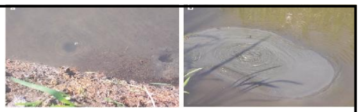
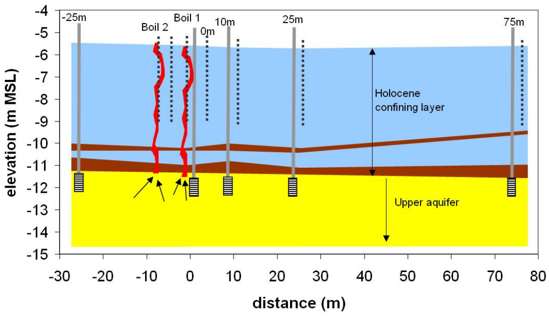
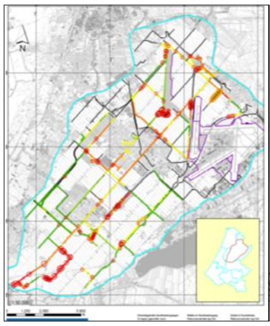
Example NL:
Salt resistant crops on salty boils

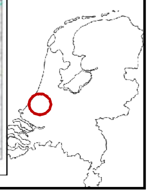


Cl-conc seepage:
(Polder Noordplas)
Diffuse : 100 mg/l
Paleochannel : 600 mg/l
Boils : 1100 mg/l

Ask Perry de Louw for details







Modelling

salt water intrusion

density dependent groundwater flow

Why mathematical modelling anyway?

A model is only a schematisation of the reality!

Why mathematical modelling anyway?

+:

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

-:

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

Numerical modelling variable density flow

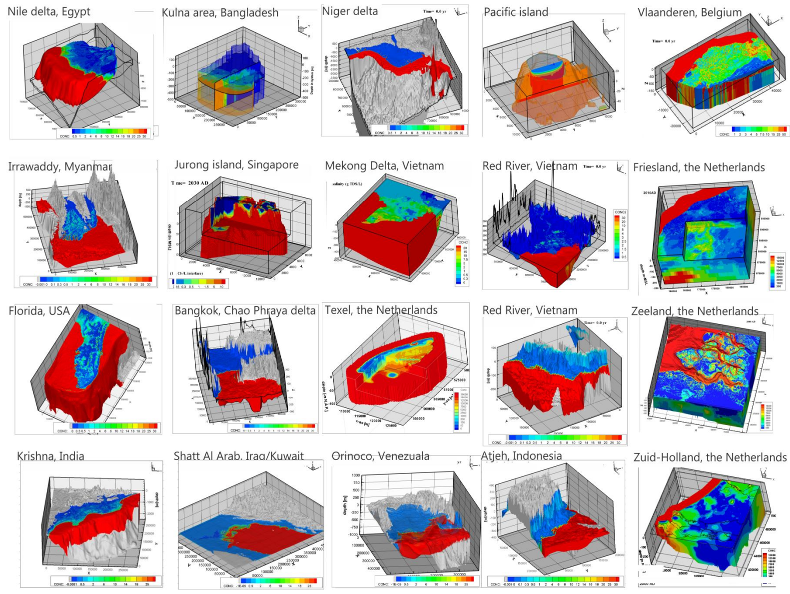
Type:

- sharp interface models
- solute transport models

State of the art:

- three-dimensional
- solute transport
- transient

3D numerical models groundwater coastal zone



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

SEAWAT (*Guo & Bennett, 98*)
METROPOL (*Sauter, '87*)
FEFLOW (*Diersch, '94*)
MVAEM (*Strack, '95*)
D3F (*Wittum et al., '98*)
MOCDENS3D (*Oude Essink, '98*)
HydroGeoSphere (*Therrien, '92*)

SWICHA (*Huyakorn et al., '87*)
SWIFT (*Ward, '91*)
FAST-C 3D (*Holzbecher, 98*)
MODFLOW+MT3D96 (*Gerven, '98*)
HST3D (*Kipp, '86*)
SUTRA (beta-version, Voss, '02)

Restrictions 3D salt water intrusion modelling

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

Restrictions 3D salt water intrusion modelling now

- the data problem:
  - -not enough hydrogeological data available
  - -e.g. the initial density distribution
  - -especially important issue in data-poor countries
- the computer problem:
  - -modelling transient 3D systems: computer only good enough at high costs
  - solution is 64 bits computer
- the numerical dispersion problem:
  - -numerical dispersion is large in case of coarse grid
  - solution is better solvers

Stability criteria for solute transport equation (I)

1. Neumann criterion:

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

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

Stability criteria for solute transport equation (II)

2. Mixing criterion:

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

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

Stability criteria for solute transport equation (III)

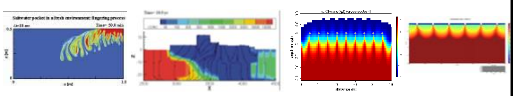
3. Courant criterion:

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

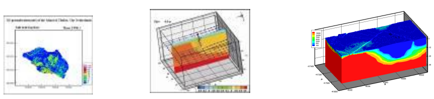
$$\Delta t_s \le \frac{\xi \Delta x}{V_{x,\max}} \qquad \Delta t_s \le \frac{\xi \Delta y}{V_{y,\max}} \qquad \Delta t_s \le \frac{\xi \Delta z}{V_{z,\max}}$$

Modelling fresh-salt groundwater on different scales

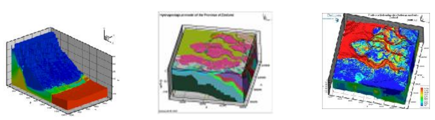
Sub-local: fingering, salty sand boils
Sri Lanka (Tsunami 2004),
Zandmotor
cell size=1cm-1m



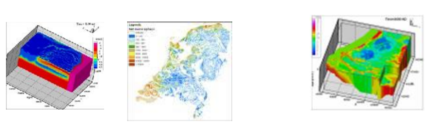
Local: rainwaterlenses, heat-cold
Tholen, Schouwen-Duiveland
cell size=5-25m



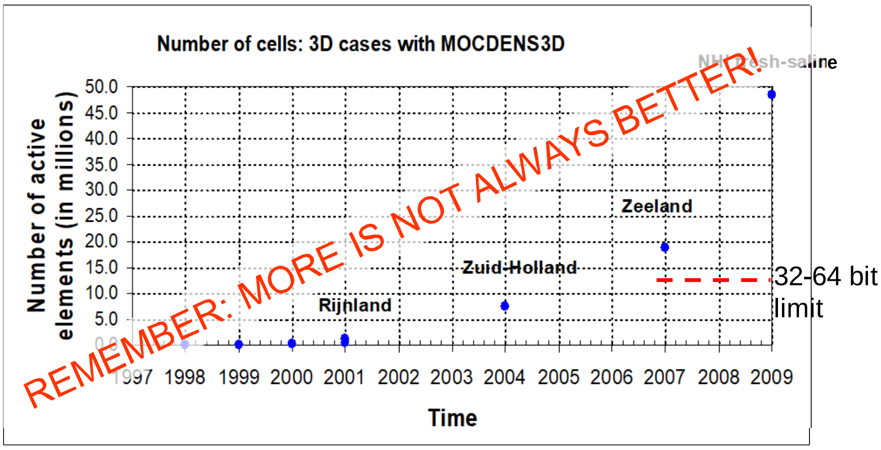
Regional:
Zeeland, Gujarat/India, Philippines
cell size=100m



National: salt load
Bangladesh, Zuid-Holland, NHI
cell size=250m-2km



Goal:
To take largest cell size possible to accurately model relevant salinisation processes



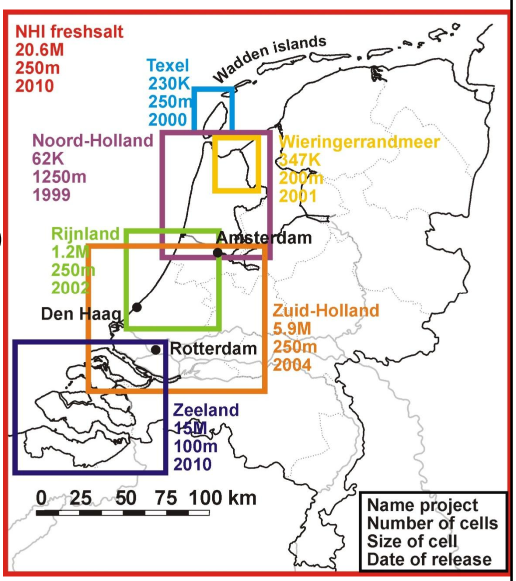
DO NOT DO THIS AT HOME (IF YOU HAVE NOT ENOUGH DATA)

Modelling effect climate change on fresh-salt groundwater

Modelling:
- variable-density
- 3D, non-steady
- groundwater flow
- coupled solute transport

Code:
MOCDENS3D (MODFLOW family)
similar to SEAWAT

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



Fields of application of fresh-saline groundwater models

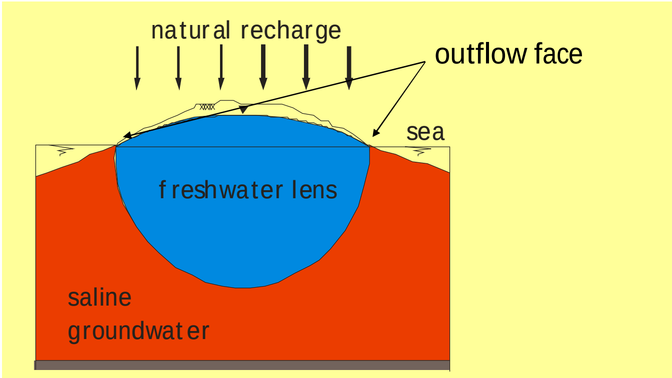
- Water system analysis in brackish-saline environments (salt loads, salt boils, freshwater lenses)
- Quantifying effects of climate change & sea level rise
- Drinking water issues: upconing saline groundwater under extraction wells
- Developing measurements to stop salinization groundwater systems (e.g. fresh keeper, coastal collectors, freshwater storage underground)
- Impact of the disasters as tsunamis on fresh groundwater resources
- Submarine Groundwater Discharge (marine water pollution, Harmful Algae)

Difficulties with variable density groundwater flow

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

problems

Outflow face at the coast is difficult to model



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

This is numerically difficult to handle

A good initial density distribution is essential

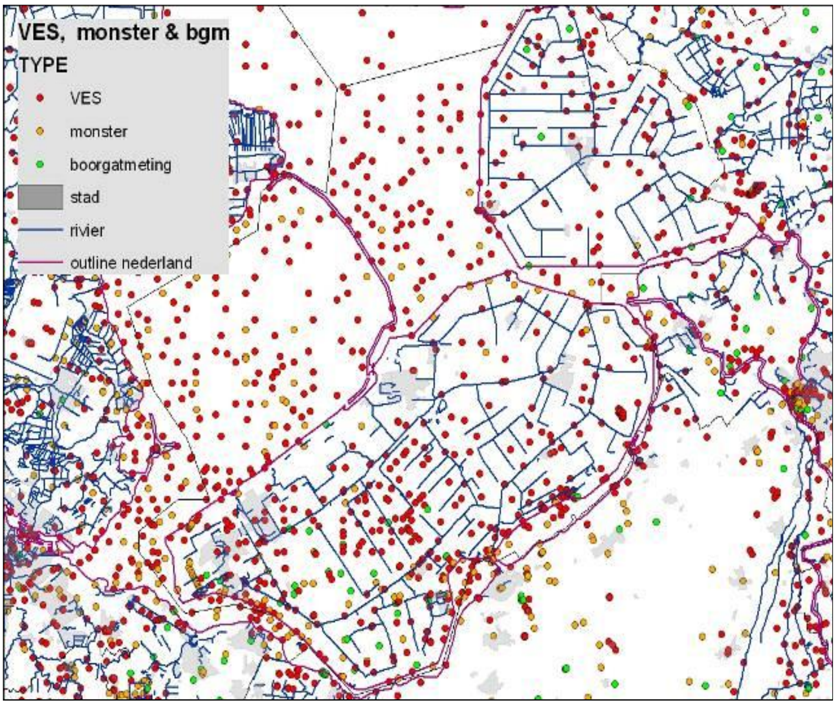
- Because groundwater and solute transport are coupled, the density influences grondwater velocities
- Numerous density measurements are necessary to get a reliable 3D density matrix

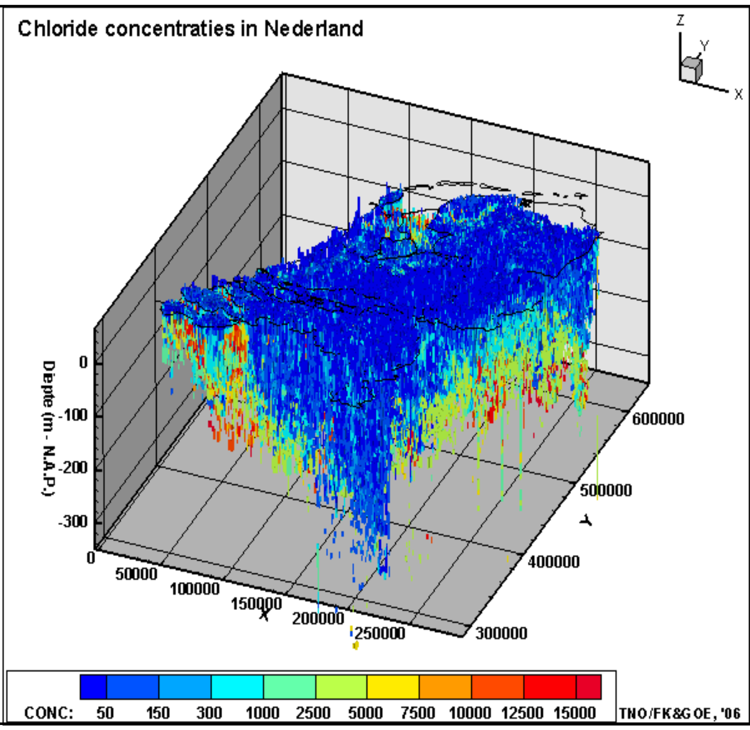
‘Procedure’ to improve initial density distribution

- Implement all chloride data
  - Analyses, Borehole, VES, Airborne techniques (HEM, SkyTem)
  - Better old then nothing
  - Better VES then nothing

- Interpolate and extrapolate
  - Sea = easy (salt)
  - Inland = fresh?

- Start with simulation (10/20/30 years) with mol.diffusion*1000 to smooth out artificial densities



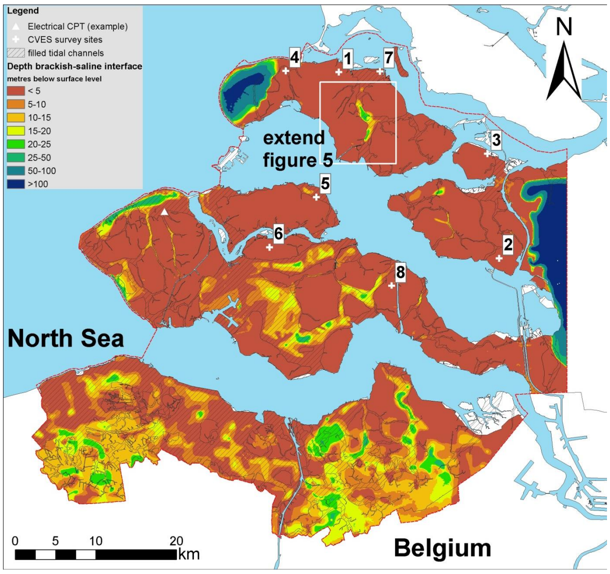


Mapping brackish-saline interface Zeeland

Combining different types of data sources:

Data type	Characteristics of measurement	# Data	Determined	Accuracy depth of interfaces
Groundwater Samples	0D in situ	721	Chloride concentration	Depends on positions of screens
Geo-electrical borehole logs	1D in situ	149	1D chloride profile, Depth fresh-brackish and brackish-saline interface, Inversions.	±1 m
Electrical CPT	1D in situ (max. depth 50 m)	71	Borehole log	±1 m
VES	1D from surface	1113	Depth brackish-saline interface, Major inversions, (1D chloride profile).	±20% of depth
EM34	1D from surface	3251	Depth brackish-saline interface	ranges of 7.5, 15 or 30 m (accuracy decreases with depth)
Groundwater Abstractions	0D in situ	716	Depth brackish-saline interface	a range depending on screen depth
Unique locations		**6021**		

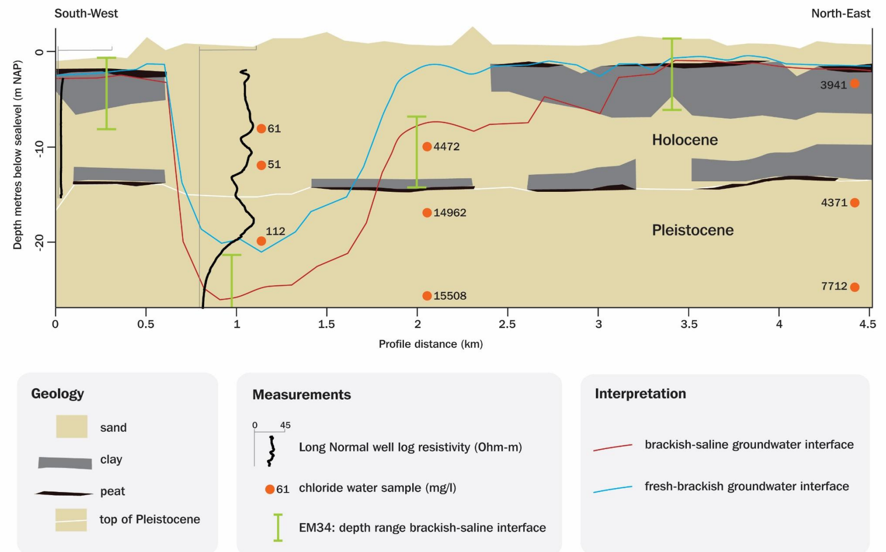
Mapping brackish-saline interface



Goes et al, 2009

Mapping brackish-saline interface

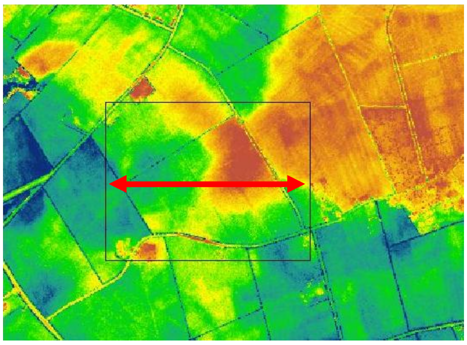
Combining different types of data sources

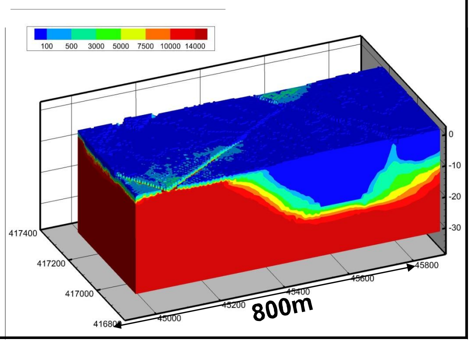


Use variable-density groundwater flow modelling

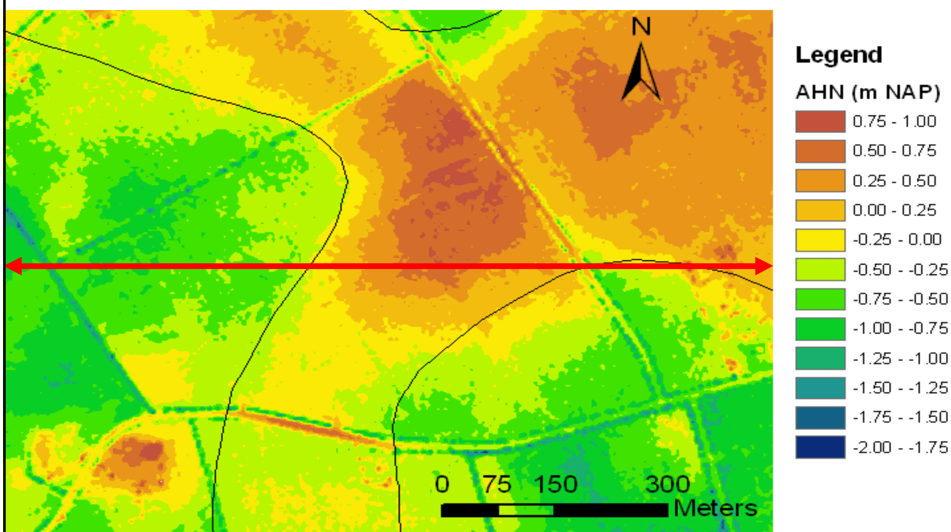
Why a model?

• variation in ground surface directly affects fresh-saline disribution





Use variable-density groundwater flow modelling

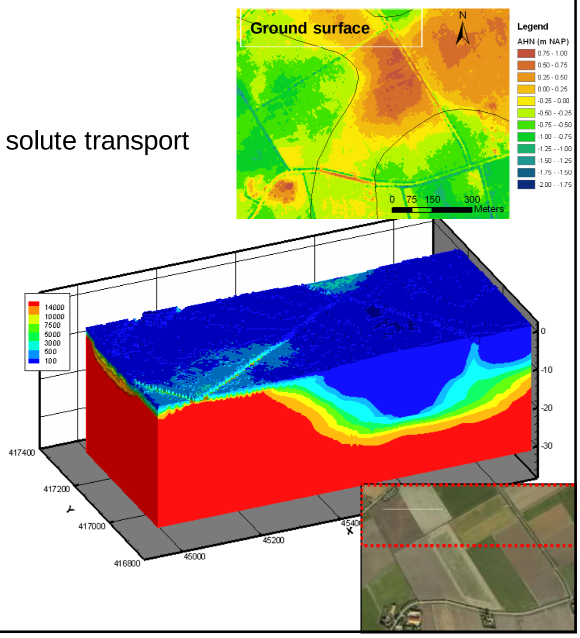


Local 3D model of the agricultural plot

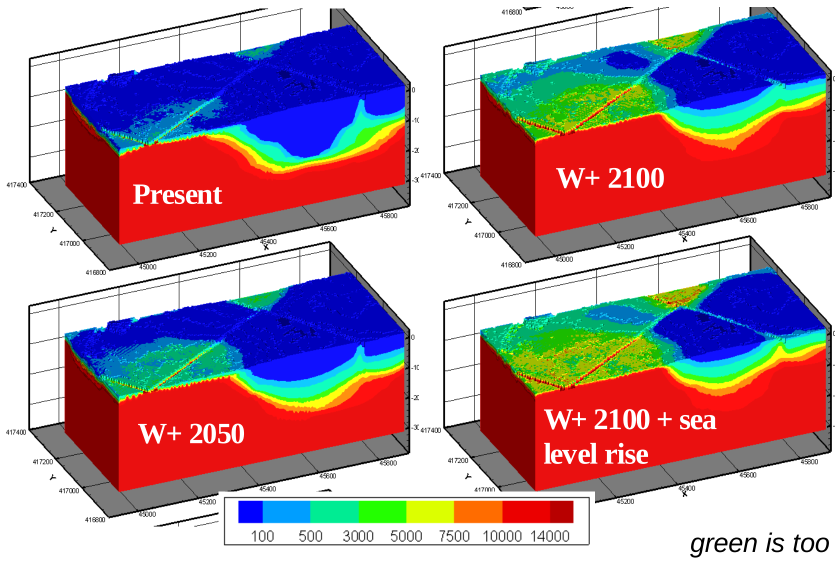
Modelling:
- variable-density
- 3D, non-steady
- groundwater flow & coupled solute transport
- model cell size: 5*5m^2

Code:
MOCDENS3D

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



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

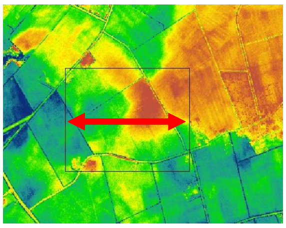


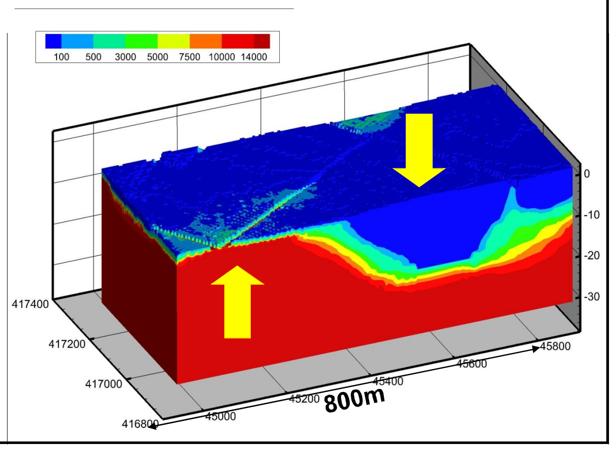
green is too salty to grow fresh crops

Use variable-density groundwater flow modelling

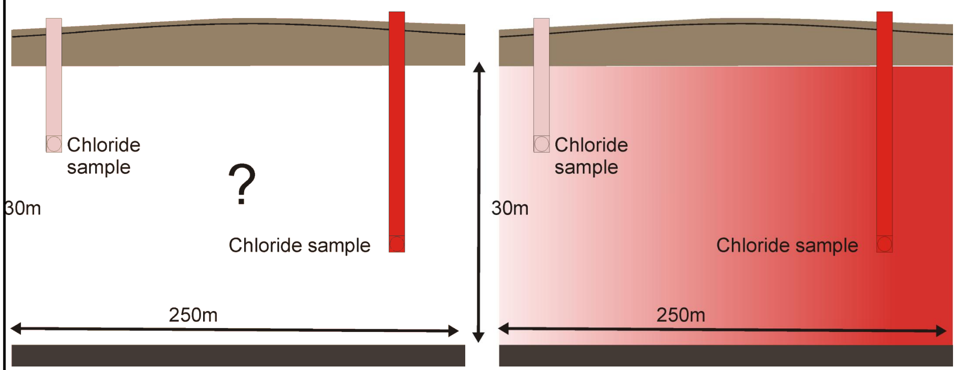
Why a model?

• variation in ground surface directly affects fresh-saline disribution

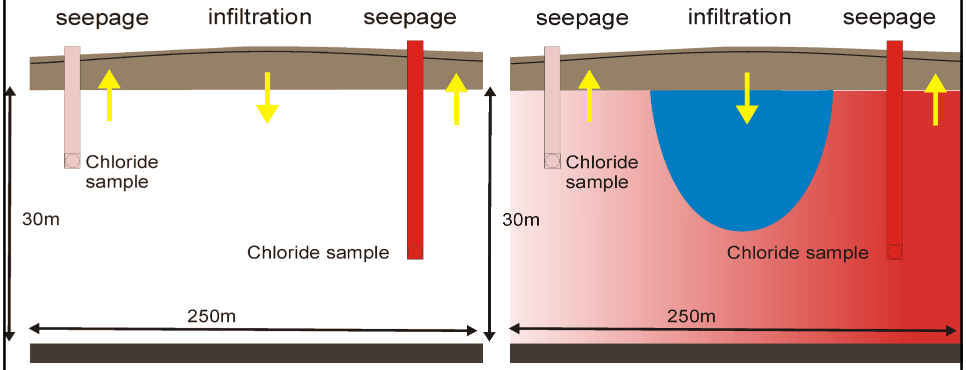




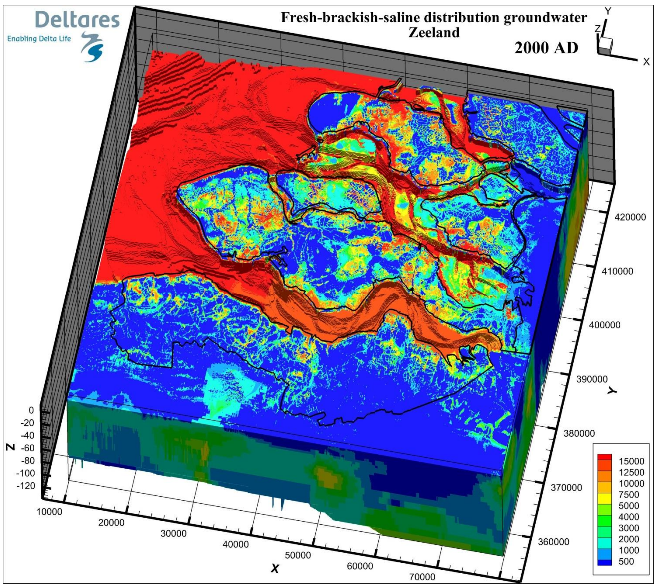
Interpolation chloride



Using flow model for better interpolate chloride

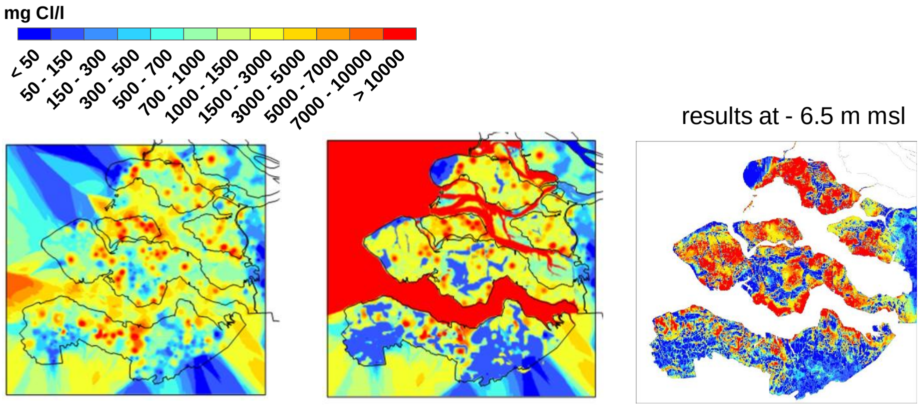


3D fresh-saline groundwater distribution



Regional groundwater model:

From chloride measurements to a 3D distribution



Step 1:
interpolating data:

- *Groundwater samples*
- *Geo-electrical borehole logs*
- *(C)VES, EM, electrical CPT*

Step 2:
including interfaces

- *Mapped fresh-brackish*
- *Mapped brackish-salt*

Step 3:
model result 2010:

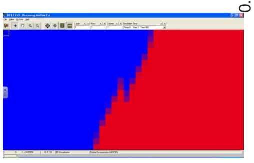
- *Model as interpolator*

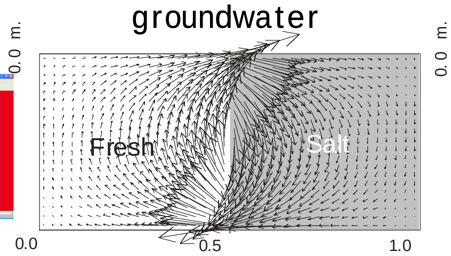
EWRMP 201511

Examples of variable-density groundwater flow

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

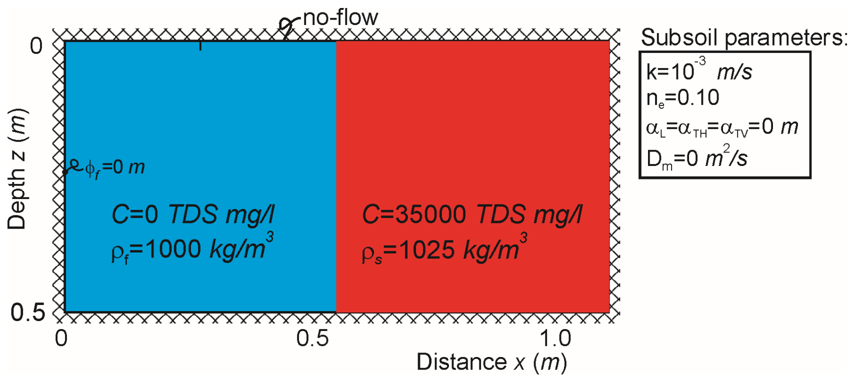
Case 1: Vertical interface between fresh and saline groundwater



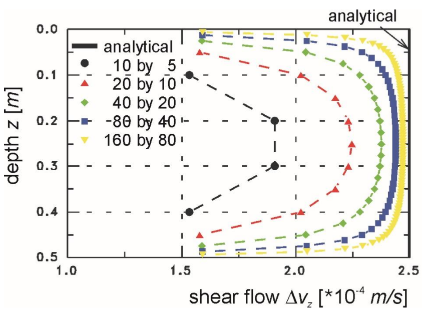


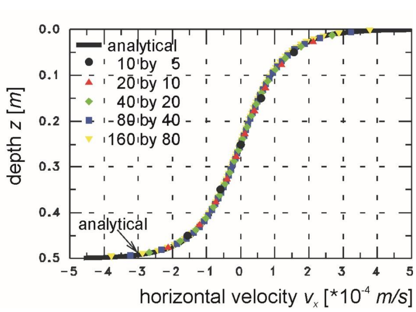
Parameters			
Layers	20	K_{hor}	1 10^{-3} m/s
Rows	1	T	2.5 10^{-5} m/s
Columns	40	Anisotropy K_{hor}/K_{ver}	1
Δx	0.025 m	n_e	0.1
Δy	1 m	α_L	0 m
Δz	0.025 m	α_T	0 m
Stress periods	15		
Initial concentration	0 and 35000 mg/l		
bouyancy	0.025		

Vertical interface



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

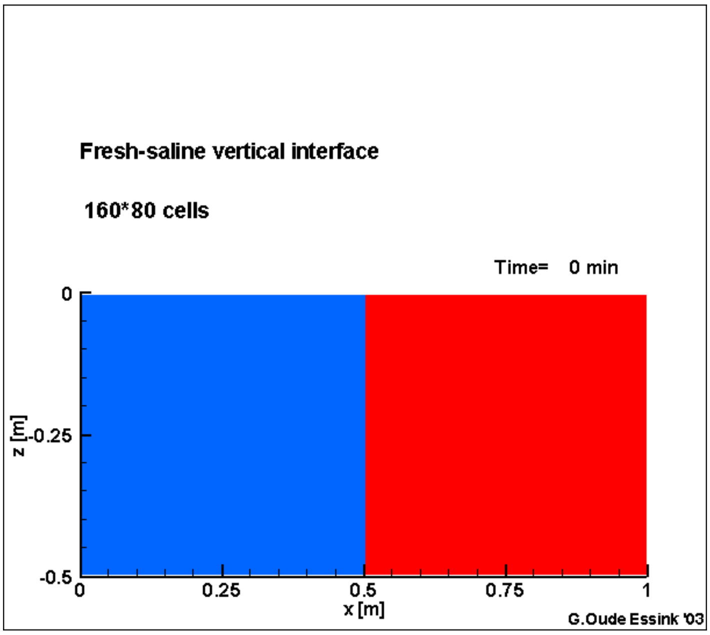




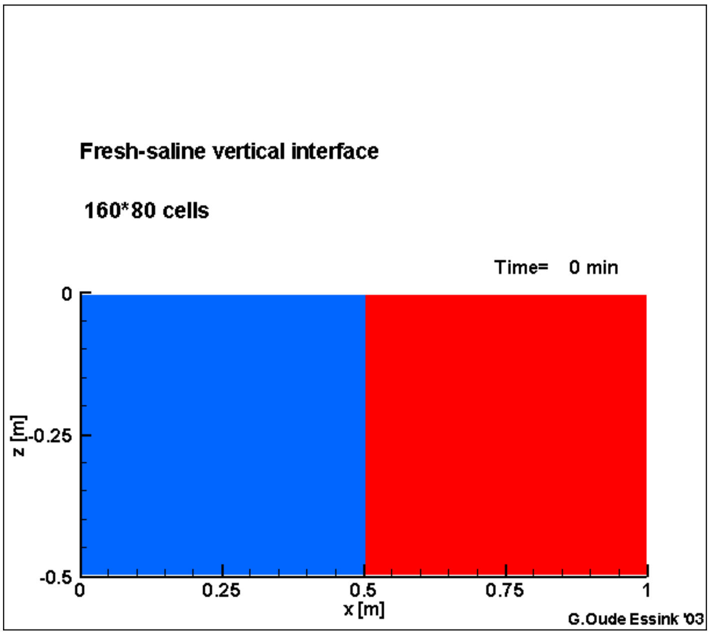
$$\Delta v_z = \frac{k}{n_e}\left(\frac{\rho_s - \rho_f}{\rho_f}\right)$$

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

Vertical interface



Vertical interface



The effect of numerical solvers on the salt transport

Examples

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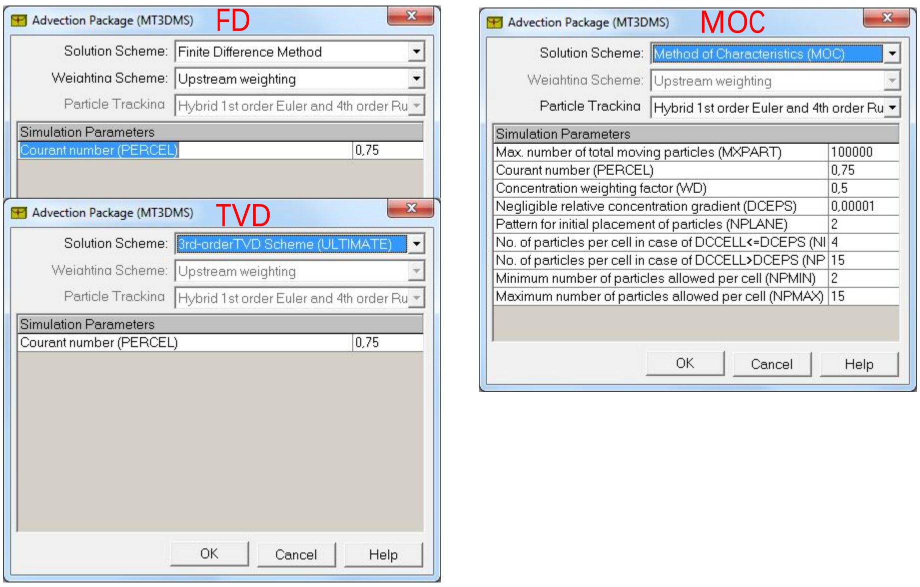
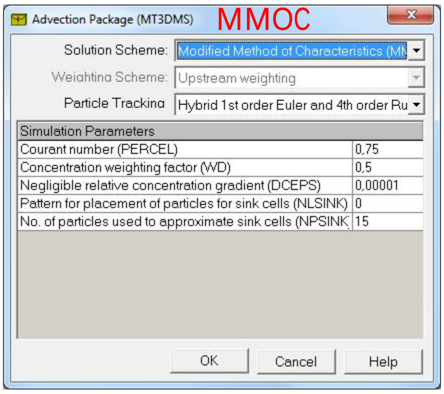
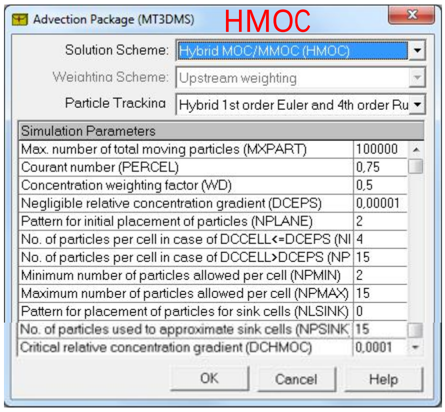
Default parameters solvers



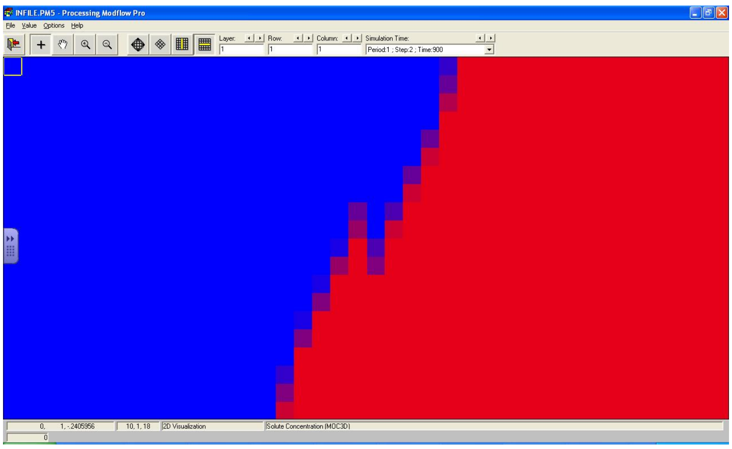
Default parameters solvers



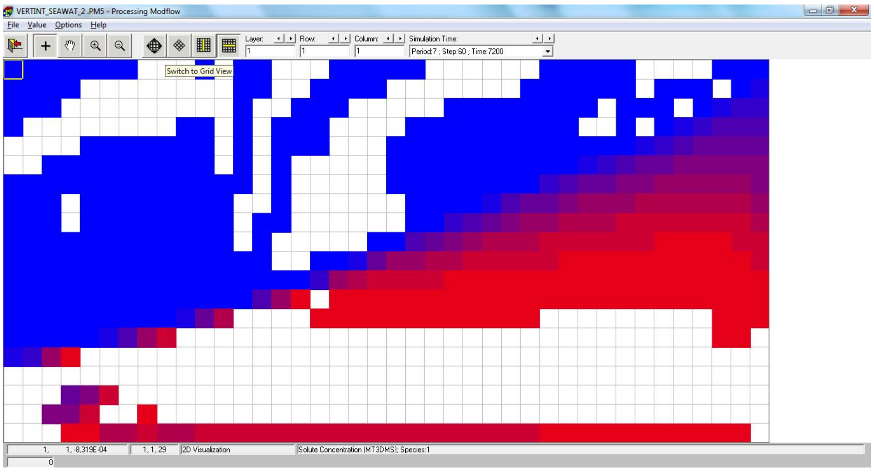


More information:
Zheng, C., & Wang, P. (1999). MT3DMS: A modular three-dimensional multispeces transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems. Technical report, Waterways Experiment Station, US Army Corps of Engineers.

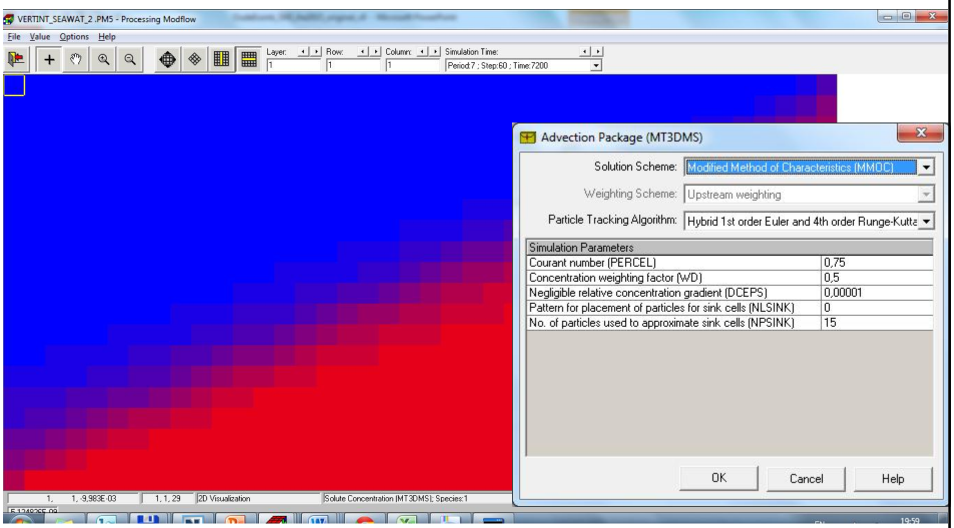
1 particle per cell



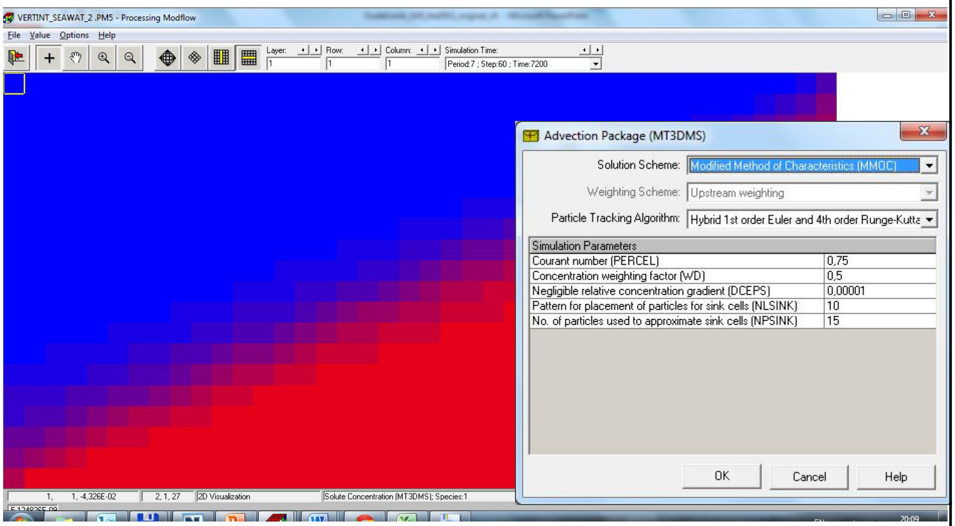
ULTIMATE



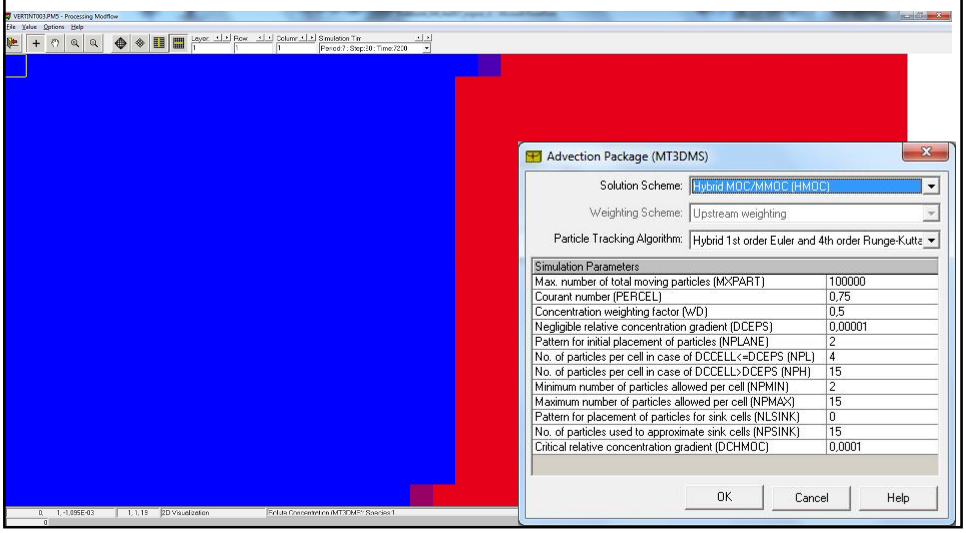
MMOC, NPLANE=0



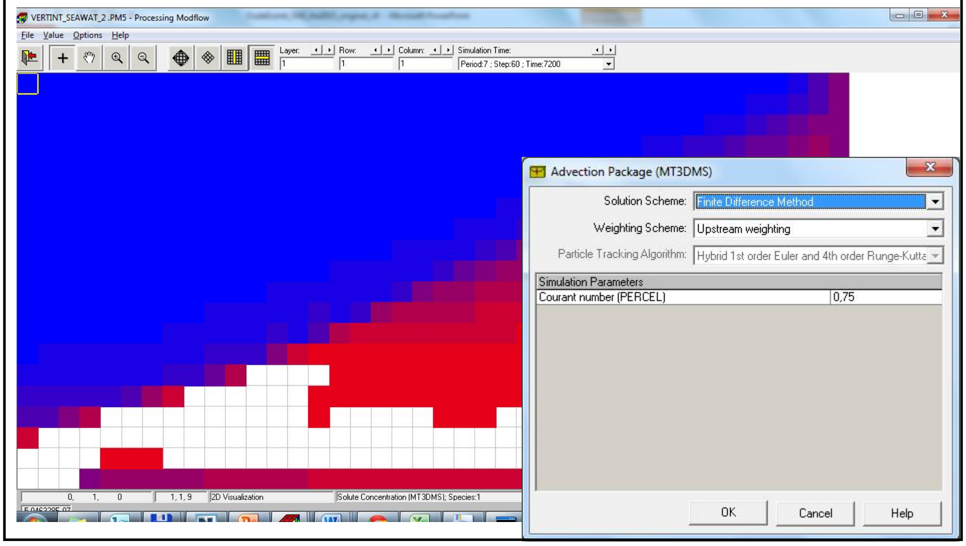
MMOC, NPLANE=10



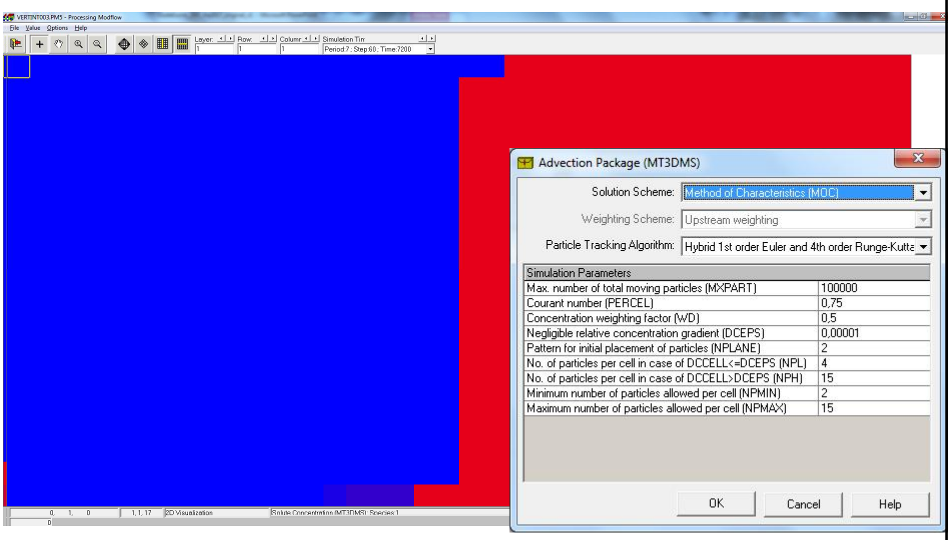
HMOC



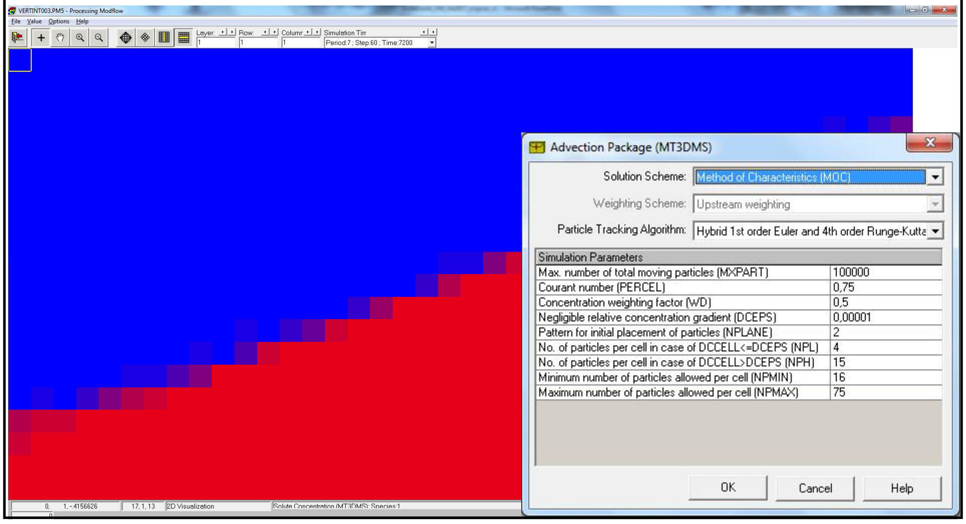
Finite Difference Method



MOC

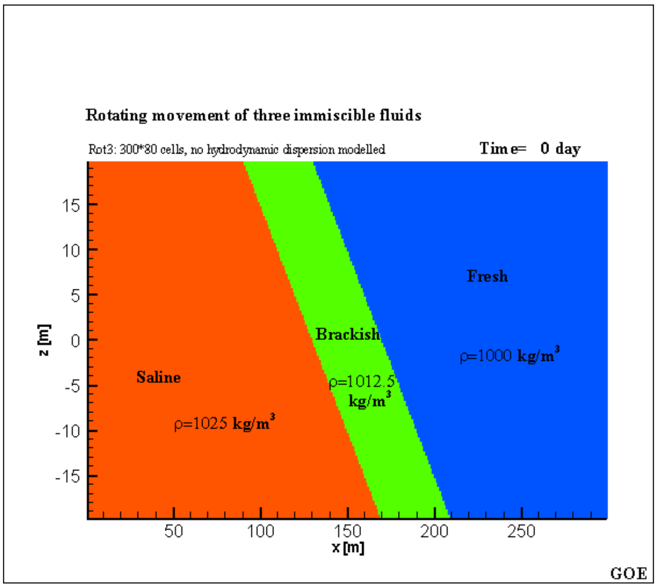


MOC

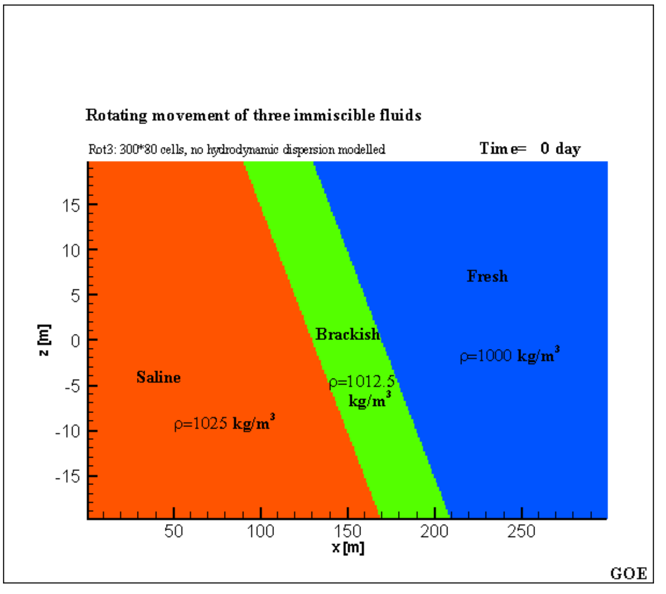


cases

Rotating immiscible interfaces

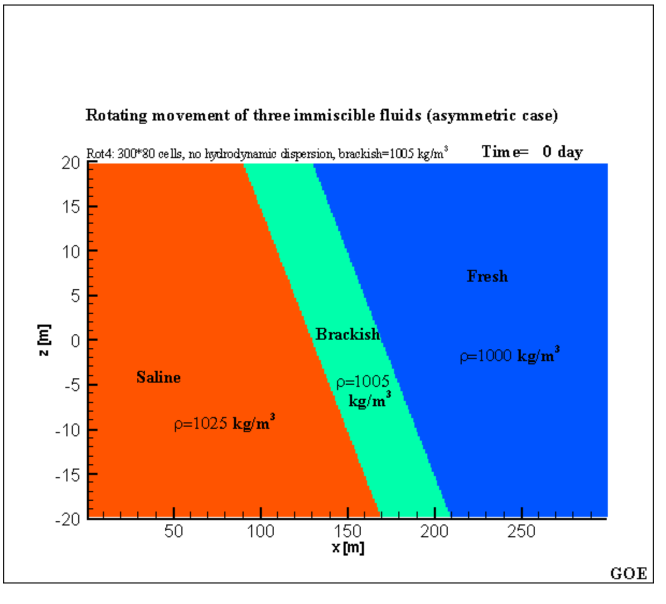


Rotating immiscible interfaces

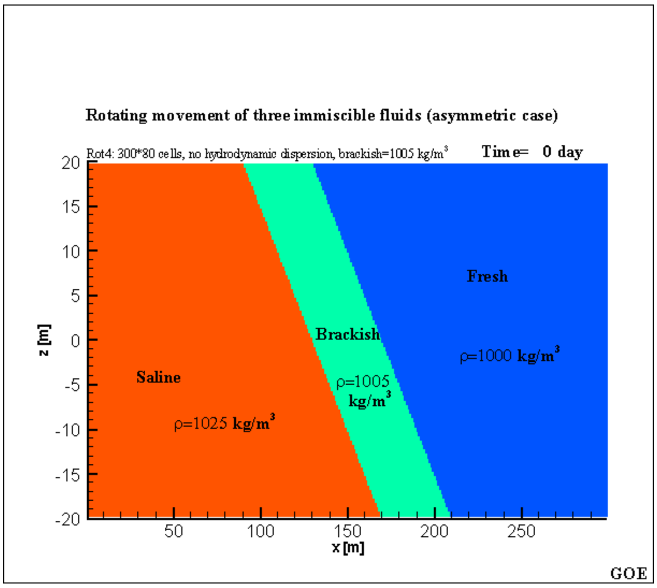


cases

Rotating immiscible interfaces (asymmetric)

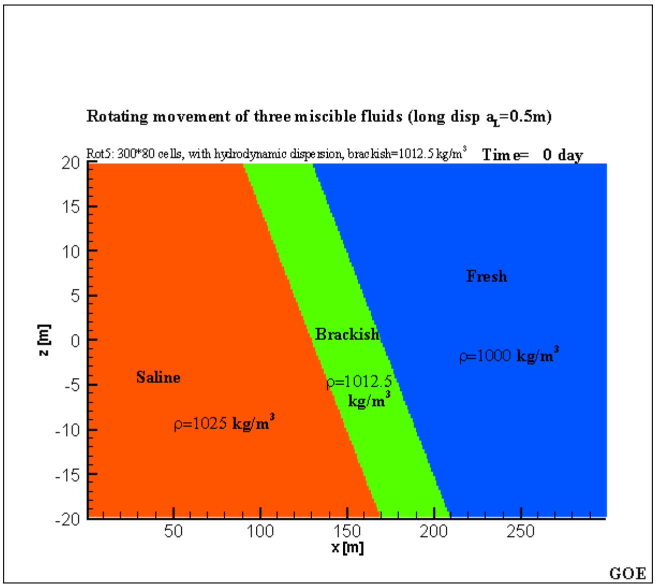


Rotating immiscible interfaces (asymmetric)



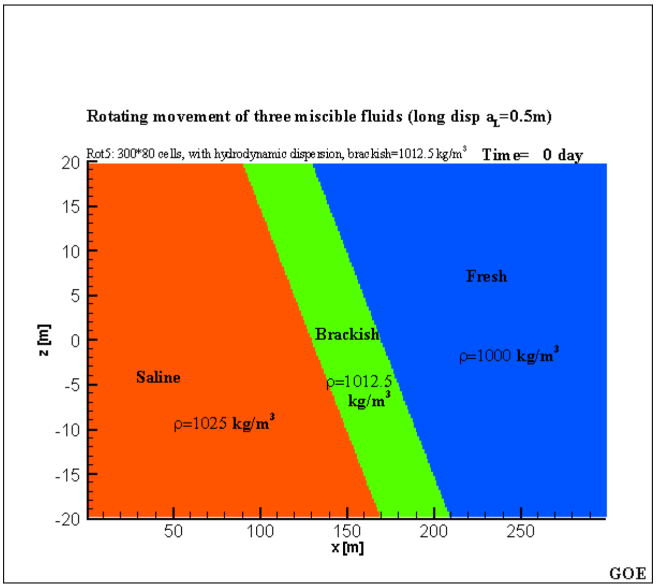
Bakker, M., Oude Essink, G.H.P. & Langevin, C. 2004. The rotating movement of three immiscible fluids, J. of Hydrology 287, 270-278

