Deltares
Enabling Delta Life

Zoetzout grondwater cursus, deel 1

Gualbert Oude Essink
Bodem en Grondwater Systemen
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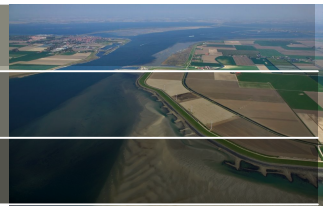
zoetzout.deltares.nl

Afleiding numerieke dispersie: 1D (IV)



$$\frac{\partial^2 C}{\partial t^2}$$

$$\frac{\partial^2 C}{\partial t^2} = \frac{\partial}{\partial t}\left(\frac{\partial C}{\partial t}\right) = \frac{\partial}{\partial t}\left(D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x}\right) = D\frac{\partial^2}{\partial x^2}\left(\frac{\partial C}{\partial t}\right) - V\frac{\partial}{\partial x}\left(\frac{\partial C}{\partial t}\right)$$

$$\frac{\partial^2 C}{\partial t^2} = D\frac{\partial^2}{\partial x^2}\left(D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x}\right) - V\frac{\partial}{\partial x}\left(D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x}\right)$$

$$\frac{\partial^2 C}{\partial t^2} = D^2\frac{\partial^4 C}{\partial x^4} - VD\frac{\partial^3 C}{\partial x^3} - VD\frac{\partial^3 C}{\partial x^3} + V^2\frac{\partial^2 C}{\partial x^2}$$

$$\frac{\partial^2 C}{\partial t^2} \approx V^2\frac{\partial^2 C}{\partial x^2}$$

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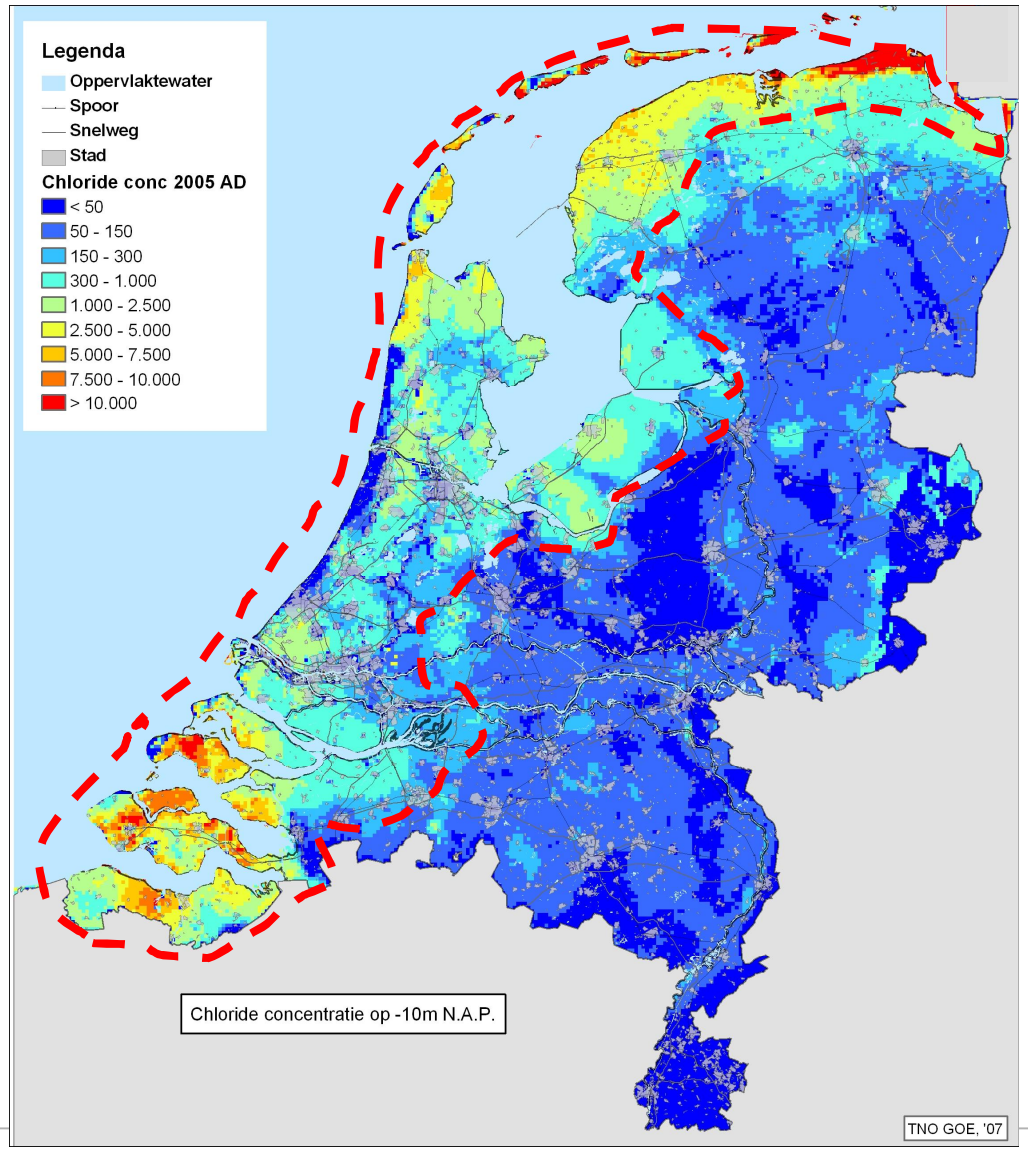
Chloride verdeling op -10m N.A.P.



gebied waar de chloride concentratie

In de ondergrond zodanig hoog is

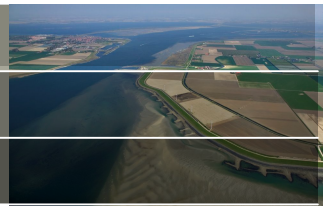
dat dichtheidseffecten op de

grondwaterstroming waarschijnlijk

een rol spelen

Drinkwater norm: < 150 mg Cl-/l
Oppervlaktewater: 200 mg Cl-/l
Noordzee: ~ 16800 mg Cl-/l
Stille Oceaan: ~19000 mg Cl-/l
Middellandse Zee: ~22000 mg Cl-/l

Verzoet of verzilt Nederland?



Oorzaken:

1. Autonome effecten
   - bodemdaling
   - inpolderingen
   - land onder NAP

2. Menselijk ingrijpen
   - peilbeheer
   - grondwateronttrekkingen
   - van zoet naar zout (VZM, Waterdunen)

3. Klimaatverandering
   - zeespiegelstijging
   - grondwateraanvulling

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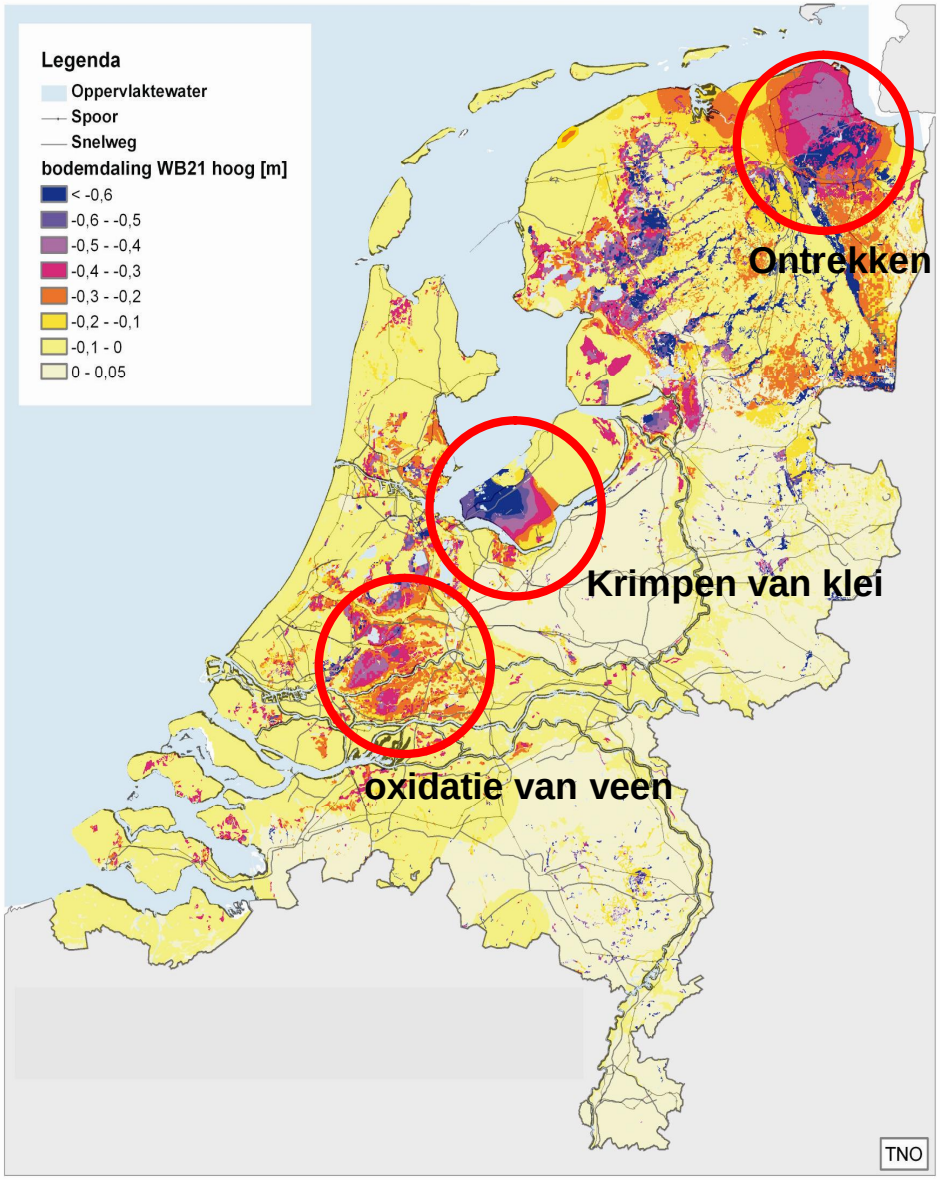
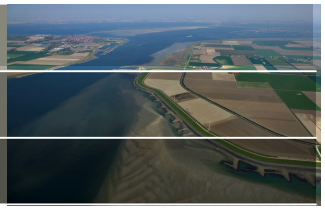
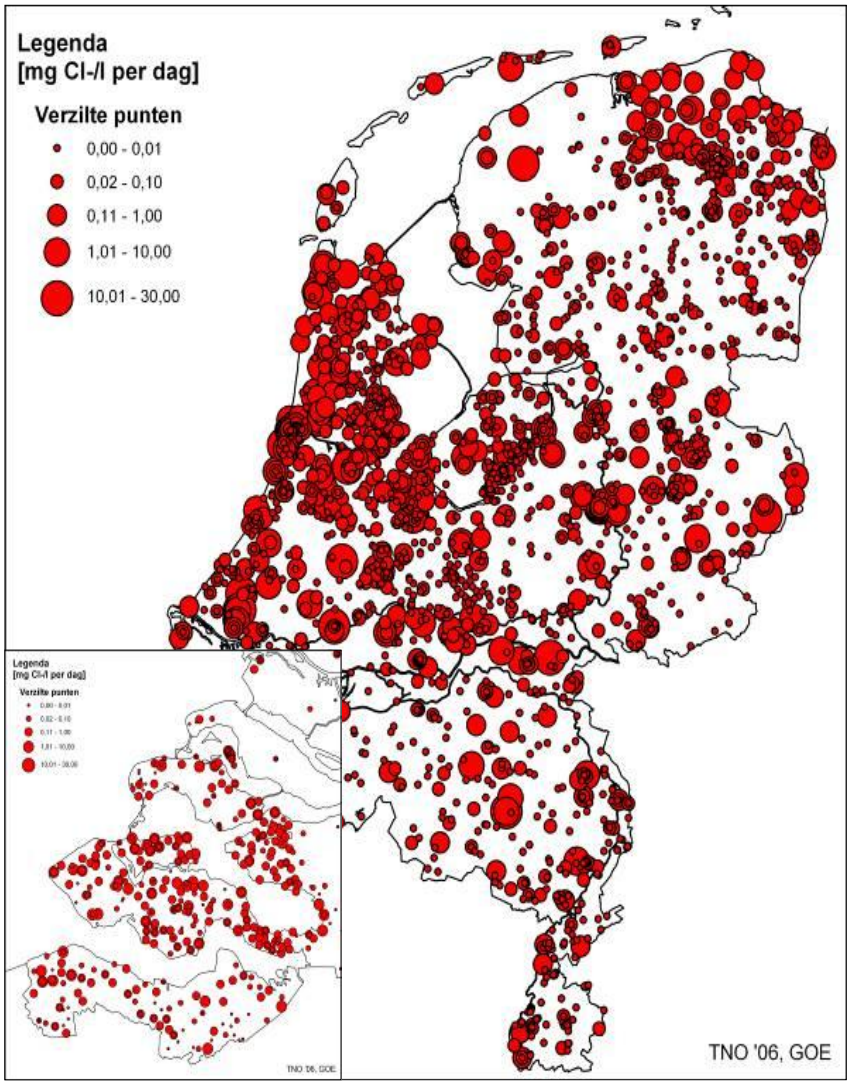
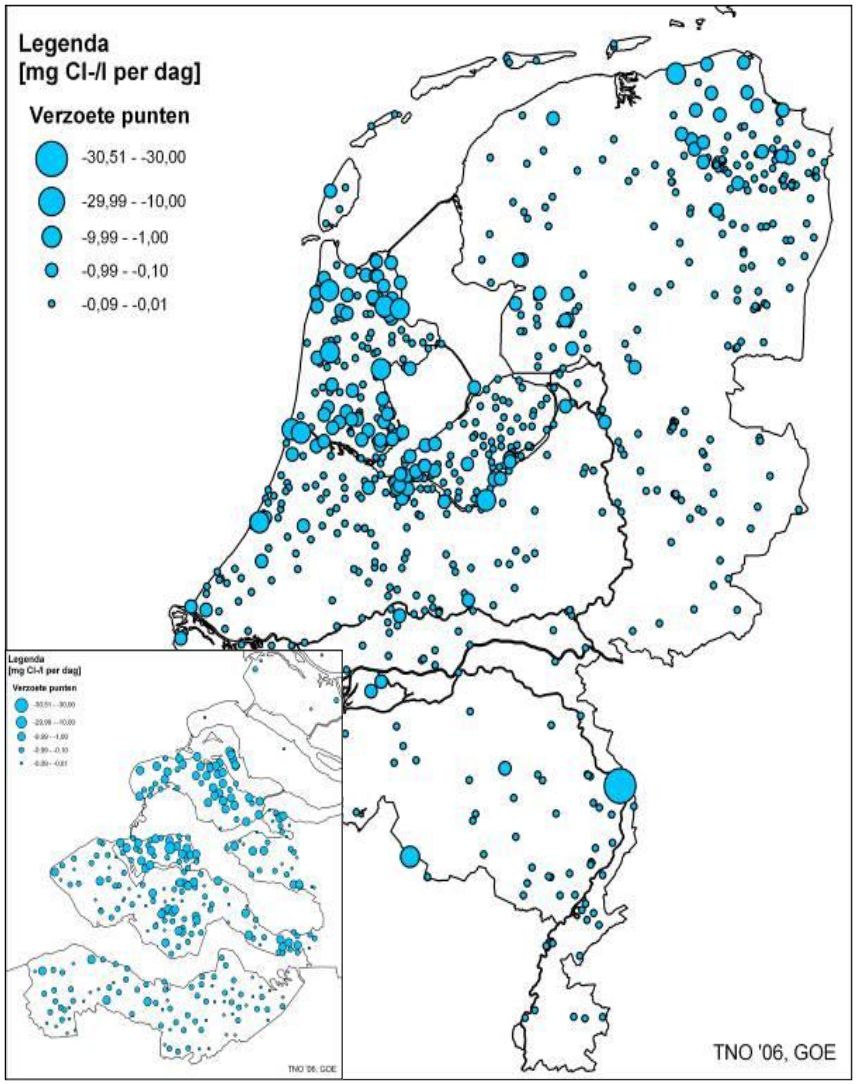
Toekomstige bodemdaling, 2050 AD



Verzoet of verzilt Nederland?







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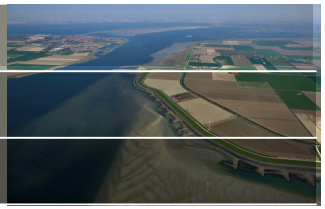
Concept van een kustgebied



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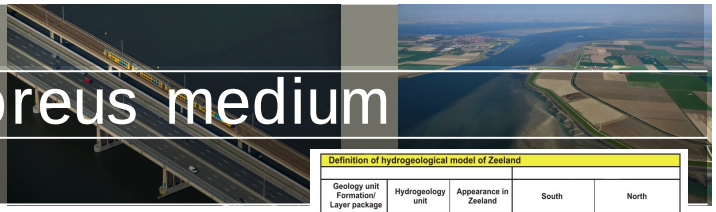
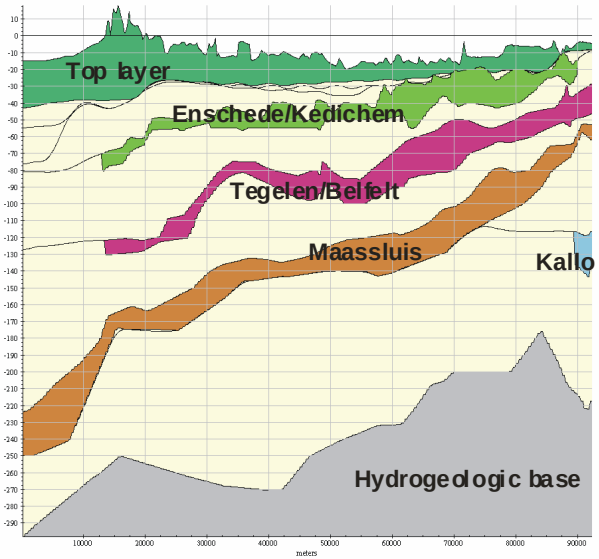
Het grondwater systeem is een poreus medium

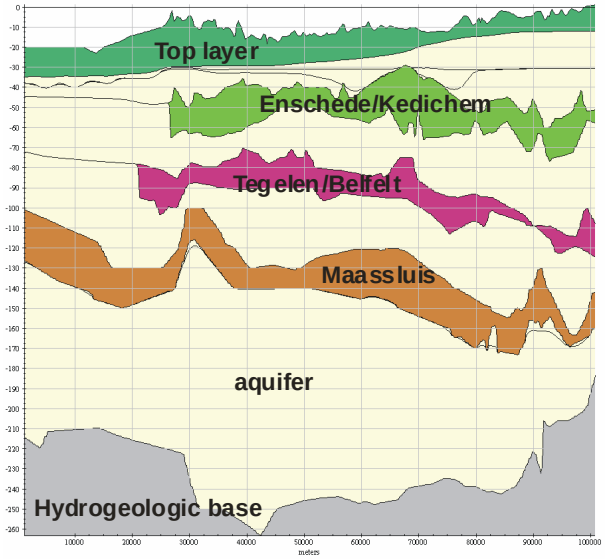


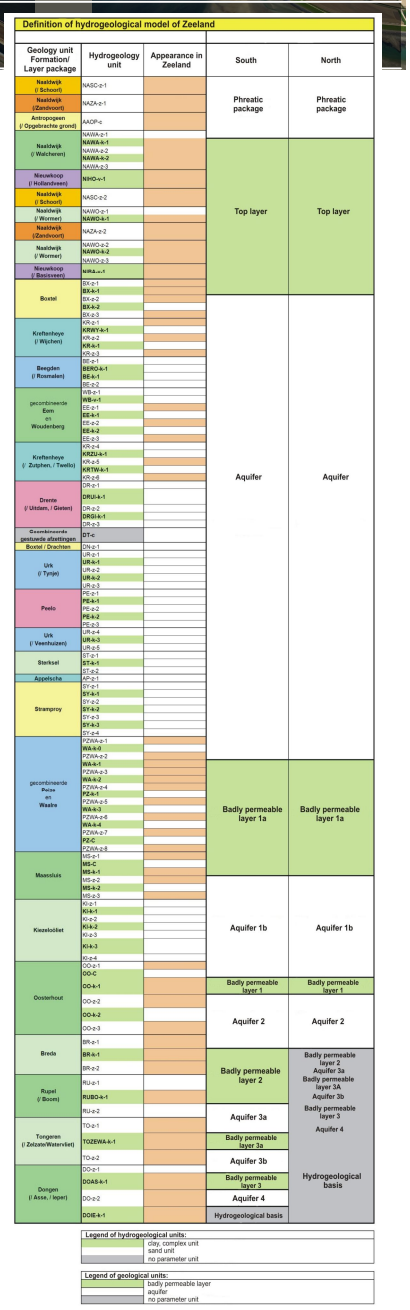
Combinatie van sediment en water

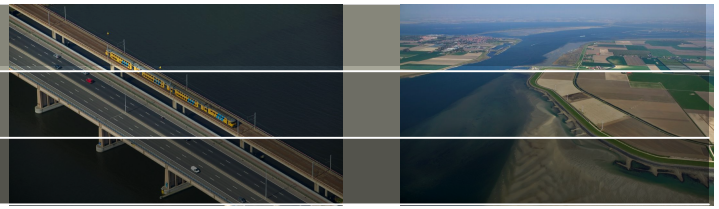
Watervoerende pakketten (aquitard): zand
Weerstandbiedend lagen (aquiclude): klei, veen, leem

Confined aquifer, semi-confined aquifer, phreatic aquifer









Poreuze media

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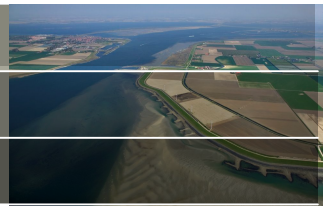
De Wet van Darcy



De beweging van water door een poreus medium is grondwaterstroming

Het kan worden beschreven door de bewegingsvergelijking:

De Wet Van Darcy

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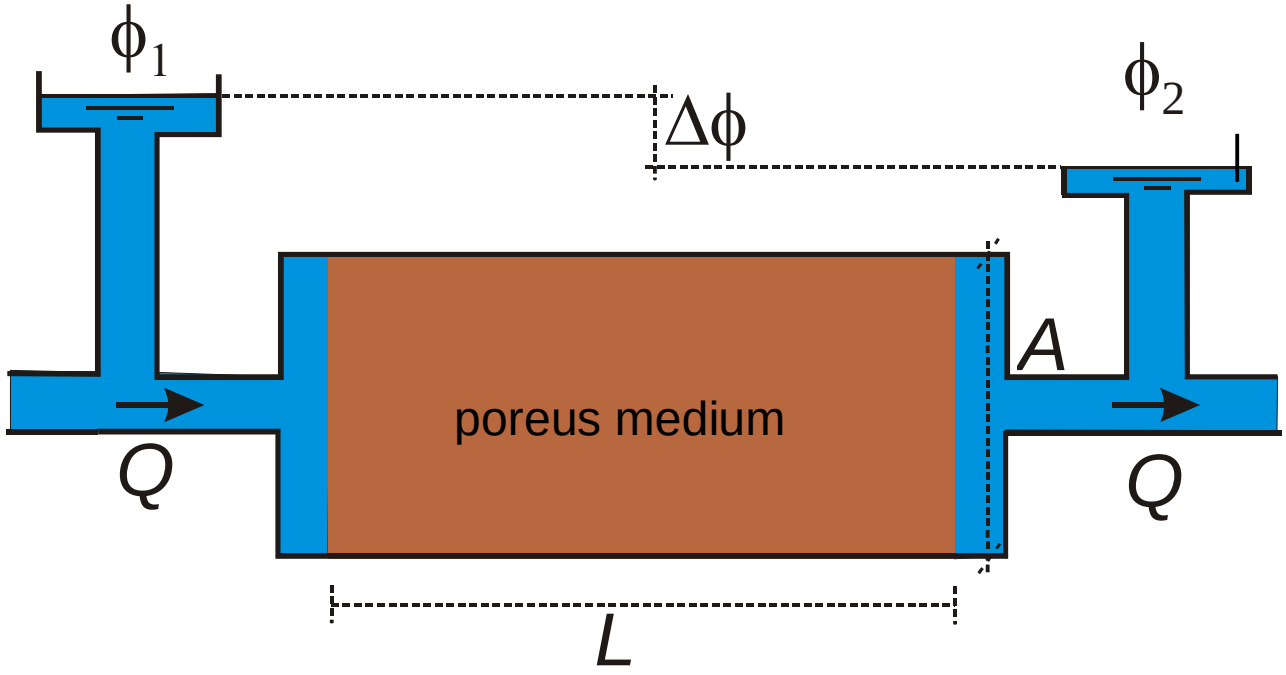
I. Wet van Darcy (1856)

$$\mathrm{Re} = \frac{\rho g R}{\mu} < 1\text{–}10$$



$$Q \propto \phi_1 - \phi_2 \qquad Q \propto \frac{1}{L} \qquad Q \propto A \quad \text{geeft} \quad Q \propto A\frac{\phi_1 - \phi_2}{L}$$

$$Q = KA\frac{\phi_1 - \phi_2}{L} \quad \text{waarin } K = \text{doorlatendheid } [L/T]$$

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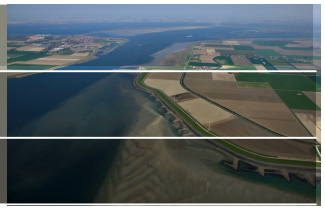
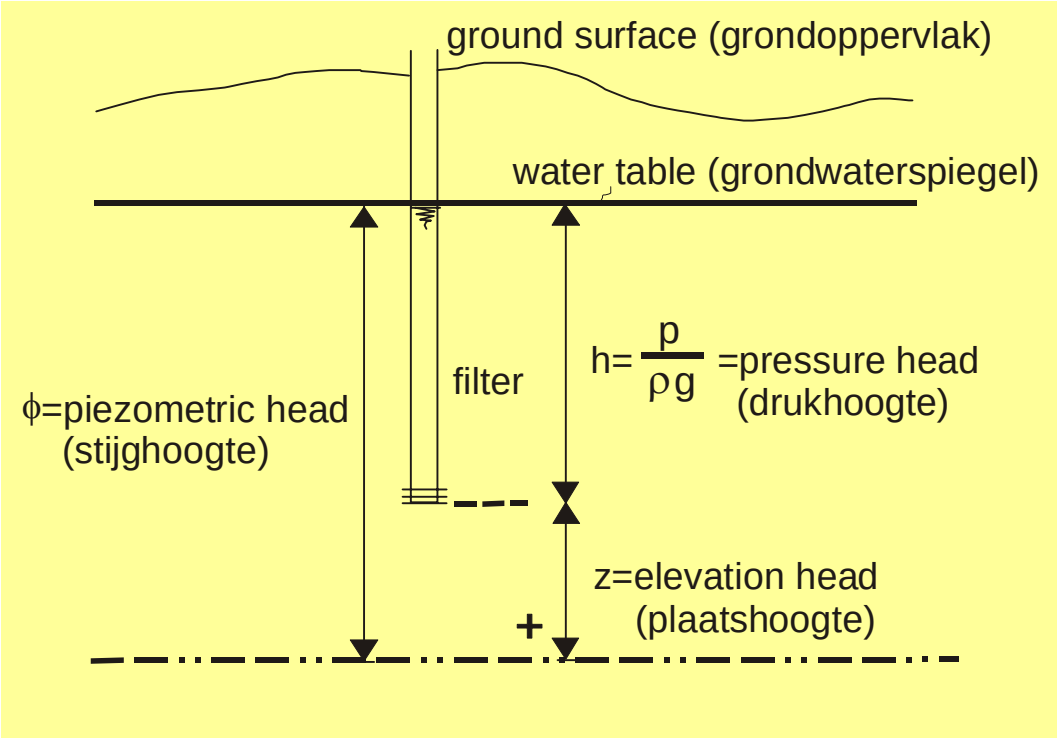
II. Wet van Darcy



In drukken: $q_x = -\frac{\kappa_x}{\mu}\frac{\partial p}{\partial x}$ $q_y = -\frac{\kappa_y}{\mu}\frac{\partial p}{\partial y}$ $q_z = -\frac{\kappa_z}{\mu}\left(\frac{\partial p}{\partial z} + \rho g\right)$

Definitie stijghoogte: $\phi = \frac{p}{\rho g} + z \quad \Leftrightarrow \quad p = \rho g(\phi - z)$



p=druk [M/*LT*^{2}]
κ=intrinsieke permeabiliteit [*L*^{2}]
μ=dynamische viscositeit [M/*LT*]
ρ=dichtheid [*M*/*L*^{3}]
g=versnelling [*L*/*T*^{2}]
k_f=hydraulische conductiviteit [*L*/*T*]

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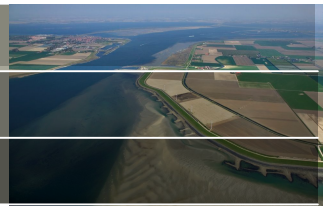
III. Wet van Darcy

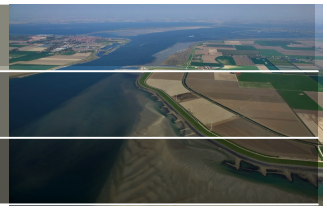


geeft $q_x = -\frac{\kappa_x \rho g}{\mu} \frac{\partial \phi}{\partial x}$ $q_y = -\frac{\kappa_y \rho g}{\mu} \frac{\partial \phi}{\partial y}$ $q_z = -\frac{\kappa_z \rho g}{\mu} \frac{\partial \phi}{\partial z}$

als $\frac{\kappa_i \rho g}{\mu} = k_i$ dan:

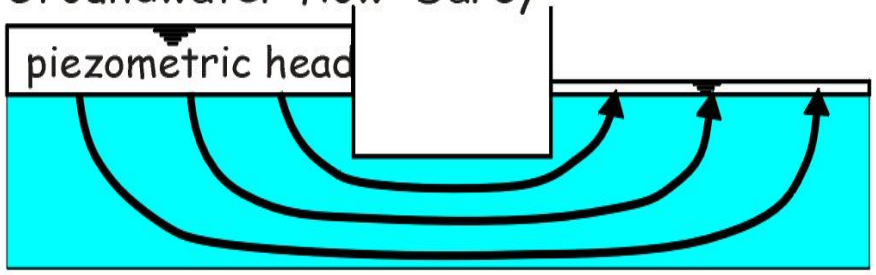
geeft $q_x = -k_x \frac{\partial \phi}{\partial x}$ $q_y = -k_y \frac{\partial \phi}{\partial y}$ $q_z = -k_z \frac{\partial \phi}{\partial z}$

Analogy physical processes



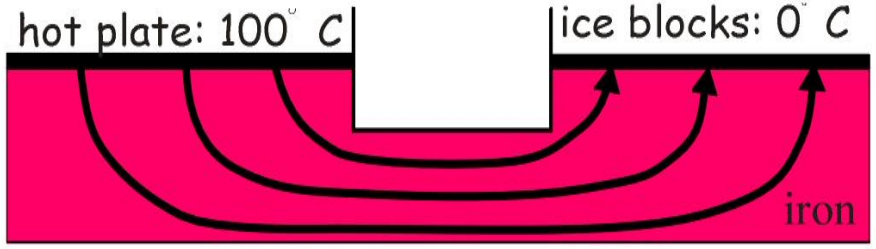
Heat transport (analogy with solute transport)

Groundwater flow: Darcy



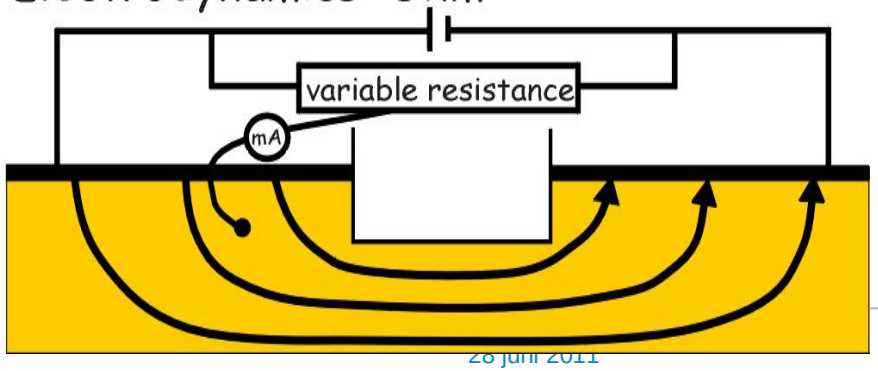
$$q = -k \frac{\partial \phi}{\partial x}$$

Heat conduction: Fourier



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

Electrodynamics: Ohm



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

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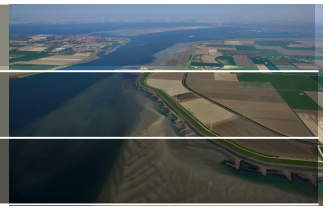
Darcy's law



Darcy's law is only valid in the case of laminar flow: viz. at relatively low velocities when water particles move more or less parallel to each other.

In other words, Darcy's law is valid as long as the so-called Reynolds number *Re* (–) does not exceed some value between 1 and 10:

$$Re = \rho q R/\mu < 1 - 10$$

where R= hydraulic radius of the pore

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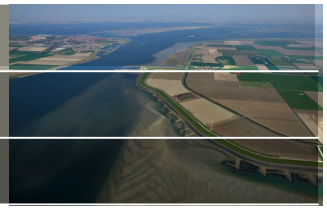
Permeability and hydraulic conductivity



The intrinsic permeability κ largely depends on the size of the pores through the effective porosity n_e.

A commonly-used equation is that of Kozeny-Carmen to clearly demonstrate the relation between κ and n_e:

Kozeny-Carmen: $\kappa = c\, d^2\, n_e^3 / (1 - ne)^2$ $[m^2]$

where c=coefficient depending on pore structure [-]
d=main grain size [L]

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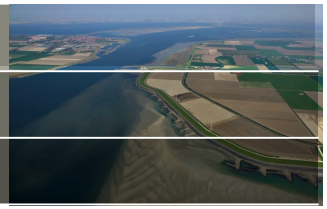
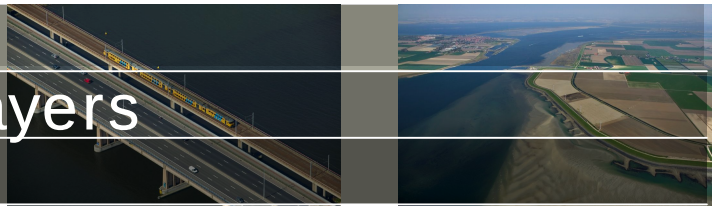
Permeability and hydraulic conductivity



Soil	k (m/s)	κ (m^2)
Unconsolidated deposits		
Clay	$<10^{-9}$	$<10^{-17}$
Sandy clay	10^{-9}-10^{-8}	10^{-16}-10^{-15}
Silt	10^{-8}-10^{-7}	10^{-15}-10^{-14}
Peat	10^{-9}-10^{-7}	10^{-16}-10^{-14}
Very fine sand	10^{-6}-10^{-5}	10^{-13}-10^{-12}
Fine sand	10^{-5}-10^{-4}	10^{-12}-10^{-11}
Coarse sand	10^{-4}-10^{-3}	10^{-11}-10^{-10}
Sand with gravel	10^{-3}-10^{-2}	10^{-10}-10^{-9}
Gravel	$>10^{-2}$	$>10^{-9}$
Rocks		
Unfractured rocks	$<10^{-9}$	$<10^{-17}$
Sandstone	10^{-10}-10^{-6}	10^{-17}-10^{-13}
Limestone & dolomite	10^{-9}-10^{-6}	10^{-16}-10^{-13}
Fractured rocks	10^{-8}-10^{-4}	10^{-15}-10^{-11}
Permeable basalt	10^{-7}-10^{-2}	10^{-14}-10^{-9}
Karst limestone	10^{-6}-10^{-2}	10^{-13}-10^{-9}

Hydraulic conductivity of more layers

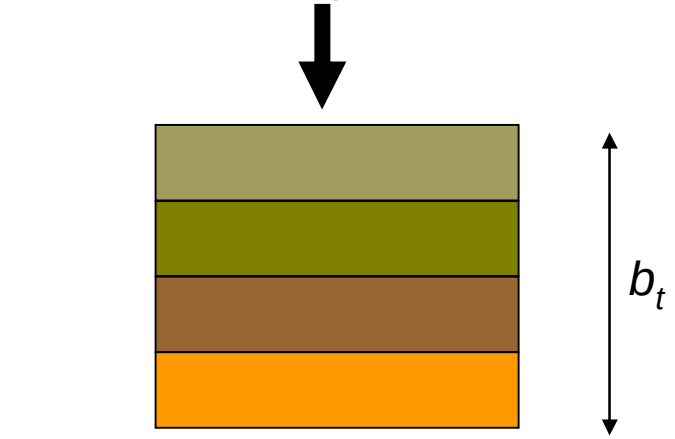


Horizontal hydraulic conductivity

$$k_h = \sum k_i \left(\frac{b_i}{b_t} \right)$$

Arithmic mean (parallel)

Vertical hydraulic conductivity



$$k_h = \frac{b_t}{\sum \left(\frac{b_i}{k_i} \right)}$$

Harmonic mean (serial)

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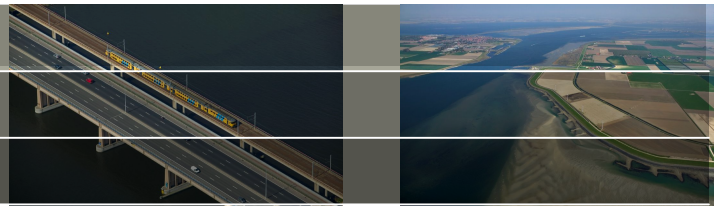

Stoftransport

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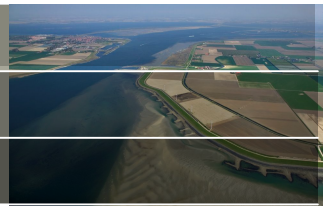
Solute transport equation



Partial differential equation (PDE):

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

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}]

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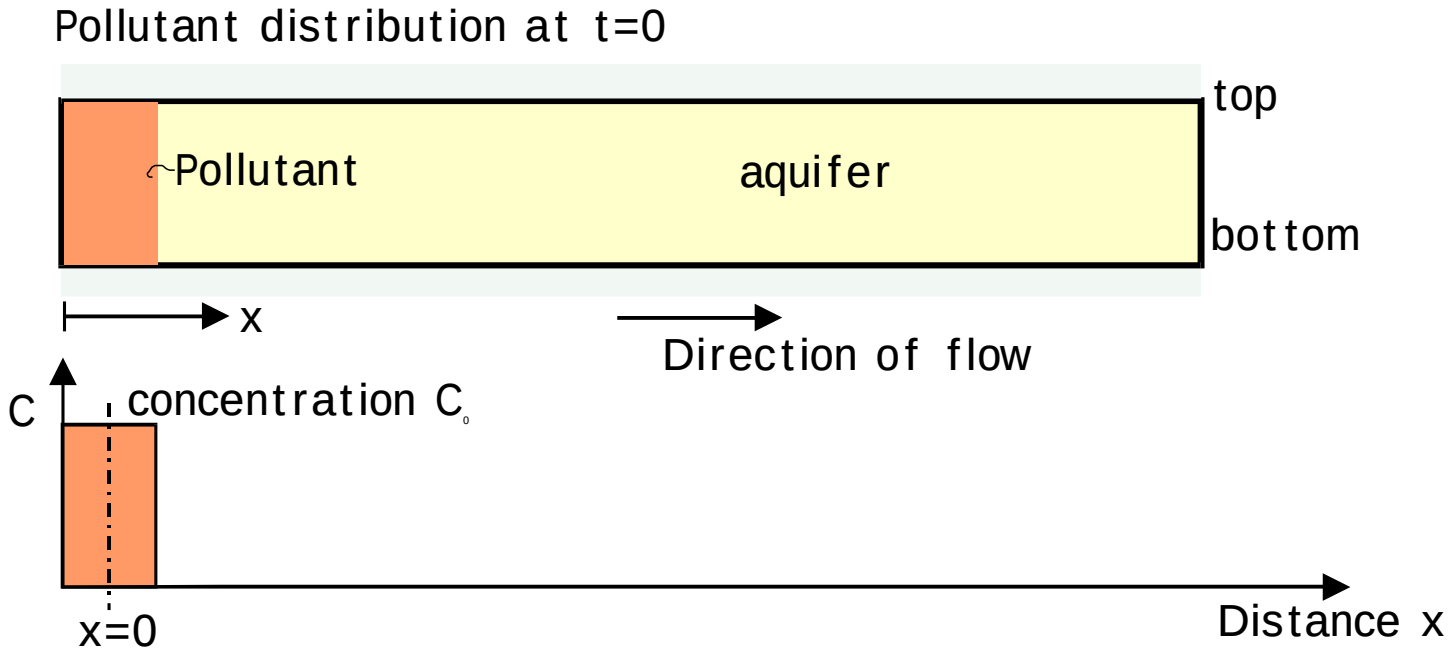
Solute transport equation: column test (I):



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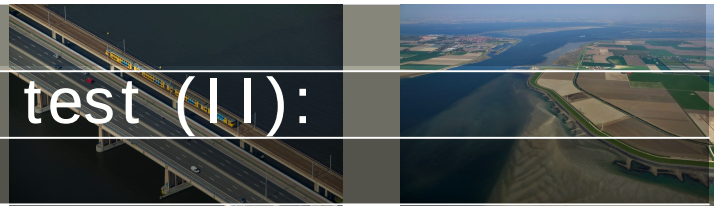
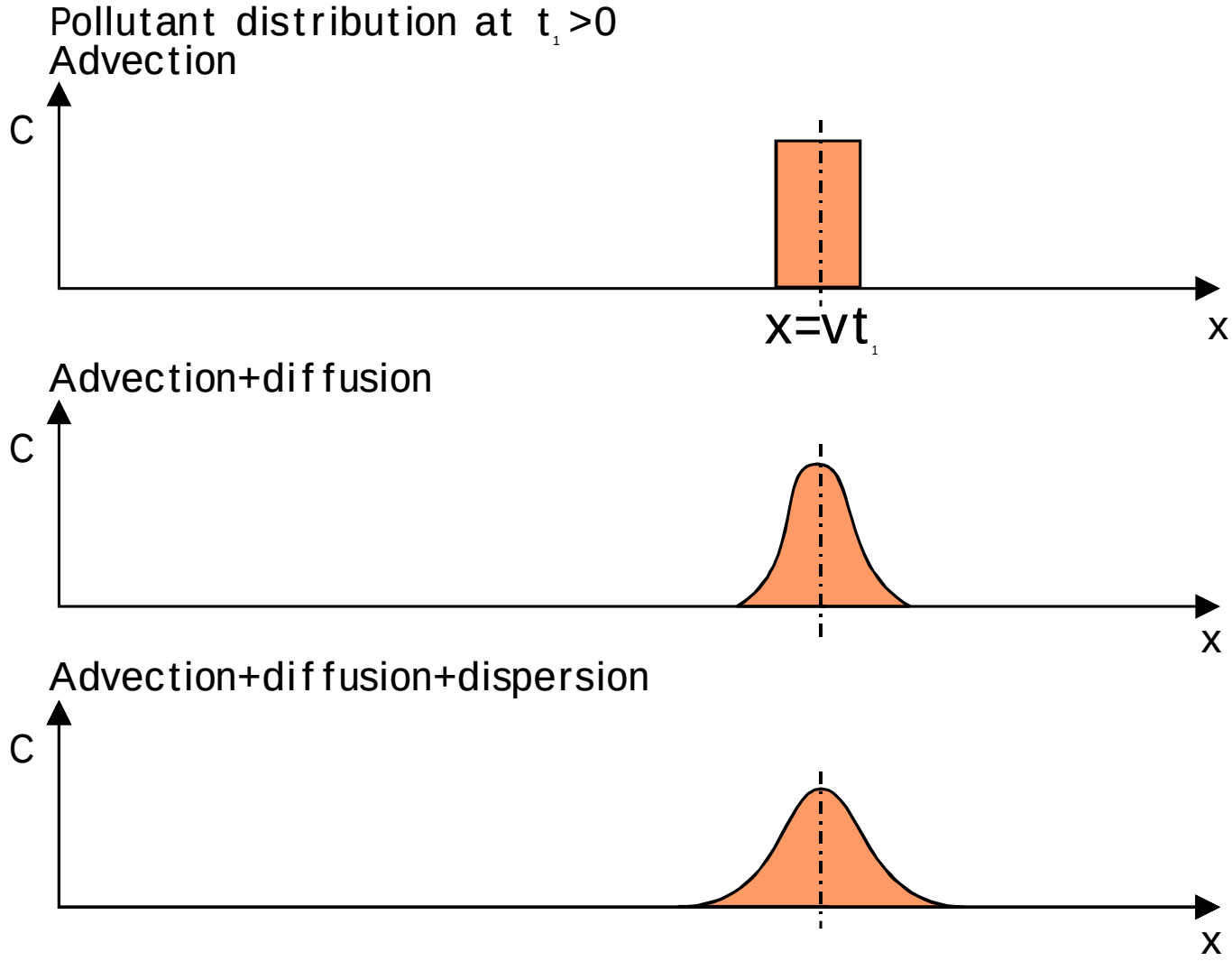
Solute transport equation: column test (II):





