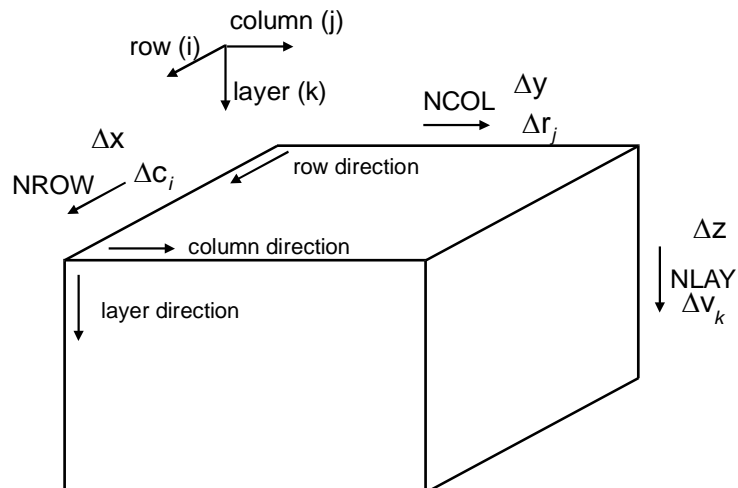
MOCDENS3D is based on MODFLOW

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

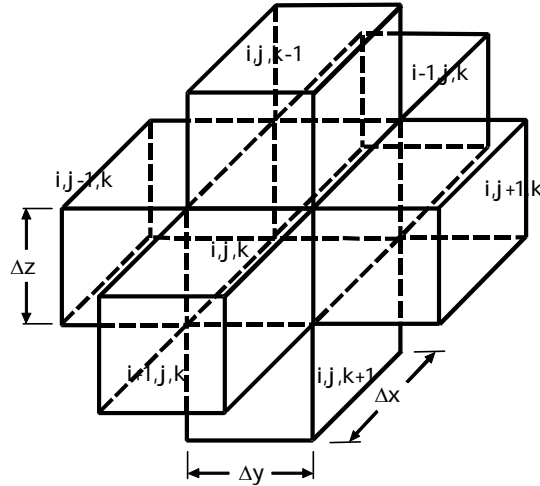
(M.G. McDonald & A.W. Harbaugh, from 1983 on)

- 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]



Continuity equation (I)

In - Out = Storage

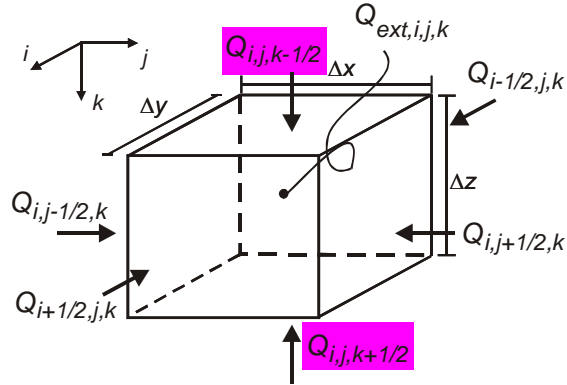
$$\frac{\partial}{\partial x} \left( k_{xx} \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{yy} \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_{zz} \frac{\partial \phi}{\partial z} \right) - W = S_s \frac{\partial \phi}{\partial t}$$

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

## Continuity equation (II)

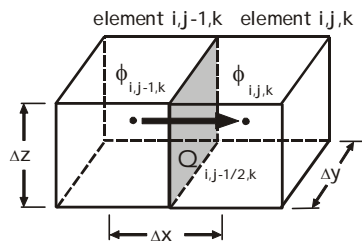
$$\sum Q_i = S_s \frac{\Delta \phi}{\Delta t} \Delta V$$

In = positive



$$\begin{aligned} & Q_{i,j-1/2,k} + Q_{i,j+1/2,k} + Q_{i-1/2,j,k} + Q_{i+1/2,j,k} + Q_{i,j,k-1/2} + Q_{i,j,k+1/2} + Q_{ext,i,j,k} \\ &= SS_{i,j,k} \frac{\phi_{i,j,k}^t - \phi_{i,j,k}^{t+\Delta t}}{\Delta t} \Delta V \end{aligned}$$