Rotating interfaces with dispersion α_L=0.5m



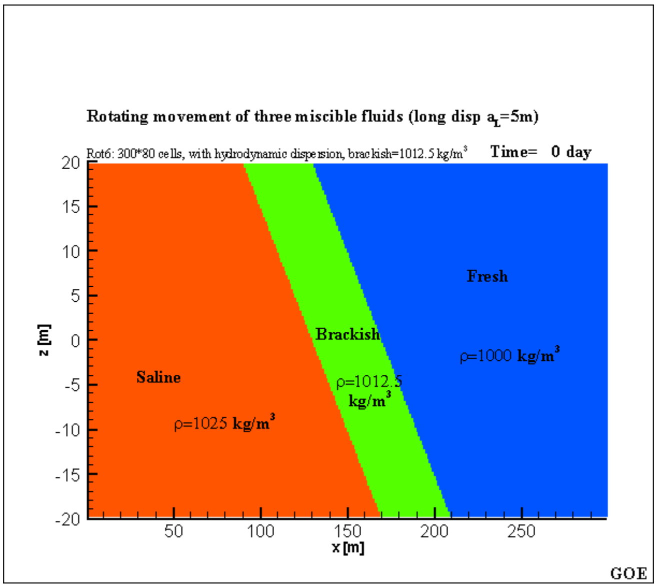
cases

Rotating interfaces with dispersion α_L=0.5m

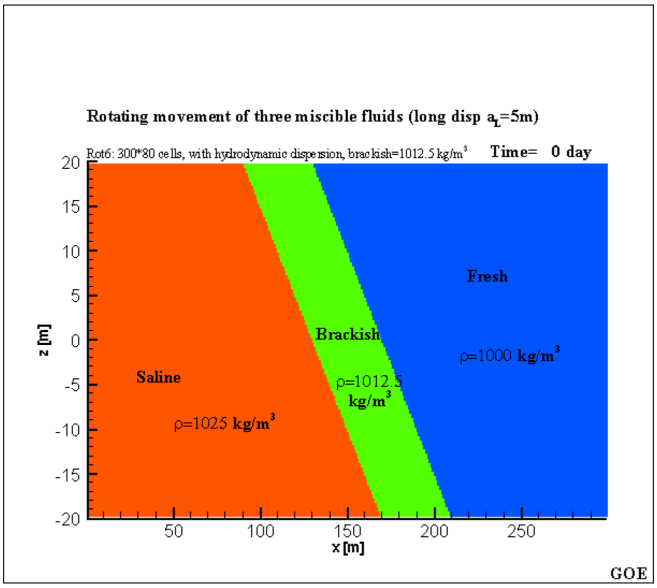


cases

Rotating interfaces with dispersion α_L=5m



Rotating interfaces with dispersion α_L=5m



Rotating immiscible interfaces

Conclusion:

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

Salt water pocket in a fresh environment

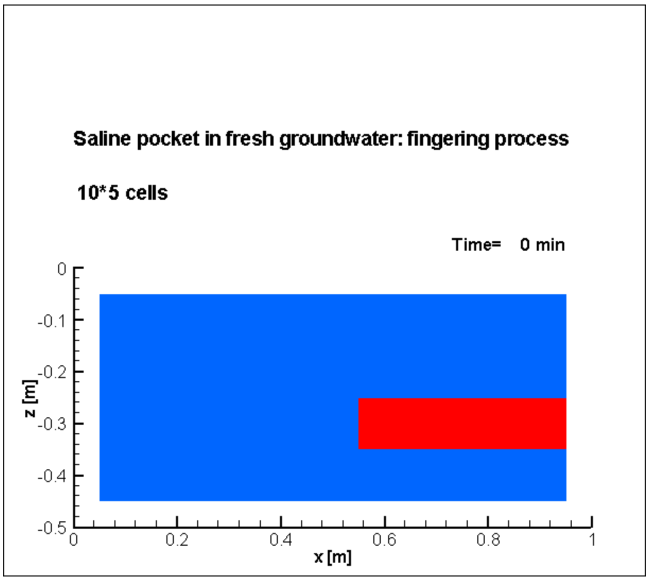
Grid convergence

Time step

cases

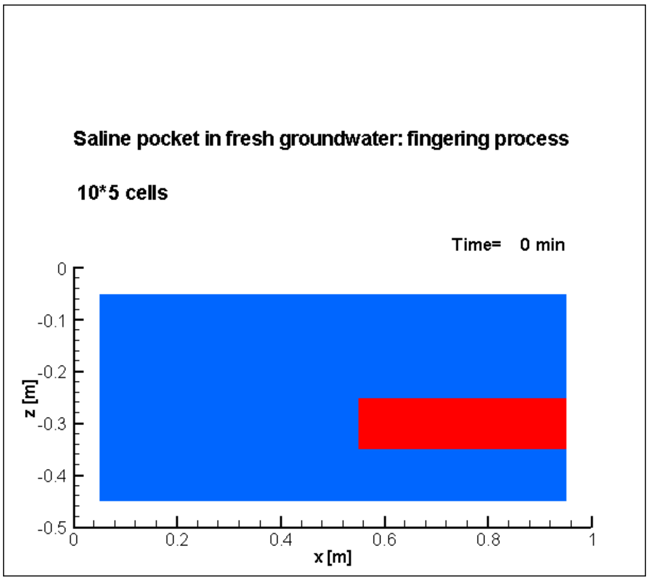
Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



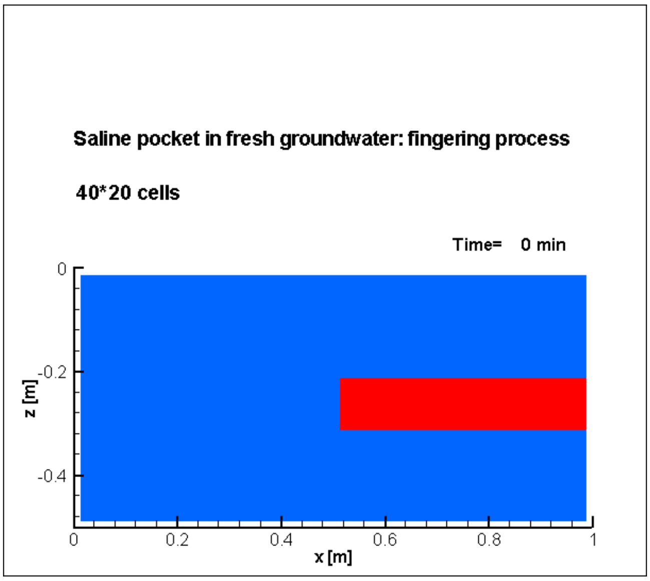
Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



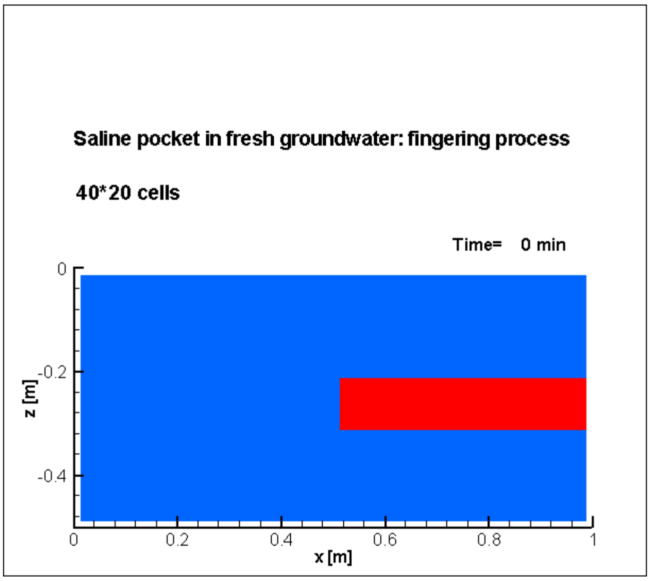
Salt water pocket in a fresh environment (II)

Effect of discretisation



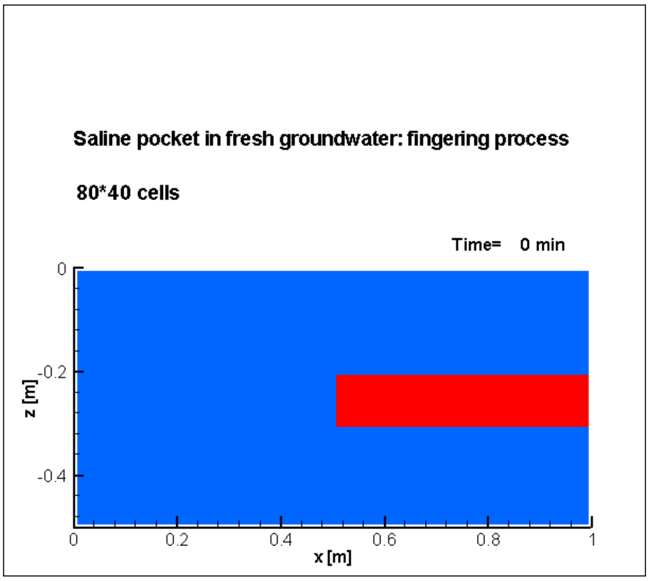
Salt water pocket in a fresh environment (II)

Effect of discretisation



Salt water pocket in a fresh environment (III)

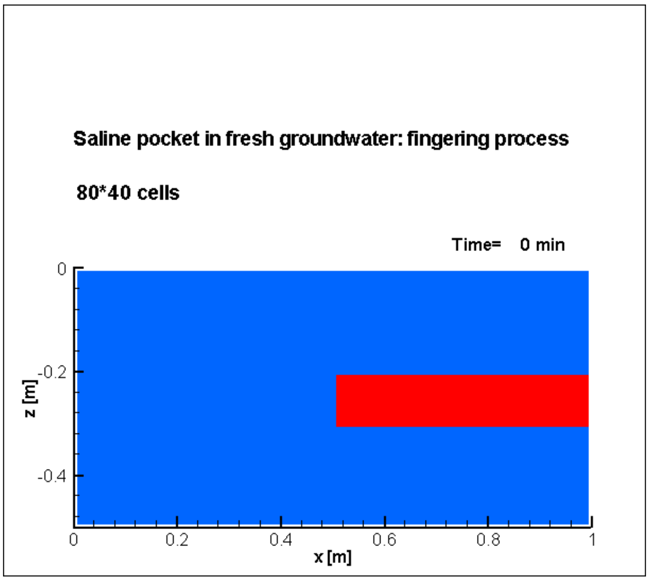
Effect of discretisation



cases

Salt water pocket in a fresh environment (III)

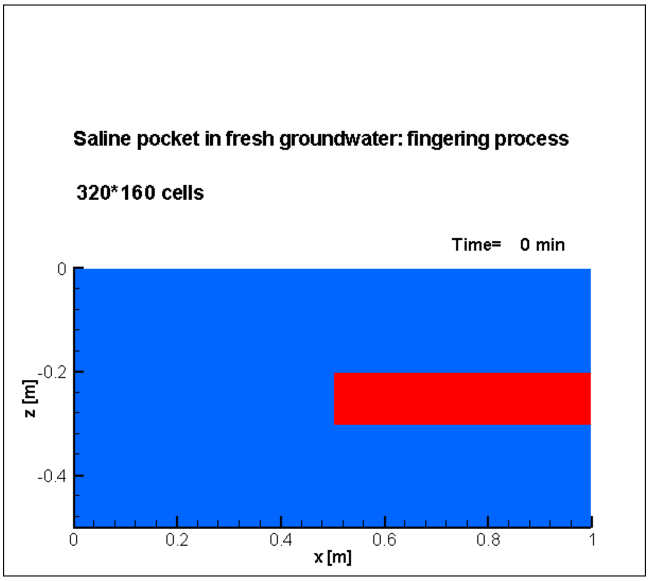
Effect of discretisation



cases

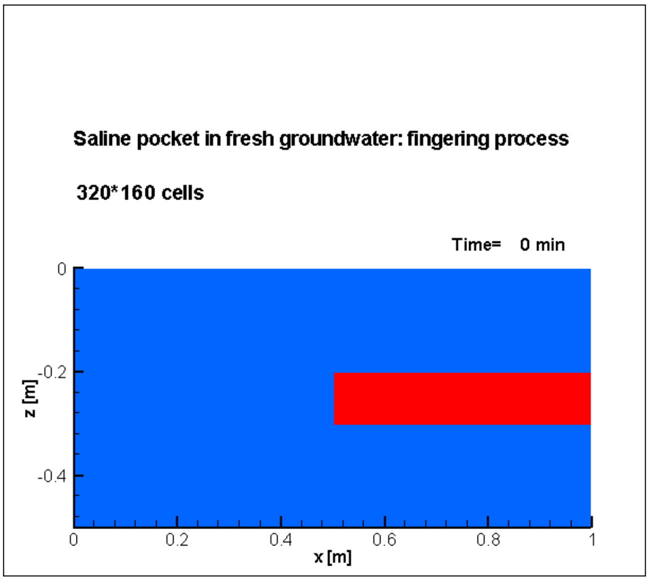
Salt water pocket in a fresh environment (IV)

Effect of discretisation



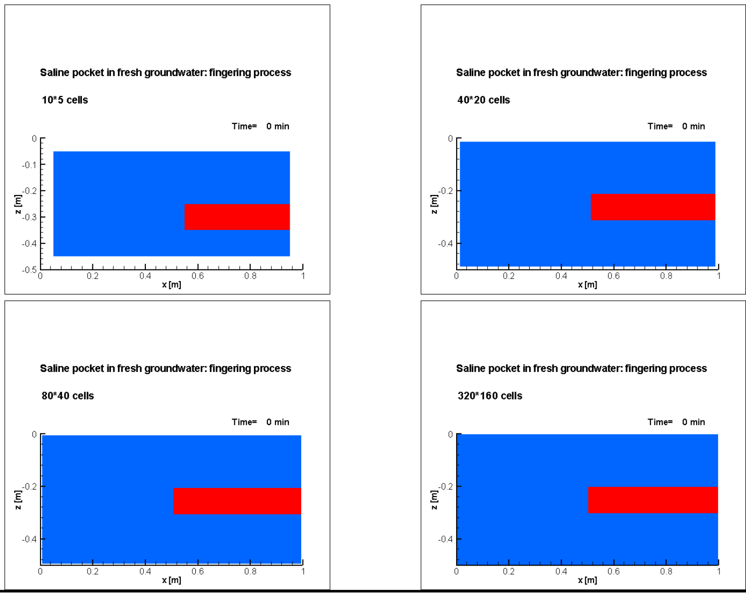
Salt water pocket in a fresh environment (IV)

Effect of discretisation

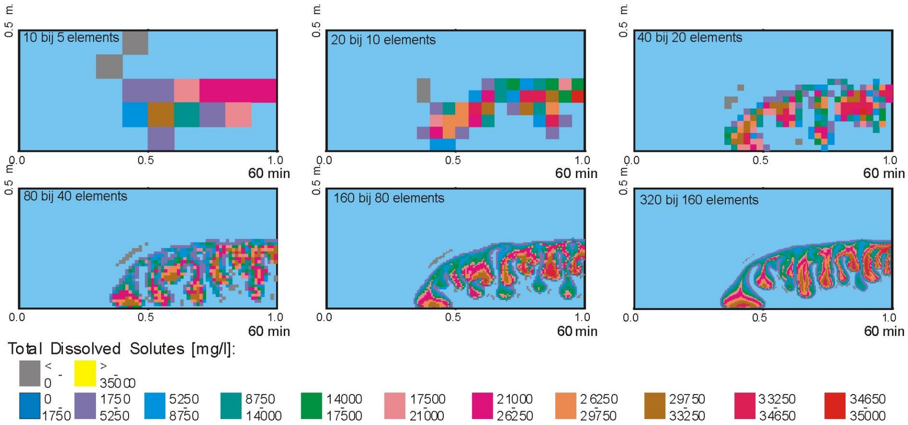


Salt water pocket in a fresh environment (V)

Effect of discretisation

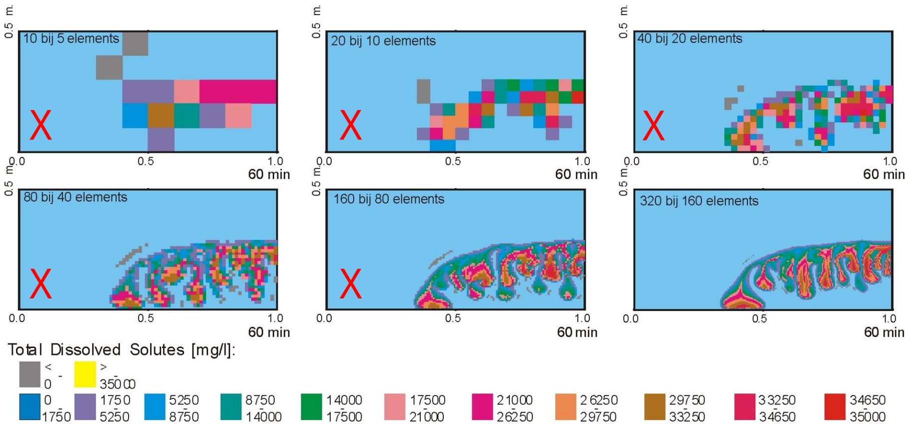


Effect of size model cell on physical process



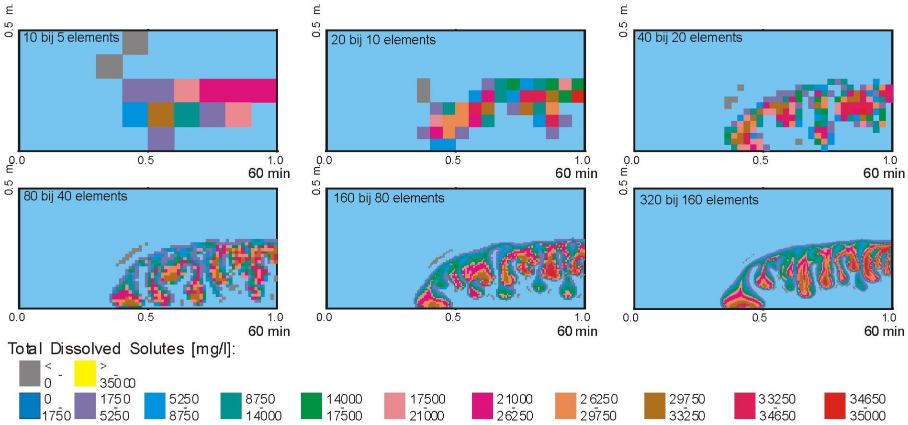
Size of cell has a large effect on modelling result!

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



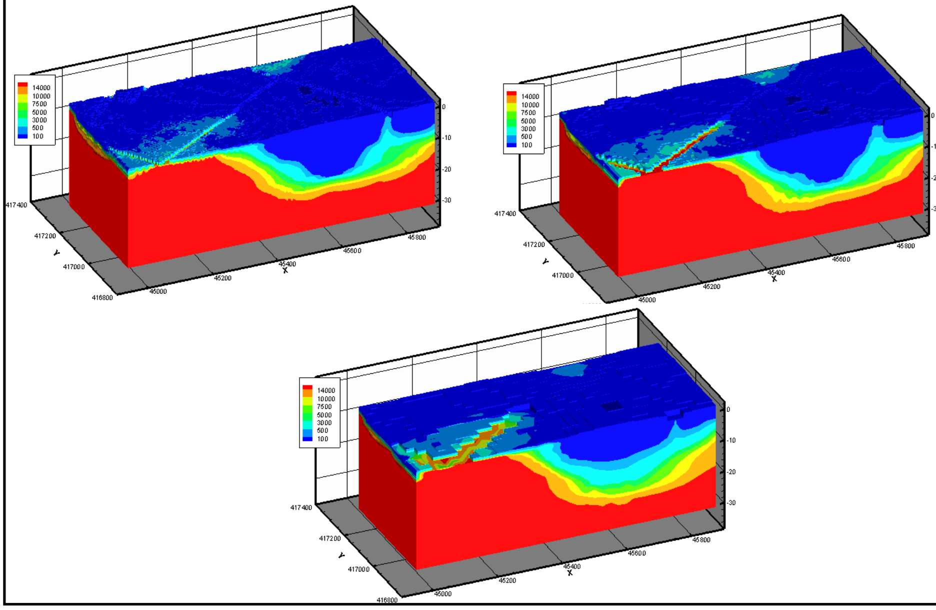
BUT: all models are GOOD for predicting the moment of touching the base!

Salt water pocket in a fresh environment (VI)

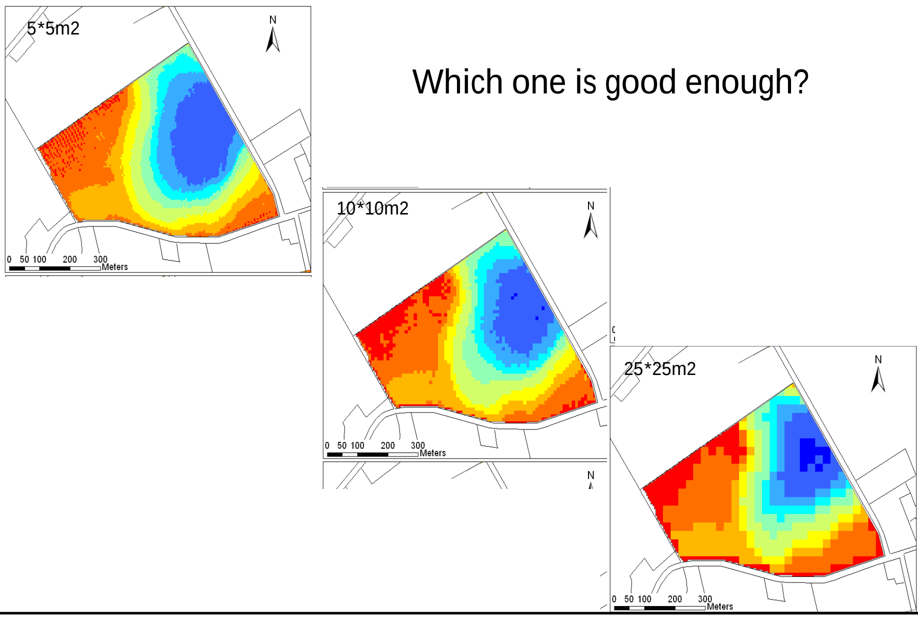
Conclusion:

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

Different model scales: 5, 10, 25m2

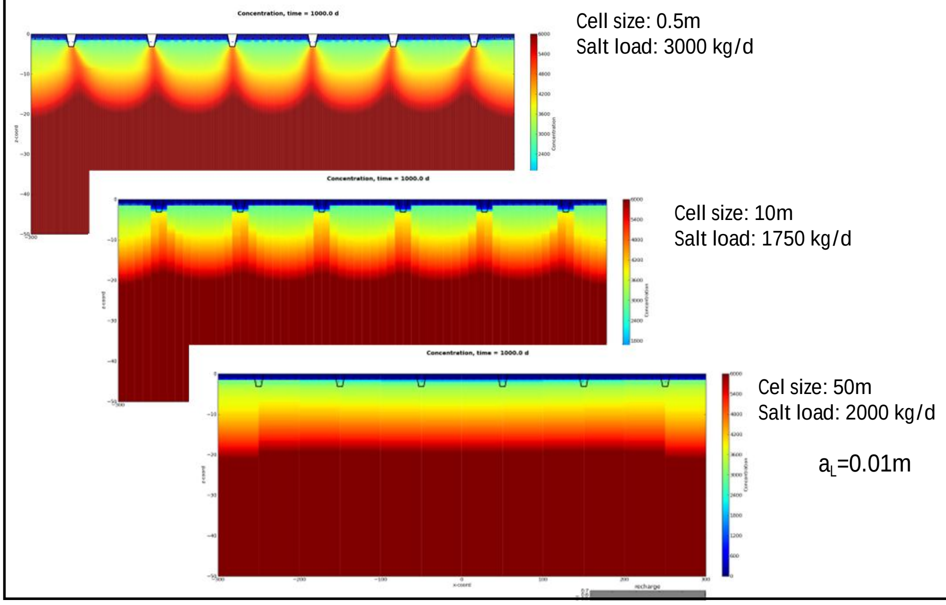


Different model scales

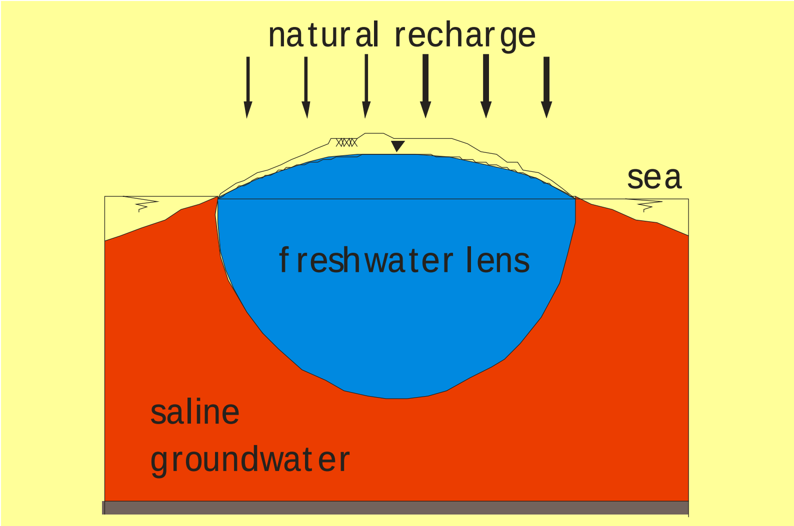


Which one is good enough?

Upscaling issues: upconing under ditch



Evolution of a freshwater lens



cases

Question:

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

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

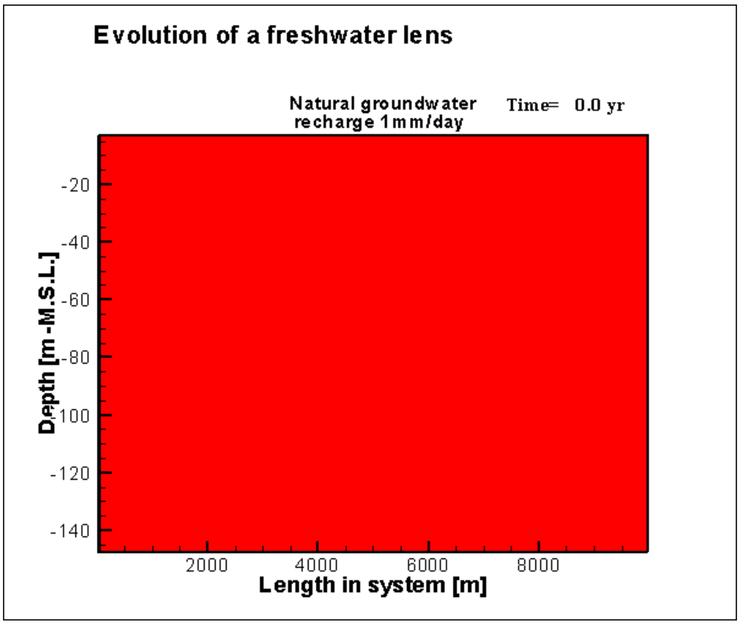
T = specific time scale

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

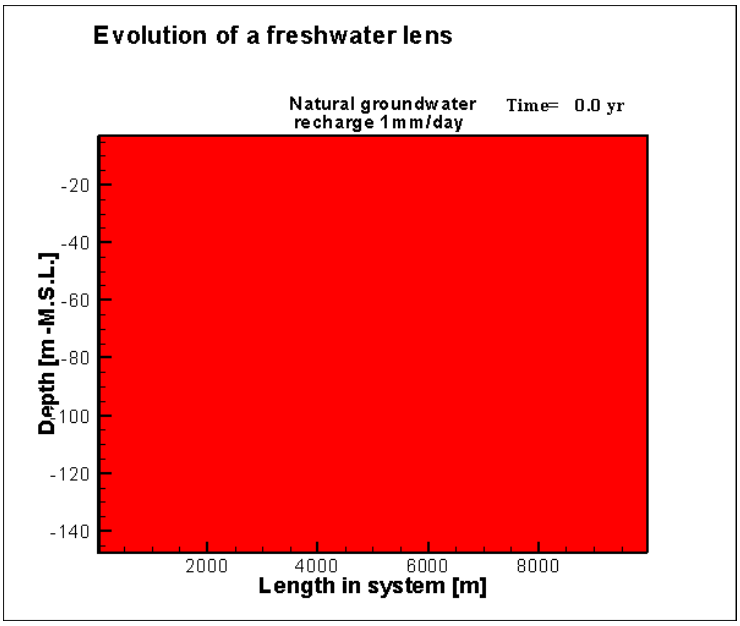
In the Netherlands: T = 75-200 jaar,

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

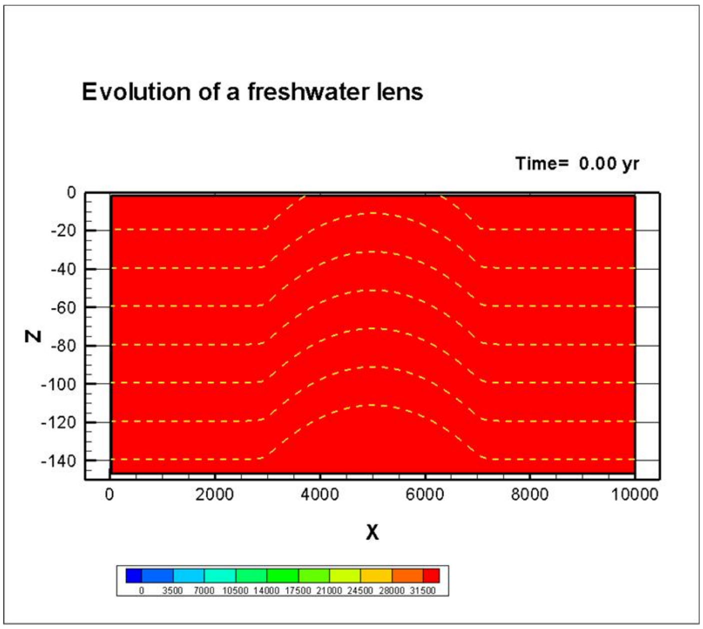
Concept: evolution freshwater lens (not Griend!)



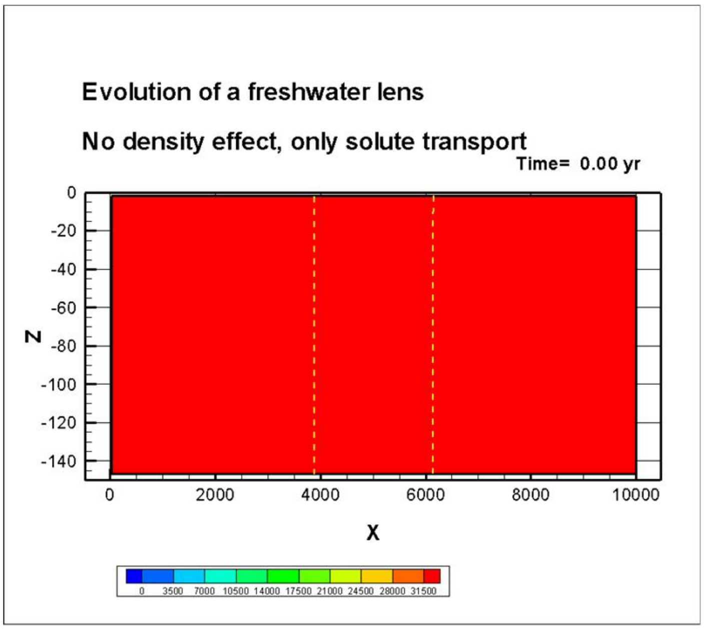
Concept: evolution freshwater lens (not Griend!)



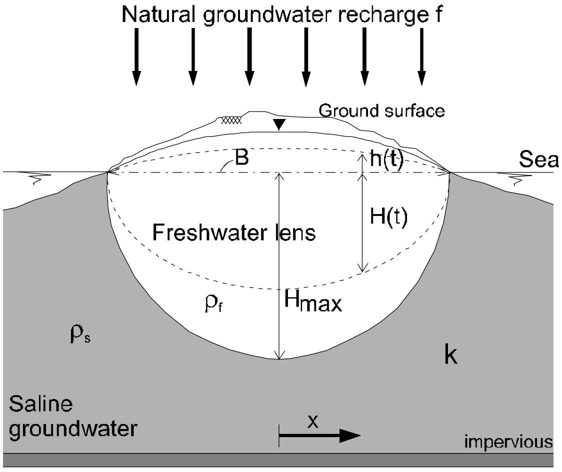
Evolution freshwater lens



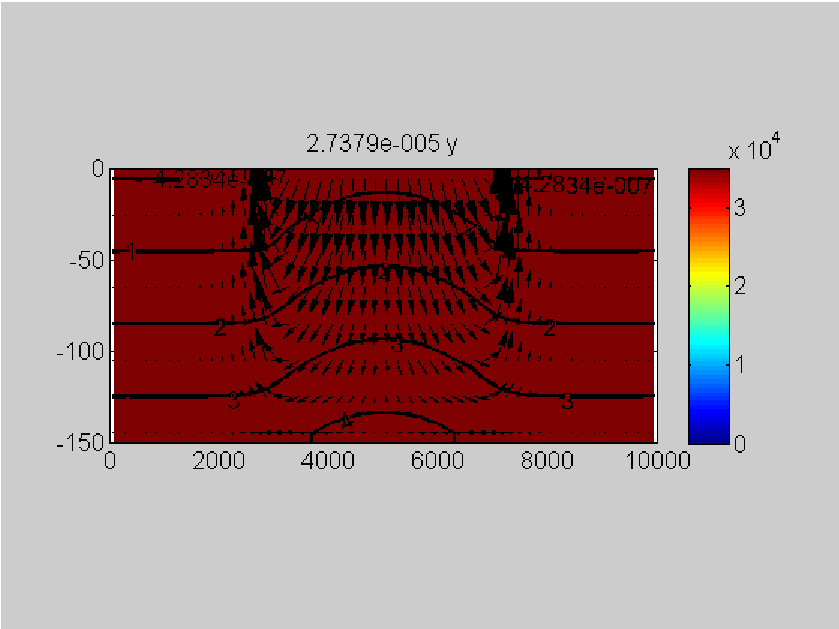
Evolution freshwater lens: no density effects



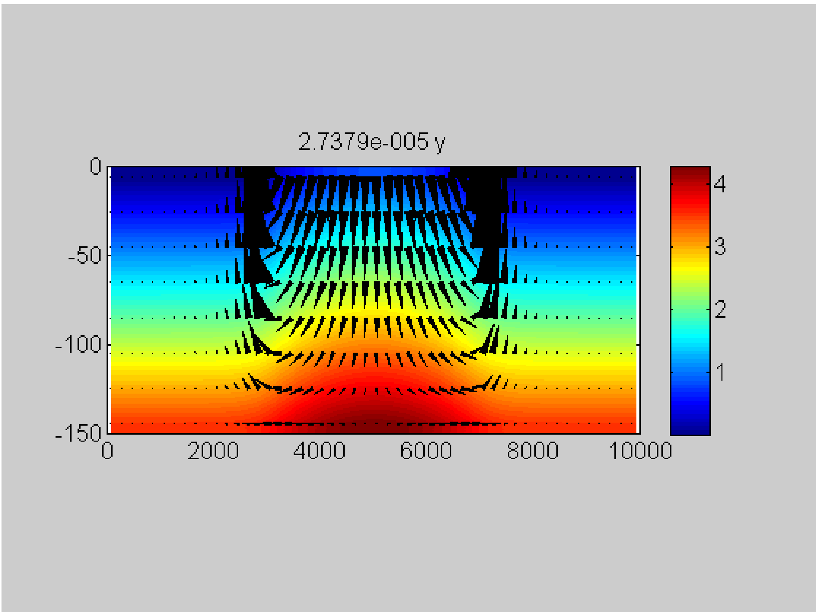
Case 2: Development of a freshwater lens



Evolution lens



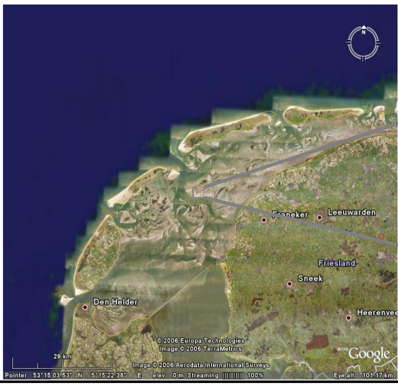
Evolution freshwater head

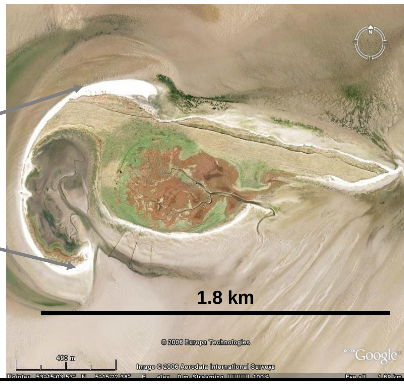


The island of Griend

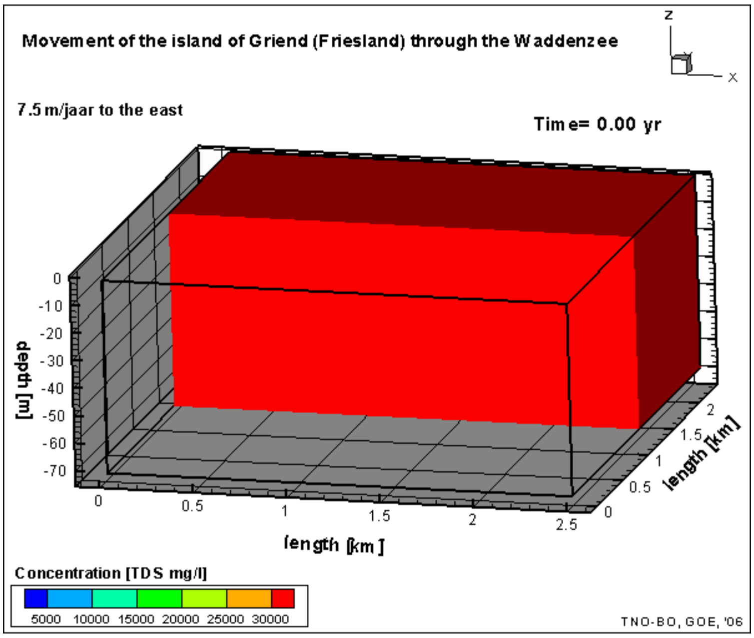
Issues:

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?

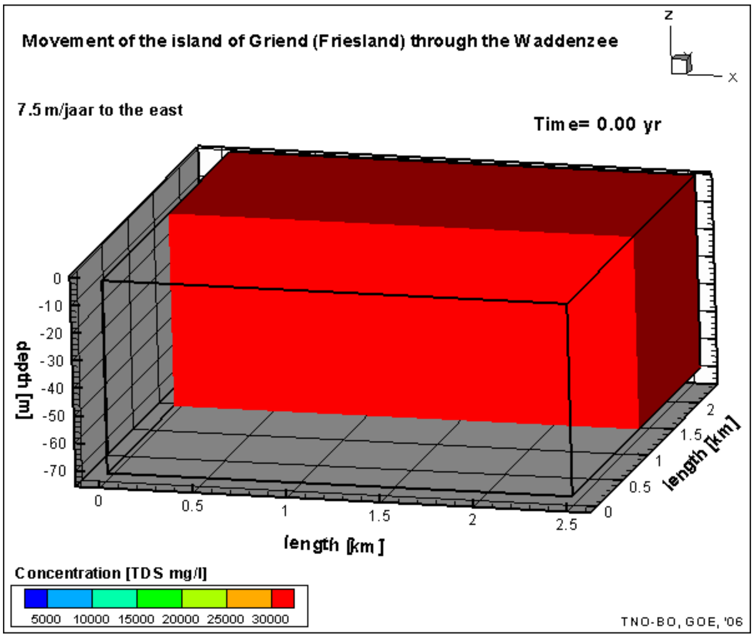




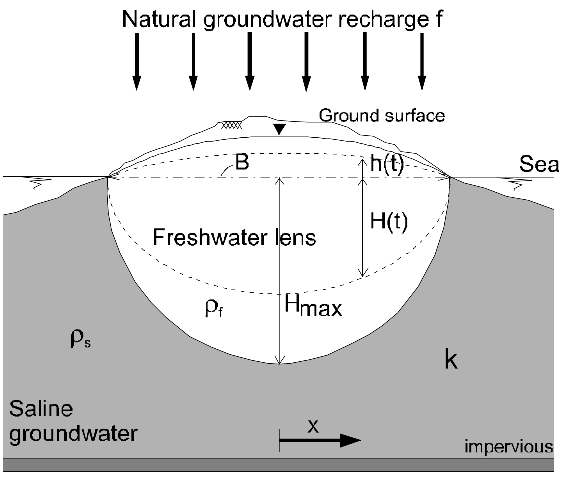
Movement of De Griend and creation of the lens



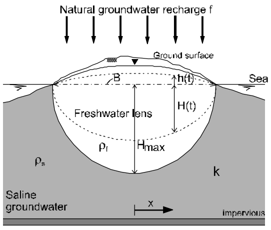
Movement of De Griend and creation of the lens



Case 2: Development of a freshwater lens

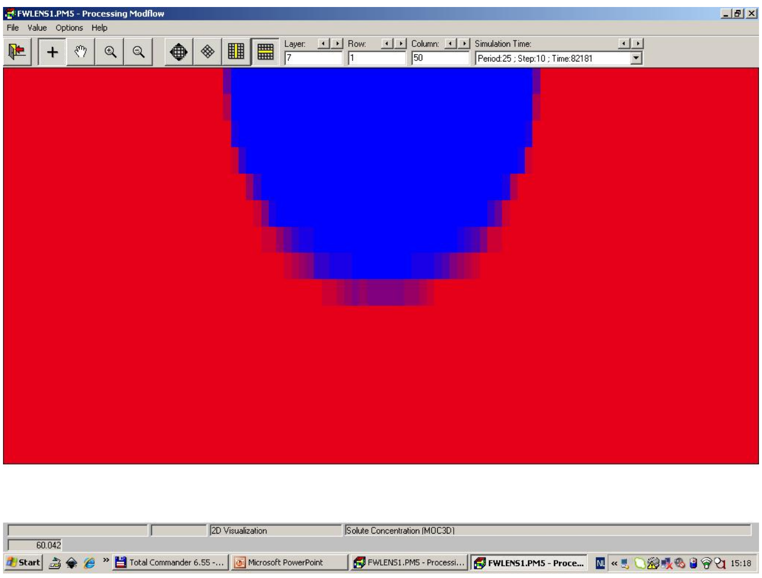


Case 2: Development of a freshwater lens

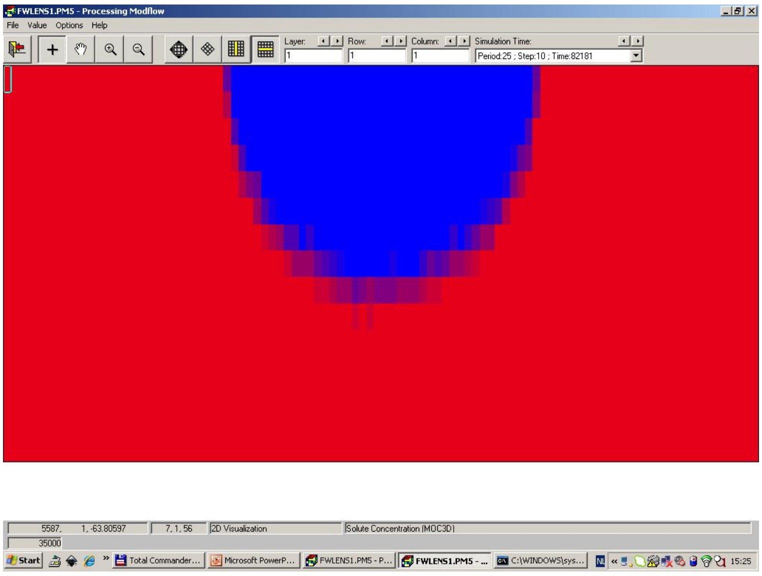


Parameters			
Layers	15	K_{hor}	20 m/d
Rows	1	T	200 m/d
Columns	100	Anisotropy K_{hor}/K_{ver}	10
Δx	100 m	ne	0.35
Δy	10 m	αL	0 m
Δz	10 m	αT	0 m
Stress periods	10	recharge	360 mm/y
Initial concentration	35000 mg/l	Recharge concentration	0 mg/l
bouyancy	0.025		

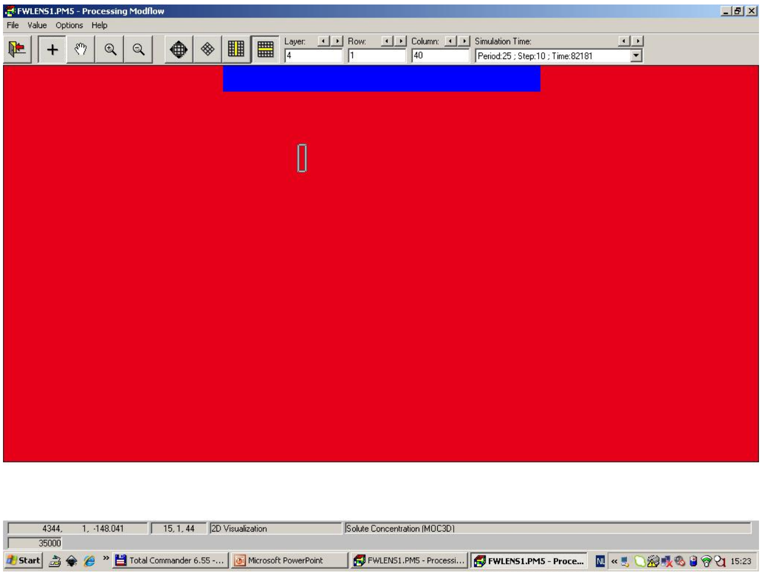
MOCDENS3D, no disp, 16part



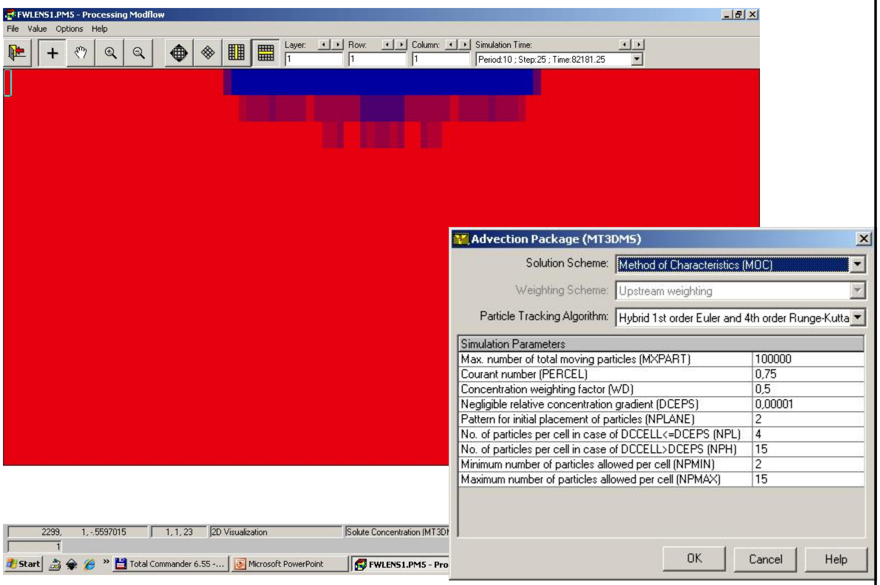
MOCDENS3D, no disp, 4part



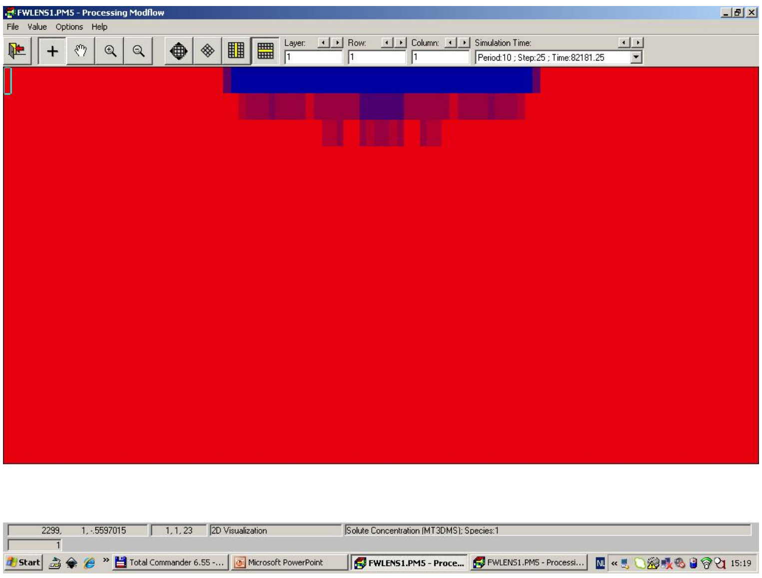
MOCDENS3D, no disp, 1part



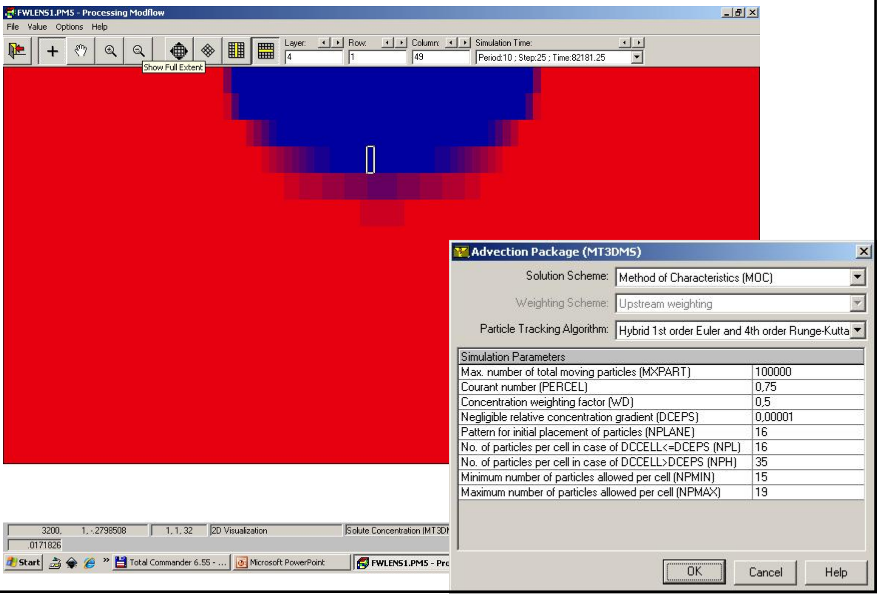
SEAWAT, MOC, NPLANE=2



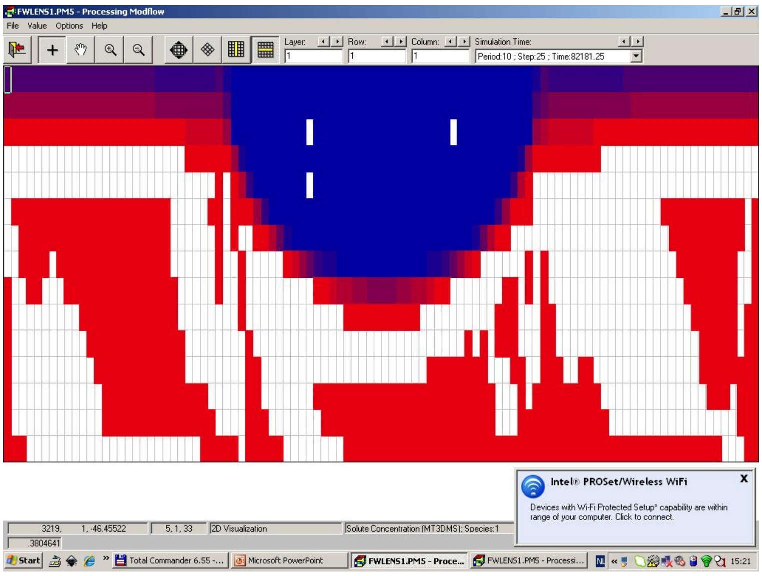
SEAWAT, MOC, 4.NPLANE=16



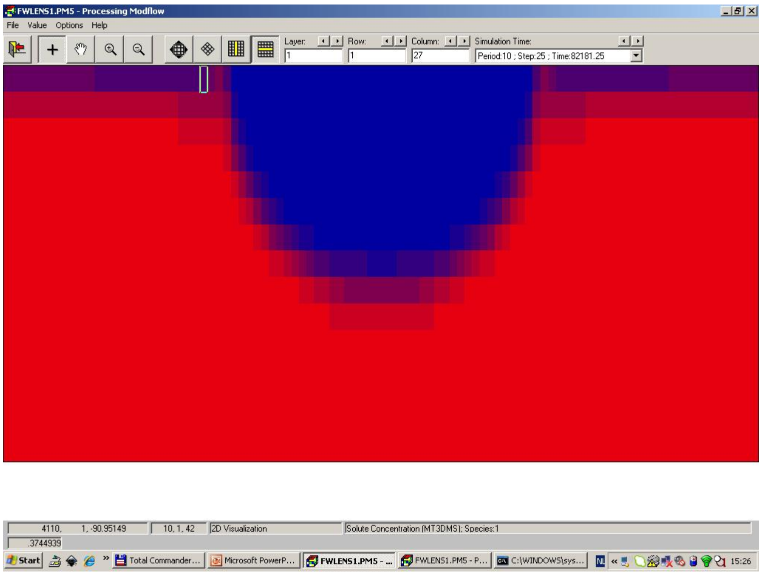
SEAWAT, MOC, 20sec, NPLANE=16, etc.