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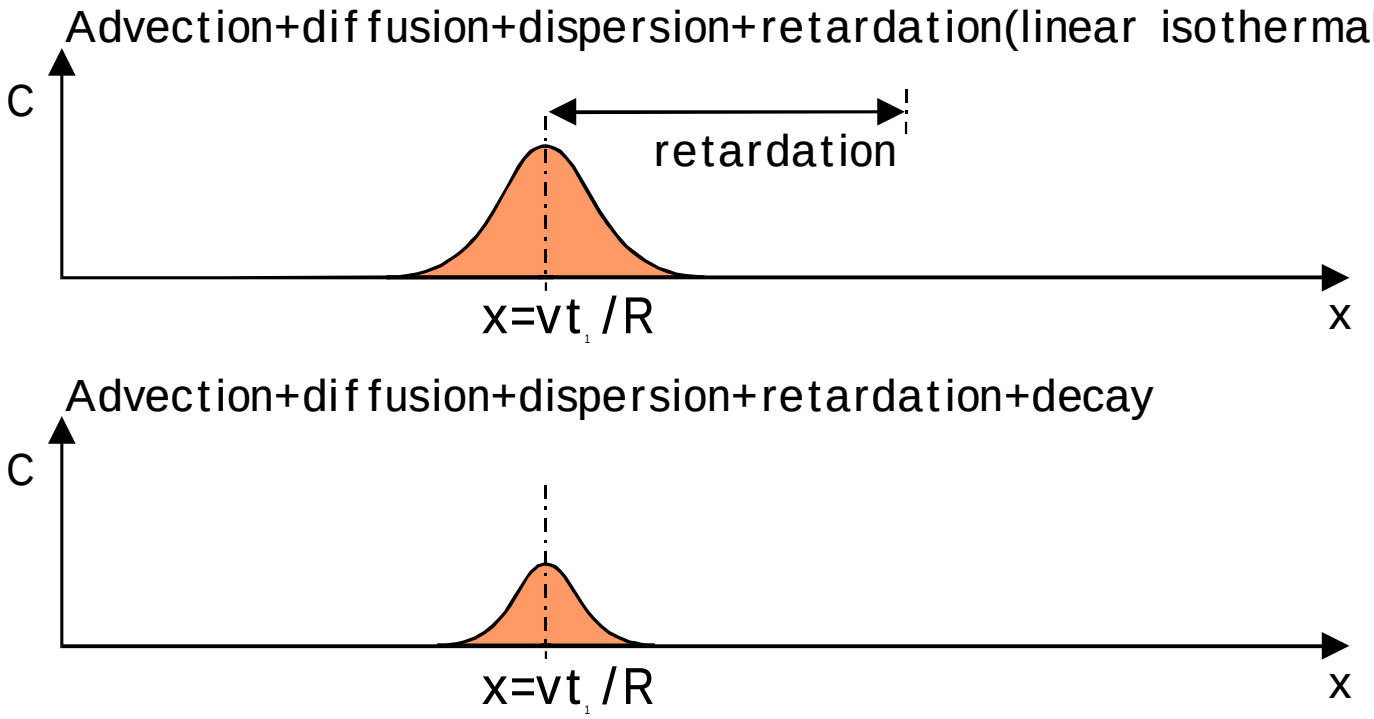
Solute transport equation: column test (III):



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Hydrodynamic dispersion

hydrodynamic dispersion
=
mechanical dispersion+ diffusion

mechamical dispersion:

- tensor (2D, 3D)
- snelheidsafhankelijk

diffusion:

- moleculair proces
- stoffen verspreiden door concentratieverschillen

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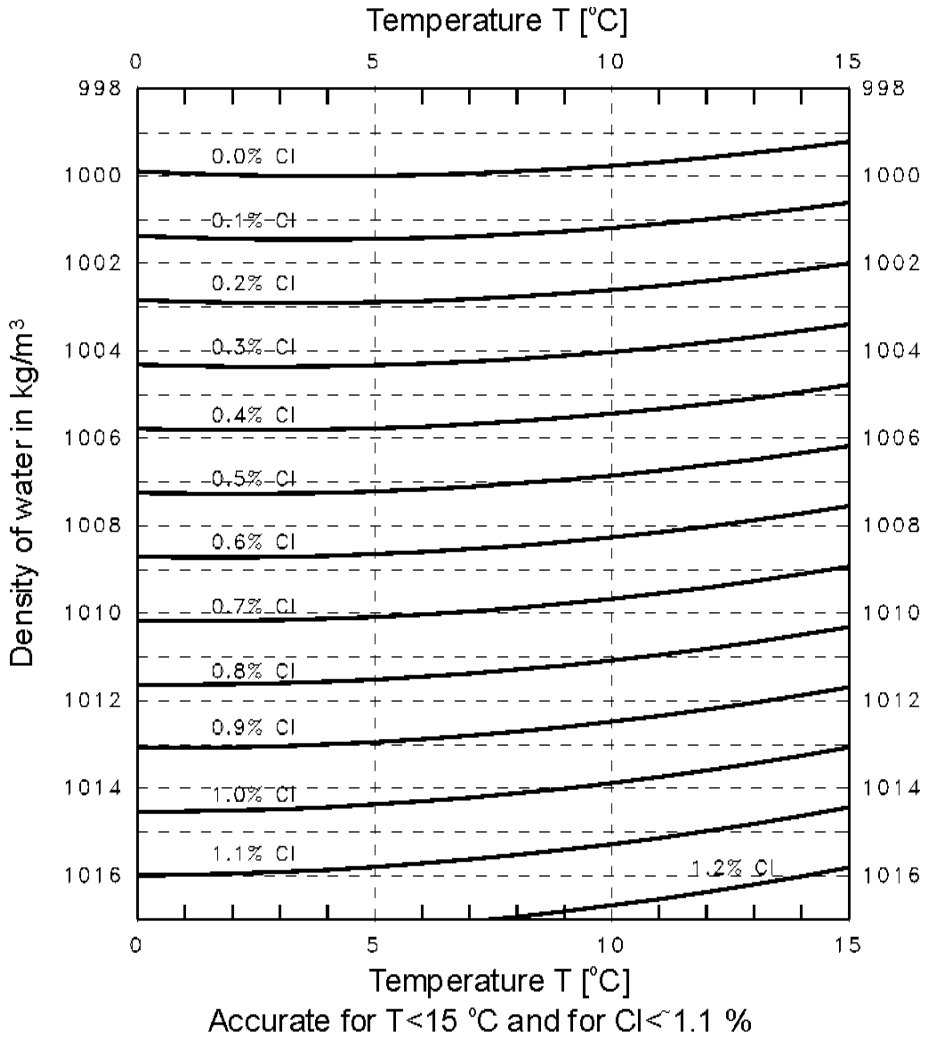
Density depends on salinity and temperature



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

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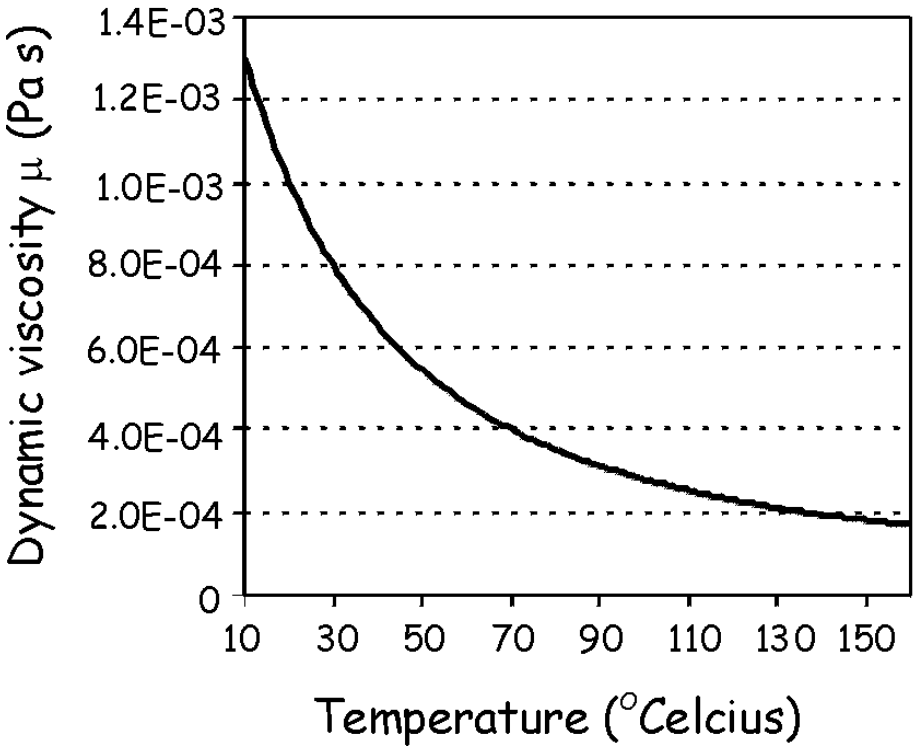
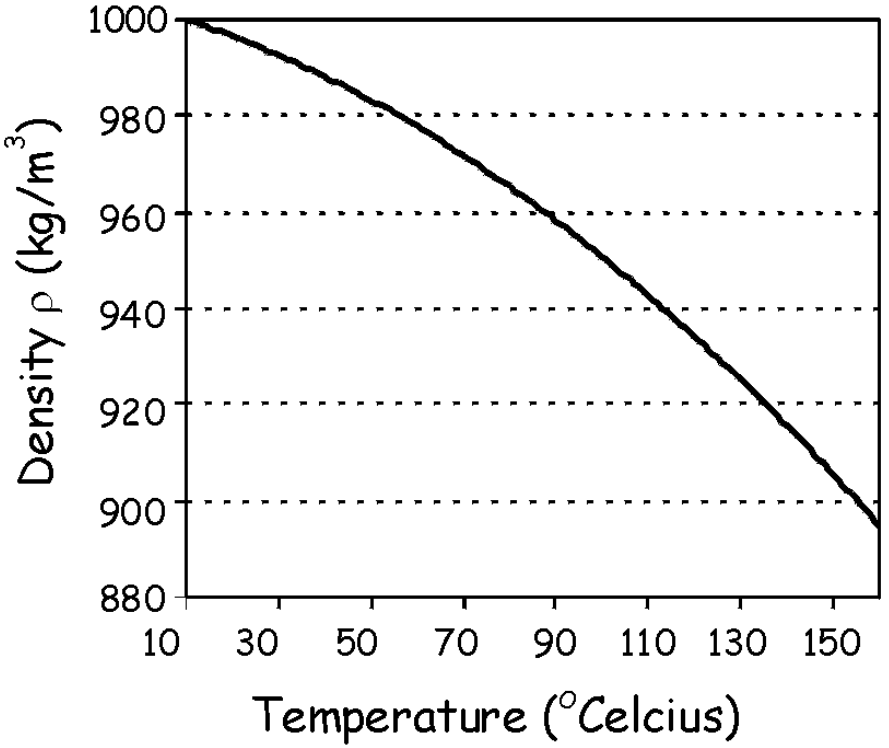
Density and viscosity depend on temperature

(10°C-160 °C)





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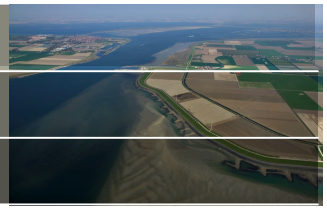
Introductie grondwater in het kustgebied



Concepten van zoutwater intrusie

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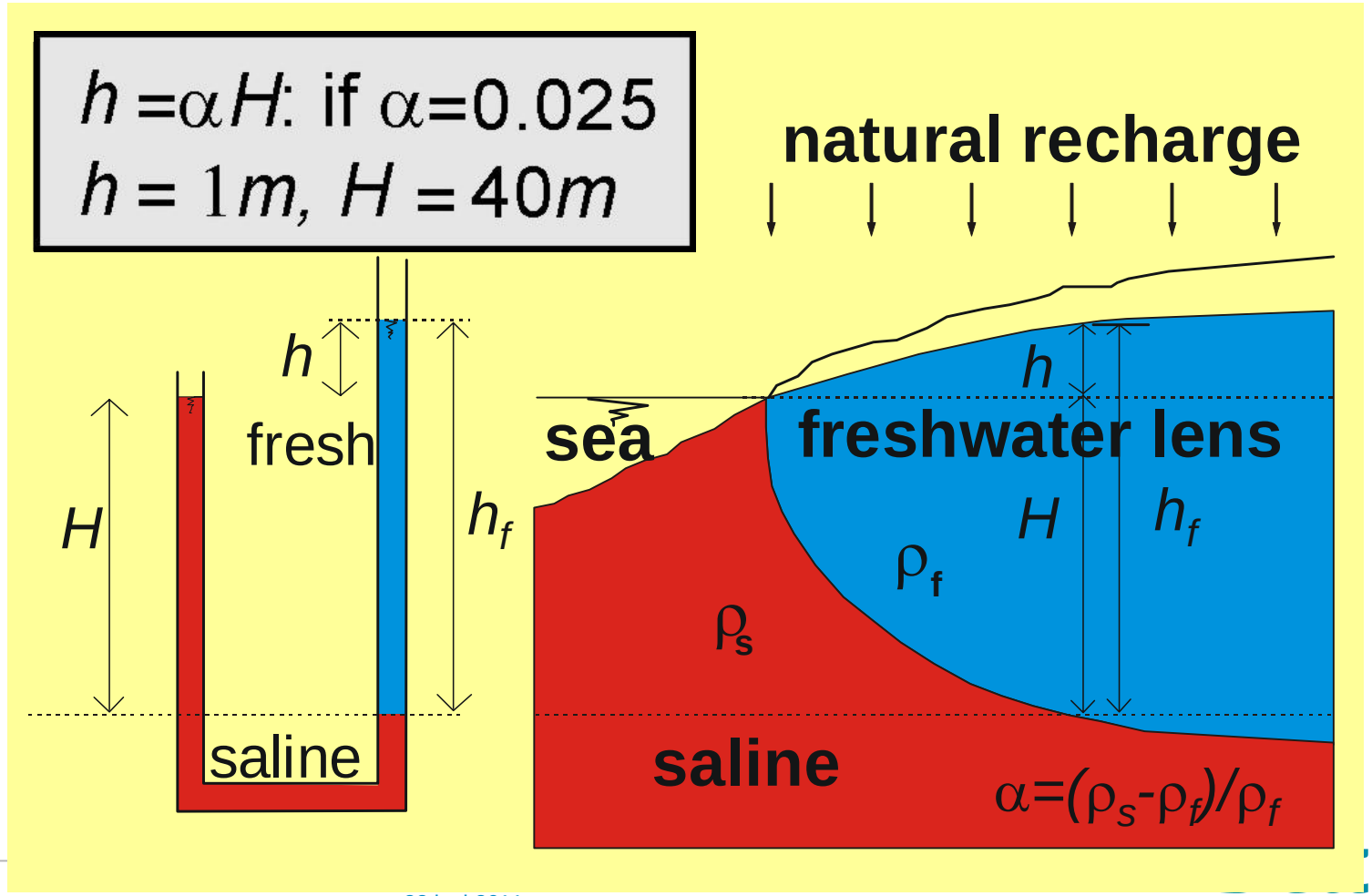
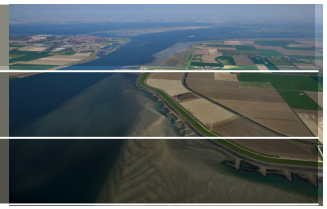
Badon Ghyben-Herzberg principe

Principe veronderstelt scherp grensvlak tussen zoet en zout grondwater

Analogie: ijsberg & zoute oceaan en graniet tectonische plaat en basalt base



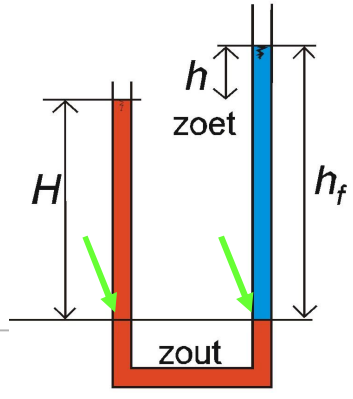



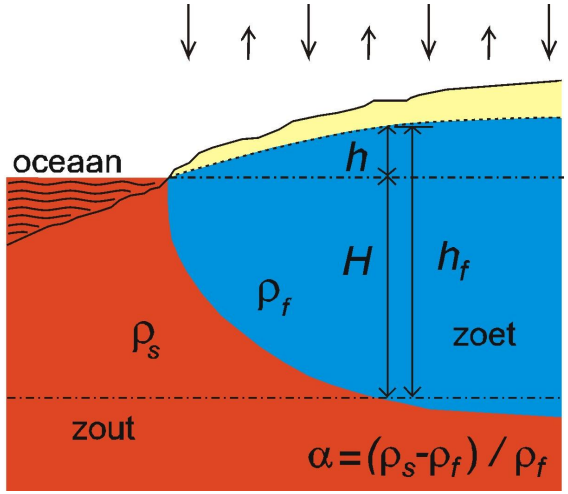
druk zout grondwater = druk zoet grondwater

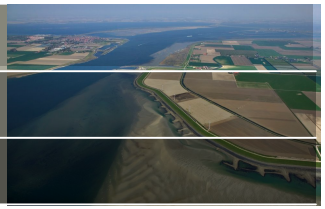
$$\rho_s H g = \rho_f (H + h) g$$

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

$$h = \alpha H$$



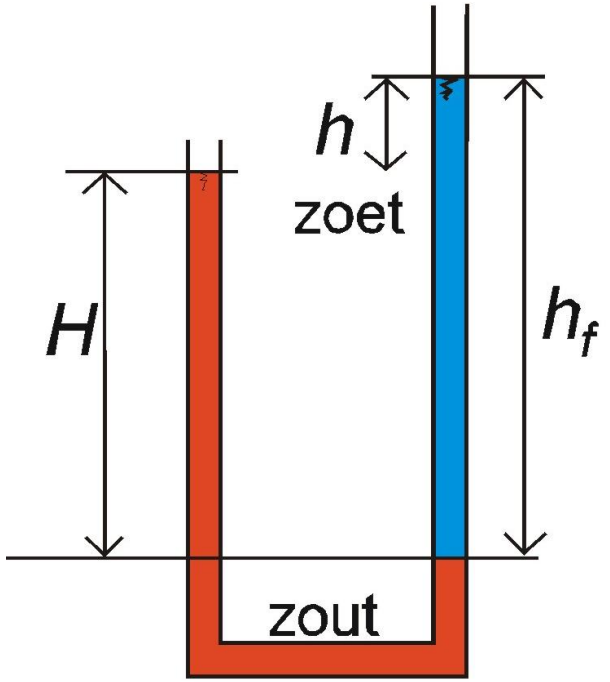


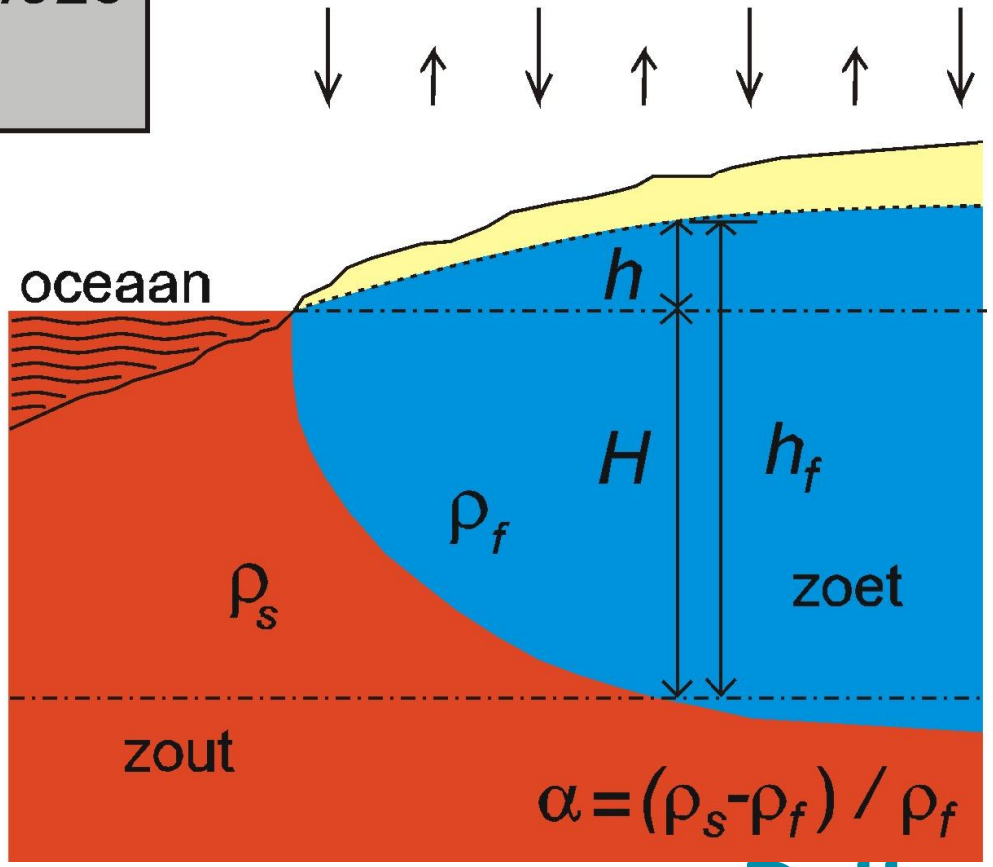



$h=\alpha H$

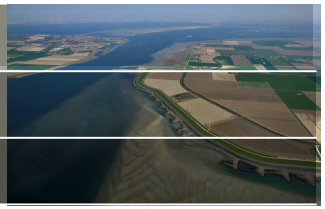
in ocean water $\alpha=0.025$

$h=1$ m, $H=40$ m





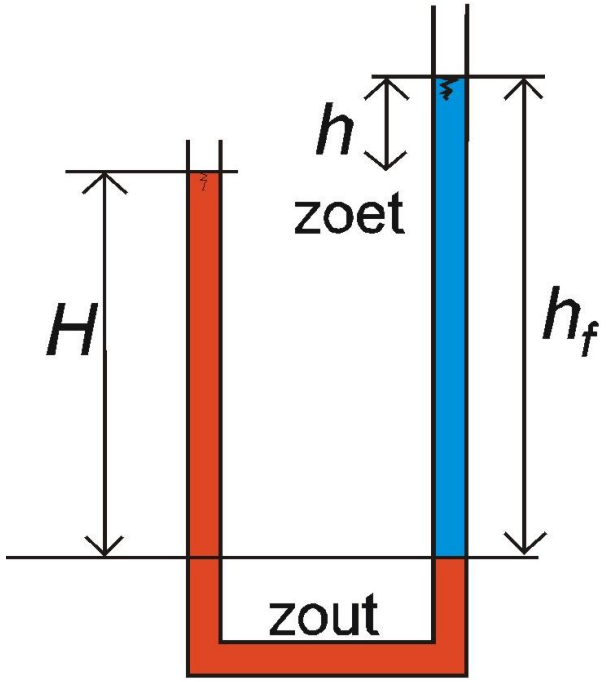
Deltares

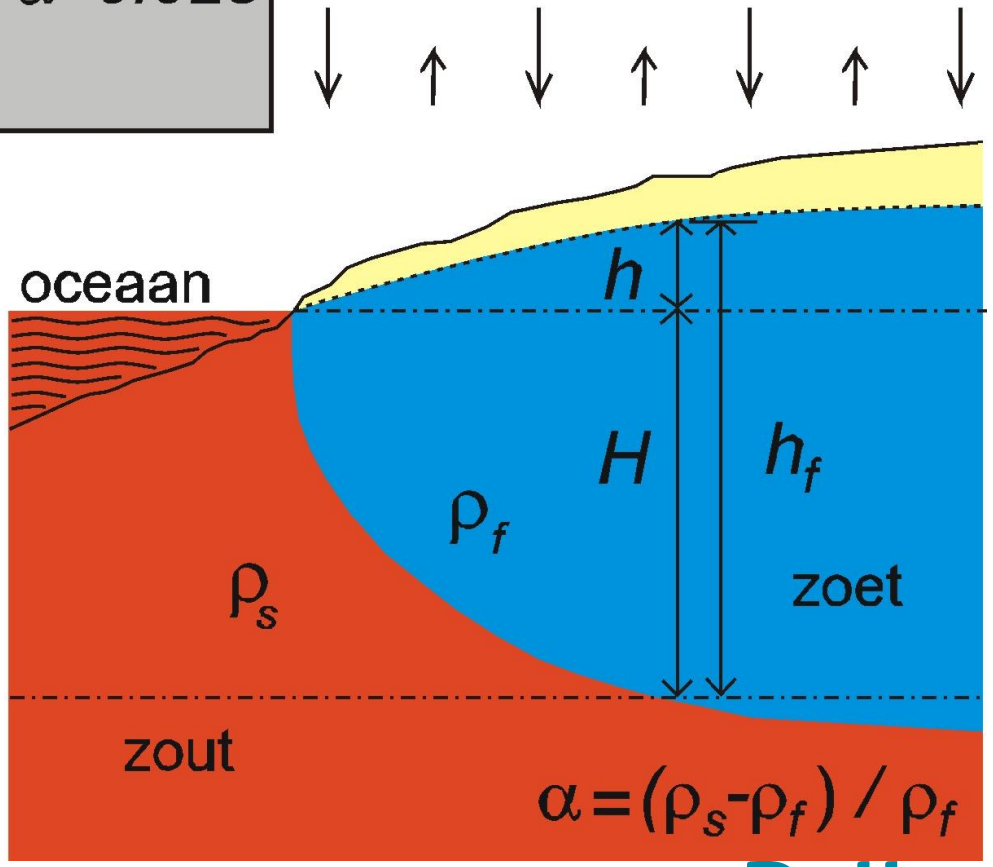



$h=\alpha H$

Mediterranean Sea $\alpha=0.028$

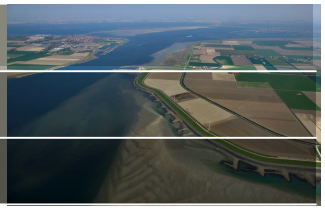
$h=1$ m, $H=35.7$ m



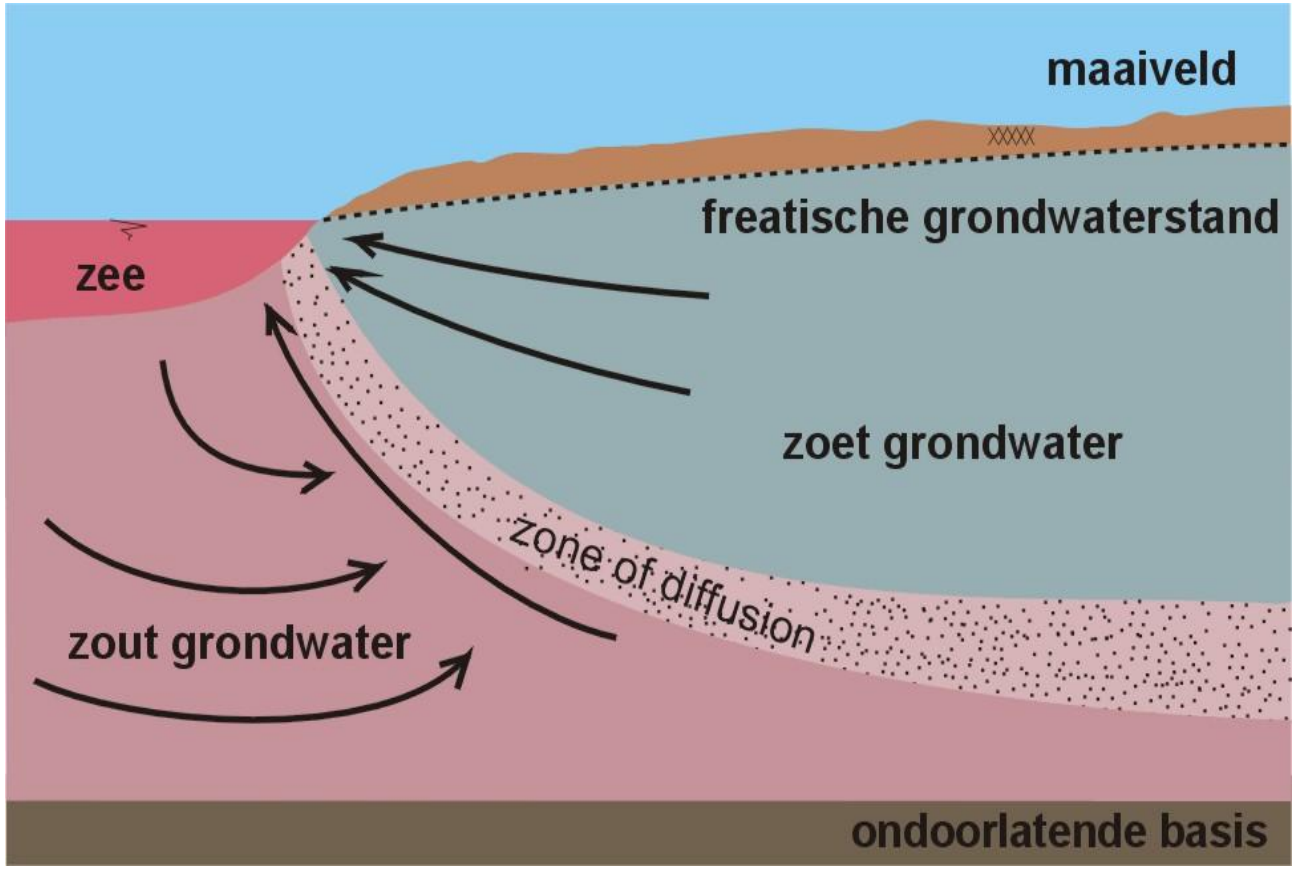


Deltares

Klassieke definitie zoutwaterintrusie

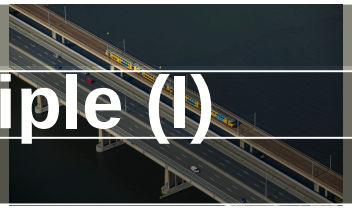


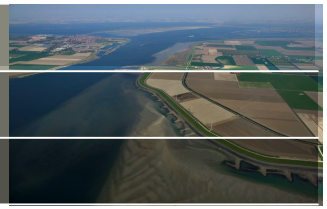
Horizontale instroming van zout grondwater in een watervoerend pakket dat zoet grondwater bevat



Deltares

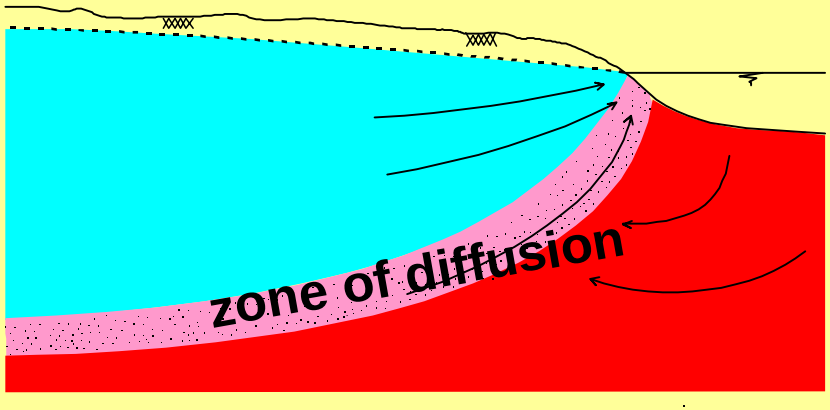
Badon Ghyben-Herzberg principle (I)



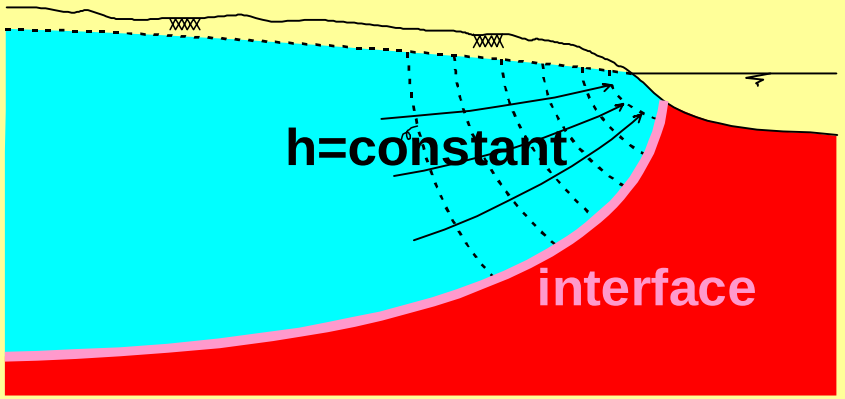


Difference between reality and Badon Ghyben-Herzberg approximation

concept: mixing zone in reality

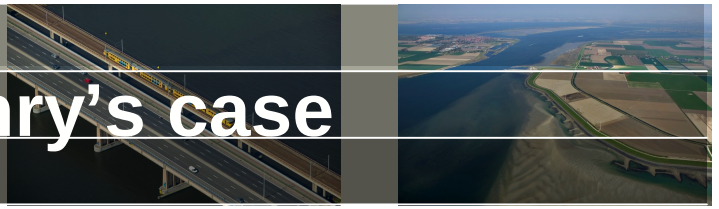


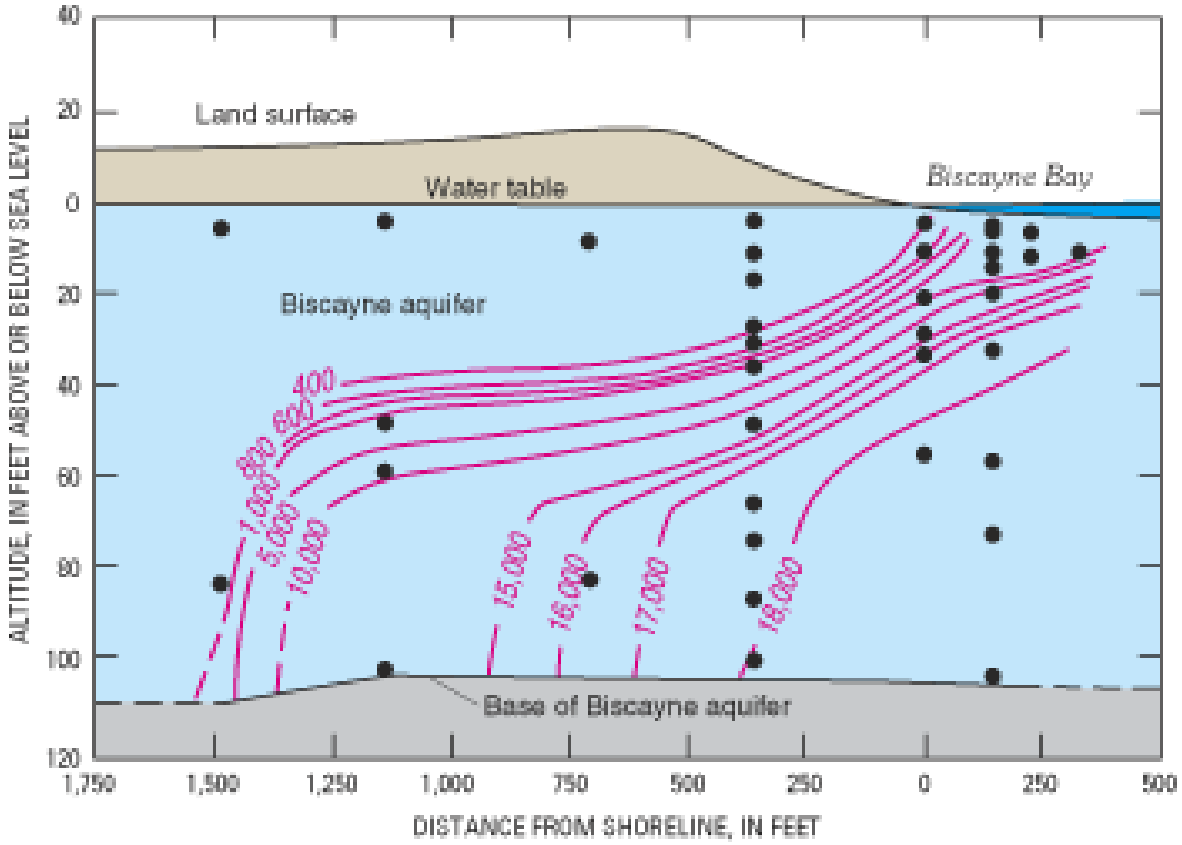
concept: interface between fresh and saline groundwater



Deltares

Biscayne aquifer, Florida: Henry's case





EXPLANATION

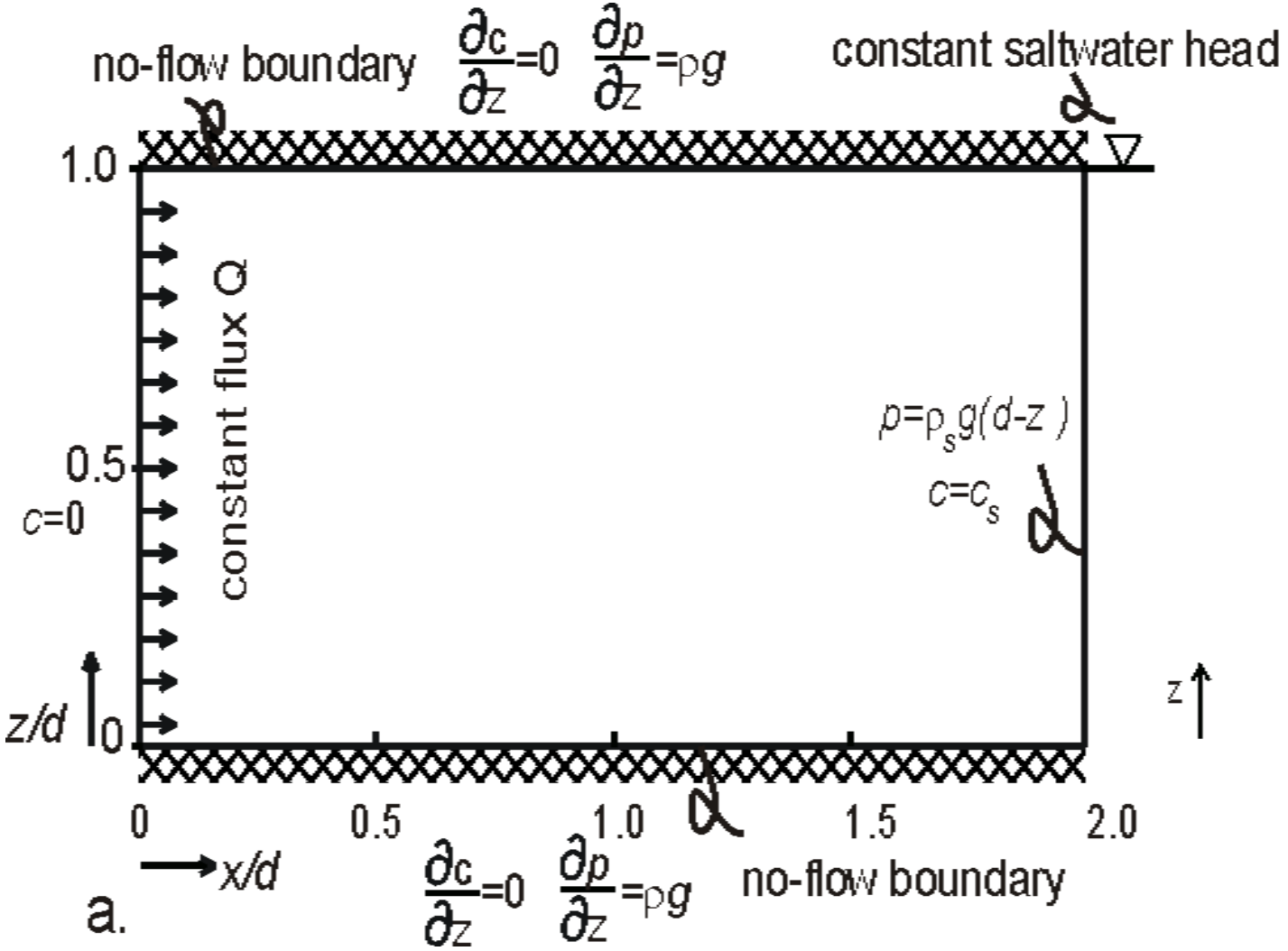
5,000 — **Line of equal chloride concentration, in parts per million**

Bottom of fully cased well from which water-quality samples were collected

Modified from Kohout (1964)

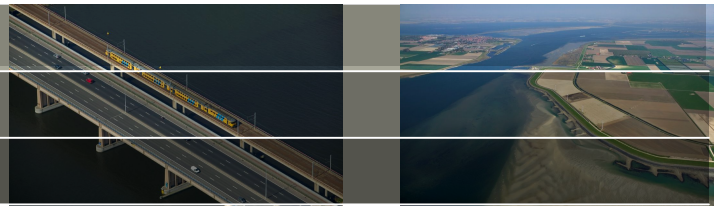
Deltares

Henry's problem (1964)