## Flow equation (Darcy's Law)



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

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

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

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

## Density dependent vertical flow equation

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

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

$$Q_z = \text{surface} * q_z$$

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

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

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

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

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

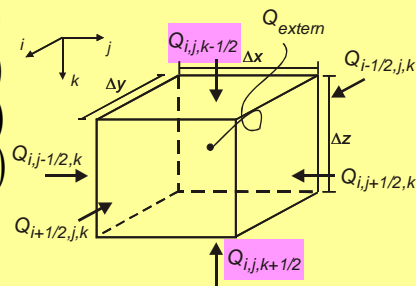
## Density dependent groundwater flow equation

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

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

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

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



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

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

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

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

Takes into account all external sources

Rewriting the term:

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

The variable density groundwater flow equation

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

and:

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

gives:

$$CV_{i,j,k-1/2} \phi_{f,i,j,k-1}^{t+\Delta t} + CC_{i-1/2,j,k} \phi_{f,i-1,j,k}^{t+\Delta t} + CR_{i,j-1/2,k} \phi_{f,i,j-1,k}^{t+\Delta t} \\ + (-CV_{i,j,k-1/2} - CC_{i-1/2,j,k} - CR_{i,j-1/2,k} - CR_{i,j+1/2,k} - CC_{i+1/2,j,k} - CV_{i,j,k+1/2} + HCOF_{i,j,k}) \phi_{f,i,j,k}^{t+\Delta t} \\ + CR_{i,j+1/2,k} \phi_{f,i,j+1,k}^{t+\Delta t} + CC_{i+1/2,j,k} \phi_{f,i+1,j,k}^{t+\Delta t} + CV_{i,j,k+1/2} \phi_{f,i,j,k+1}^{t+\Delta t} = RHS_{i,j,k}$$

with:

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

$$RHS_{i,j,k} = -Q'_{i,j,k} - SC1_{i,j,k} \phi'_{f,i,j,k} / (\Delta t)$$

$$-CV_{i,j,k-1/2} BUOY_{i,j,k-1/2} \Delta v_{k-1/2} + CV_{i,j,k+1/2} BUOY_{i,j,k+1/2} \Delta v_{k+1/2}$$

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

## 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

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

## Method of Characteristics (MOC)

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

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left( D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (C V_i) + \frac{(C - C)W}{n_e}$$

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

### 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  $\Delta t_{\text{solute}}$
- 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

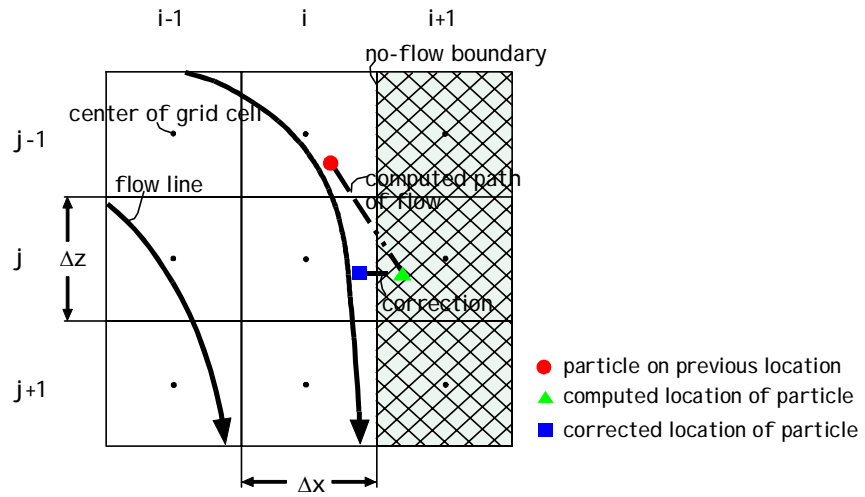
1. Determine concentration gradients at old timestep  $k-1$
2. Move particles to model advective transport
3. Concentration of particles to concentration in element node
4. Determine concentration gradients on new timestep  $k^*$
5. Determine concentration in element node after advective, dispersive/source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