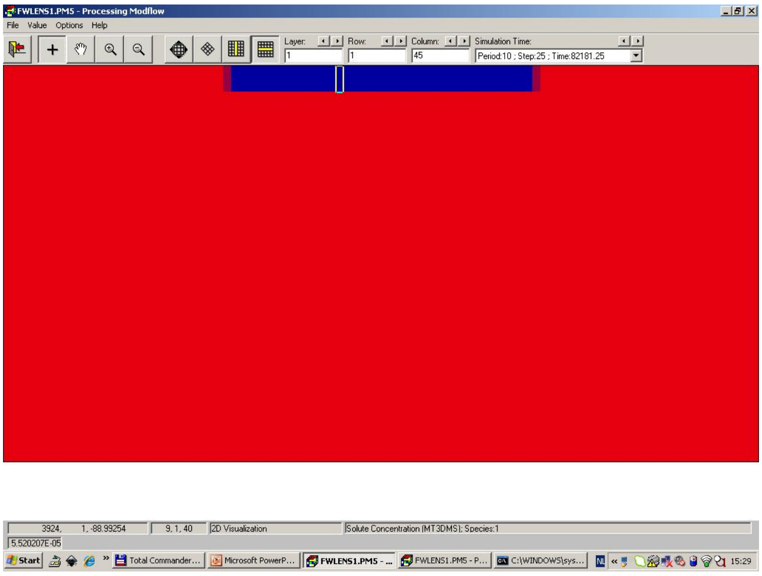
SEAWAT, ULTIMATE, 16.56sec



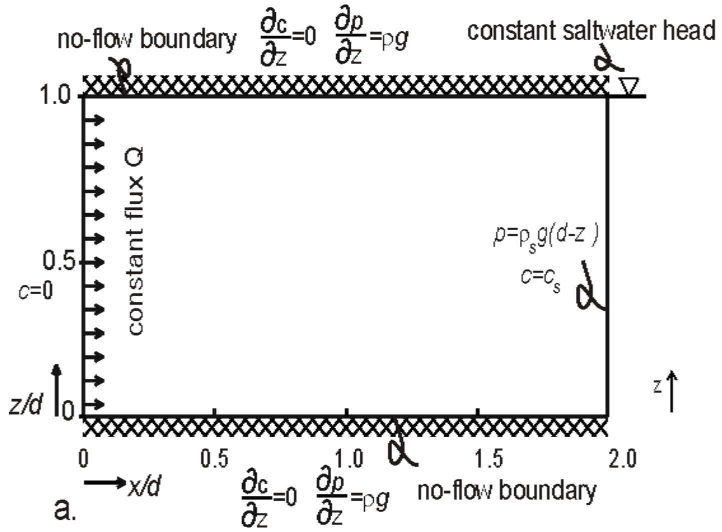
SEAWAT, MMOC, 8.5sec



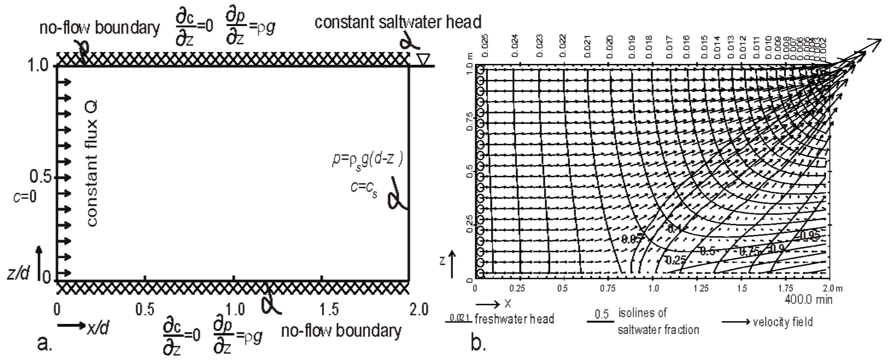
SEAWAT, HMOC, 6.8sec



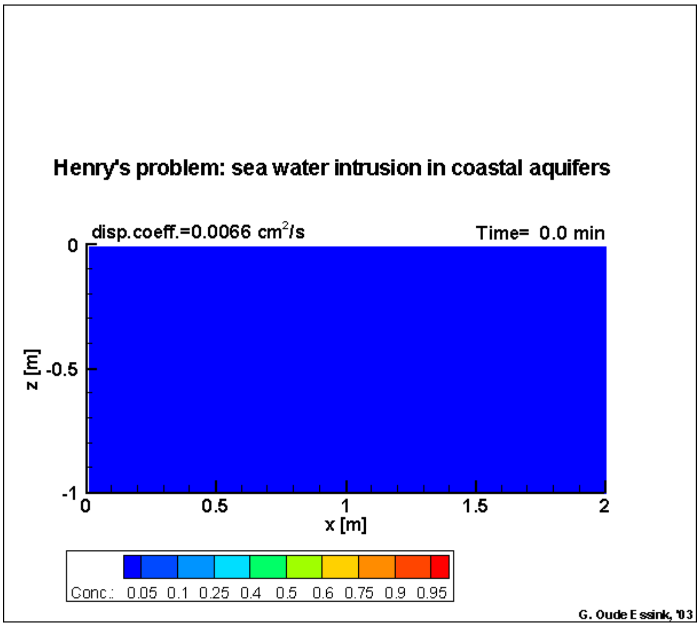
Henry's problem (1964)



Henry's problem



Henry's problem

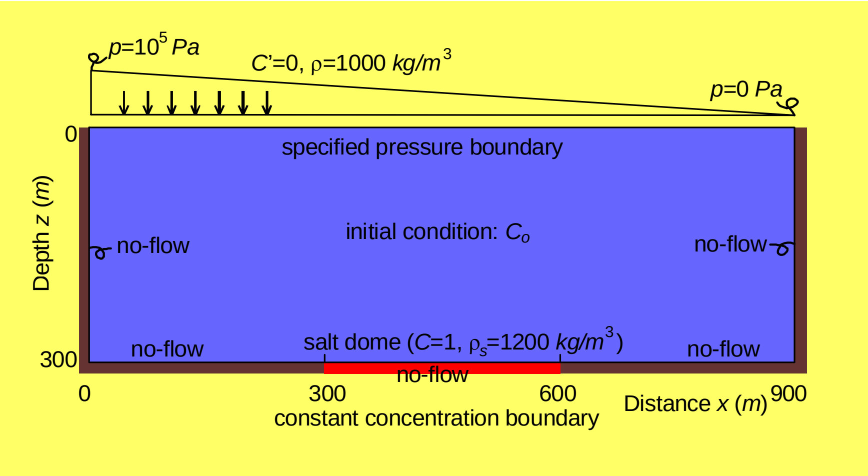


Henry's problem

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

Hydrocoin:

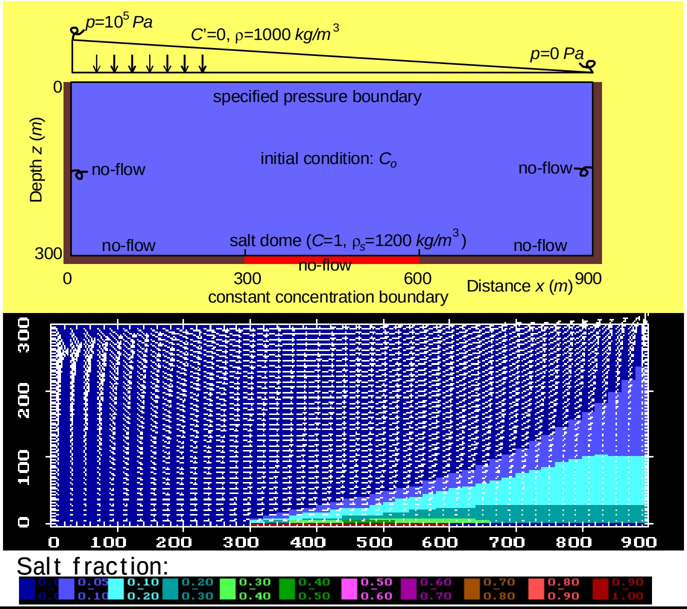
disposal of high-level nuclear waste
groundwater movement near salt domes
Gorleben salt dome, Germany



cases

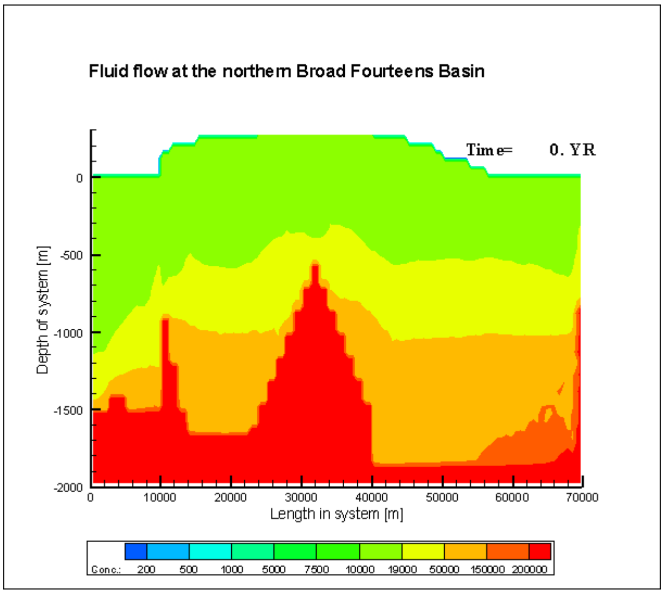
Hydrocoin:

groundwater movement near salt domes



Broad 14 Basin, North Sea

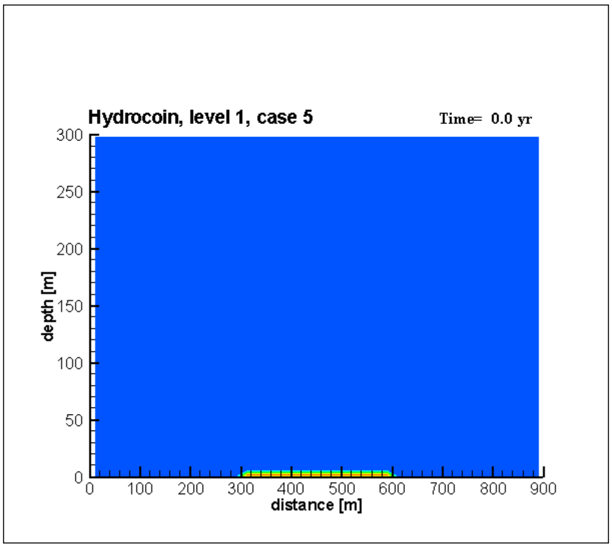
Geofluids'03, with L. Bouw



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

Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

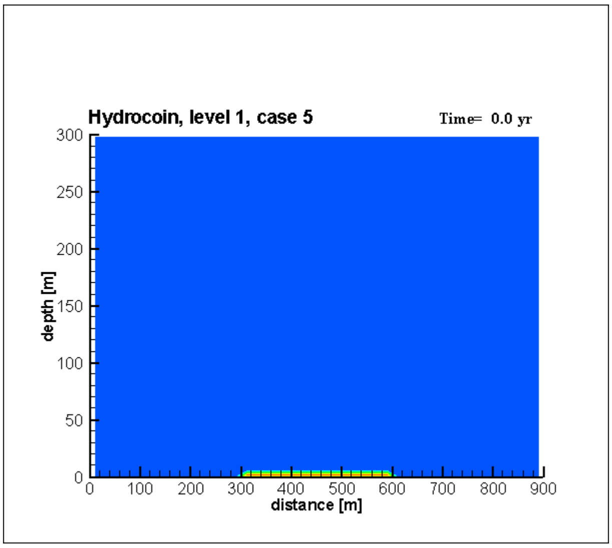


recirculation type

cases

Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

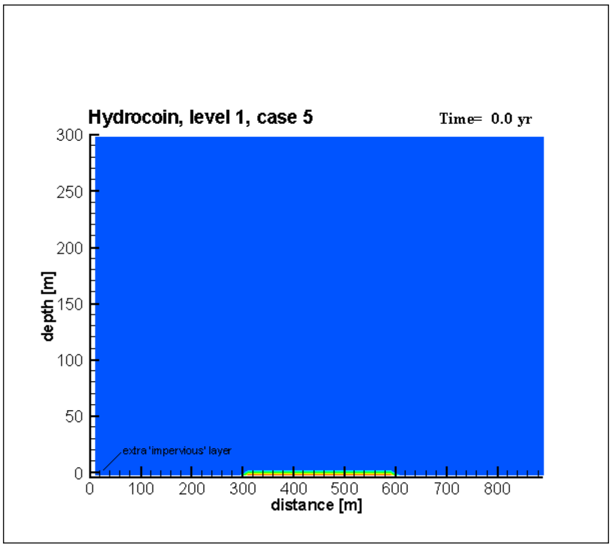


recirculation type

cases

Hydrocoin: effect of boundary condition (II)

supply of brine through only hydrodynamic dispersion

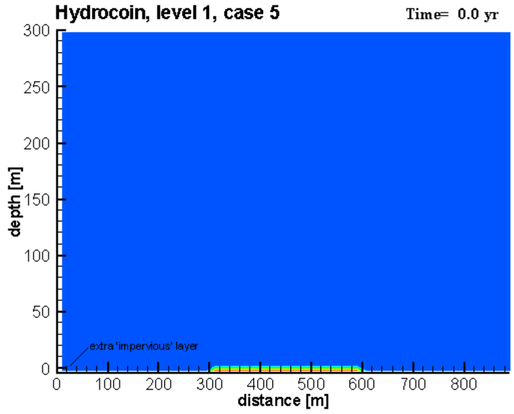


swept-forward type

cases

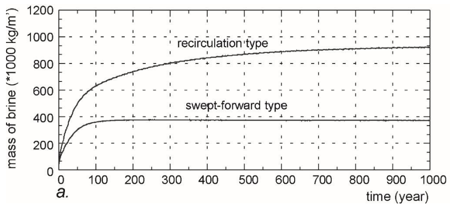
Hydrocoin: effect of boundary condition (II)

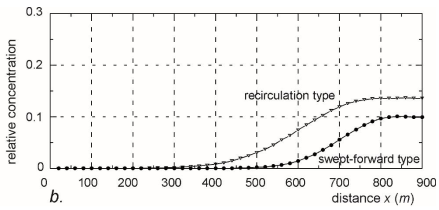
supply of brine through only hydrodynamic dispersion



swept-forward type

Hydrocoin: difference recirculation vs swept forward



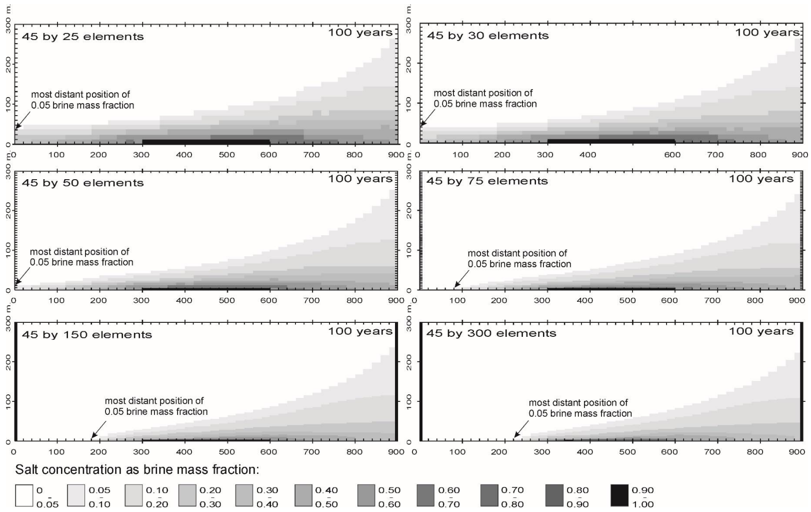


total mass of brine

brine conc at depth=200m

Lecture notes, p. 86-91

Hydrocoin: effect of vertical grid size

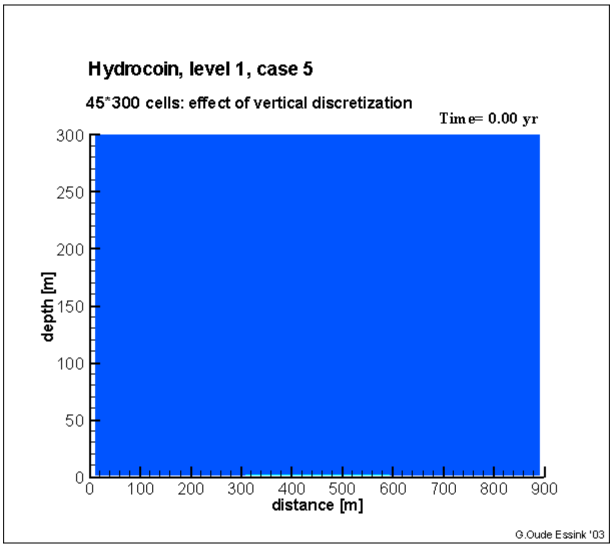


Recirculation type

cases

Hydrocoin: effect of vertical discretization (III)

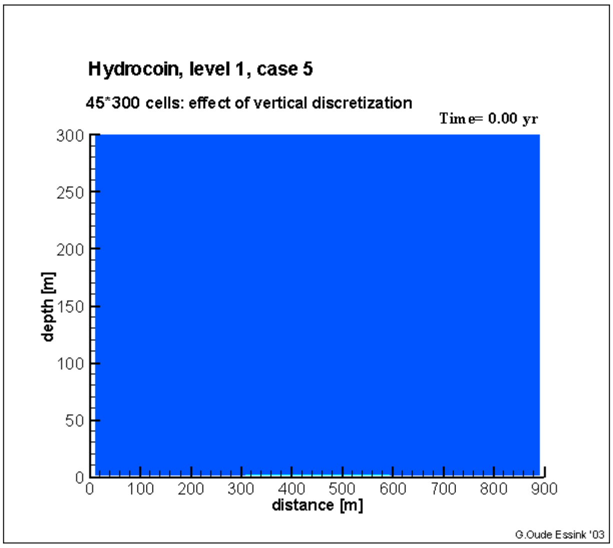
more vertical cells give better solution



like the swept-forward type

Hydrocoin: effect of vertical discretization (III)

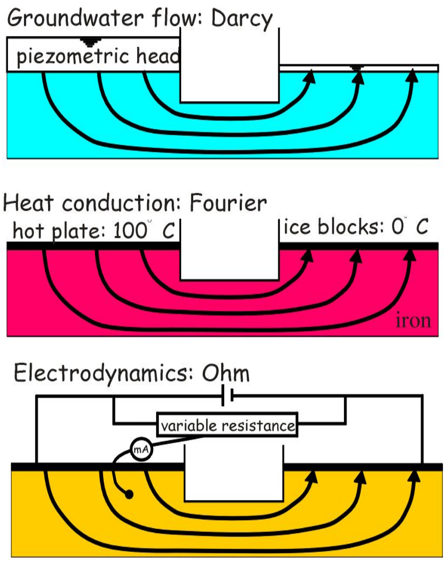
more vertical cells give better solution



like the swept-forward type

Analogy physical processes

Heat transport (analogy with solute transport)



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

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

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

Conduction and convection of heat

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

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

thermal conductivity [Joule/(ms °C)]

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

continuity equation

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

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

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

Analogy solute and heat transport

Solute: advection-dispersion equation

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

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

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

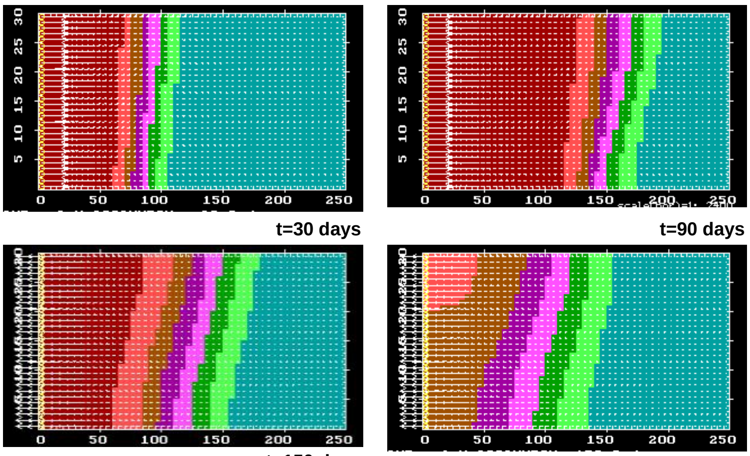
Equation of state: relation density & temperature

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

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	$\frac{n_e \lambda_e + (1-n_e)\lambda_s}{n_e \rho c_f}$
λ	0

Energy storage in geothermal reservoirs

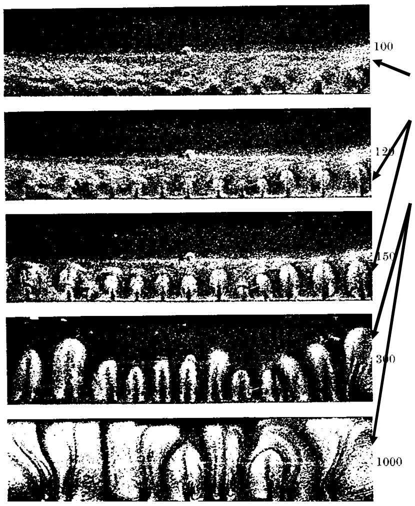


t=30 days   t=90 days   t=150 days   t=210 days

Temperature (degrees Celcius):

Elder problem (I)

It is originally a heat transport problem



Phases:

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

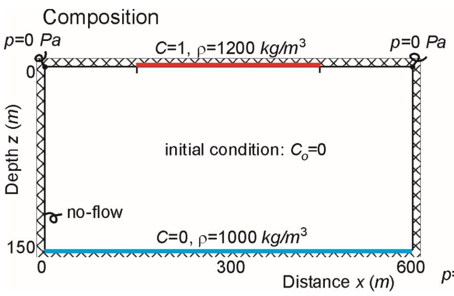
Convection of heat occurs when:

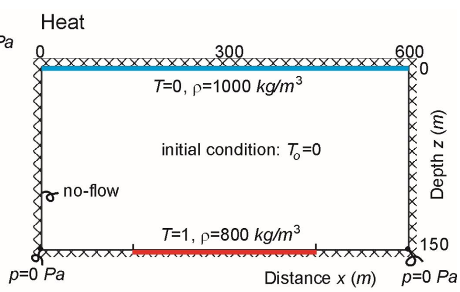
Rayleigh number > $4\pi^2$

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

Elder problem (II)

Anology composition and heat



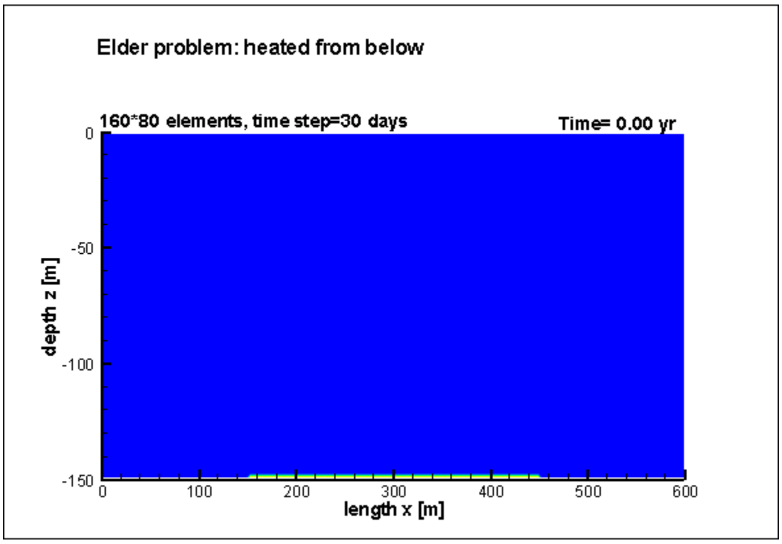


Lecture notes, p. 91-96

cases

Elder problem (III)

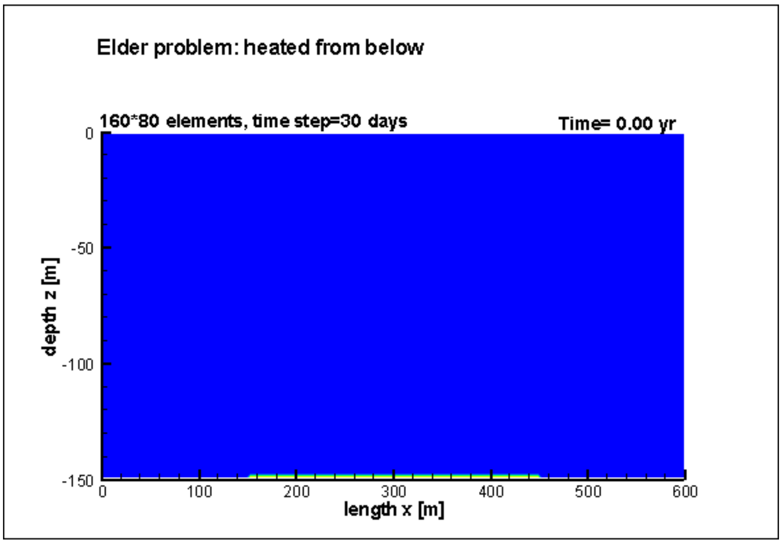
Development of convection cells (Rayleigh number=400)



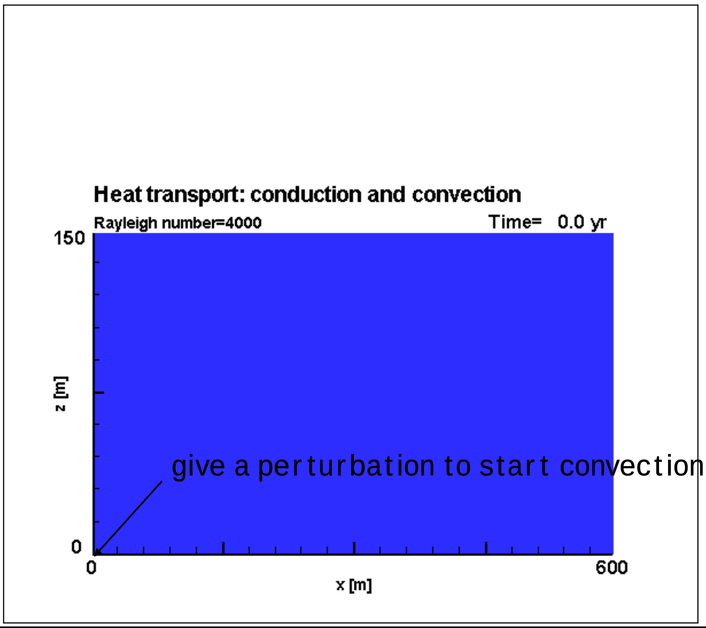
cases

Elder problem (III)

Development of convection cells (Rayleigh number=400)



Heat transport (Rayleigh number=4000)



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

Sri Lanka
Some days after December 26th, 2004

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

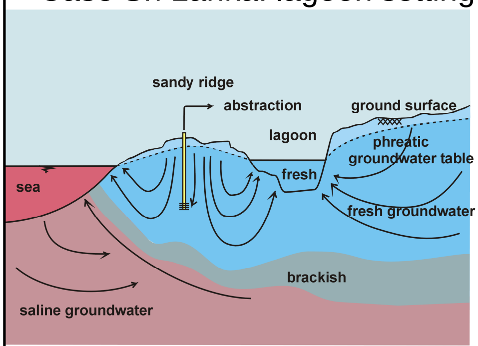
Impression of relevant salinisation processes by conceptual models of salt water intrusion in coastal aquifers:

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

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

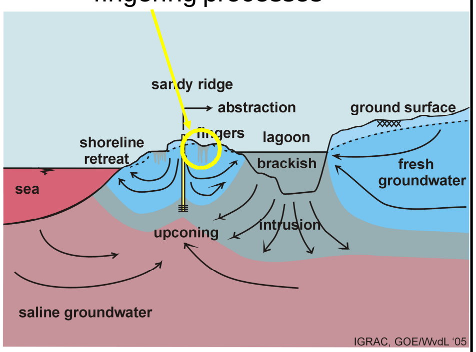
Concept 1: Fingering processes in the subsoil

Case Sri Lanka: lagoon setting



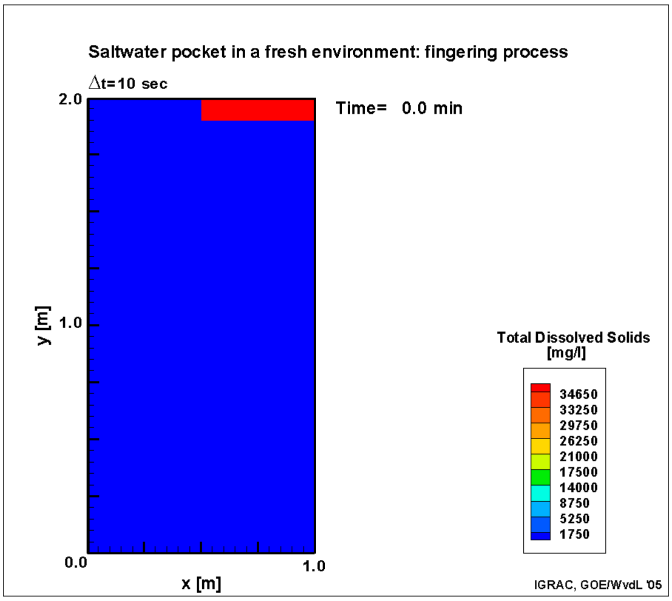
Before the Tsunami

fingering processes

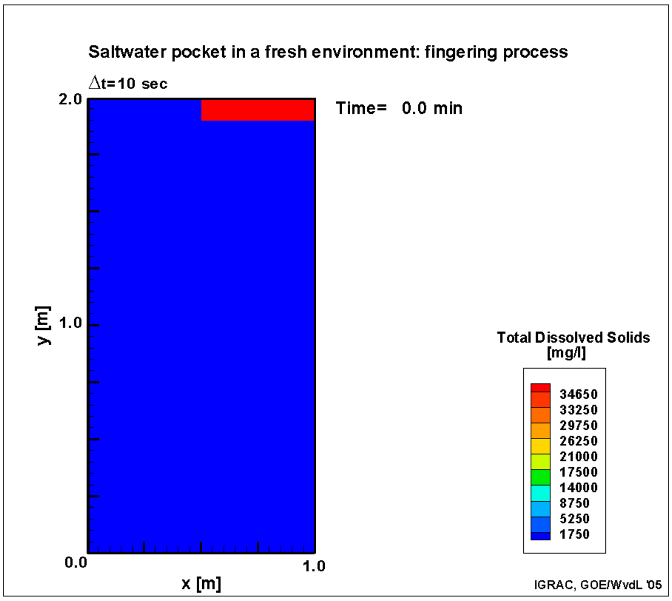


After the Tsunami

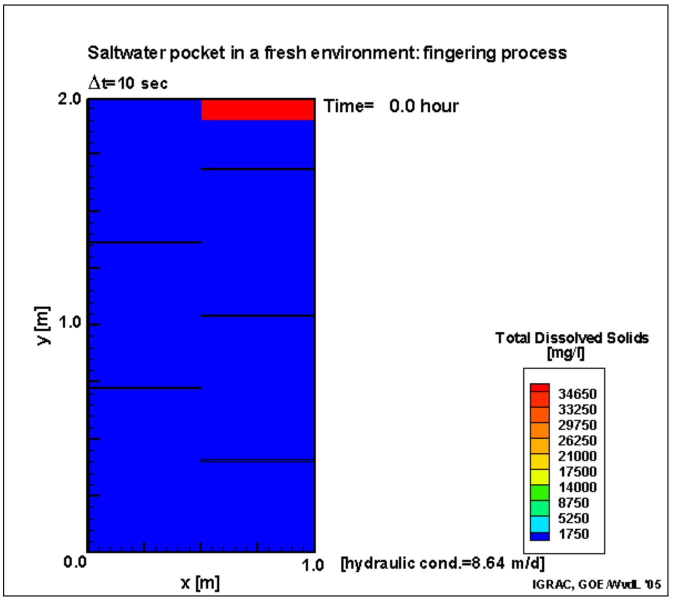
Concept 1: Fingering processes in the subsoil



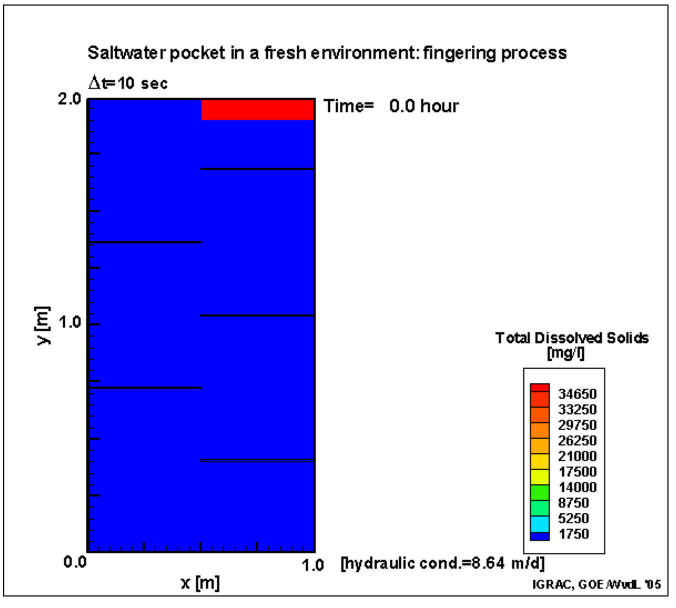
Concept 1: Fingering processes in the subsoil



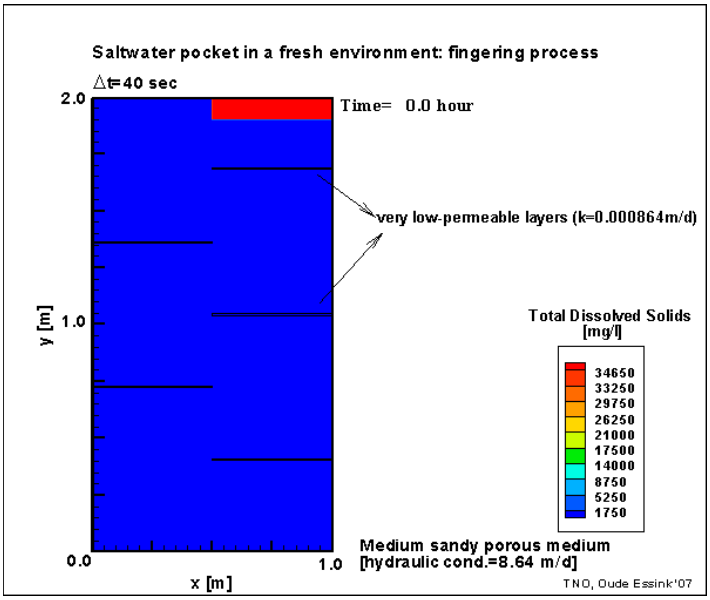
Concept 1: Fingering processes in the subsoil



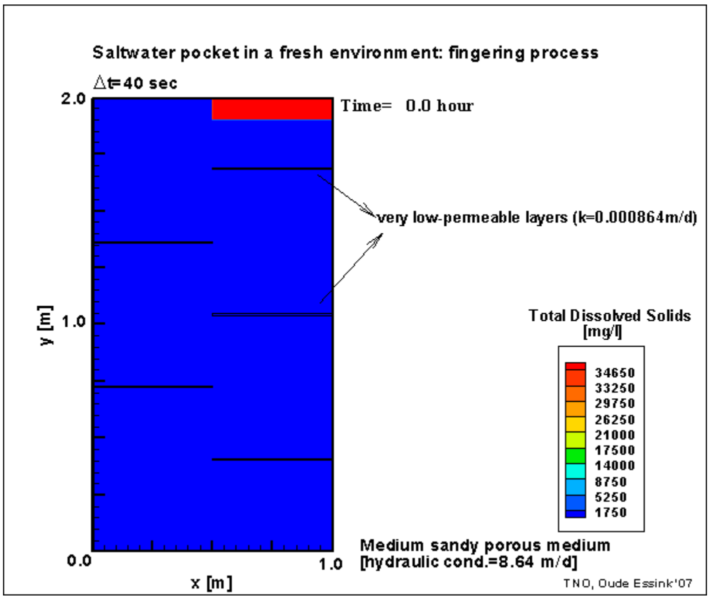
Concept 1: Fingering processes in the subsoil



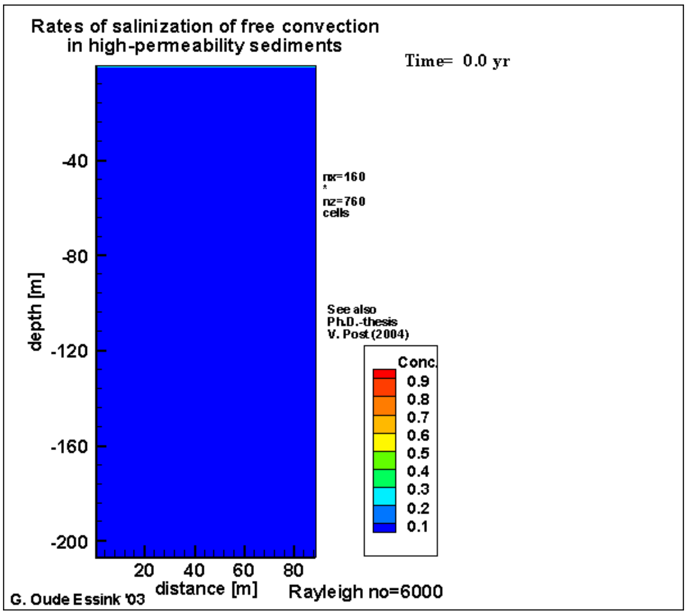
Concept 1: Fingering processes in the subsoil



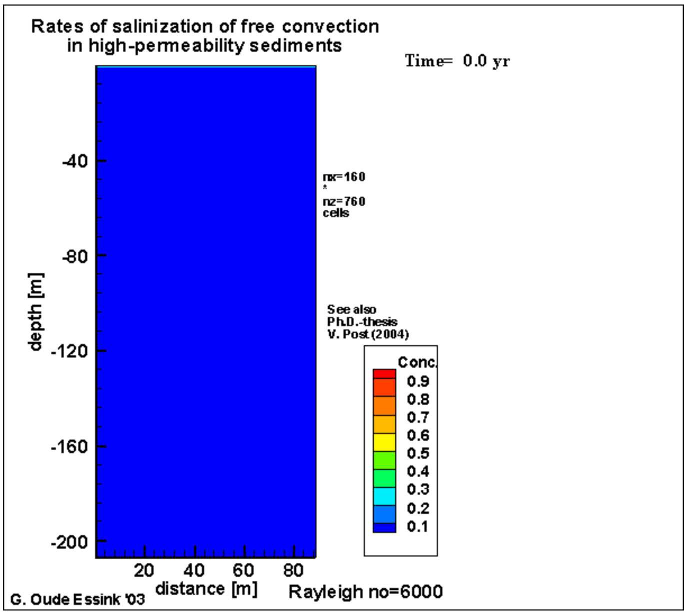
Concept 1: Fingering processes in the subsoil



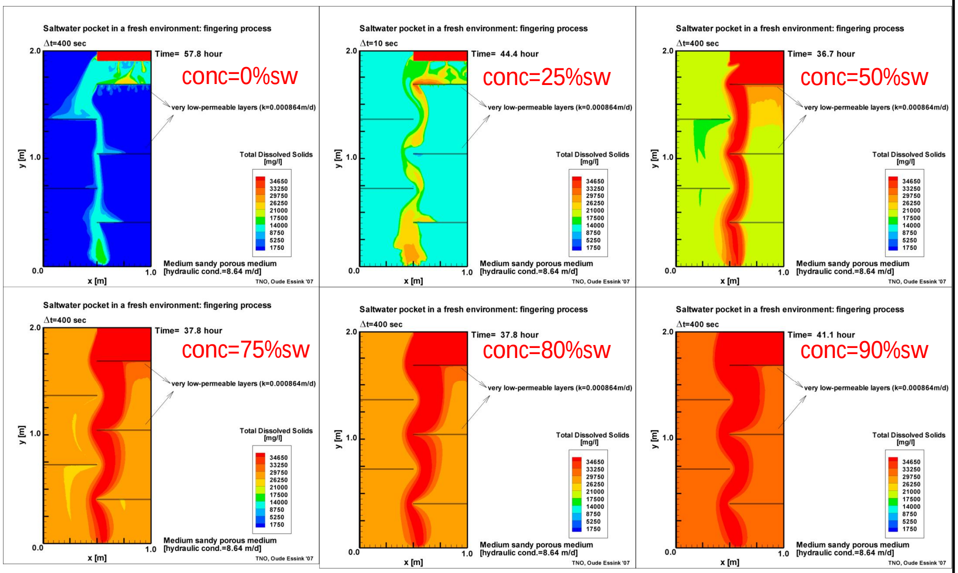
Concept 1: Fingering processes in the subsoil



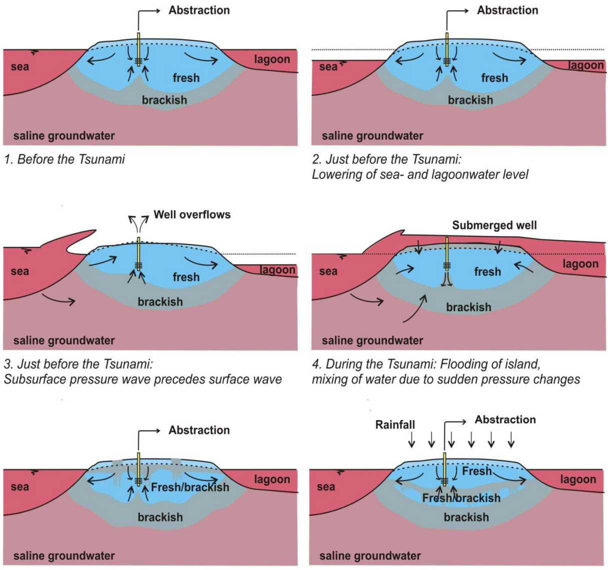
Concept 1: Fingering processes in the subsoil



Fingering processes in the subsoil



Concept 2: Evolution of a freshwater lens after flooding



1. Before the Tsunami

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

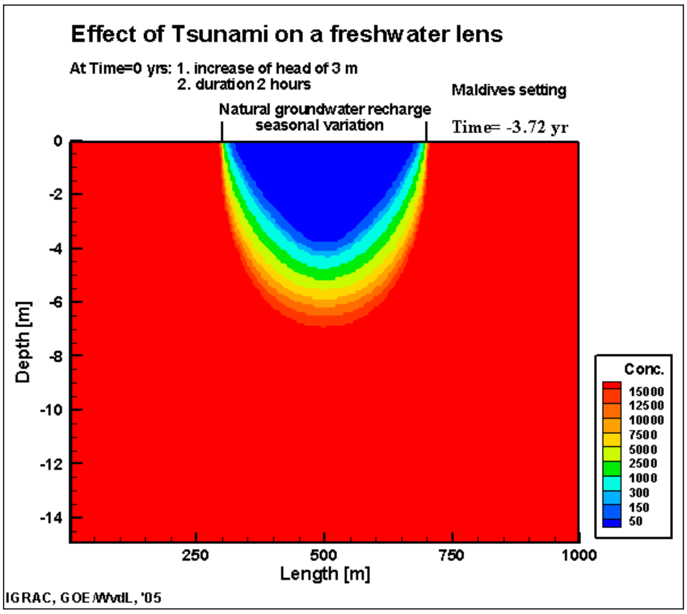
3. Just before the Tsunami: Subsurface pressure wave precedes surface wave

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

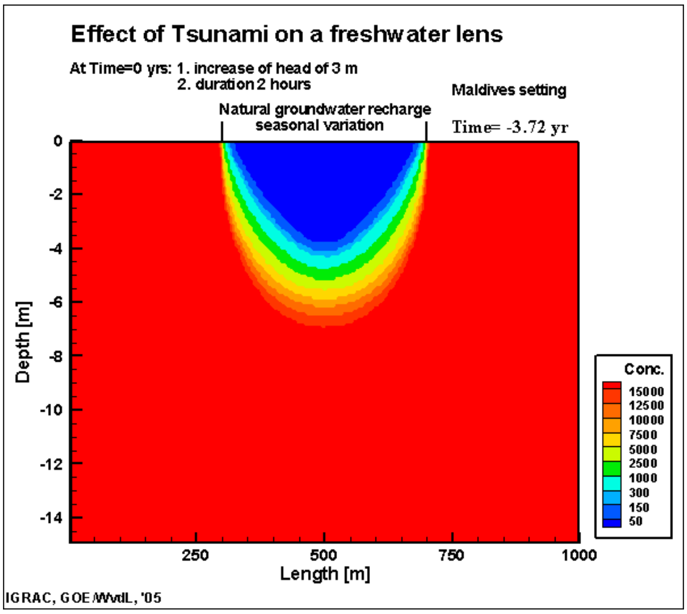
5. After the Tsunami Freshwater mixed with brackish water

6. After the Tsunami Recharge by rainfall replaces brackish water

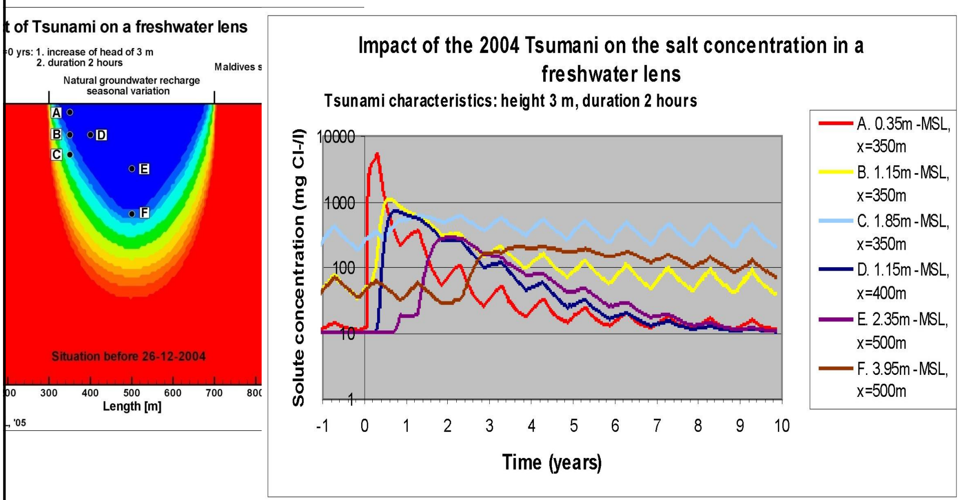
Concept 2: Evolution of a freshwater lens after flooding



Concept 2: Evolution of a freshwater lens after flooding

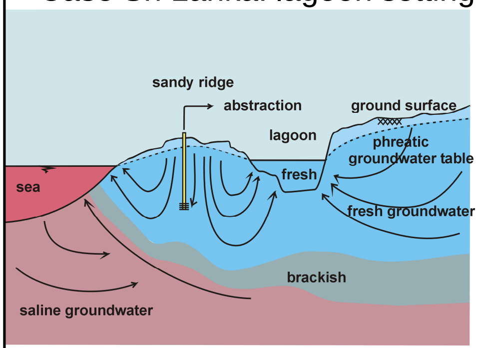

Effect of Tsunami on a freshwater lens
At Time=0 yrs: 1. increase of head of 3 m
2. duration 2 hours
Maldives setting
Natural groundwater recharge
seasonal variation
Time= -3.72 yr
Depth [m]
Length [m]
Conc.
IGRAC, GOE/WvdL, '05

Concept 2: Evolution of a freshwater lens after flooding

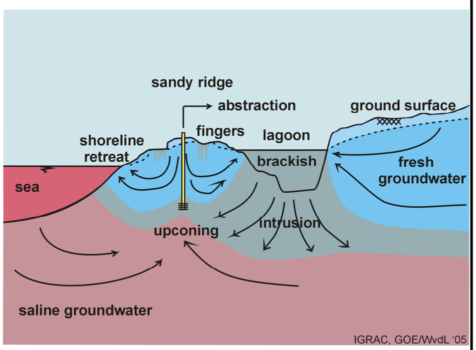


Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

Case Sri Lanka: lagoon setting

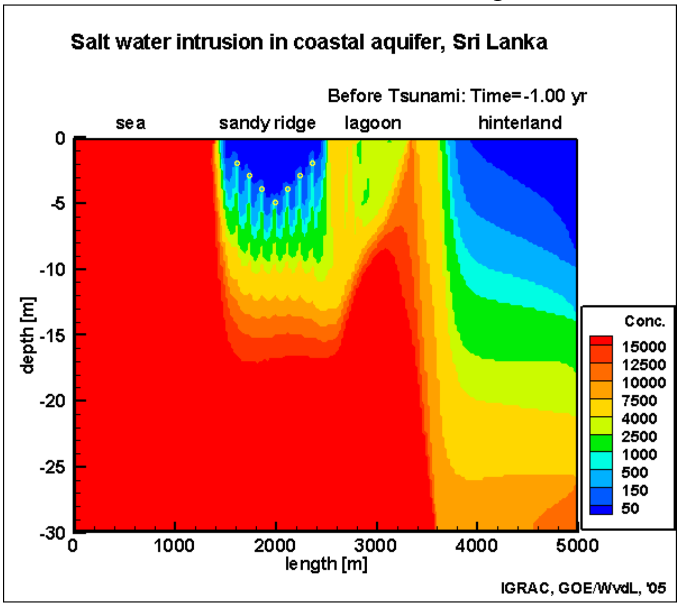


Before the Tsunami

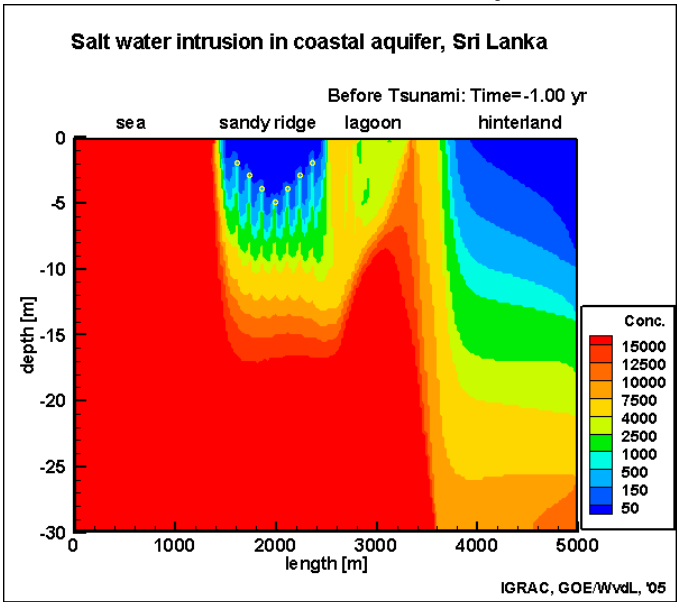


After the Tsunami

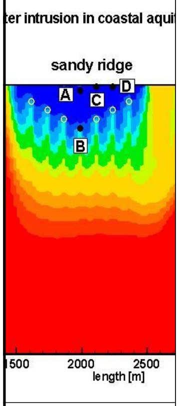
Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

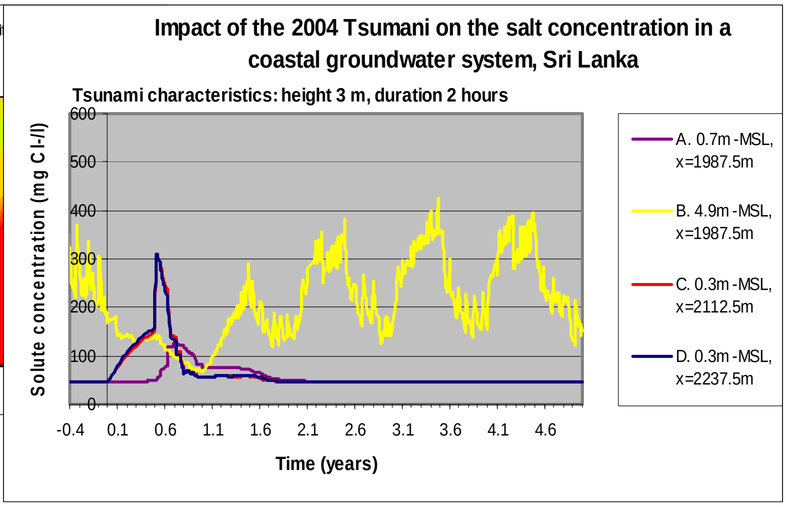


Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon



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



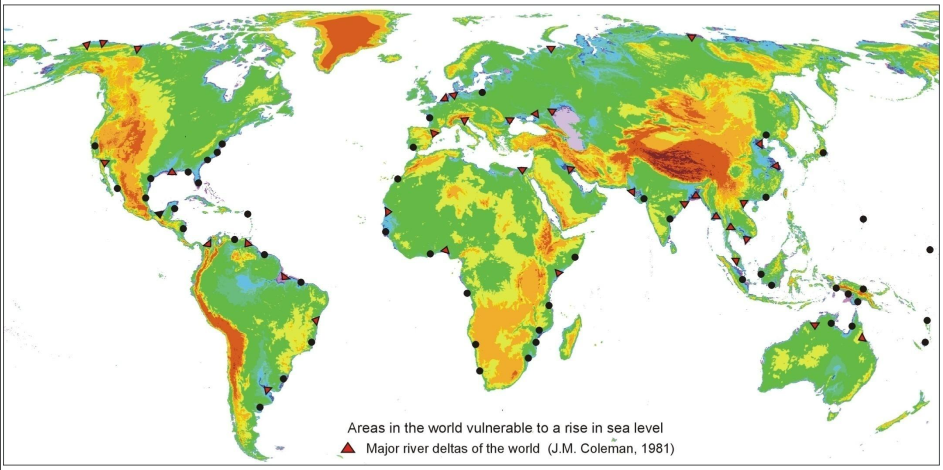


Effect sea level rise

Effects of sea level rise on groundwater resources in deltaic areas

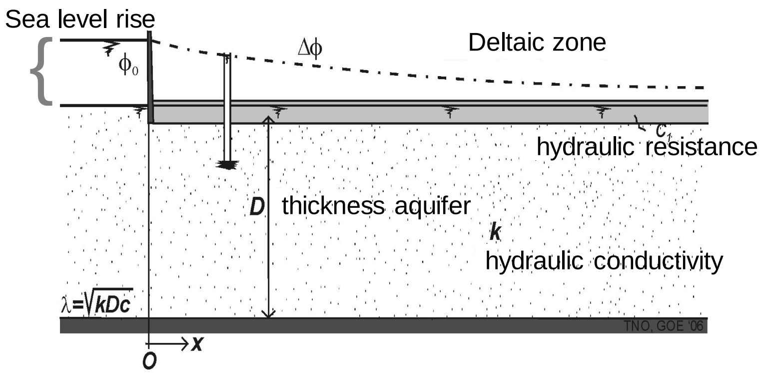
1. Increase of salt water intrusion
2. Increase of upconing under groundwater extraction wells
3. Increase of piezometric head
4. Increase of seepage and salt load to the surface water system
5. Risk of instable Holocene aquitards
6. [Decrease of fresh groundwater reservoirs due to decrease in natural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

Effects of sea level rise on groundwater resources in deltaic areas



Digital Elevation Model (DEM)

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



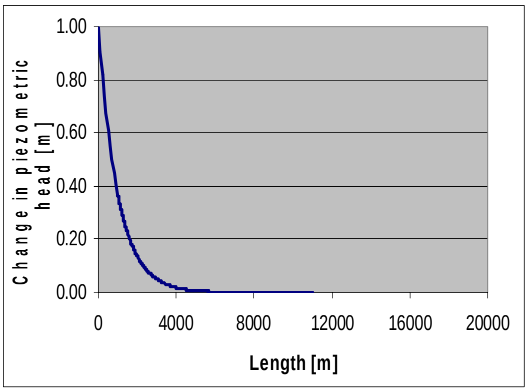
$$\Delta\phi(x) = \phi_0 e^{-x/\lambda}$$

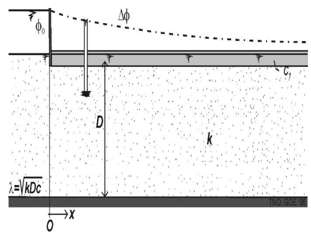
$$\lambda = \sqrt{kDc}$$

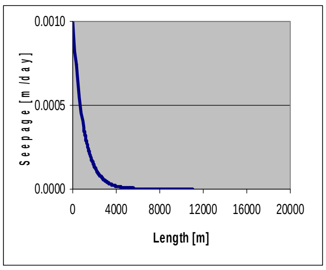
- Zone of influence is equal to sqrt(kDc)
- At x=3λ, only 5% of sea level rise is detectable

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

kD = 1000 m^2/day
c = 1000 day
λ = 1000 m



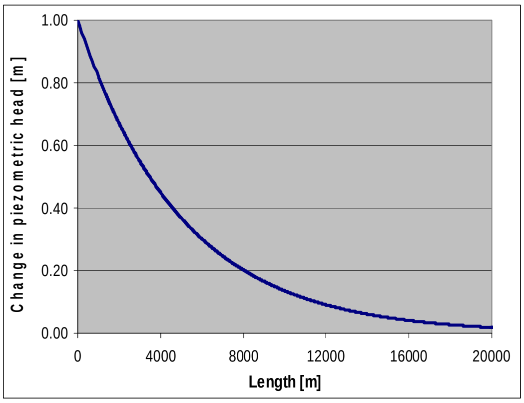


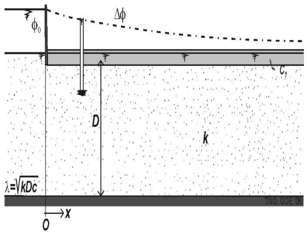


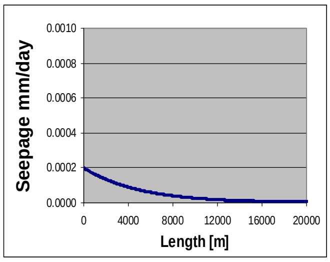
Effect of sea level rise:

Case 2 with Dutch subsoil parameters

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

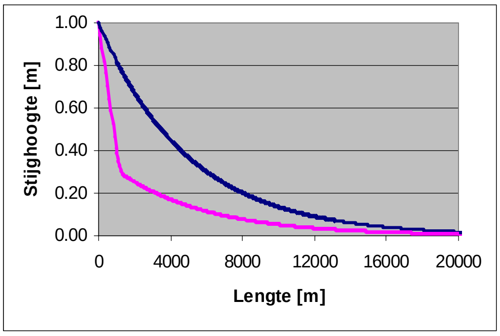


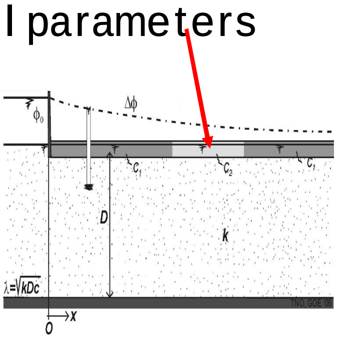


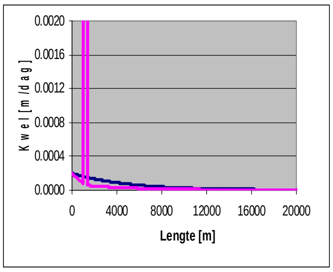


Case 3 with Dutch subsoil parameters

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

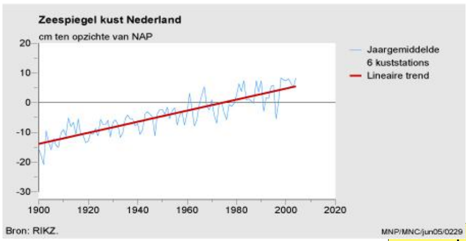


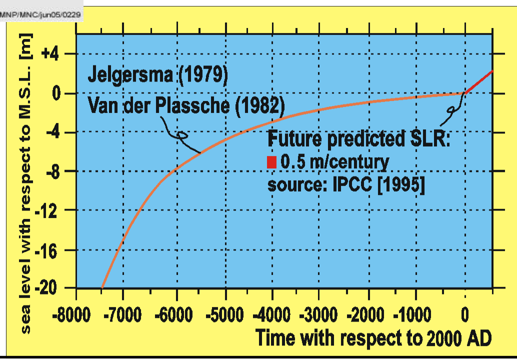




Climate change is HOT!