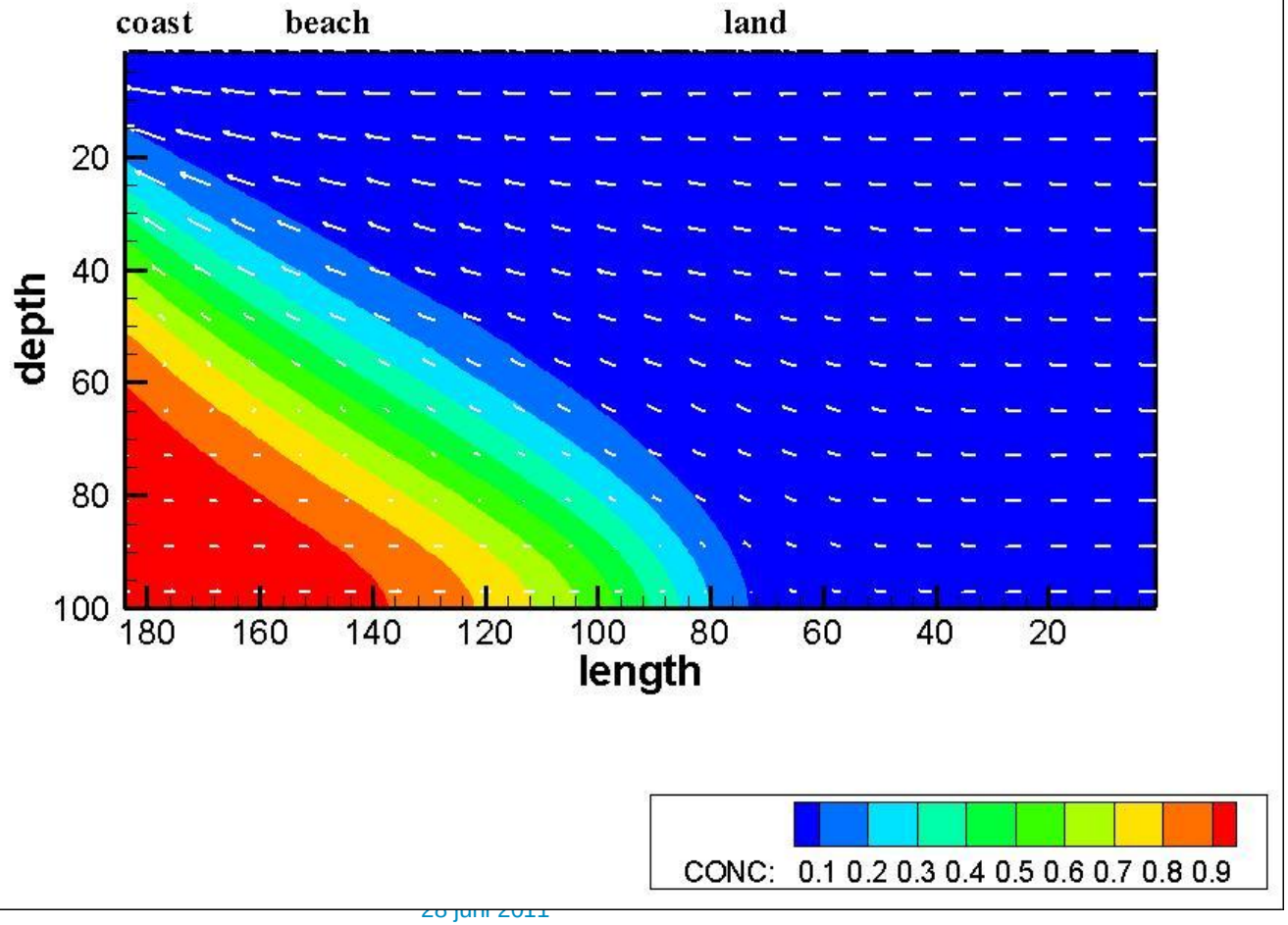


Deltares

Definitie zoutwaterintrusie

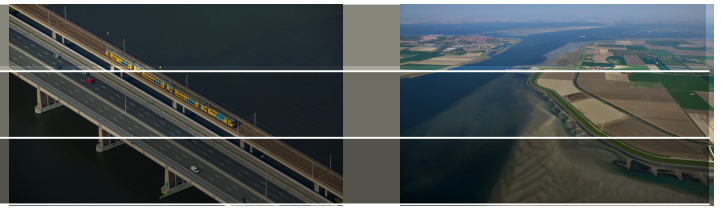


Numerical model: Henry's case

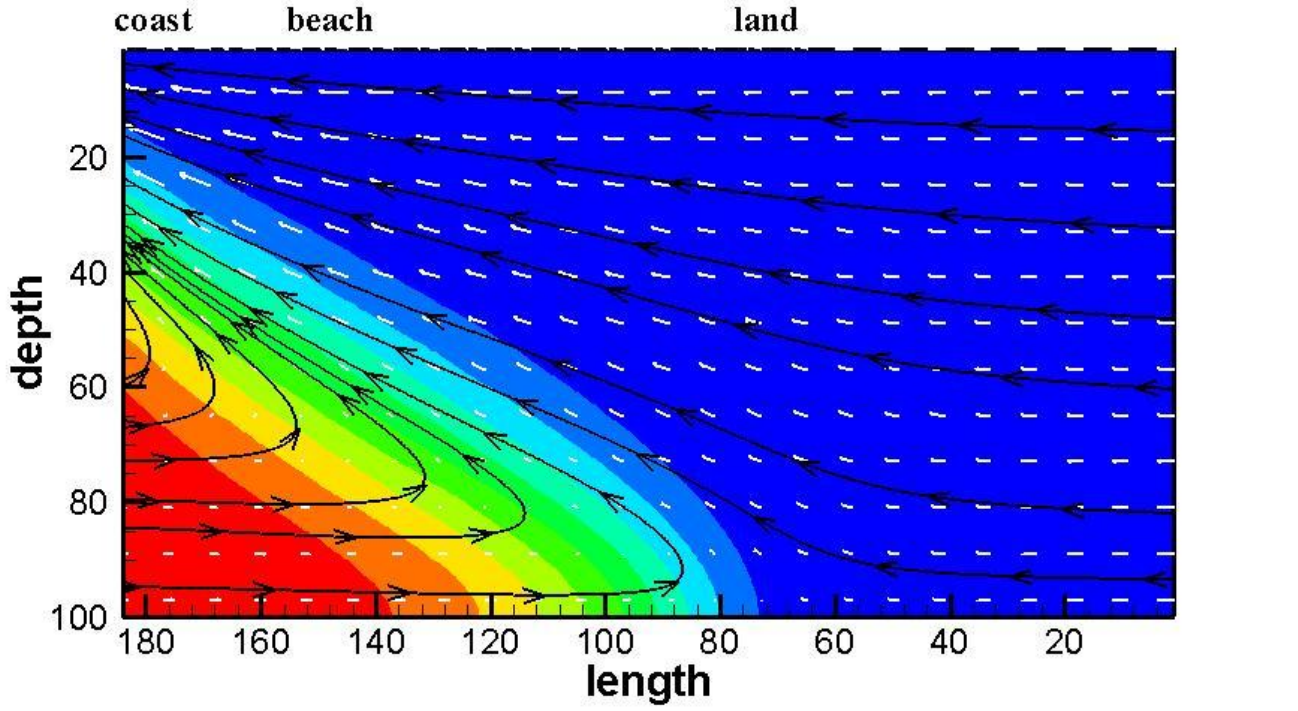


Deltares

Definitie zoutwaterintrusie

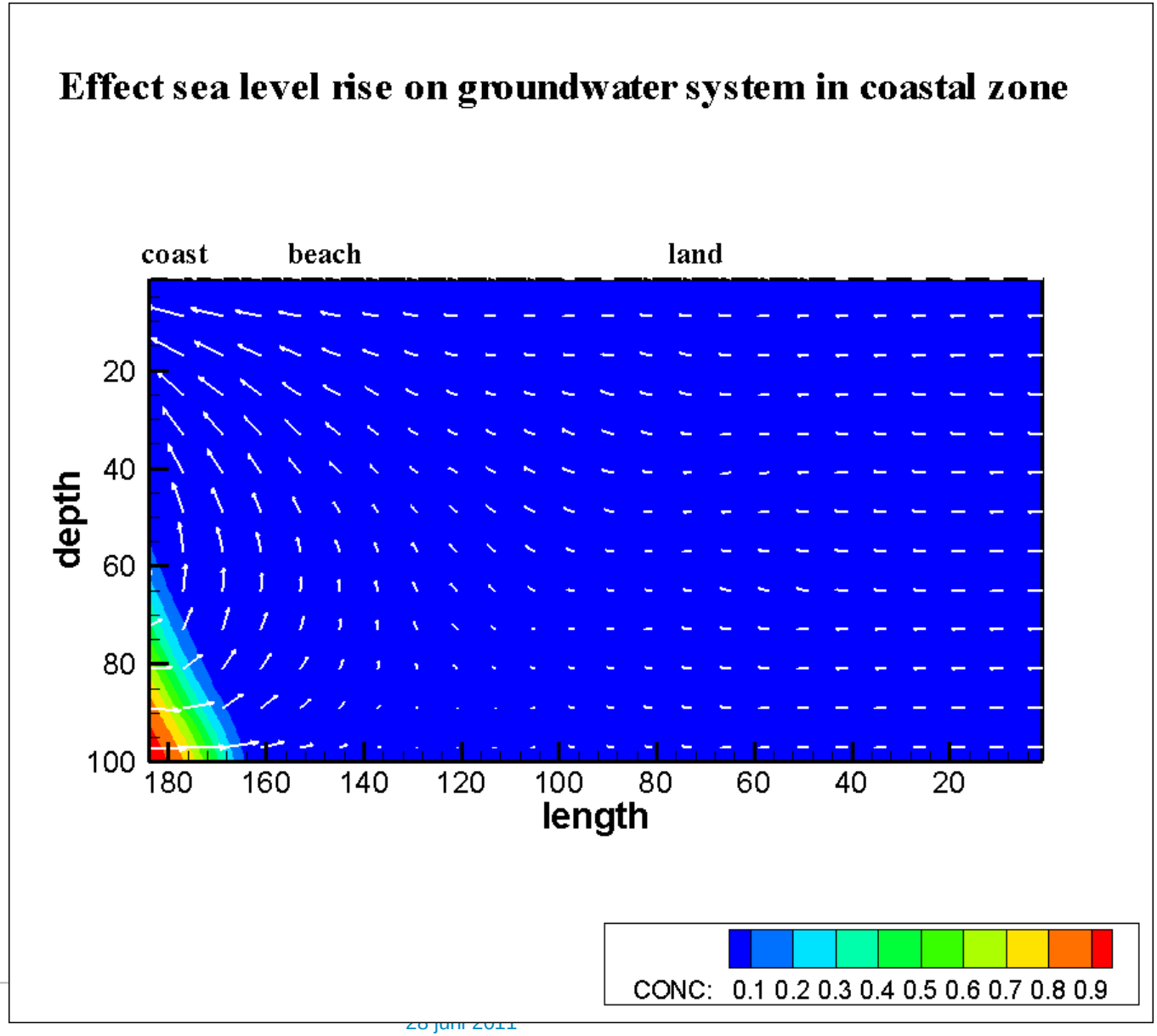


Numerical model: Henry's case



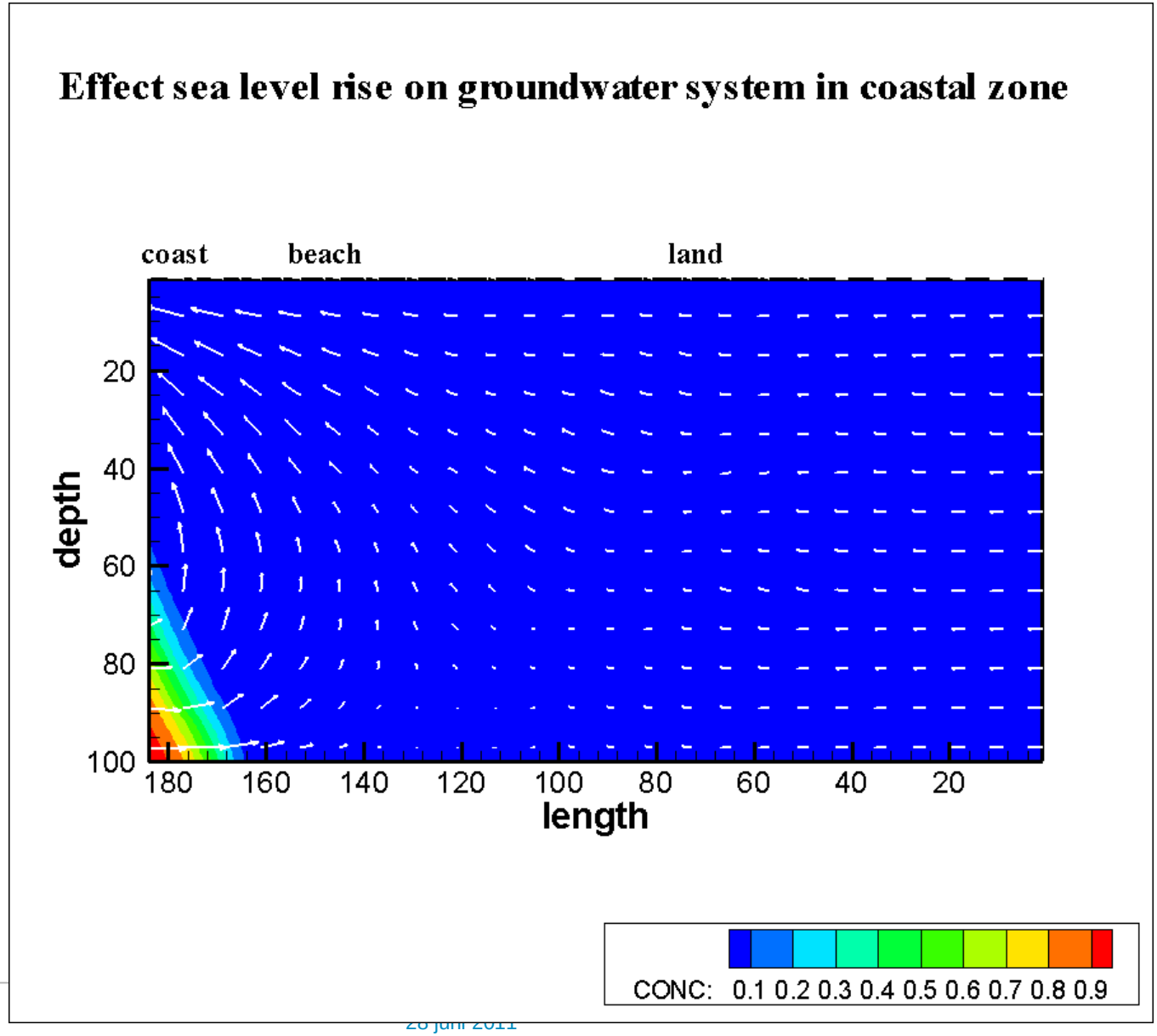
Deltares

Zeespiegelstijging en zoutwaterintrusie



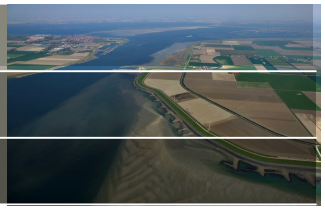
Deltares

Zeespiegelstijging en zoutwaterintrusie



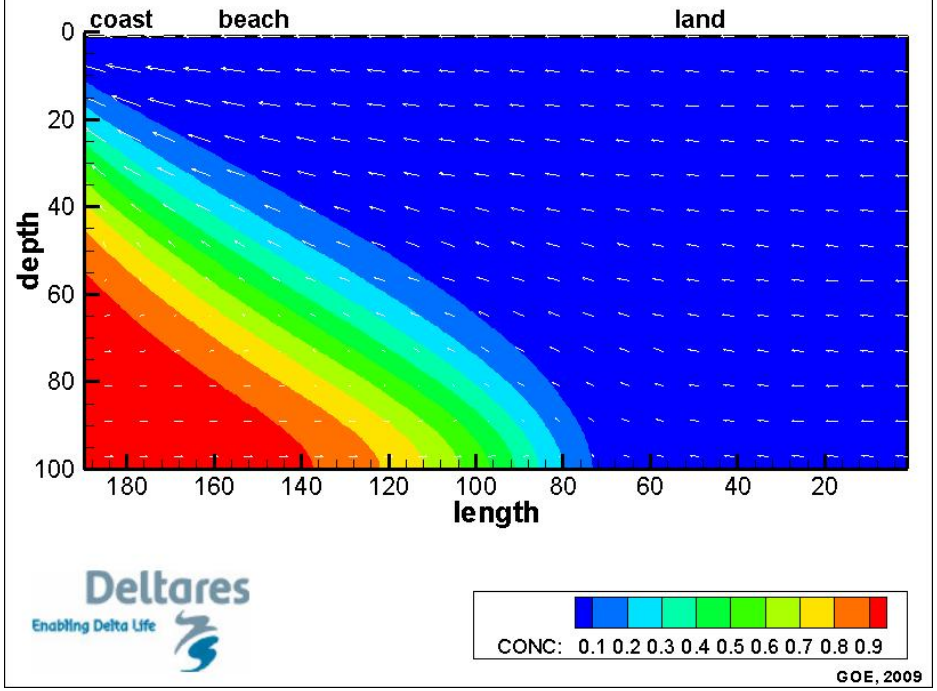
Deltares

Sea level rise and salt water intrusion



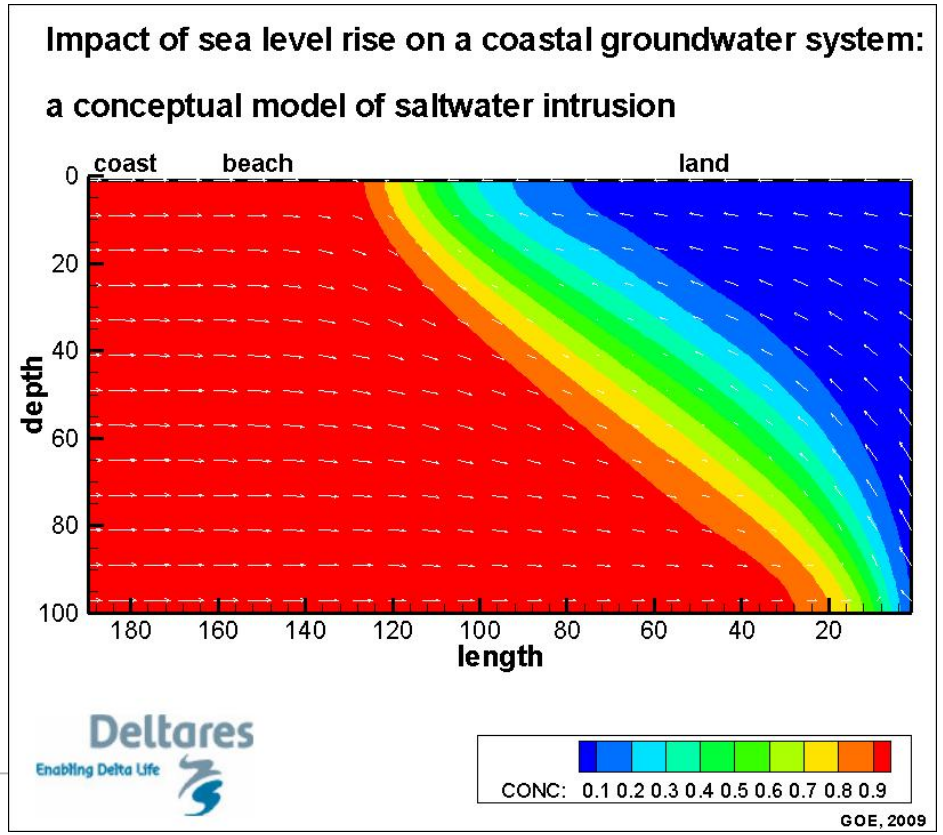
Impact of sea level rise on a coastal groundwater system:

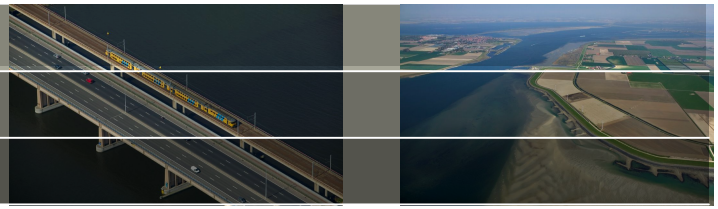
a conceptual model of saltwater intrusion



Impact of sea level rise on a coastal groundwater system:

a conceptual model of saltwater intrusion

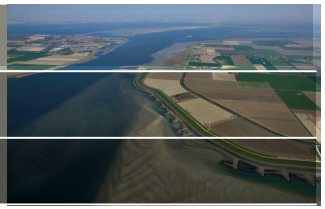




Klimaatverandering en zeespiegelstijging

Deltares

Ons toekomstige grondwatersysteem



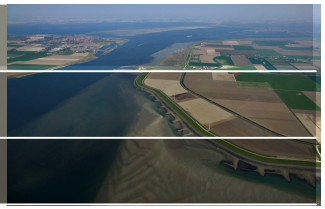
Wat komt er allemaal op ons af?

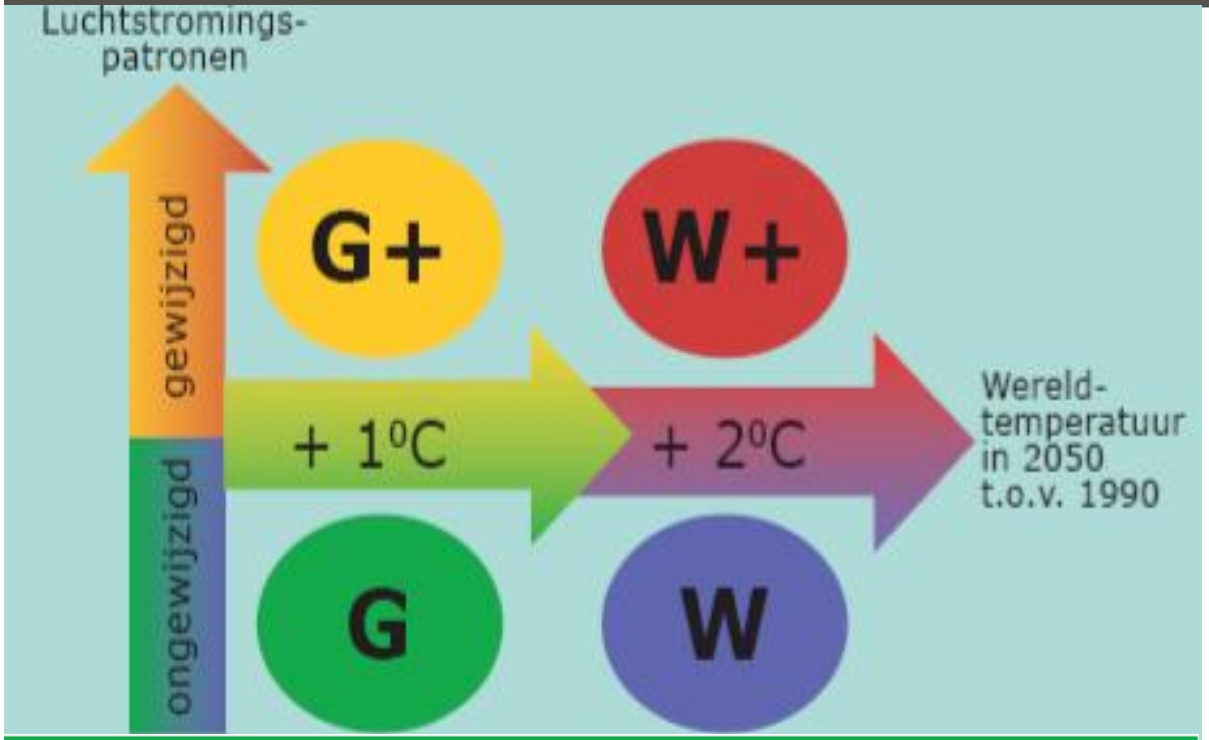
- Klimaatverandering
- Grondwaterwinning
- Ontwikkeling energiegebruik/productie
- Bodemdaling
- Ontwikkeling ruimtegebruik
- Politiek, Beleid & Waterbeheer

Directe invloed door de mens op het grondwater is belangrijker dan klimaateffect

Deltares

KNMI'06 scenario's



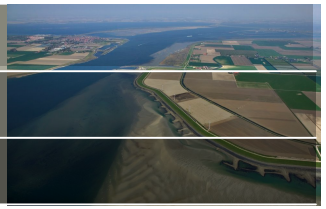


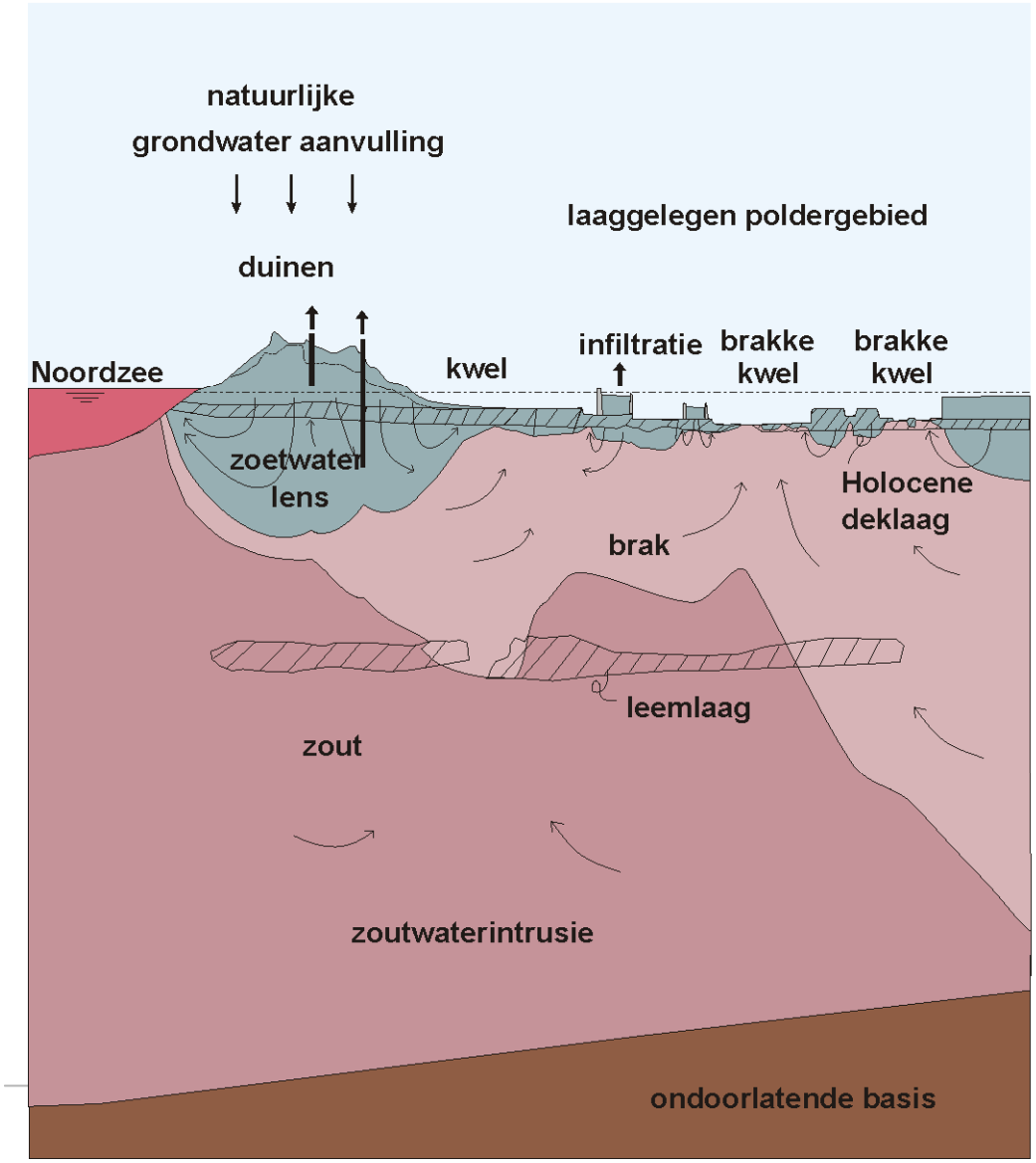
G	Gematigd	1°C temperatuurstijging op aarde in 2050 ten opzichte van 1990 geen verandering in luchtstromingspatronen in West Europa
G+	Gematigd +	1°C temperatuurstijging op aarde in 2050 ten opzichte van 1990 + winters zachter en natter door meer westenwind + zomers warmer en droger door meer oostenwind
W	Warm	2°C temperatuurstijging op aarde in 2050 ten opzichte van 1990 geen verandering in luchtstromingspatronen in West Europa
W+	Warm +	2°C temperatuurstijging op aarde in 2050 ten opzichte van 1990 + winters zachter en natter door meer westenwind + zomers warmer en droger door meer oostenwind

Bron: Van der Hurk et al. (2006)

Deltares

Het Nederlandse grondwatersysteem

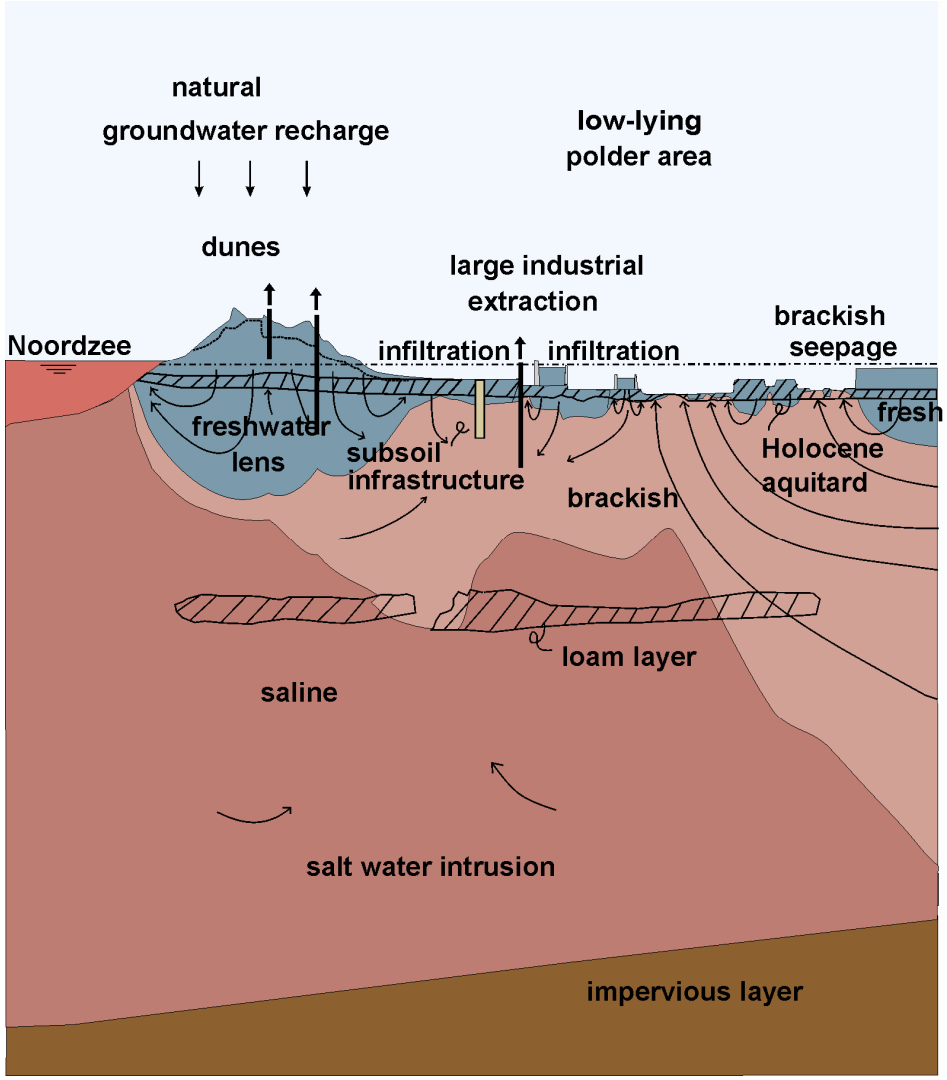




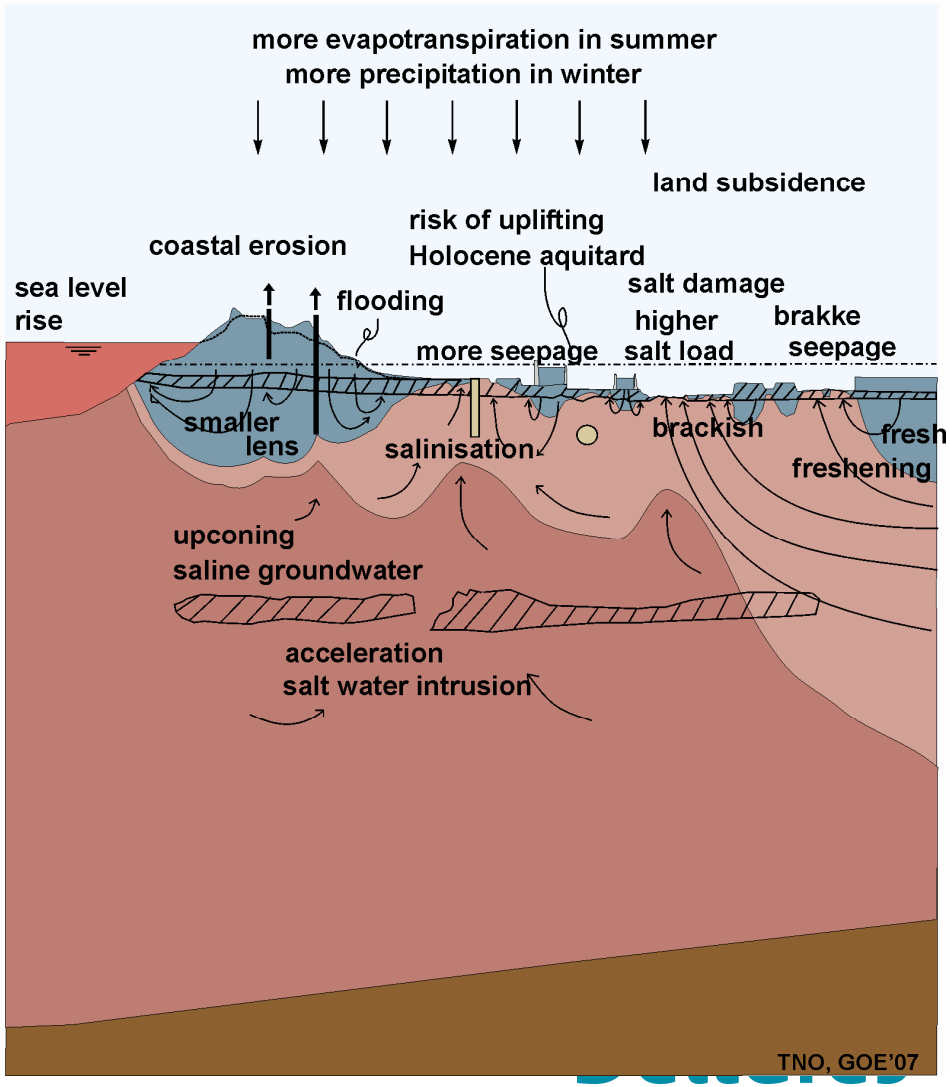
Peilverlagingen in het verleden hebben grondwaterstromingen naar het binnenland veroorzaakt

Het Nederlandse grondwatersysteem staat onder druk

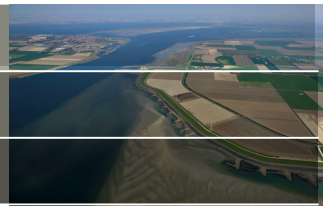
Present processes



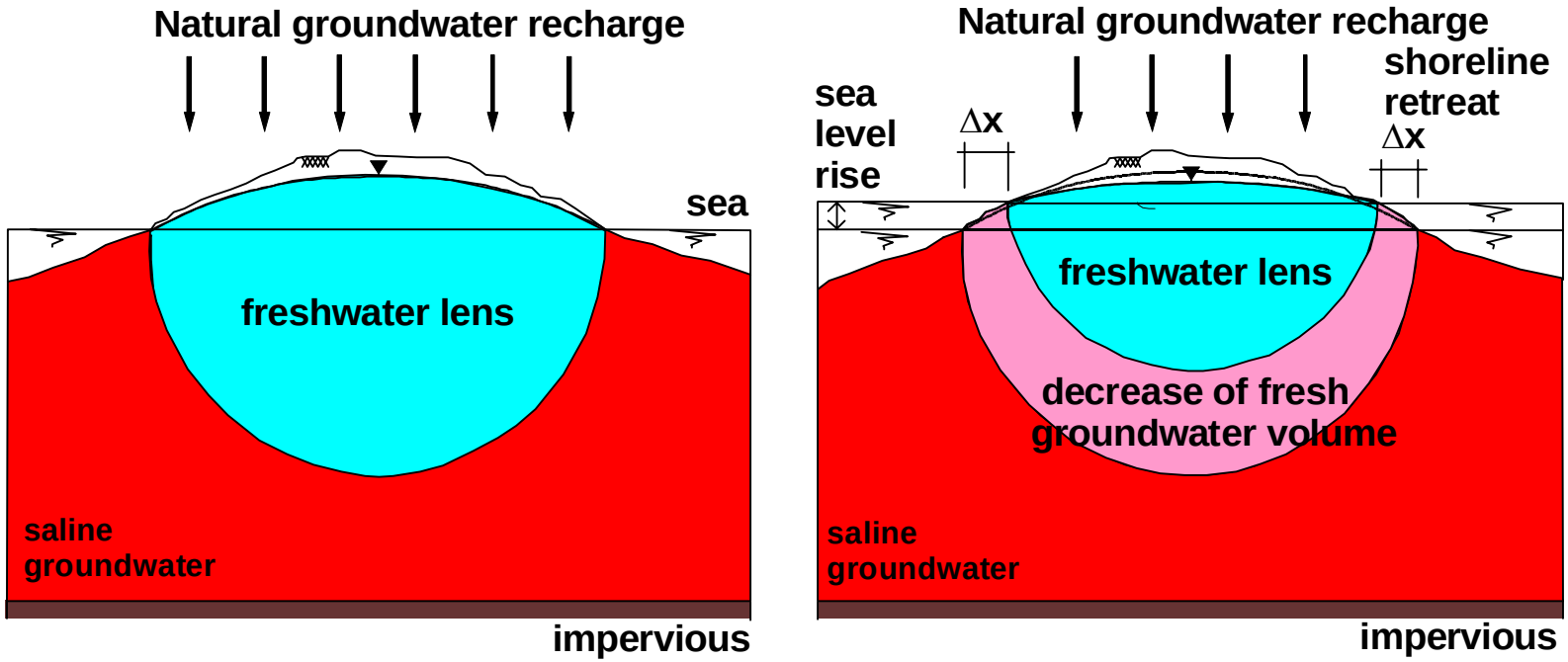
Future changes



Effect of a relative sea level rise (1):

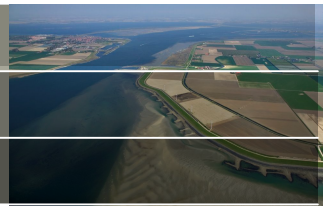


Deep aquifer

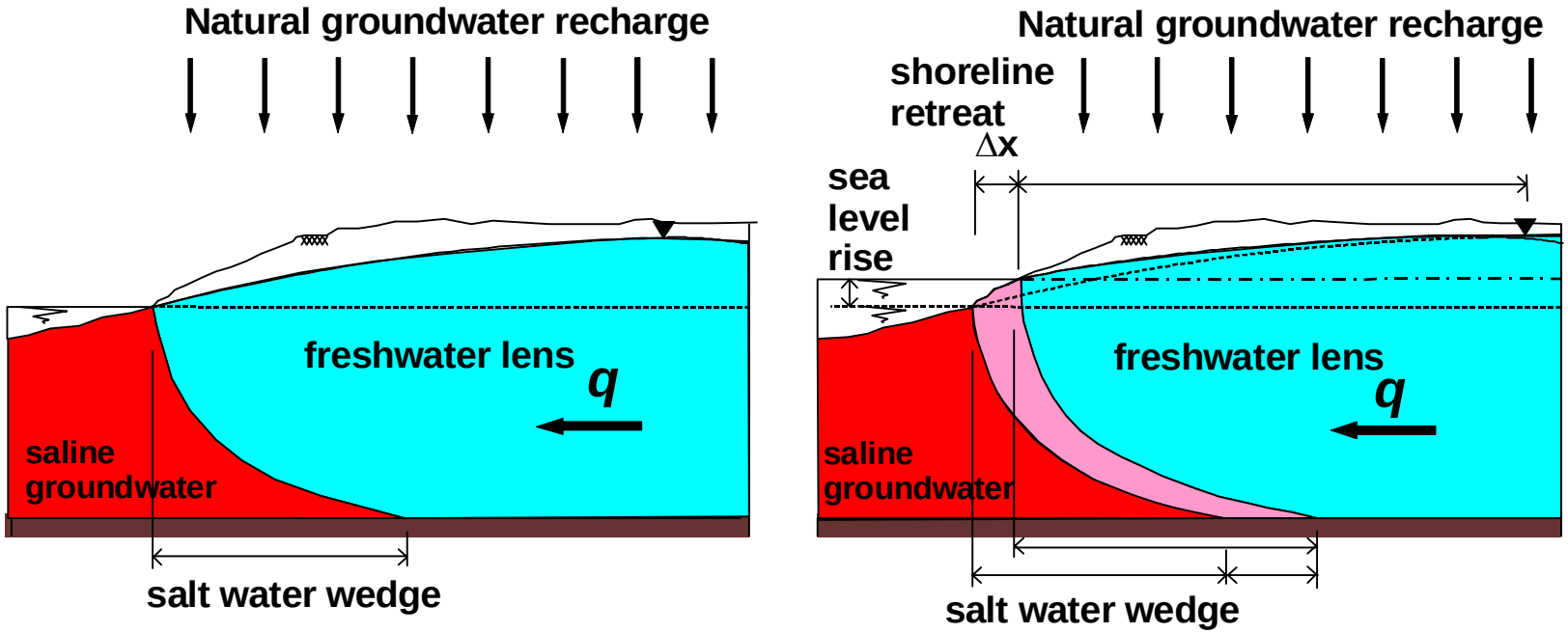


Deltares

Effect of a relative sea level rise (2):

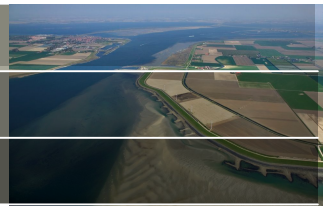


Shallow aquifer

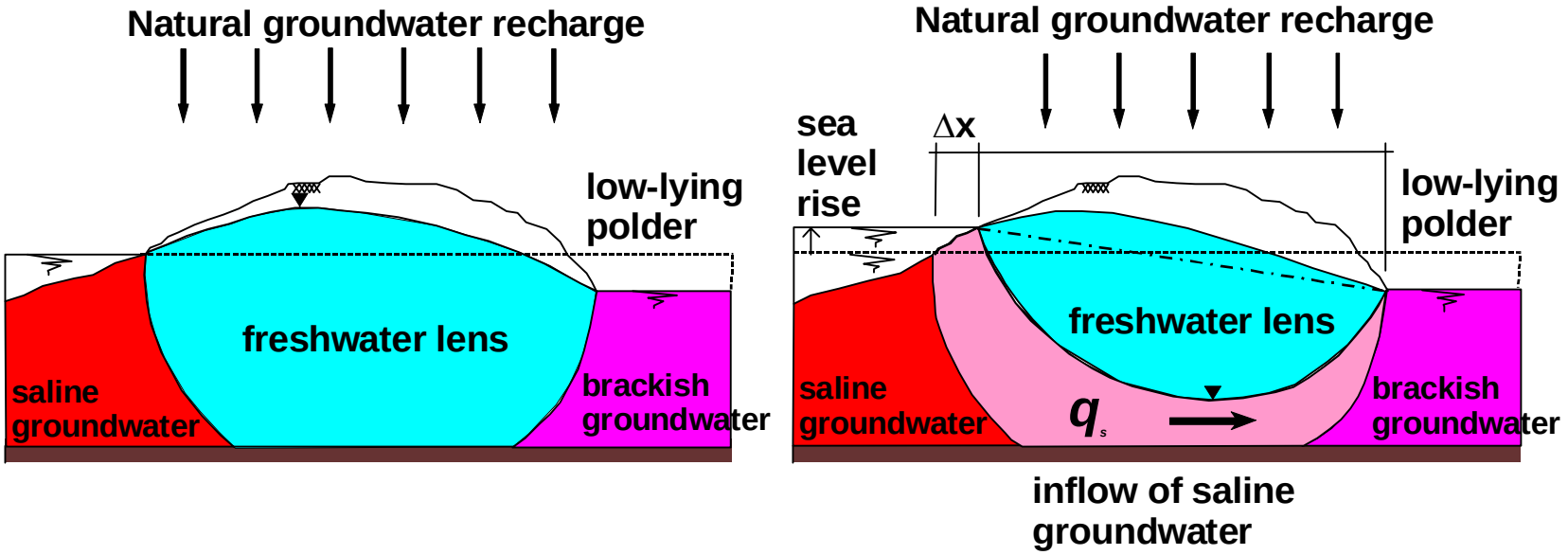


Deltares

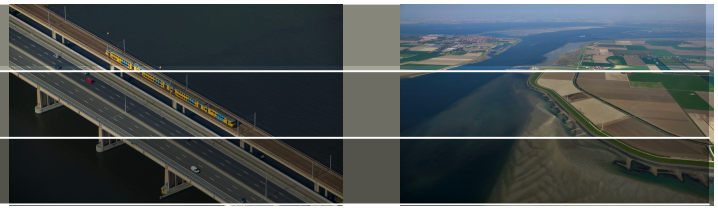
Effect of a relative sea level rise (3):



Shallow aquifer



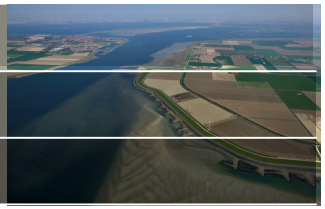
Deltares



Effecten voor het oppervlaktewater systeem en de landbouw

Deltares

Gevolgen verzilting



Gevolgen verzilting grondwater:

- Zoutschade gewassen
- Zoutbelasting vanuit het grondwater naar het oppervlaktewater
- [Verzilting ontrrekkingputten]

Bron: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

Deltares

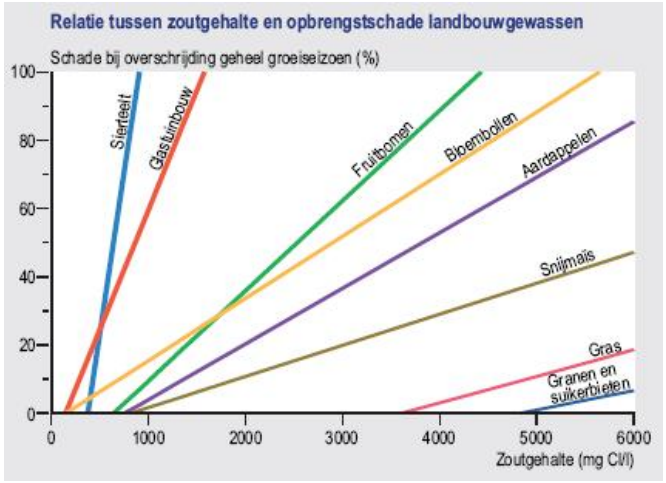
Gevolgen verzilting: zoutschade aan gewassen bij wortelzone

Belangrijke parameters:

- Chloride concentratie bij wortelzone
- Landgebruik
- Gevoeligheid gewassen

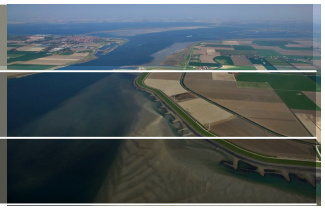
Landgebruik	Drempel-waarde wortelzone (mg Cl-/l)	Helling wortelzone (-)	Gewasopbrengst prijspeil 2050 (Euro/ha)
gras	3606	0.0078	1080
aardappelen	756	0.0163	4240
bieten	**4831**	0.0057	2640
granen	4831	0.0058	880
glastuinbouw	1337	0.0141	17850
boomgaard	642	0.0264	11900
bollen	**153**	0.0182	26000

Bron: Roest et al., 2003 en Haskoning



Bron: MNP, 2005

Deltares

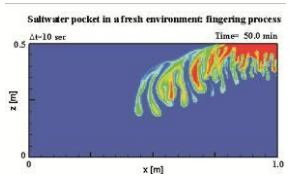


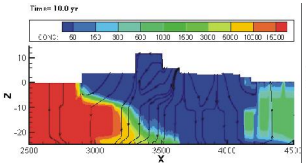
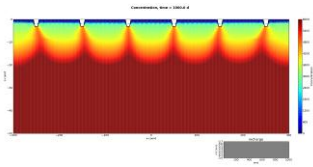
Modelleren zoet-zout grondwater

Deltares

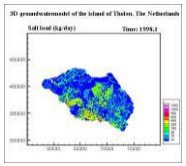
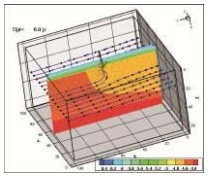
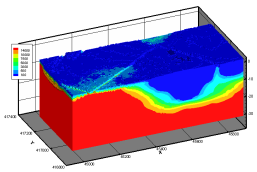
Verschillende modelschalen om verschijnselen te analysen

Sub-local: fingering, zoute wellen
Sri Lanka (Tsunami 2004), De Zandmotor
modelschaal=1cm-1m

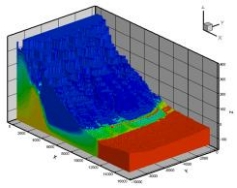
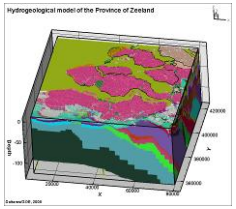


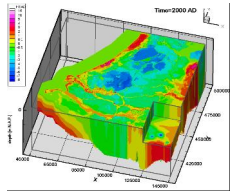
Local: regenwaterlenzen, WKO,
Tholen, Schouwen-Duiveland
modelschaal=5-25m

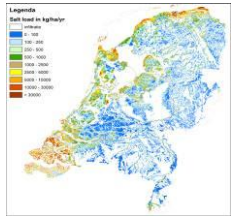




Regionaal:
Zeeland, Gujarat/India, Philippines
modelschaal=100m

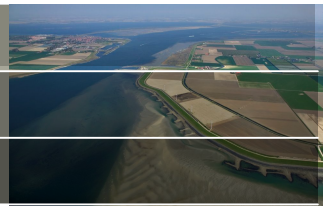
Nationaal: salt load
Zuid-Holland, NHI
modelschaal=250m-1km





Deltares

Numerieke computer modellen:



ROTZOOI IN = ROTZOOI UIT

echter…

- steeds betere 3D geologische opbouw (REGIS II, Geotop)
- steeds betere 3D initiële dichtheidsverdeling
- steeds betere concepten
- steeds betere ijkings technieken
- steeds nauwkeuriger (snellere computers, meer geheugen)

Modelling effect climate change on fresh-salt groundwater

Modelling:

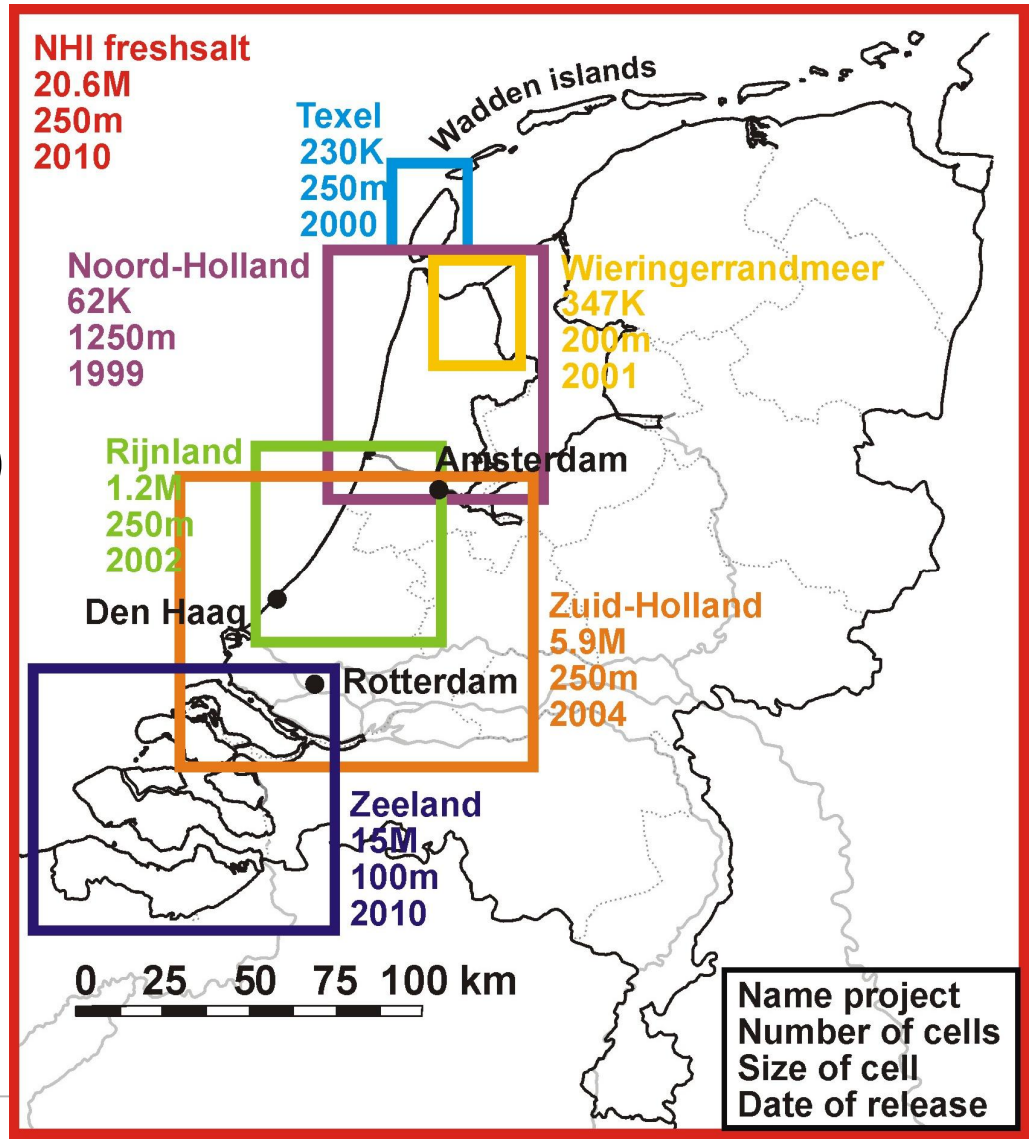
- variable-density
- 3D, non-steady
- groundwater flow
- coupled solute transport