### Stability criteria (III) 3. Courant criterium

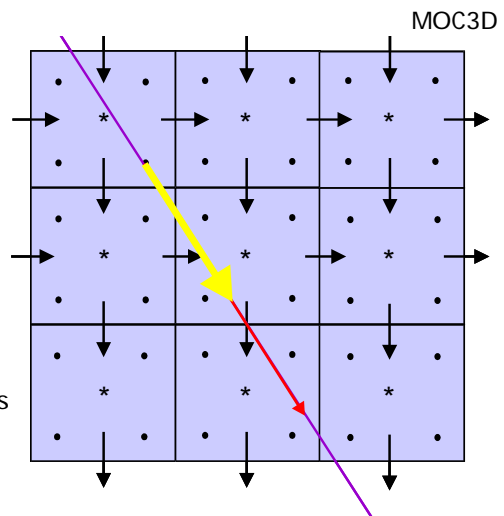
- \* Node element
- Particle
- Velocity direction
- Movement particles

$$0 < \xi \leq 1$$

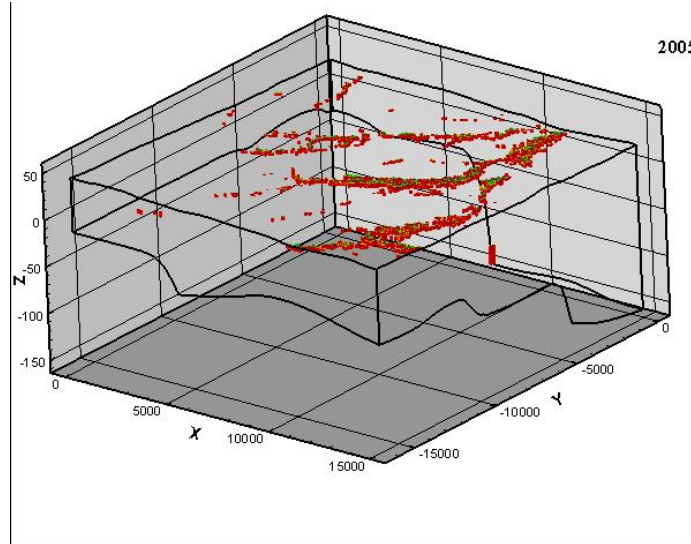
$$\Delta t_s \leq \frac{\xi \Delta x}{V_{x,\max}}$$

$$\Delta t_s \leq \frac{\xi \Delta y}{V_{y,\max}}$$

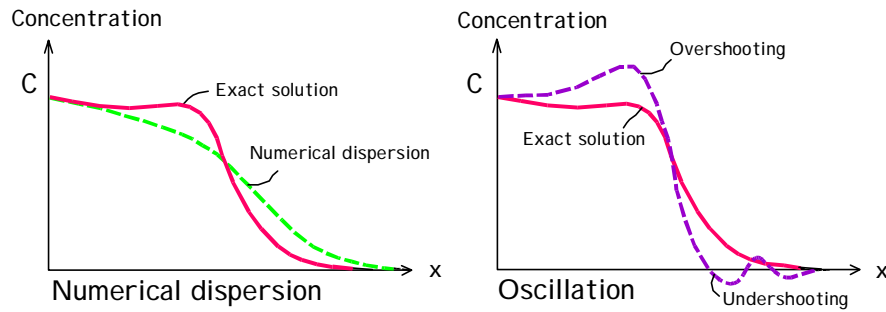
$$\Delta t_s \leq \frac{\xi \Delta z}{V_{z,\max}}$$



Courant criterion: places where timestep is smaller than 40 days



### Numerical dispersion and oscillation



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

## Numerical dispersion problem (I)

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

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

$$\text{where: } Pe = \frac{V\Delta x}{D_h}$$

$V$  = effective velocity [L/T]

$\Delta x$  = dimension grid cell [L]

$D_h$  = hydrodynamic dispersion [L<sup>2</sup>/T]

## Numerical dispersion problem (II)

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

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

where  $\alpha_L$  = longitudinal dispersivity [L]

What does that mean?

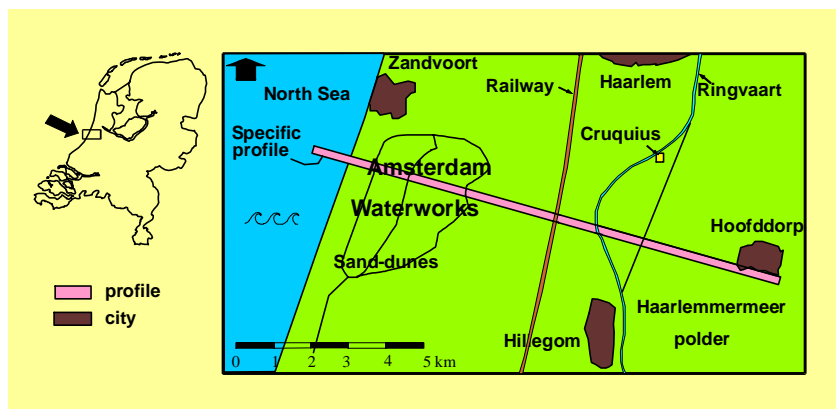
If  $\alpha_L$  is small, then  $\Delta x$  should be small too!!