Past and future sea level rise in the Netherlands

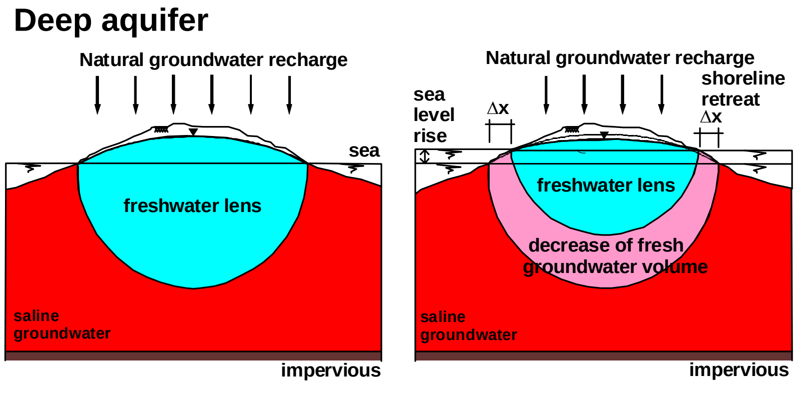




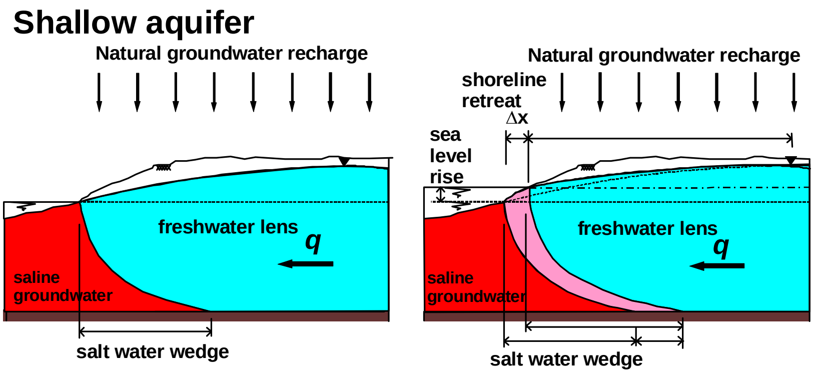
Implementing new KNMI06 climate scenarios

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

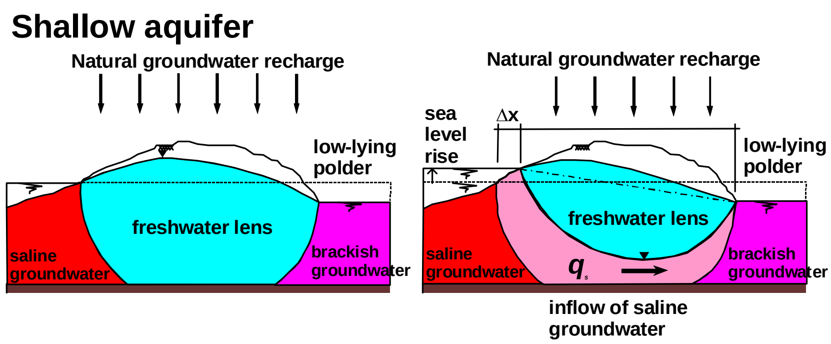
Effect of a relative sea level rise (1):



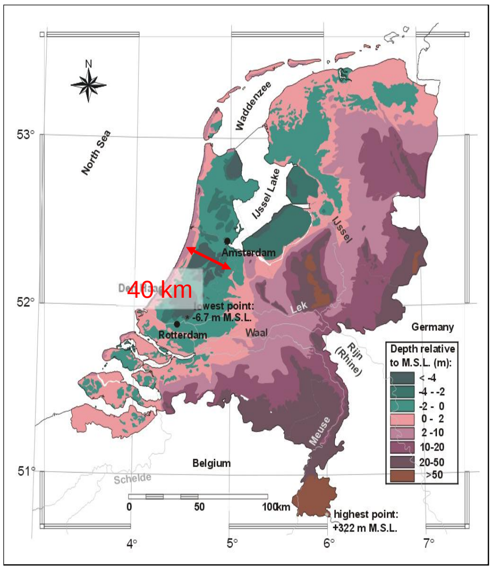
Effect of a relative sea level rise (2):

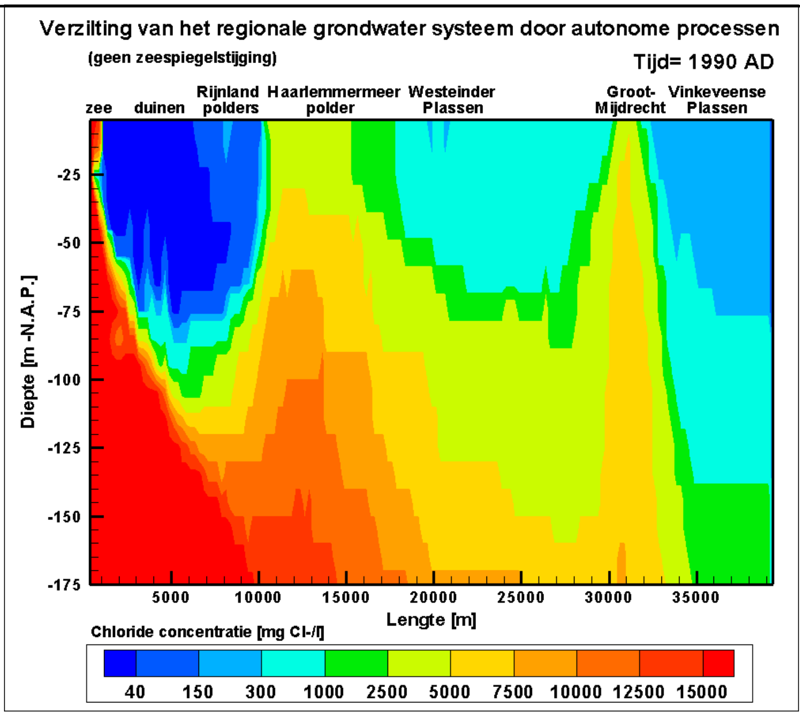


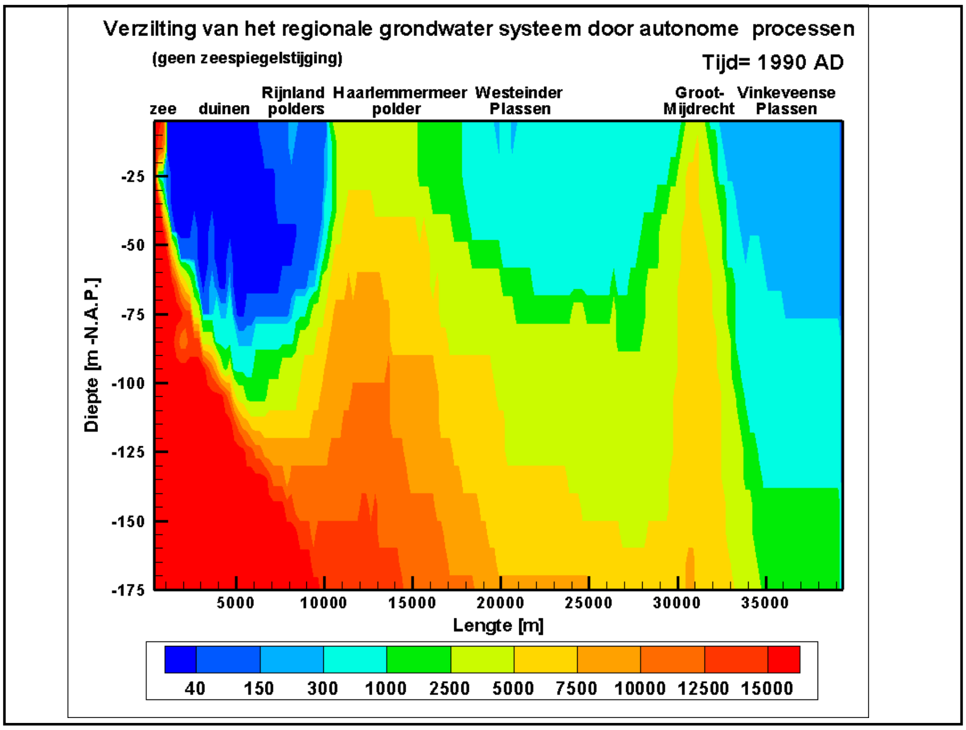
Effect of a relative sea level rise (3):



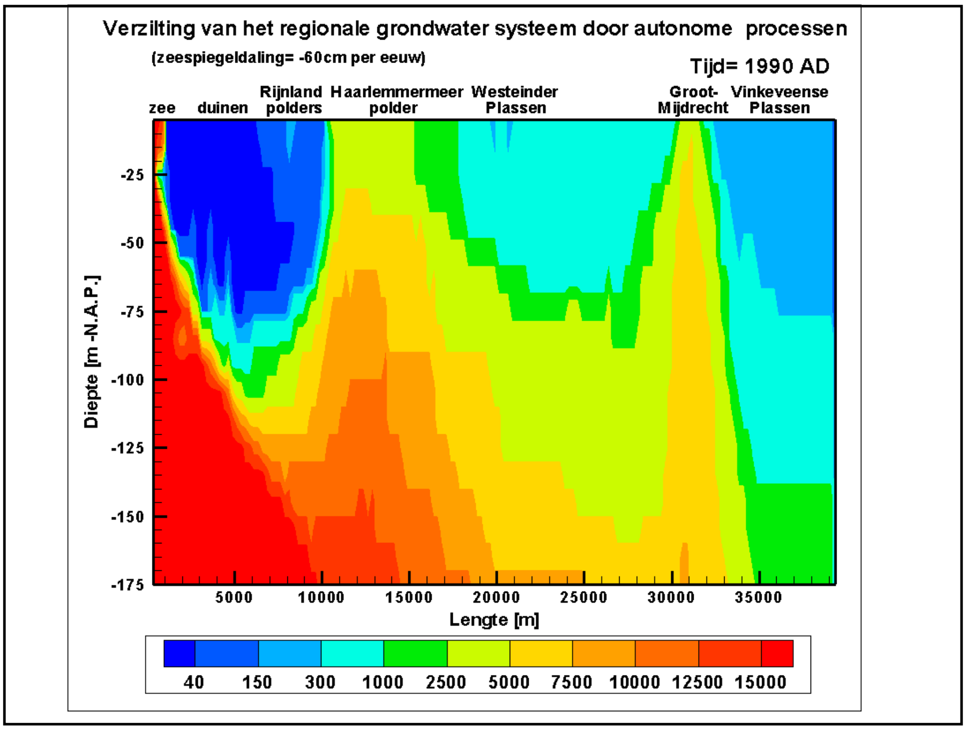
2D Profile and effect sea level rise



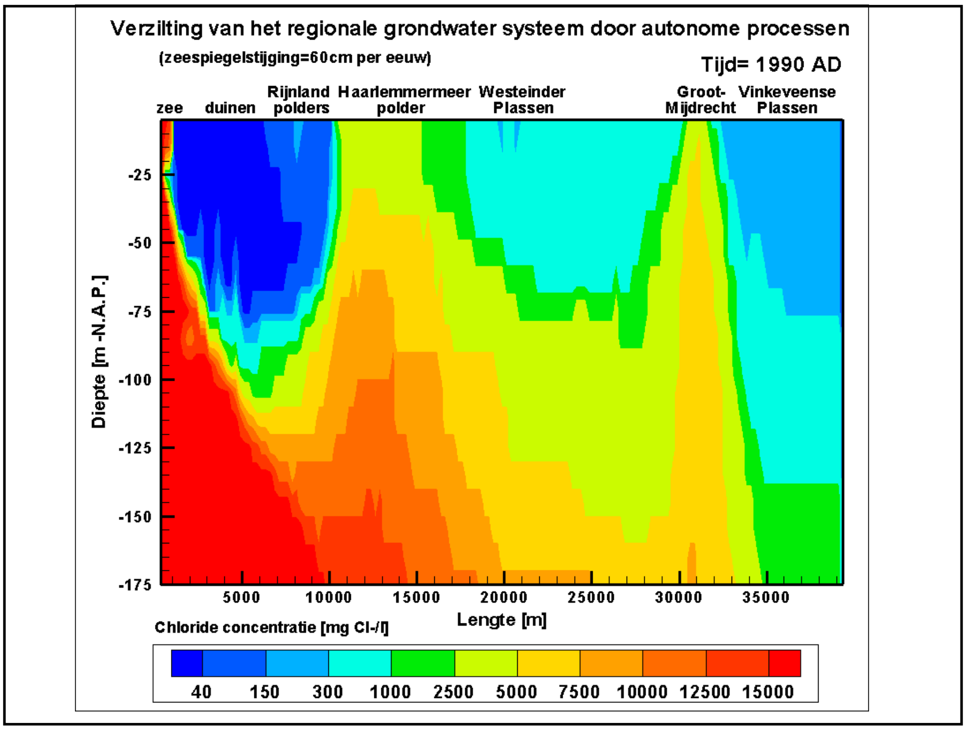


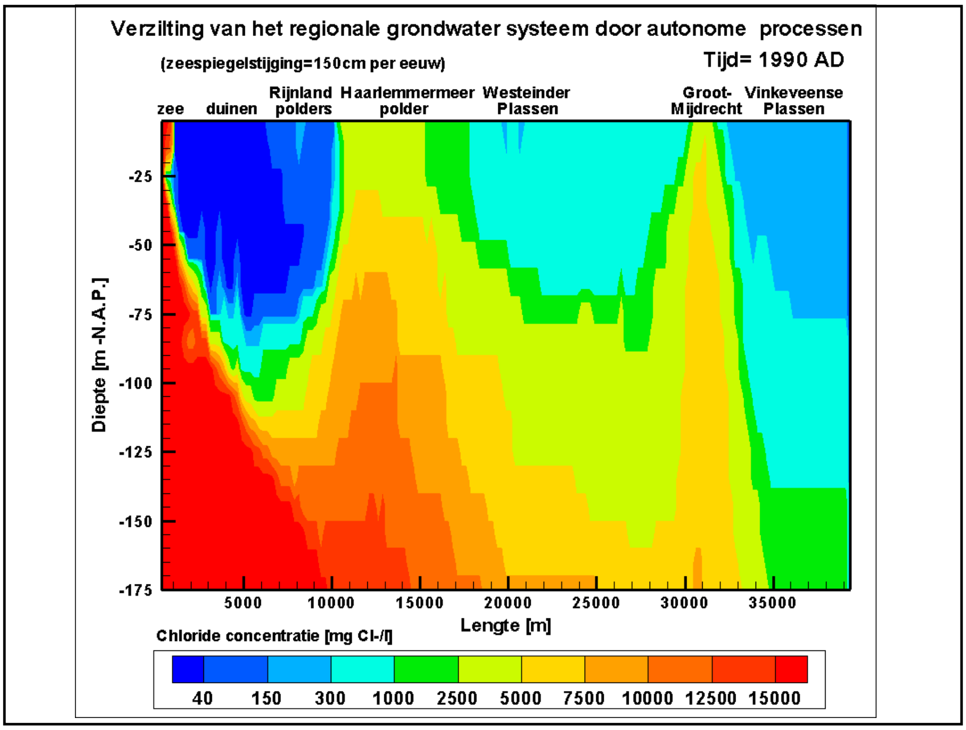


Verzilting van het regionale grondwater systeem door autonome processen
(geen zeespiegelstijging)
Tijd= 1990 AD
zee duinen Rijnland polders Haarlemmermeer polder Westeinder Plassen Groot-Mijdrecht Vinkeveense Plassen
Diepte [m -N.A.P.]
-25 -50 -75 -100 -125 -150 -175
5000 10000 15000 20000 25000 30000 35000
Lengte [m]
40 150 300 1000 2500 5000 7500 10000 12500 15000



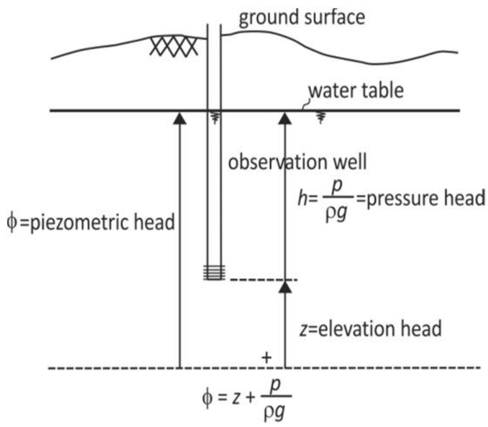
Verzilting van het regionale grondwater systeem door autonome processen
(zeespiegeldaling= -60cm per eeuw)
Tijd= 1990 AD
zee duinen Rijnland polders Haarlemmermeer polder Westeinder Plassen Groot-Mijdrecht Vinkeveense Plassen
Diepte [m -N.A.P.]
-25 -50 -75 -100 -125 -150 -175
5000 10000 15000 20000 25000 30000 35000
Lengte [m]
40 150 300 1000 2500 5000 7500 10000 12500 15000


Verzilting van het regionale grondwater systeem door autonome processen
(zeespiegelstijging=60cm per eeuw)
Tijd= 1990 AD
zee
duinen
Rijnland polders
Haarlemmermeer polder
Westeinder Plassen
Groot-Mijdrecht
Vinkeveense Plassen
Diepte [m -N.A.P.]
-25
-50
-75
-100
-125
-150
-175
5000
10000
15000
20000
25000
30000
35000
Lengte [m]
Chloride concentratie [mg Cl-/l]
40 150 300 1000 2500 5000 7500 10000 12500 15000


Verzilting van het regionale grondwater systeem door autonome processen
(zeespiegelstijging=150cm per eeuw)
Tijd= 1990 AD
zee
duinen
Rijnland polders
Haarlemmermeer polder
Westeinder Plassen
Groot-Mijdrecht
Vinkeveense Plassen
Diepte [m -N.A.P.]
-25
-50
-75
-100
-125
-150
-175
5000
10000
15000
20000
25000
30000
35000
Lengte [m]
Chloride concentratie [mg Cl-/l]
40 150 300 1000 2500 5000 7500 10000 12500 15000

Point water head
and
Freshwater head ϕ_f

Piezometric head ϕ



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

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

Freshwater head ϕ_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 ϕ_f

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

$$\phi_f = h_f + z$$

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

e.g.:
ρ_s=1025kg/m3
h=10m
ϕ_f=10.25m

Special case: hydrostatic pressure: q_z=0

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

no vertical flow

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

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

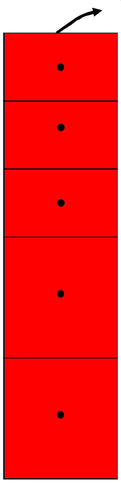
$$\phi_{f2} = \phi_{f1} - \frac{\rho - \rho_f}{\rho_f}(z2 - z1)$$

↓ +

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

Hydrostatic boundary condition at the sea

Water level=+0m MSL



Δz=5m — $\rho = 1025\,\text{kg/m3} \longrightarrow \phi_{f1} = 0\,\text{m} + 0.025 * 2.5\text{m} = 0.0625\text{m}$

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

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

Δz=10m — $\rho = 1025\,\text{kg/m3} \longrightarrow$

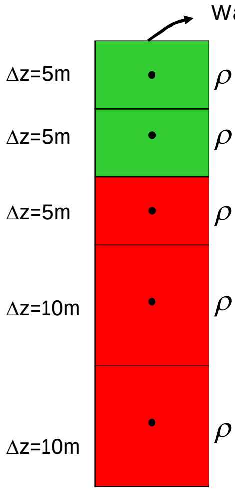
$\phi_{f4} = 0.3125 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.50\text{m}$

Δz=10m — $\rho = 1025\,\text{kg/m3} \longrightarrow$

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

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

Hydrostatic boundary condition at the sea



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

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

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

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

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

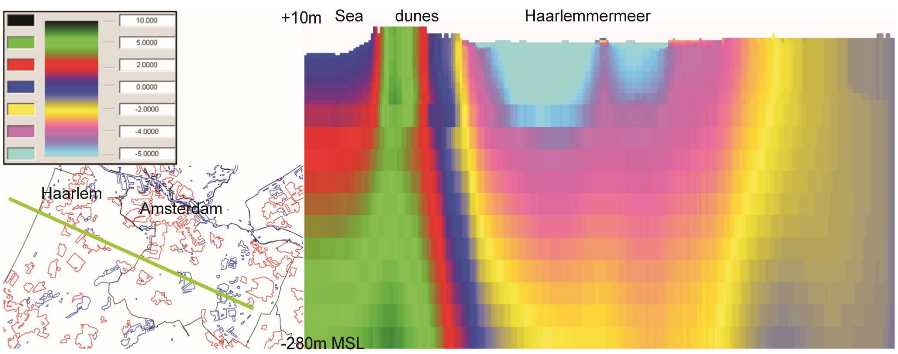
$\phi_{f4} = 0.1625 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.35\text{m}$

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

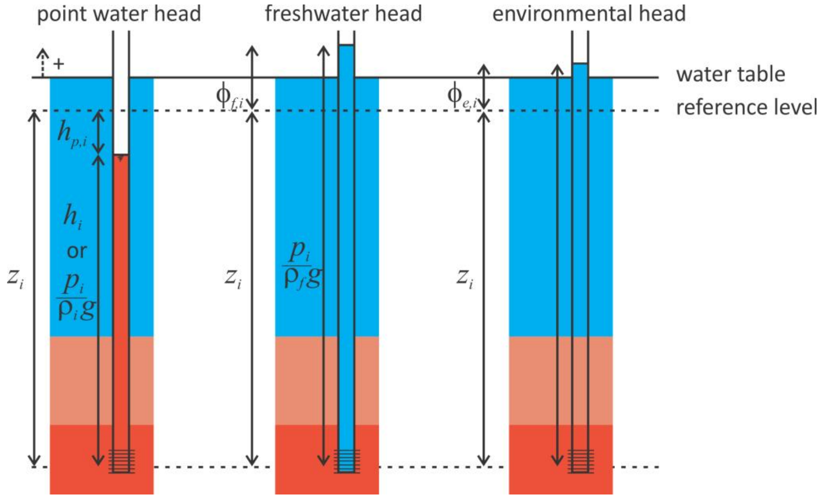
$\phi_{f5} = 0.35 + 0.025 * (5\text{m} + 5\text{m}) = 0.60\text{m}$

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

Example 2D profile NHI model freshwater head ϕ_f



Which one is useful?



Post, Kooi and Simmons, 2007, Ground Water

Point water head

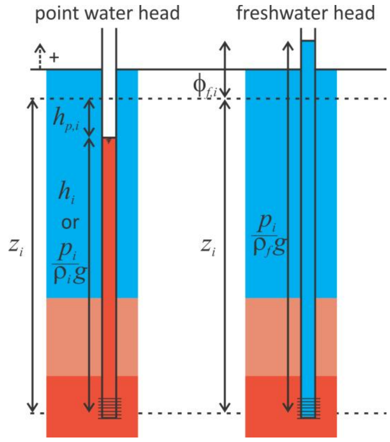
$$h_{p,i} = z_i + h_i \longleftrightarrow h_i = h_{p,i} - z_i$$

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

Freshwater head

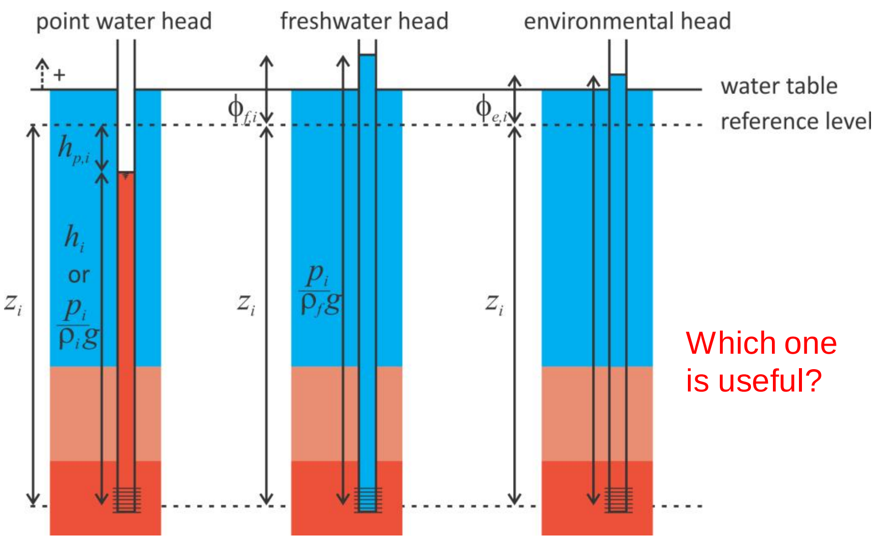
$$\phi_{f,i} = z_i + \frac{p_i}{\rho_f g} \longleftrightarrow \phi_{f,i} = z_i + \frac{h_i \rho_i}{\rho_f}$$

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



Post, Kooi and Simmons, 2007, Ground Water

$$h_{f,i} = \frac{\rho_i}{\rho_f} h_i - \frac{\rho_i - \rho_f}{\rho_f} z_i \qquad h_{f,i} = z_i + \frac{P_i}{\rho_f g}$$



Which one is useful?

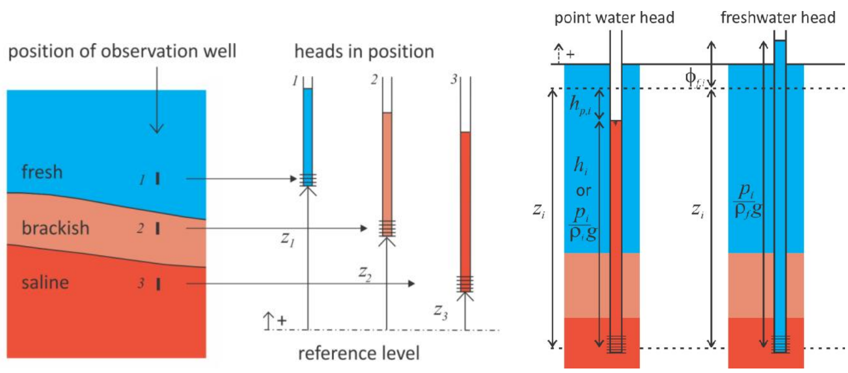
Post, Kooi and Simmons, 2007, Ground Water

Point water head Freshwater head

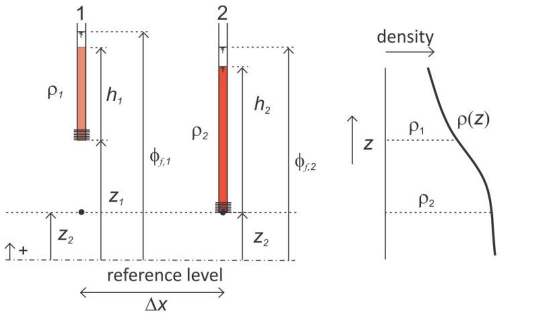
Example 1: $h_{p,i}$=-1 *m MSL*, ρ_i =1025 *kg/m*$^{-3}$, z_i=-11*m MSL*: $\phi_{f,i}$=-0.75*m MSL*.

Example 2: $h_{p,i}$=0 *m MSL*, ρ_i =1025 *kg/m*$^{-3}$, z_i=-10*m MSL*: $\phi_{f,i}$=0.25*m MSL*.

Example 3: $h_{p,i}$=0 *m MSL*, ρ_i =1025 *kg/m*$^{-3}$, z_i=-100*m MSL*: $\phi_{f,i}$=2.50*m MSL*.



Freshwater head ϕ_f: horizontal flow?

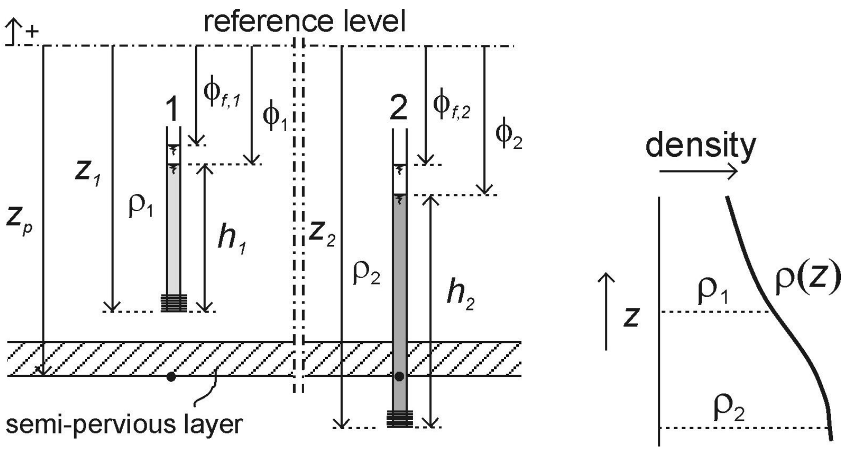


$$p_1^{at\ z=z_2} = \rho_1 g h_1 + \int_{z_2}^{z_1} \rho(z) g dz \qquad \phi_{f,1}^{at\ z=z_2} = z_2 + \frac{\rho_1}{\rho_f} h_1 + \frac{1}{\rho_f g}\int_{z_2}^{z_1} \rho(z) g dz$$

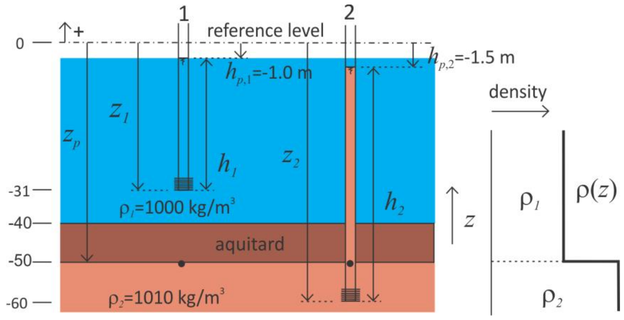
$$p_2^{at\ z=z_2} = \rho_2 g h_2 \qquad \phi_{f,2}^{at\ z=z_2} = z_2 + \frac{\rho_2}{\rho_f} h_2$$

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

Freshwater head ϕ_f : vertical flow?

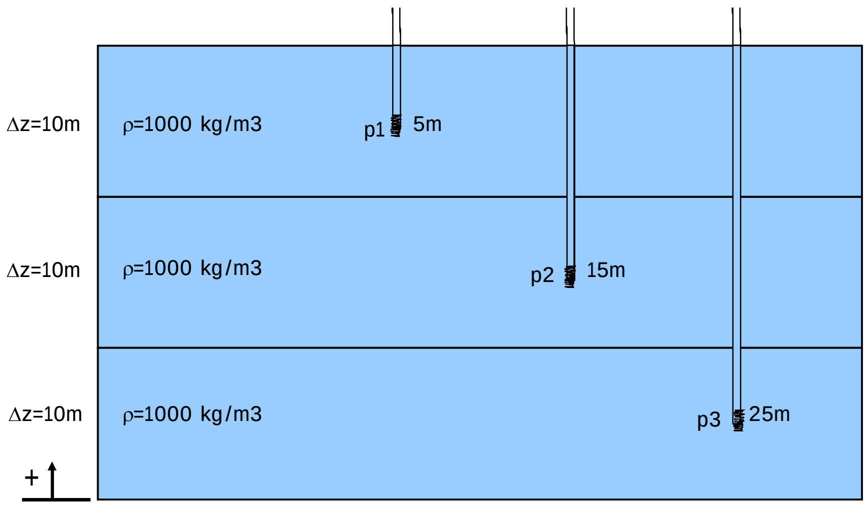


Freshwater head ϕ_f

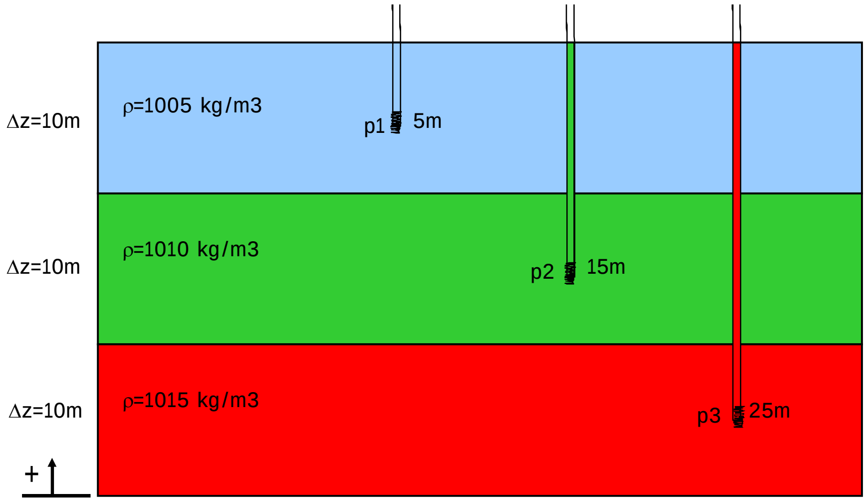


$$\phi_{f,1}^{z=-50} = -50 + \frac{1000}{1000}30 + \frac{1}{1000g}\int_{-50}^{-31} 1000 g dz = -50 + 30 + 19 = -1.0$$

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

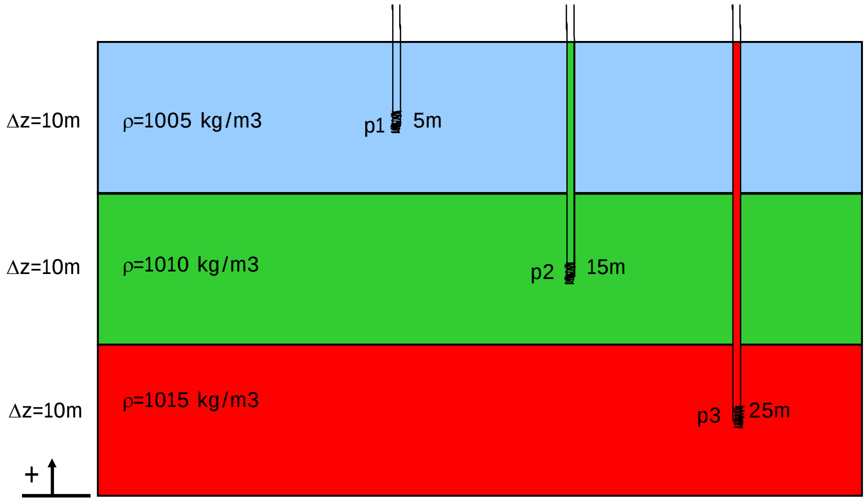


No flow



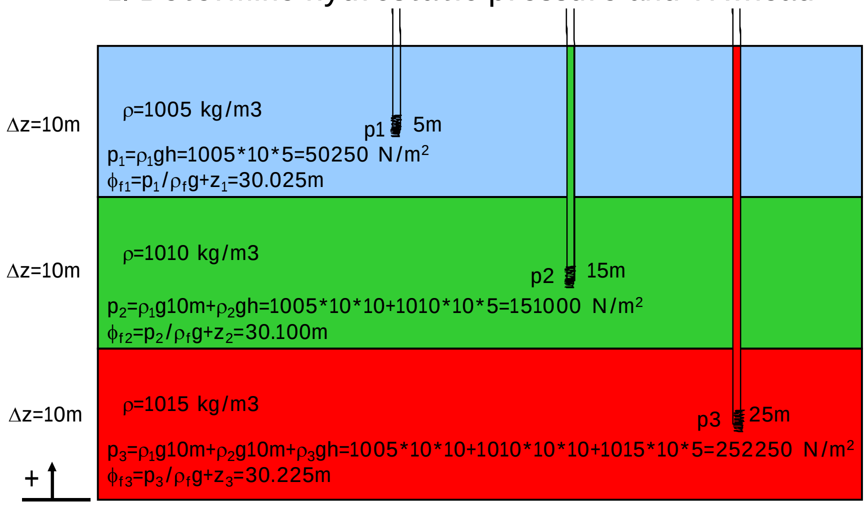
Flow or no flow? (if p≠hydrostatic than flow)

Calculate to freshwater head!



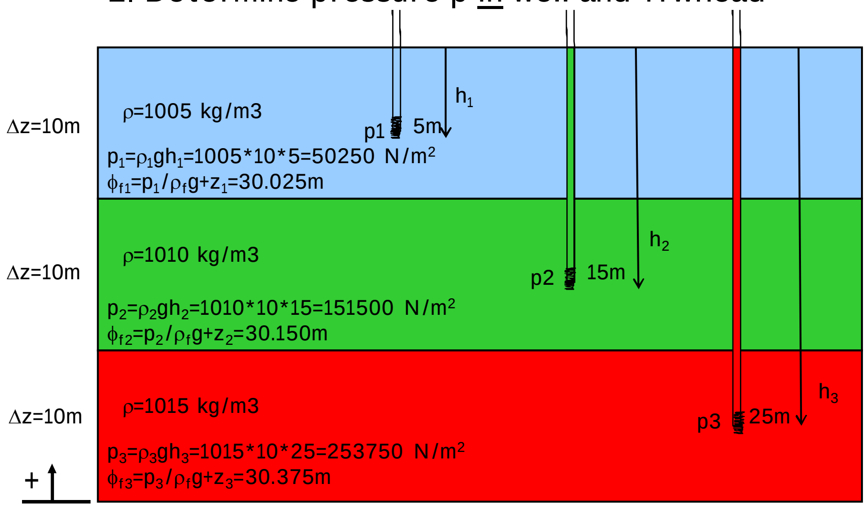
1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)

1. Determine hydrostatic pressure and frwhead



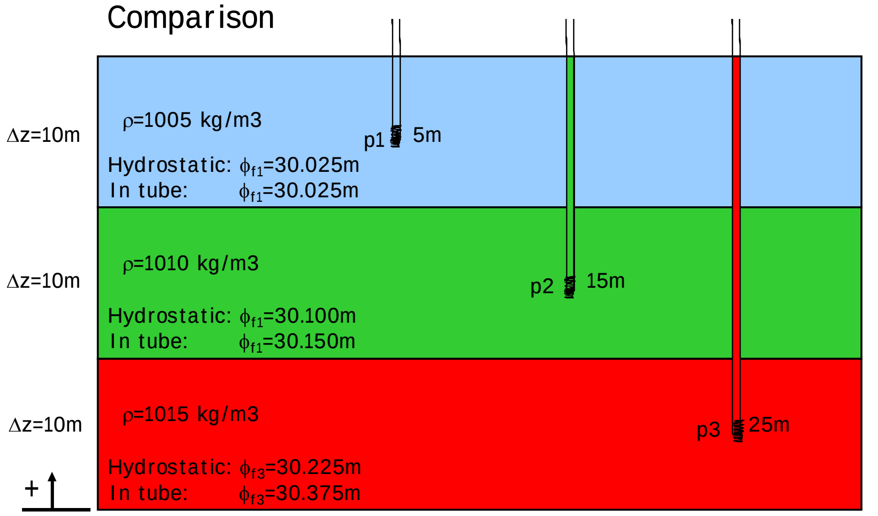
1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)

2. Determine pressure p <u>in</u> well and frwhead



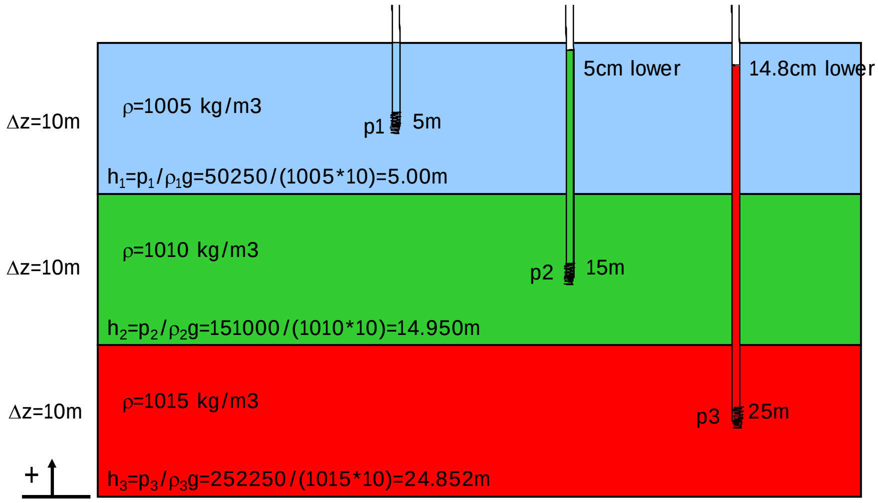
1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)

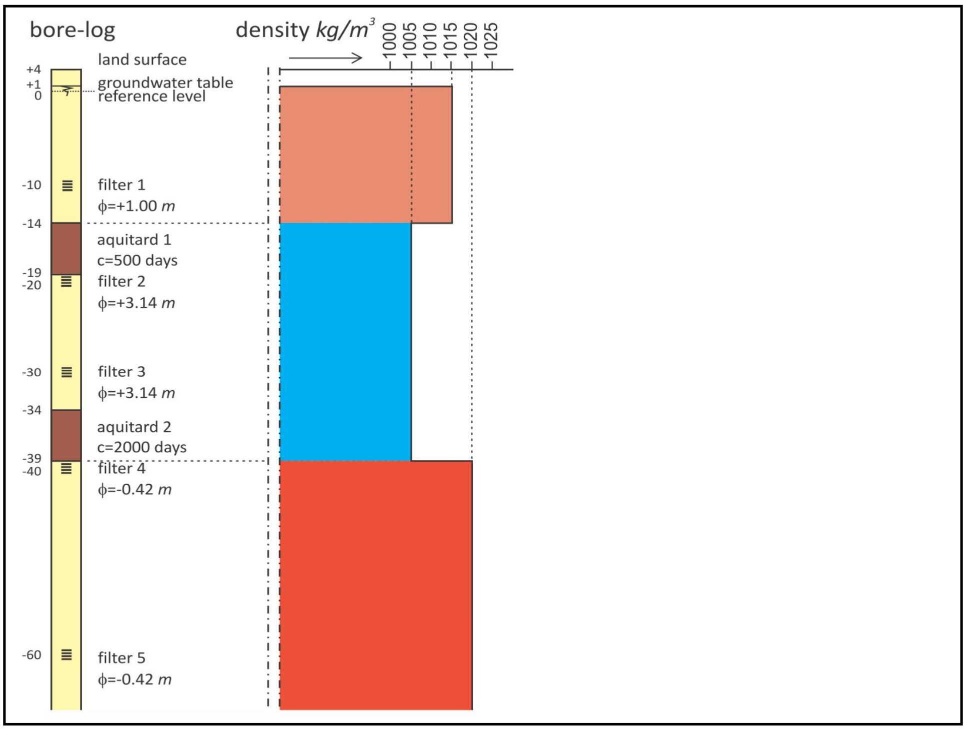
Comparison



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

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



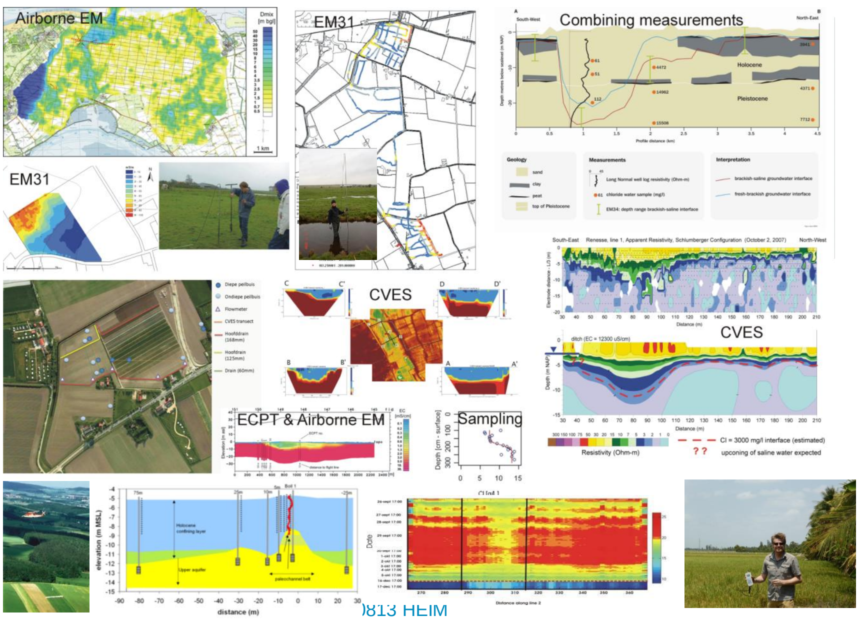


Take home message

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

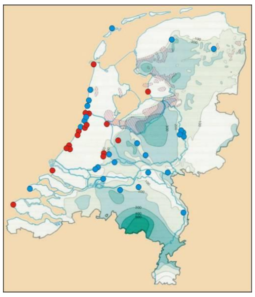
Monitoring

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



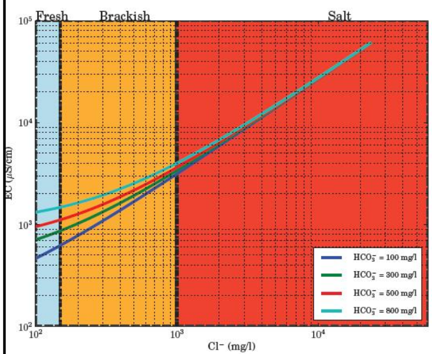
Pumping stations with salinisation

Pumping stations closed due to salinisation

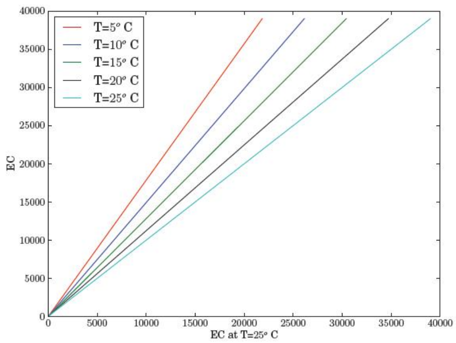
- Methods:
  1. Direct: water sample available
  2. Indirect: conductance of the subsoil

Source: V. Post, 2007

EC and Chloride



EC-Cl at different HCO_3^- concentrations.

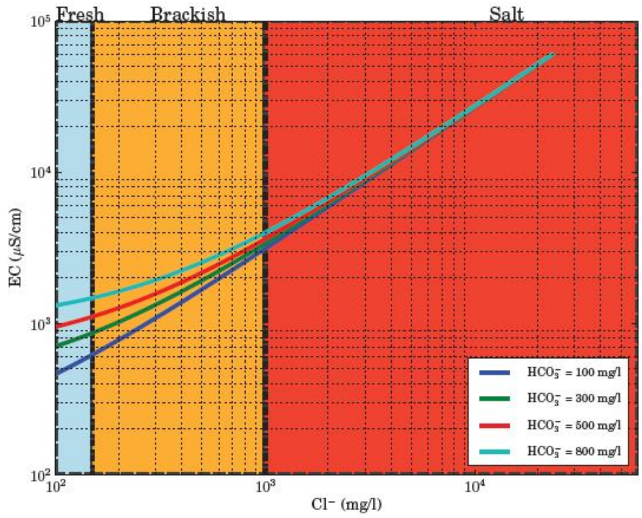


(b) EC and temperature standardized EC.

P. Pauw, 2009

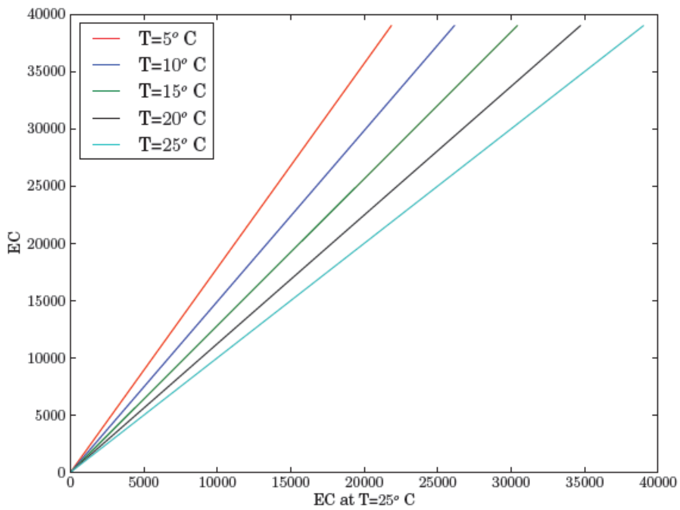
20120622 SWIM22

EC and Chloride



20120€ EC-Cl at different HCO_3^- concentrations.

EC and Chloride



2((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 disturbence

Source: Koos Groen

Surface measurements

Measuring system	Physical parameter	Geology/terrain information
Ground penetrating radar	EM traveltime, diaelectric 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 disturbence

Source: Koos Groen

Cone Penetration Tests

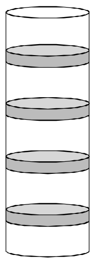
Measuring system	Physical parameter	Geology/terrain information
mechanical CPT	Cone resistance Friction resistance	Lithology Geotechnical parameters
Electrical conductivity	Electrical formation conductivity	Water salinity
Contnuous water pressure	Water pressure	Lithology Piezometric head
Water pressure 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	•High accuracy •Detection trends	•Costly •Point measurement
2. Well screens in observation well	•High accuracy •Detection trends •High vertical resolution	•Costly
3. Sediment sample (extraction milliliters of water)	•High accuracy •High vertical resolution	•Very costly and time consuming

Direct methods 1 and 2



Source: V. Post, 2007

Monitoring salt in groundwater: Indirect methods

Indirect methods measure the **conductance** of:

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

AND

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

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

Source: V. Post, 2007

Monitoring salt in groundwater: Indirect methods

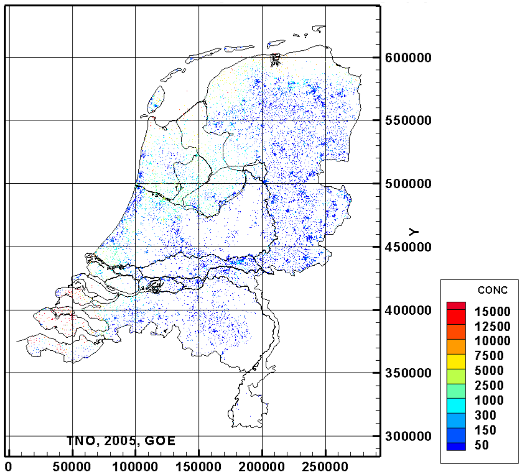
Method	**Advantages**	**Disadvantages**
1. Electrical conductance measurements	•High resolution (3D) •Depth ~200 m	•Time consuming
2. Electromagnetic measurements	•Fast	•Limited vertical resolution •Sensitive for underground conductors (pipes)
3. Satellites	•Suitable for large areas	•Small vertical resolution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

Source: V. Post, 2007

Method used at Deltares

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

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



Source: Oude Essink et al (2005)

Electrical conductance measurements

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

Source: TNO

Source: V. Post, 2007

Electrical conductance measurements

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

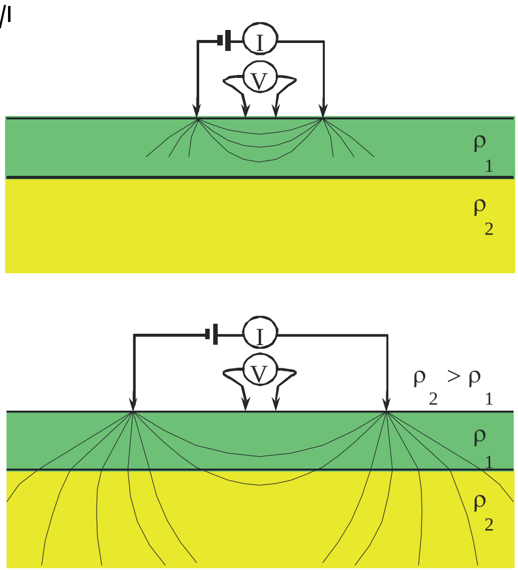
Source: V. Post, 2007

Source: Vitens

Principle geo-elektrical measurement

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

Ra = constant * V/I



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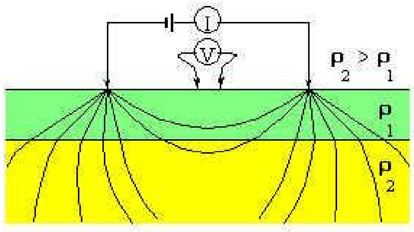
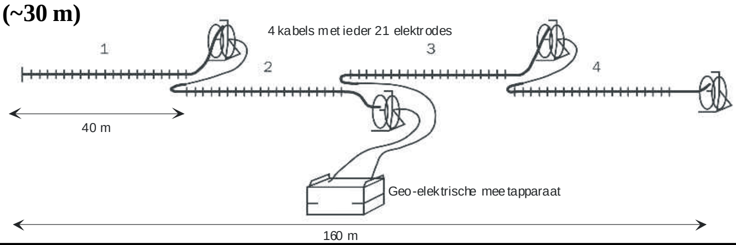
Types geo-electrical measurements

- 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)**

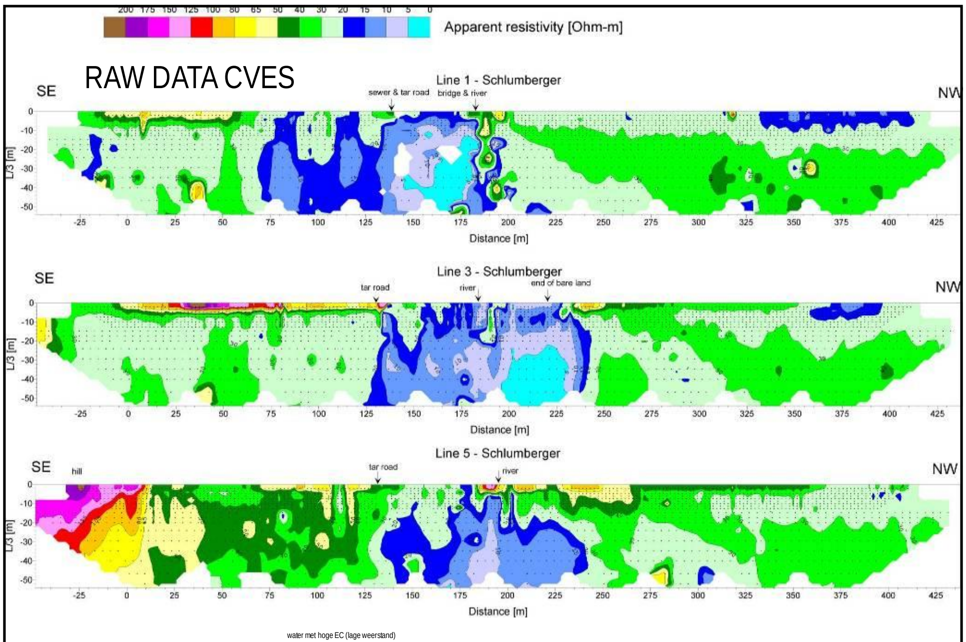


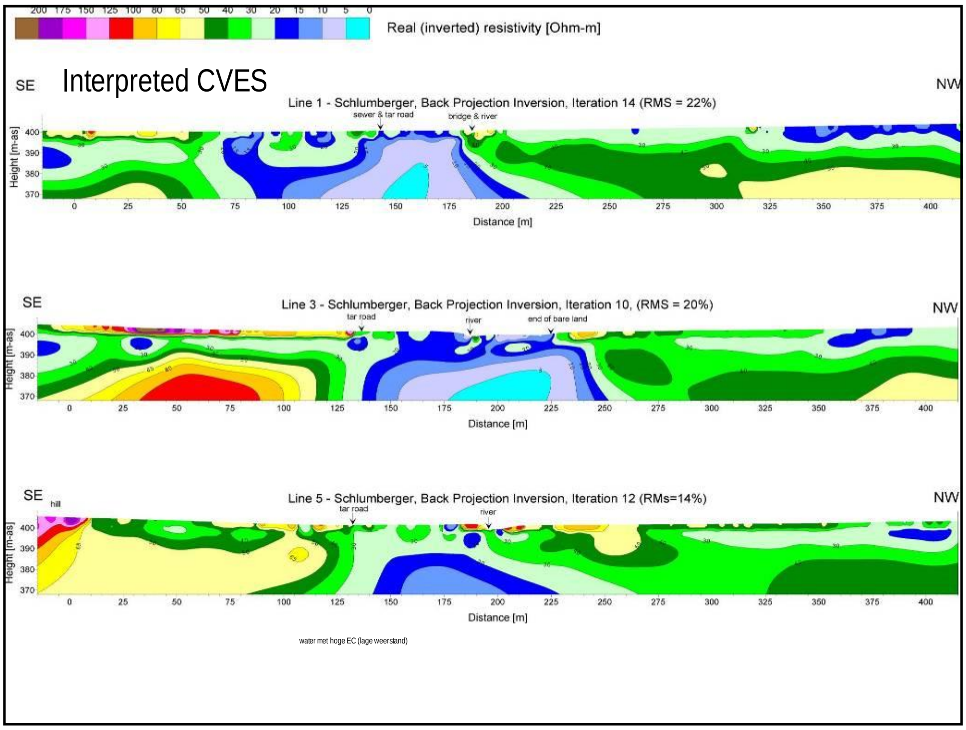
20120622 SW

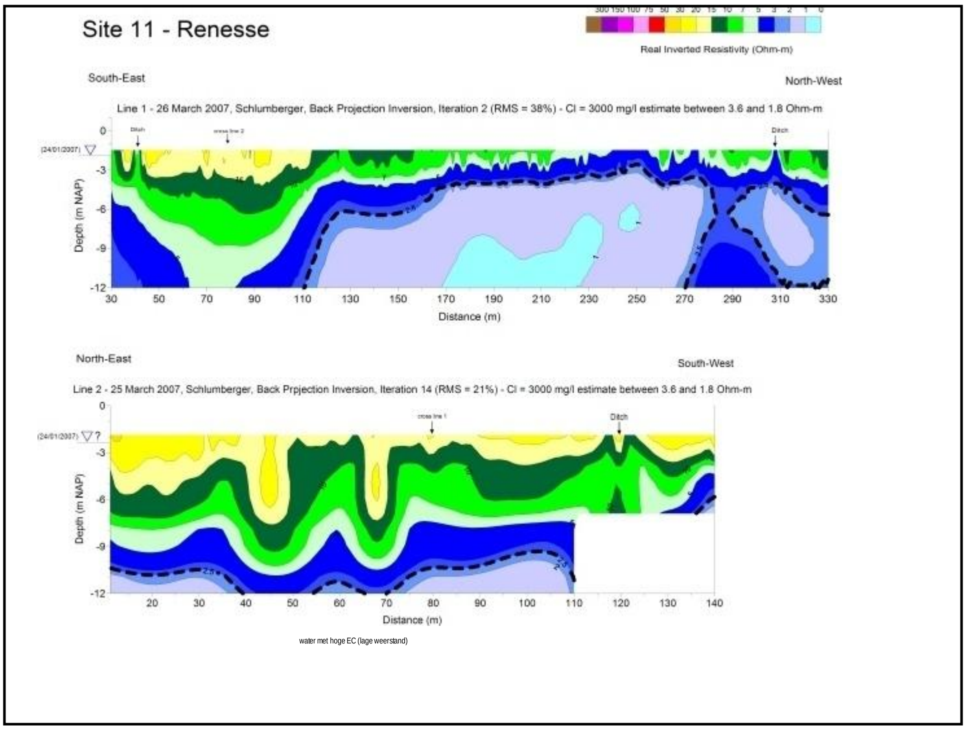
VES measurement end 1950s/begin 1960s

CVES
measurements 2010s

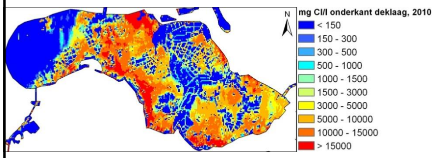
RAW DATA CVES

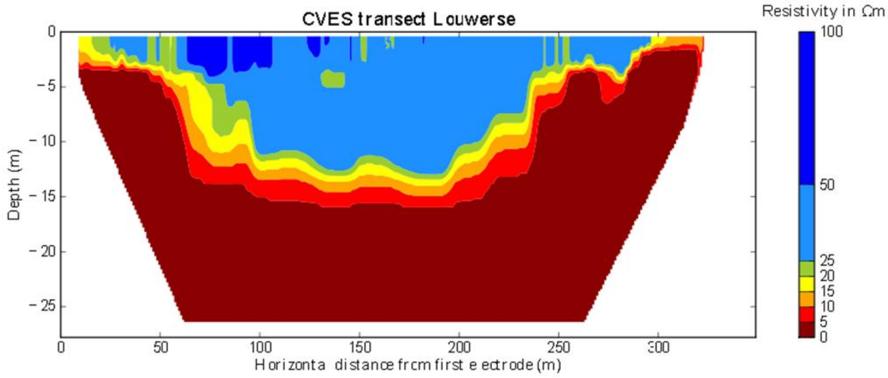



Real (inverted) resistivity [Ohm-m]
200 175 150 125 100 80 65 50 40 30 20 15 10 5 0
Interpreted CVES
SE
NW
Line 1 - Schlumberger, Back Projection Inversion, Iteration 14 (RMS = 22%)
sewer & tar road
bridge & river
Height [m-as]
Distance [m]
Line 3 - Schlumberger, Back Projection Inversion, Iteration 10, (RMS = 20%)
tar road
river
end of bare land
Line 5 - Schlumberger, Back Projection Inversion, Iteration 12 (RMs=14%)
hill
water met hoge EC (lage weerstand)


Site 11 - Renesse
Real Inverted Resistivity (Ohm-m)
South-East
North-West
Line 1 - 26 March 2007, Schlumberger, Back Projection Inversion, Iteration 2 (RMS = 38%) - Cl = 3000 mg/l estimate between 3.6 and 1.8 Ohm-m
Ditch
Depth (m NAP)
Distance (m)
North-East
South-West
Line 2 - 25 March 2007, Schlumberger, Back Prjection Inversion, Iteration 14 (RMS = 21%) - Cl = 3000 mg/l estimate between 3.6 and 1.8 Ohm-m
Ditch
water met hoge EC (lage weerstand)

Possible measures for sandy creeks





Monitoring salt in groundwater: Indirect methods

- Electrical conductance measurements

$\rho_s = F^* \rho_w$

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

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

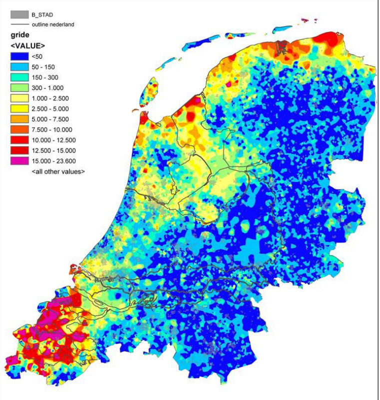
→ *F varies with the resistance of the groundwater*

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

VES measurements are used in combination with borehole logging

Source: Oude Essink, 2005

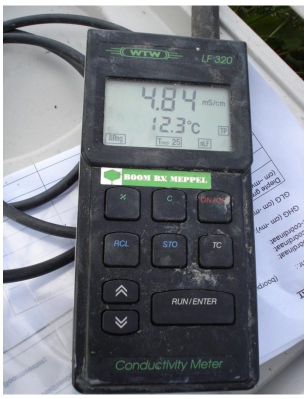
Result: chloride concentration bottom Holocene toplayer



Source: Oude Essink, 2005

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

T-EC probe



CLIWAT CLIMATE & WATER

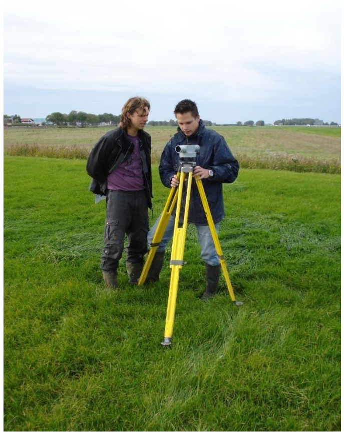
The Interreg IVB North Sea Region Programme