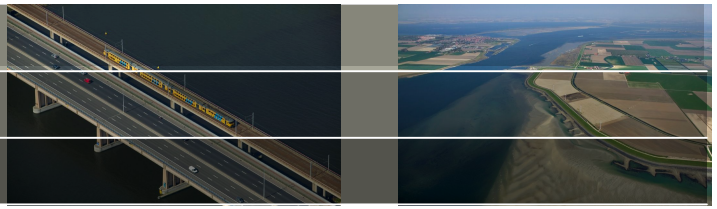
Code:

MOCDENS3D (MODFLOW family)
similar to SEAWAT

Assessing effects:

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



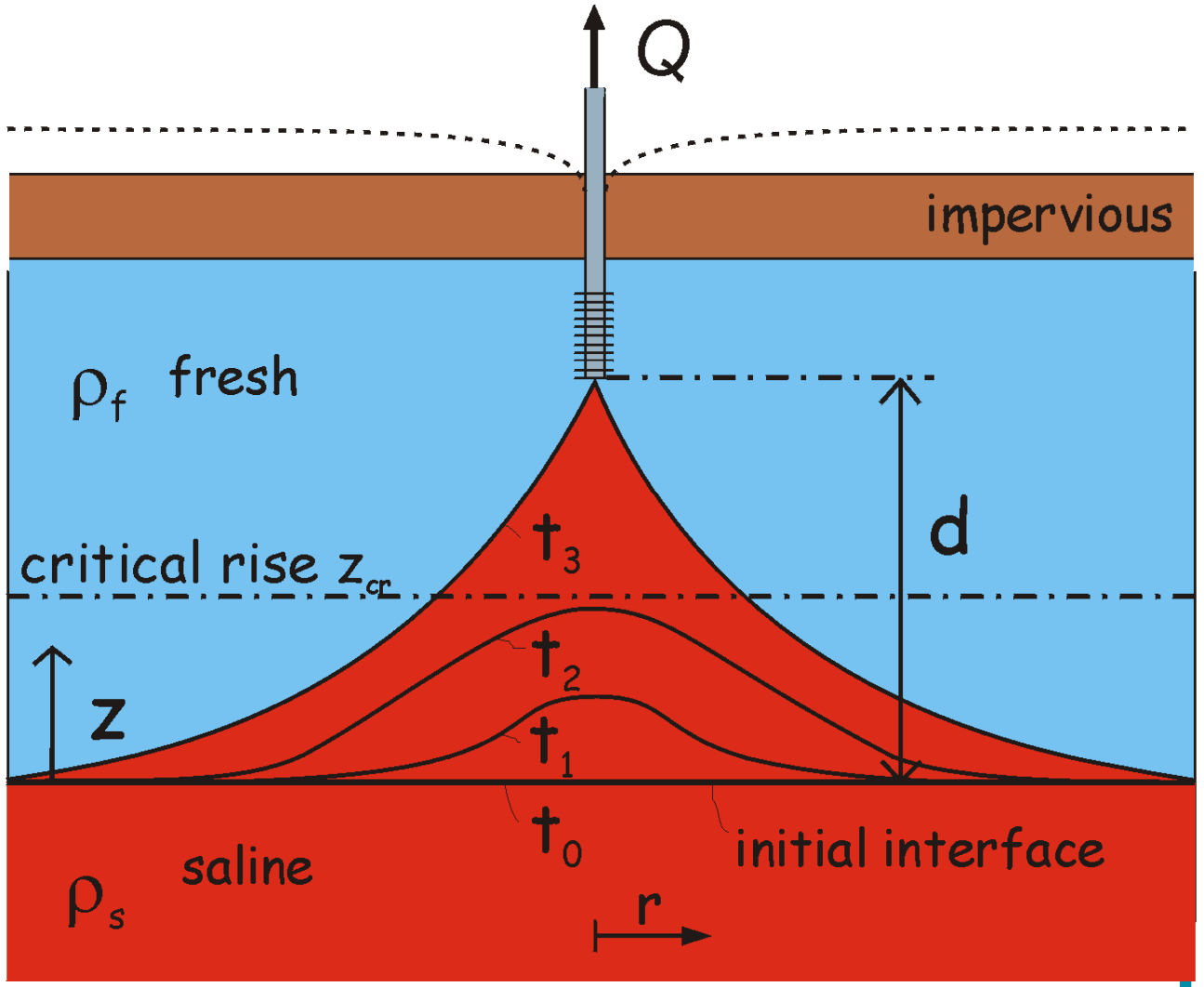


Opkegeling van zout grondwater

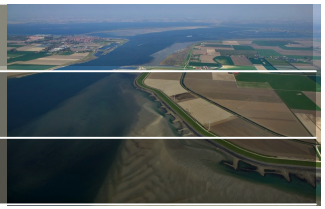
onder een onttrekkingsput

Deltares

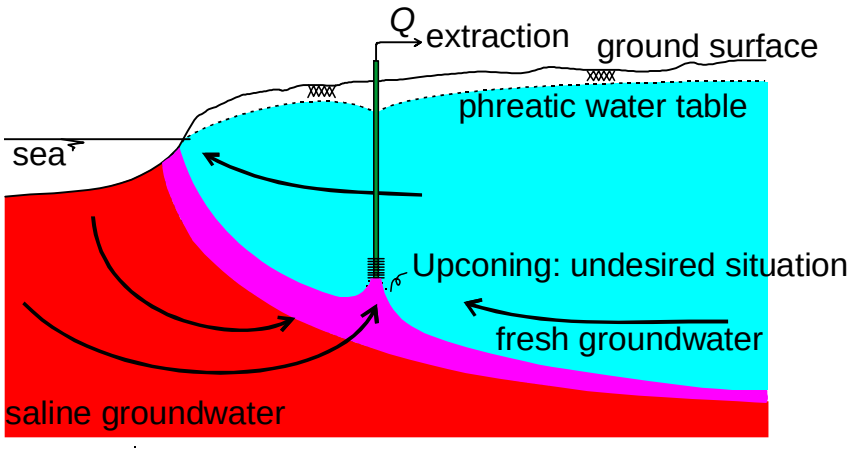
Opkegeling van zout grondwater onder een onttrekkingsput



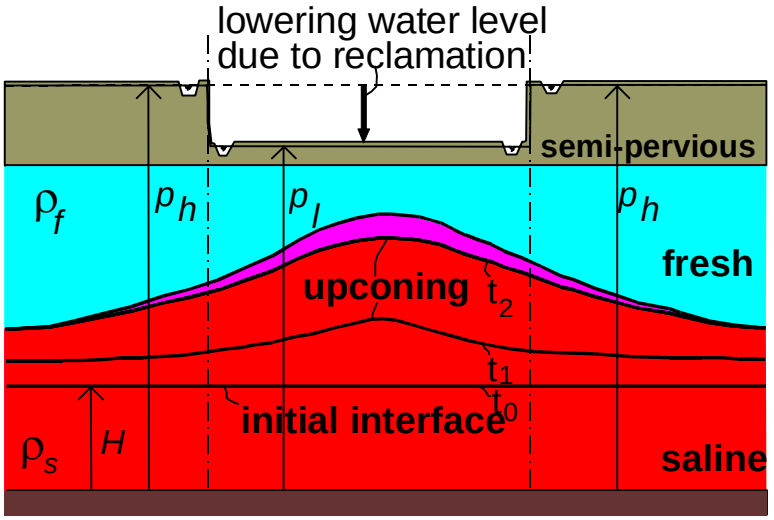
Upconing of saline groundwater



Under an extraction well



Under a low-lying area

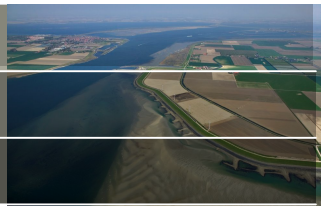


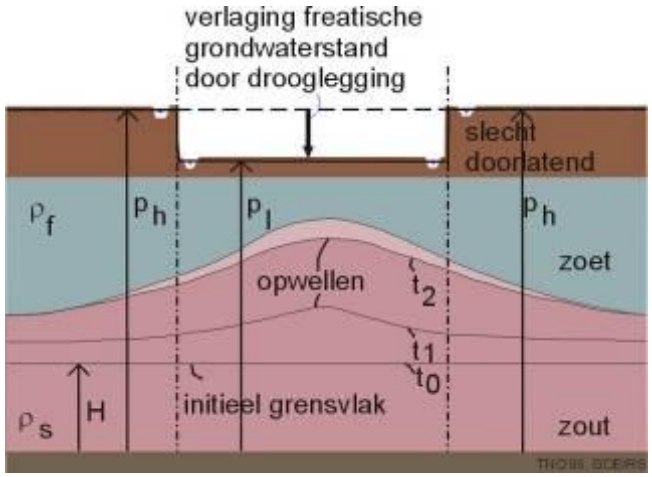
- movement of saline groundwater to extraction wells
- increase in salinity (>150-200 mg Cl-/l)
- lowering of the piezometric head (leads to land subsidence:
  e.g. Los Angeles: 9 m in the 1930's)

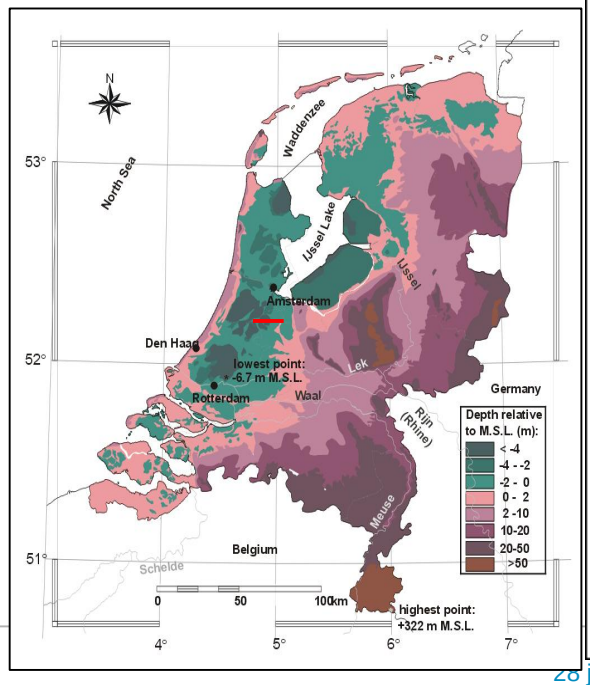
'Solutions': reduce extraction rate, abandon well, inundate polder

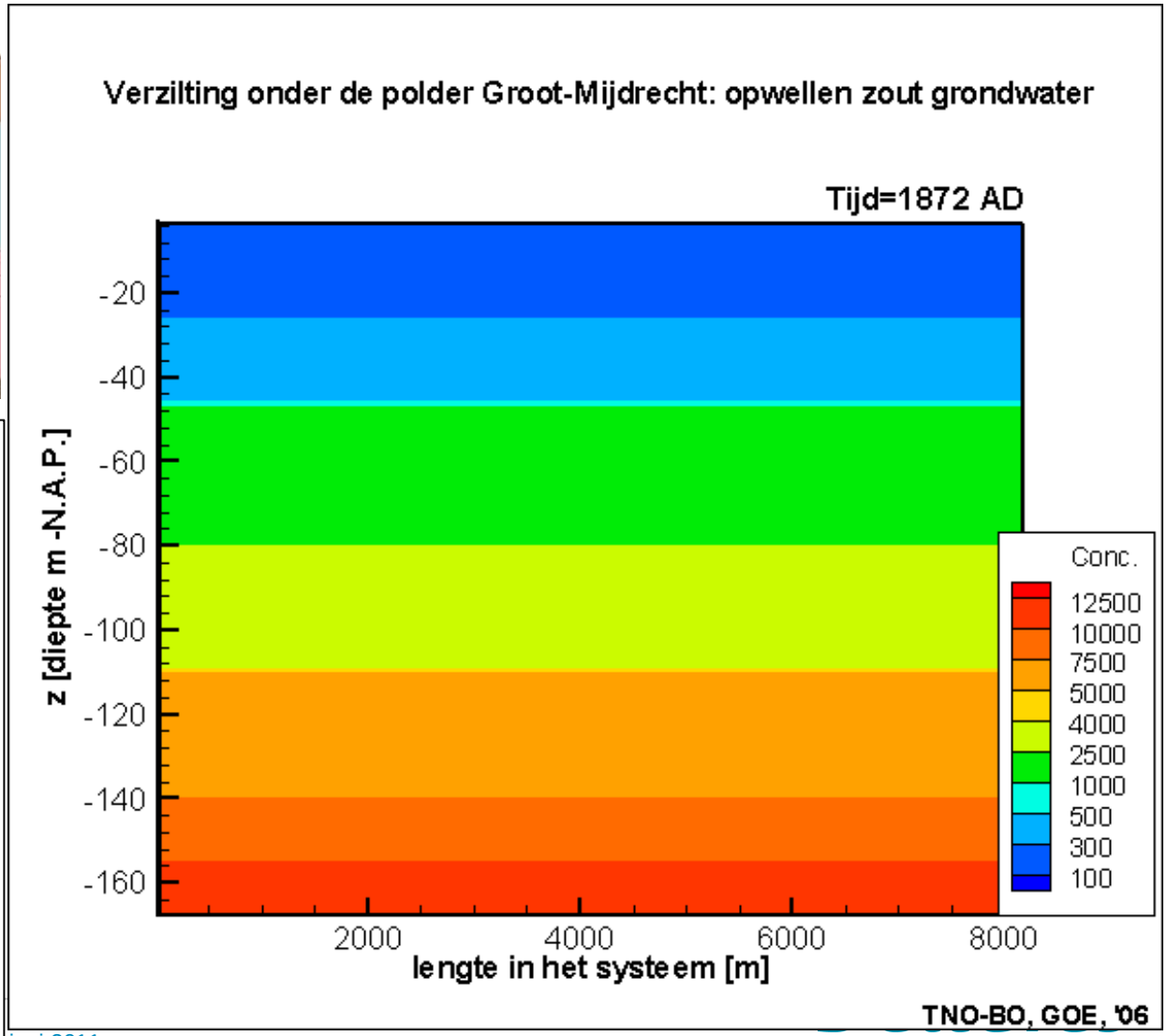
Deltares

Upconing under a low-lying polder

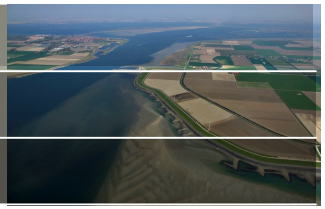


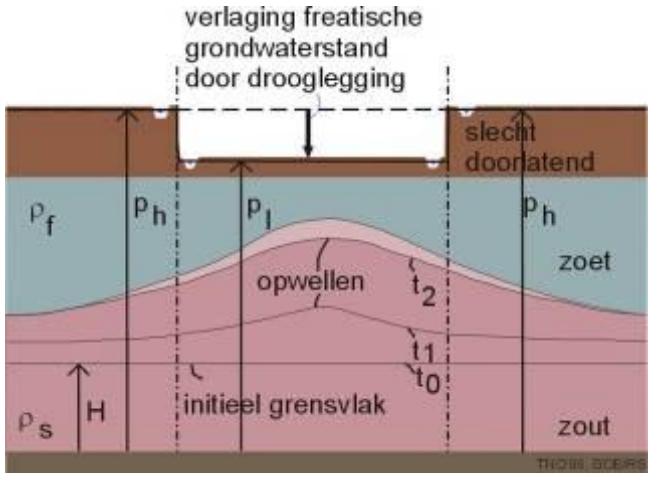


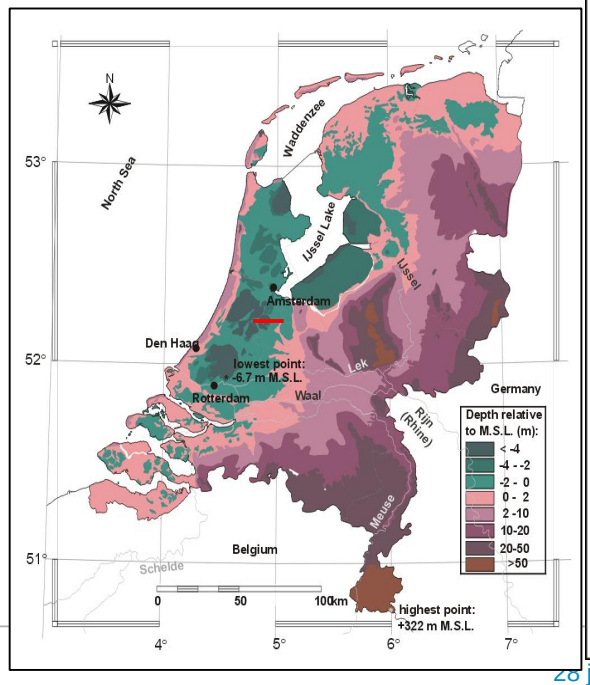


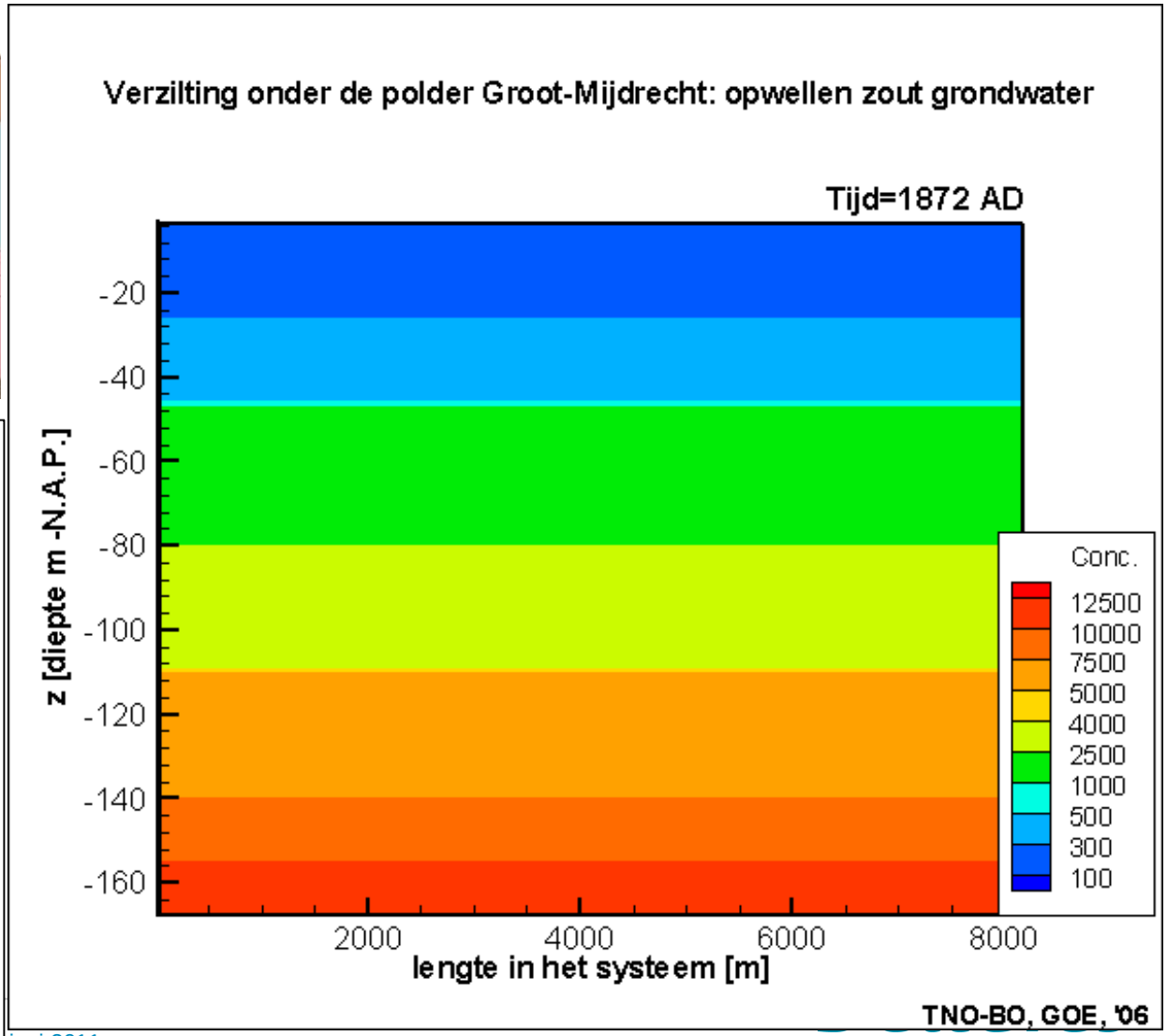


Upconing under a low-lying polder

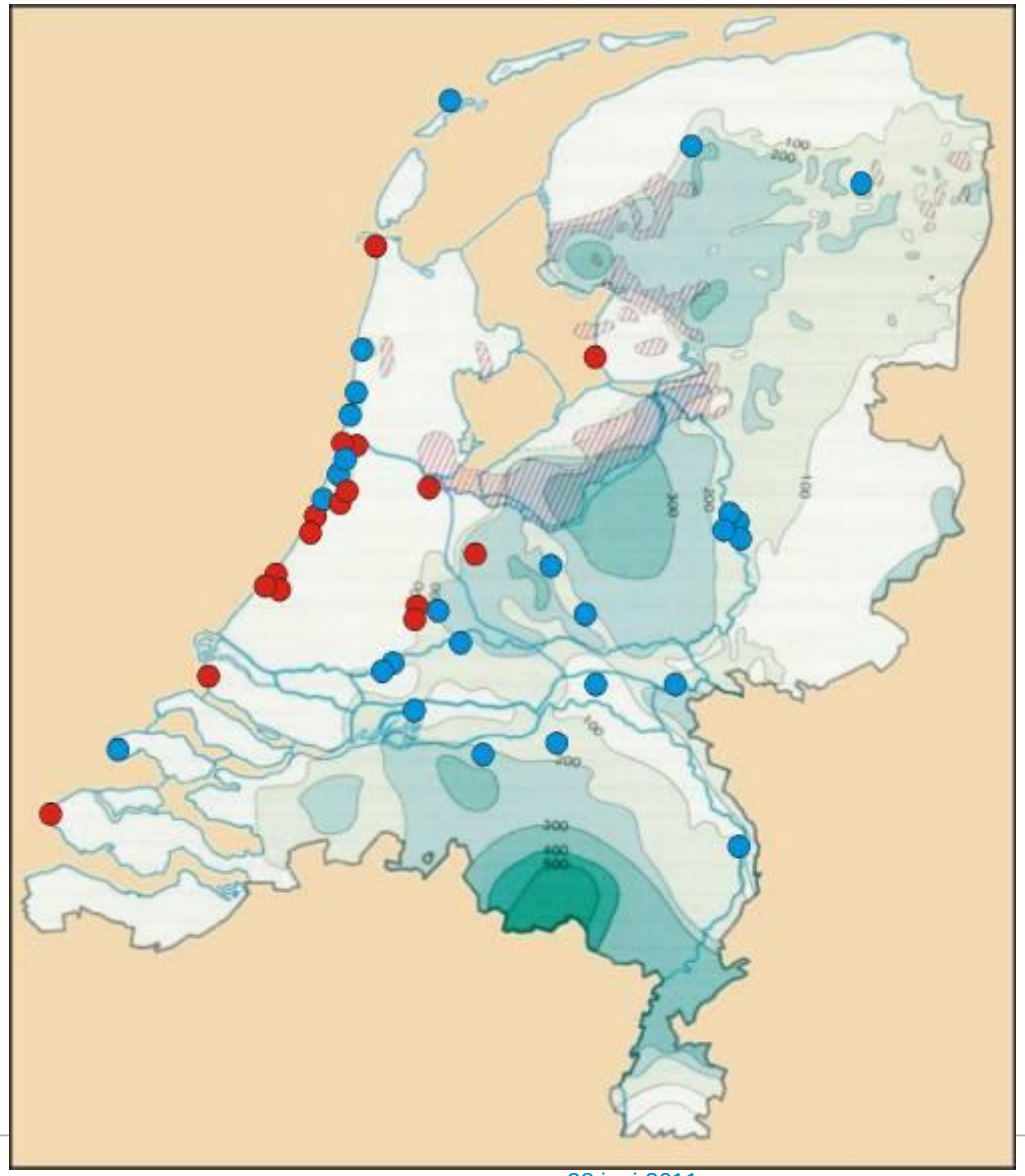


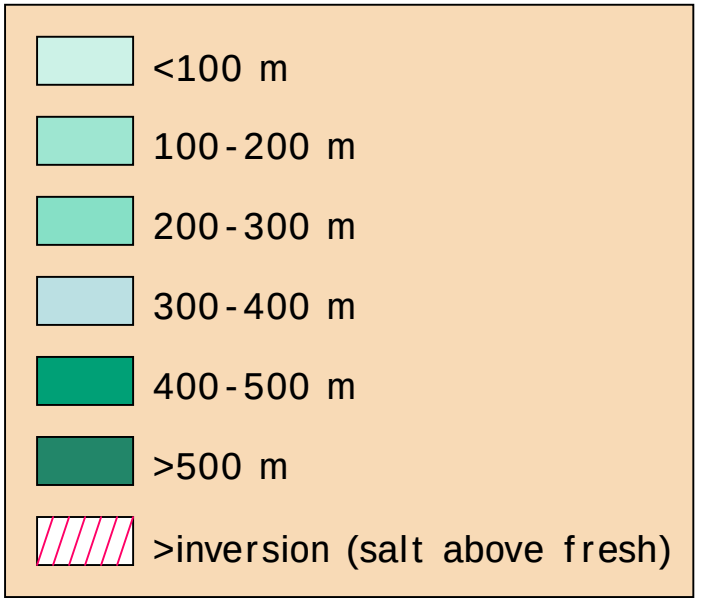






Availability of fresh groundwater for drinking water

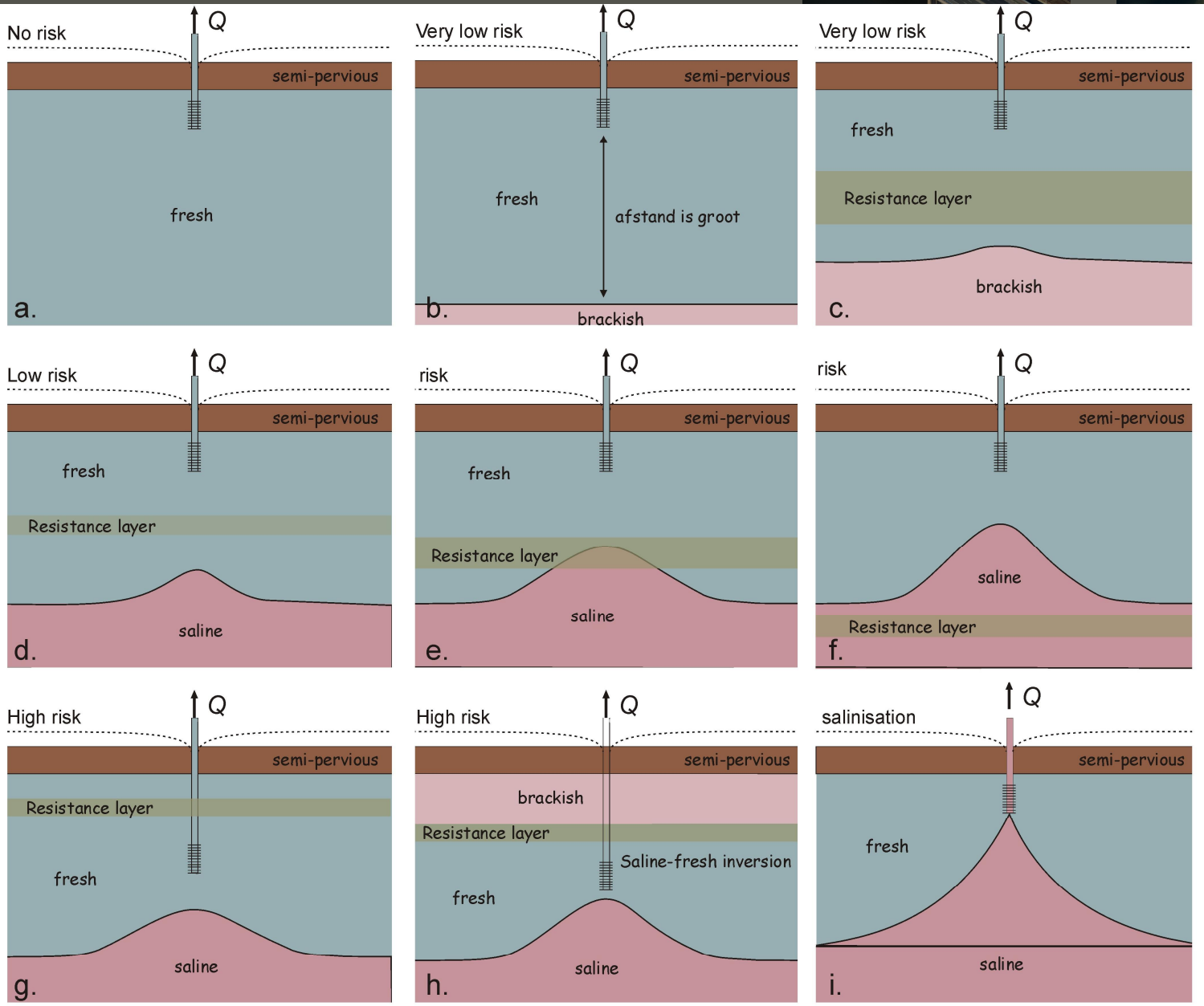


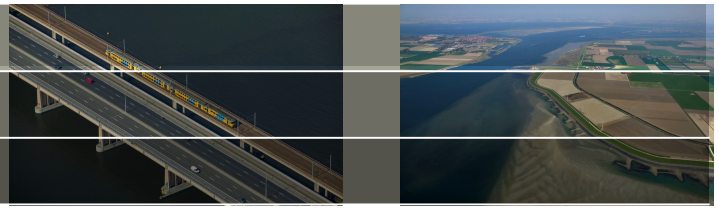


Pumping stations with salinisation

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

Different risks of upconing saline groundwater

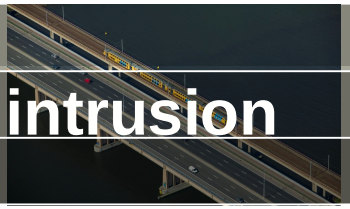


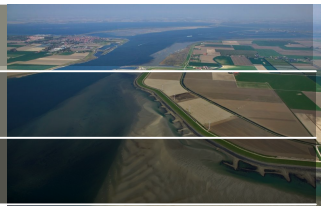


Technische maatregelen

Deltares

Measures to compensate salt water intrusion

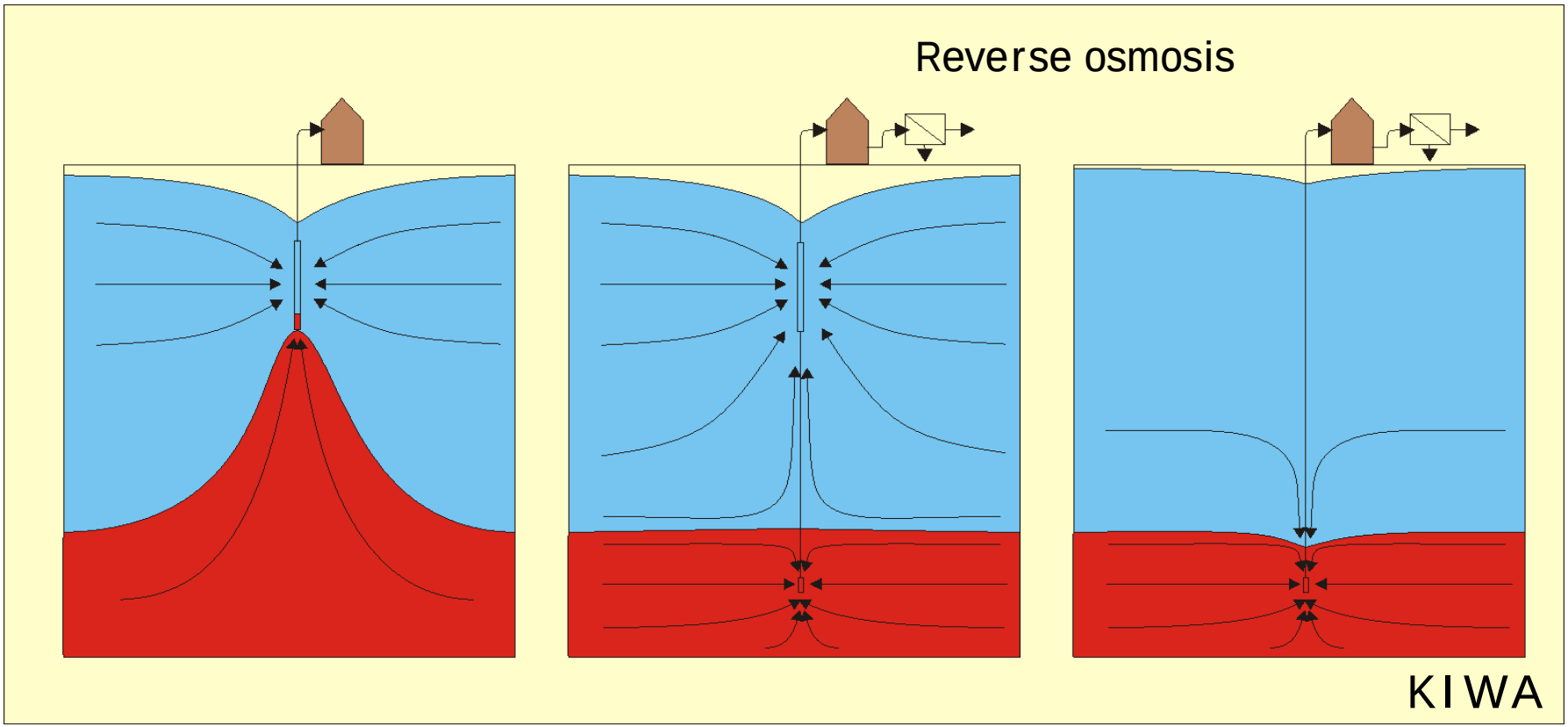




- ‘The Fresh Holder’
- Extraction of saline/brackish groundwater
- Infiltration of fresh surface water
- Modifying pumping rates
- Land reclamation in front of the coast
- Creating physical barriers (chrystallisation or biosealing)

Deltares

Solution: The Fresh Holder

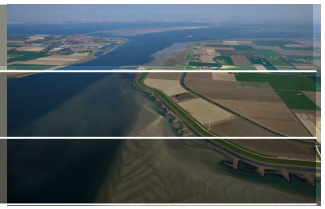


Upconing can be prevented by the extraction of brackish groundwater

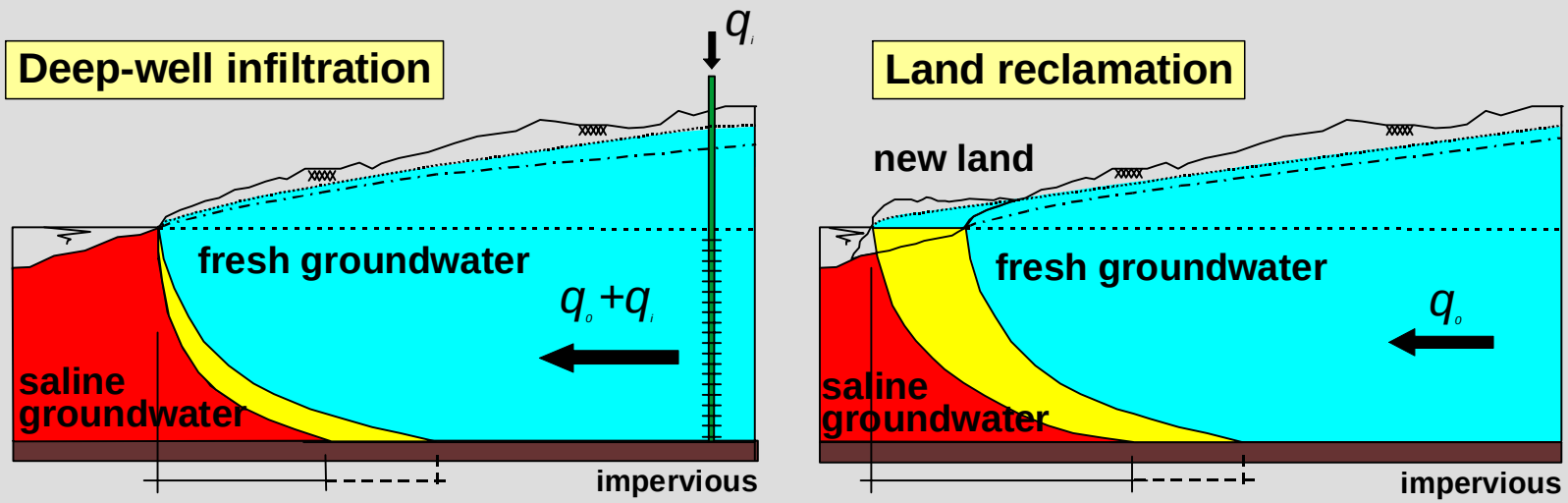
This brackish groundwater can be transformed to water of agricultural water quality by using the membrane filtration technique

Deltares

Countermeasures of salt water intrusion (1)

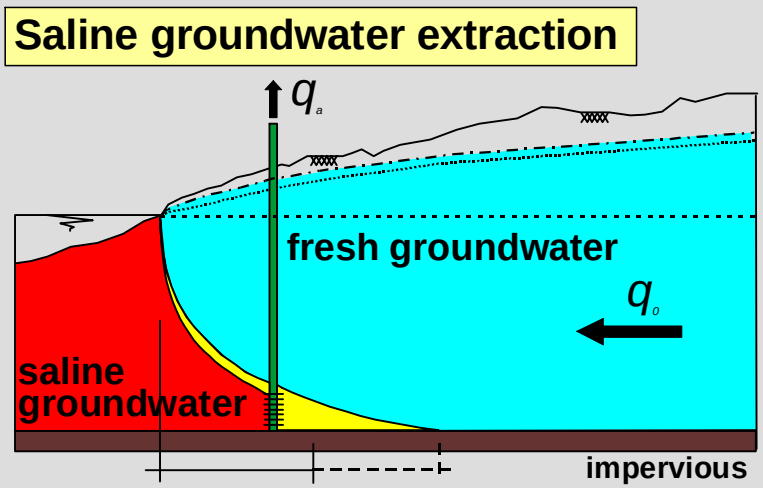


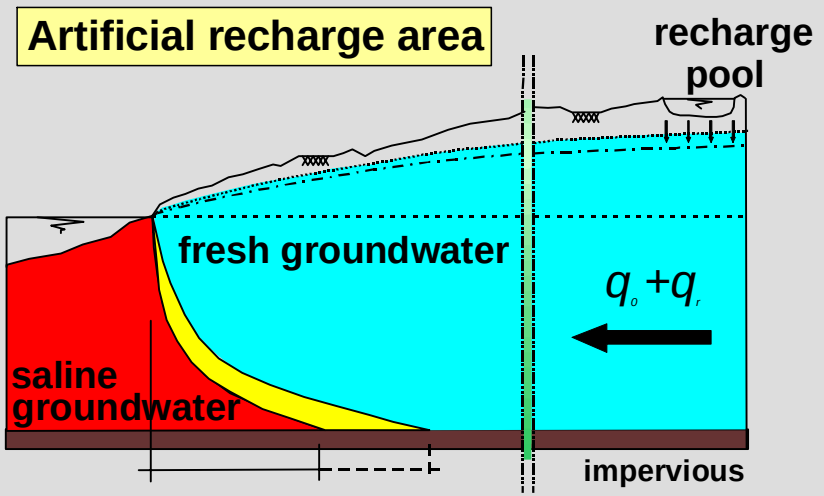
increase of fresh groundwater volume due to countermeasure



Deltares

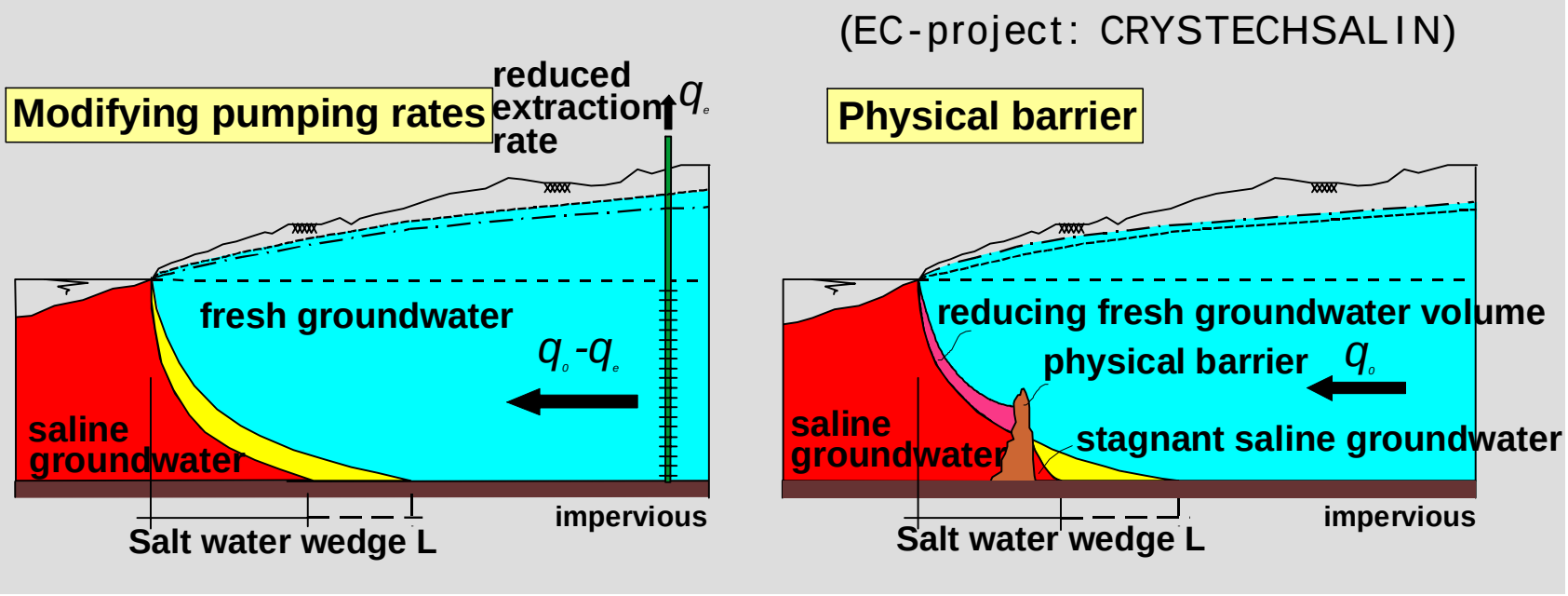
Countermeasures of salt water intrusion (2)





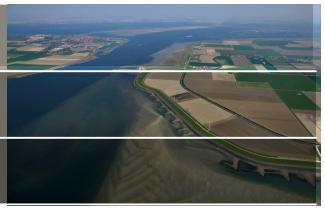
Deltares

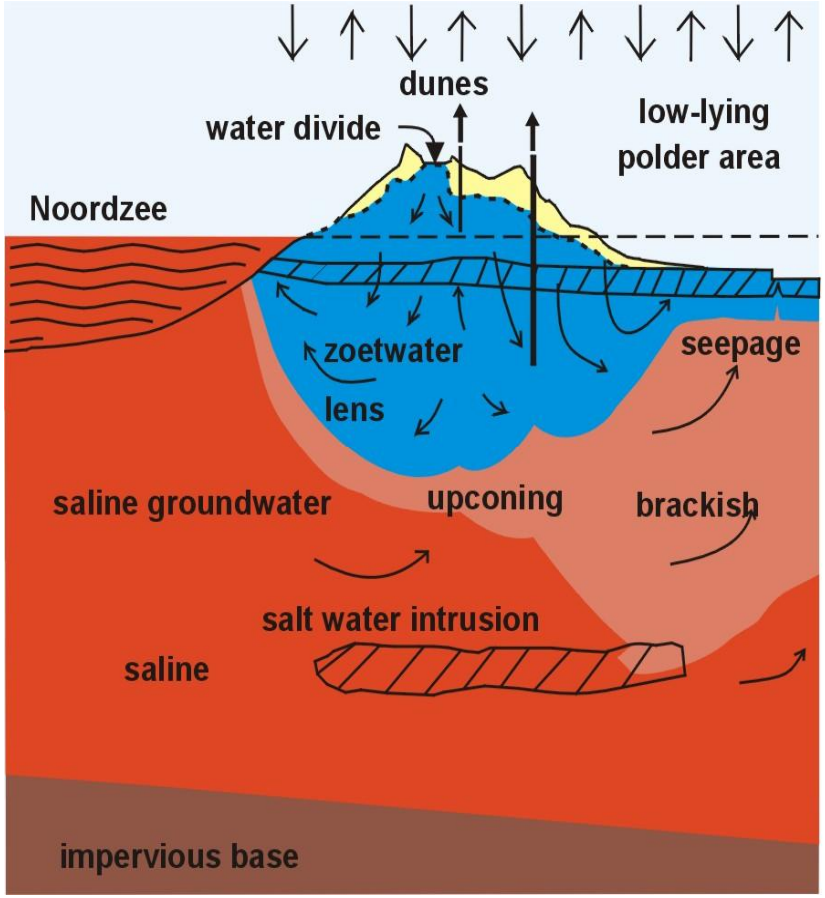
Countermeasures of salt water intrusion (3)