### Numerical dispersion problem (III)

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

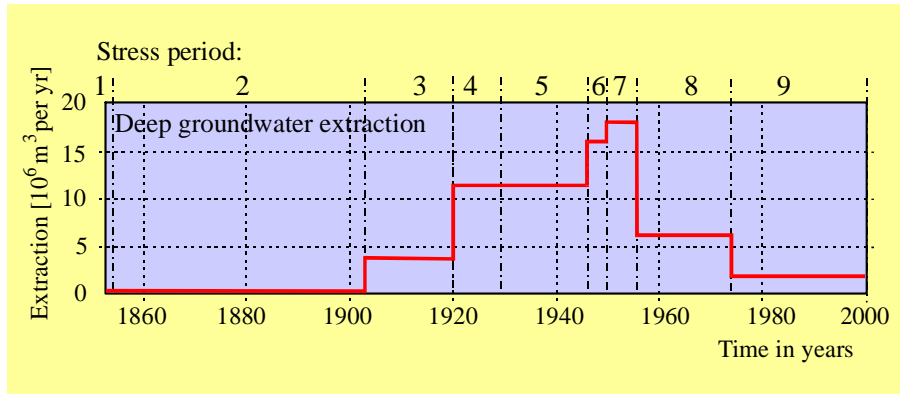
### Effect of $\alpha_L$ on the salinisation of the aquifer (I)

Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



### Effect of $\alpha_L$ on the salinisation of the aquifer (II)

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

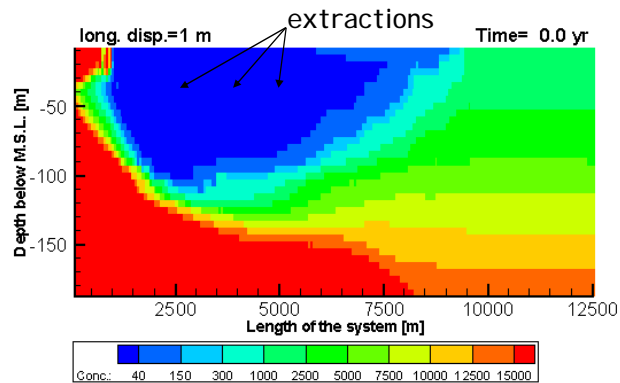


### Effect of $\alpha_L$ on the salinisation of the aquifer (III)

$\alpha_L = 1 \text{ m}$

Initial situation: 154 years ago

Profile Amsterdam Waterworks-Haarlemmeerpolder

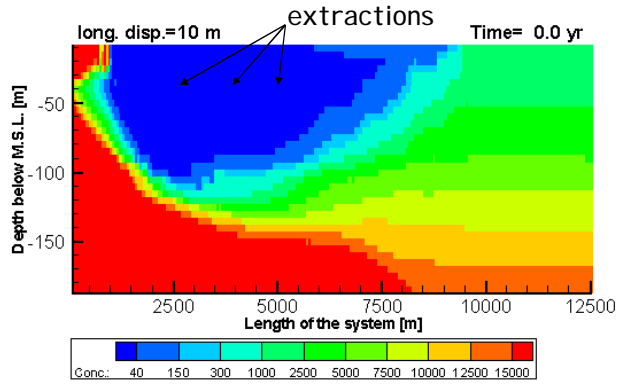


Effect of  $\alpha_L$  on the salinisation of the aquifer (IV)

$\alpha_L = 10$  m

Initial situation: 154 years ago

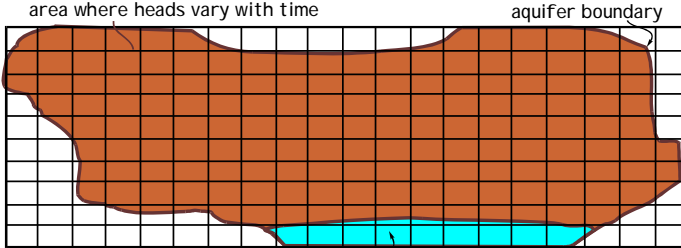
Profile Amsterdam Waterworks-Haarlemmeerpolder