WETTERSKIP FRYSLÂN

provinsje fryslân provincie fryslân

T EC fieldwork

Altitude measurements



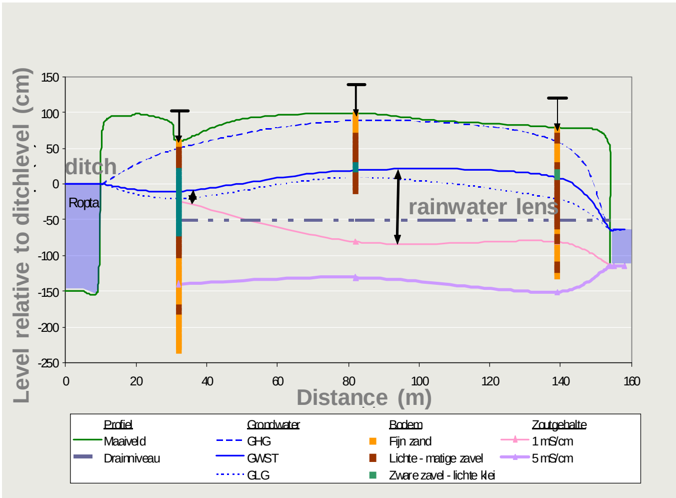
CLIWAT CLIMATE & WATER

The Interreg IVB North Sea Region Programme

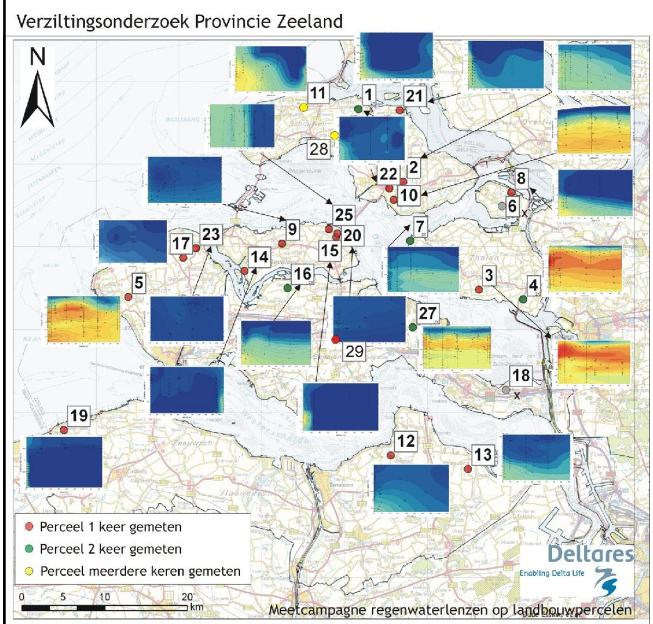
WETTERSKIP FRYSLÂN

provinsje fryslân
provincie fryslân

Use field measurements to understand the process



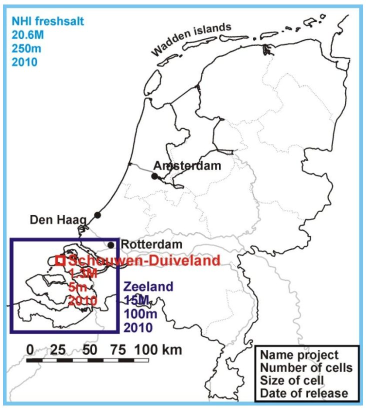
TEC-probe Monitoring campaign 2005-2009

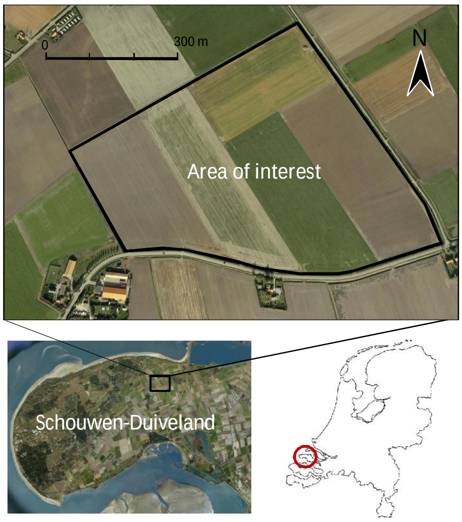


CliWat www.cliwat.eu

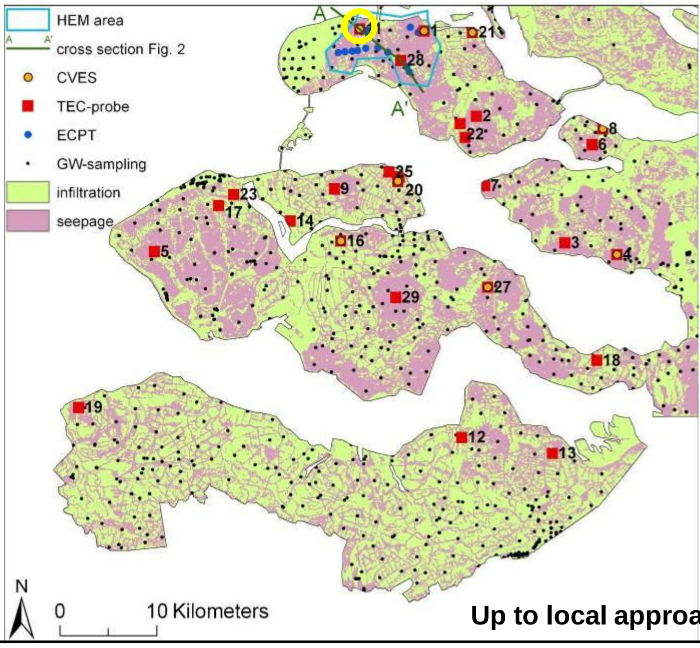
- Transnational project in the North Sea Region
- Main objectives:
  - to evaluate the physical and chemical impacts of climate change on groundwater and surface water systems
  - to provide data for adaptive and sustainable water management and infrastructure.
- Different innovative monitoring techniques (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



Up to local approach

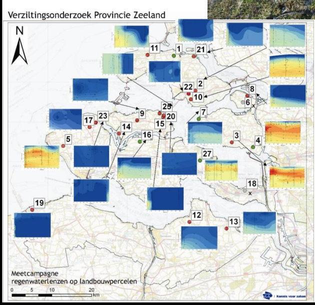
Example: Assessing effect of climate change on salt water intrusion

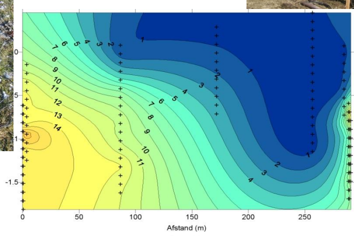
Source: Oude Essink, 2009

Monitoring:

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

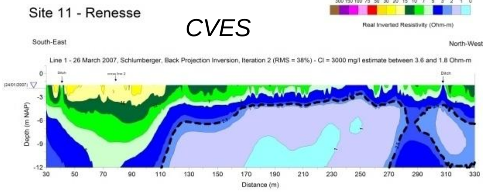
TEC probe



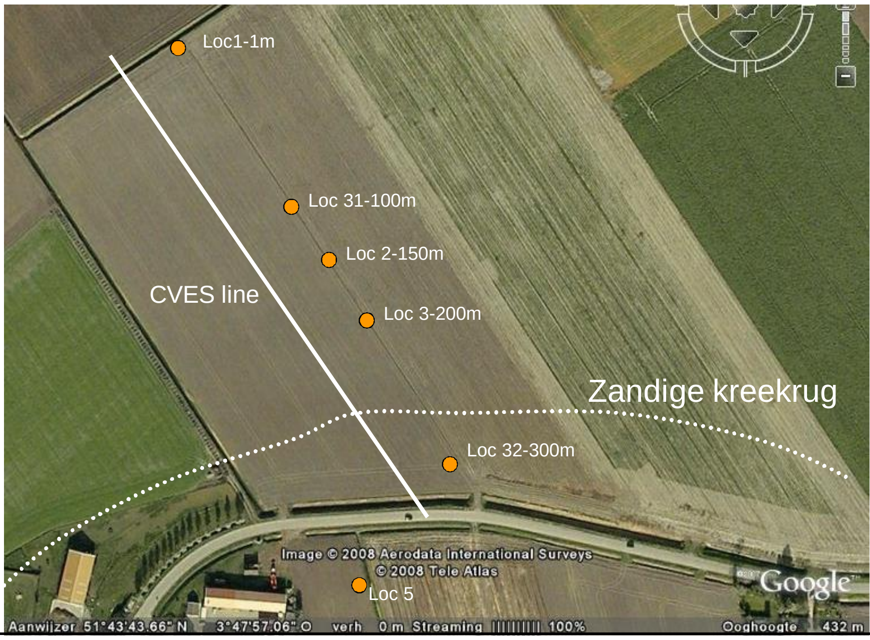


Site 11 - Renesse

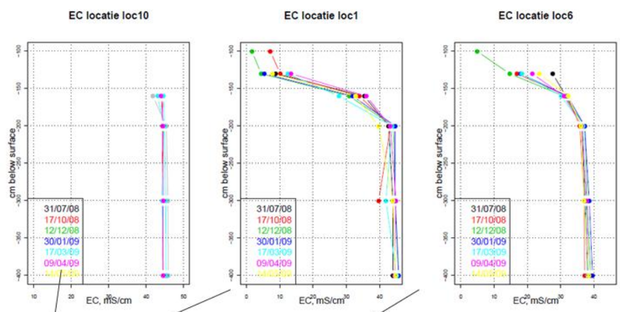
CVES

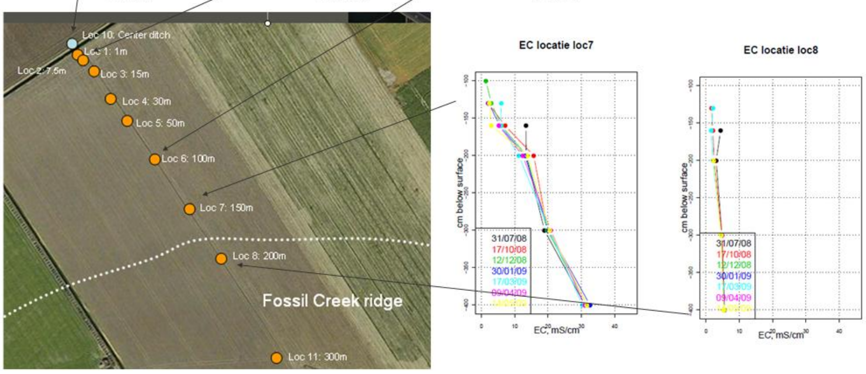


Site 11: from infiltration to seepage



Groundwater sampling: Salt distribution in time

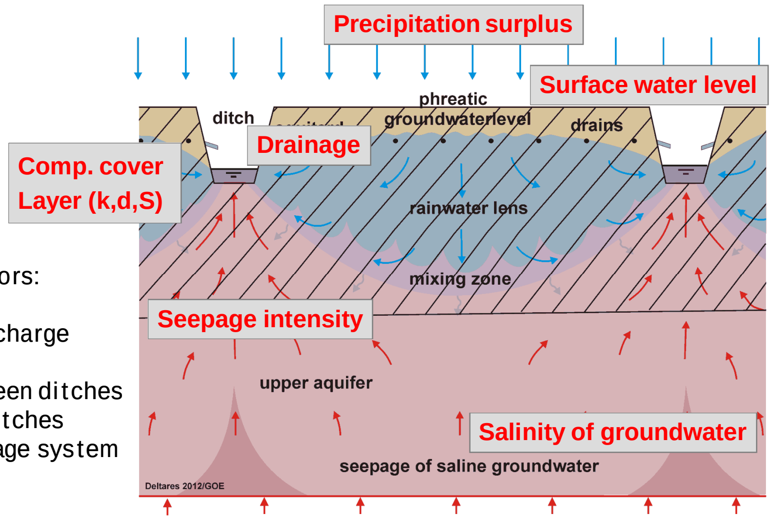




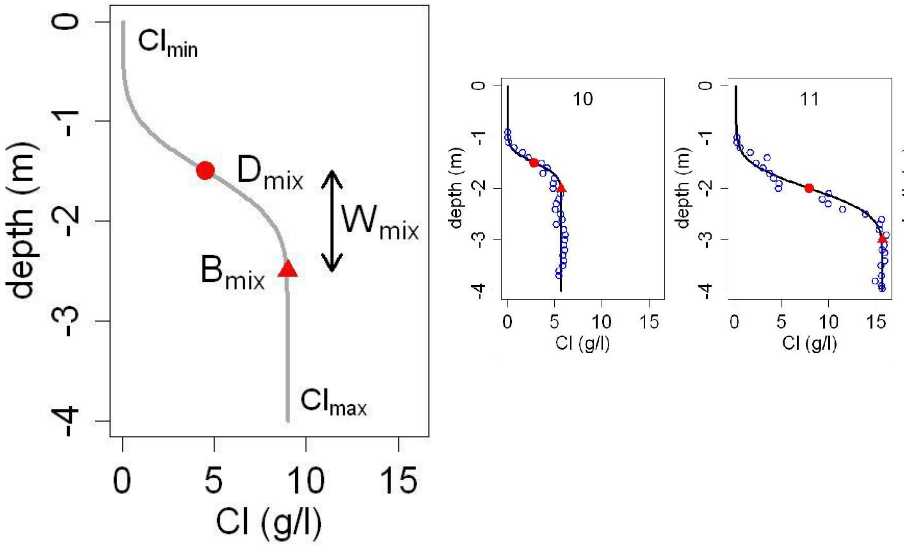
Factors controlling fresh-salt interface

Important factors:

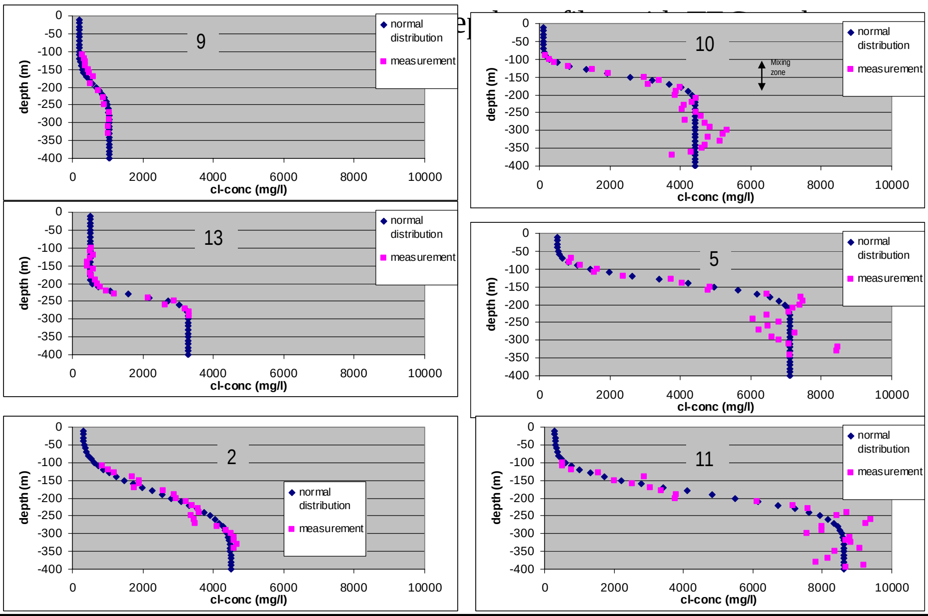
-natural grw recharge
-geology
-distance between ditches
-water levele ditches
-capacity drainage system

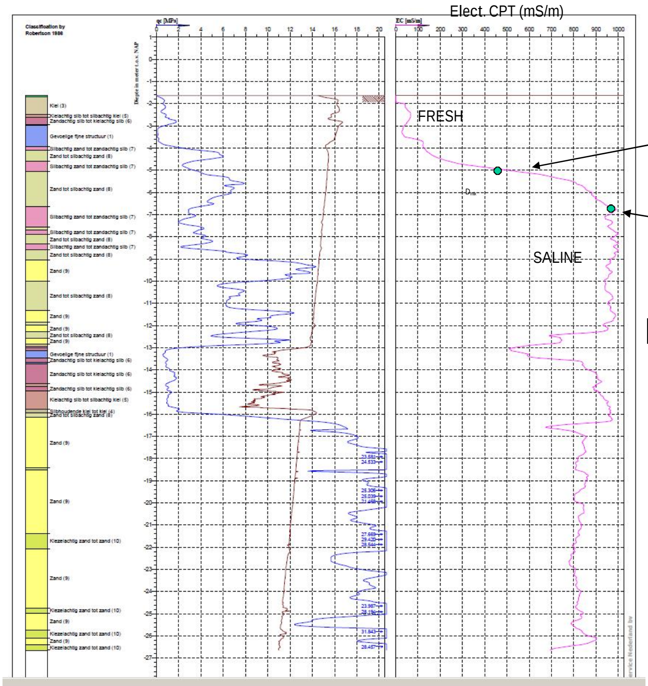


Lens characteristics



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.



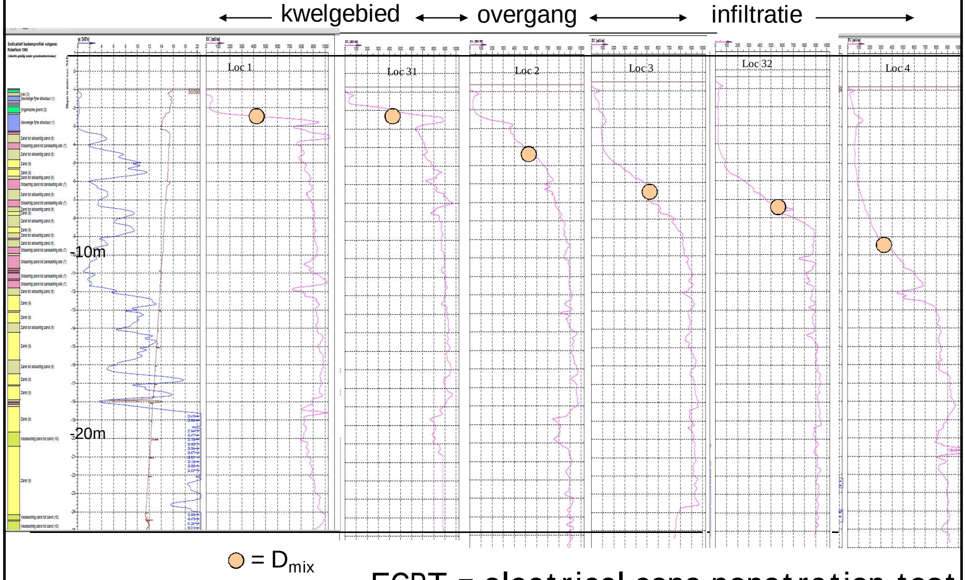


a) Depth of transition, D_{mix}, zone between 2 types of groundwater (fresh-saline)

b) Start of transition, S_{mix},

Electrical CPT

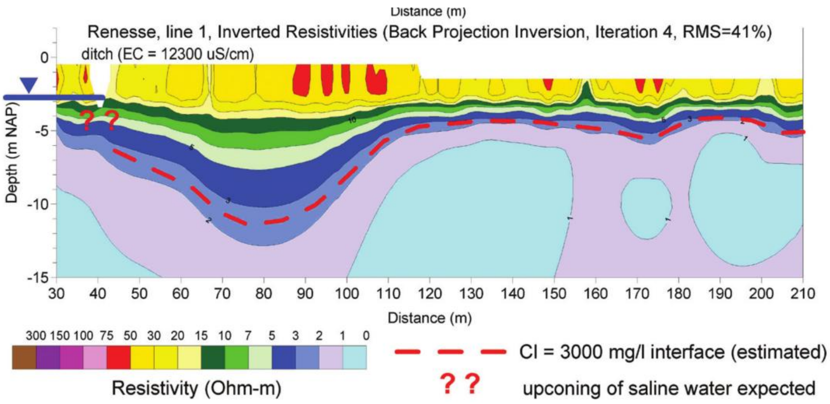
Results from ECPT's (soundings)



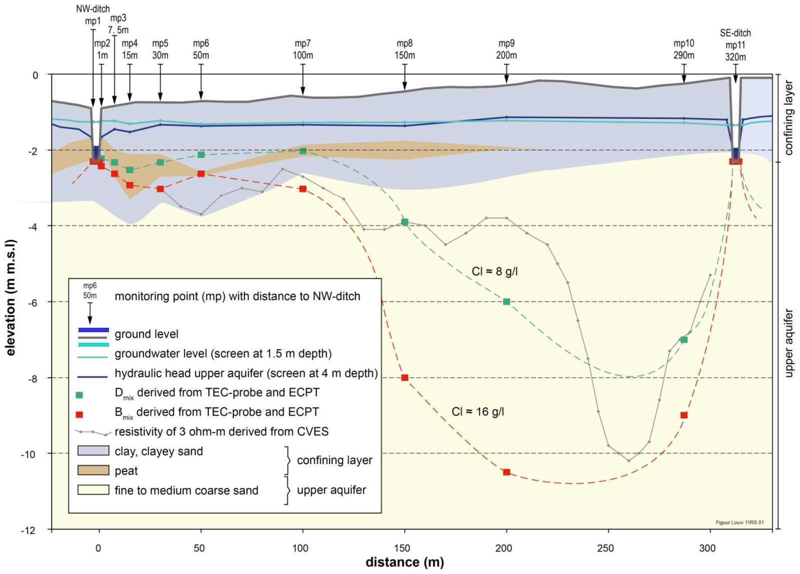
ECPT = electrical cone penetration test

CVES

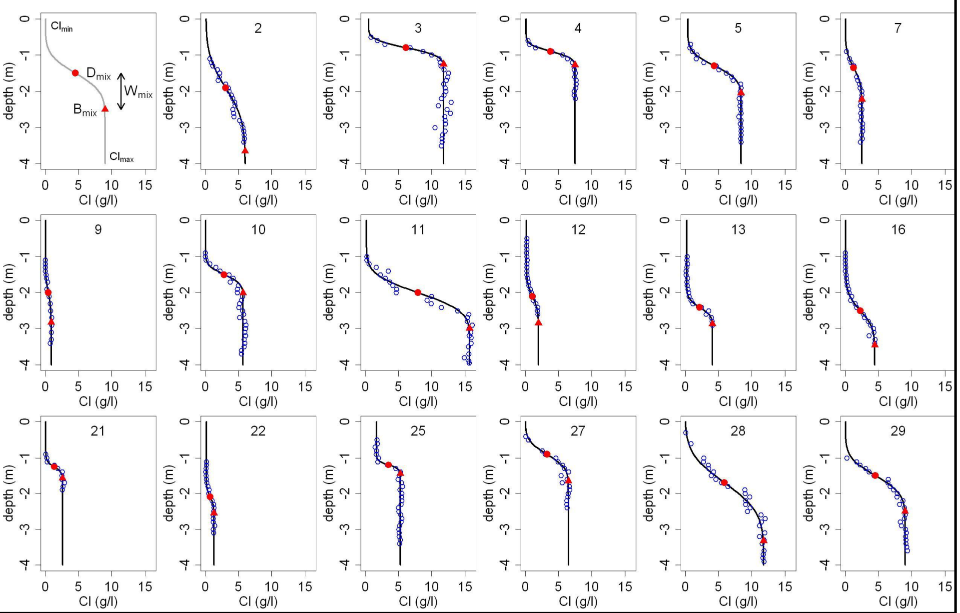
CVES: continuous vertical eletrical sounding



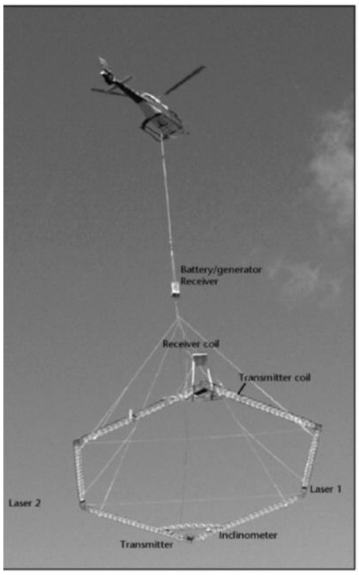
Seepage / infiltration determines thickness rainwaterlens



TEC-probe results

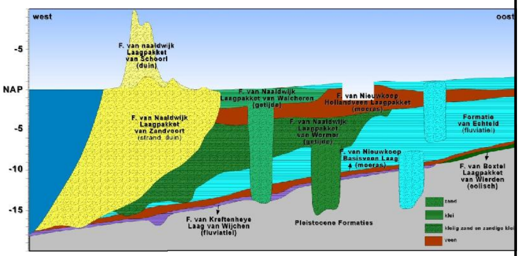


Electrical conductance measurements



10 juni 2013

From bulk to groundwater resistivity

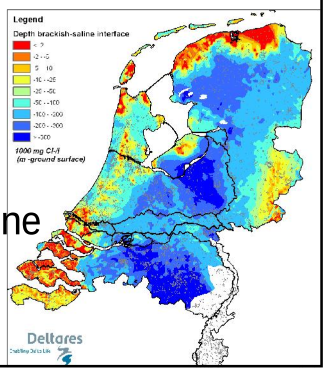


EC^{bulk}

EC lithology

EC groundwater

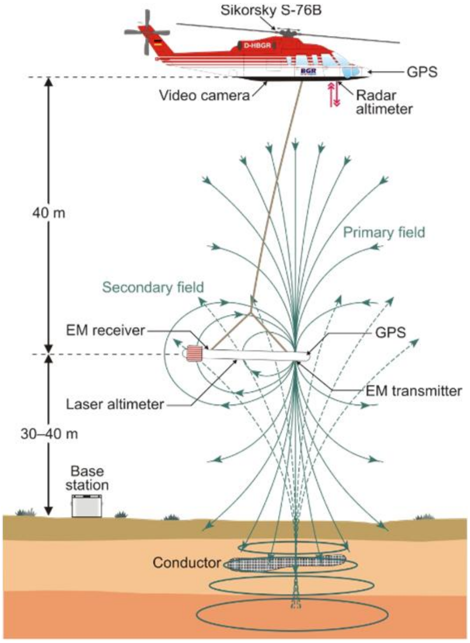
→ fresh-brackish-saline



EC = Electrical Conductivity = conductivity

BGR helicopter-borne geophysical system

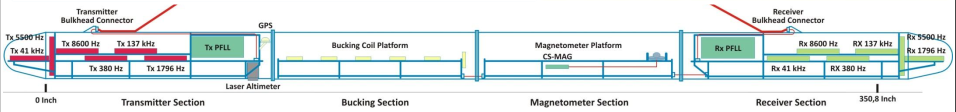
Airborne geophysical survey system	
Helicopter:	Sikorsky S-76B
Helicopter equipment:	GPS-Navigation GPS-Tracking Radar and barometric altimeters Video camera
Standard equipment:	Electromagnetic system Magnetometer Laser altimeter Gamma-ray spectrometer
Optional equipment:	Laser scanner Pulse radar *Stepped frequency* - 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

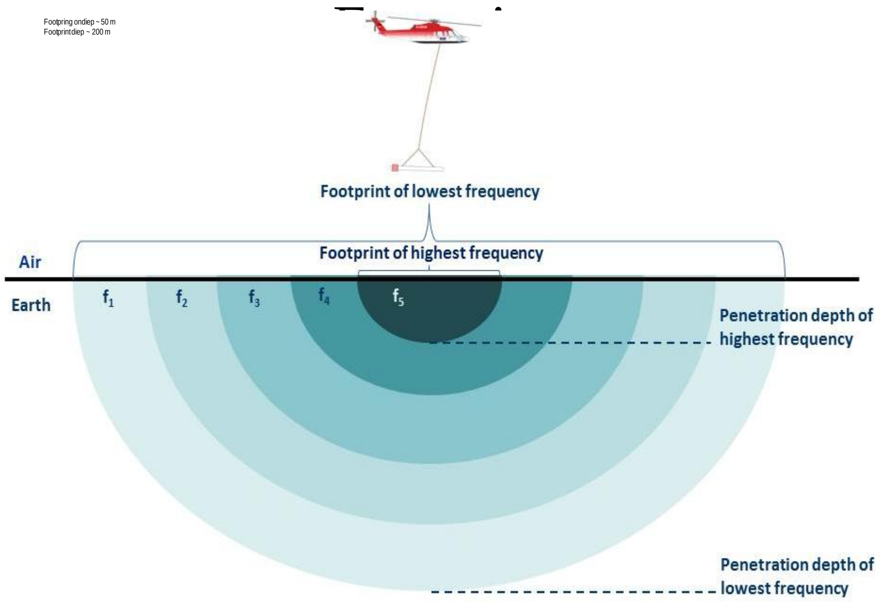


Meeting in Utrecht Feb. 25th 2014

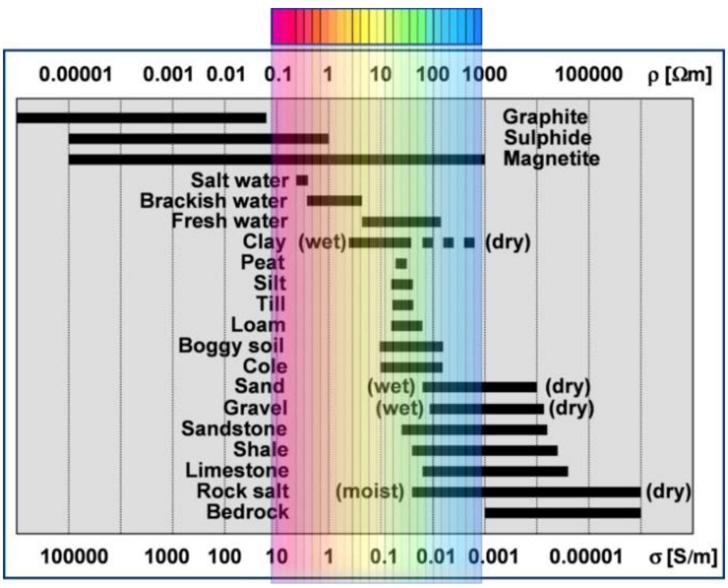
BGR helicopter-borne geophysical system

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

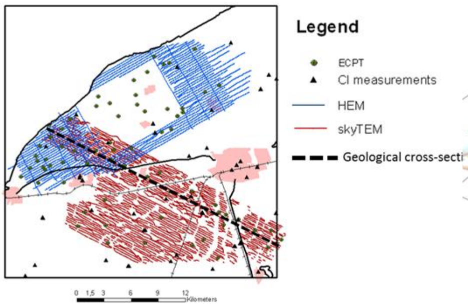


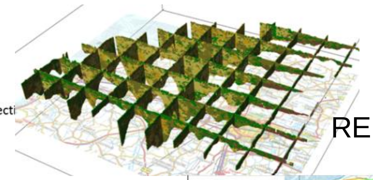


Typical resistivities / conductivities

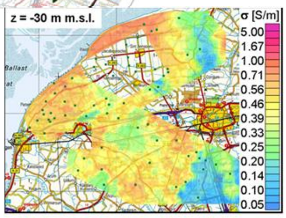


Case Wetterskip Fryslân

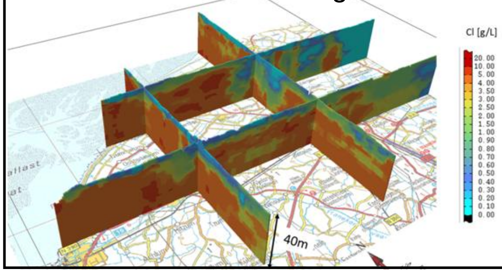


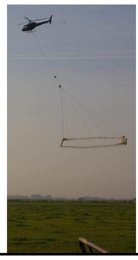


REGIS

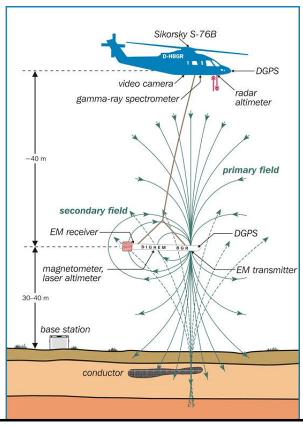


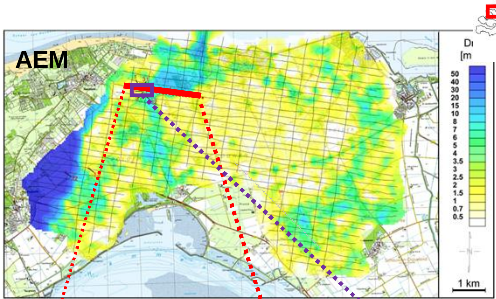
3D zoet-zout verdeling

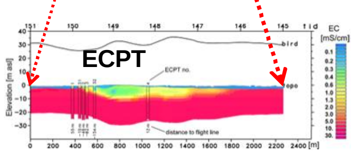


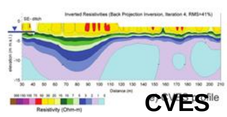


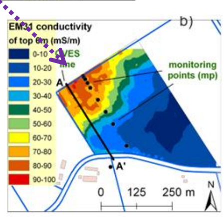
Case Schouwen-Duiveland





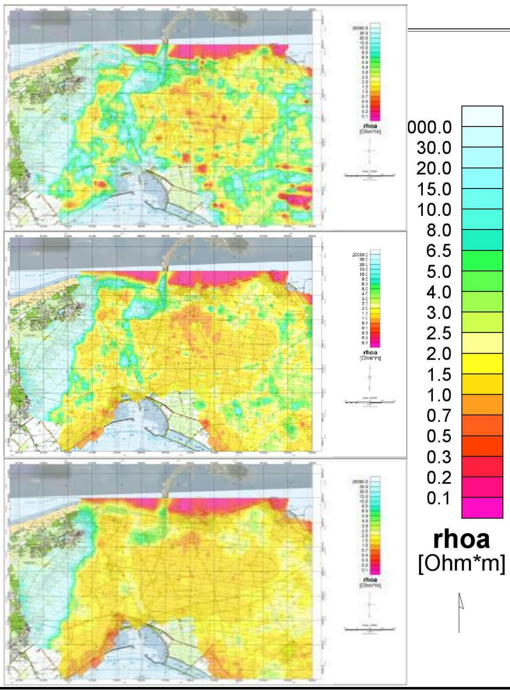


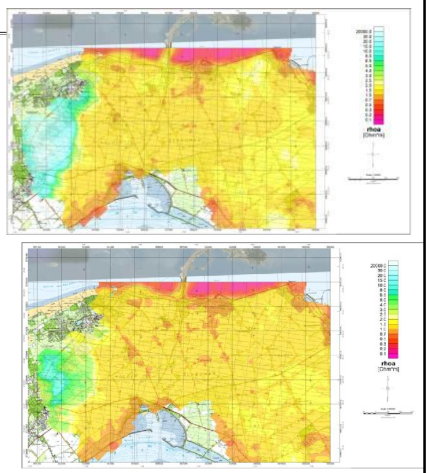




EM31

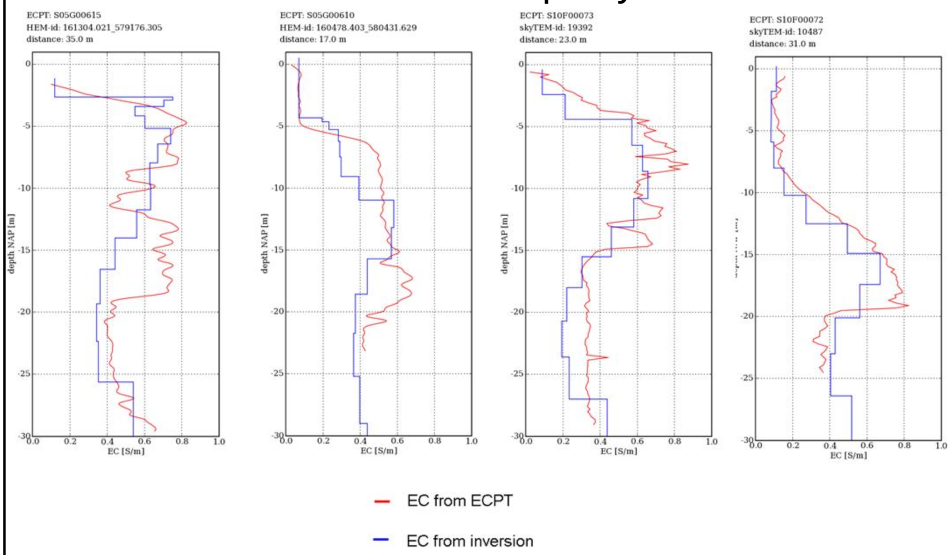
conventional monitoring techniques





HEM results with depth

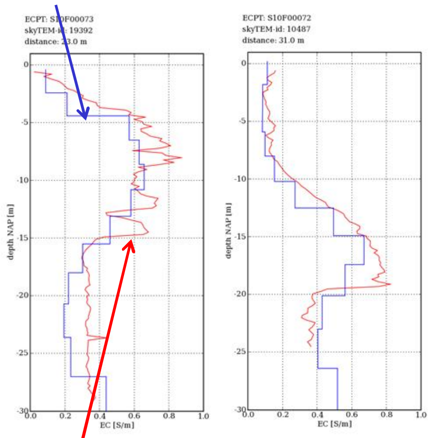
Compare Airborne EM with ECPT
Case Wetterskip Fryslân



3D characterising fresh-saline groundwater

How much samples in 1 week on 900km²?

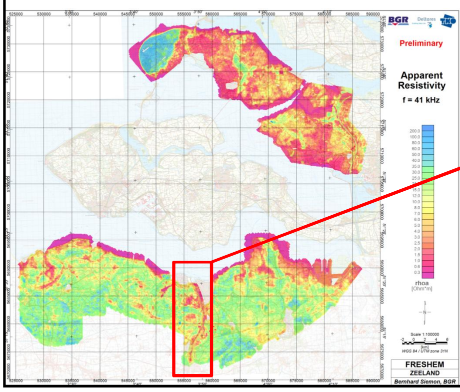
AEM: 80000 data points

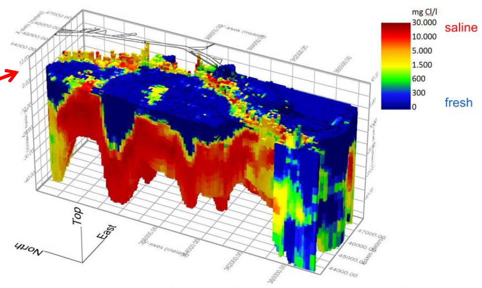


In-situ: >100 data points

3D Characterisation of the subsoil

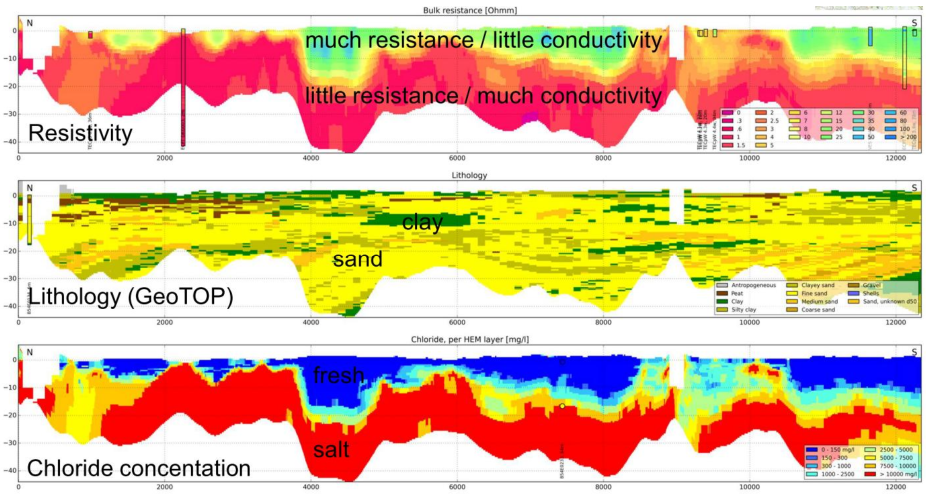
Airborne EM surveys:
much cheaper, faster, 3D,
and as equal accurate as
conventional geophysical methods





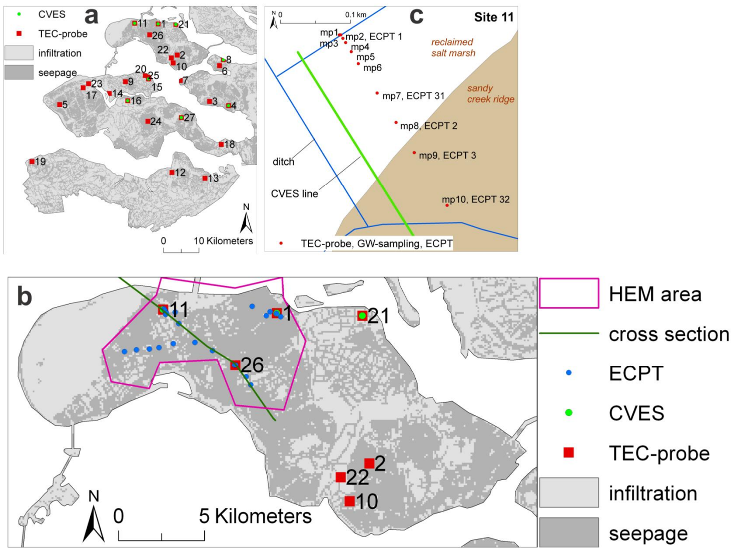
FRESHEM pilot Canal zone, visualization in iMOD

Example NL, Zeeland, project FRESHEM



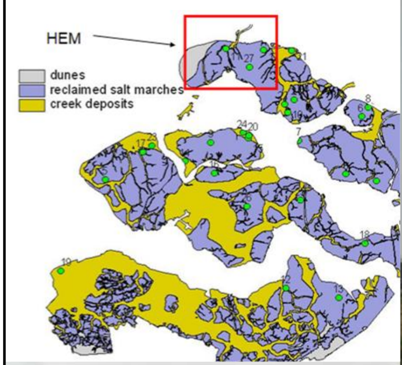
20160524 Ara Sul

Combining monitoring techniques



10 juni 2013

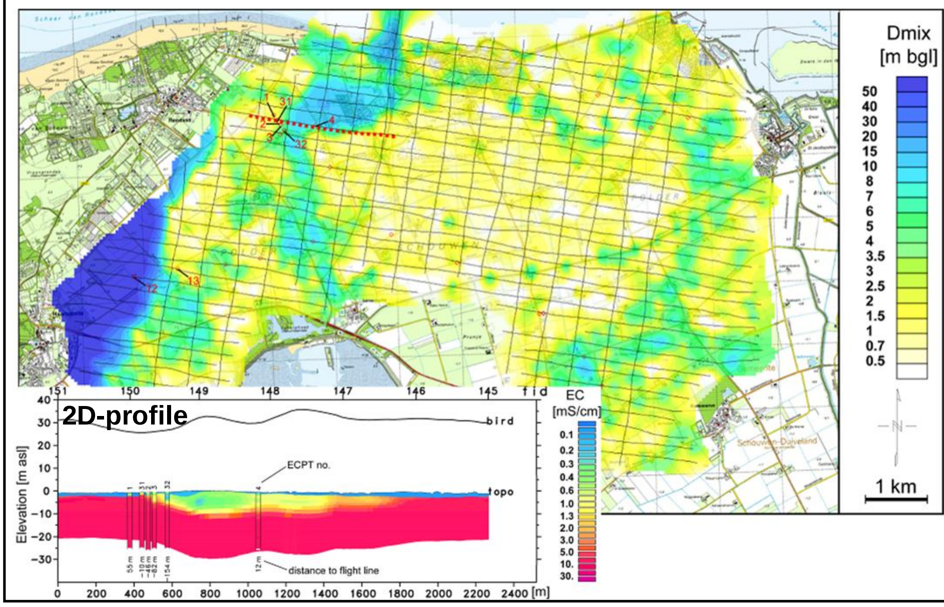
Helicopter-EM data for mapping fresh-saline groundwater



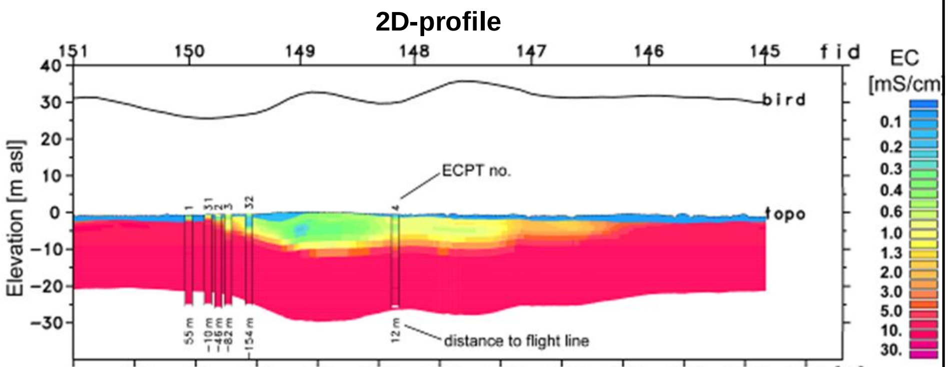
Interreg IV-B

CLIWAT
CLIMATE & WATER

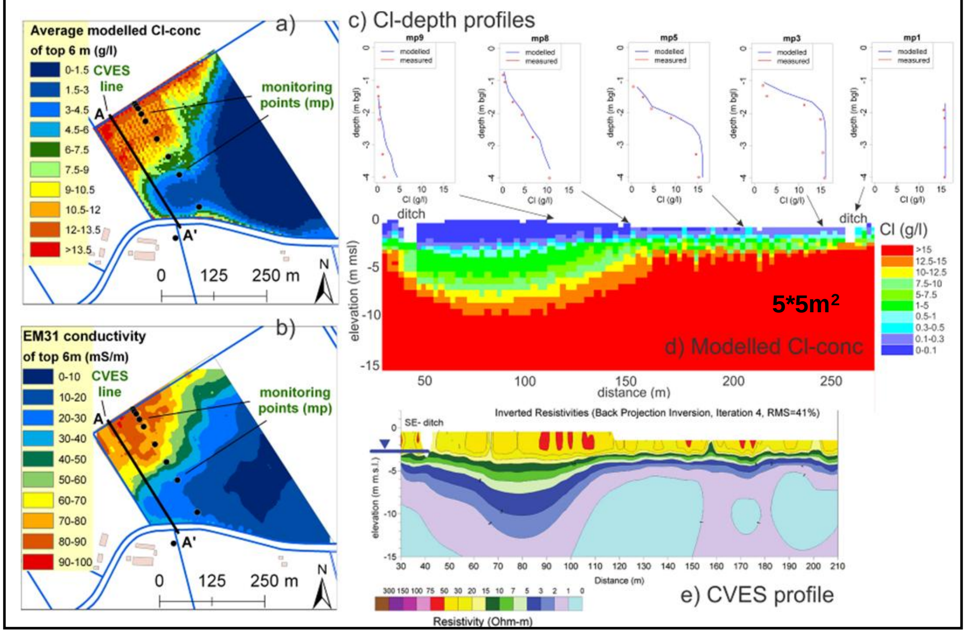
Thickness rainwater lens (D_{mix}) by HEM



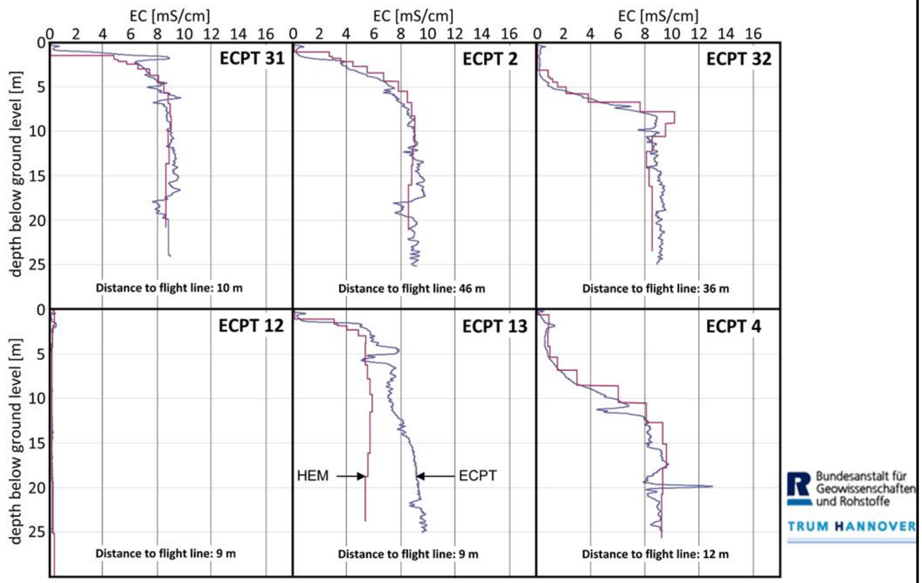
Thickness rainwater lens (D_{mix}) by HEM



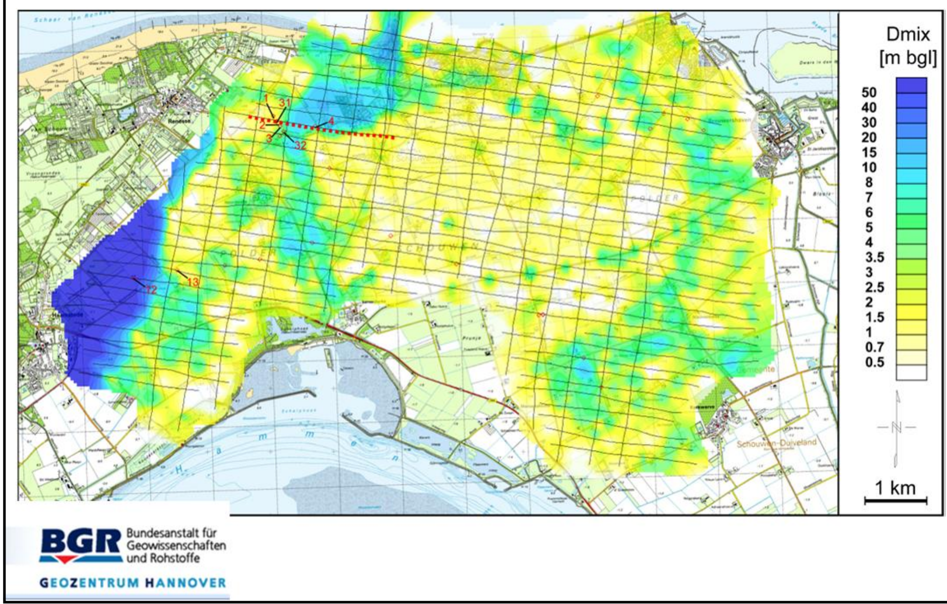
Comparison monitoring data with model results



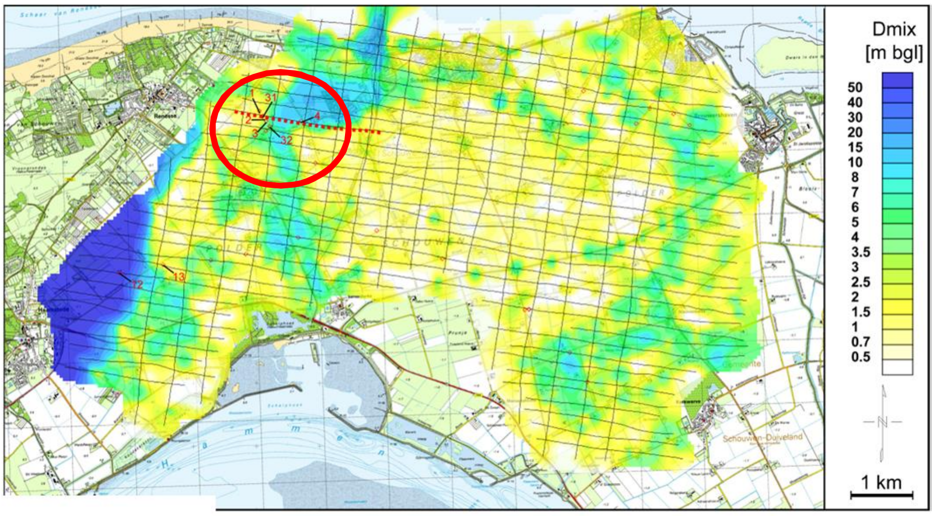
Comparison HEM – ECPT



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



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

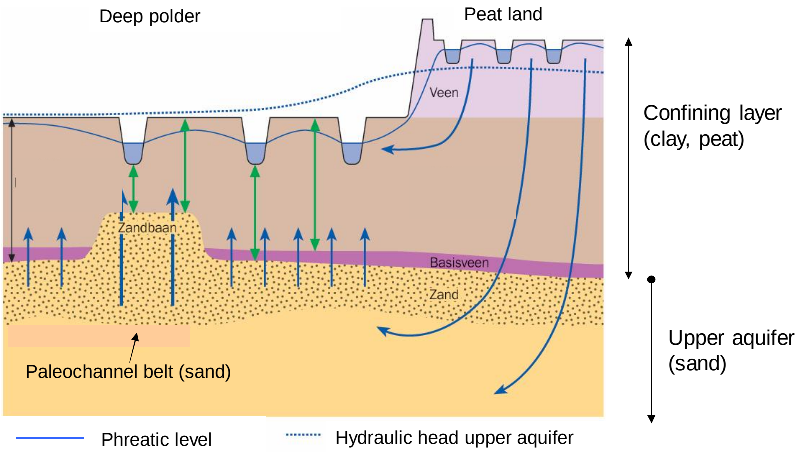


BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER

Salty boils

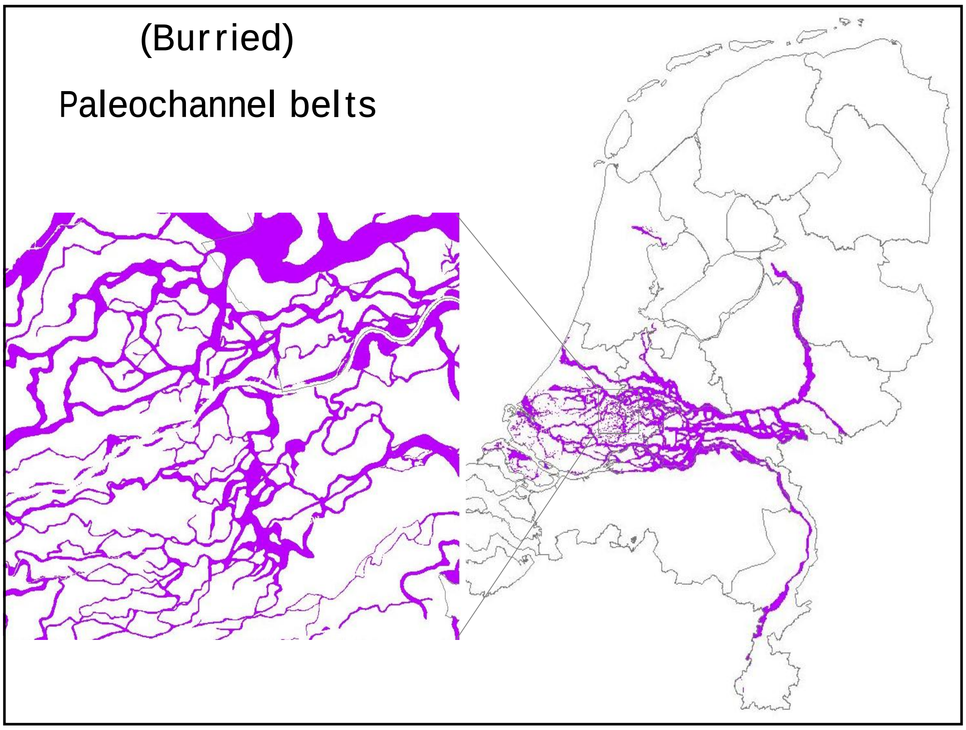
Louw, P.G.B., de, Oude Essink, G.H.P., Stuyfzand, P.J., Zee, van der, S.E.A.T.M., 2010, Upward groundwater flow in boils as the dominant mechanism of salinization in deep polders, The Netherlands, J. Hydrol. 394, 494-506.

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

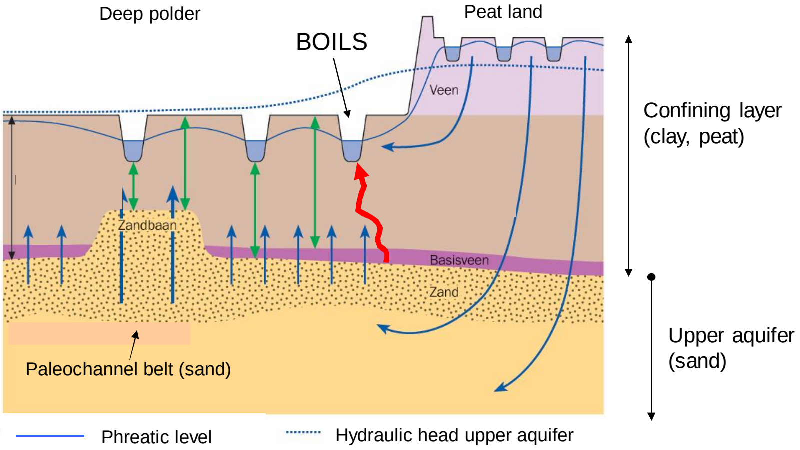


(Burried)

Paleochannel belts

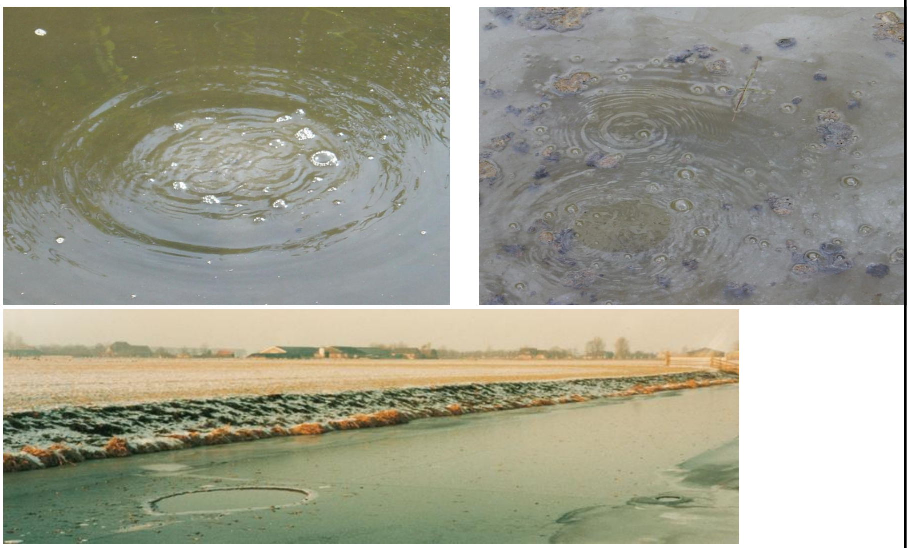


Preferential seepage via boils

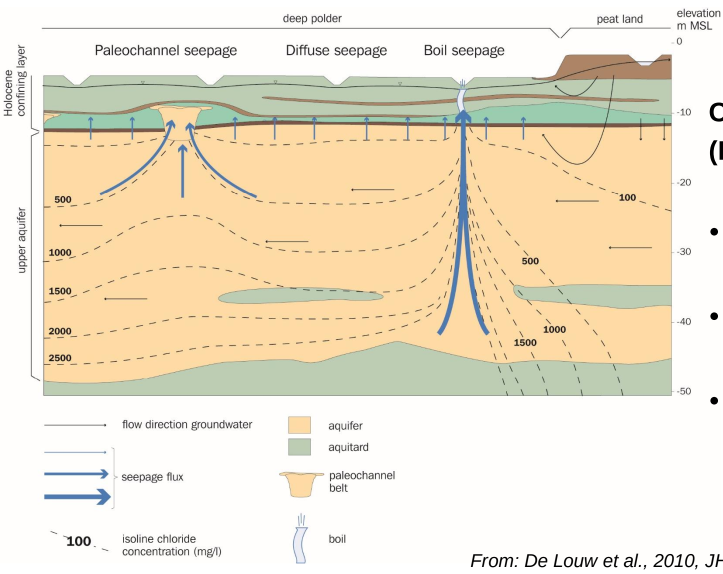


Preferential saline seepage via boils

Preferential saline seepage via boils



Three types of upward groundwater seepage

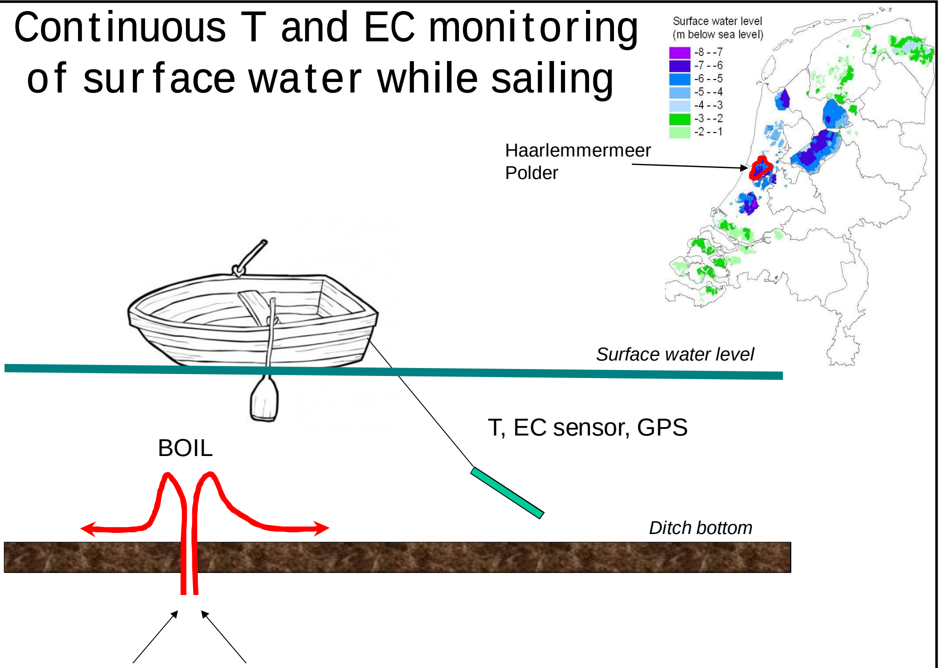


Cl-conc seepage:
(Polder Noordplas)

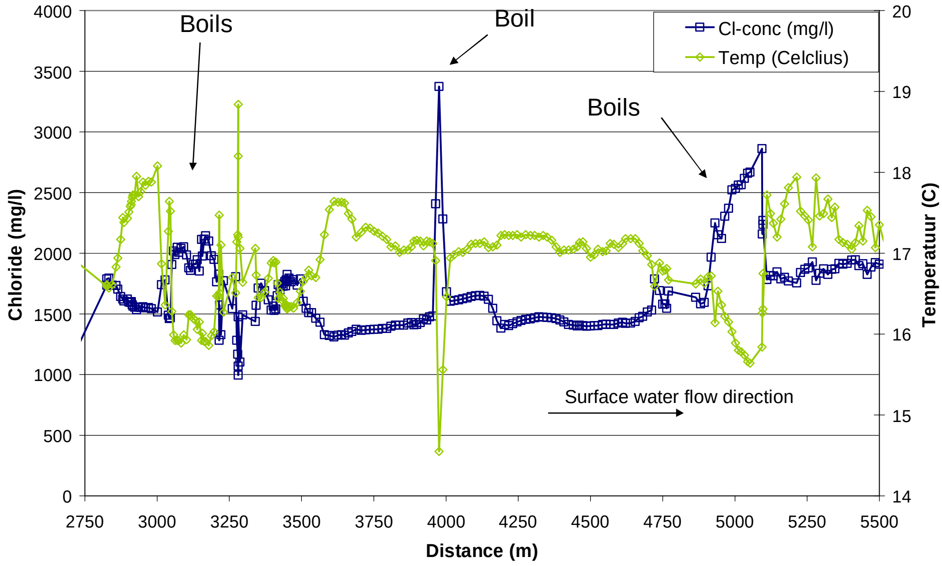
- Diffuse : 100 mg/l
- Paleochannel : 600 mg/l
- Boils : 1100 mg/l

From: De Louw et al., 2010, JHydr.