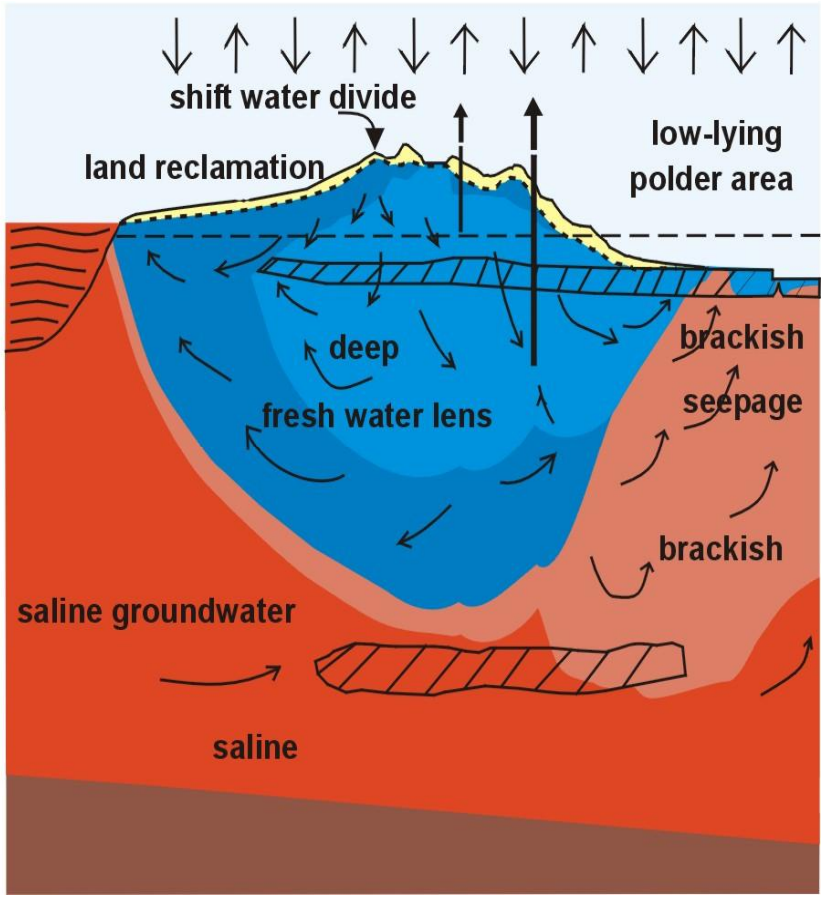


Deltares

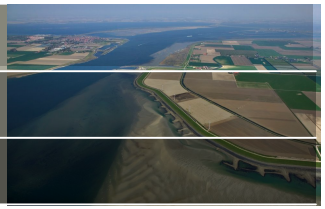
Landaanwinning en de zoetwaterlens







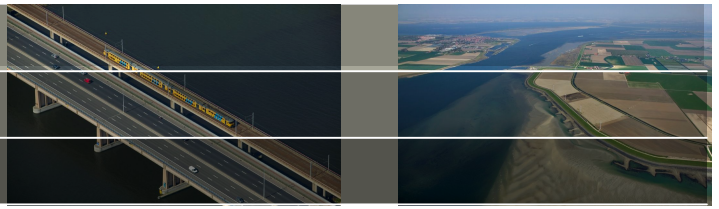
Deltares

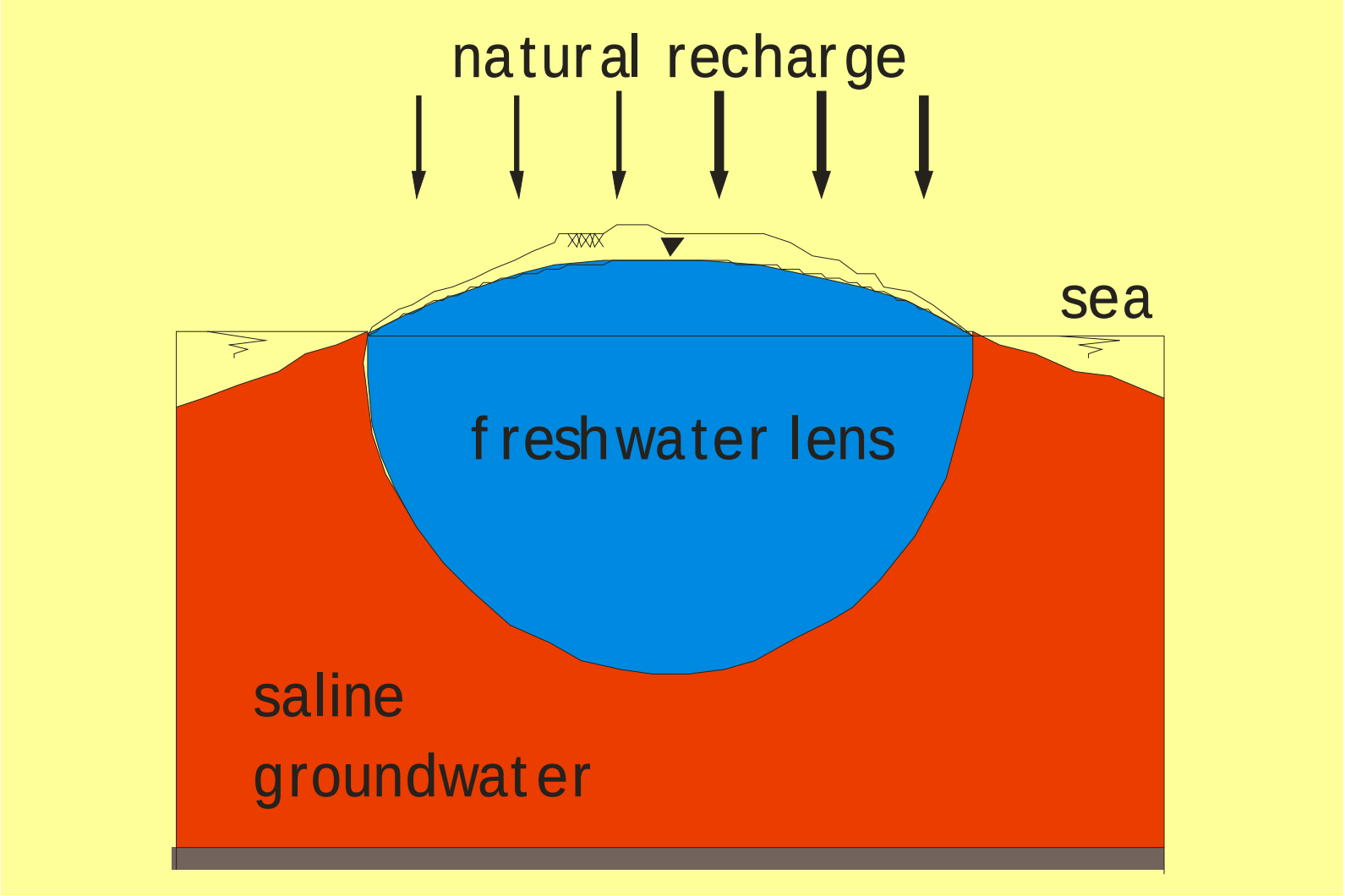


Voorbeelden zoet-zout grondwater

Deltares

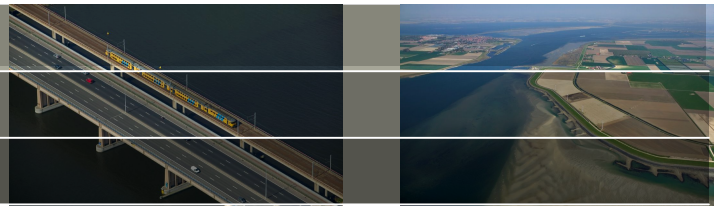
Evolution of a freshwater lens

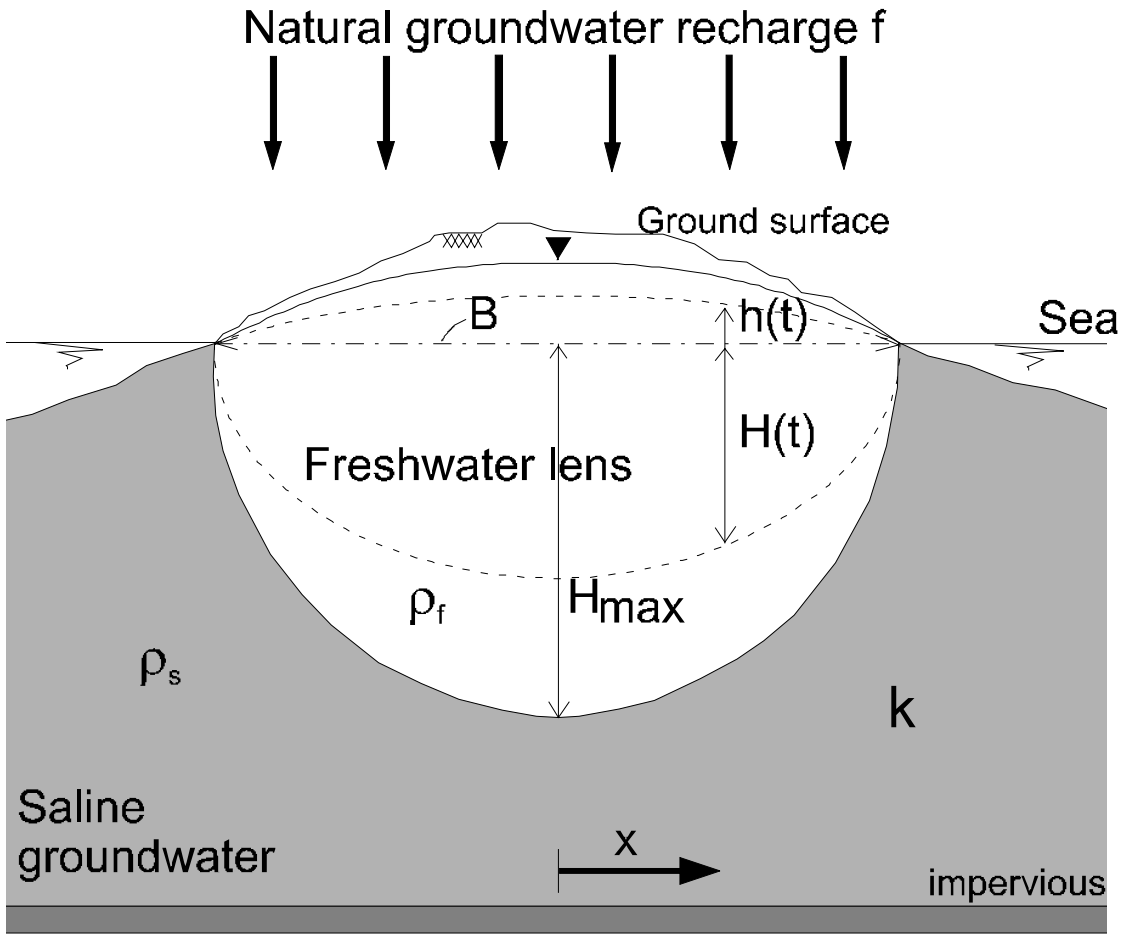




Deltares

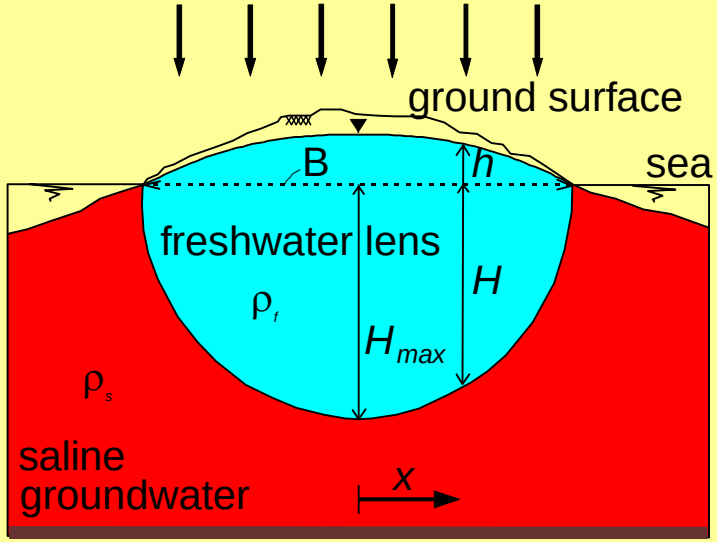
Development of a freshwater lens





Deltares

Zoetwaterlens duingebied: analytische vergelijking



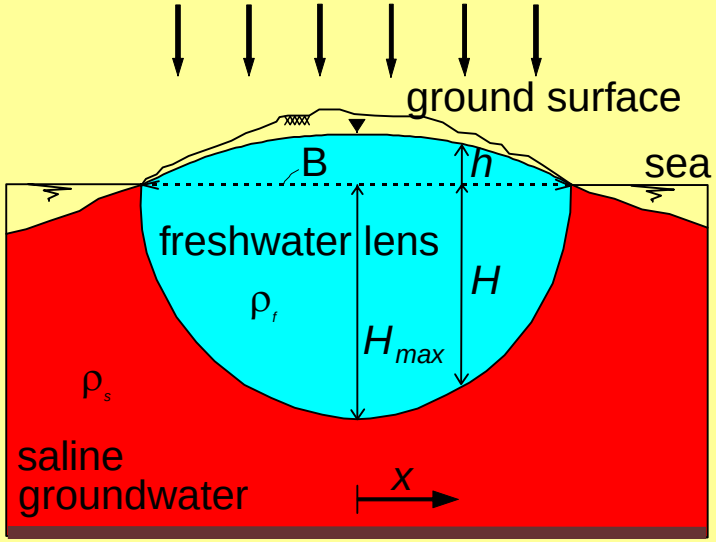
Depth of fresh-saline interface H

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

$$h = \alpha H$$

Deltares

Zoetwaterlens duingebied: analytische vergelijking



Depth of fresh-saline interface H

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

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

$$n_e = 0.35$$

Maximal thickness lens

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

Volume lens (wrong in lectures notes)

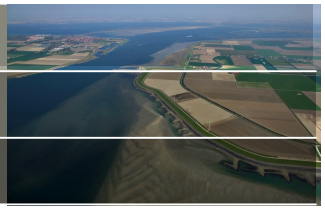
$$V = 35203\text{m}^3/\text{m}'$$

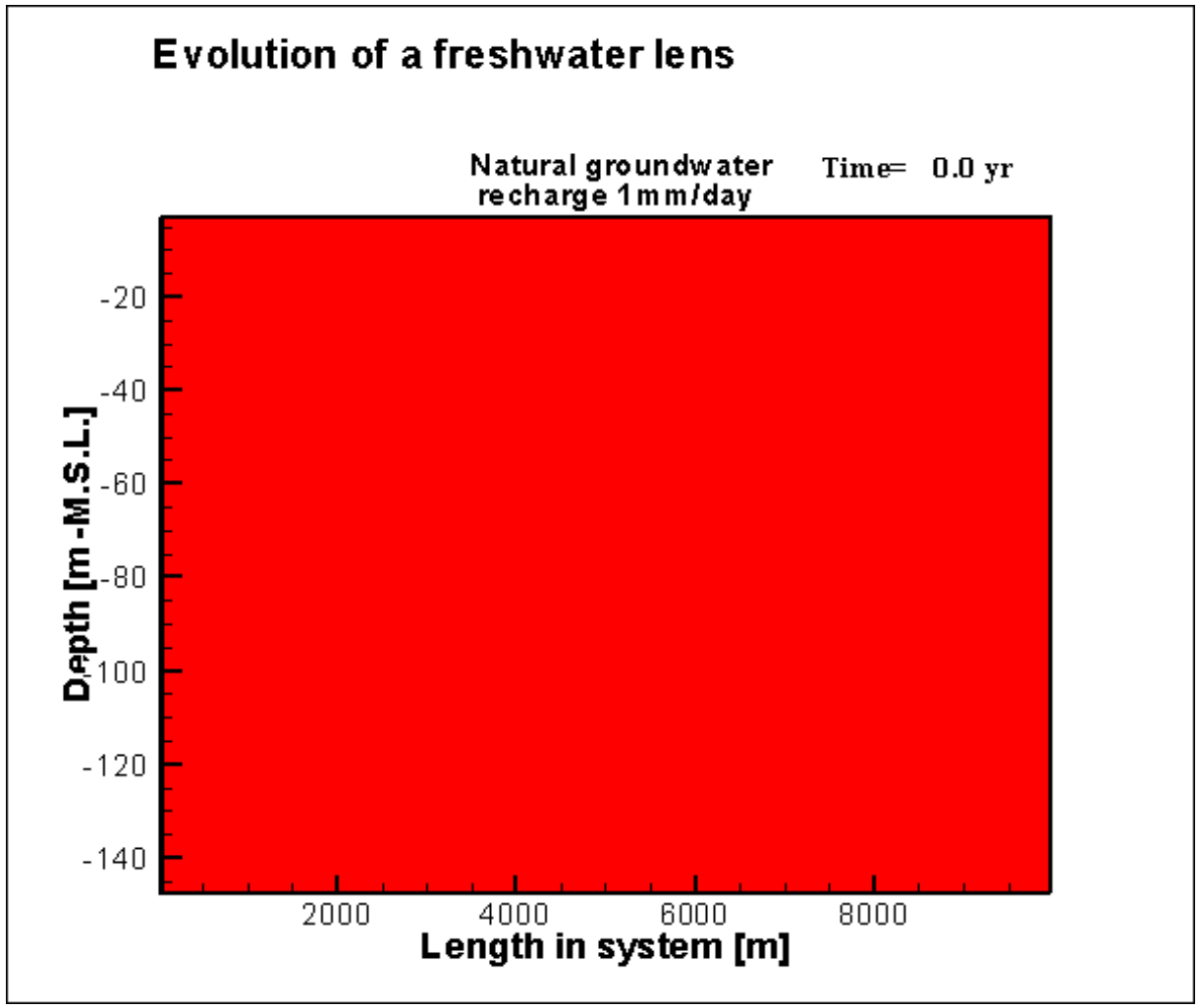
Characteristic time

$$\text{T} = \frac{35203}{2}\text{days} = 48.2\text{years}$$

Deltares

Ontwikkeling van een zoetwaterlens





T = karakteristieke tijdschaal

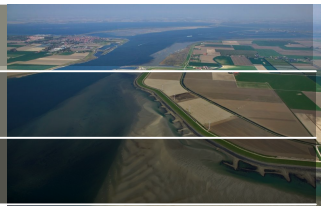
T = tijdsduur voordat lens 95% van zijn uiteindelijke vorm heeft

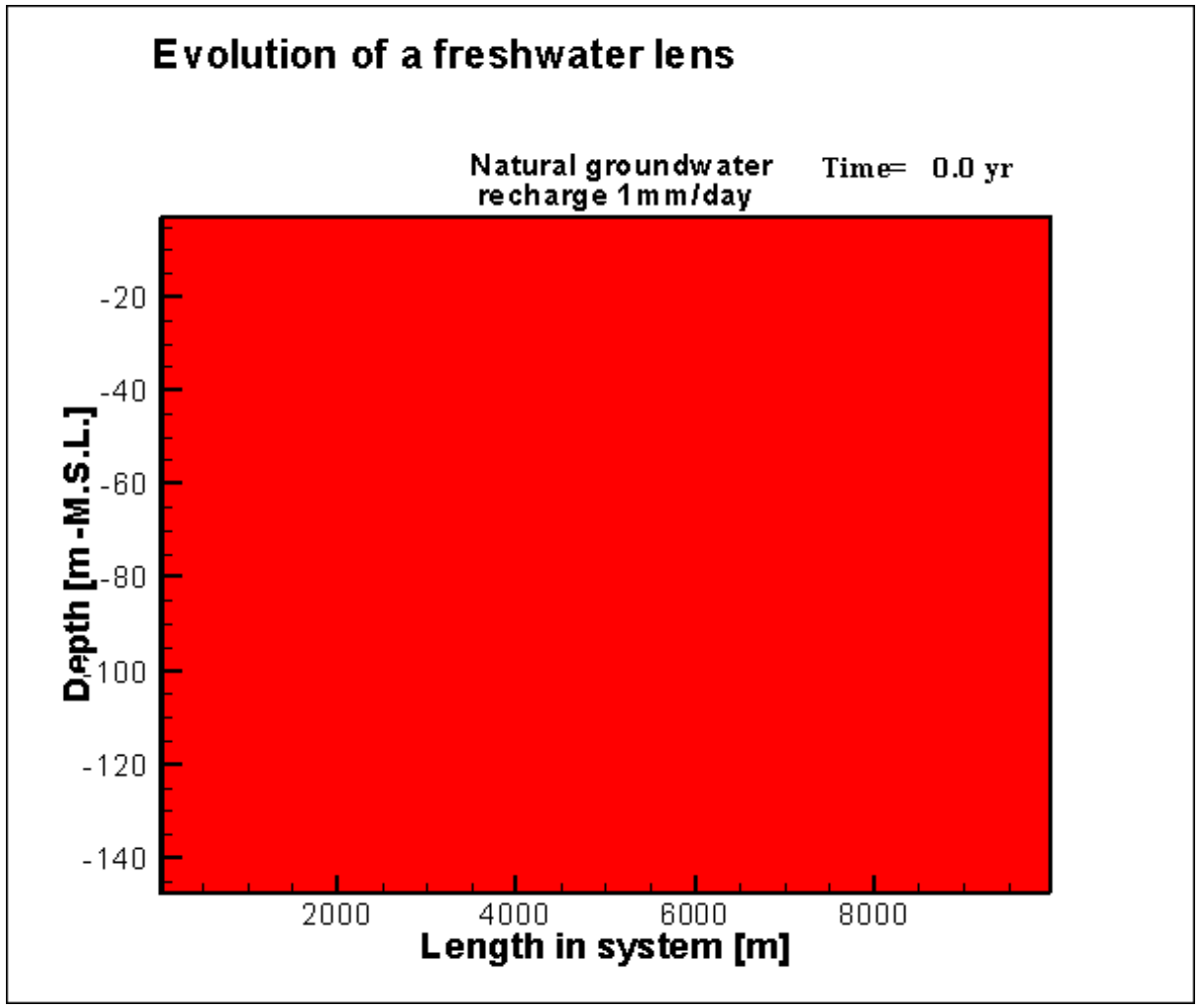
In Nederland: T = 75-200 jaar,

afhankelijk van:
- breedte duingebied
- neerslag
- doorlatendheid bodem

Deltares

Ontwikkeling van een zoetwaterlens





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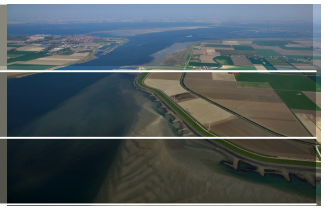
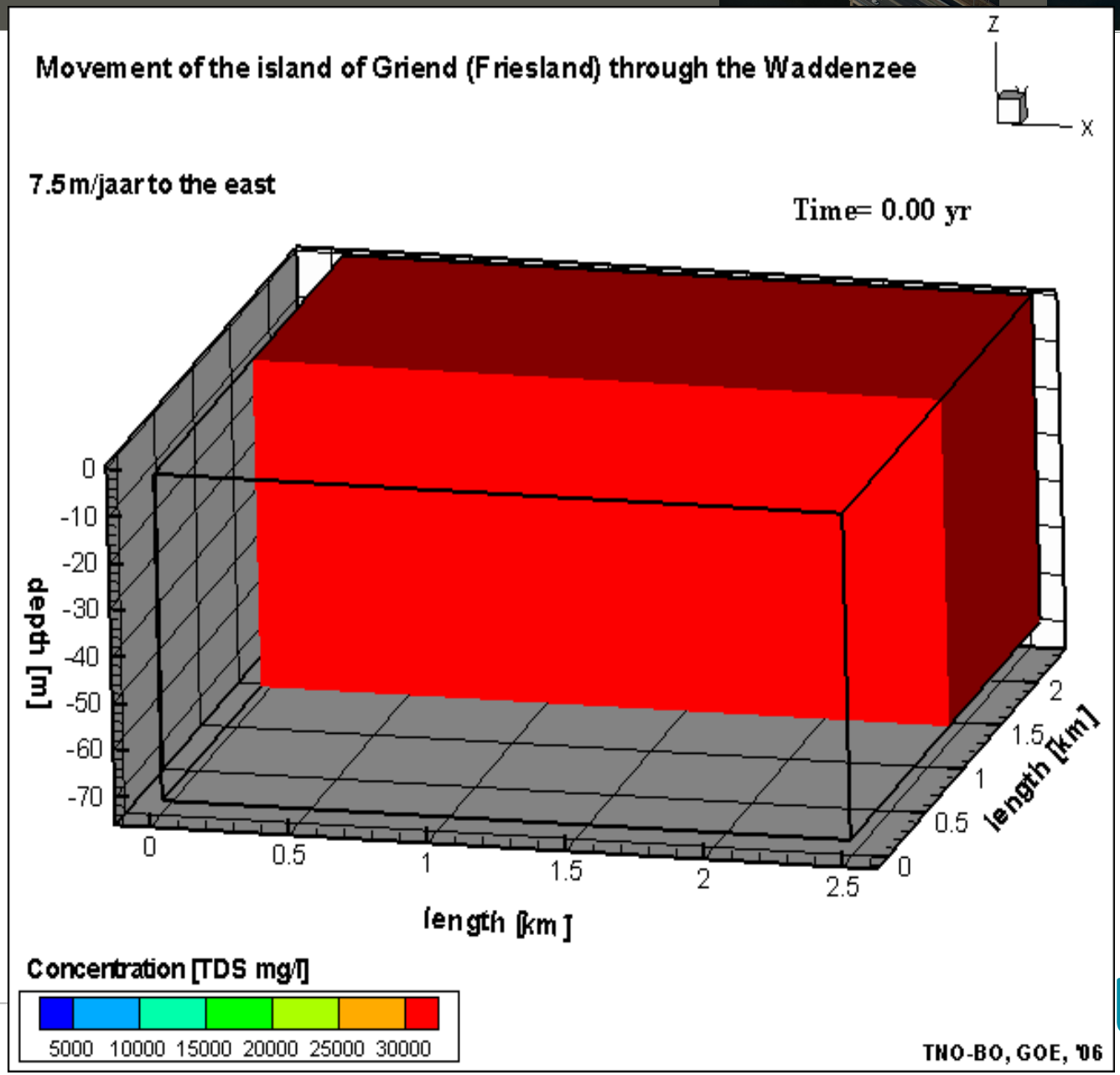
Deltares

Griend

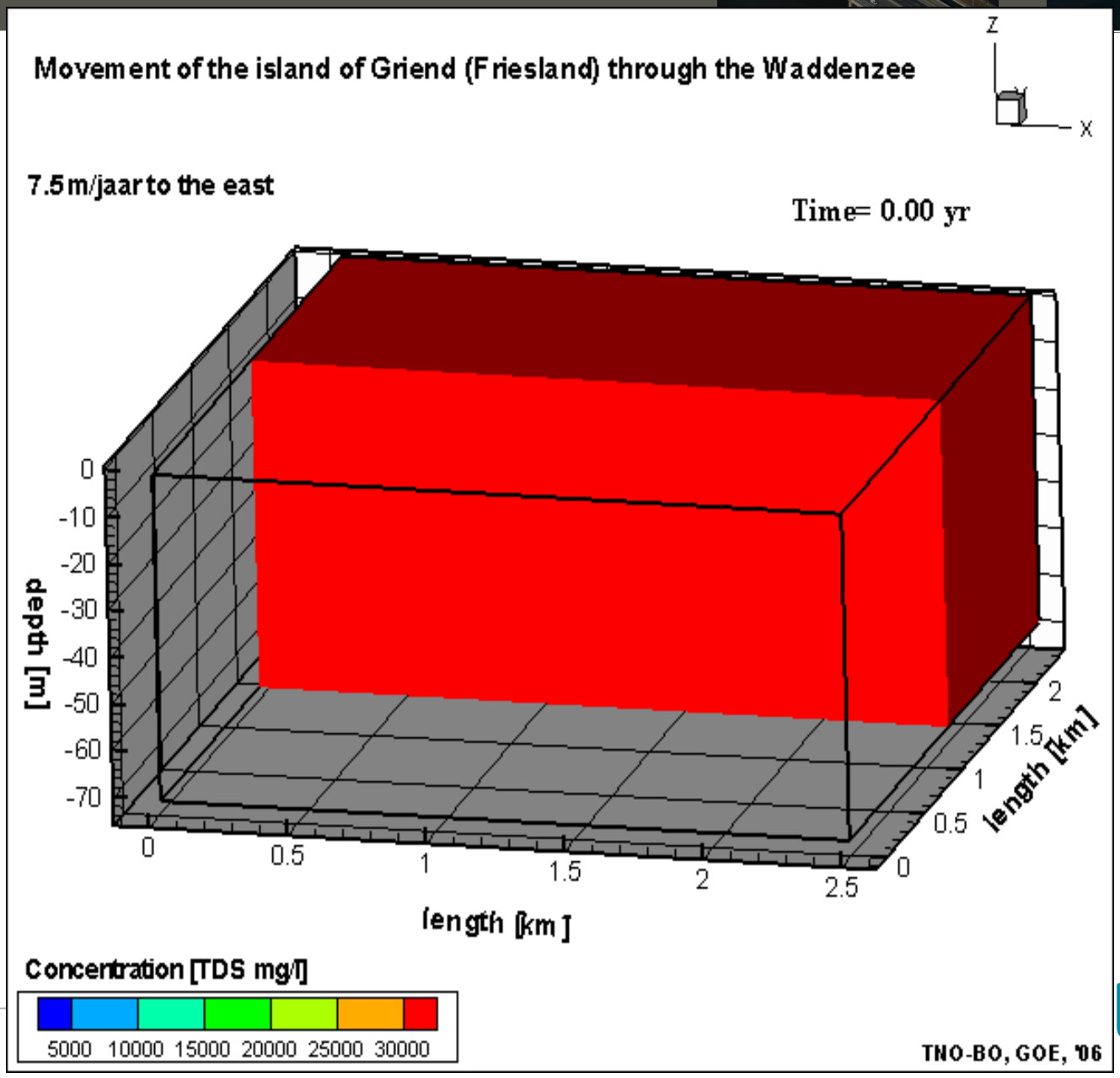


1. Het kleine eiland beweegt ~7.5m per jaar naar het oosten
2. Effect op de zoetwatervoorraad:
   - Kan er een zoetwater lens ontwikkelen?
   - Wat is de dikte van de lens?

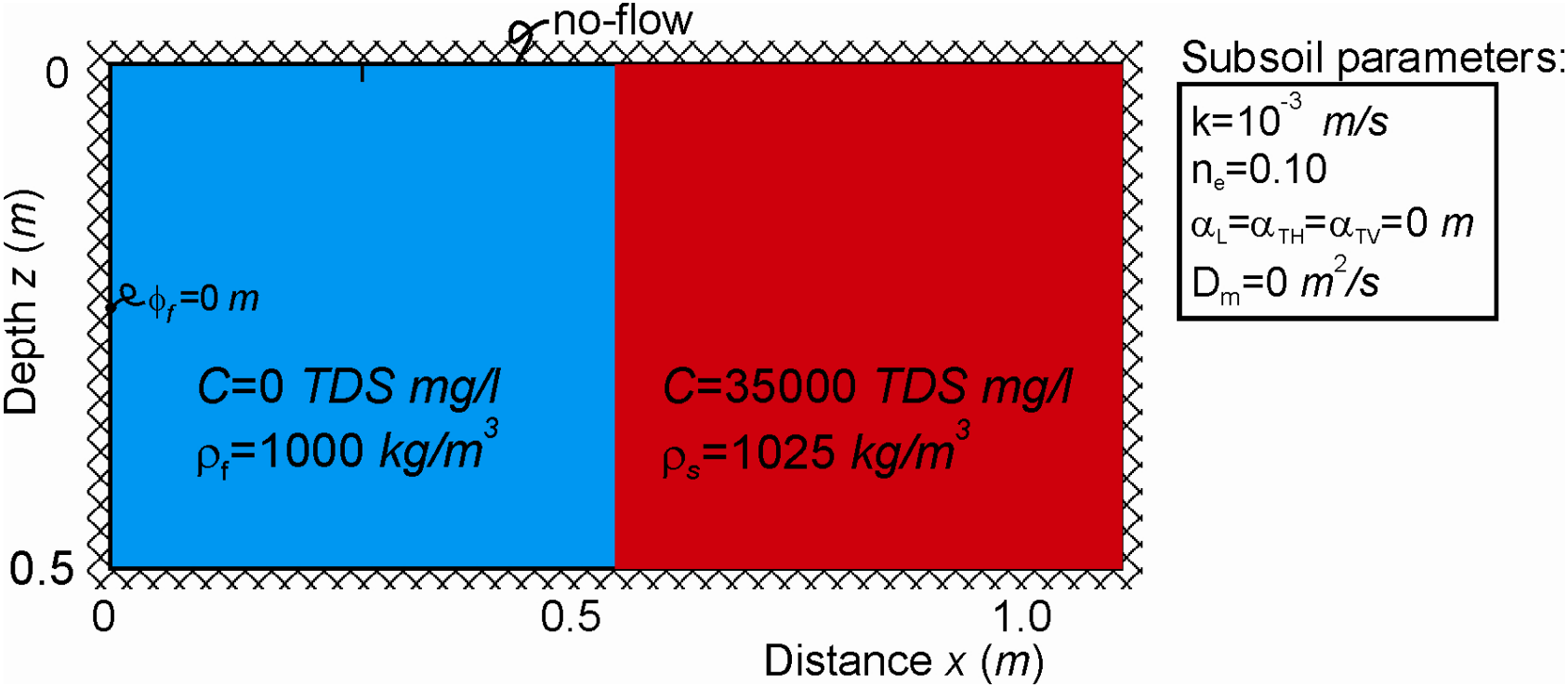
Beweging van De Griend en de creatie van de lens



Beweging van De Griend en de creatie van de lens



Vertical interface between fresh and saline groundwater

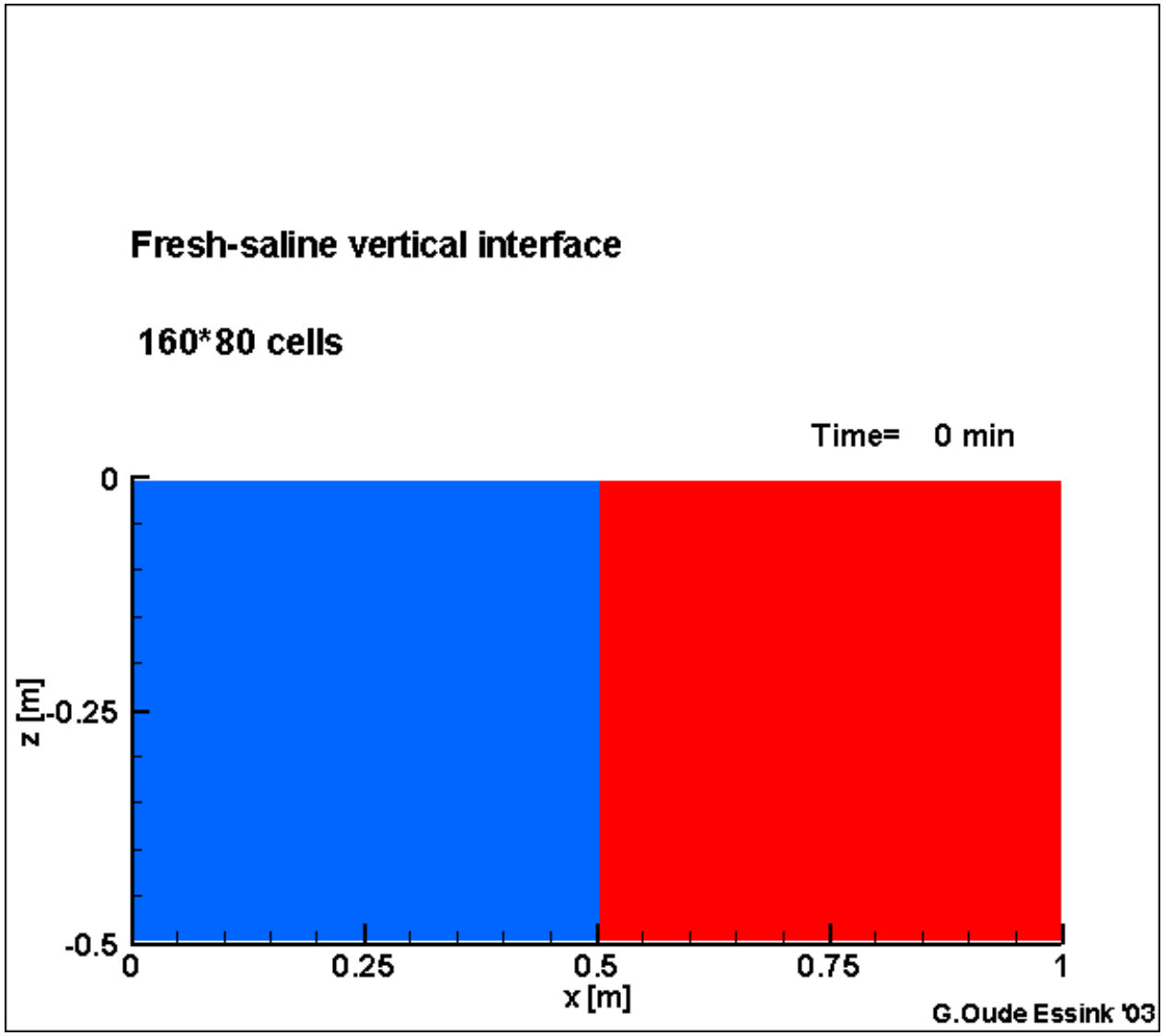


Subsoil parameters:

- $k=10^{-3}$ m/s
- $n_e=0.10$
- $\alpha_L=\alpha_{TH}=\alpha_{TV}=0$ m
- $D_m=0$ m^2/s