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	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	1	0	
0	0	0	0	0	0	-1	-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<sup>3</sup> per day should be inserted  
in an element as:

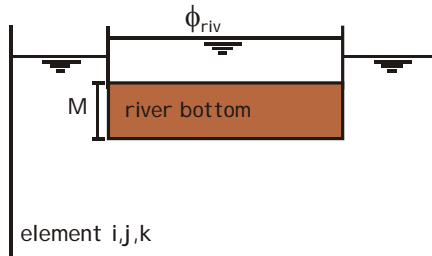
$$Q_{ext,i,j,k} = P_{i,j,k} \phi_{i,j,k}^{t+\Delta t} + Q'_{i,j,k}$$

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

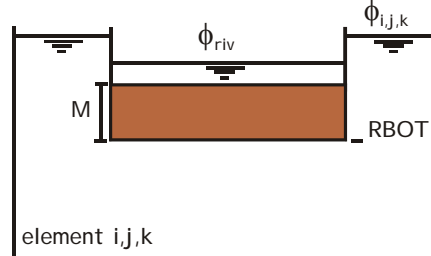
$$Q'_{i,j,k} = -10$$

## 2. River package (I)

river loses water



river gains water



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

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

## 2. River package (II)

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

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

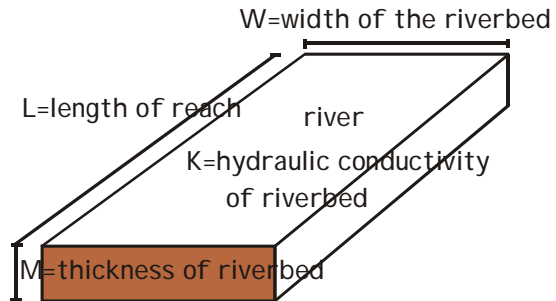
$$Q_{ext,i,j,k} = P_{i,j,k} \phi_{i,j,k}^{t+\Delta t} + Q'_{i,j,k}$$

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

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

## 2. River package (III)

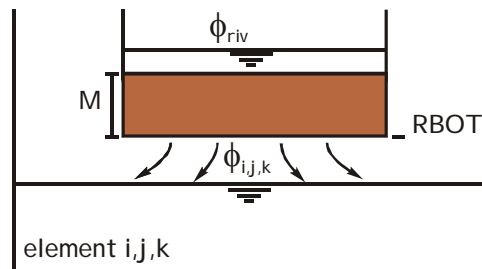
Determine the conductance of the river in one element:



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

## 2. River package (IV)

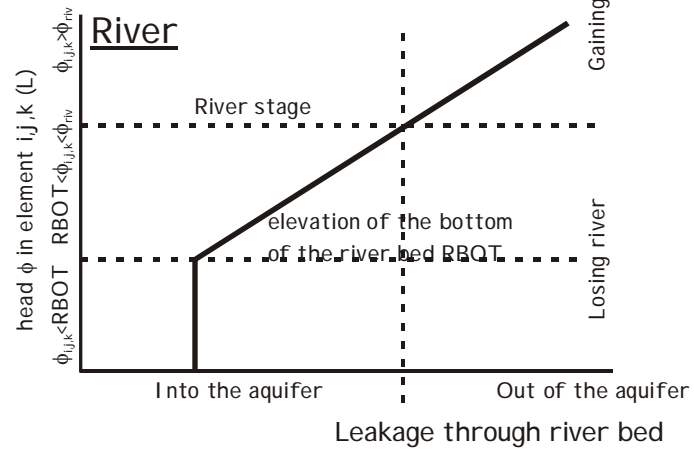
Leakage to the groundwater system



Special case:

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

## 2. River package (V)



## 3. Recharge package

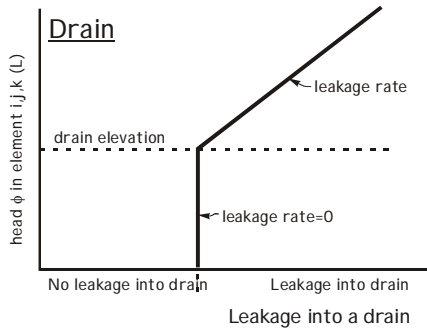
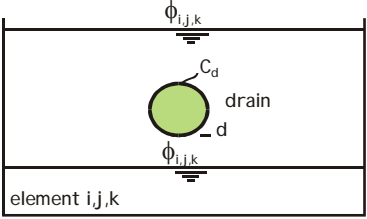
$$Q_{rec} = I\Delta x\Delta y$$

4. Drain package

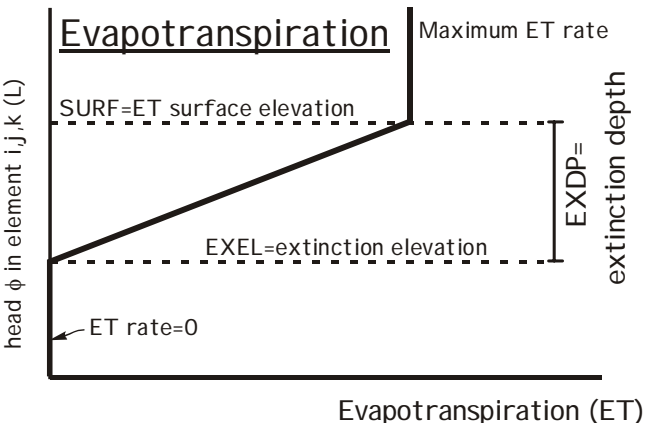
$$Q_{dm} = C_{dm} (\phi_{i,j,k} - d)$$

Special case:

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

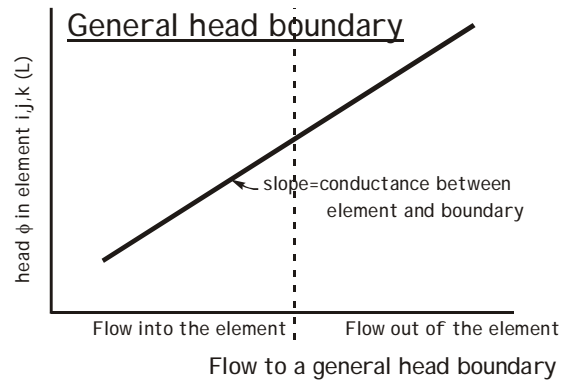
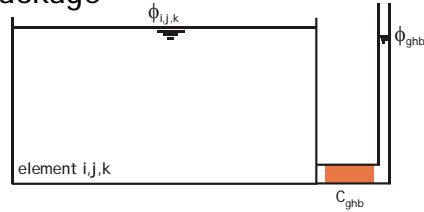


5. Evapotranspiration package



## 6. General head boundary package

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

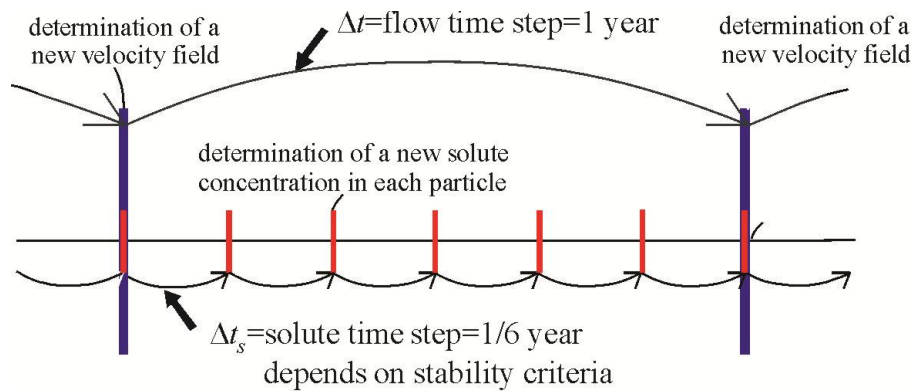


- 1 (name).bas-file
- 2 (name).bcf-file
- 3 (name).moc-file
- 4 (name).wel-file
- 5 (name).riv-file
- 6 (name).drn-file
- 7 (name).ghb-file
- 8 (name).sip-file
- 9 densin.dat-file
- 10 (name).nam-files

## 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



- \* velocity field remains constant during 1 year
- \* solute concentration changes during each solute time step