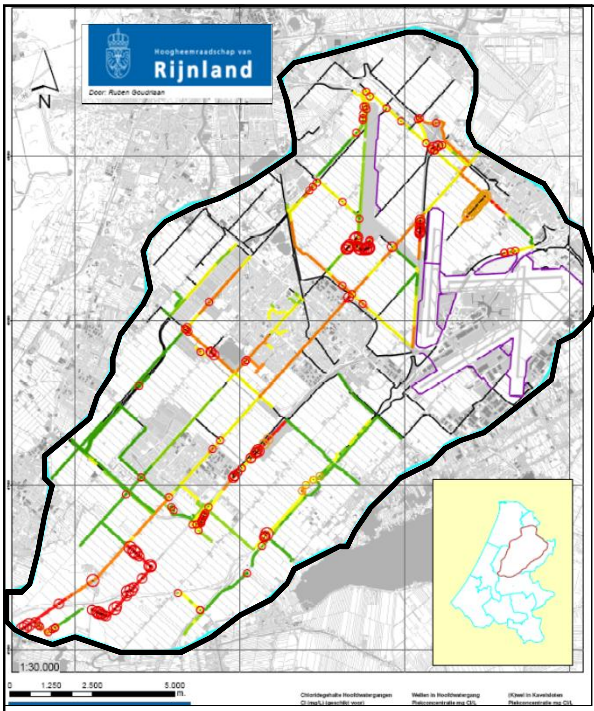
Continuous T and EC monitoring of surface water while sailing



T and EC measurements in surface water (canal)



Mapped boils and Cl-conc. surface water



Boils

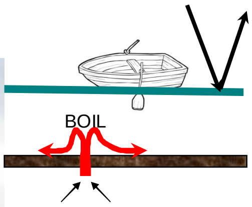
- Cl = 500 -2000 mg/l
- Cl > 2000 mg/l

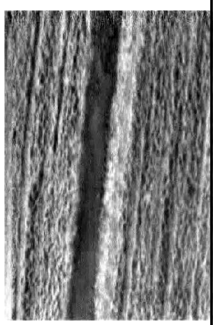
Cl-conc surface water

- 0-300 mg/l
- 300-600 mg/l
- 600-1000 mg/l
- > 1000 mg/l

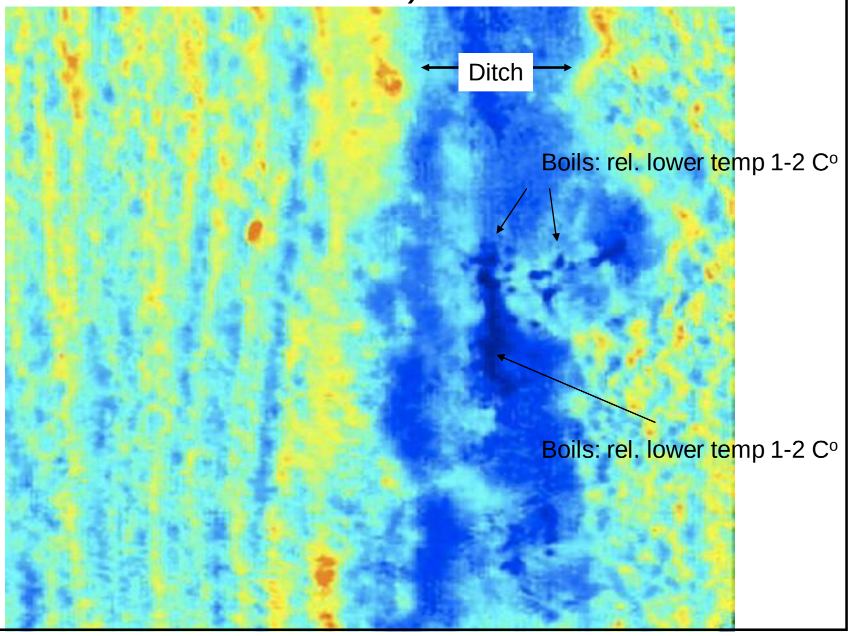
LARS technology (TNO Industry): <u>Thermal Infra-red</u>

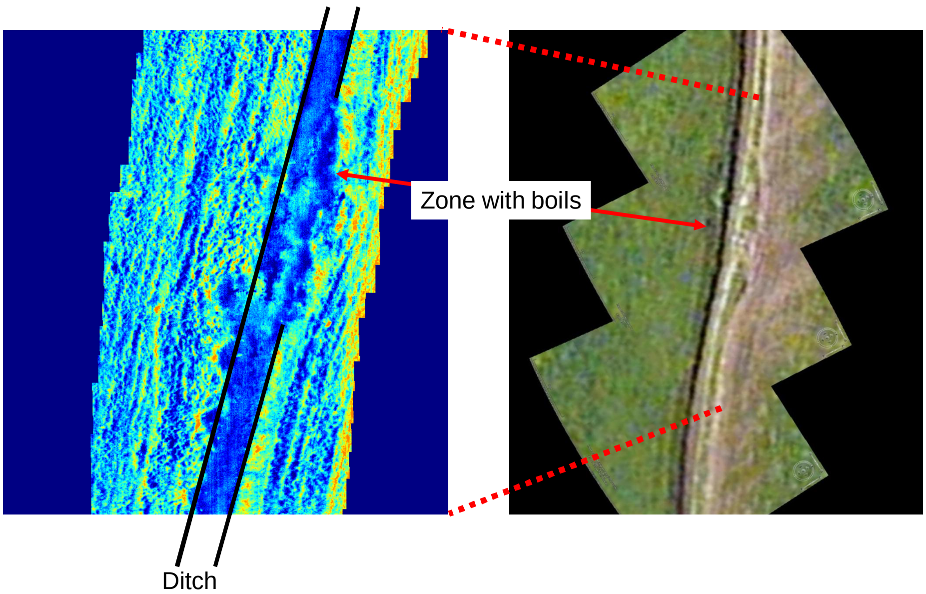
- Altitude: 0-150 m
- Temp-detection using Thermal Infra Red sensors (only surface !)

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

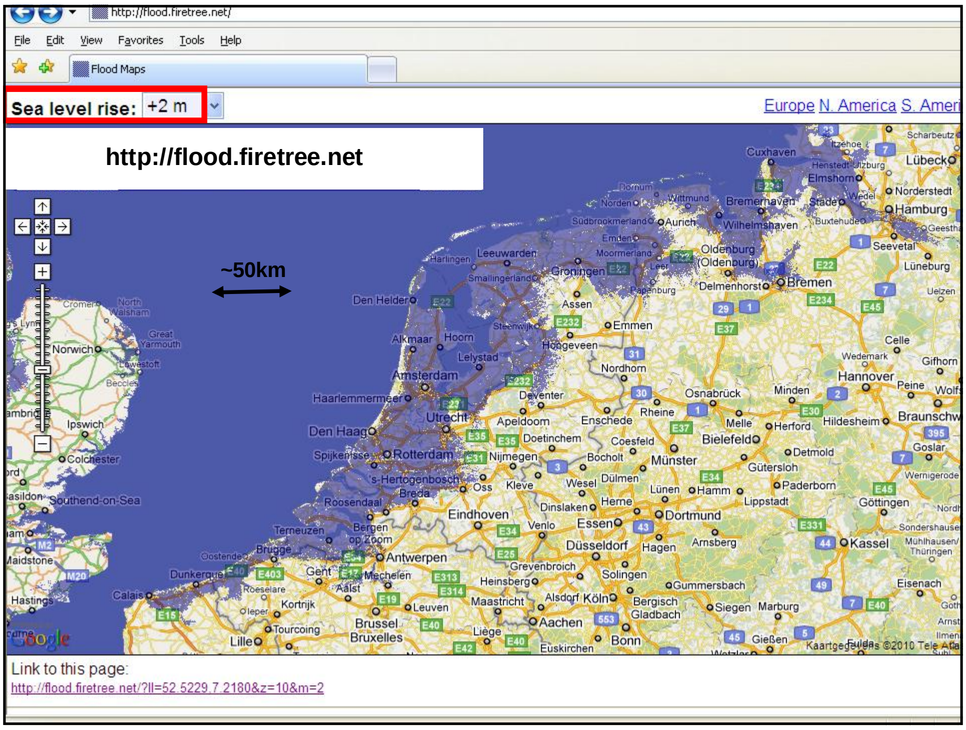




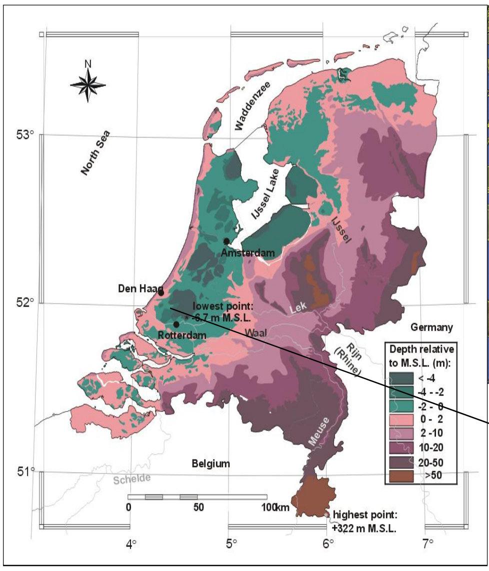
To get an idea about the possible future effects of sea level rise and climate change in your delta ...

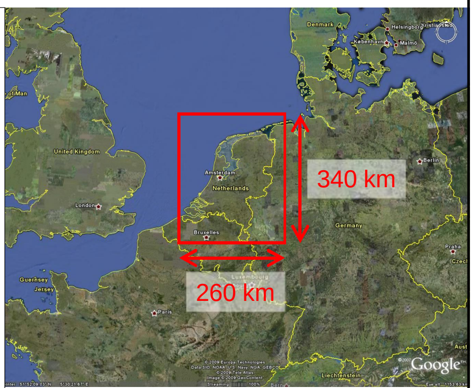
evaluate of the past water management in the Dutch delta

Salt water intrusion in the Netherlands



The ‘low-lying’ lands: Netherlands





The city of Delft

Case study: The Netherlands

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

Intensive water management system

Coping with salt water intrusion problems since 1950's

The 'low-lying' lands: Netherlands

The facts:

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

The Great Flooding in february 1953

Combination of high tide and heavy storm:

-1853 casualties
-2000 km^2 flooded

Infrastructure to protect our low-lying land from flooding

River flooding in 1995

Combination of heavy rains upstream the catchment
& short retention time

Dike collapse 2003

Combination of peat dike instability and very dry summer

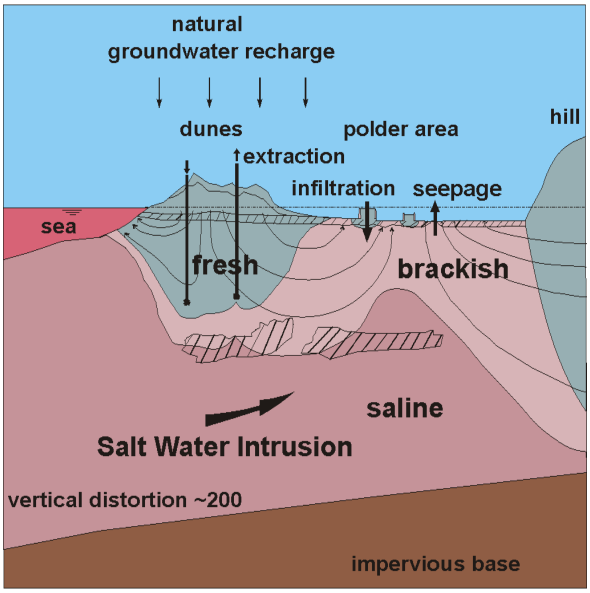
Estimated water management costs 'to keep our feet dry'

Costs up till 2050 in billion euros:

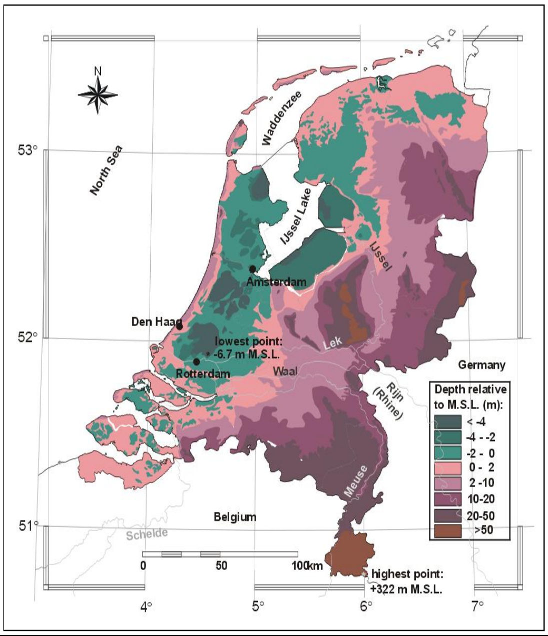
rivers: upper part	5.7
rivers: lower part	5.6
low-lands	1.7
coastal zone	8.0
infrastructure	3.5
purchase of ground	2.0
	-----+
	26.5 billion euros

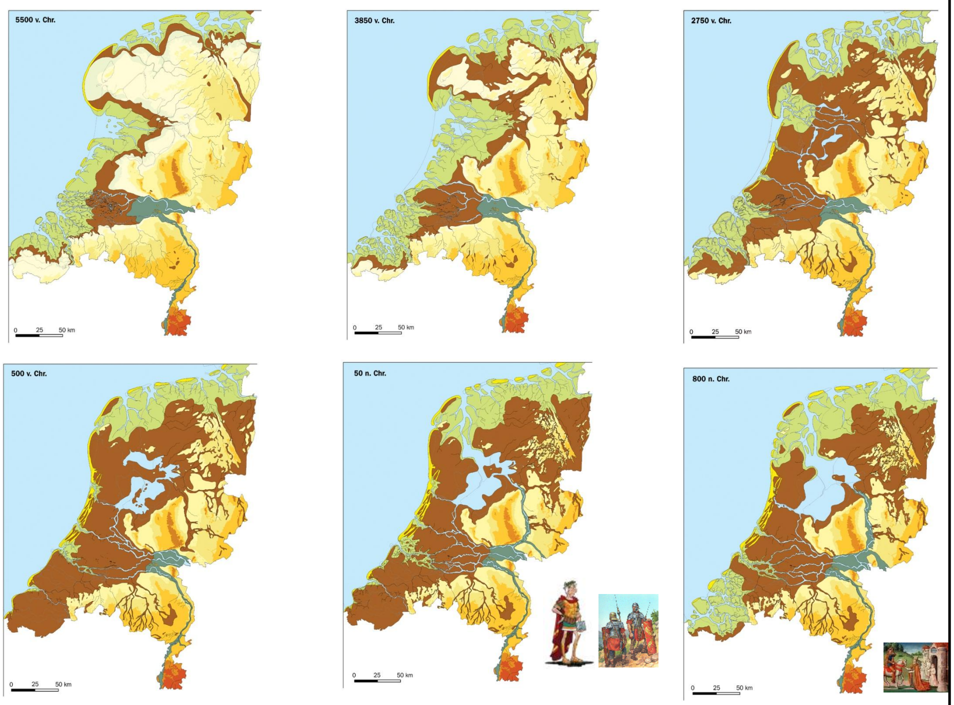
Dutch setting

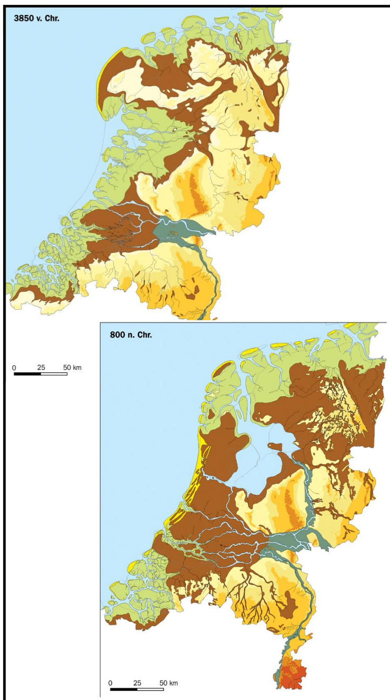
Salt water intrusion in the Netherlands

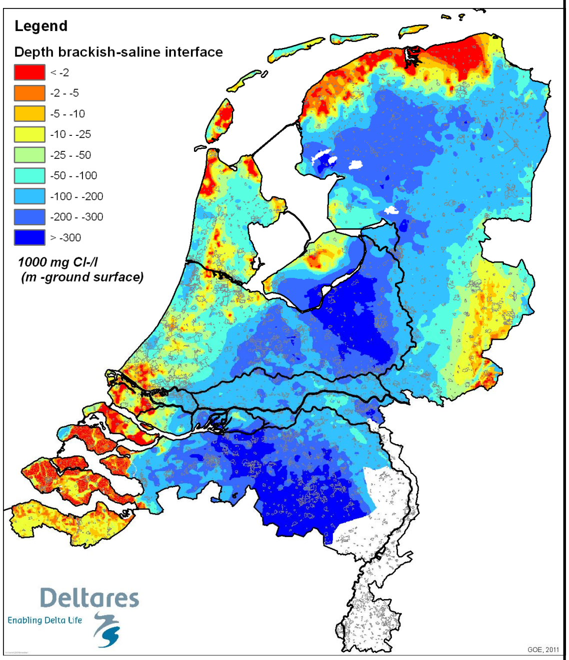


Present ground surface in the Netherlands

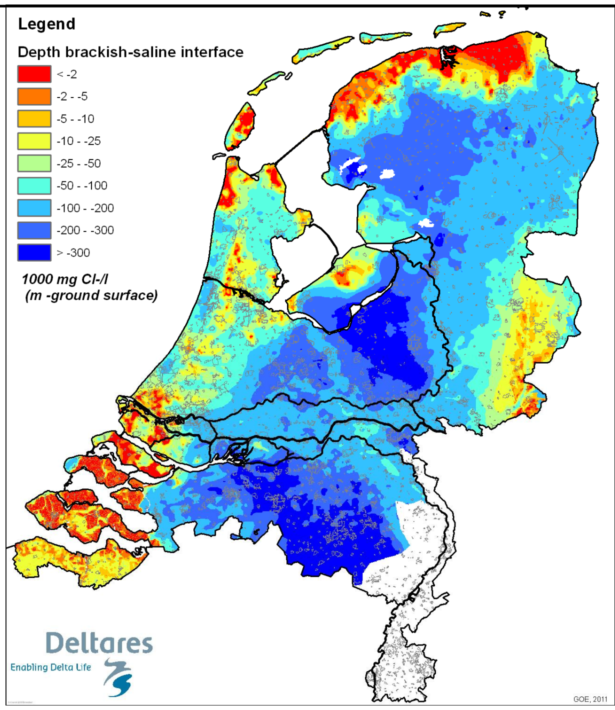




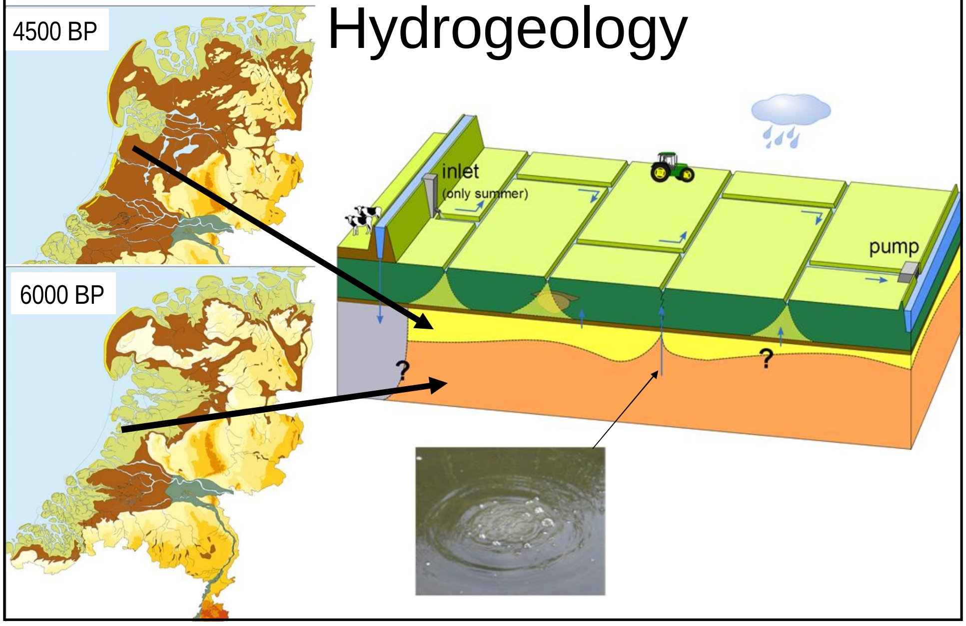




Fresh-Salt interface



Hydrogeology



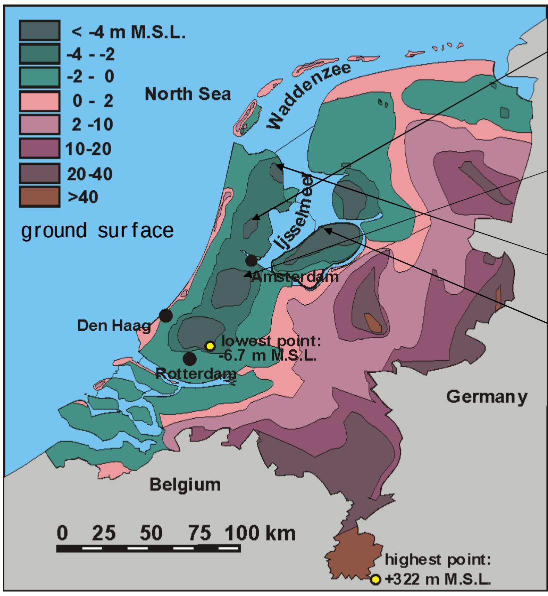
Salinisation of the Dutch subsurface

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

Anthropogenic causes:
- land subsidence
- polder level lowering
- groundwater extractions

Future developments (climate change):
- sea level rise
- changes in recharge

Abrupt land subsidence



position polders:

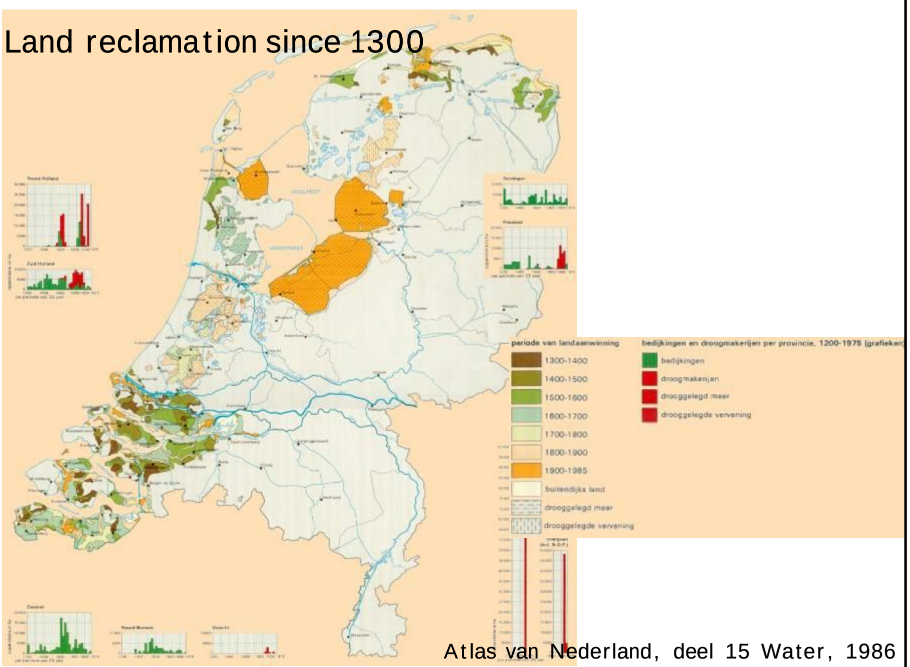
Beemster 1608-1612
Wormer 1625-1626
Schermer 1633-1635
Purmer 1618-1622

Haarlemmermeer polder 1850-1852

Wieringermeer polder ~1930

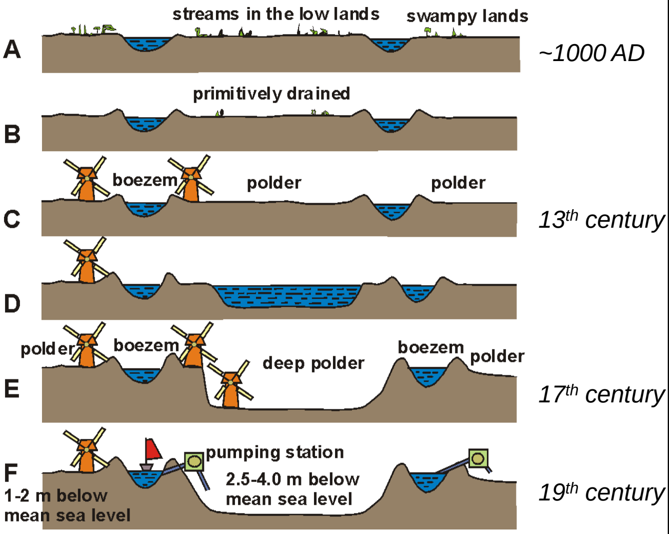
Flevo polders 1950-60s

Land reclamation since 1300



Atlas van Nederland, deel 15 Water, 1986

Development of the Dutch 'Polder' Landscape

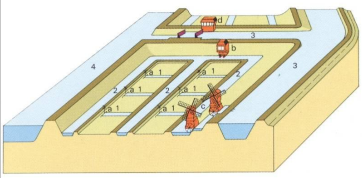


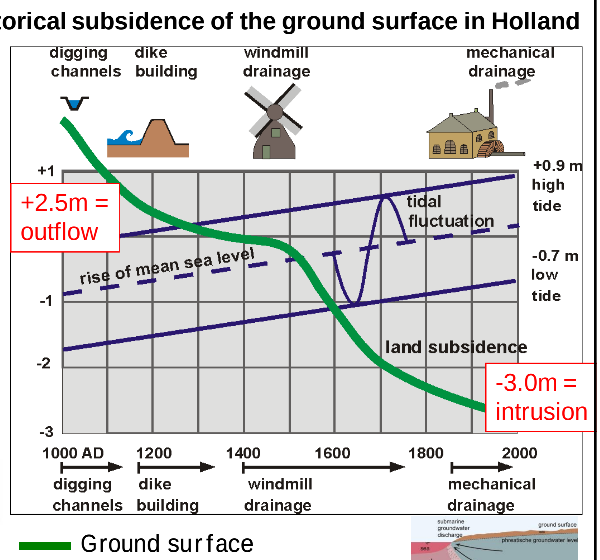
From fresh water outflow to salt water inflow

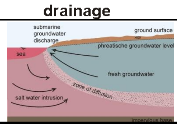
Causes:

- Autonomous processes
- Land subsidence
- Abrupt land reclamation

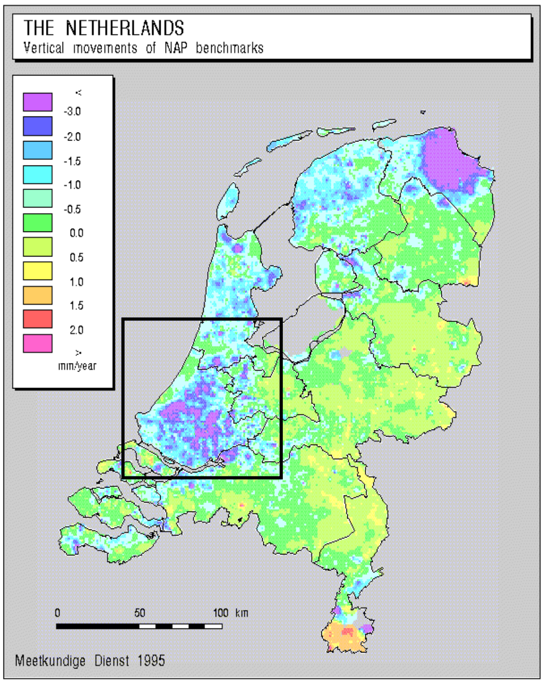
- Climate change
- Sea level rise
- Change in net recharge







Land subsidence
related to M.S.L.



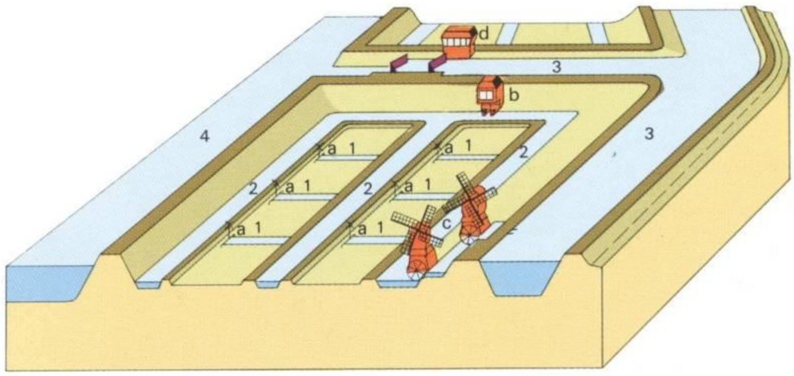
Land subsidence

up to 1 m per century

The polder system

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

a sophisticated drainage system



The polder system

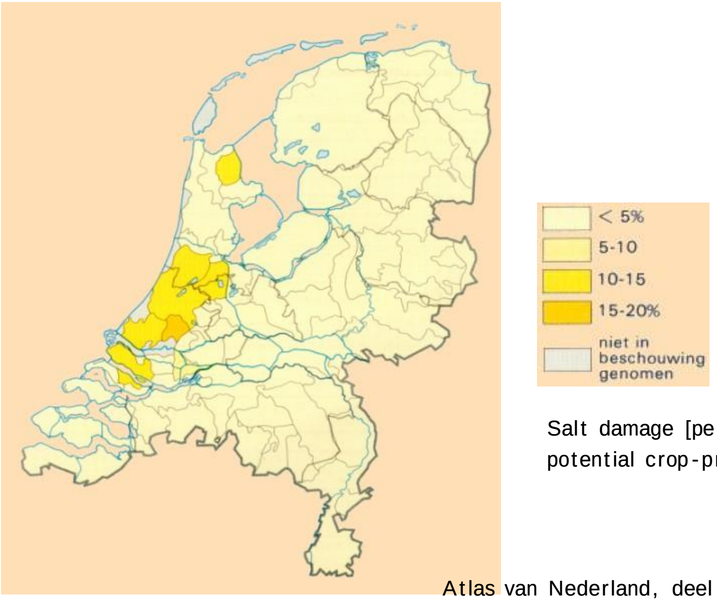
Many agricultural plots with different water levels throughout the season

The polder system

The polder system

Bulb farms at the landside of the sand dunes

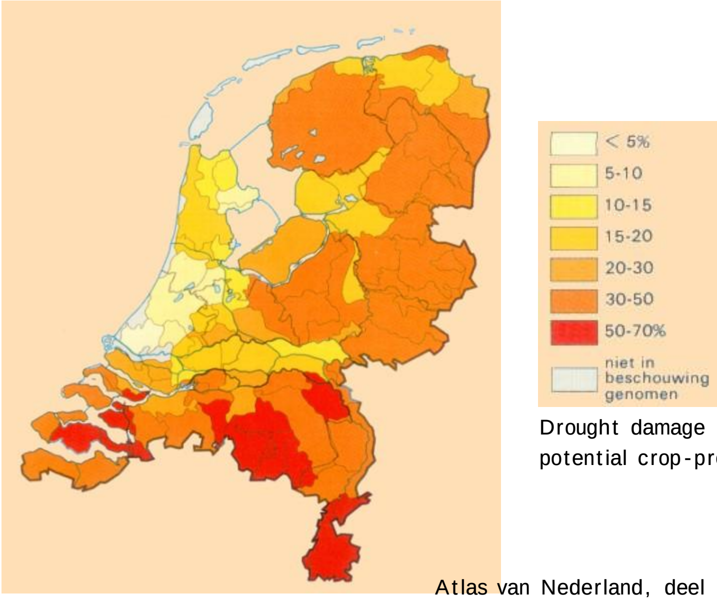
Salt damage in 1976 (very dry year)



Salt damage [percentage] in potential crop-production

Atlas van Nederland, deel 15 Water, 1986

Drought damage in 1976 (very dry year)



Drought damage [percentage] in potential crop-production

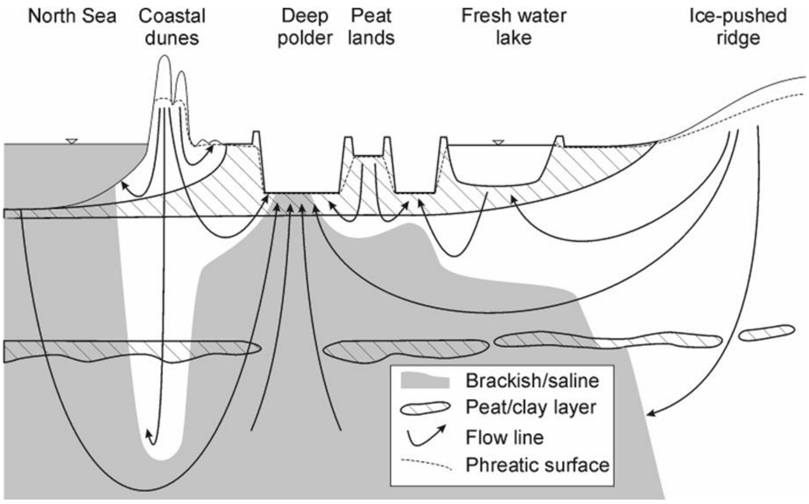
Atlas van Nederland, deel 15 Water, 1986

'Wetting' damage

Normal situation

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

Now focus on groundwater…



Threats to water management due to climate change:

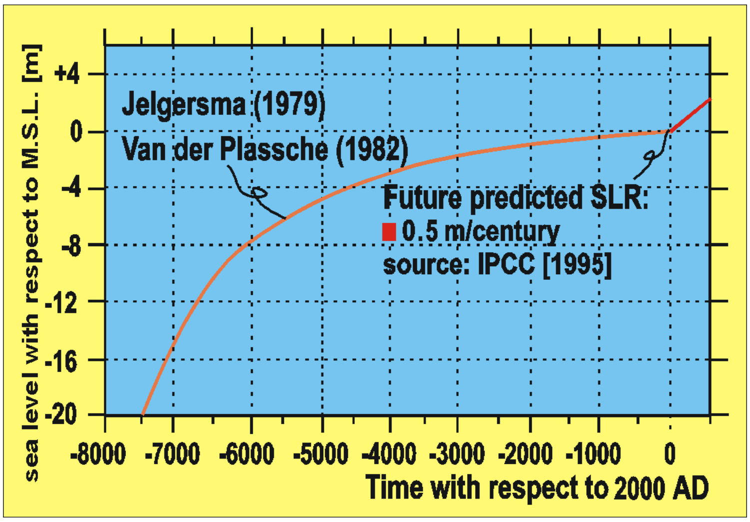
Short term threats:
- -flooding
- -dike collapse
- -drought

asks for operational water management

Long term threats:
- -salt water intrusion
- -land subsidence
- -smaller fresh groundwater resources

asks for strategic water management

Past and future sea level rise in the Netherlands

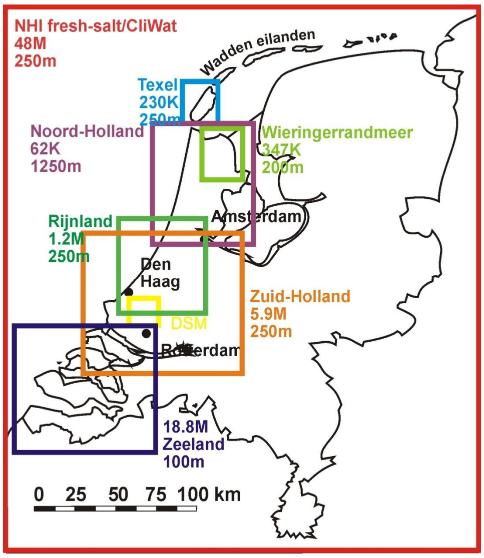


Numerical variable density models at Deltares

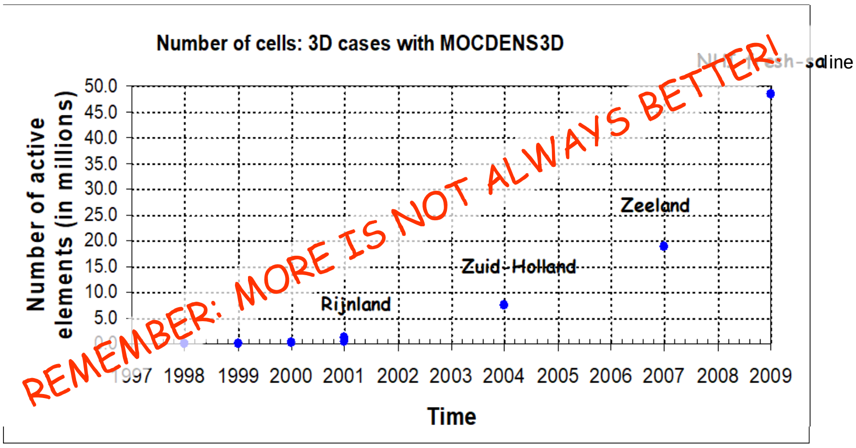
Characteristics:
- variable-density groundwater
- fresh, brackish and saline
- 3D, non-steady
- coupled solute transport

Code (MODFLOW family):
MOCDENS3D
SEAWAT

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

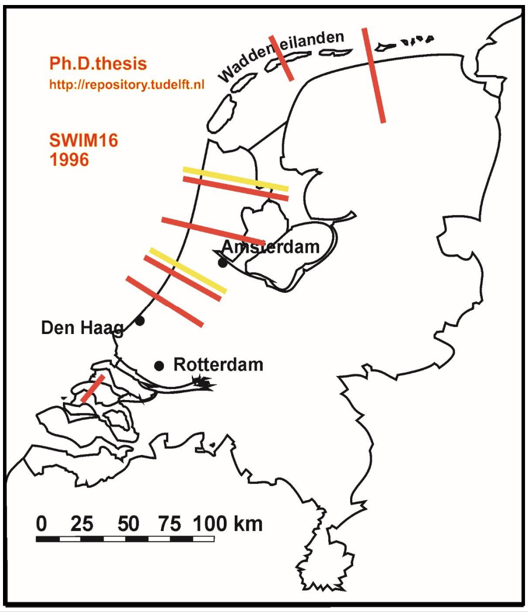


'DO NOT DO THIS AT HOME!' (DATA PROBLEM)



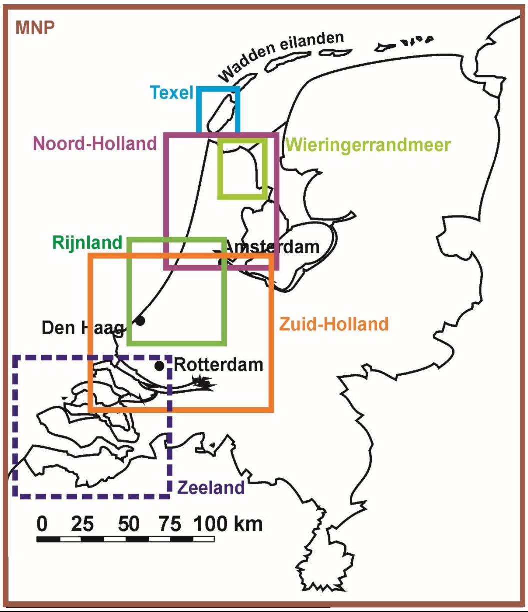
Modelling effect sea level rise on salt water intrusion

2D models



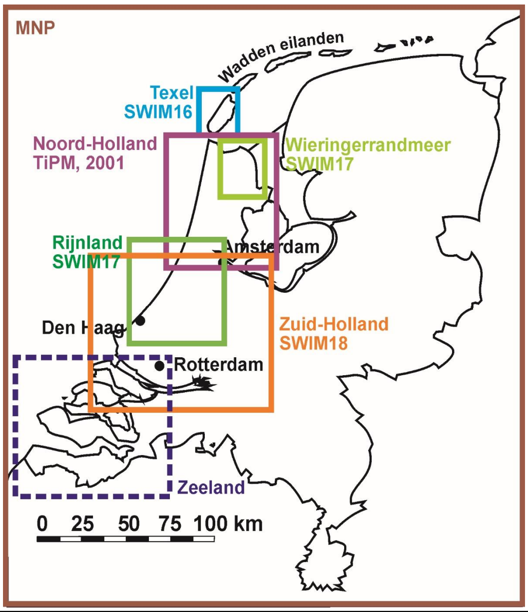
Modelling effect sea level rise on salt water intrusion

3D models



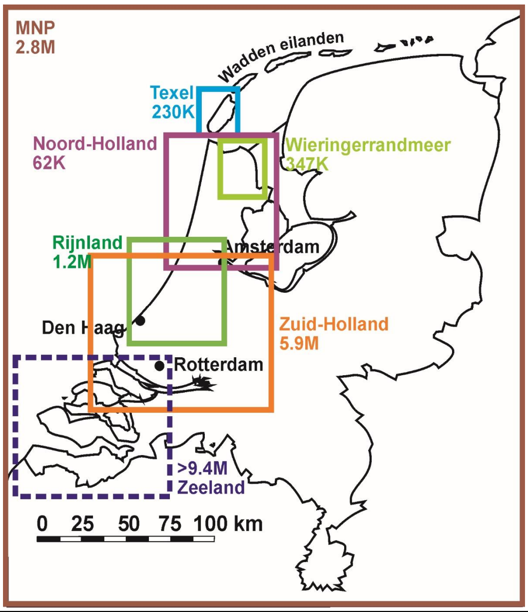
Modelling effect sea level rise on salt water intrusion

3D models
SWIM



Modelling effect sea level rise on salt water intrusion

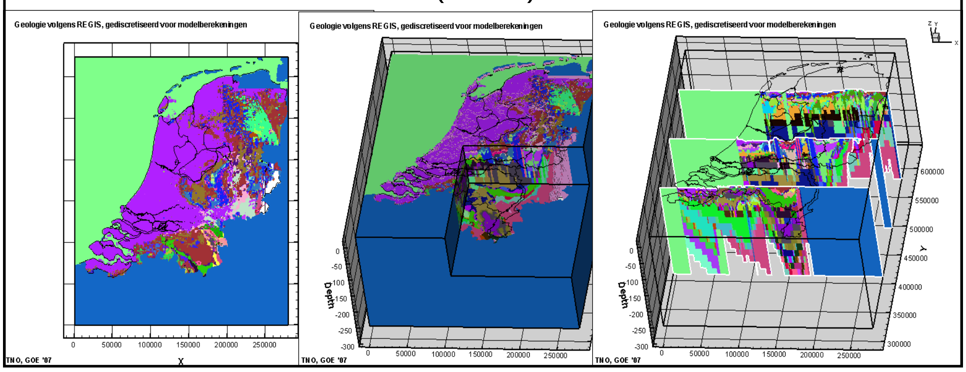
3D models number cells



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

Using the national subsoil parametrisation

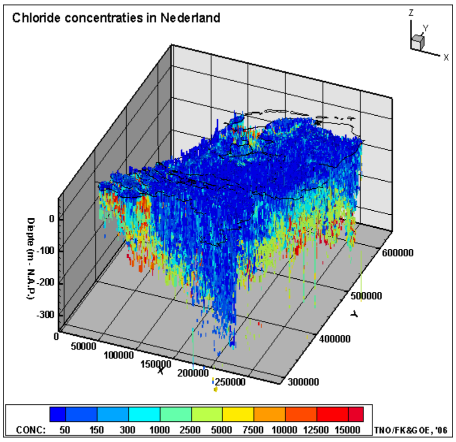
- REGIS V2
- Top geological system from +10m up to -280m M.S.L.
- 31 modellayers with thicknesses: 2*5m; 10*2m; 8*5m en 11*20m
- cellsize 1000x1000m (coarse)

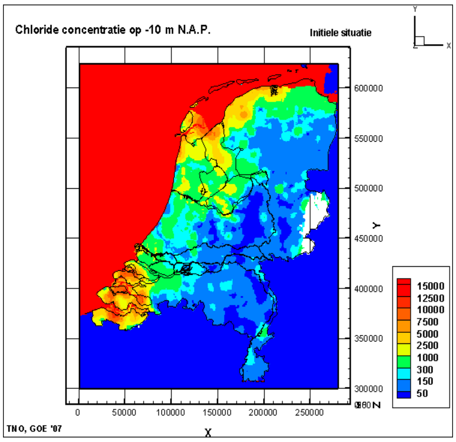


Recent model study for the whole Netherlands on the effect of sea level rise of water management (2)

Using the national 3D salt concentration in groundwater

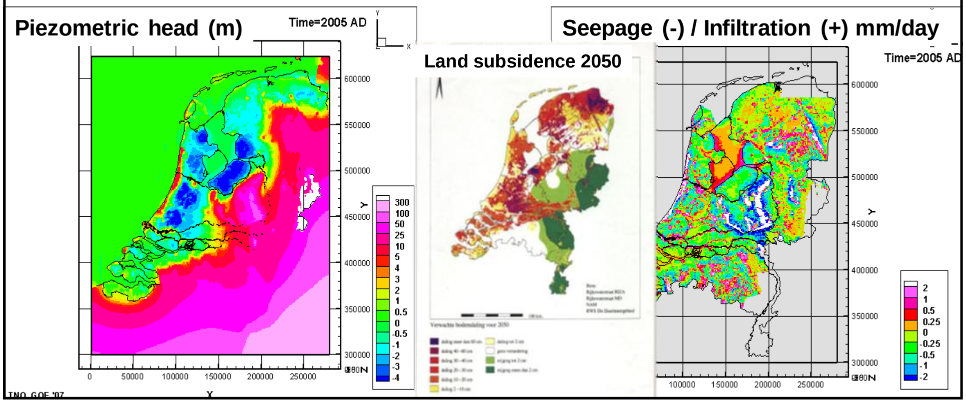
Zoet-Zout REGIS: ~65000 measuring points (analyses, VES, Borehole)



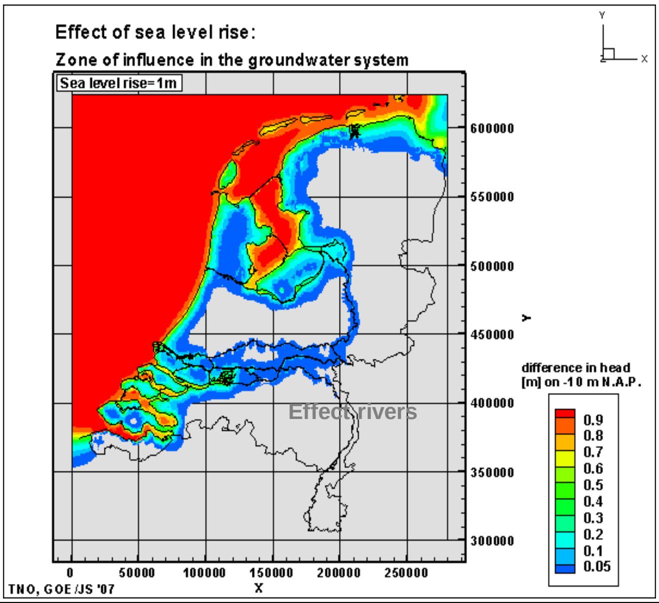


Recent model study for the whole Netherlands on the effect of sea level rise of water management (3)

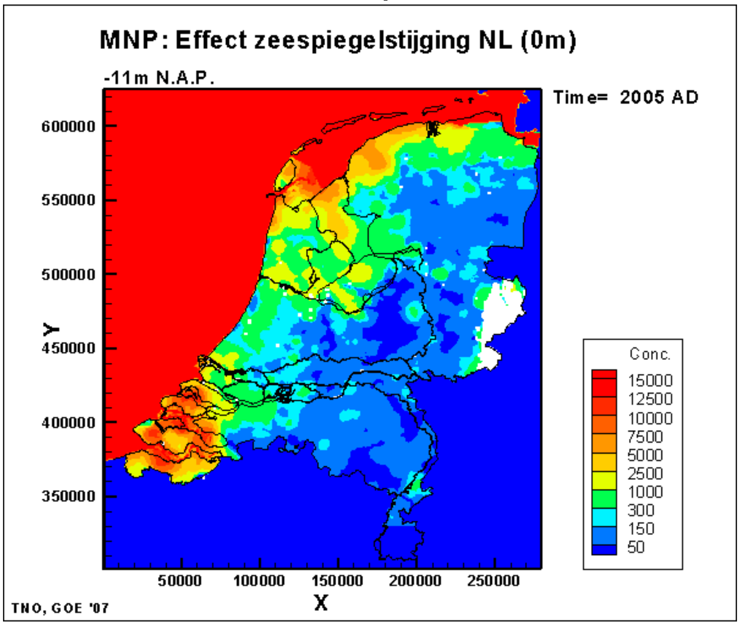
- Variable-density 3D groundwater flow model and coupled solute transport
  - 10 scenario's, including extreme sea level rise
  - including land subsidence estimates



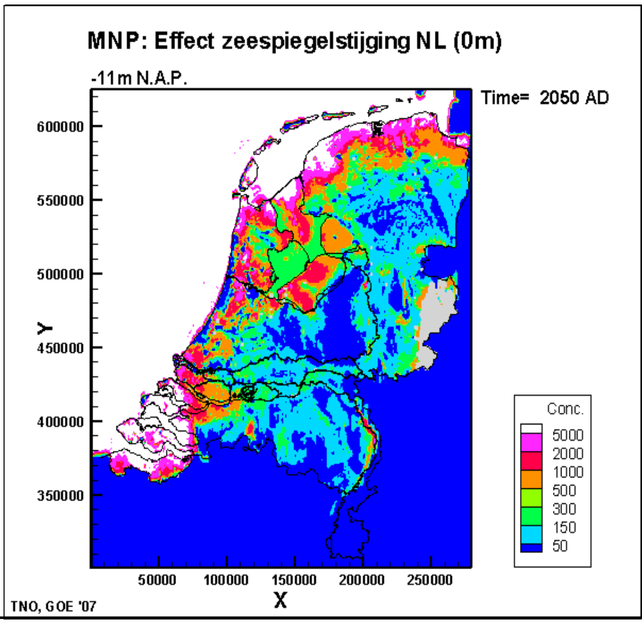
Results: zone of influence 1m sea level rise



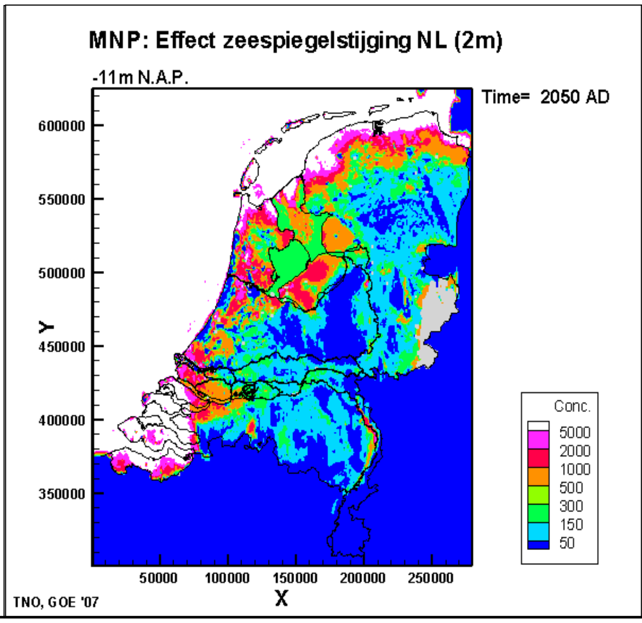
Salinisation over the period 2000-2050



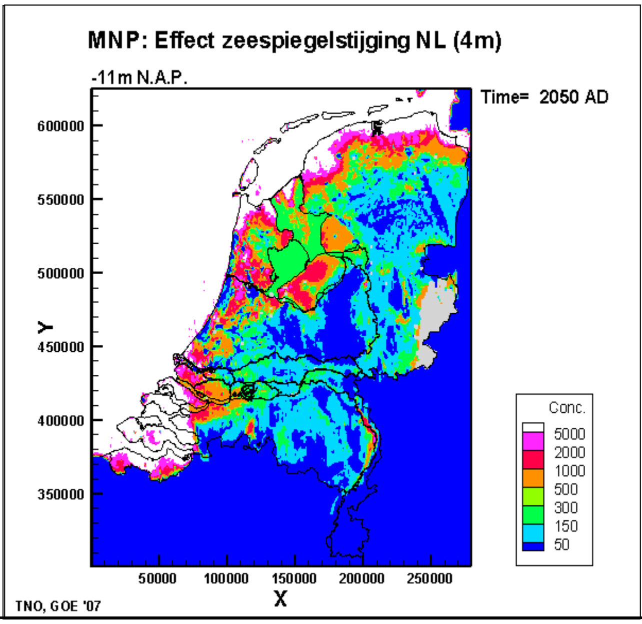
Salinisation subsoil at 0m sea level rise in 2050



Salinisation subsoil at 2m sea level rise in 2050

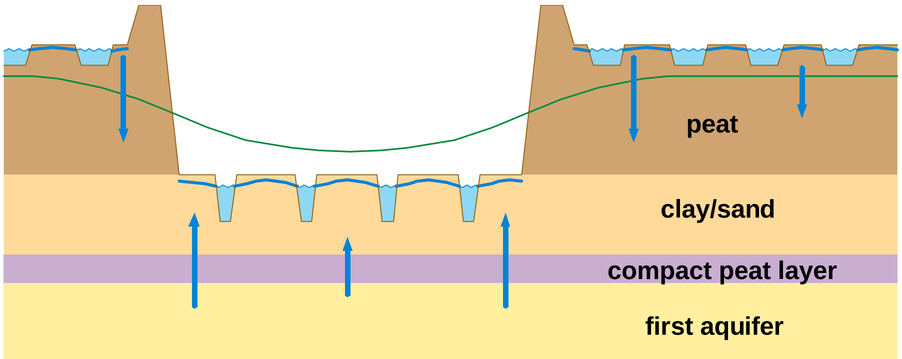


Salinisation subsoil at 4m sea level rise in 2050

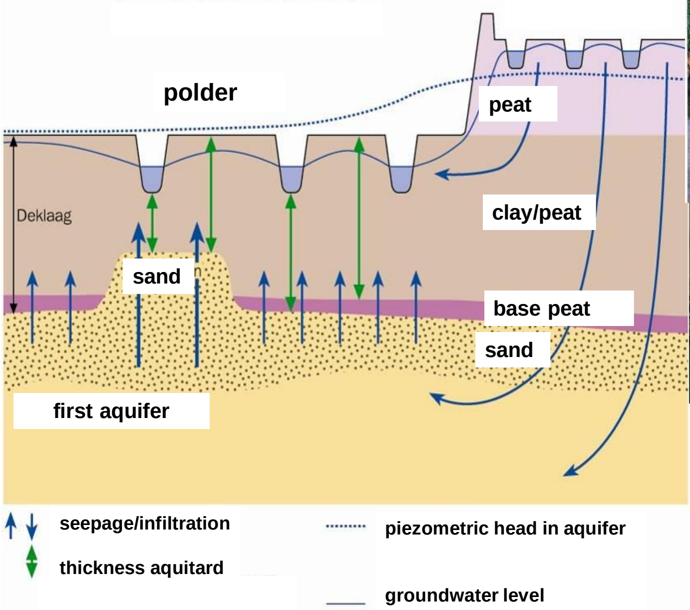


Salty wells

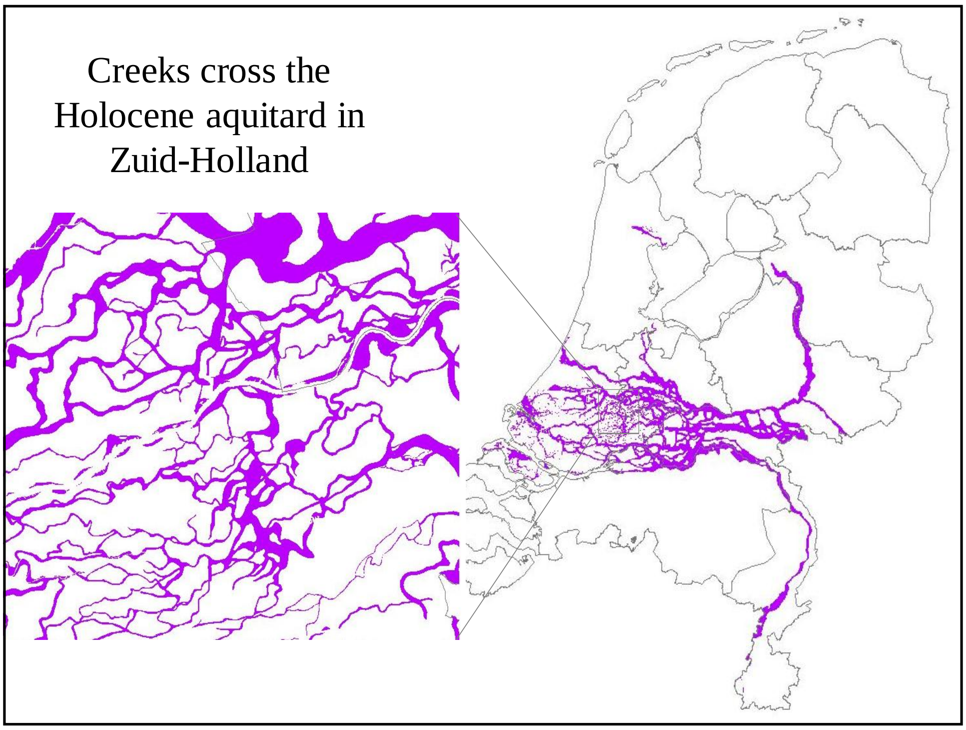
Seepage and infiltration situation around deep polders