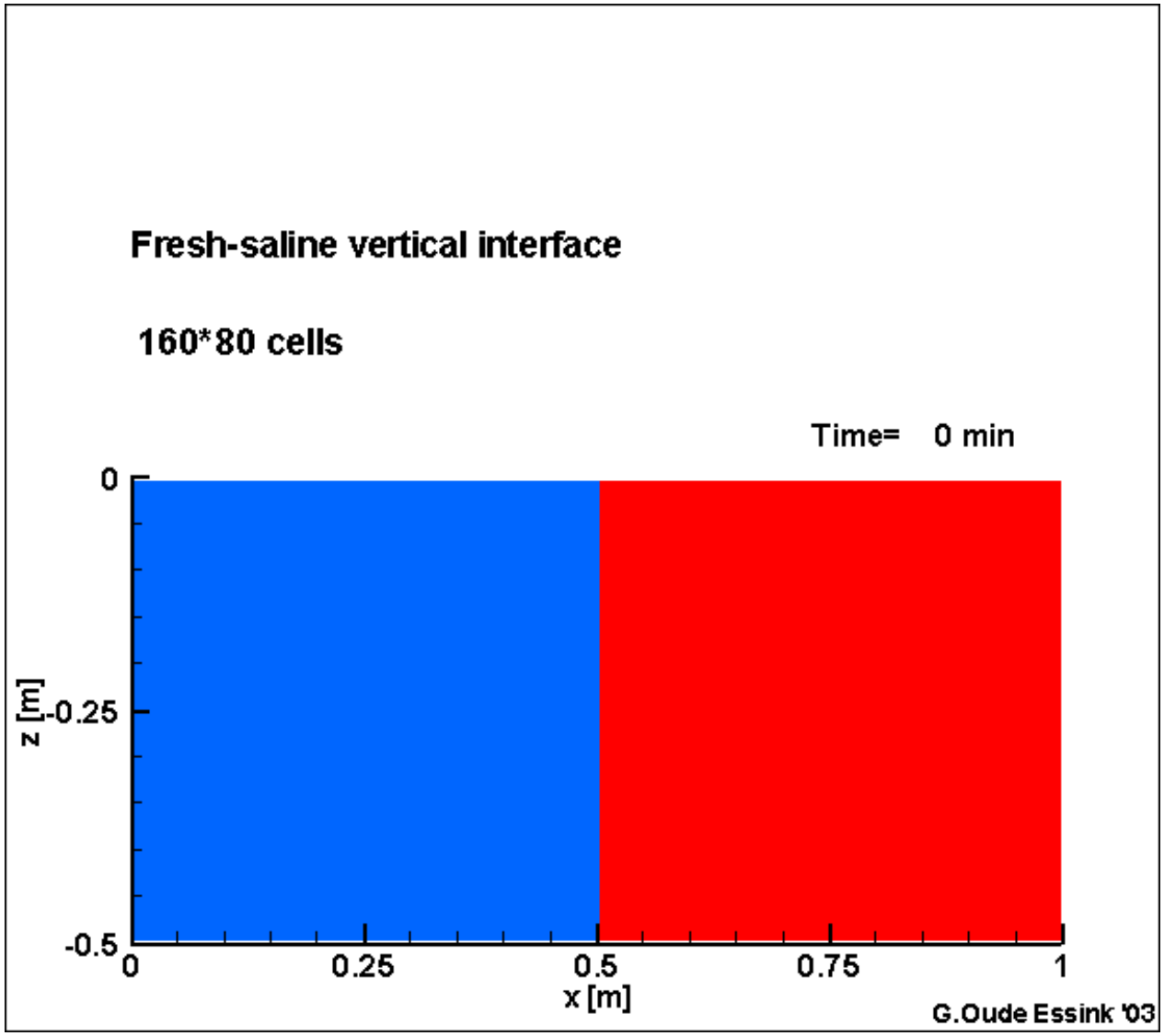
Deltares

Dichtheidsafhankelijke grondwaterstroming



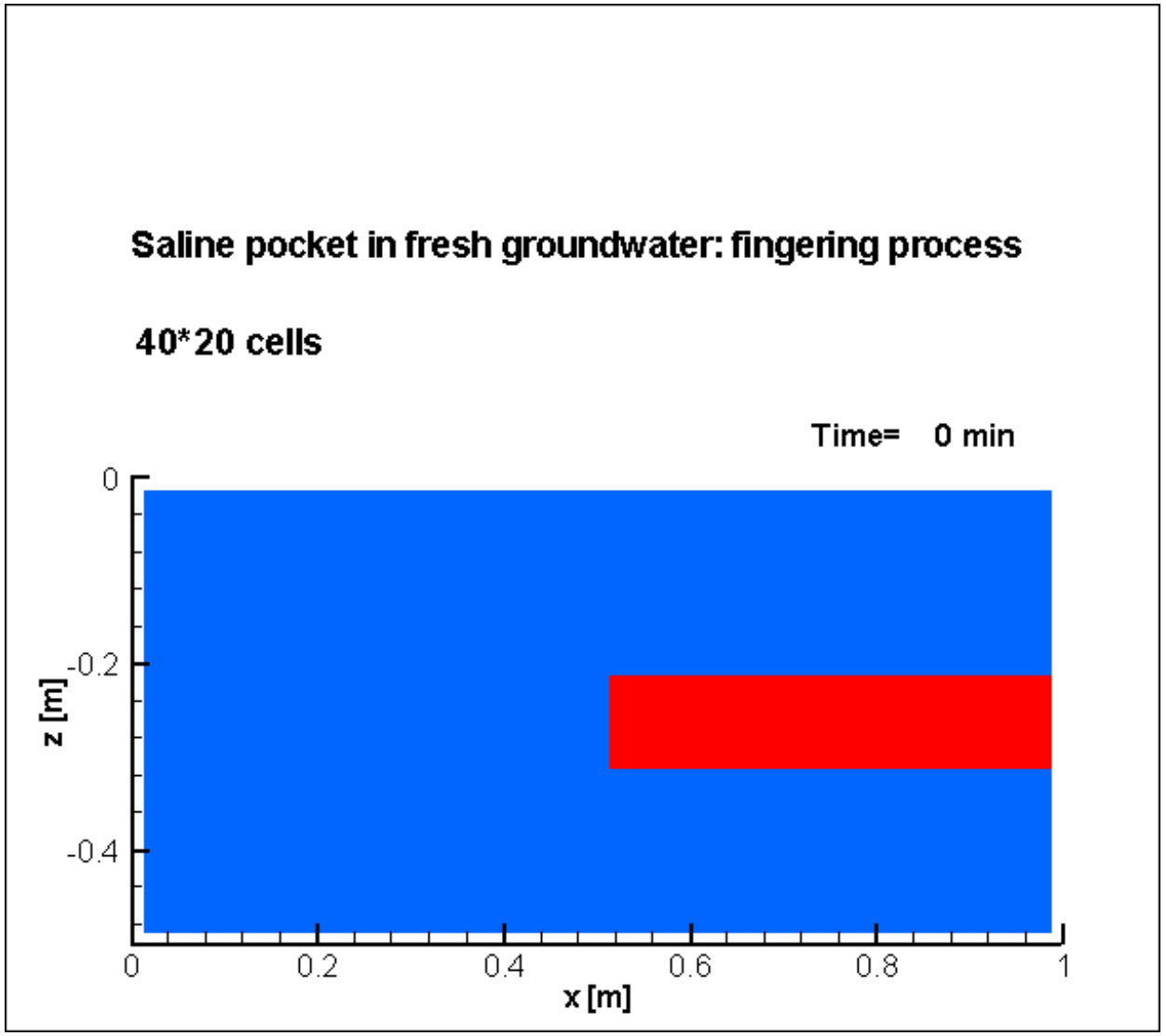
Deltares

Dichtheidsafhankelijke grondwaterstroming



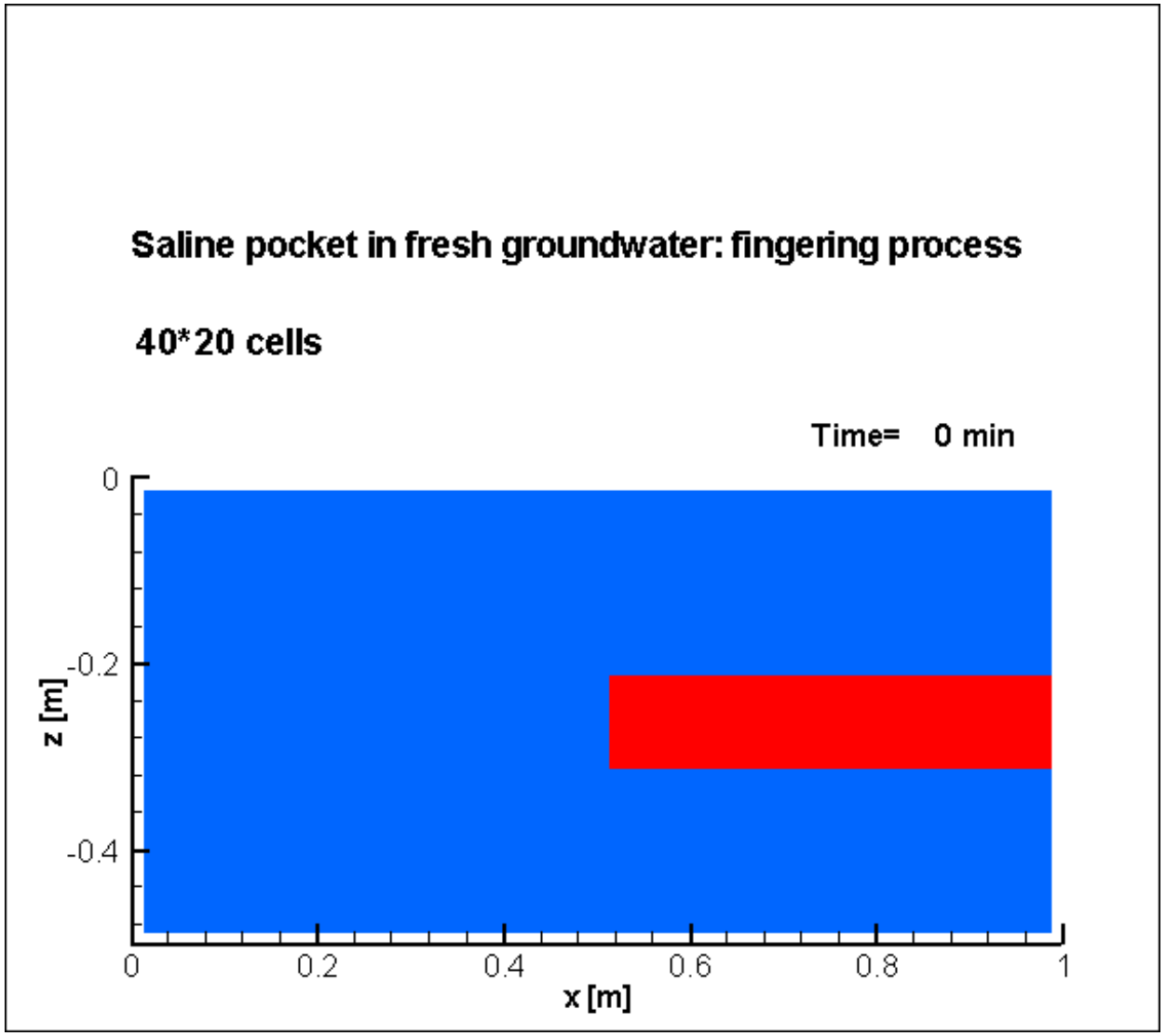
Deltares

Dichtheidsafhankelijke grondwaterstroming



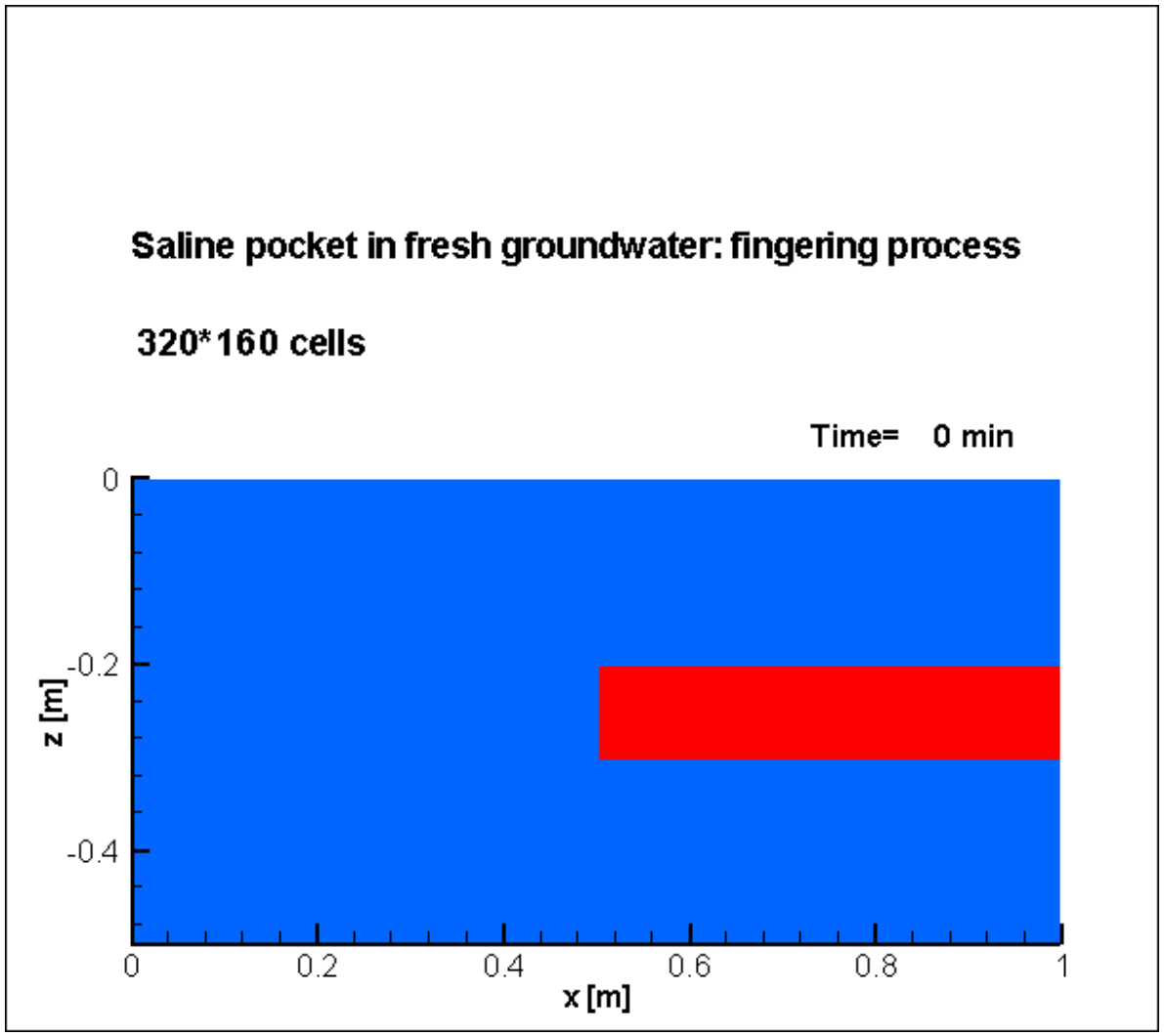
Deltares

Dichtheidsafhankelijke grondwaterstroming



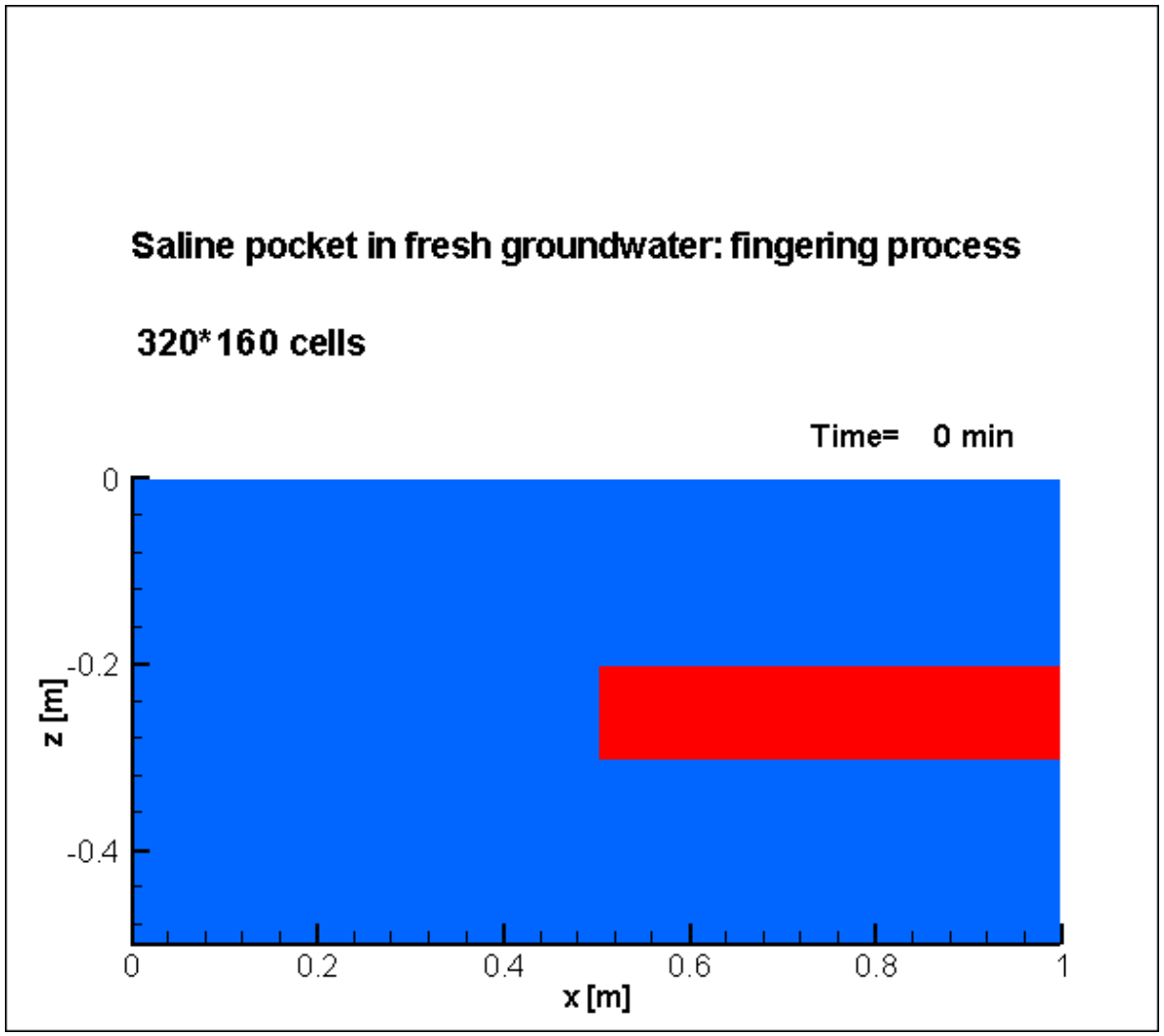
Deltares

Dichtheidsafhankelijke grondwaterstroming



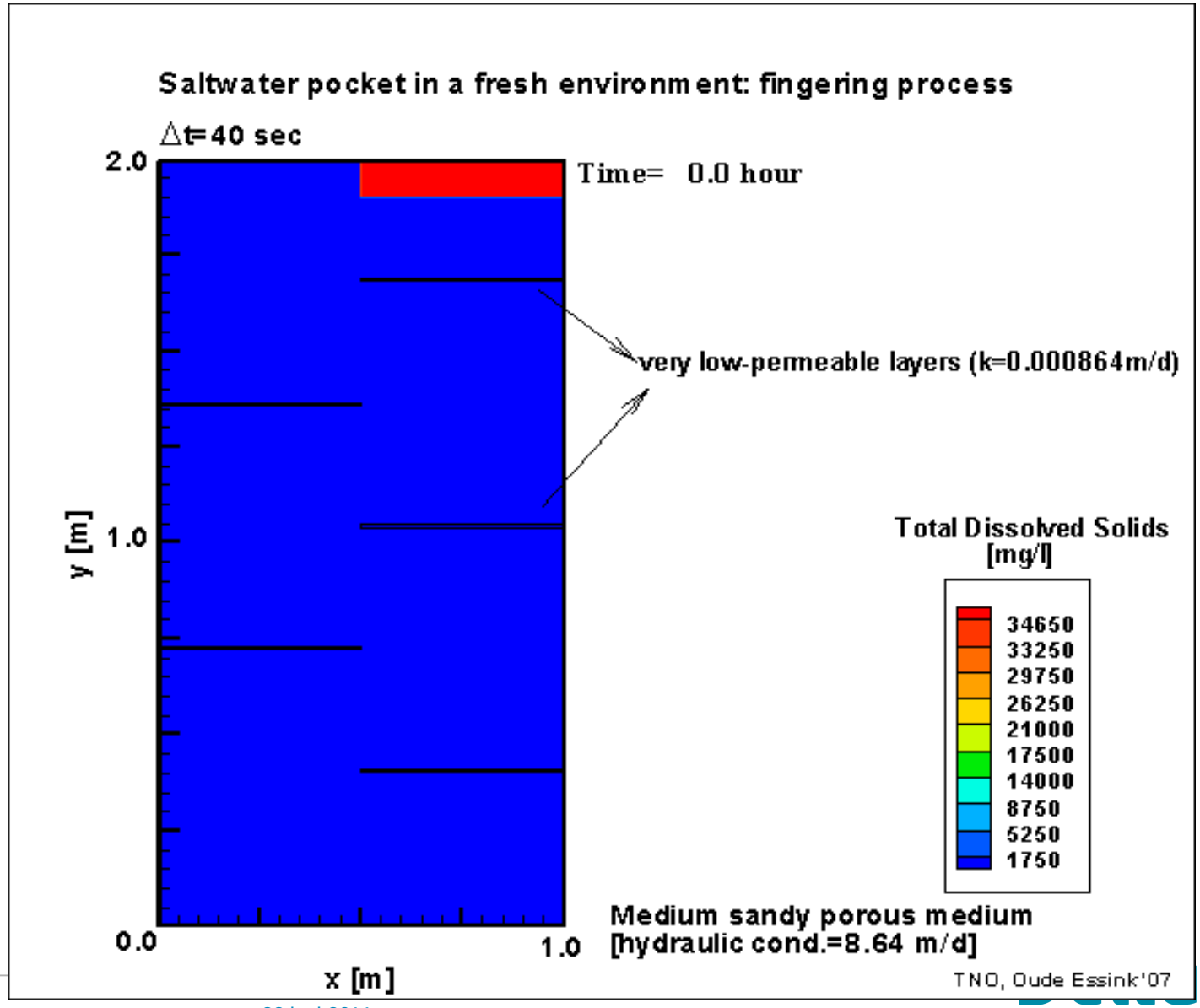
Deltares

Dichtheidsafhankelijke grondwaterstroming

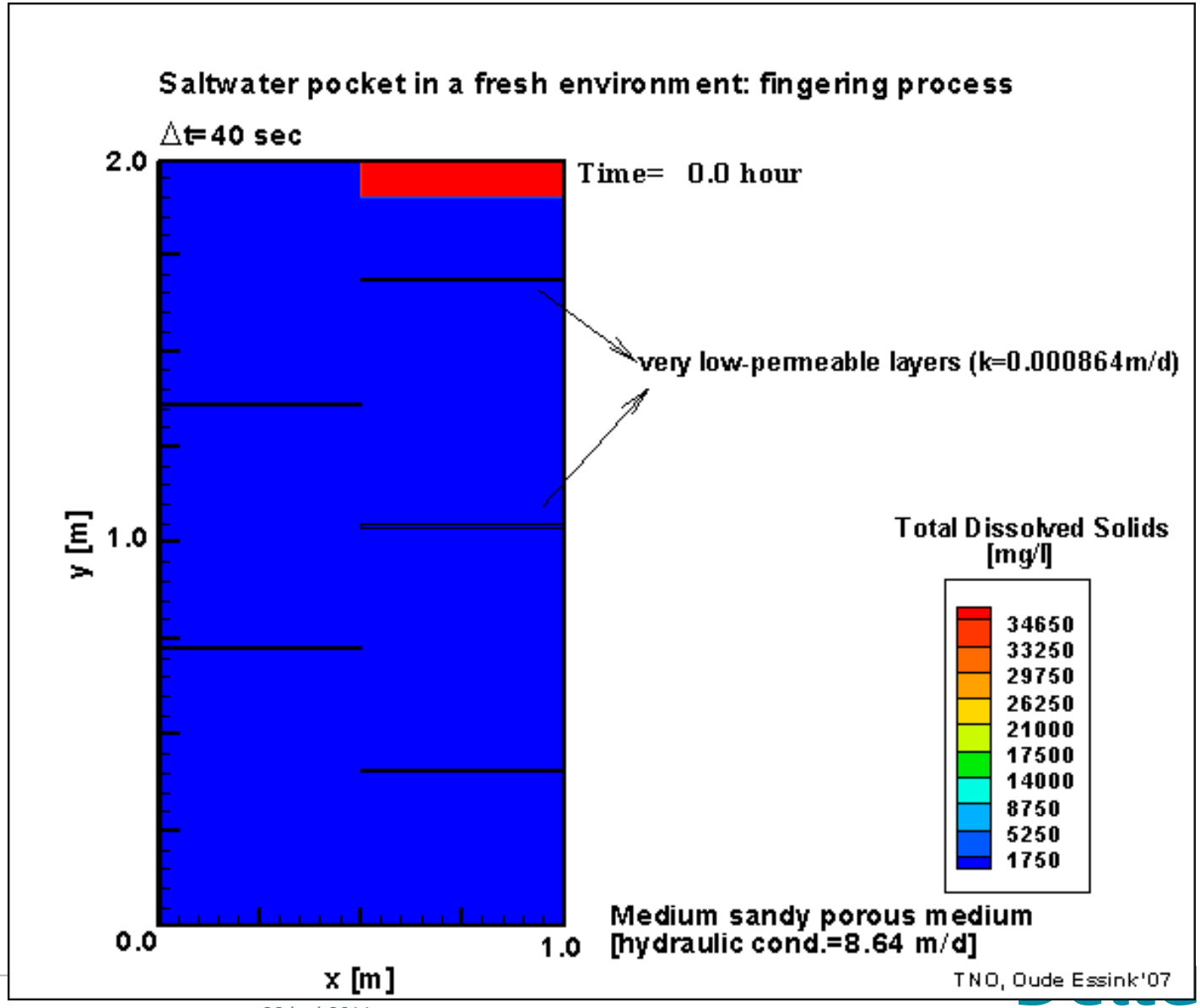


Deltares

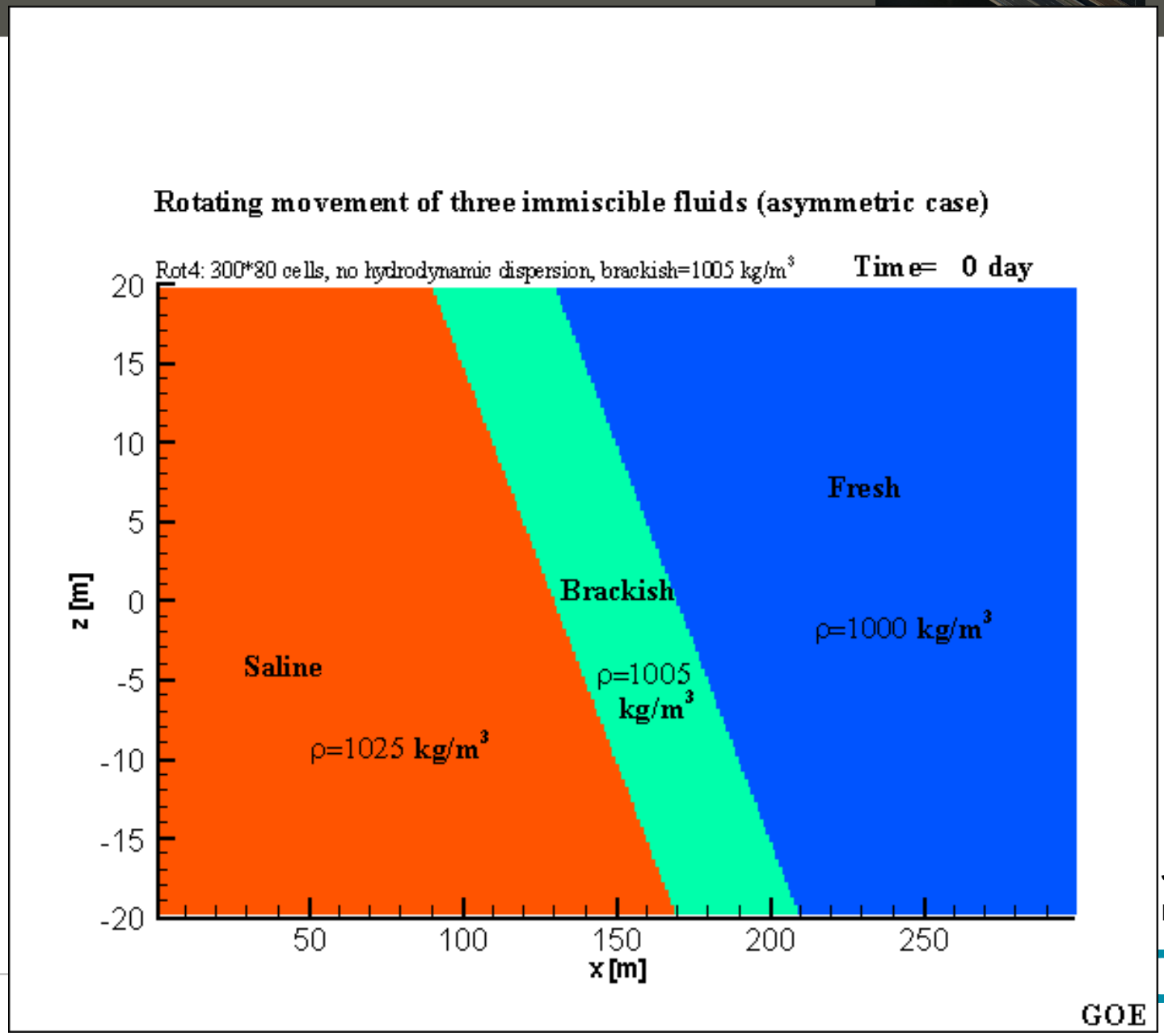
Fingering processen in de ondergrond



Fingering processen in de ondergrond



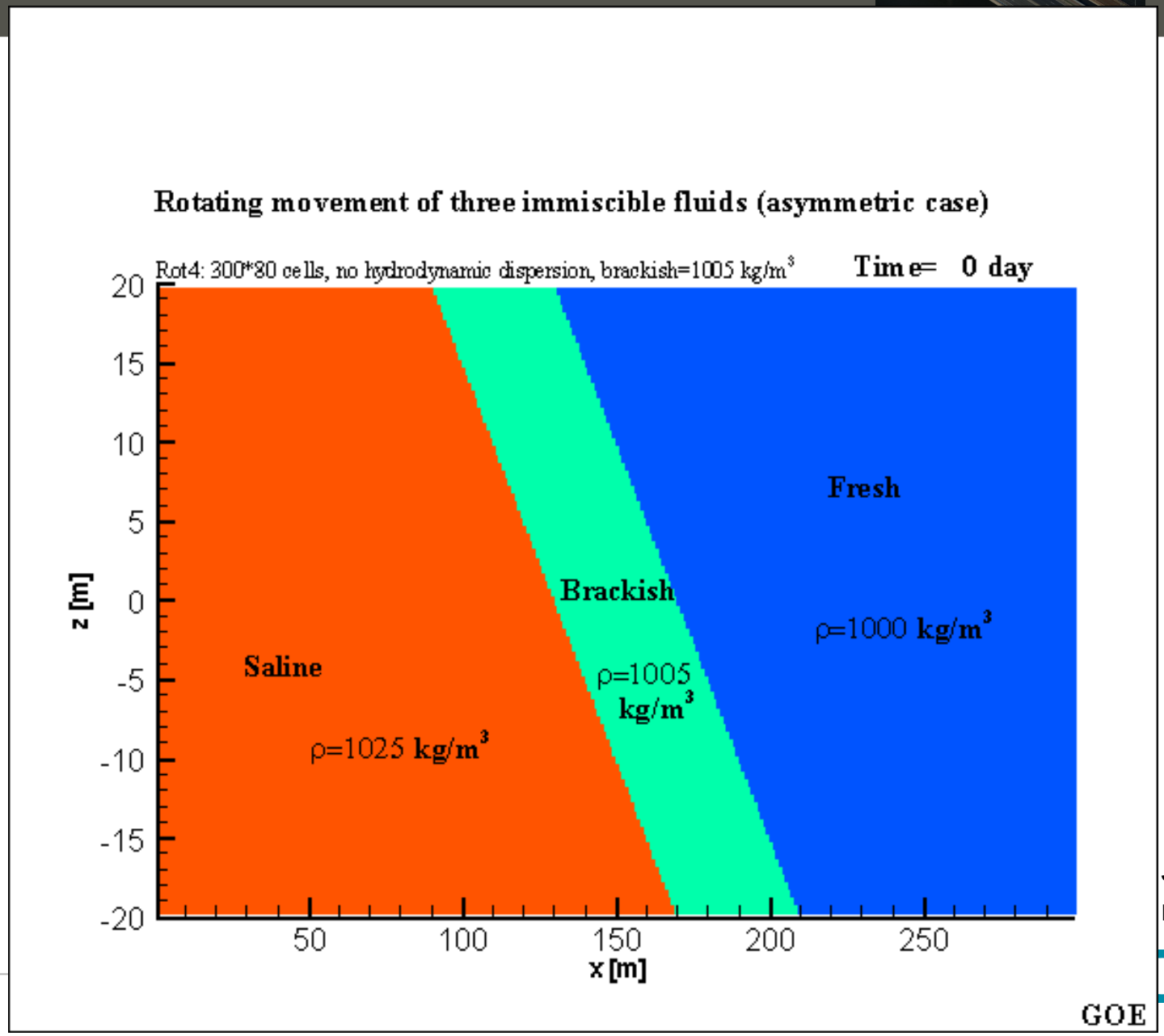
Roterend asymmetrisch scherp grensvlak



J. Hydrology, 2004
nr. 287, pp. 270-278

Deltares

Roterend asymmetrisch scherp grensvlak



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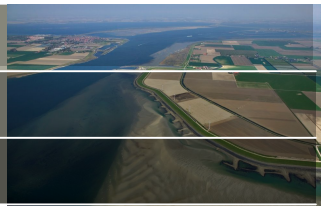
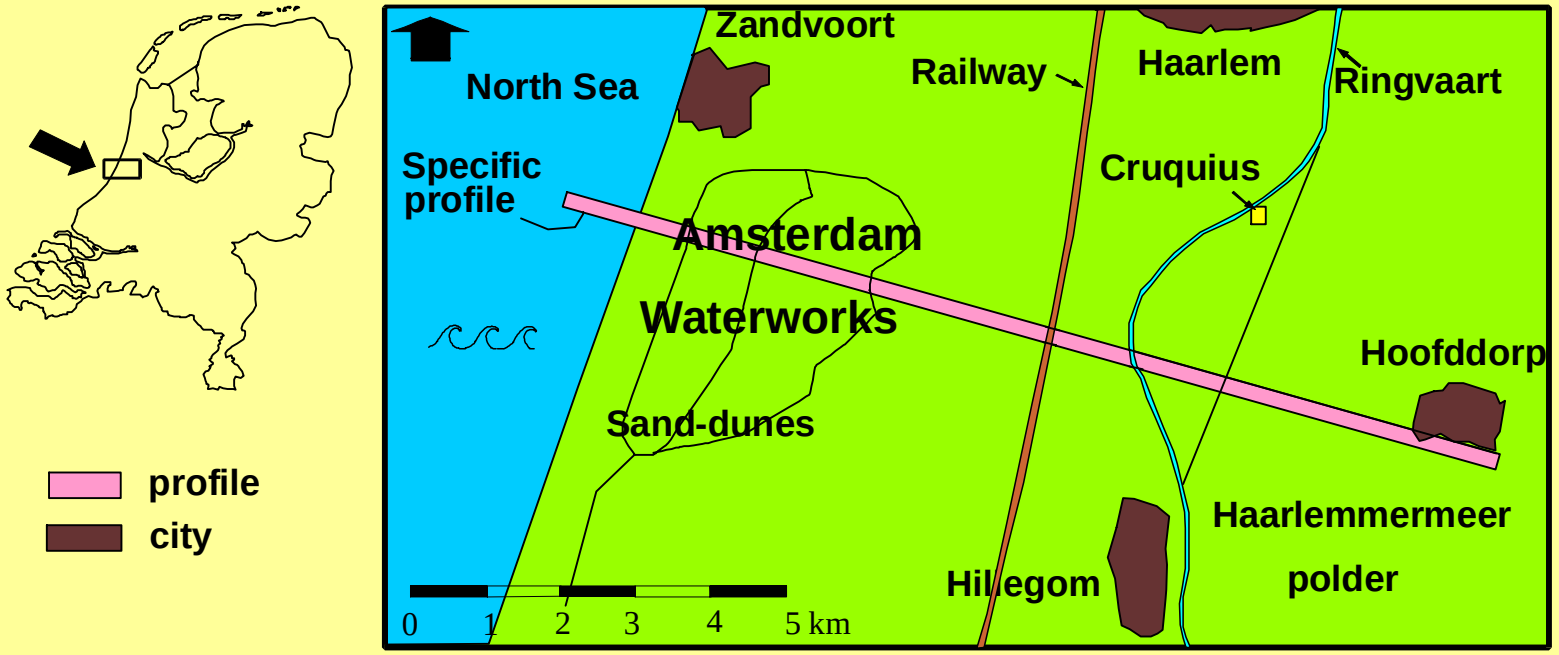


Mijn eerste zoet-zout model

Deltares

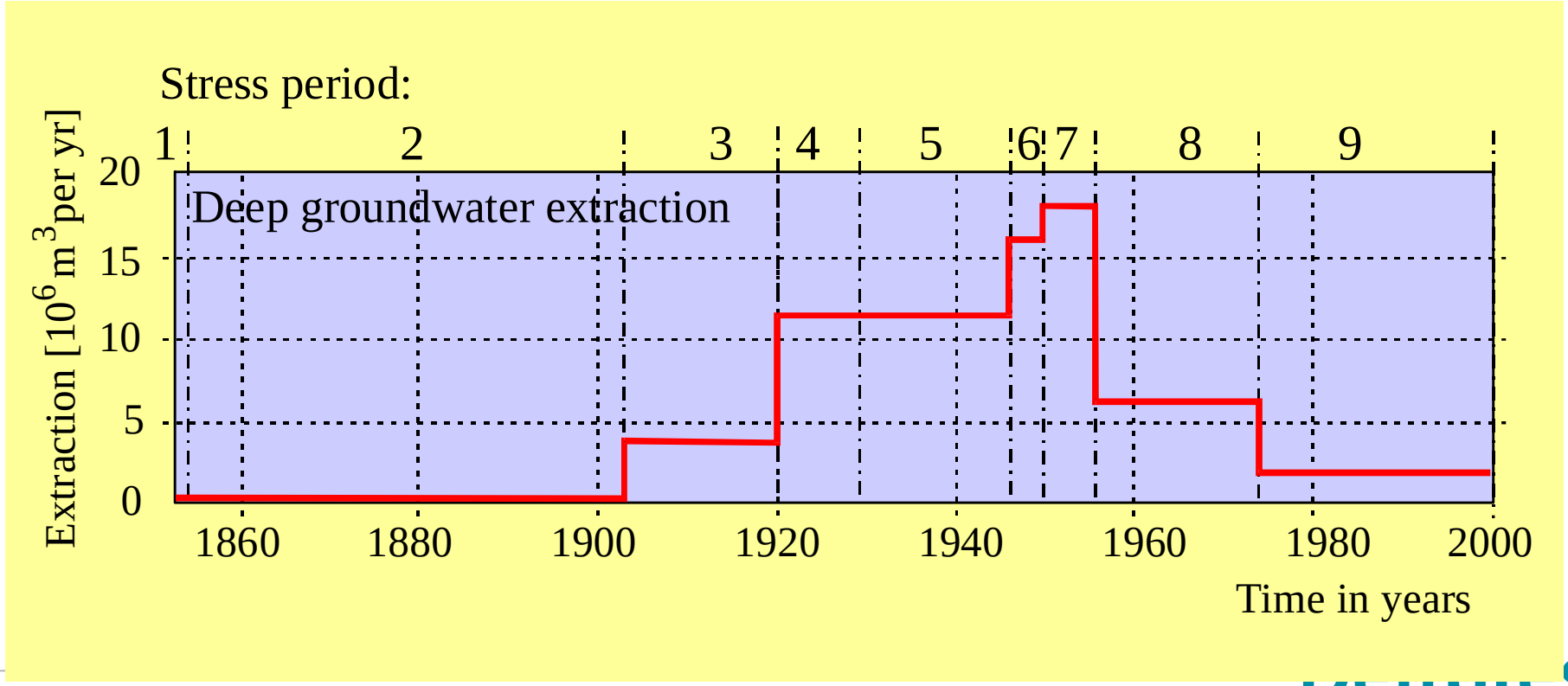
Zoutwaterintrusie in een typisch Hollands profiel

Positie profiel Duingebied Waternet, Rijnland polders
en Haarlemmermeer polder

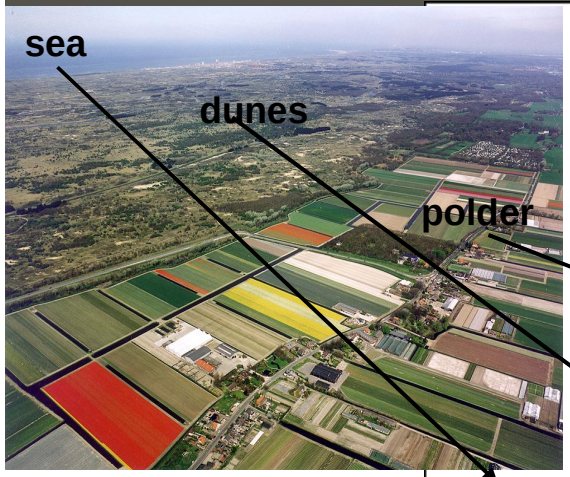


Zoutwaterintrusie in een typisch Hollands profiel

Grondwater onttrekkingen uit het middelste watervoerend pakket uit het duingebied Waternet



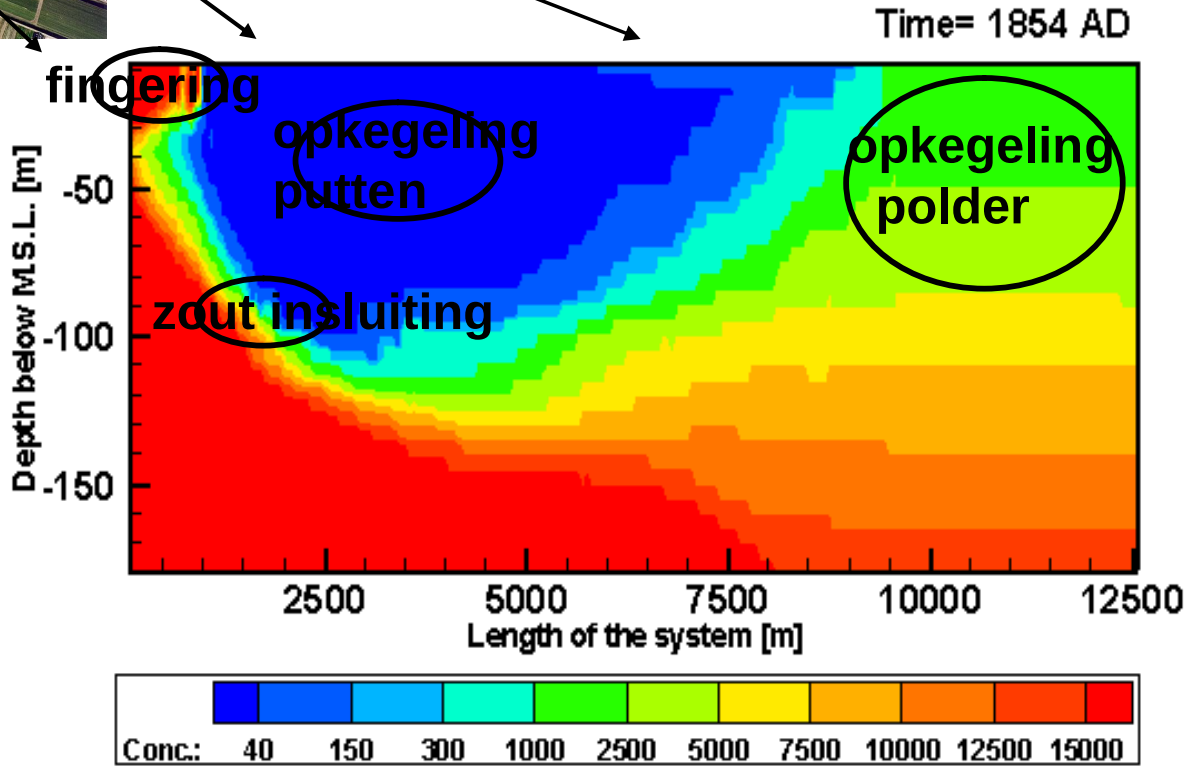
Zoutwater intrusie in het Nederlandse kustgebied



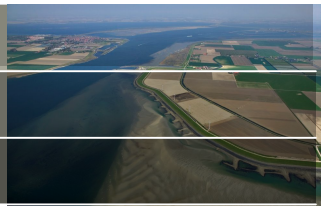
Salinisation of the groundwater flow system

caused due to groundwater extractions and lowering of the ground surface of the Haarlemmermeer polder

Profile Amsterdam Waterworks-Haarlemmermeerpolder



Zoutwater intrusie in het Nederlandse kustgebied



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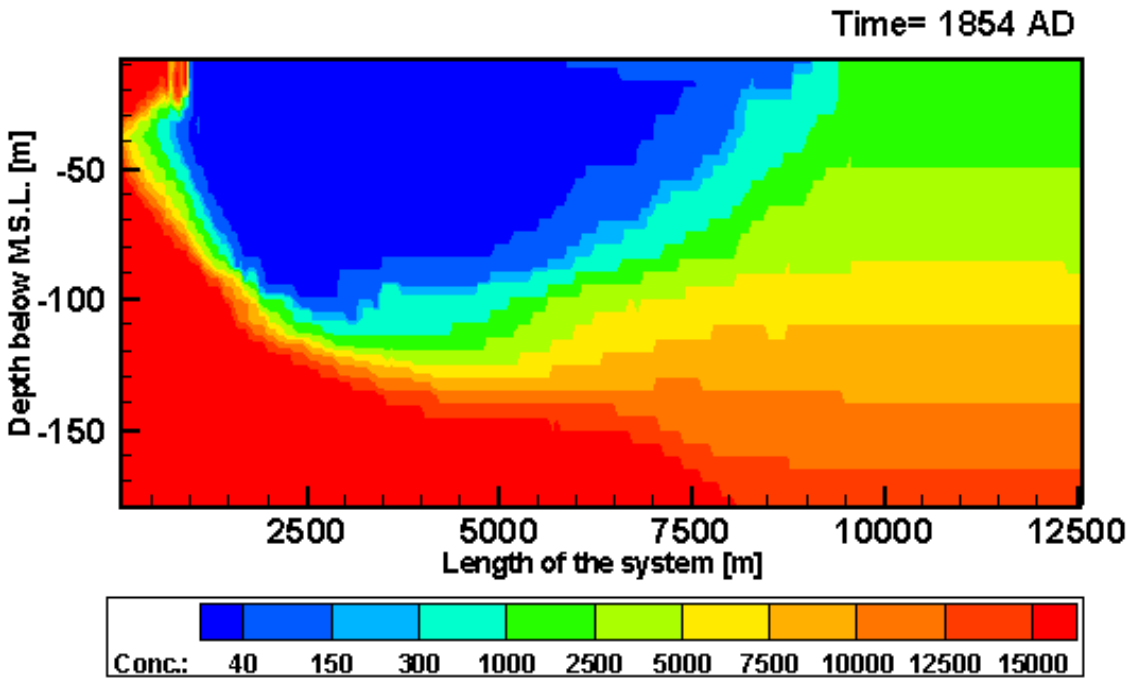
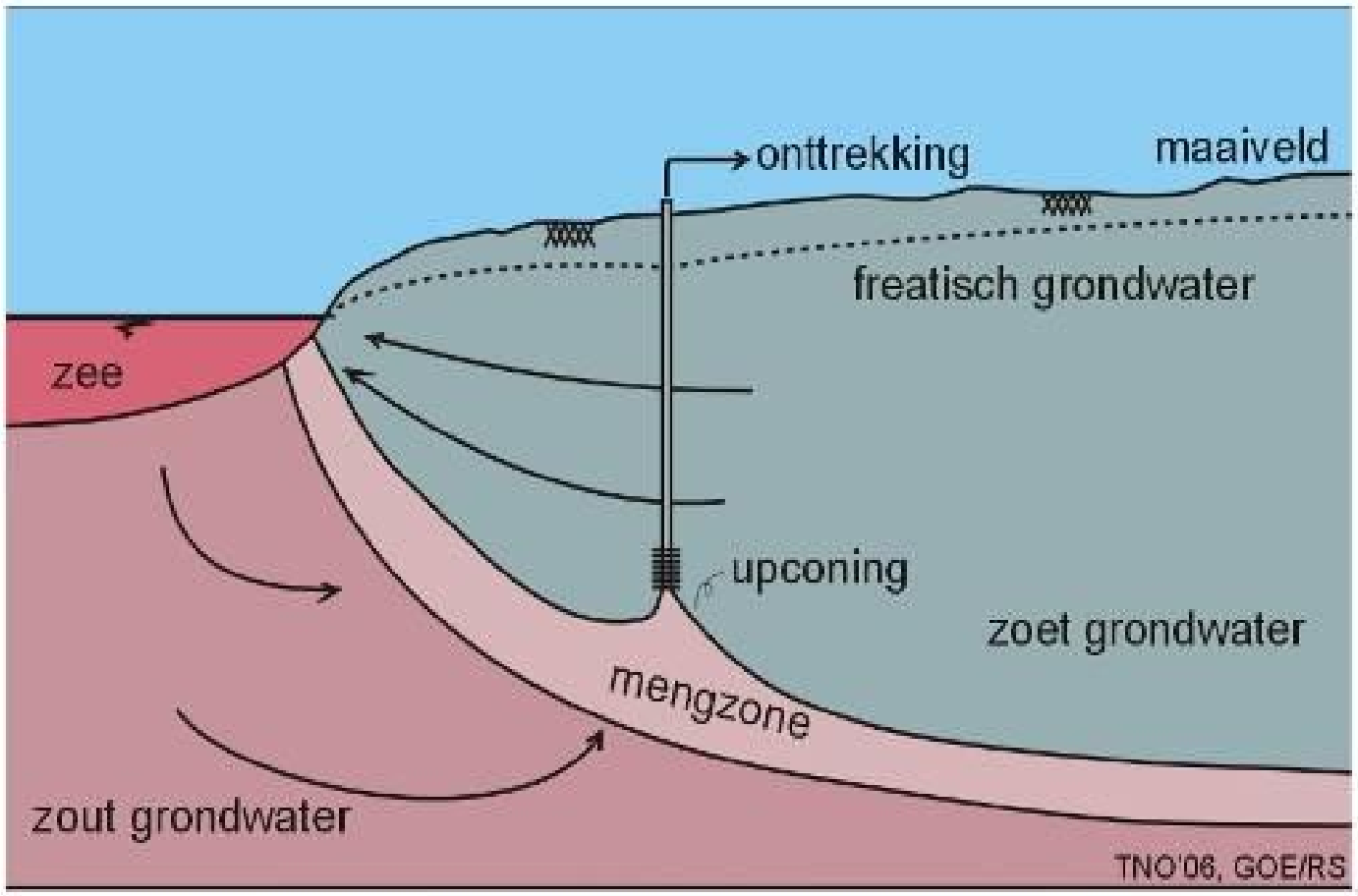


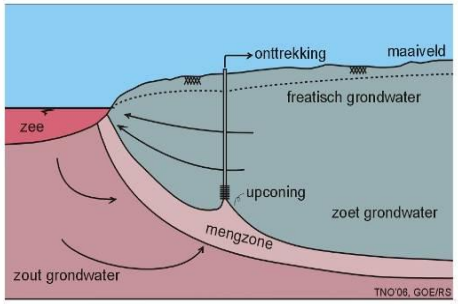
Deltares

Opkegeling van brak-zout grondwater, voorbeeld

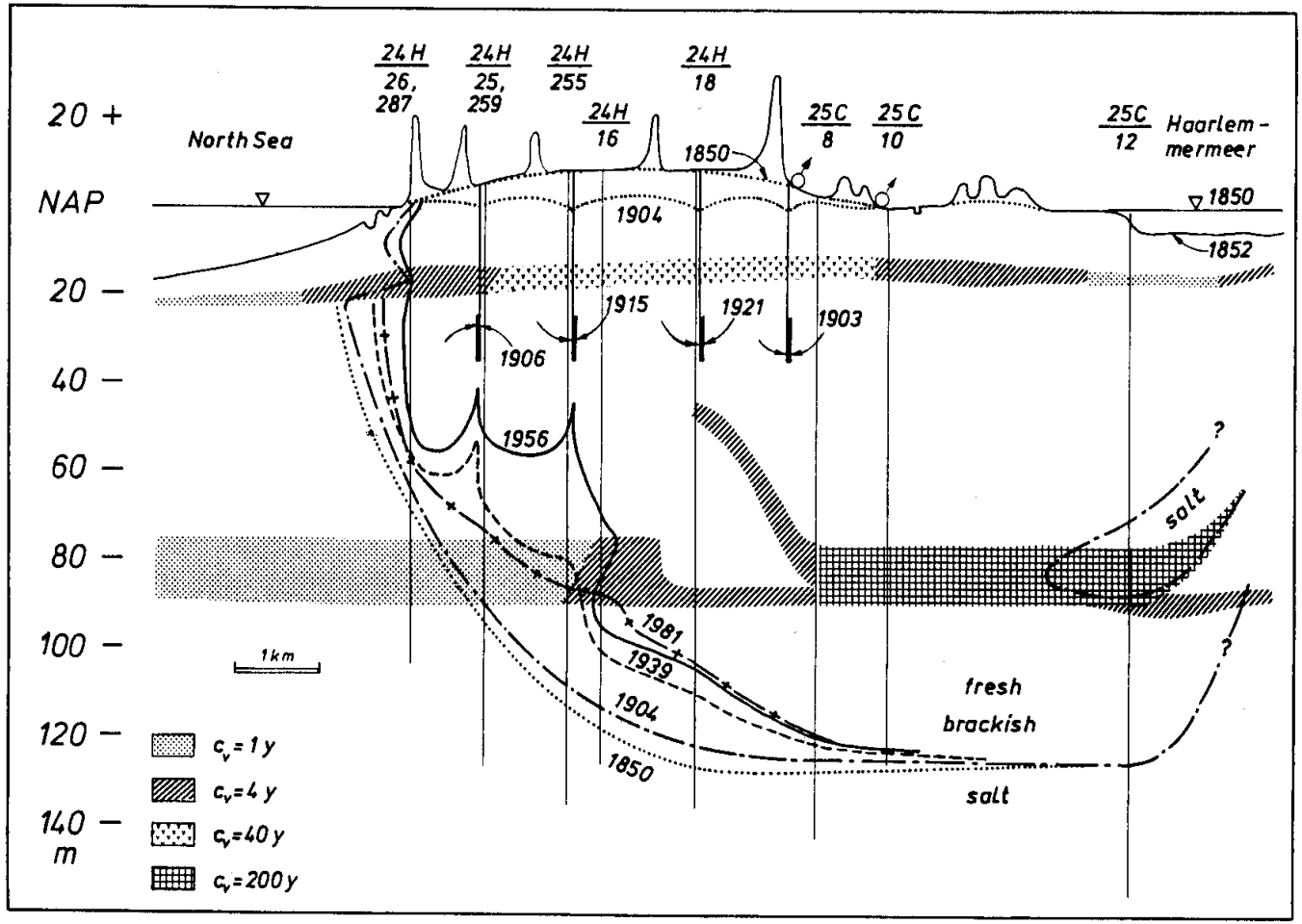


Deltares

Opkegeling van brak-zout grondwater, voorbeeld

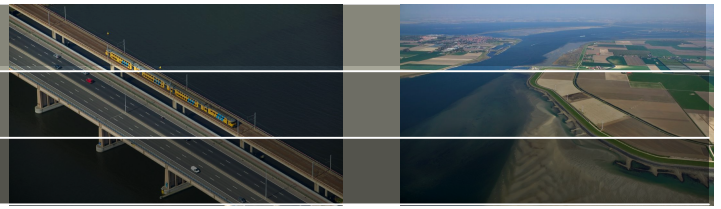


Zandvoort - Haarlemmermeer



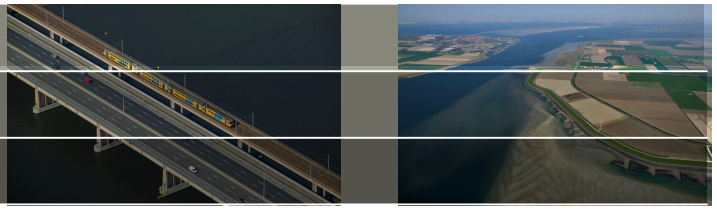
Stuyfzand, ‘93

Deltares



Grondwateronttrekkingen in het kustgebied veroorzaken opkegeling van brak-zout grondwater

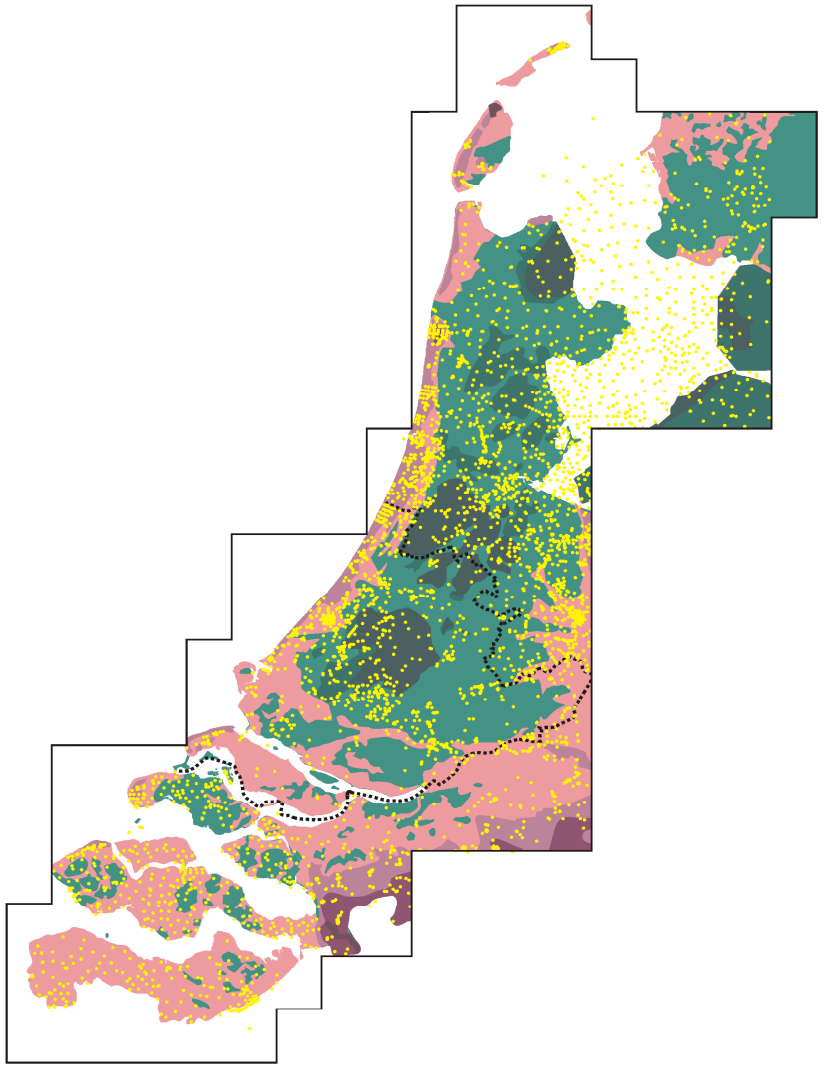
Deltares



Initiele zoet-zout verdeling

Deltares

Database kustgebied: positie Cl--observatie filters



Data: DINO-Qua

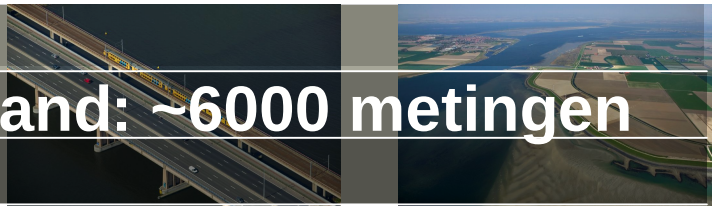
- **17500 Chloride-metingen**
- **Diepte (m)**

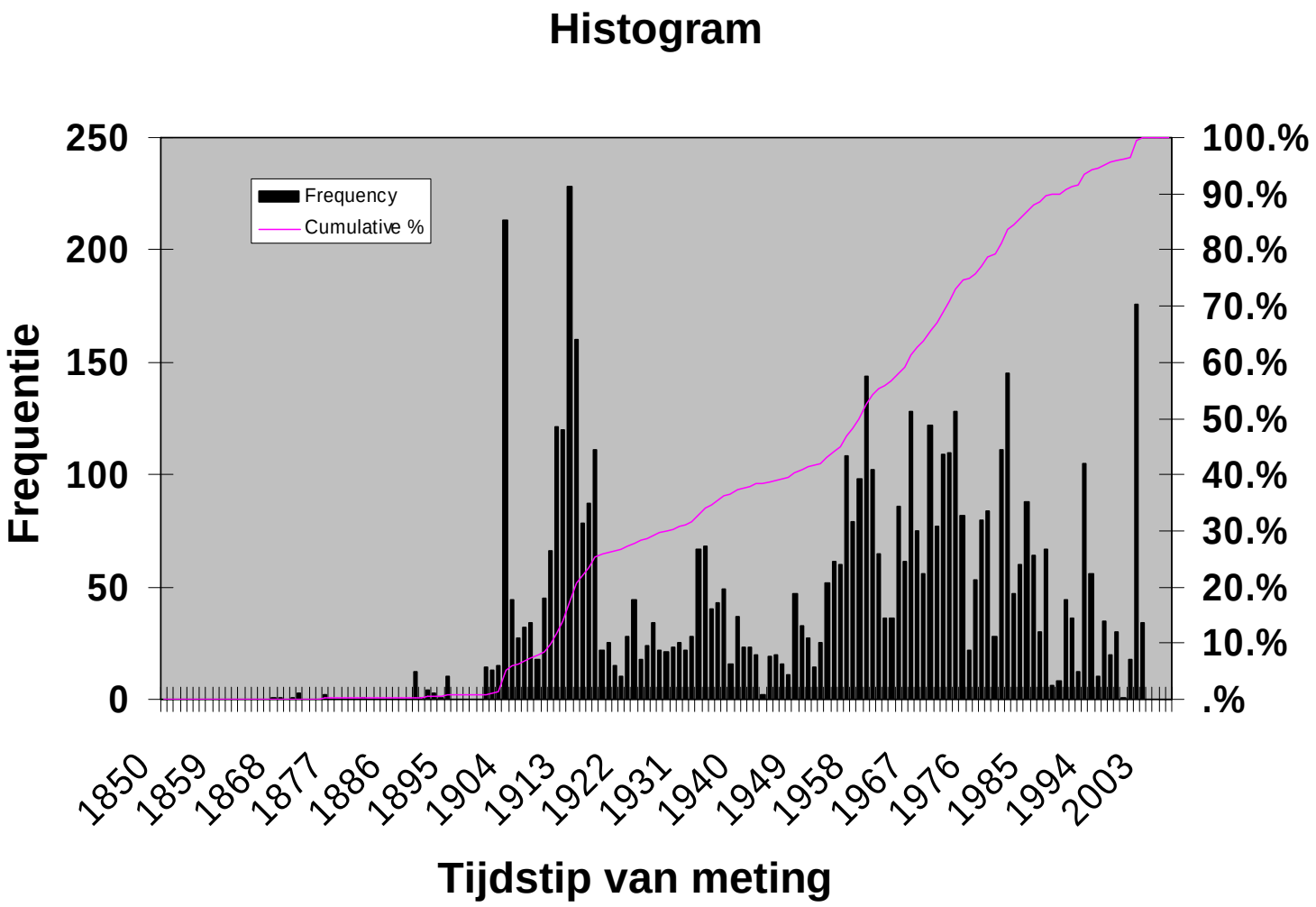
		Aantal
mv-	-5	4135
-5	-10	1095
-10	-25	5287
-25	-50	3678
-50	-75	1438
-75	-100	760
-100	-200	982
-200	-300	110
> -300		16

- **Maximaal 64 metingen in 1 put**
- **Langste tijdreeks in 1 filter: 72 jaar**
- **Eerste meting op 2 jan 1853**
- **Aantal tijdreeksen**
  (minimaal twee metingen in een filter)
  2126 (gehele gebied)

Deltares

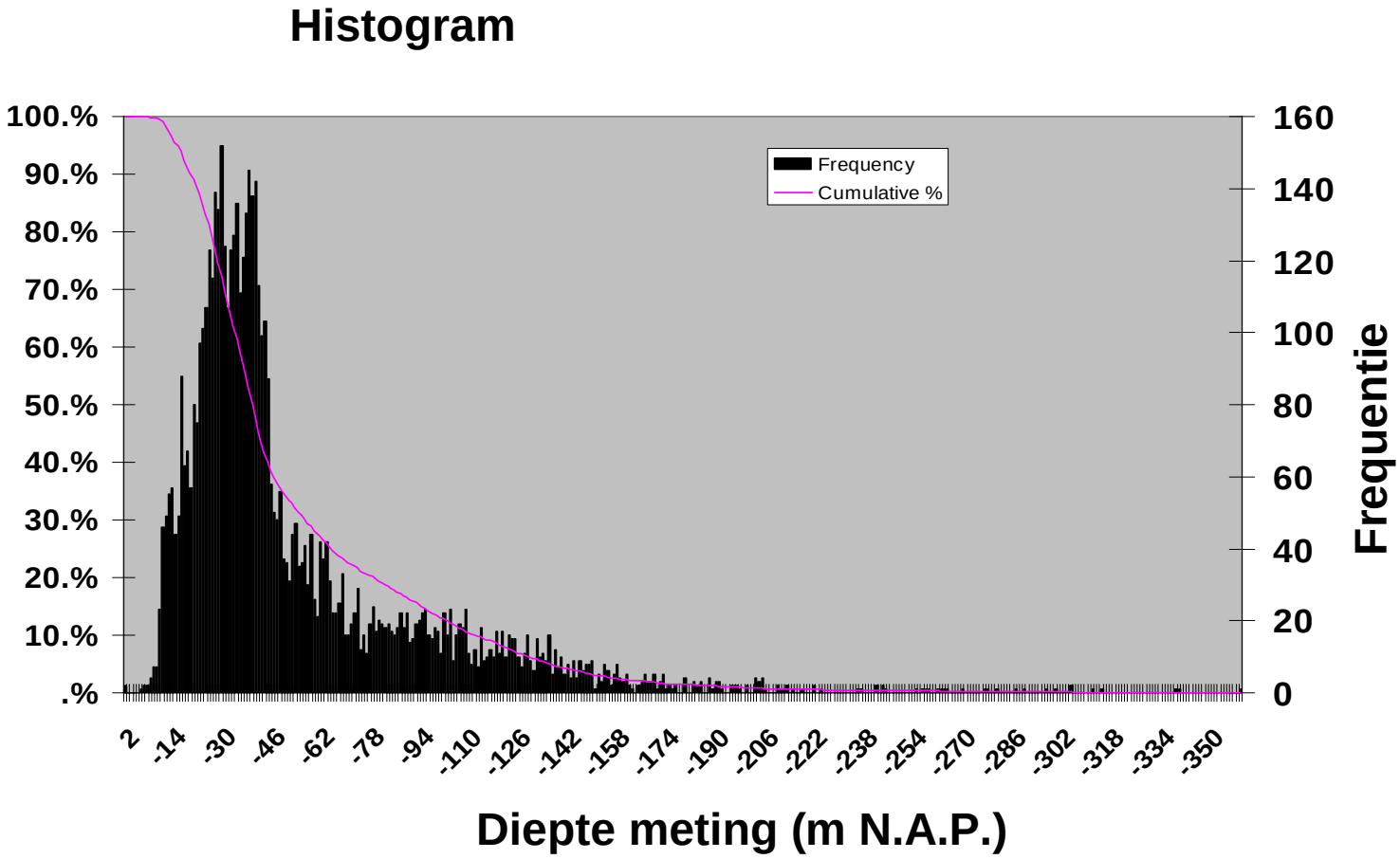
Chloride concentraties in Zuid-Holland: ~6000 metingen





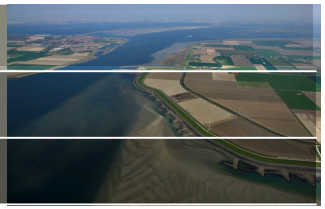
Deltares

Chloride concentraties in Zuid-Holland : ~6000 metingen

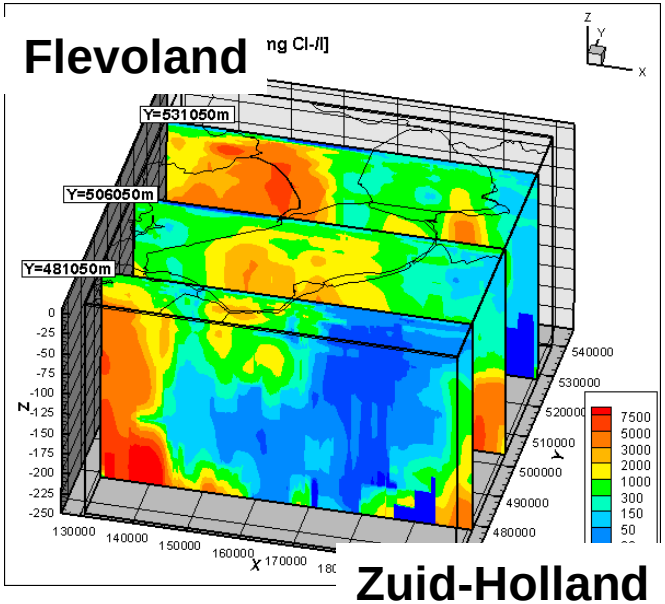


Deltares

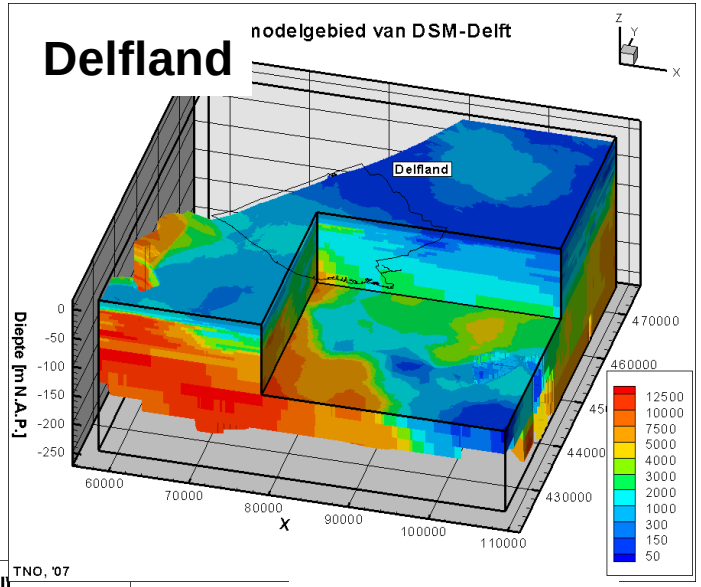
Enkele regionale studies



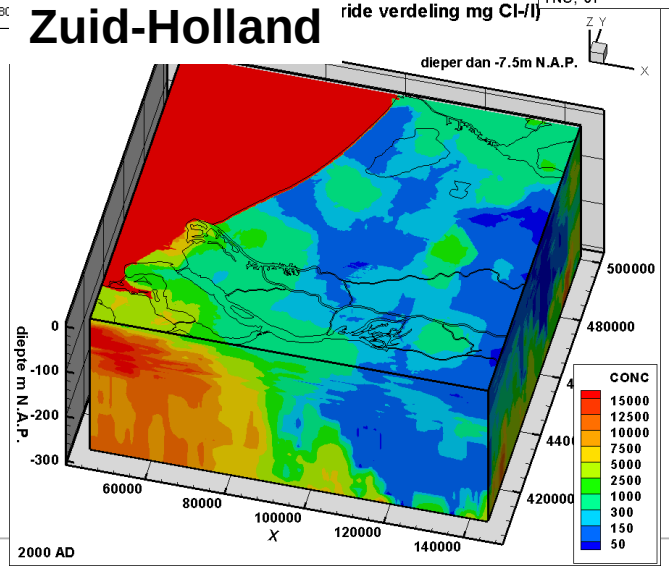
Flevoland



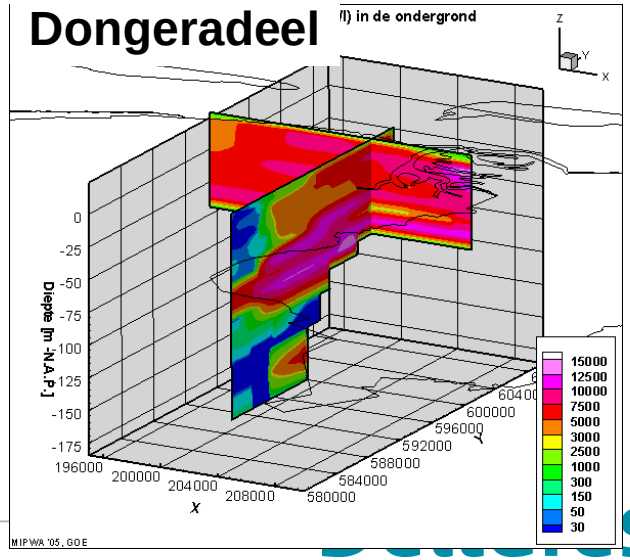
Delfland

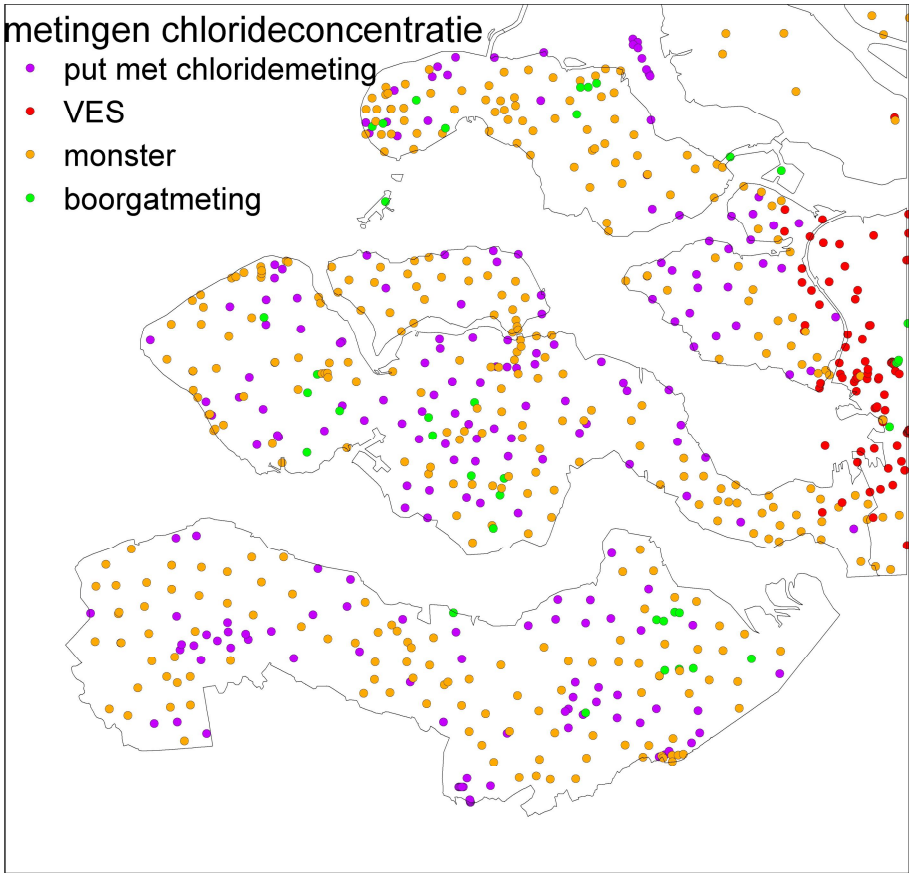


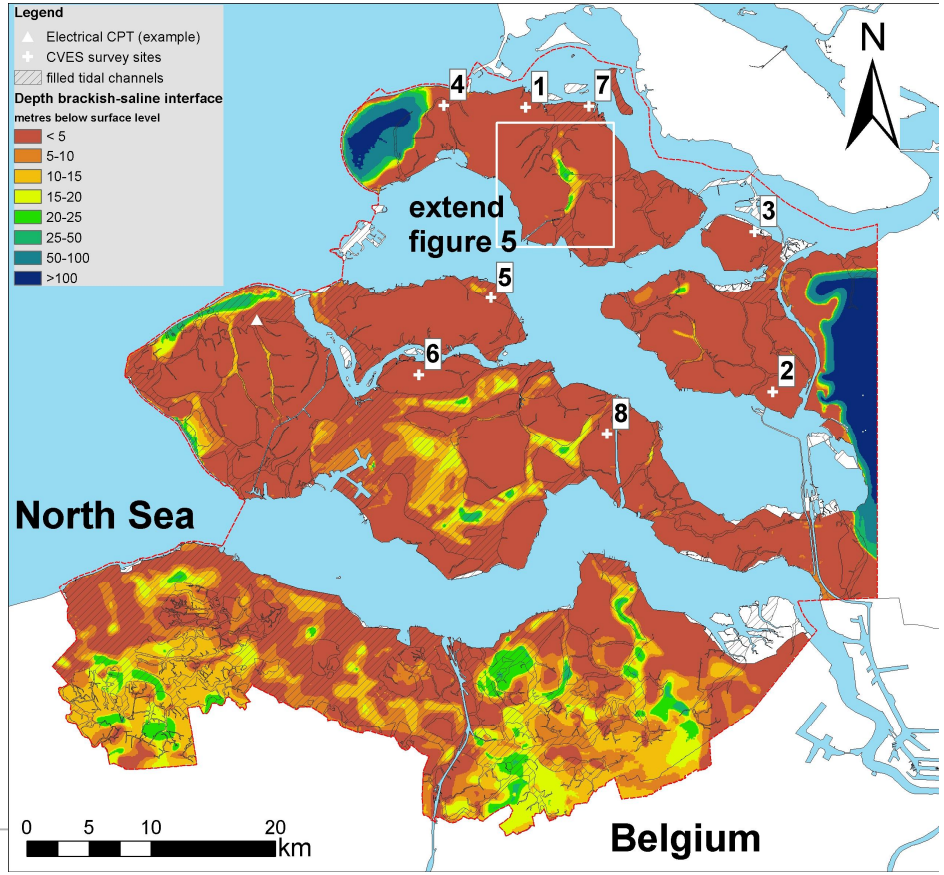
Zuid-Holland

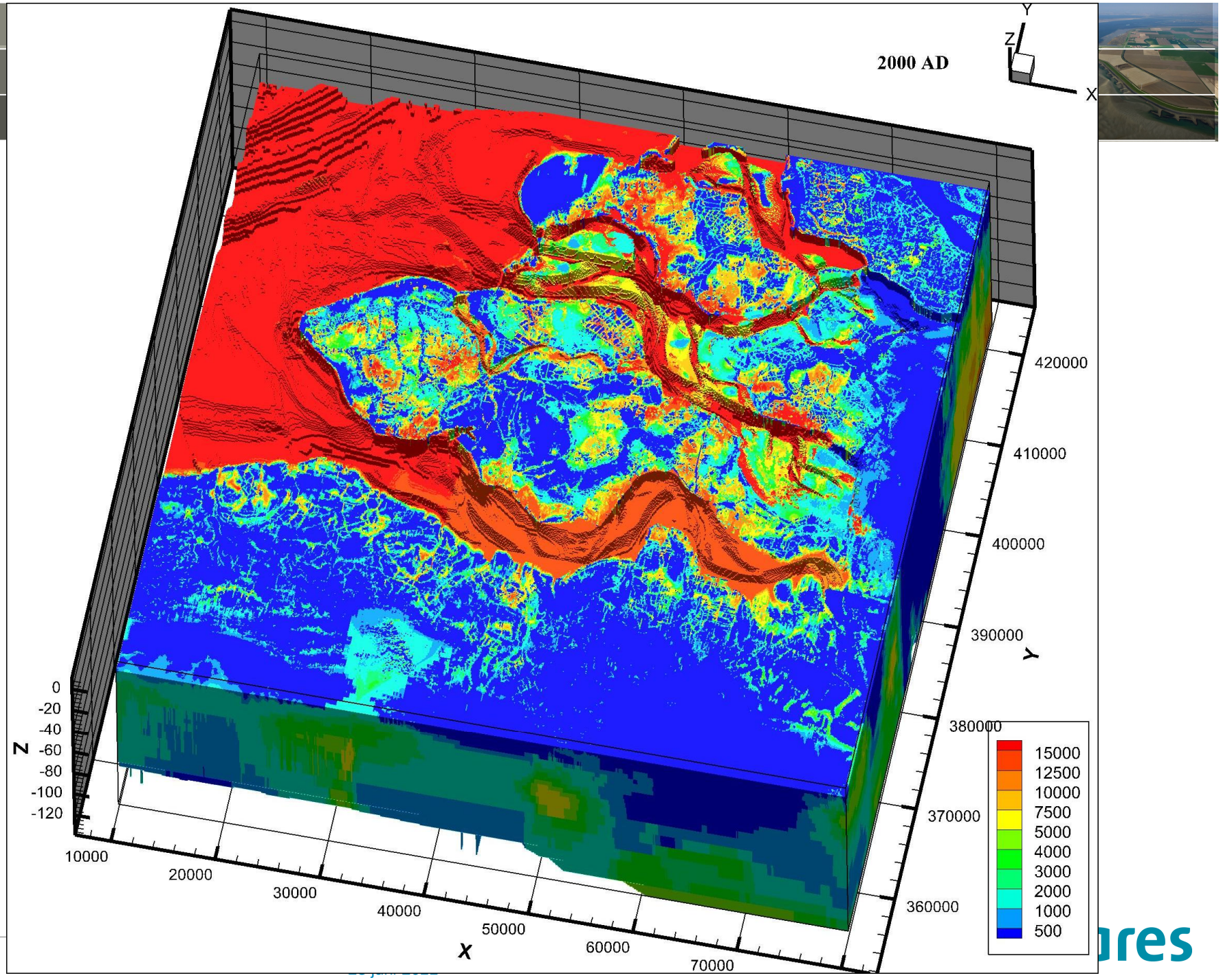


Dongeradeel




metingen chlorideconcentratie
put met chloridemeting
VES
monster
boorgatmeting


Legend
Electrical CPT (example)
CVES survey sites
filled tidal channels
Depth brackish-saline interface
metres below surface level
< 5
5-10
10-15
15-20
20-25
25-50
50-100
>100
N
extend figure 5
North Sea
Belgium
0 5 10 20
km
1
2
3
4
5
6
7
8


2000 AD
Y
Z
X
420000
410000
400000
390000
Y
380000
370000
360000
0
-20
-40
-60
-80
-100
-120
Z
10000
20000
30000
40000
50000
60000
70000
X
15000
12500
10000
7500
5000
4000
3000
2000
1000
500

Modelling effect climate change on fresh-salt groundwater

Modelling:

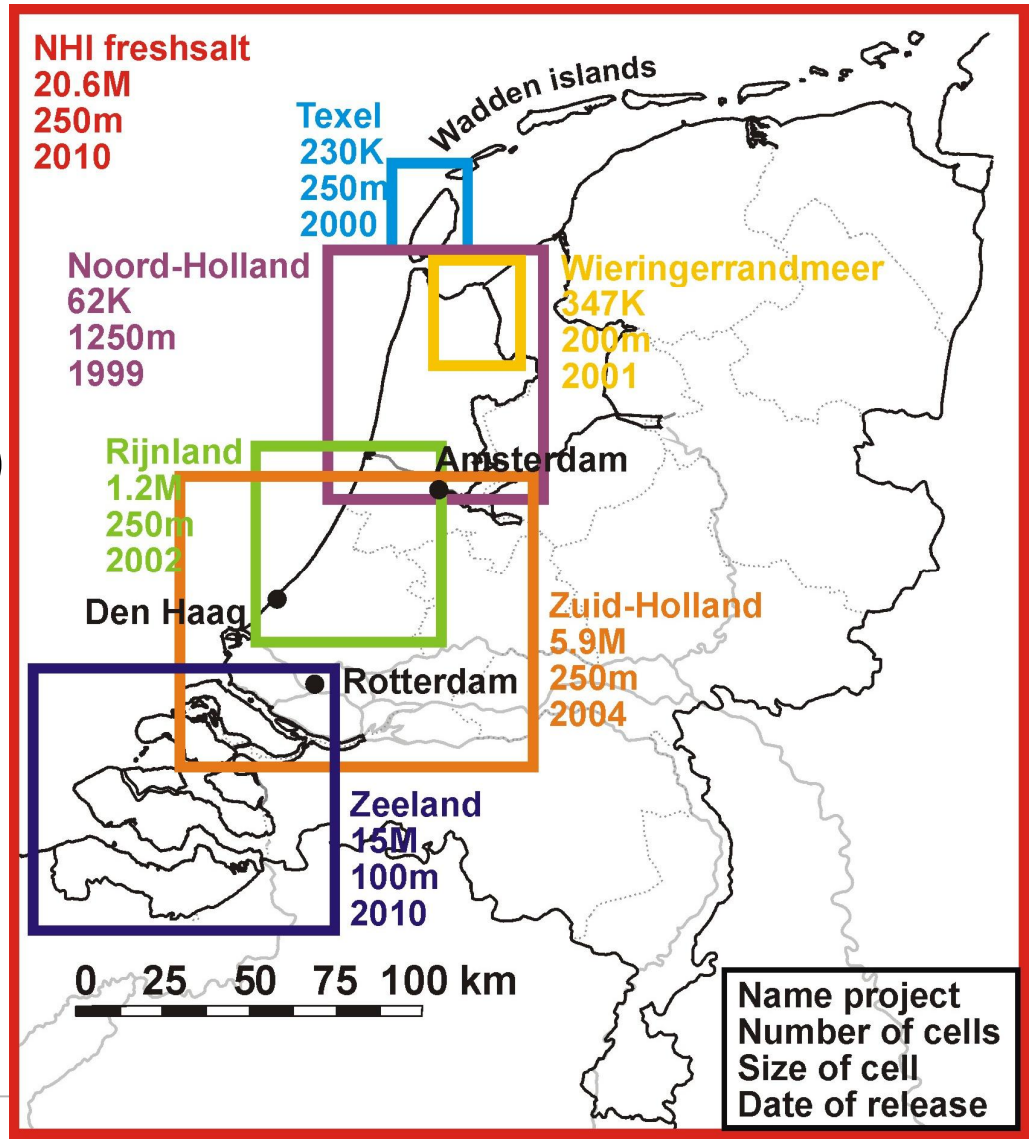
- variable-density
- 3D, non-steady
- groundwater flow
- coupled solute transport

Code:

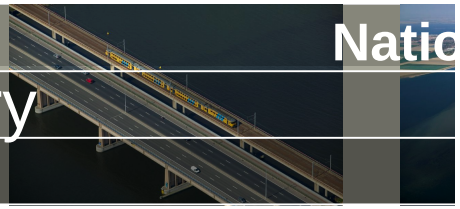
MOCDENS3D (MODFLOW family)
similar to SEAWAT

Assessing effects:

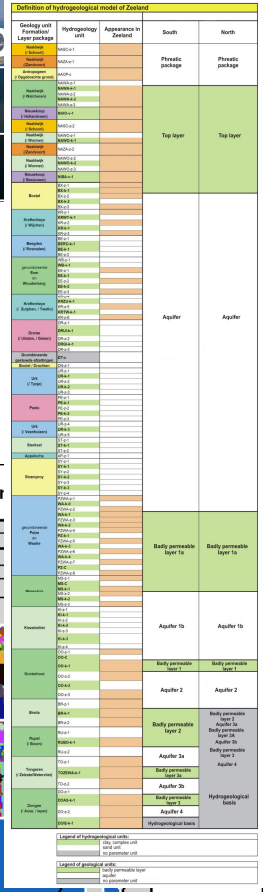
- autonomous salinisation
- sea level rise
- changing recharge pattern
- land subsidence
- changing extraction rates
- adaption measures

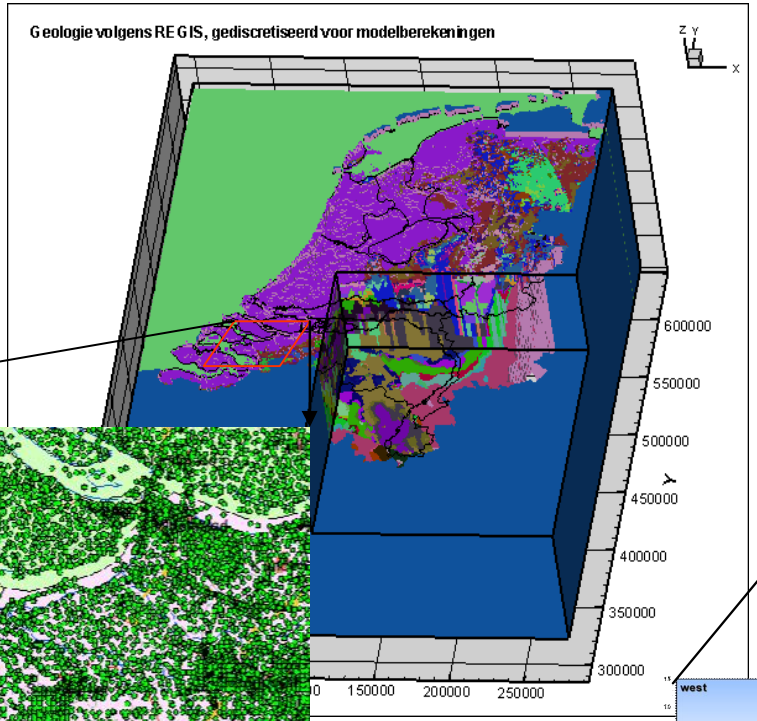


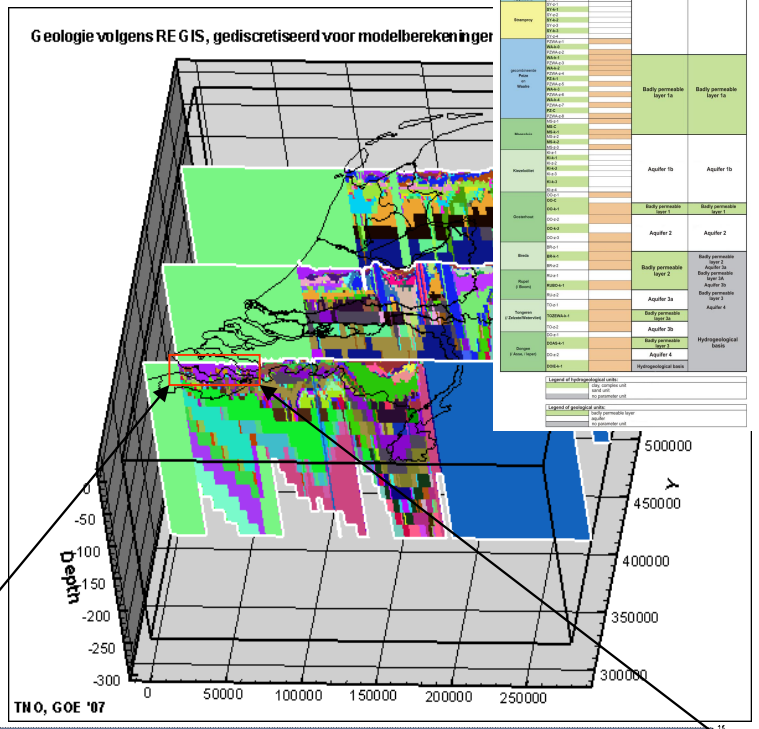
The Netherlands is a data-rich country

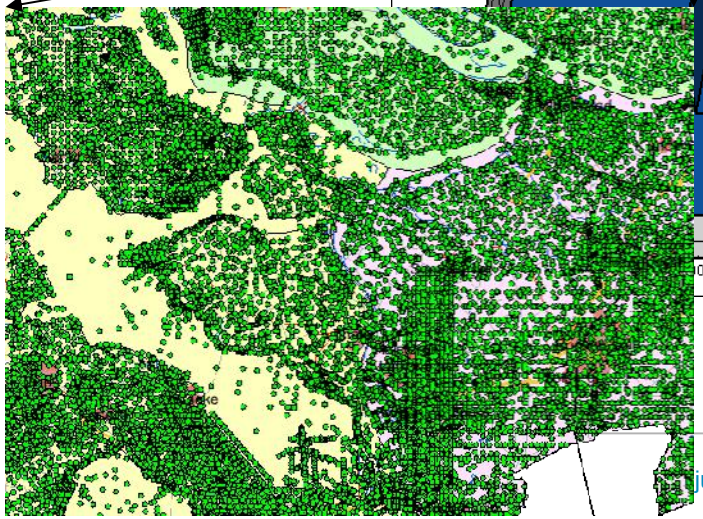


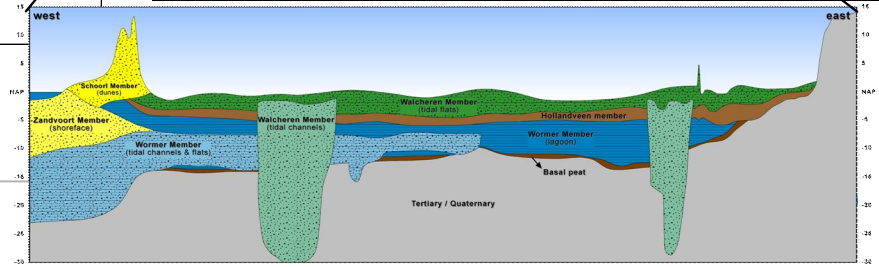
REGIS Regional Geohydrogeological Information System (tops bottoms layers)
65000 chloride measuremenst since 1854



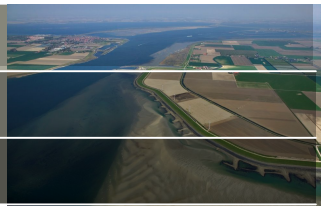




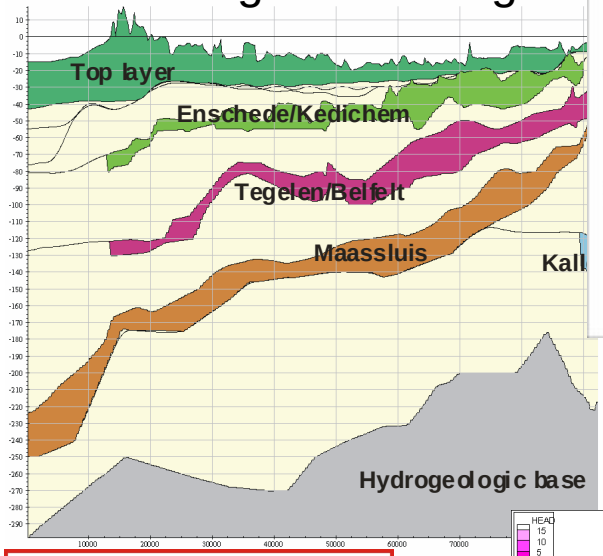


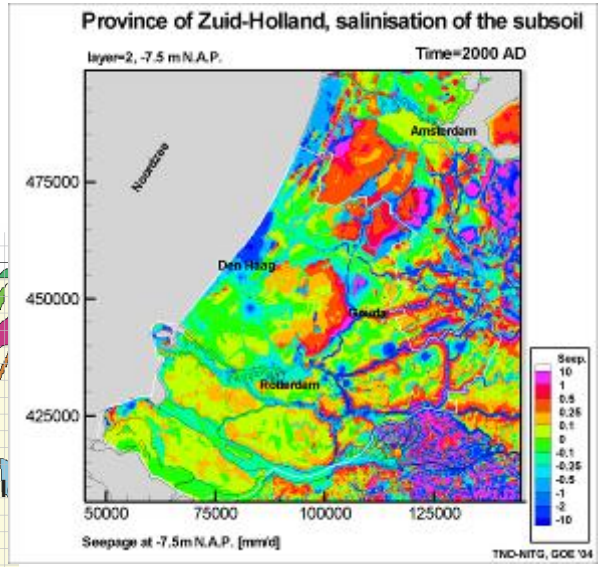


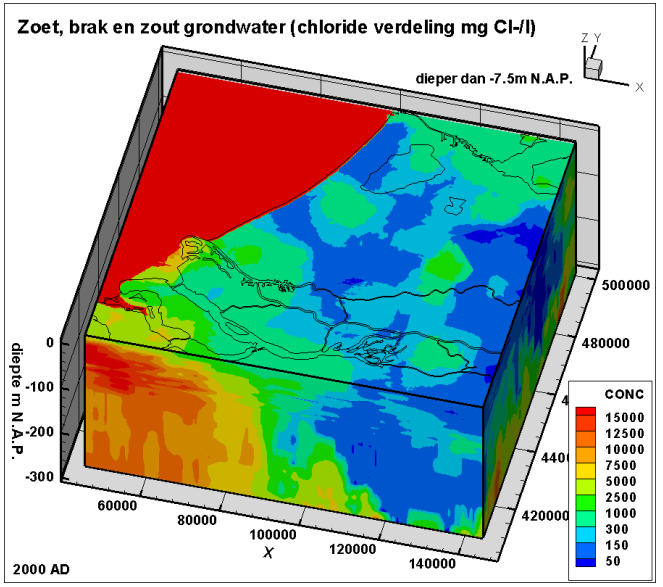
Province Zuid-Holland (2004, update 2008, etc.)