Risk of instable Holocene aquitards (1)

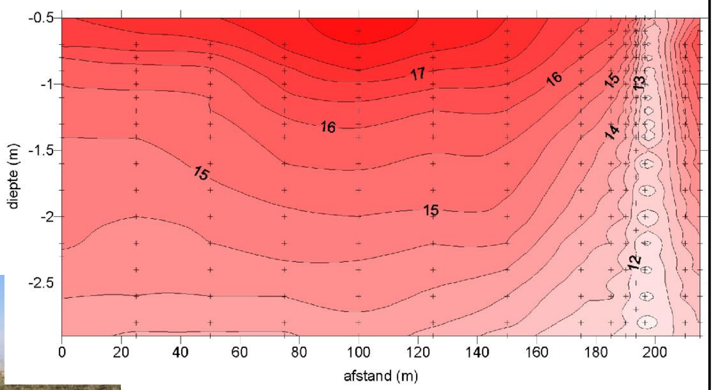


Creeks cross the Holocene aquitard in Zuid-Holland

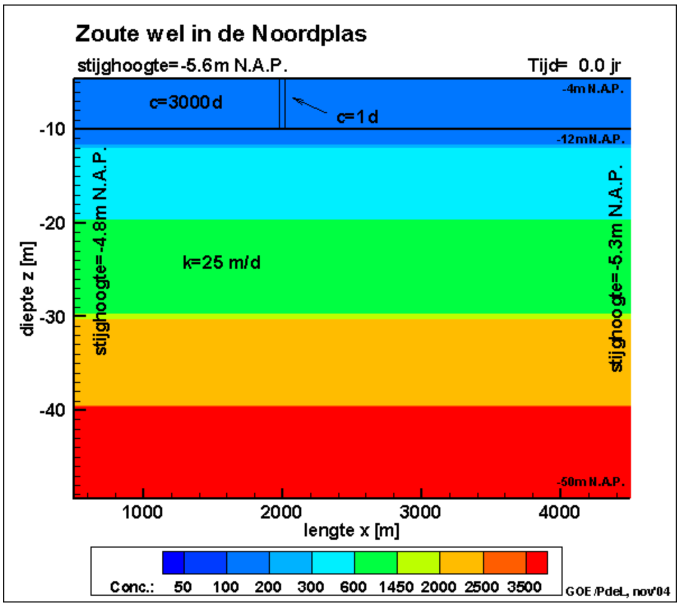


'*Wells*' (weak spots in Holocene layer)

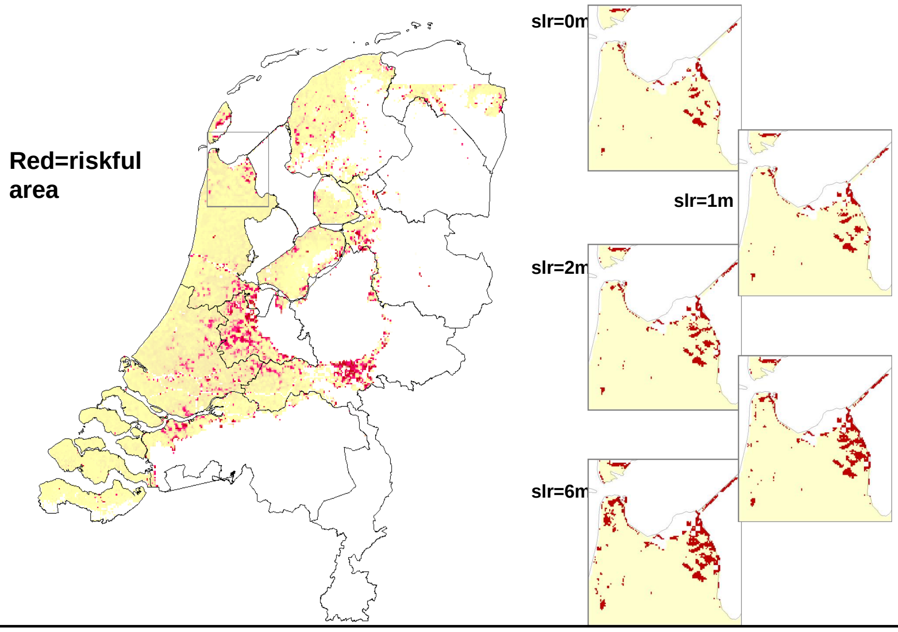
Temperature measurements



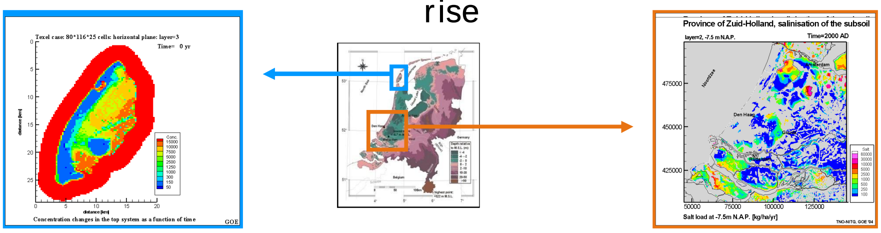
Simulation of salt groundwater towards *wells*



Risk of instable Holocene aquitards (2)



Quantification hydrogeological impacts of sea level rise



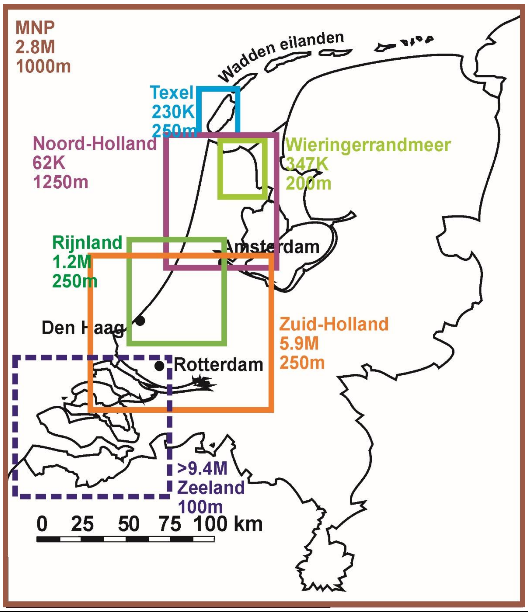
Situation at 2100 AD with sea level rise of 0.5m/century,

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

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

Modelling effect sea level rise on salt water intrusion

3D models
number cells
grid size



Characteristics 3D Cases (I): geometry & subsoil

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

* calibration with seepage & salt load in polders

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

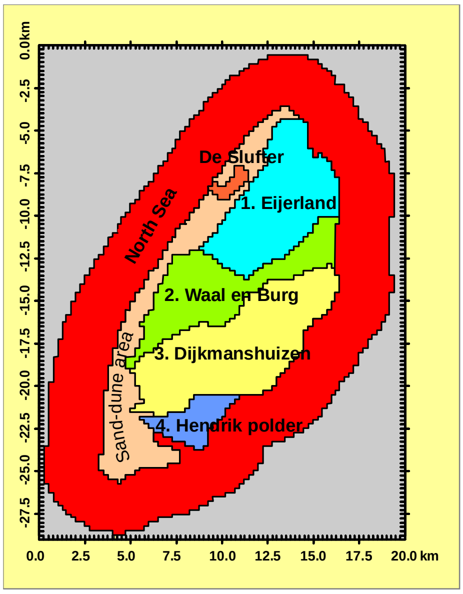
Characteristics 3D Cases (II): model parameters

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

convergence head criterion= $10^{-5}/10^{-4}$ m
flow time step Δt=1 year

Model of the island of Texel

Characteristics of the island of Texel (I)



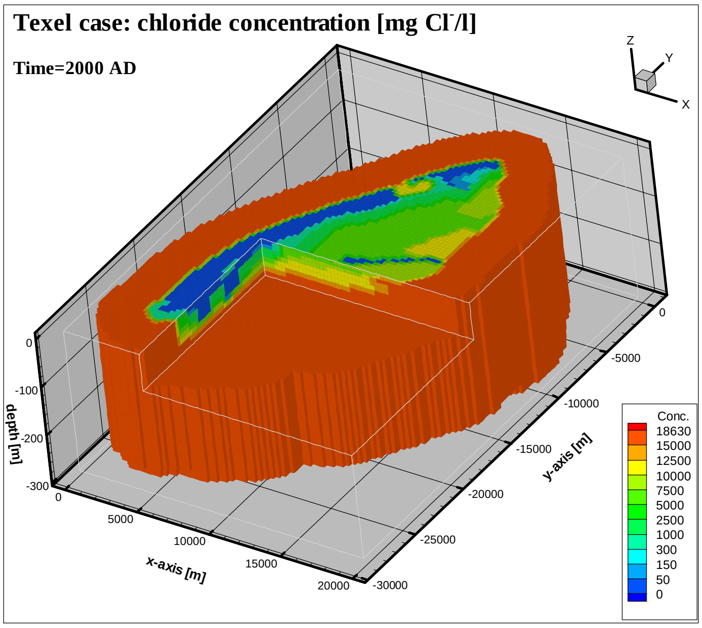
- Tourist island in summer time
- Land surface: 130 km²
- Polder areas:
  1. Eijerland
  2. Waal en Burg
  3. Dijkmanshuizen
  4. Hendrik polder

Sand-dune area at western side

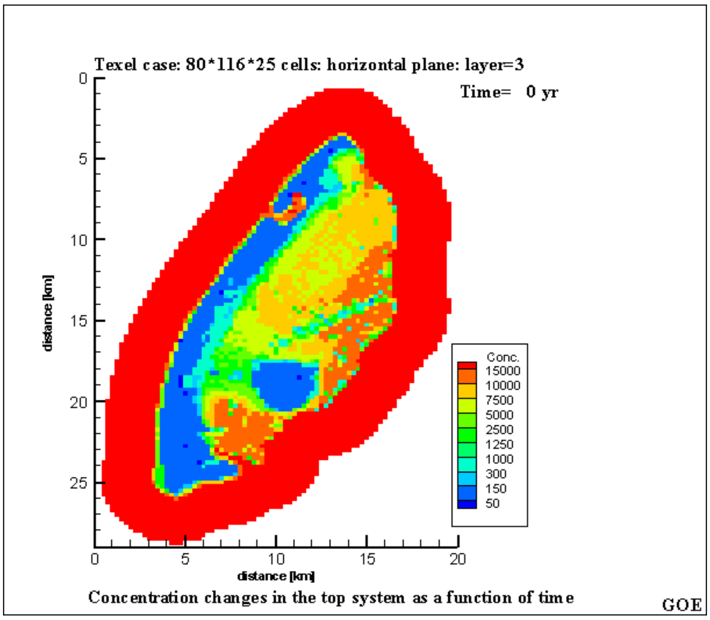
'De Slufter' is a tidal salt-marsh

North Sea surrounds the island

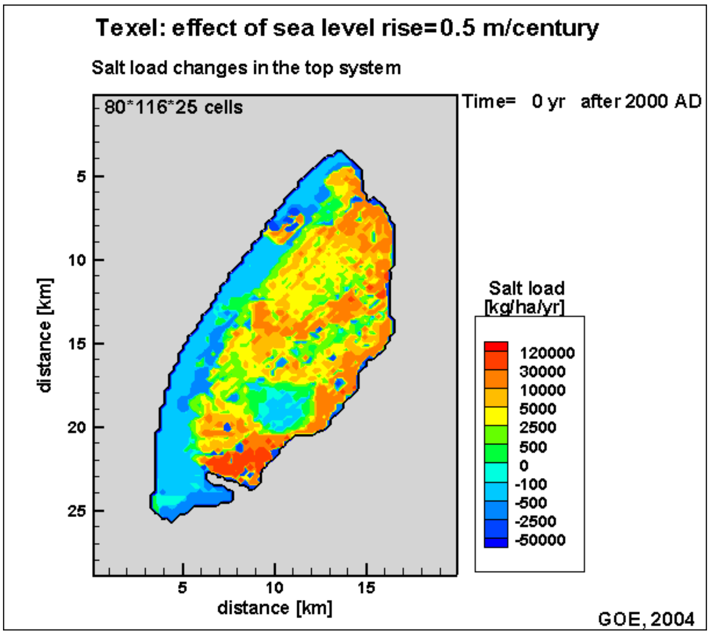
Texel: present 3D chloride distribution



Texel: reference case=autonomous development

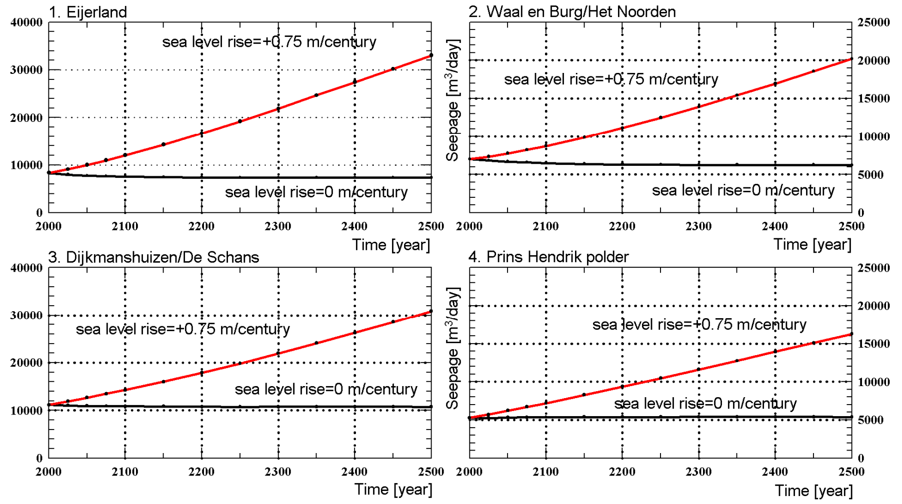


Texel: effect of sea level rise on salt load



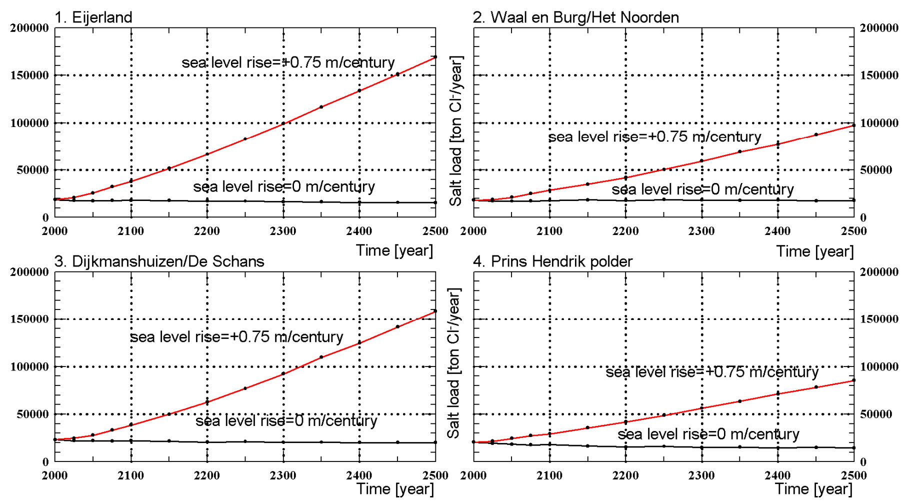
Texel

Texel: change in seepage of the four polders



Texel

Texel: change in salt load of the four polders



Model of the Province of Zuid-Holland

Case study: Province of Zuid-Holland

European water framework directive

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

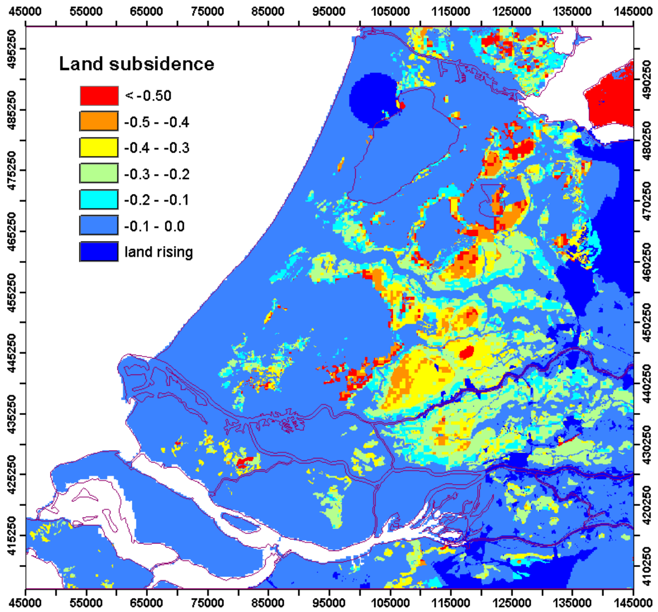
Identification of all fresh groundwater bodies in the province

How fast is the salinisation process?

More seepage, more salt load?

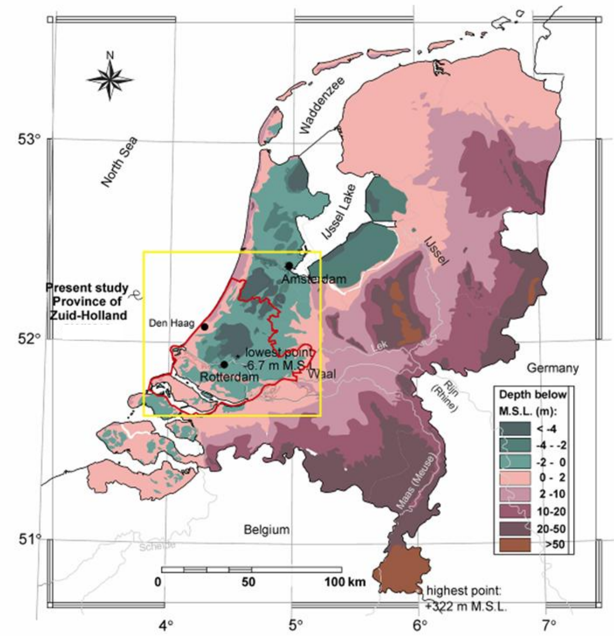
Land subsidence

2050



Source: RIZA

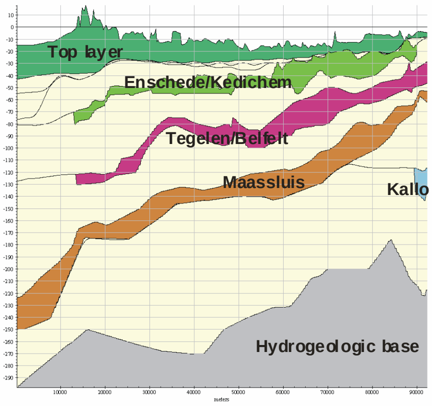
Location of the Province of Zuid-Holland

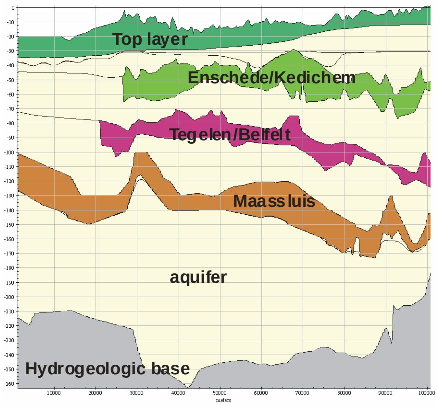


Numerical model description

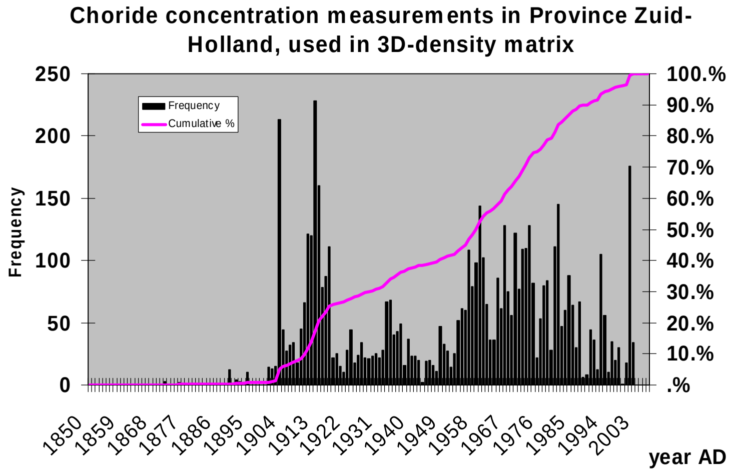
- variable-density groundwater flow
- coupled solute transport
- MOCDENS3D
- area: 100km * 92.5km * 300m depth
- 400 *370 cells, 40 layers
- ~4 million active cells
- uses most accurate Dutch 3D subsurface schematization available
- 9 aquifers and aquitards
- uses 5772 chloride concentration measurements

Position and name of aquitards

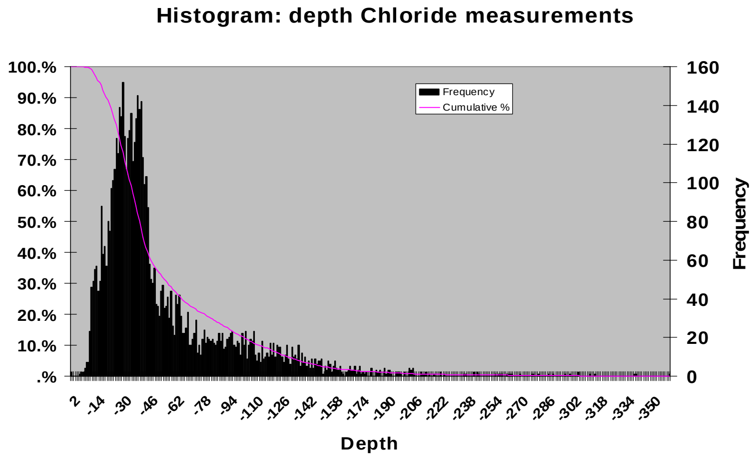




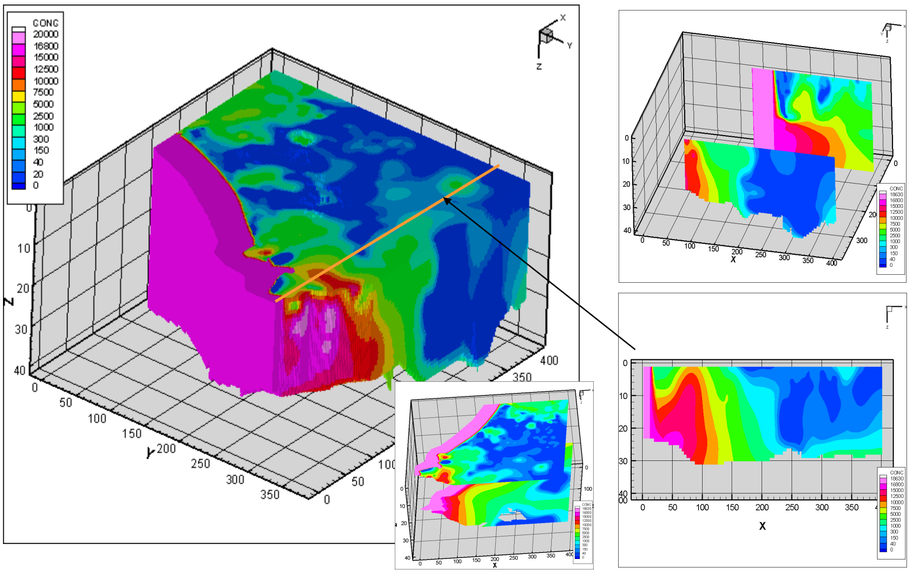
3D interpolation of chloride-concentration



3D interpolation of chloride-concentration



Initial chloride distribution

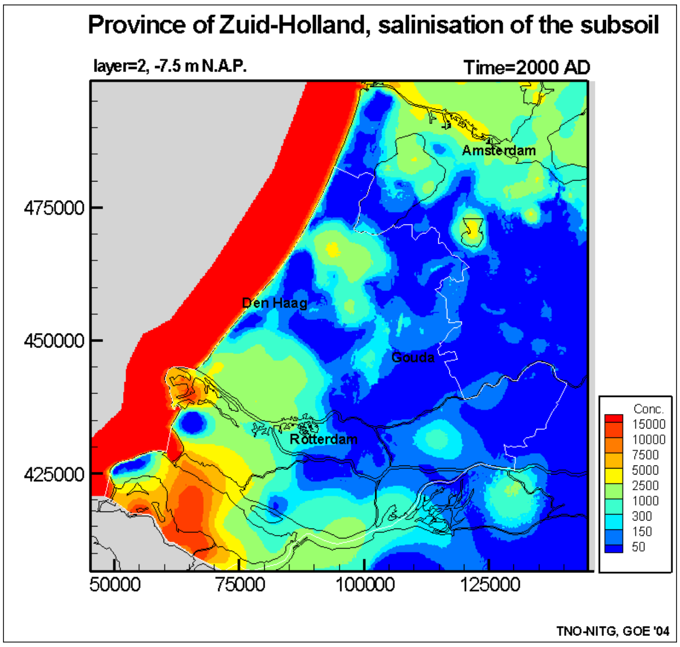


Present freshwater volume

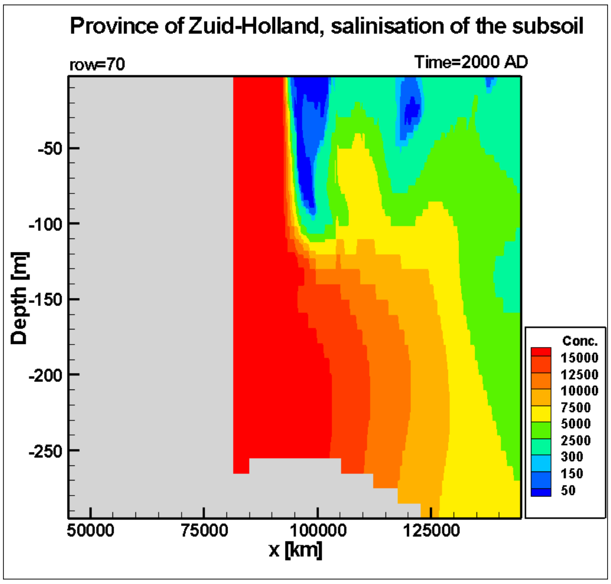
27 billion m^3

36% fresh, 14% brackish, 50% saline

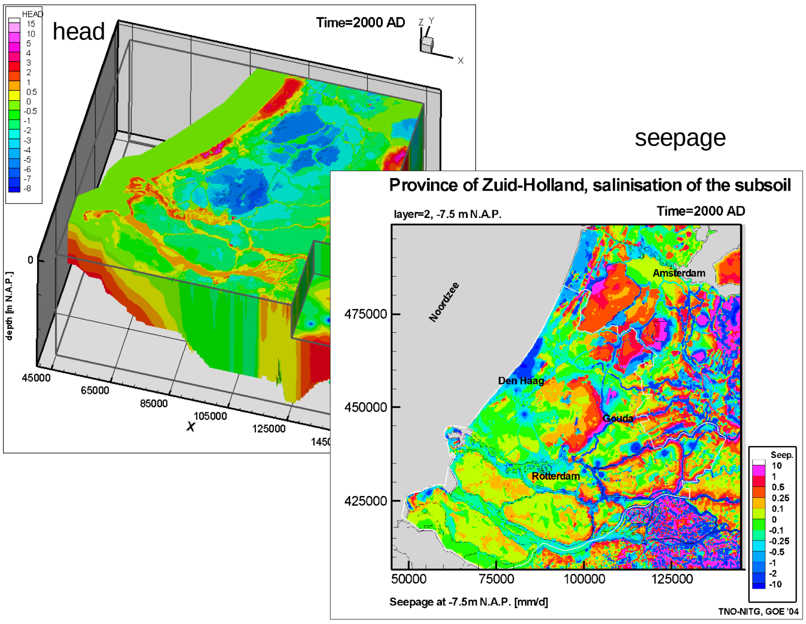
Results: Chloride conc. in 200 yrs



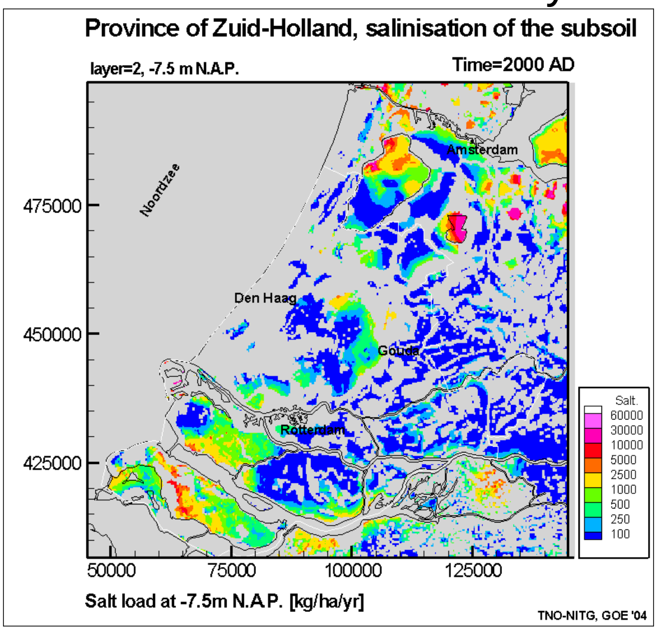
Results: Chloride conc. in 200 yrs



Results: freshwater head and seepage at 2000 AD



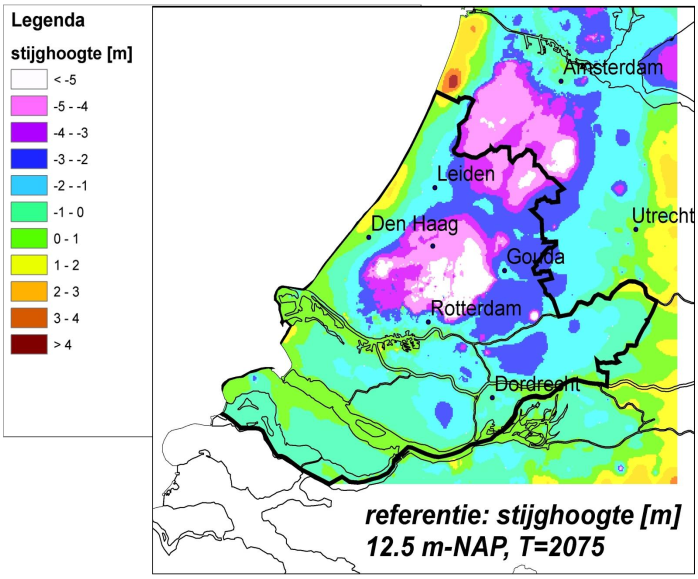
Results: Salt load in 200 yrs



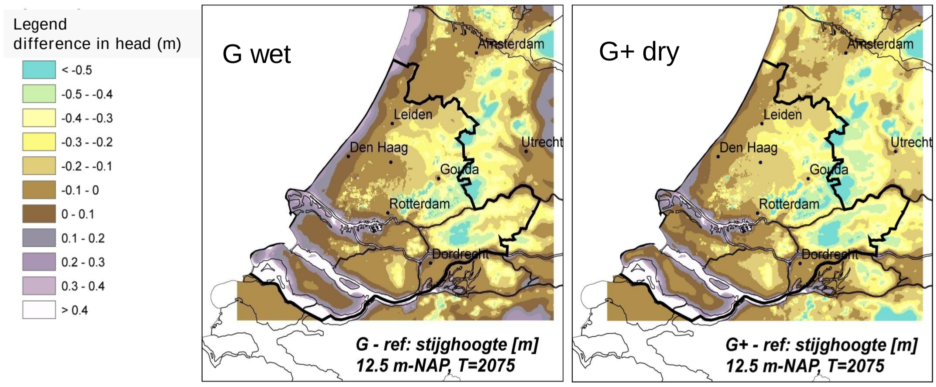
Effect sea level rise, change in natural groundwater recharge and land subsidence on freshwater head in aquifer

Some regional modelling results

Freshwater head at -12.5 M.S.L.



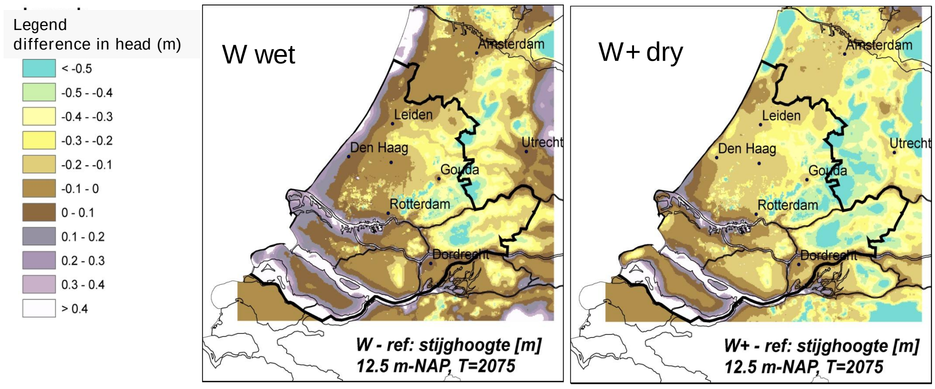
Difference in freshwater head on op -12.5 N.A.P.: G scenarios



Sea level rise is 60 cm

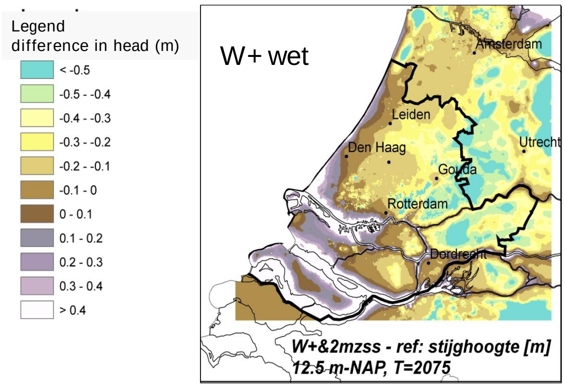
Including change in natural groundwater recharge

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



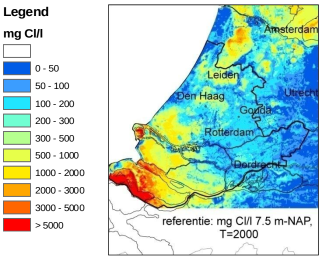
Sea level rise is 85 cm

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



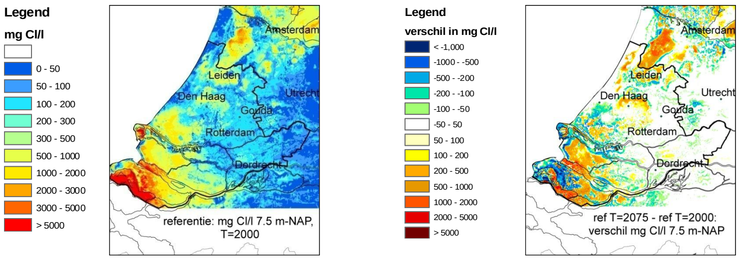
Sea level rise is 200 cm

Salinisation/freshening Netherlands?: Present situation



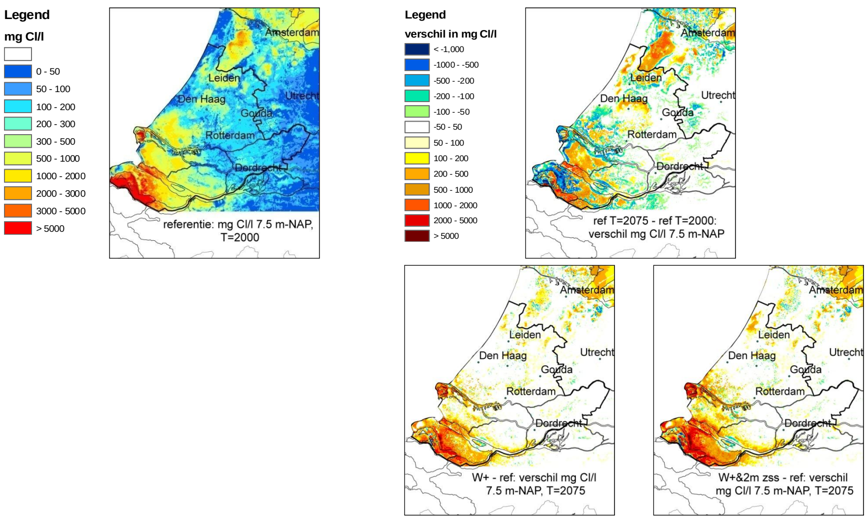
modelstudy

Salinisation/freshening Netherlands?: Autonomous processes



modelstudy

Salinisation/freshening Netherlands?: climate change



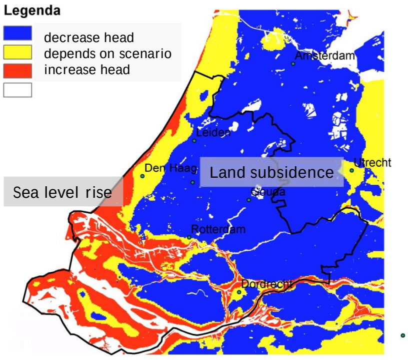
85 cm sea level rise

200 cm sea level rise

modelstudy

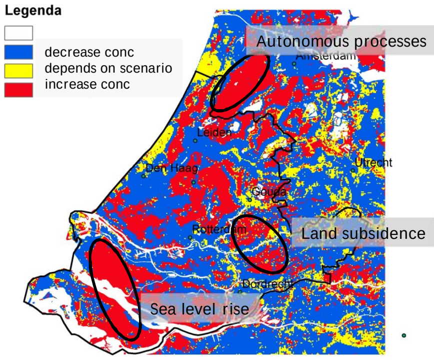
Effect climate scenarios in 2075 on

freshwater head



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

salinisation



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

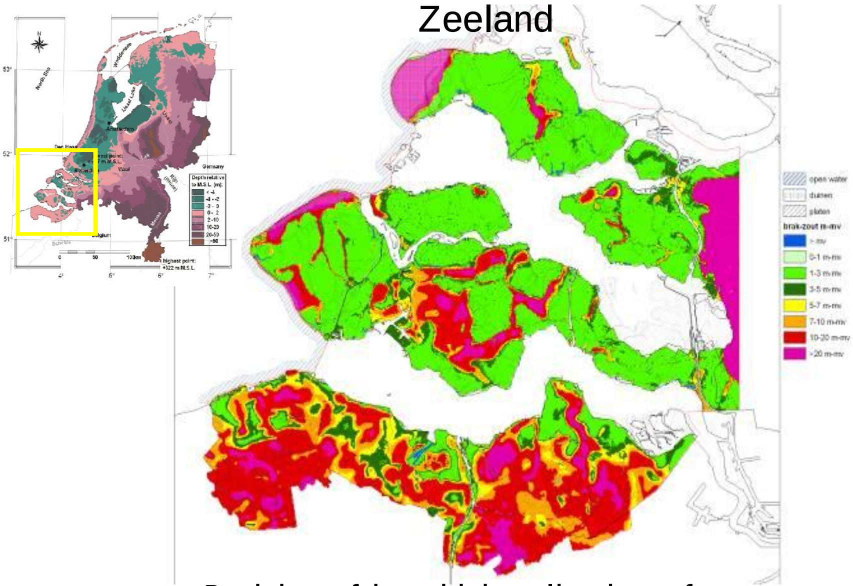
Modelstudie PZH

Rainwater lenses in an agricultural setting

Shallow dynamic freshwater bodies flowing upon brackish-saline groundwater

- density dependent
- dynamics: seasonal & long-year

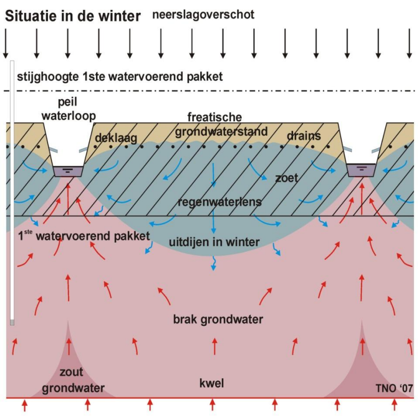
Salinisation of the phreatic groundwater in Zeeland



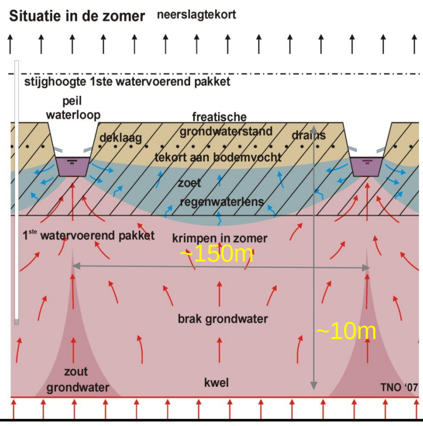
Position of brackish-saline interface

Salinisation of the phreatic groundwater in Zeeland

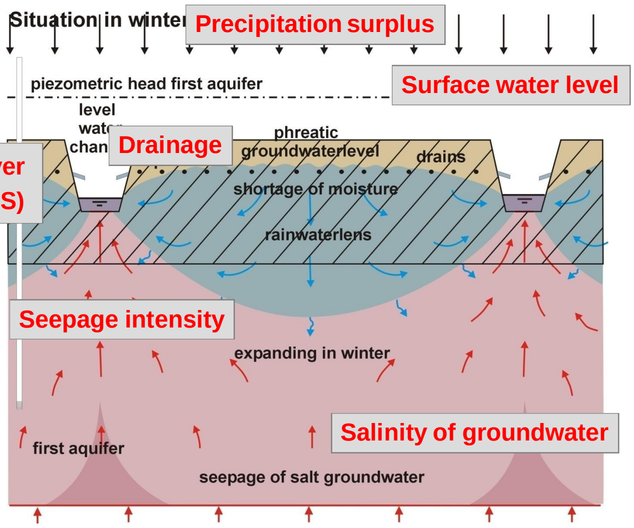
Dynamic rainwater lenses floating on saline groundwater



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



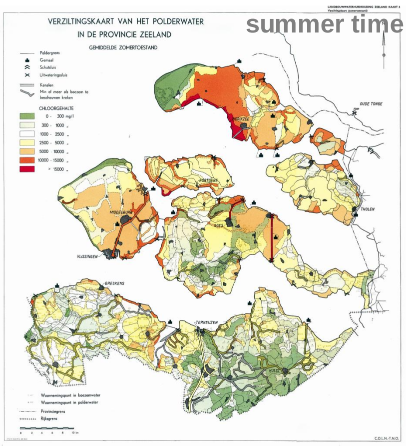
Factors controlling fresh-salt interface

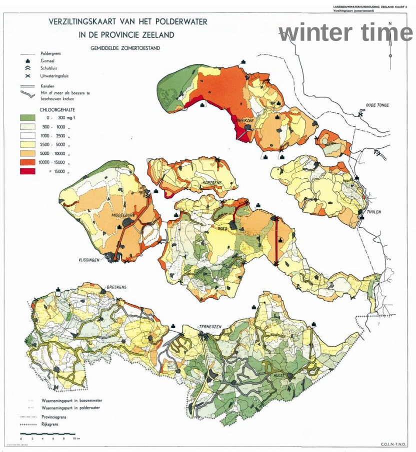


Important factors:

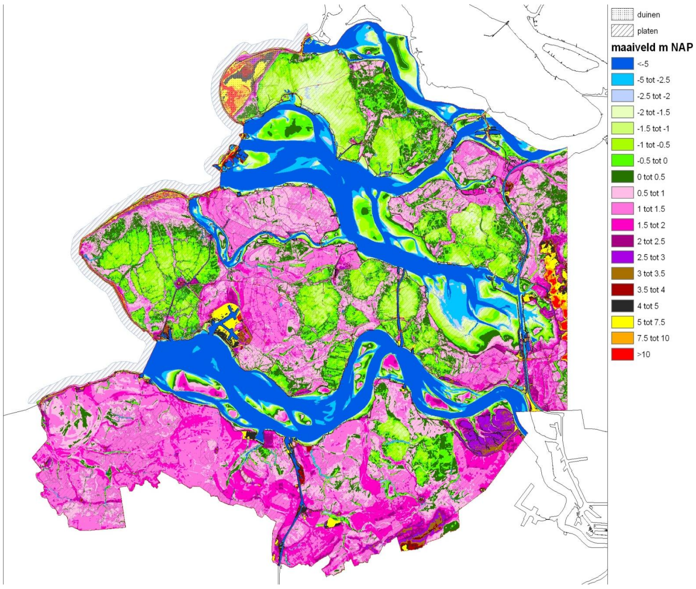
- natural groundwater recharge
- geology
- distance between ditches
- water levele ditches
- capacity drainage system

Salinisation surface water

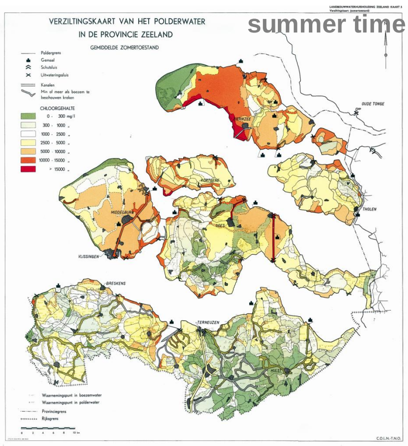


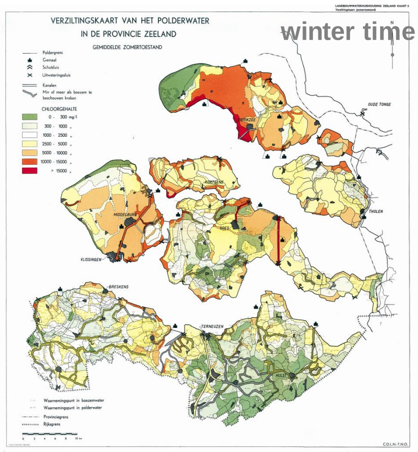


Position of the ground surface



Salinisation surface water





Problem definition dynamic freshwater lenses

Salt in the agricultural plots originates from:

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

The salinisation will increase due to:

- sea level rise
- climate change
- water level management

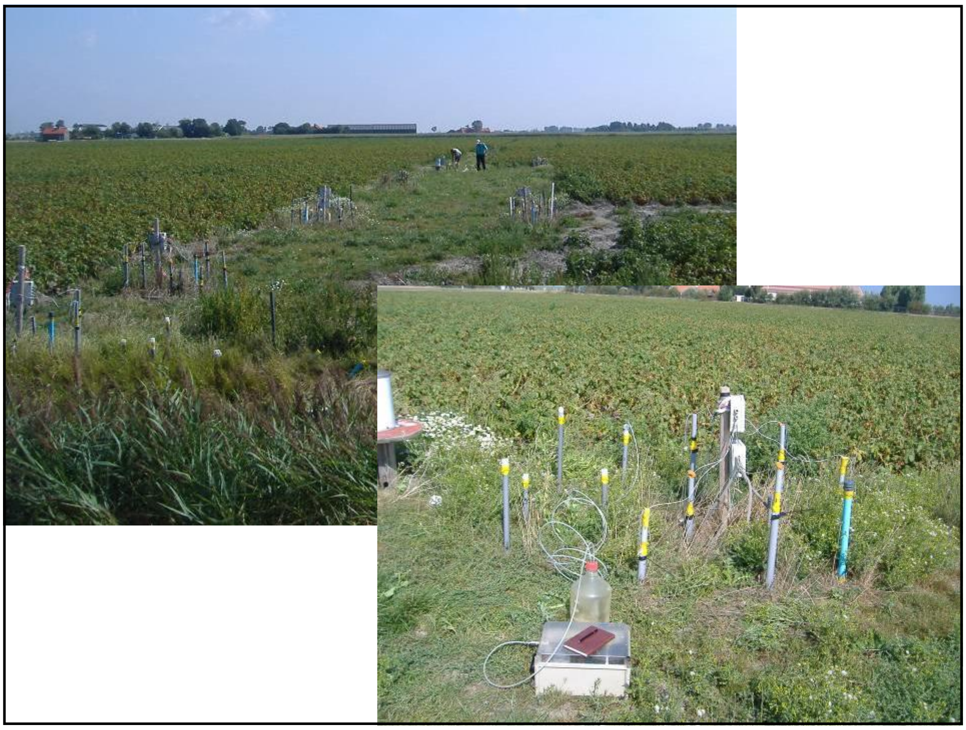
How to tackle the problem?

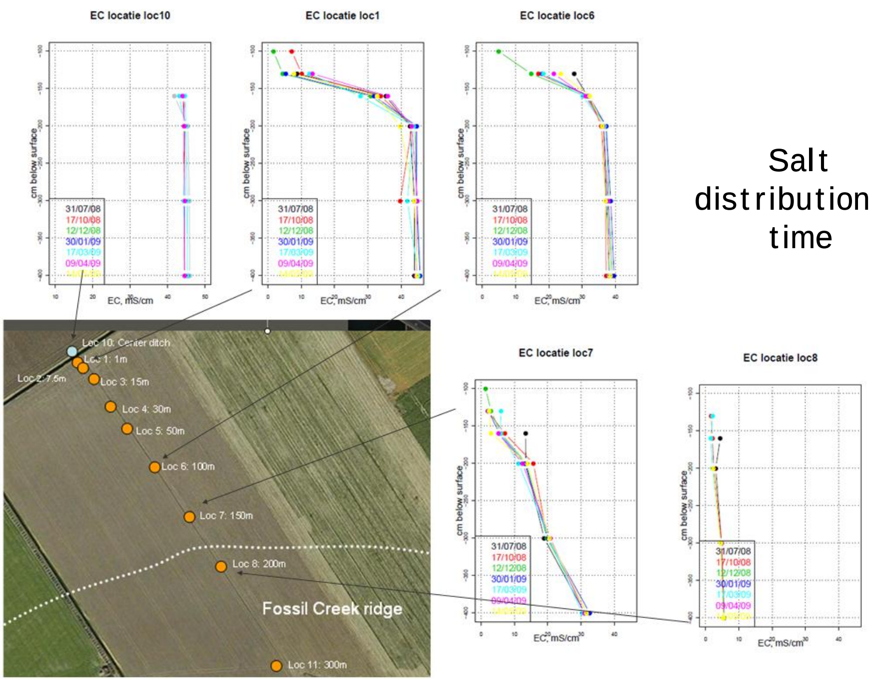
Field measurements at parcels

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

Modelling

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

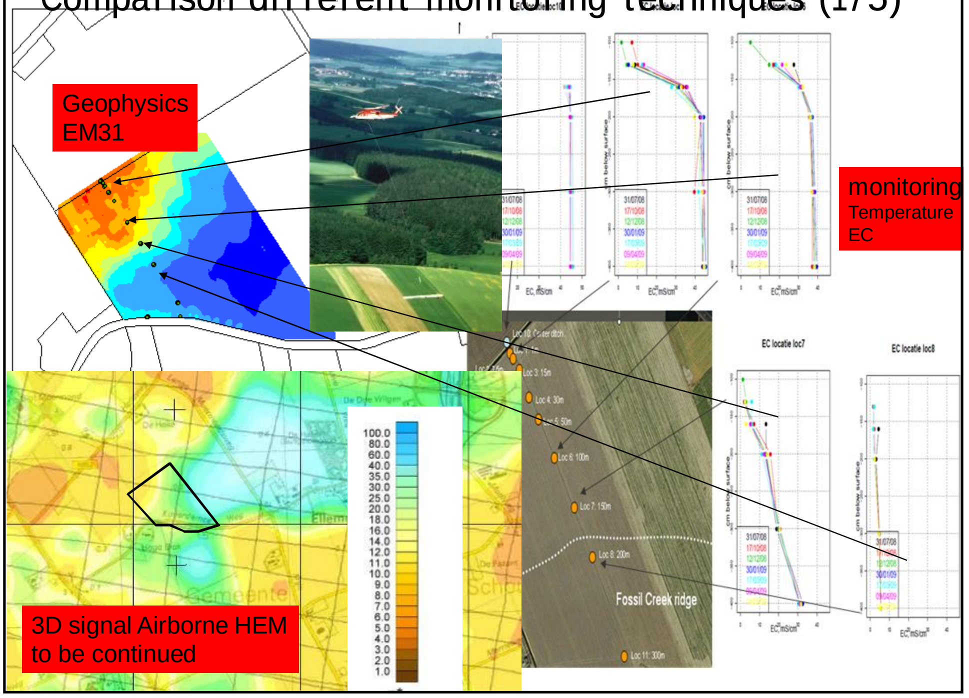




Salt distribution in time

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

Comparison different monitoring techniques (1/5)

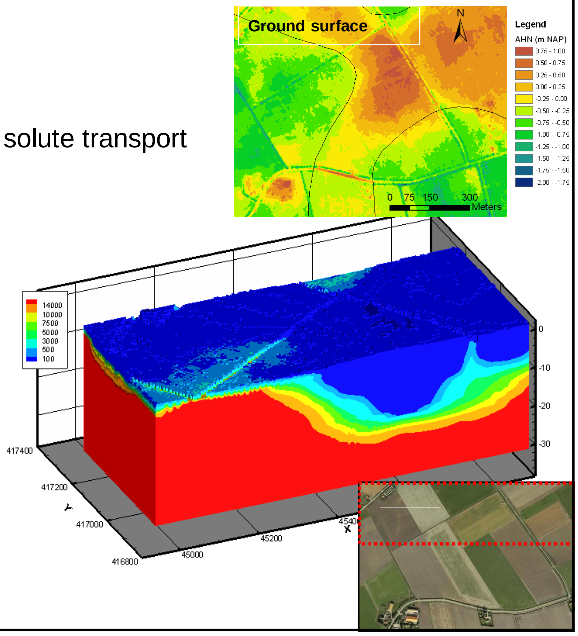


Local 3D model of the agricultural plot

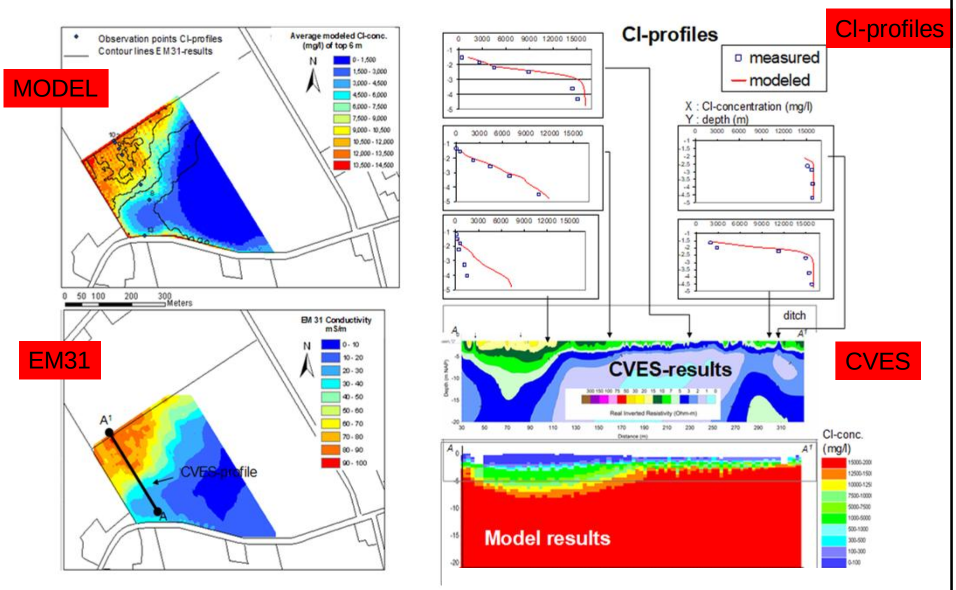
Modelling:
- variable-density
- 3D, non-steady
- groundwater flow & coupled solute transport
- model cell size: 5*5m^2

Code:
MOCDENS3D

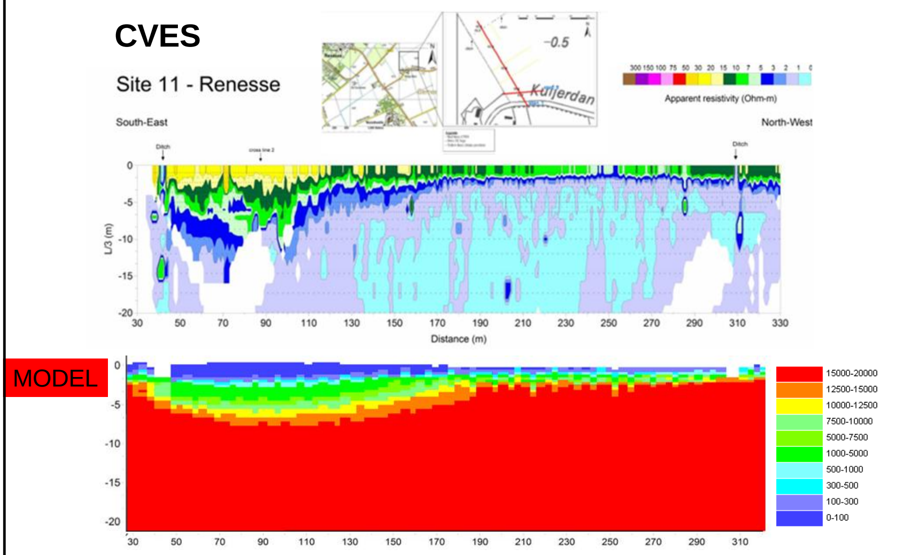
Assessing effects:
- autonomous salinisation
- sea level rise
- changing recharge pattern
- (adaption measures)



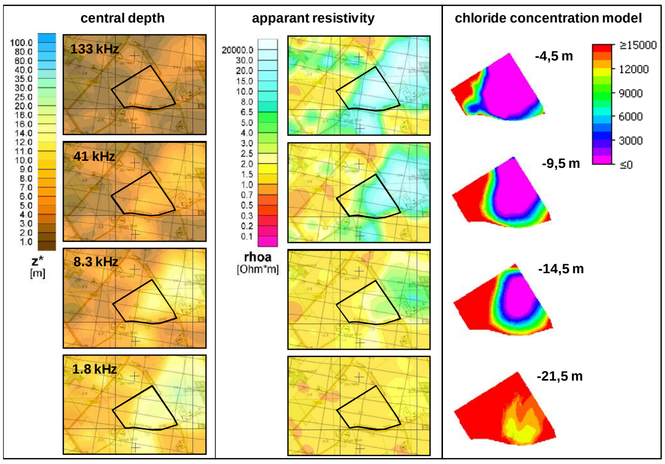
Comparison model with EM31, CVES, profiles



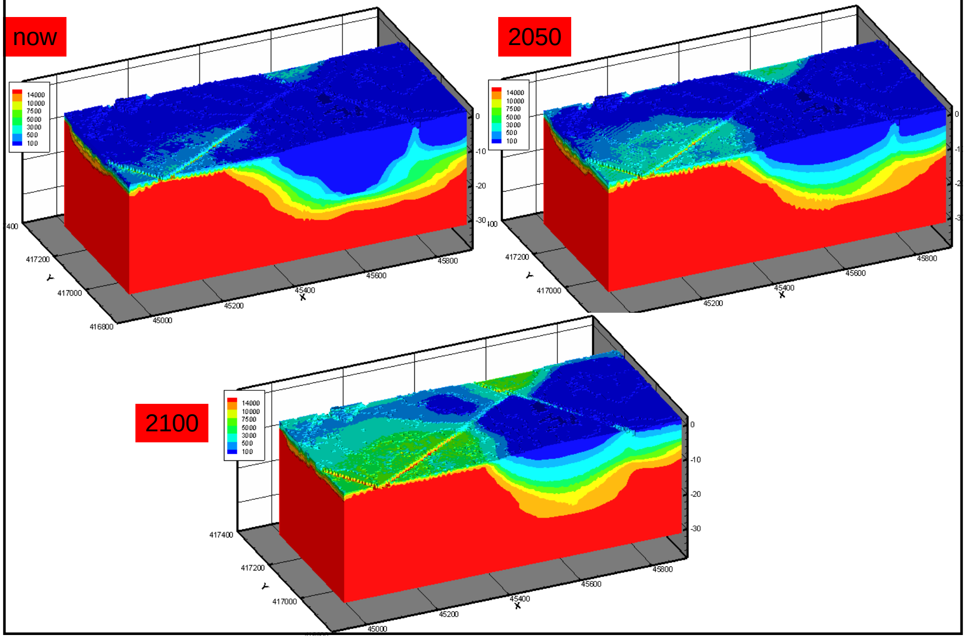
Comparison 3D model and CVES



HEM data



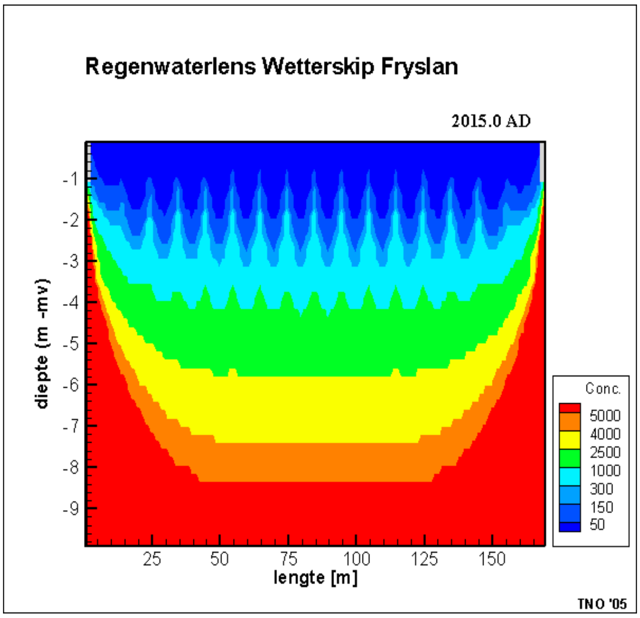
Climate change scenario (dry): model result



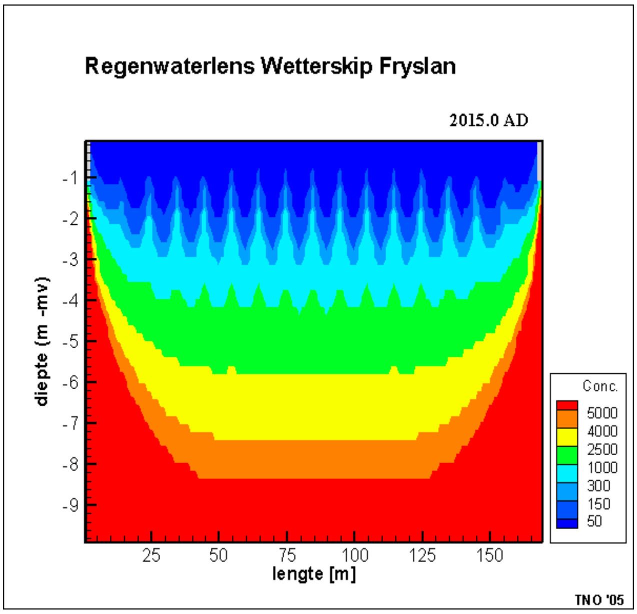
To be continued…

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

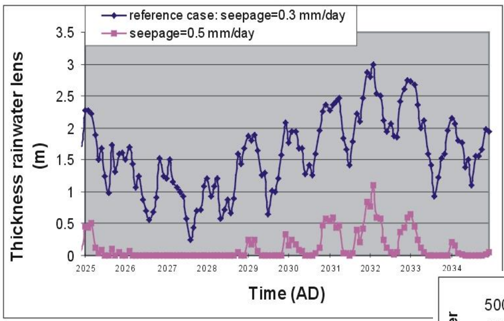
Model the dynamics of fresh-brackish-salt interface



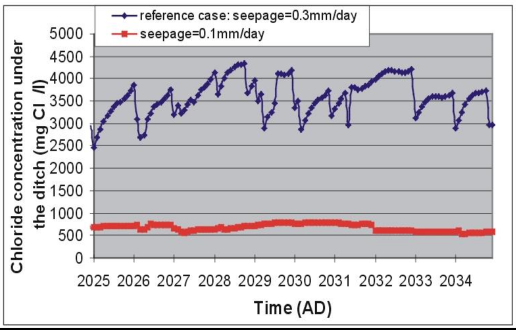
Model the dynamics of fresh-brackish-salt interface



Thickness of the lens and salt load to surface water varies



depends on seepage



Conclusions (salinisation Dutch aquifers):

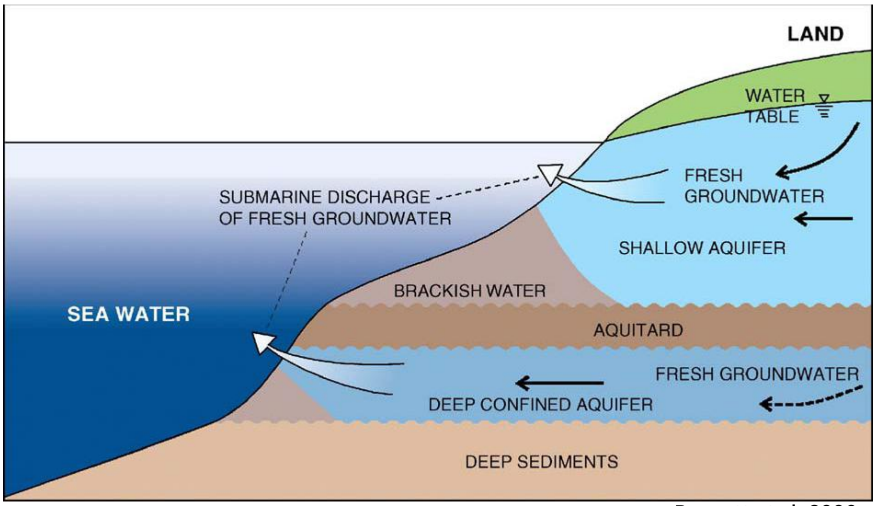
- Salinisation in the Netherlands is a non-stationary process
- Three physical processes threaten the Dutch aquifers:
  - autonomous development
  - land subsidence
  - sea level rise
- Increase in seepage and salt load can be severe during the coming 50/100 years
- Modelling techniques are available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

Recommendations (salinisation Dutch aquifers):

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

What is Submarine Groundwater Discharge (SGD)?

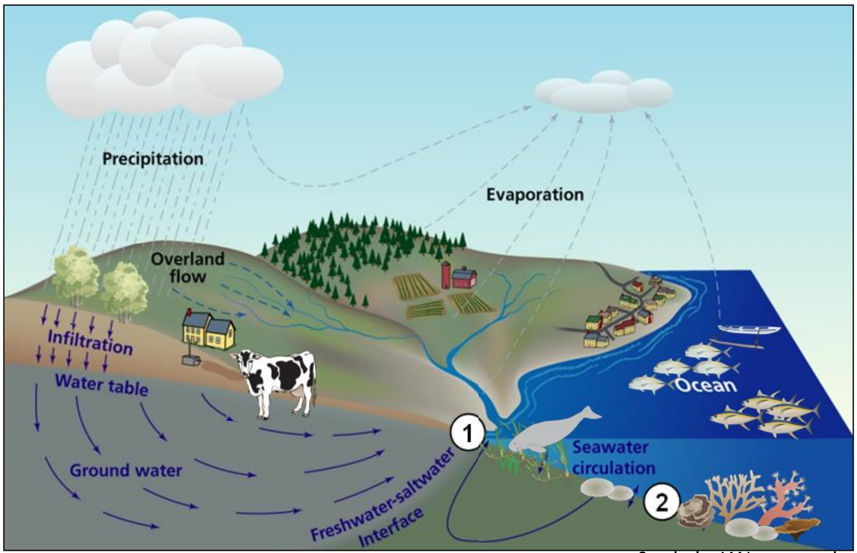
any flow of water out across the sea floor



Burnett et al, 2006

Why study SGD?

Nutrients are transported from land to sea via SGD pathway



Symbols: IAN.umces.edu

Why study SGD?

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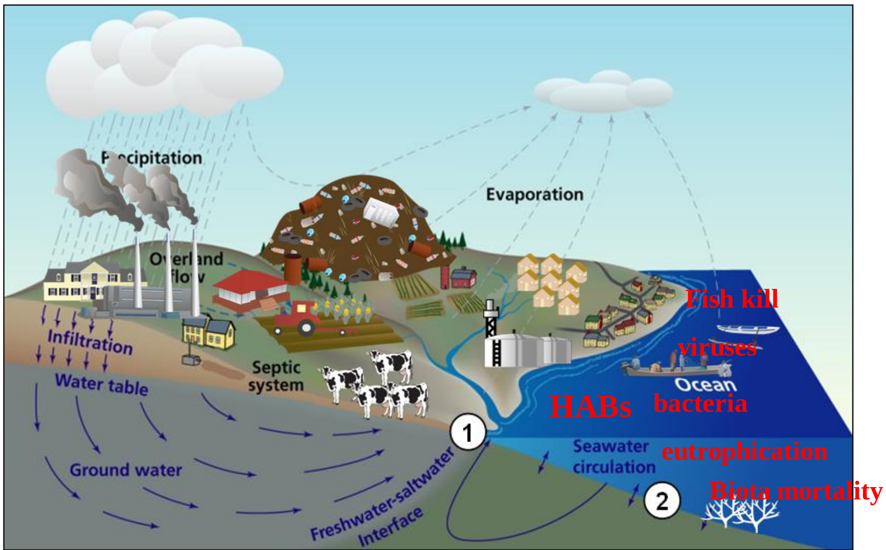
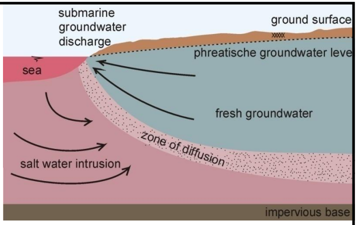
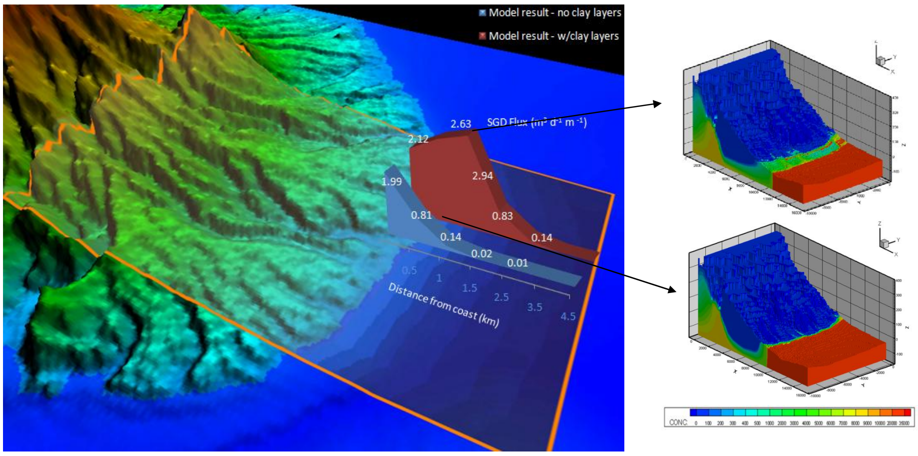


Symbols: IAN.umces.edu

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

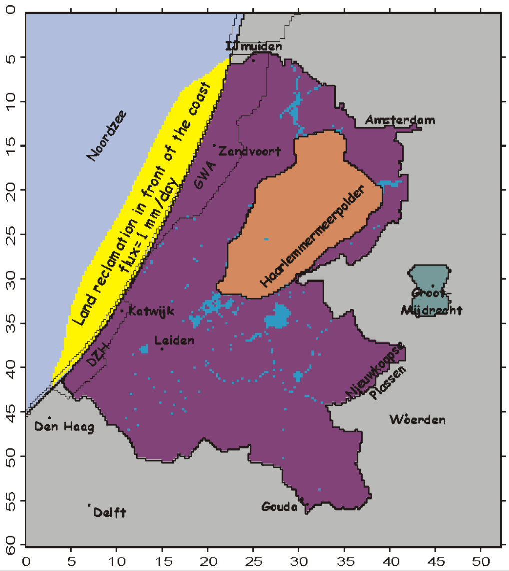
Challenges for the future

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

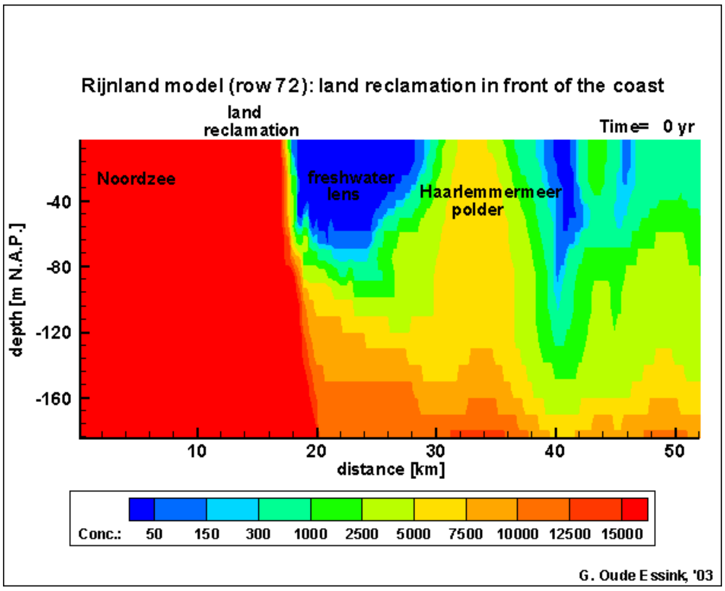
Possible measures to compensate salt water intrusion

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

1. Rijnland model: land reclamation case



1. Land reclamation in front of the coast

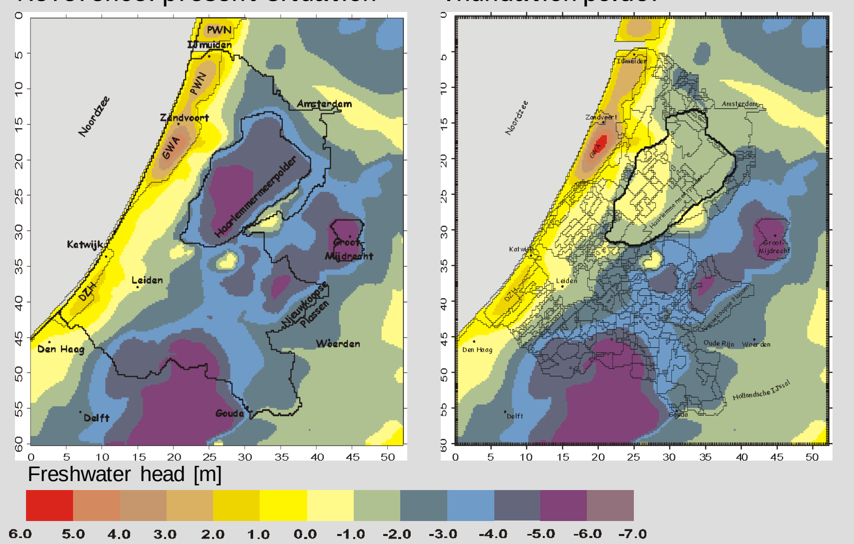


Rijnland

2. Rijnland model: Inundation Haarlemmermeerpolder

Calculated present phreatic water head

Reference: present situation Inundation polder

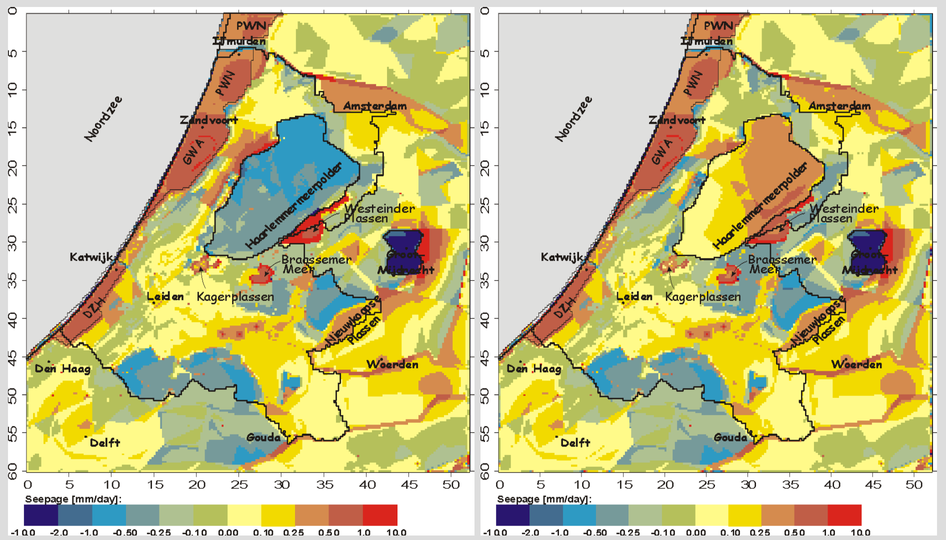


Rijnland

2. Rijnland model : Inundation Haarlemmermeerpolder

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

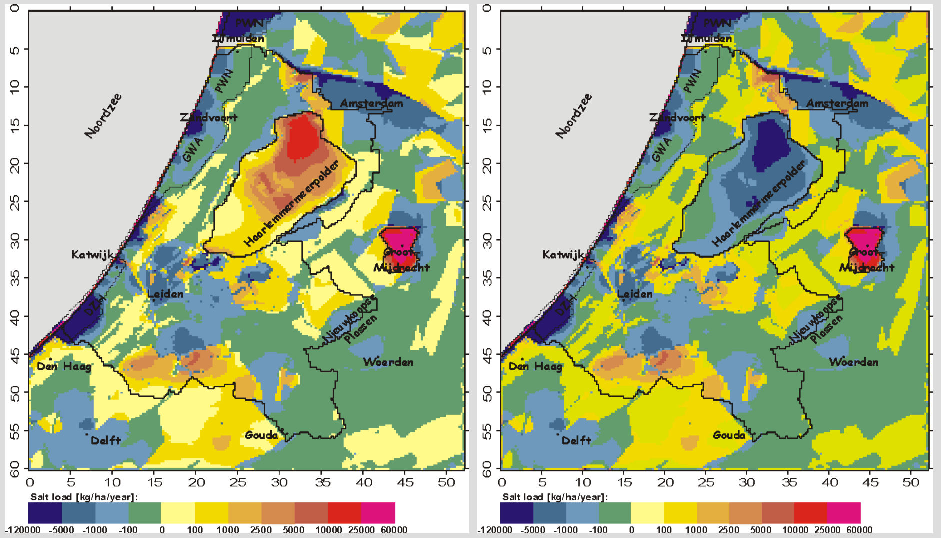
Reference: present situation Inundation polder



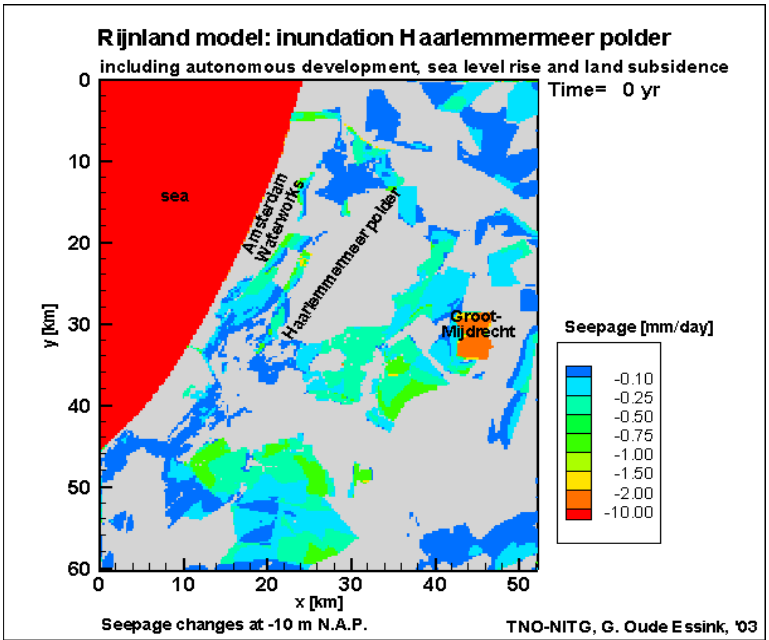
2. Rijnland model: Inundation Haarlemmermeerpolder

Calculated salt load on –10 m M.S.L.

Reference: present situation | Inundation polder



2. Rijnland model: Inundation Haarlemmermeerpolder



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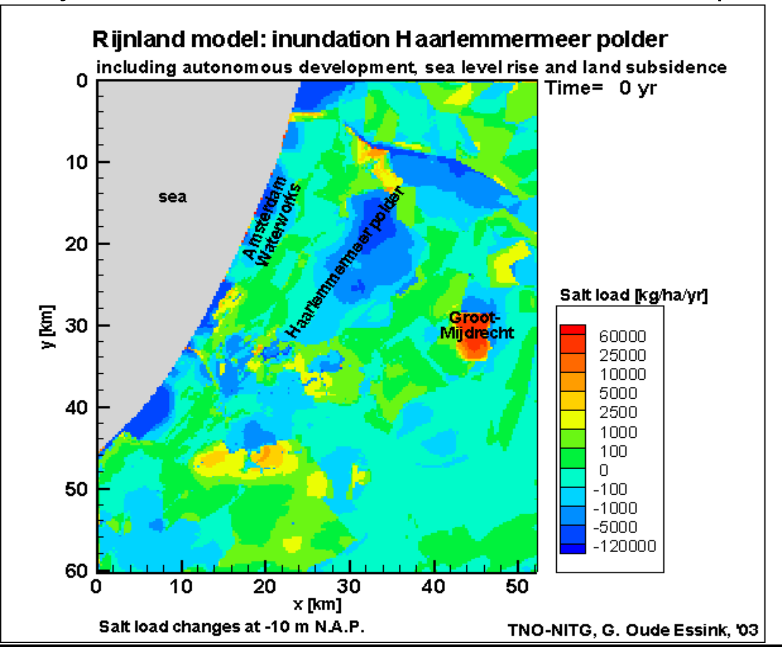
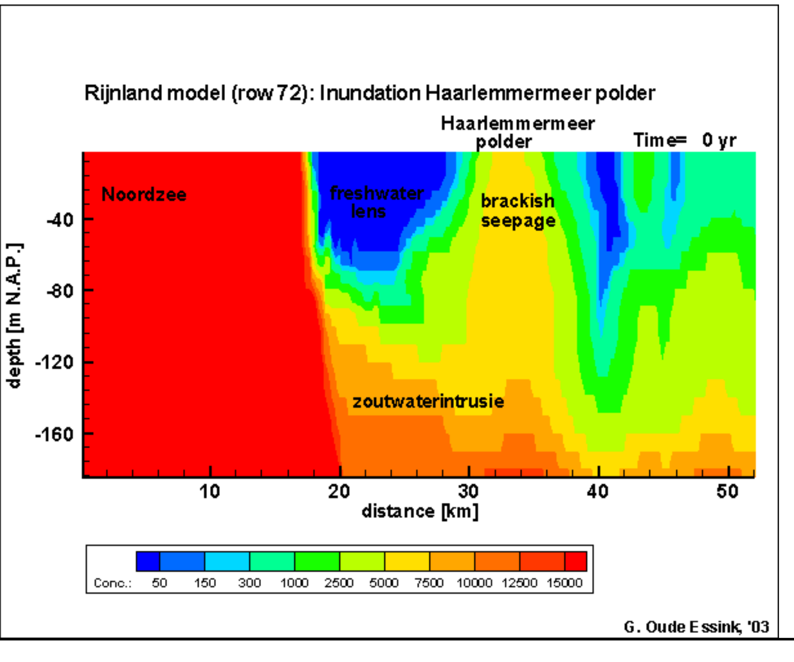
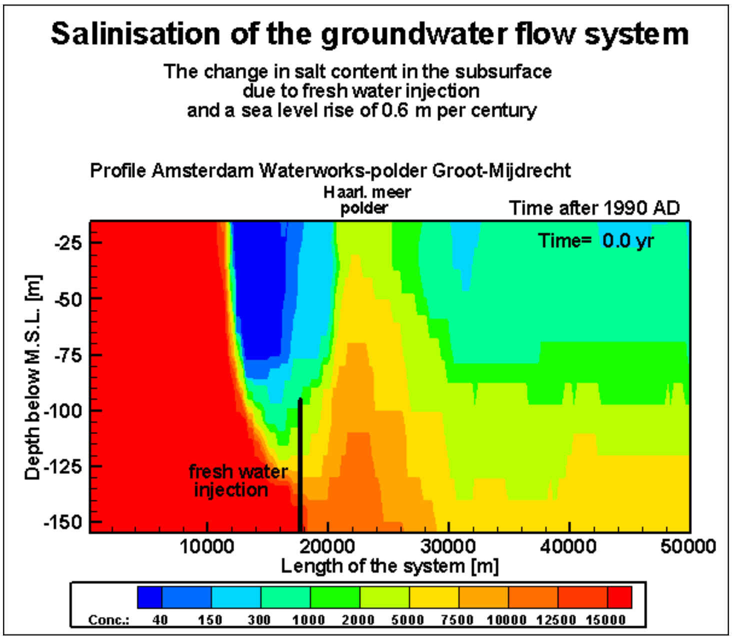


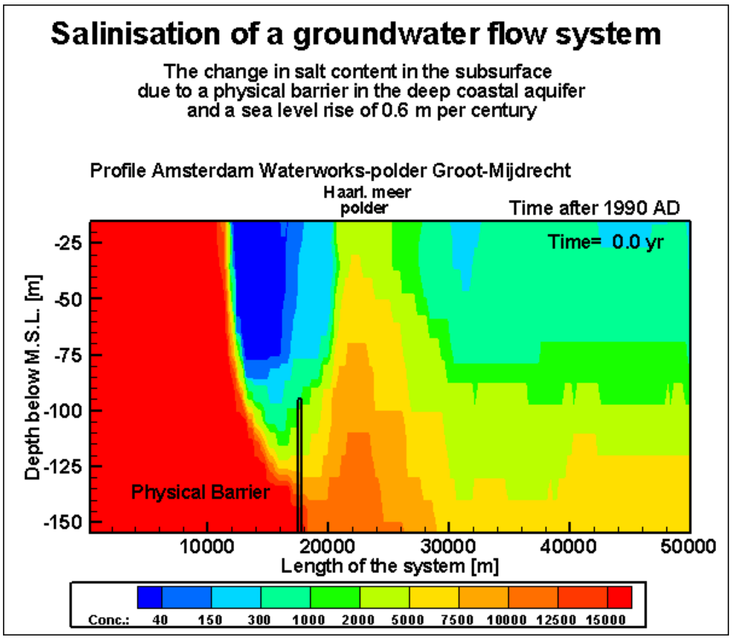
2. Rijnland model: Inundation Haarl.polder (conc, 500 jr)



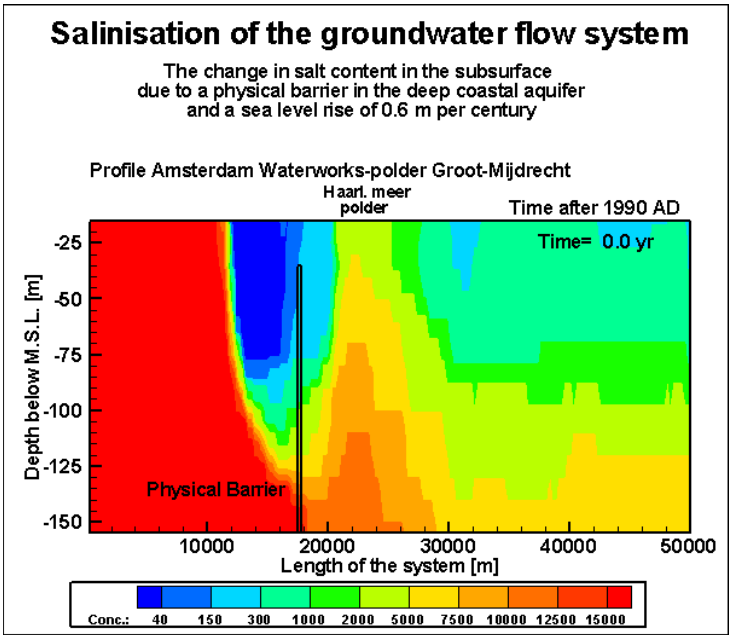
4. Injection of fresh water (conc, 1000 yr)



5. Physical barrier (conc, 1000 yr)



5. Physical barrier (conc, 1000 yr)



Solute transport models

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

Solute transport equation

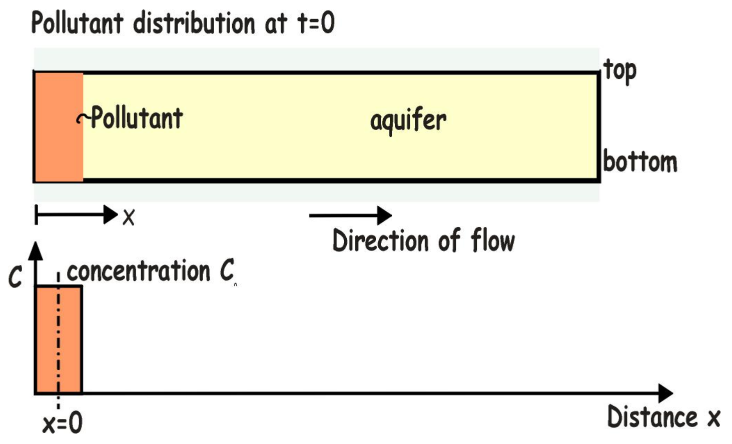
Partial differential equation (PDE):

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

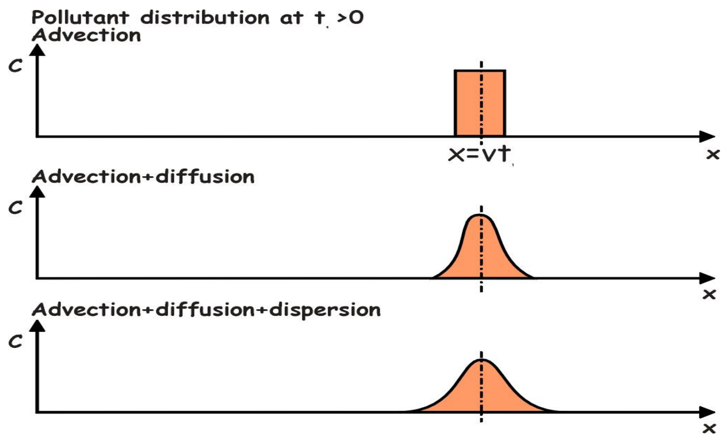
change in concentration | dispersion diffusion | advection | source/sink | decay

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

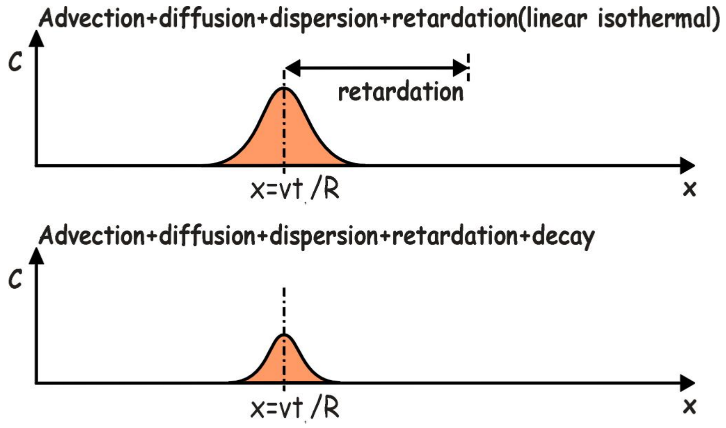
Solute transport equation: column test (I):



Solute transport equation: column test (II):



Solute transport equation: column test (III):



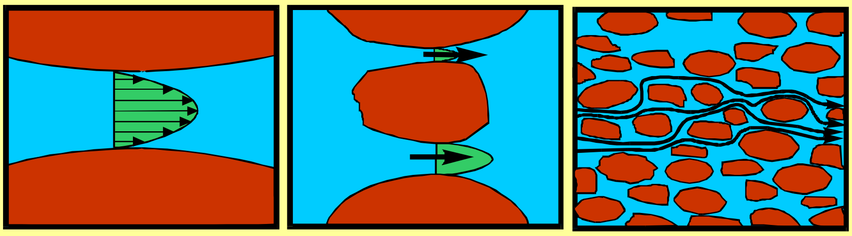
Hydrodynamic dispersion

hydrodynamic dispersion
=
mechanical dispersion+ diffusion

mechanical dispersion:
- tensor
- velocity dependant

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

Mechanical dispersion



Differences in velocity in the pore | **Differences in velocity due to variation in pore-dimension** | **Differences in velocity due to variation in velocity direction**

Solute transport equation: diffusion (I)

diffusion is a slow process: diffusion equation

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

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

similarity with non-steady state groundwater flow equation

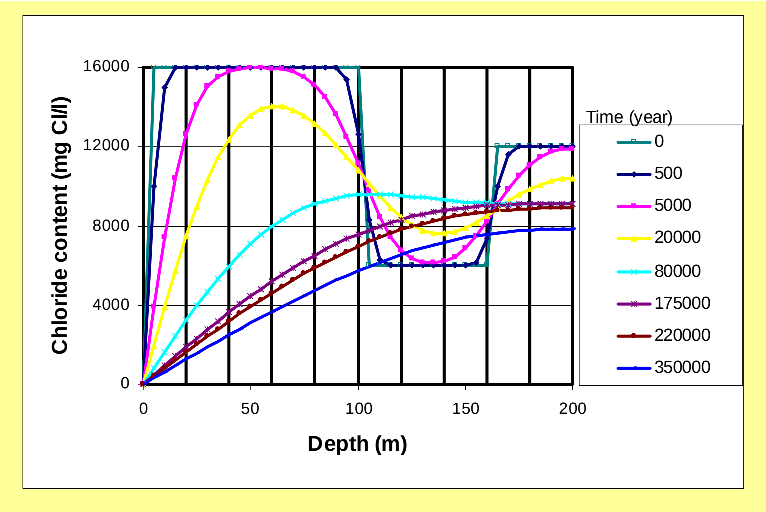
$$S\frac{\partial \phi}{\partial t} = T\frac{\partial^2 \phi}{\partial x^2} + N \qquad \frac{T\Delta t}{S\Delta x^2} < 0.5$$

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

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

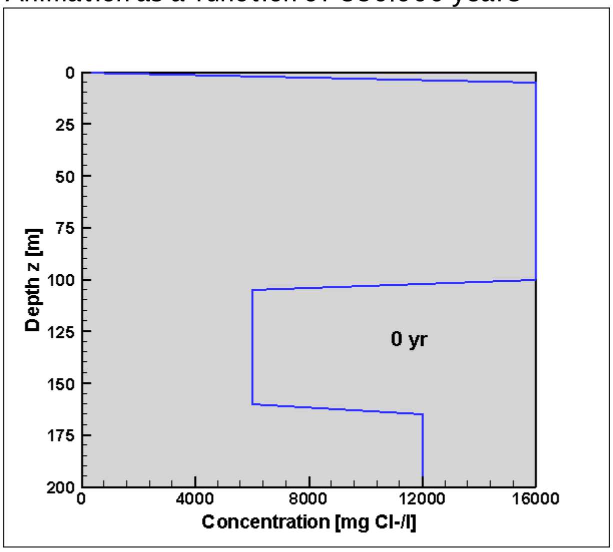
Solute transport equation: diffusion (II)

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



Solute transport equation: diffusion (III)

Animation as a function of 350.000 years



Groundwater flow equation (MODFLOW, 1988)

Darcy

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

Continuity

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

buoyancy term

Freshwater head

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

Advection-dispersion equation (MOC3D, 1996)

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

Equation of state: relation density & concentration

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

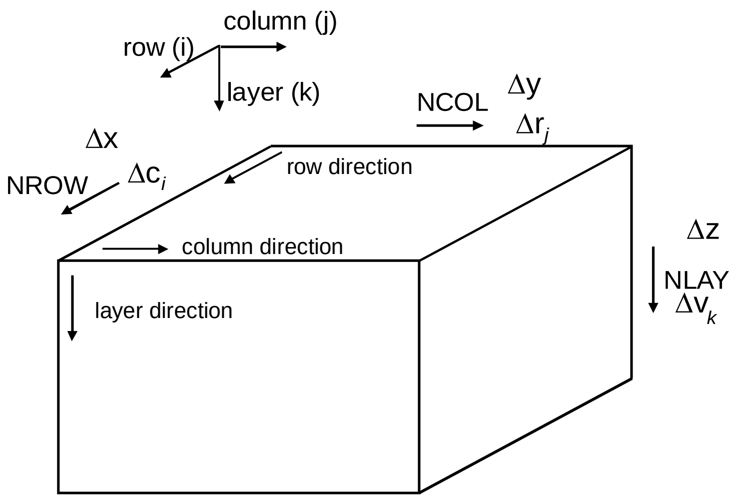
MOCDENS3D is based on MODFLOW

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

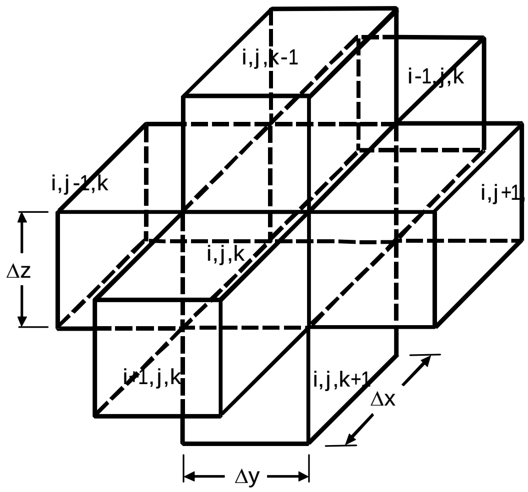
(M.G. McDonald & A.W. Harbaugh, from 1983 on)

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

Nomenclature MODFLOW element [i,j,k]



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



MODFLOW

Continuity equation (I)

In - Out = Storage

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

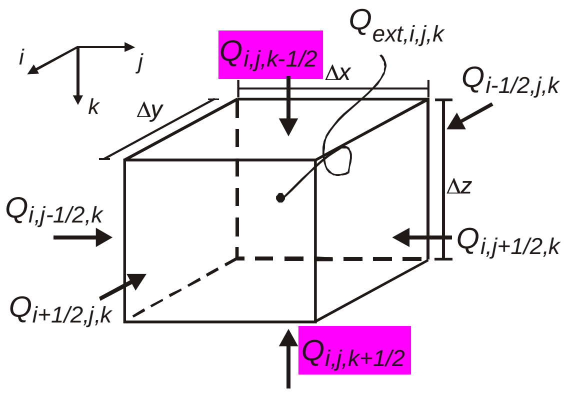
$$\sum Q_i = S_s \frac{\Delta \phi}{\Delta t}\Delta V$$

MOCDENS3D

Continuity equation (II)

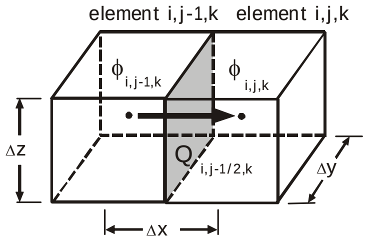
$$\sum Q_i = S_s \frac{\Delta \phi}{\Delta t}\Delta V$$

In = positive



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

Flow equation (Darcy's Law)



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

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

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

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

Density dependent vertical flow equation

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

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

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

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

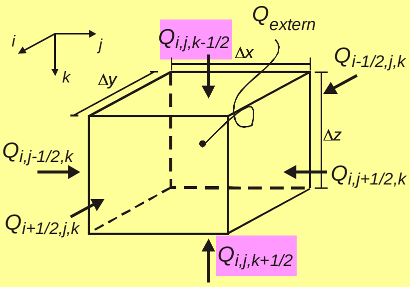
$$Q_{i,j,k-1/2} = CV_{i,j,k-1/2}\left(\phi_{f,i,j,k-1} - \phi_{f,i,j,k} + BUOY_{i,j,k-1/2}\Delta z\right)$$

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

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

Density dependent groundwater flow equation

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



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

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

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

Takes into account all external sources

Rewriting the term:

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

Thé variable density groundwater flow equation

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

and:

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

gives:

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

with :

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

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

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

Equation of state

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

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

or

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

MODFLOW

Method of Characteristics (MOC)

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

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

Lagrangian approach:

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

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

MOC3D

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

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

The Peclet number stands for the ratio between advection and dispersion

Procedure of MOC: advective transport by particle tracking

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

Steps in MOC-procedure

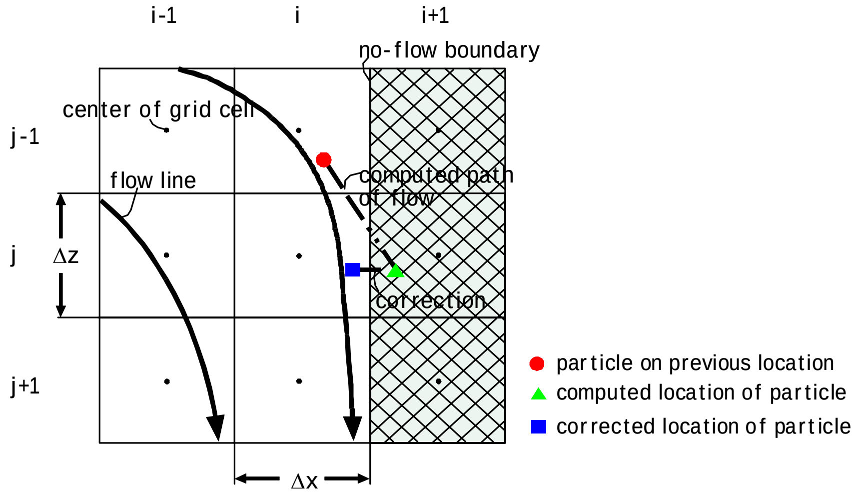
1. Determine concentration gradients at old timestep k-1
2. Move particles to model advective transport
3. Concentration of particles to concentration in element node
4. Determine concentration gradients on new timestep k*
5. Determine concentration in element node after advective, dispersive/source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

Konikow and Bredehoeft, 1978

Causes of errors in MOC-procedure

1. Concentration gradients
2. Average from particles to node element, and visa versa
3. Concentration of sources/sinks to entire element
4. Empty elements
5. No-flow boundary: reflection in boundary

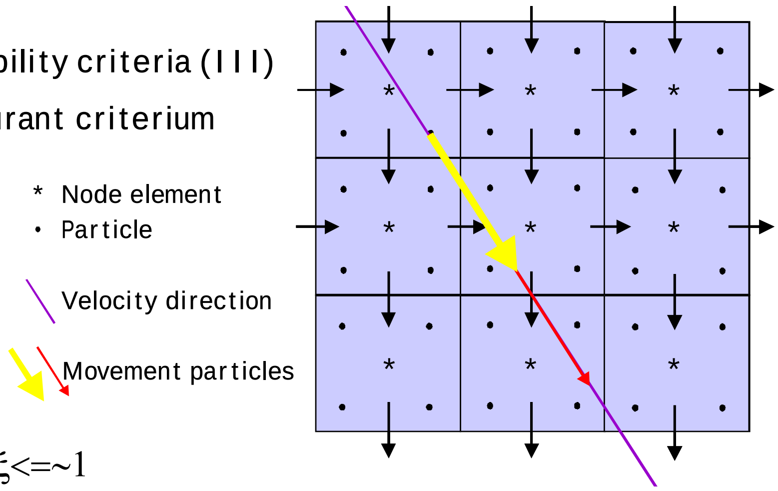
Reflection in boundary



MOC3D

Stability criteria (III)

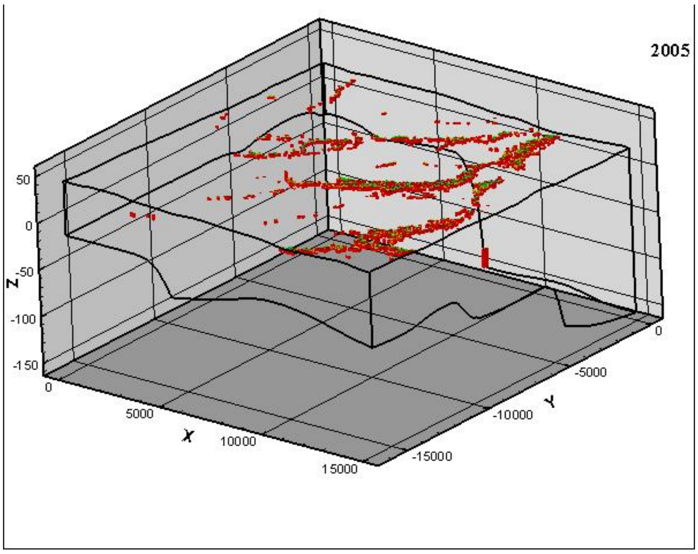
3. Courant criterium



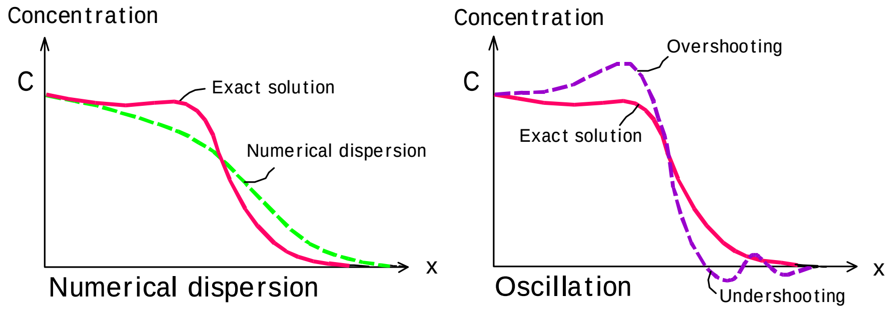
$0<\xi<=\sim 1$

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

Courant criterion: places where timestep is smaller than 40 days



Numerical dispersion and oscillation



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

Numerical dispersion problem (I)

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

Peclet number $Pe \leq 2$ to 4

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

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

Numerical dispersion problem (II)

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

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

where α_L = longitudinal dispersivity [L]

What does that mean?

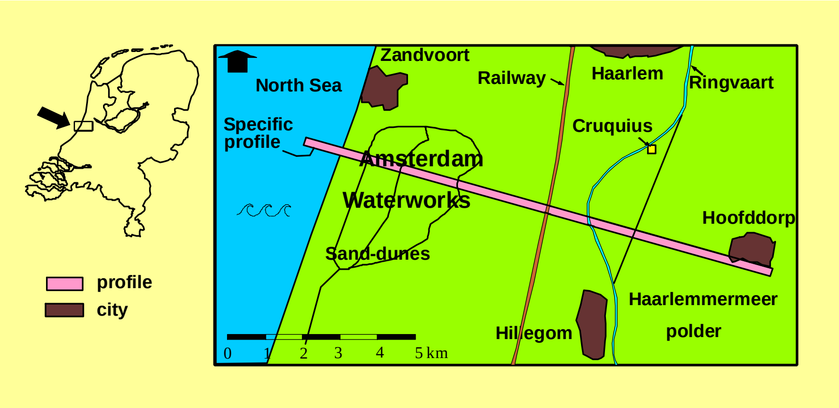
If α_L is small, then Δx should be small too!!

Numerical dispersion problem (III)

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

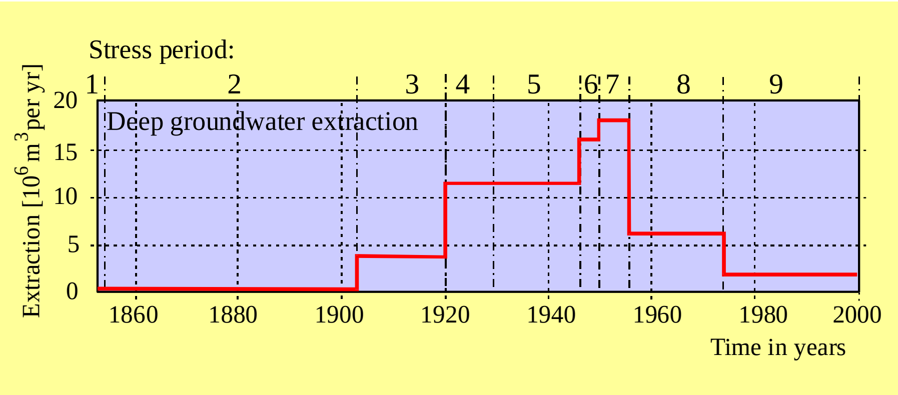
Effect of α_L on the salinisation of the aquifer (I)

Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



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

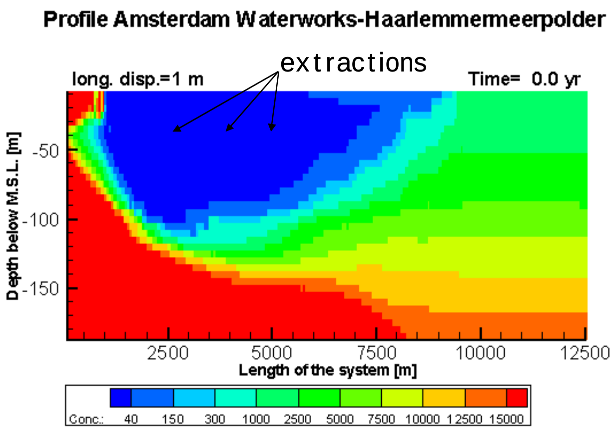
Grondwater extractions out of the middle aquifer in the sand-dune area of Amsterdam Waterworks



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

α_L=1 m

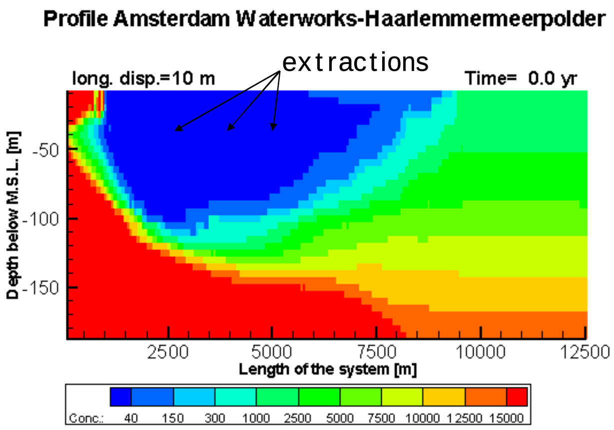
Initial situation: 154 years ago



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

α_L=10 m

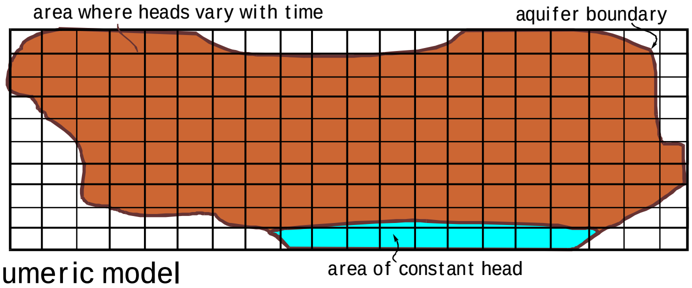
Initial situation: 154 years ago



MODFLOW

Boundary conditions in MODFLOW (I)

Example of a system with three types of boundary conditions



Numeric model

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

Boundary conditions in MODFLOW (II)

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

Packages in MODFLOW

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

MODFLOW

1. Well package

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

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

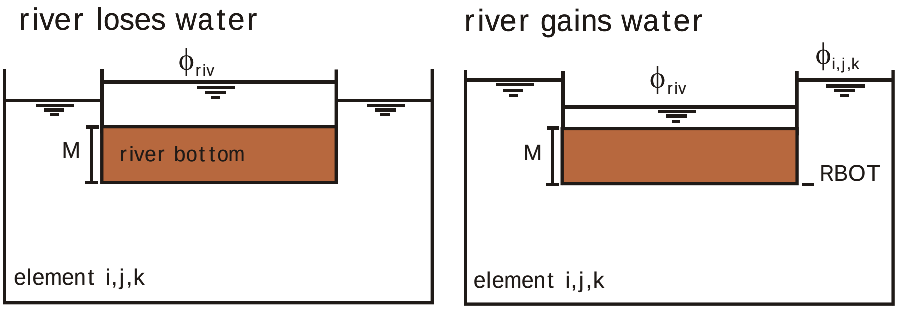
$$Q_{ext,i,j,k} = P_{i,j,k}\phi_{i,j,k}^{t+\Delta t} + Q'_{i,j,k}$$

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

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

MODFLOW

2. River package (I)



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

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

MODFLOW

2. River package (II)

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

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

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

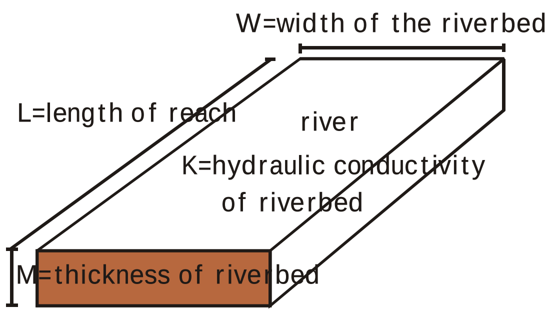
$$Q_{ext,i,j,k} = 20\left(3 - \phi_{i,j,k}\right)$$

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

MODFLOW

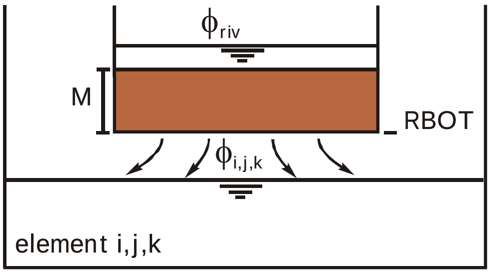
2. River package (III)

Determine the conductance of the river in one element:



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

2. River package (IV)
Leakage to the groundwater system

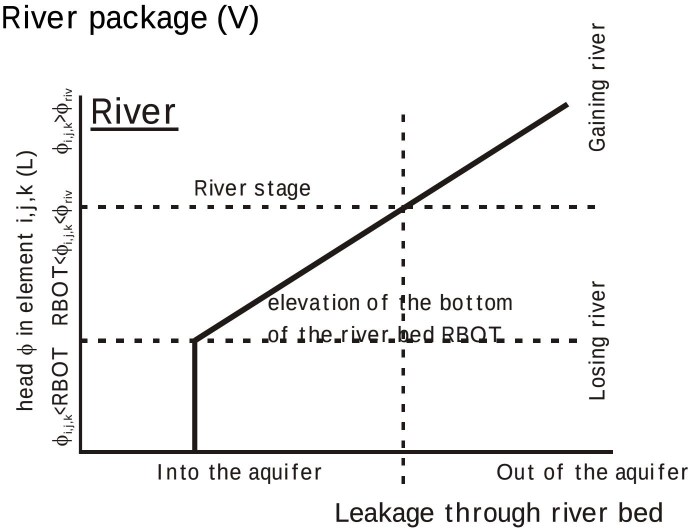


Special case:

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

MODFLOW

2. River package (V)

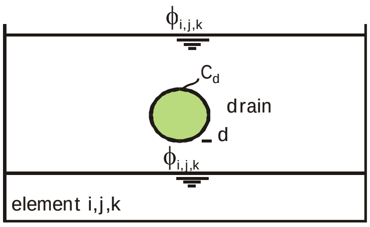


3. Recharge package

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

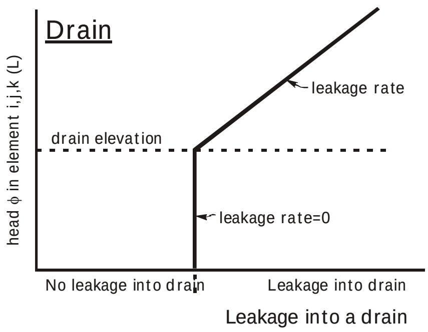
4. Drain package

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

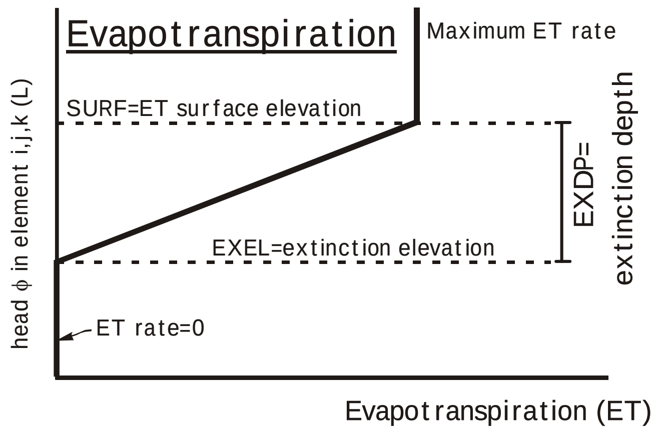


Special case:

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

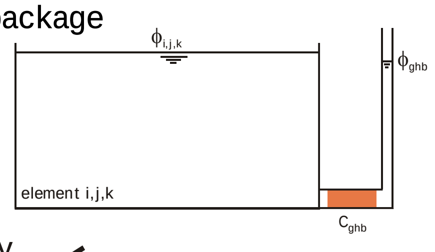


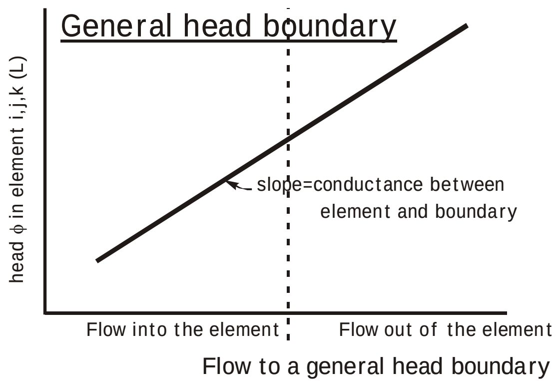
5. Evapotranspiration package



6. General head boundary package

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





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

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