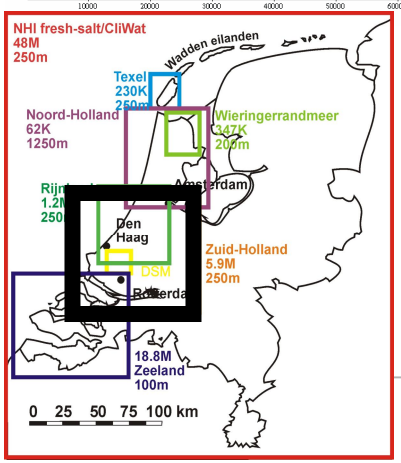


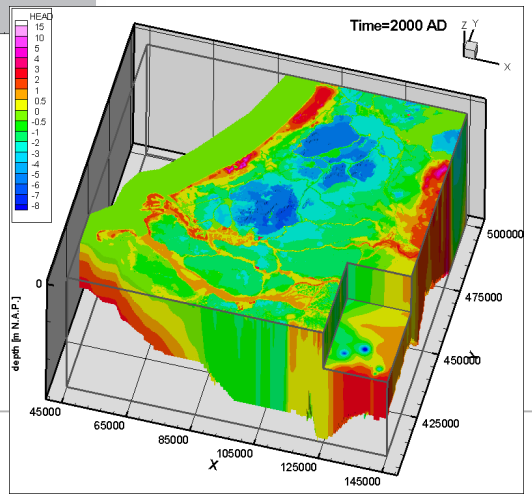
- Land subsidence
- Sea level rise
- Change in recharge

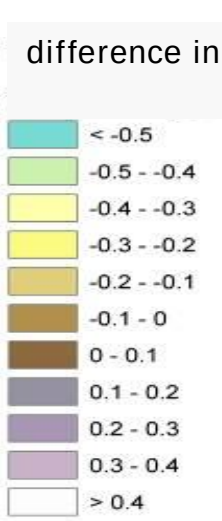


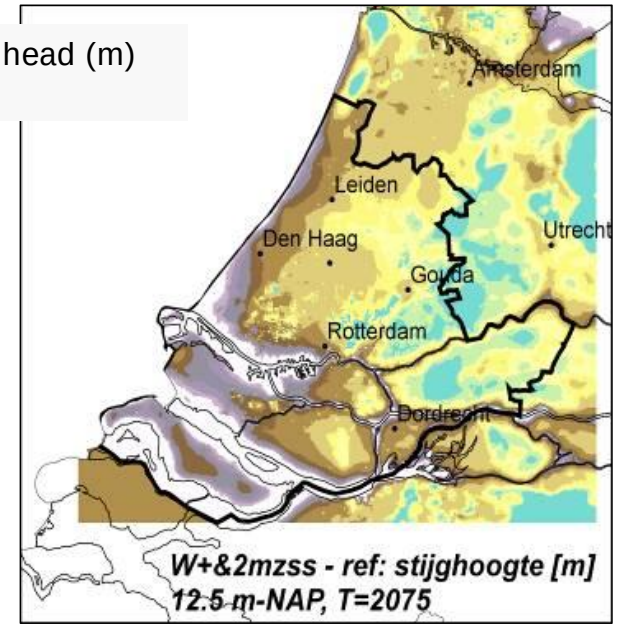




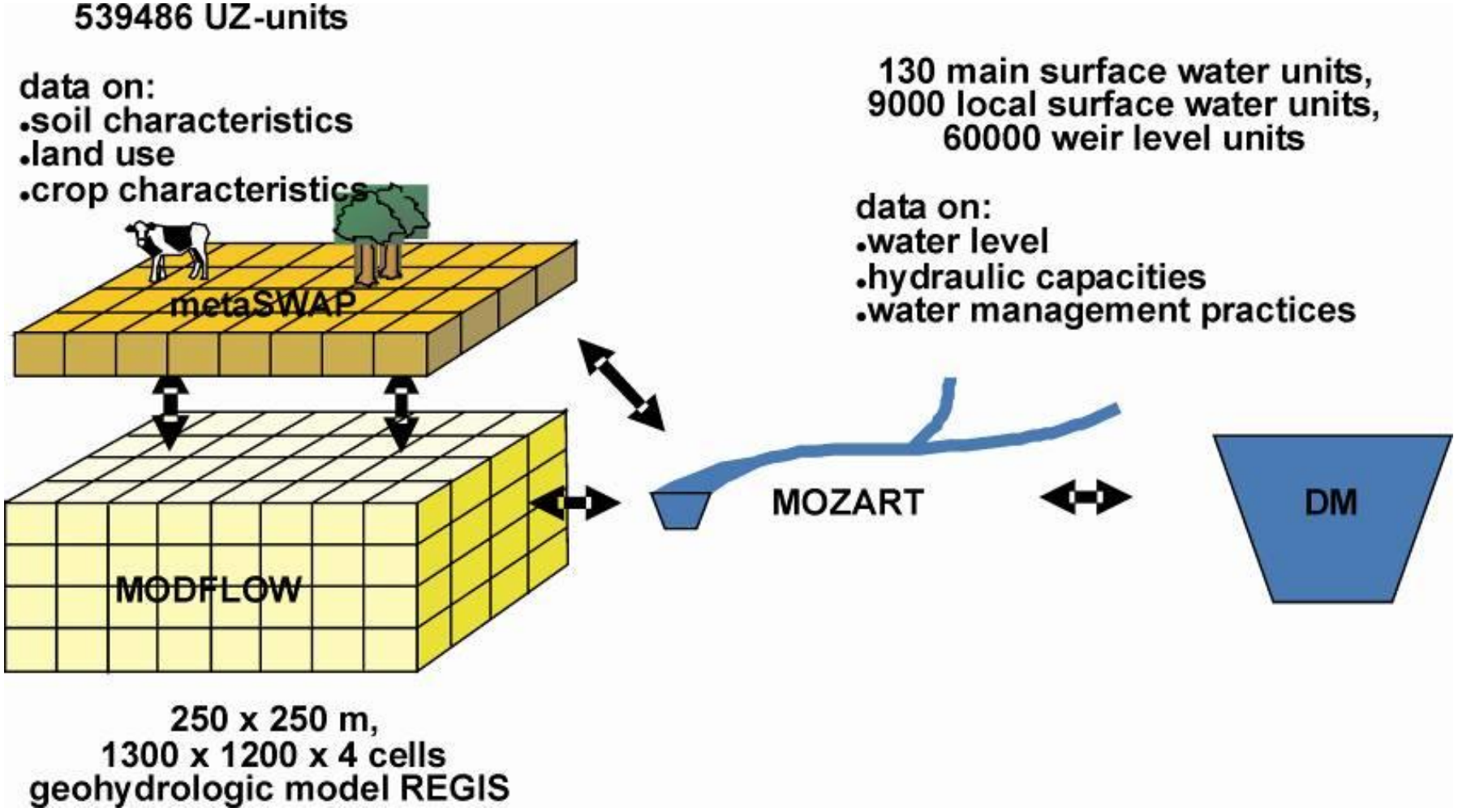






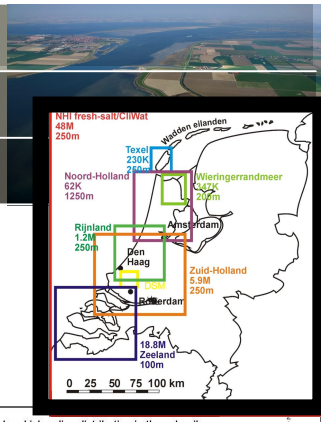


Nationaal Hydrologisch Instrumentarium NHI



Deltares

Netherlands Hydrological modelling Instrument for fresh-saline groundwater



Using the national subsoil parametrisation

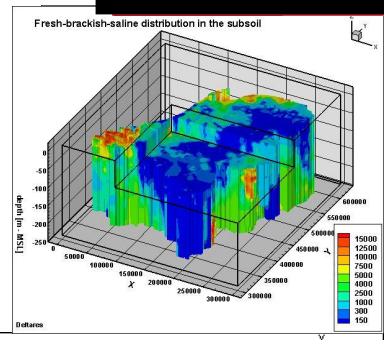
4 layers based on REGIS and NHI

31 model layers with varying thicknesses: 2*5m; 10*2m; 8*5m en 11*20m

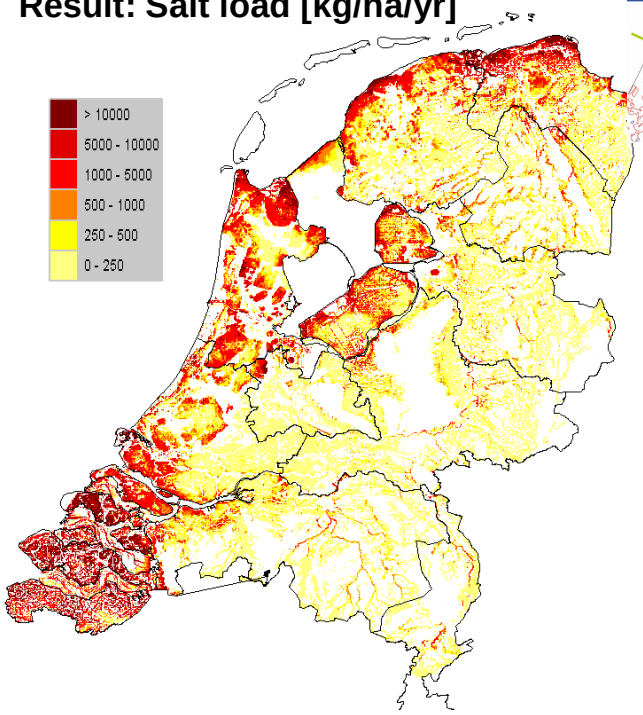
cellsize 250x250m

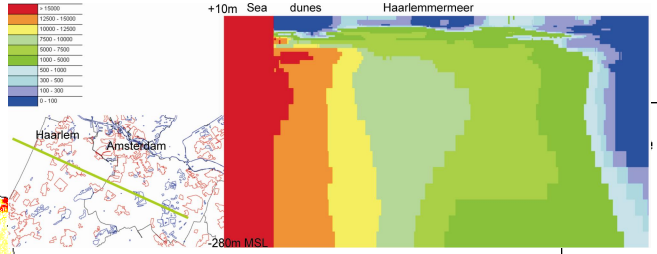
Using the national 3D salt concentration in groundwater

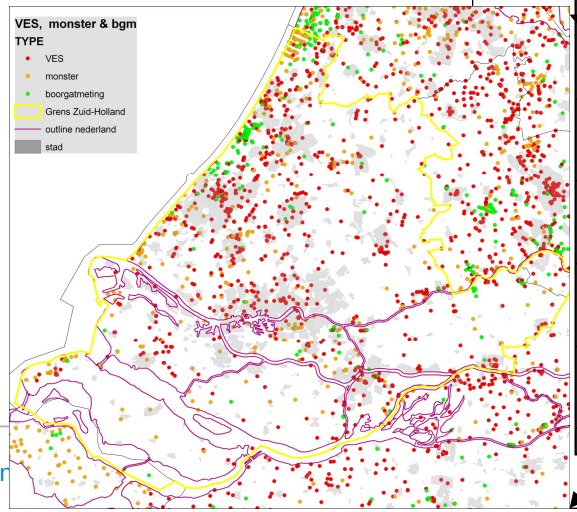
Fresh-saline REGIS: ~65000 measuring points (analyses, VES, Borehole)

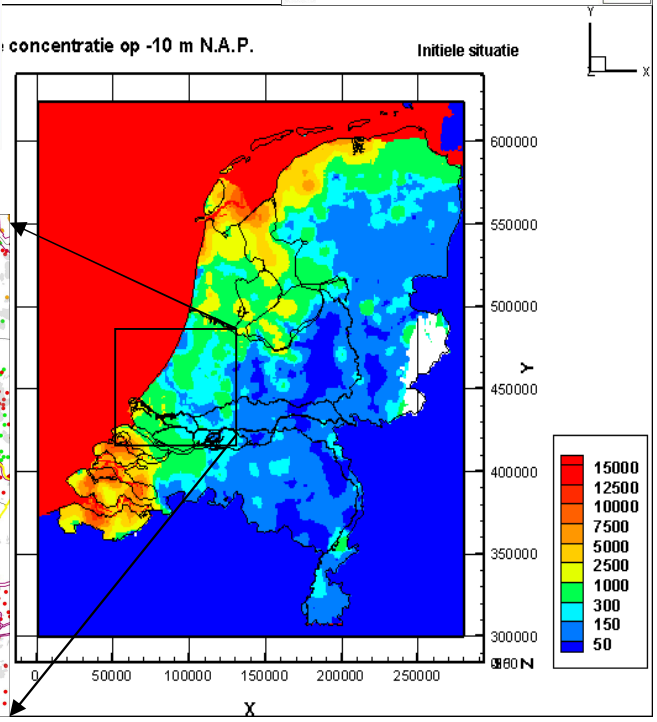


Result: Salt load [kg/ha/yr]

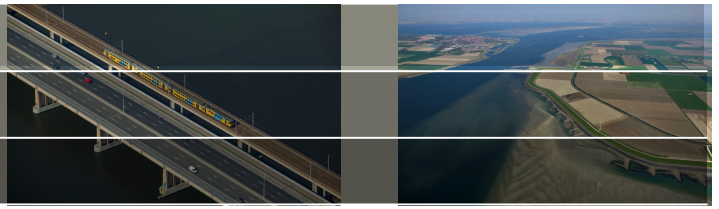




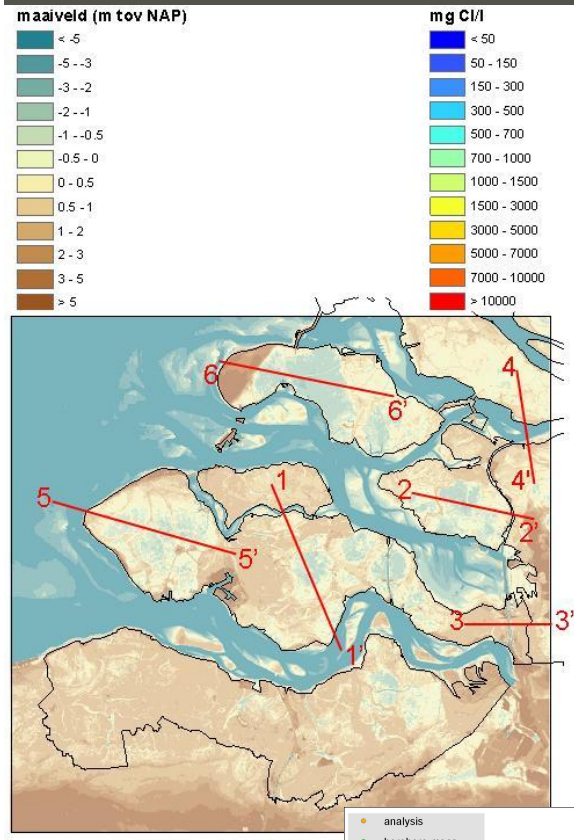


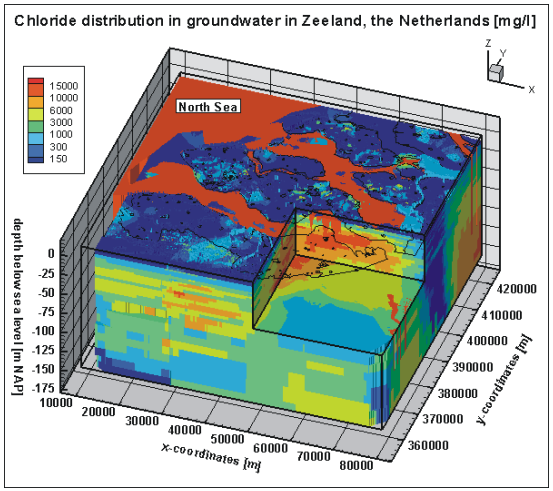


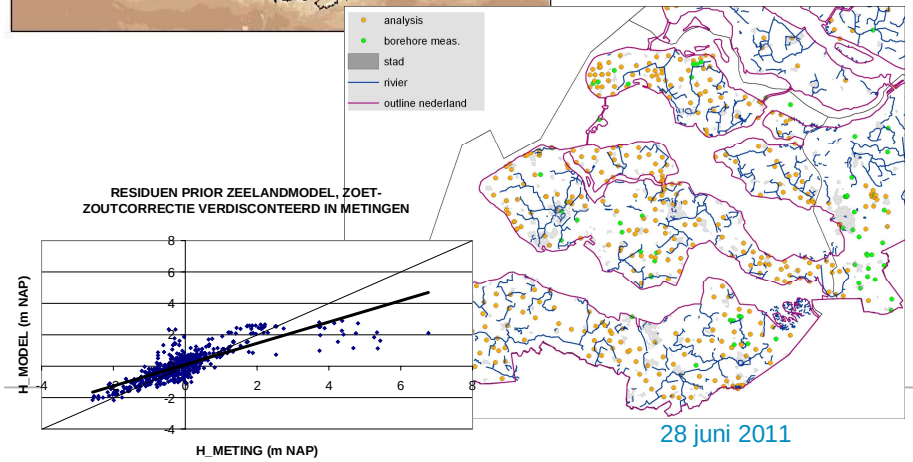
3D model Zeeland



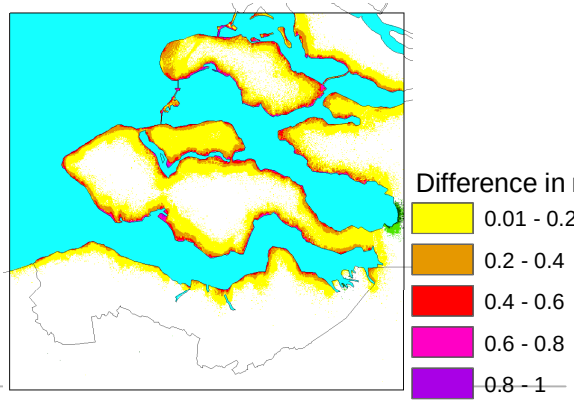
- Cels 100*100 m^2
- Top modellayers 0.5 m thickness
- Calibrated
- Improved 3D initial fresh saline field



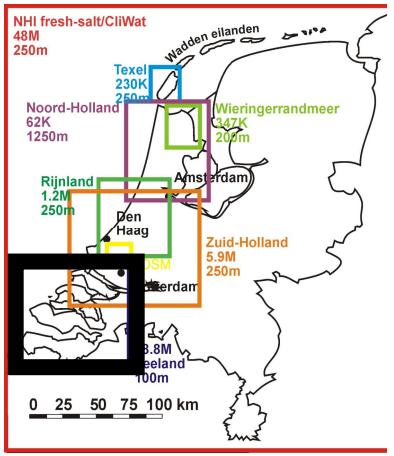




28 juni 2011



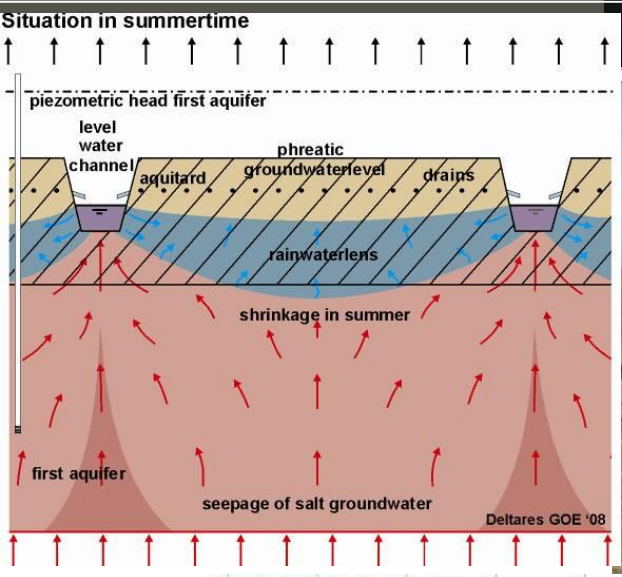
Freshwater head sea level +1m



Assessing climate change effect on freshwater lenses

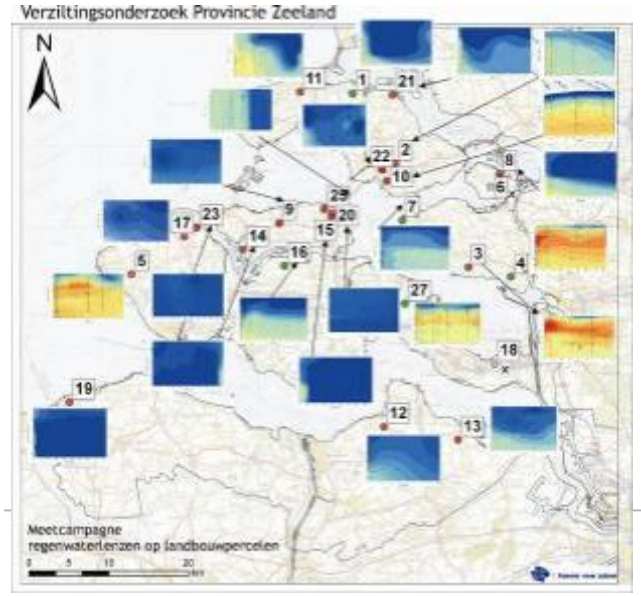
Monitoring:

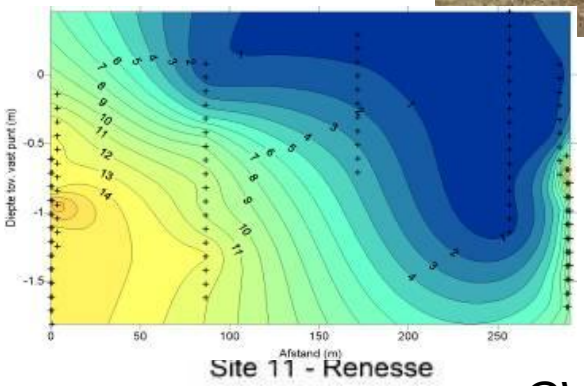
- Geology
- TEC-probe
- Sampling (head & conc)
- EM31
- CVES
- HEM



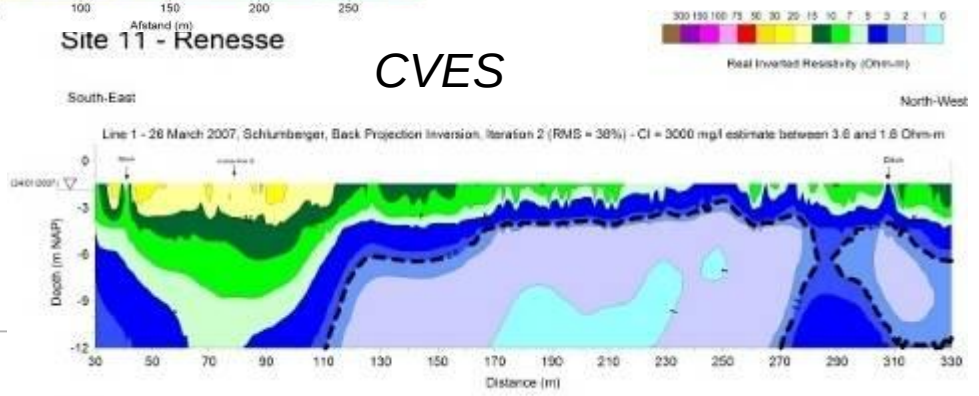
TEC probe

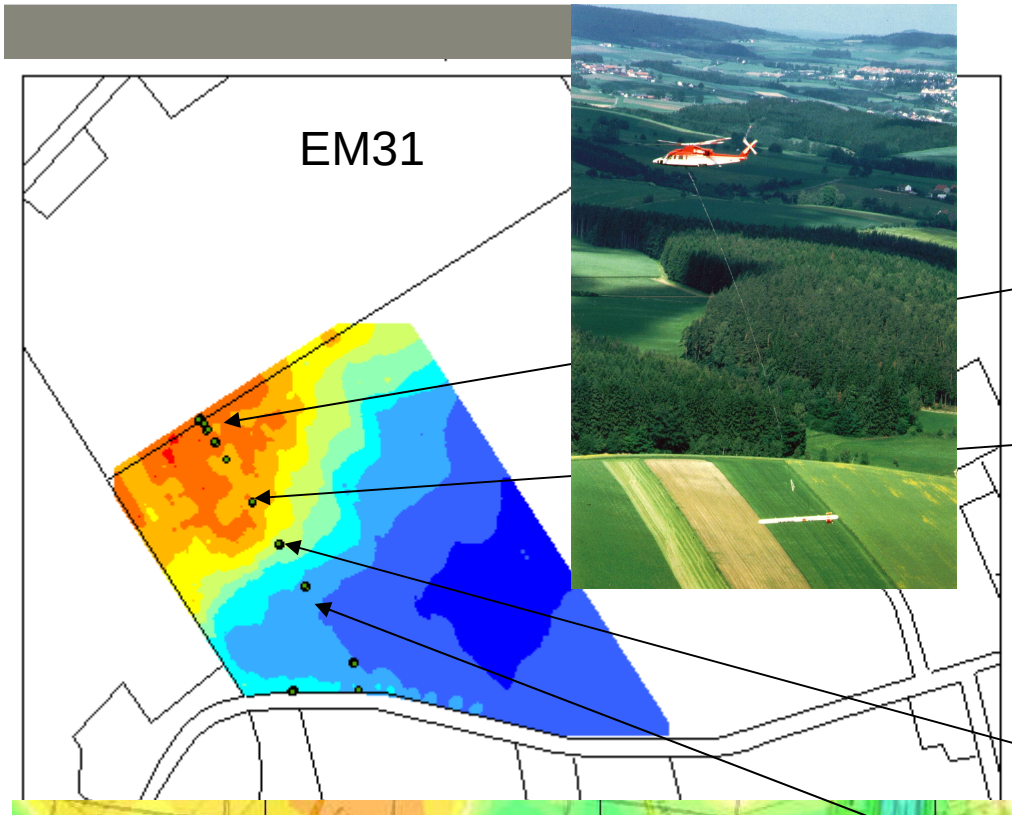
Groundwater modeling

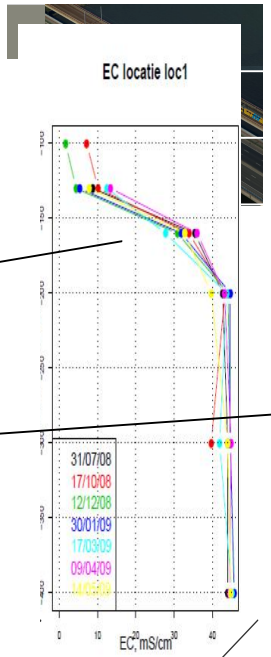


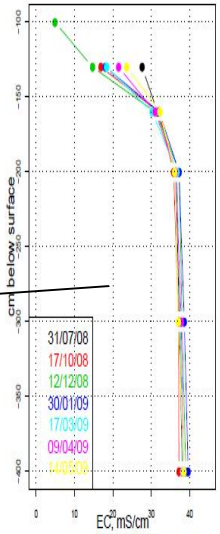


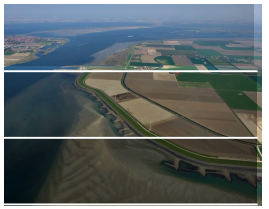
CVES



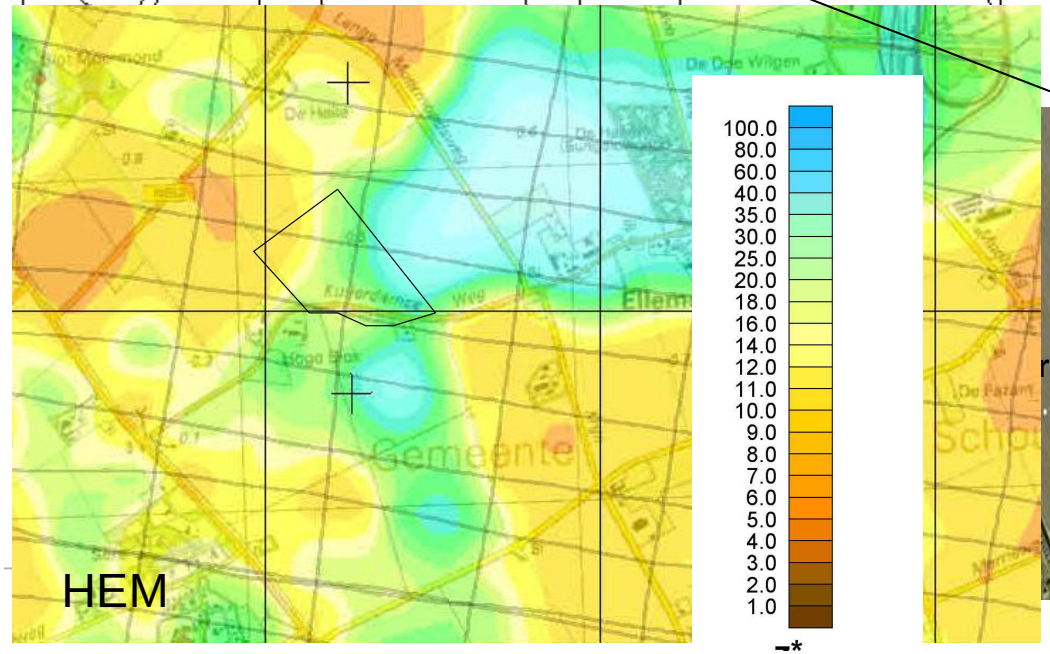


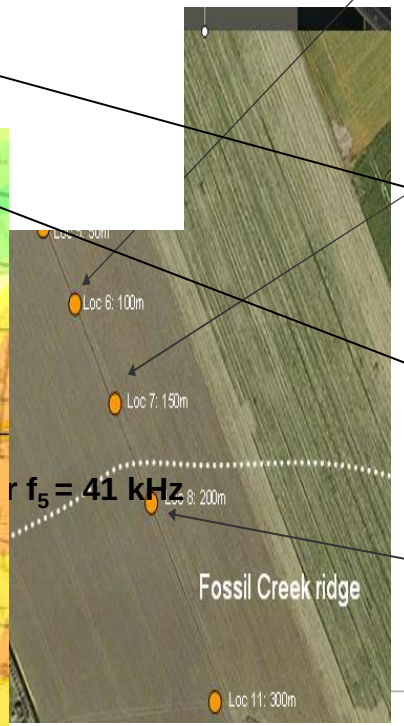




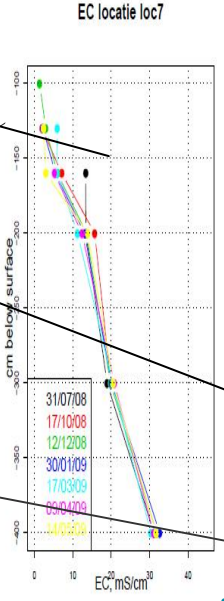


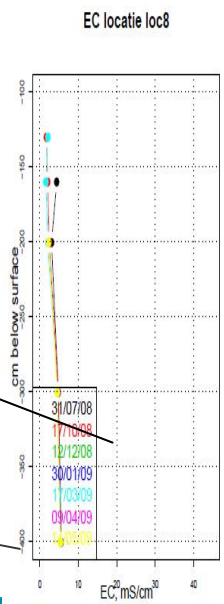
Sampling

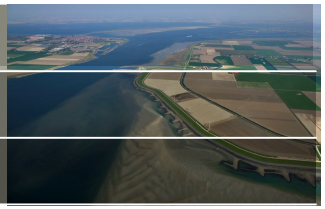




r f_5 = 41 kHz

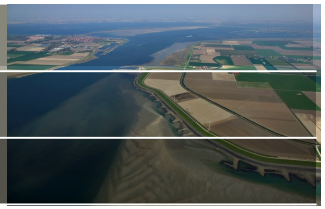






28 juni 2011

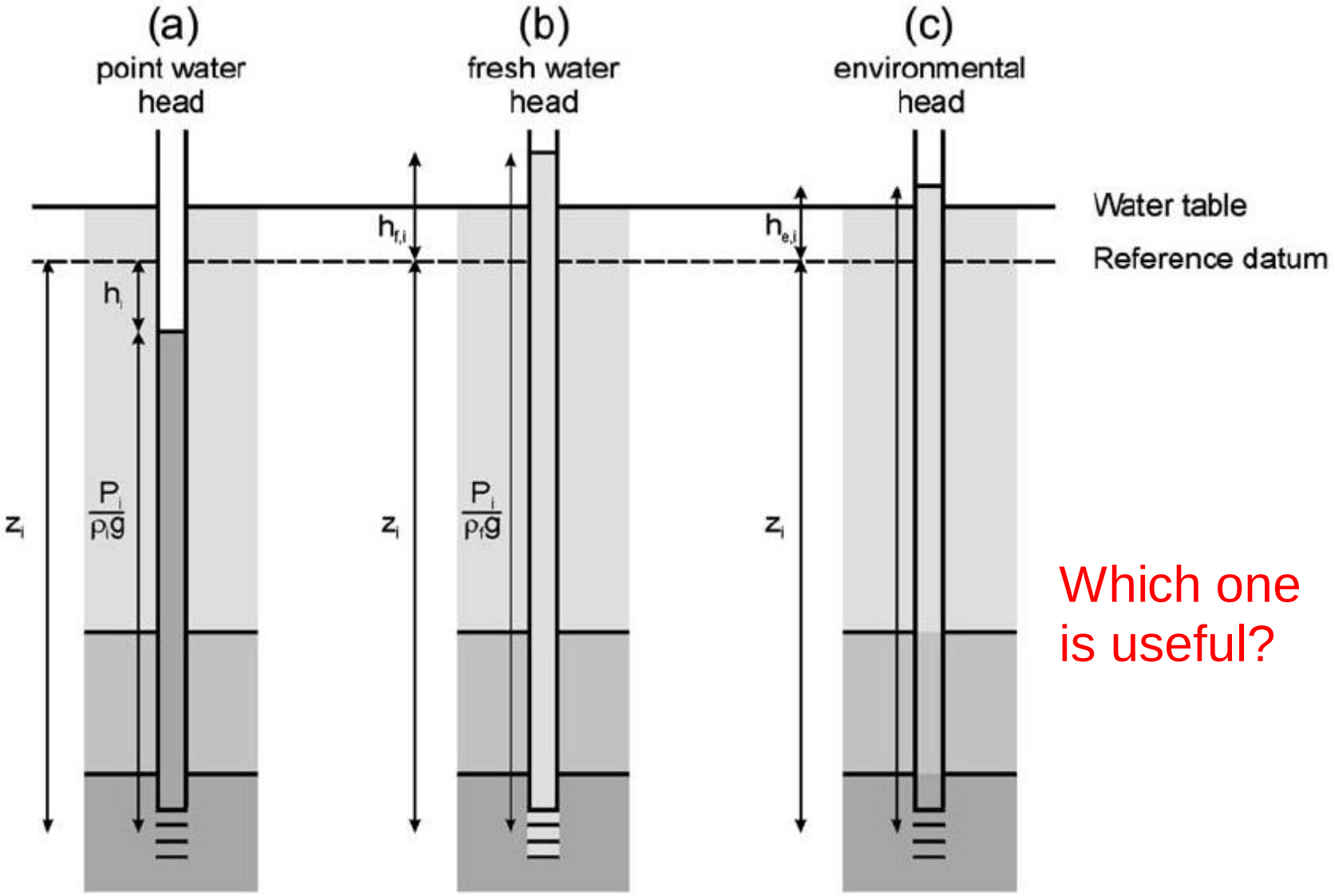
Deltares



Zoetwaterstijghoogte

Deltares

There are three common ways to define head

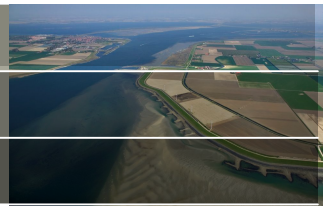


Which one is useful?

Post, Kooi and Simmons, 2007, Ground Water

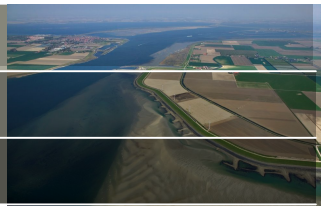
Deltares

Zoetwaterstijghoogte ϕ_f



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

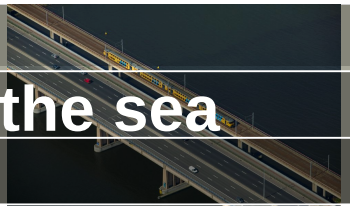
- Vergelijken grondwater met verschillende dichtheden
- Fictieve parameter
- In plaats van drukken
- Verwarrend (zoetwaterstijghoogte staat loodrecht op stroomlijnen)

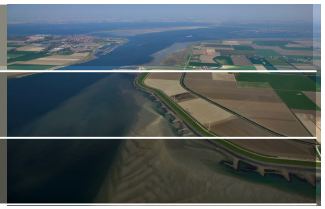


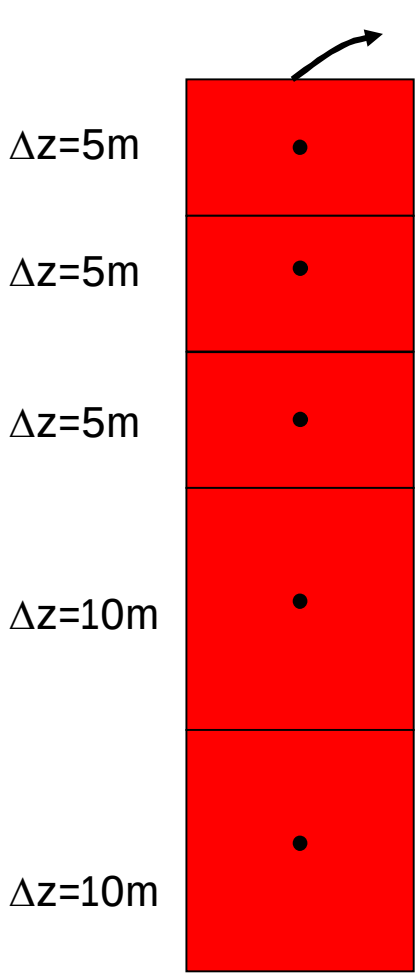
28 juni 2011

Deltares

Hydrostatic boundary condition at the sea







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

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

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

$$\rho = 1025\ \mathrm{kg/m3} \longrightarrow$$

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

$$\rho = 1025\ \mathrm{kg/m3}$$

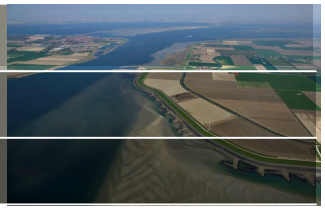
$$\longrightarrow$$

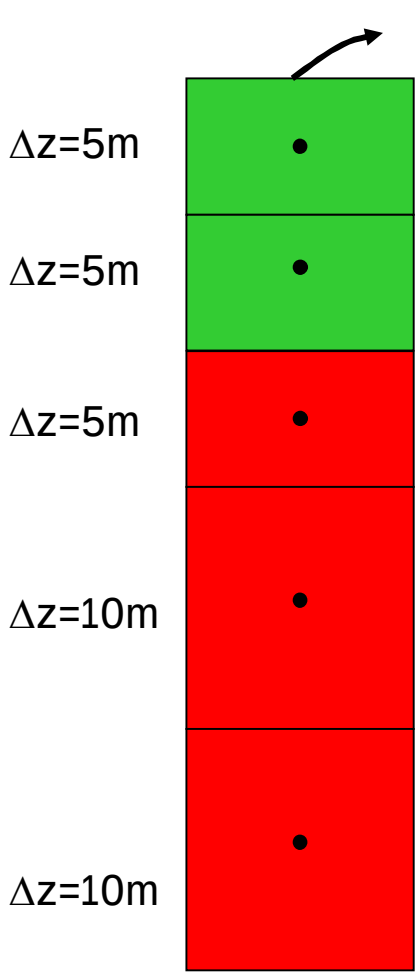
$$\phi_{f5} = 0.50 + 0.025 * (5\mathrm{m} + 5\mathrm{m}) = 0.75\mathrm{m}$$

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

Deltares

Hydrostatic boundary condition at an estuary





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

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

$\rho = 1025\ \mathrm{kg/m3} \longrightarrow$

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

$\rho = 1025\ \mathrm{kg/m3} \longrightarrow$

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

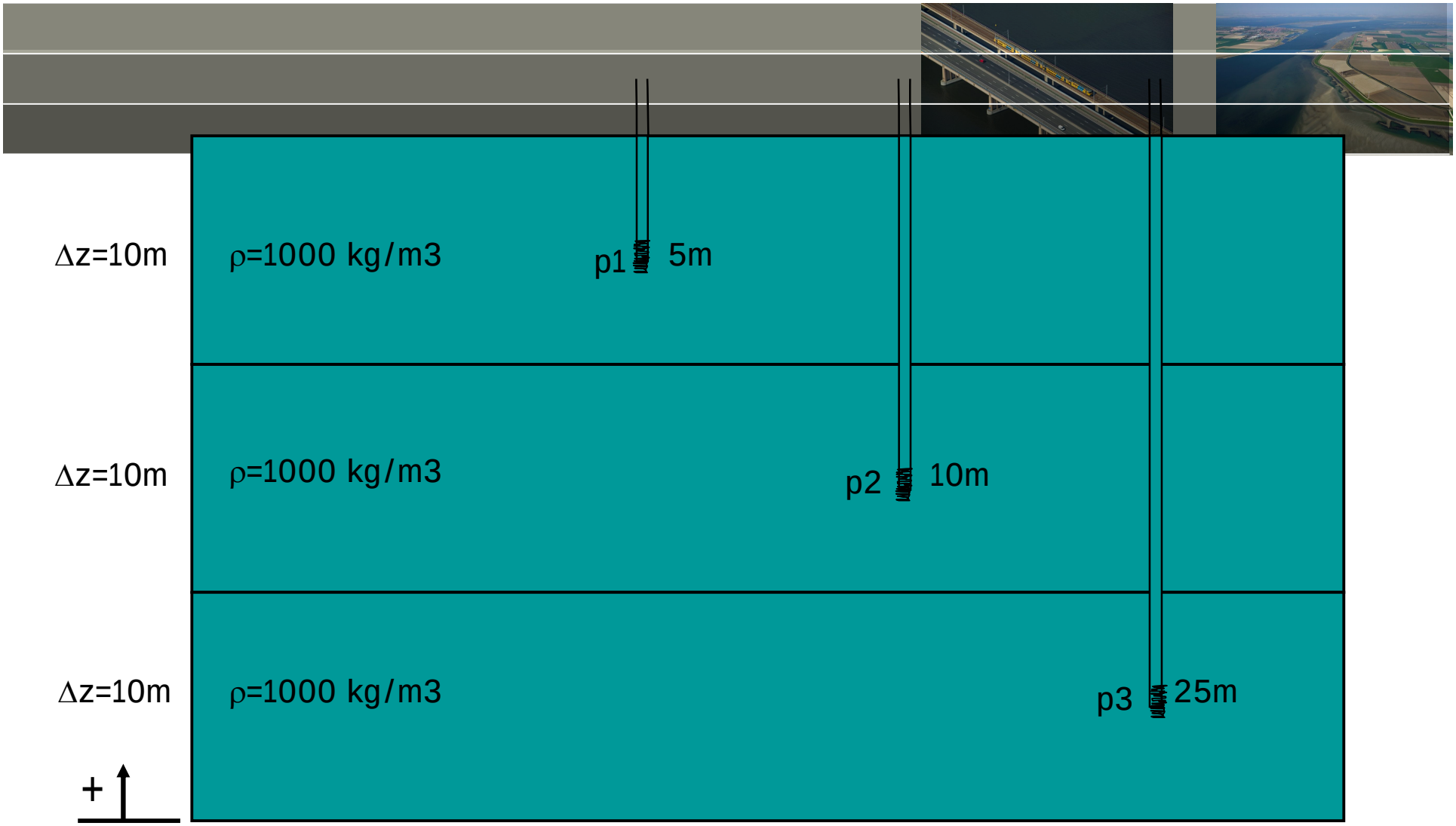
$\rho = 1025\ \mathrm{kg/m3}$

$\longrightarrow$

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

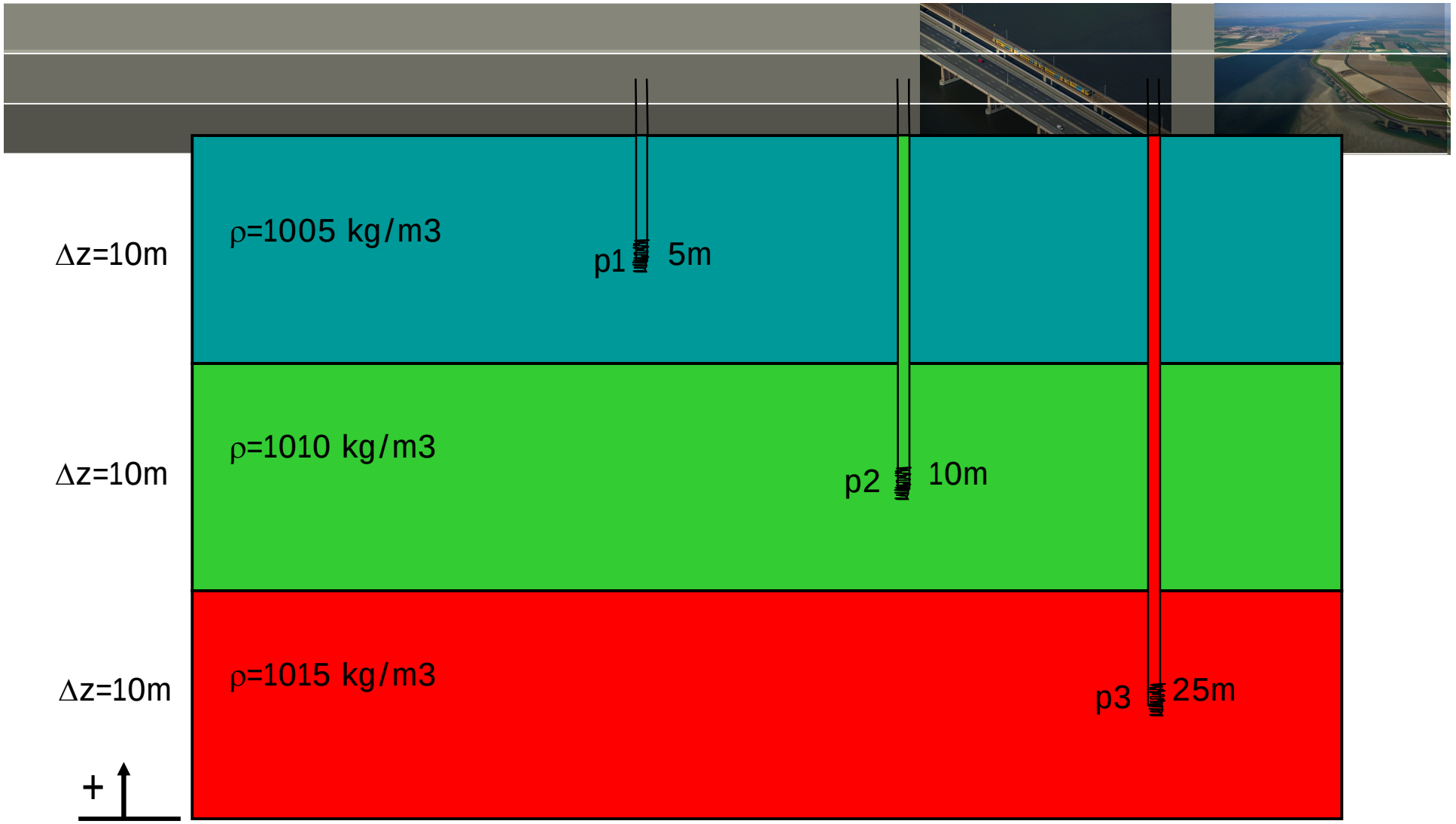
$$\phi_{f2} = \phi_{f1} + \frac{\rho - \rho_f}{\rho_f}(\Delta z)$$

Deltares



No flow

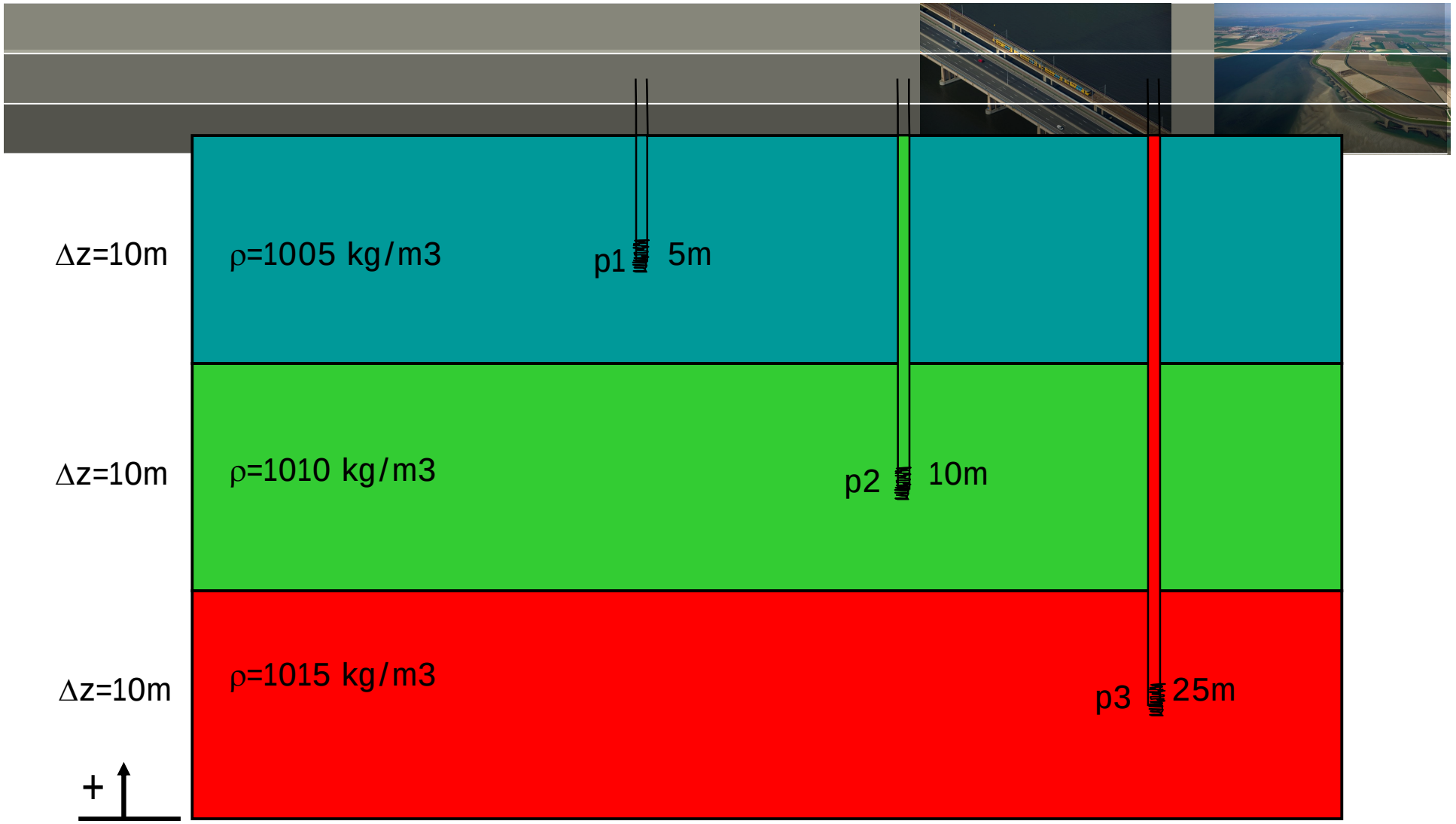
Deltares



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

Calculate to freshwater head!

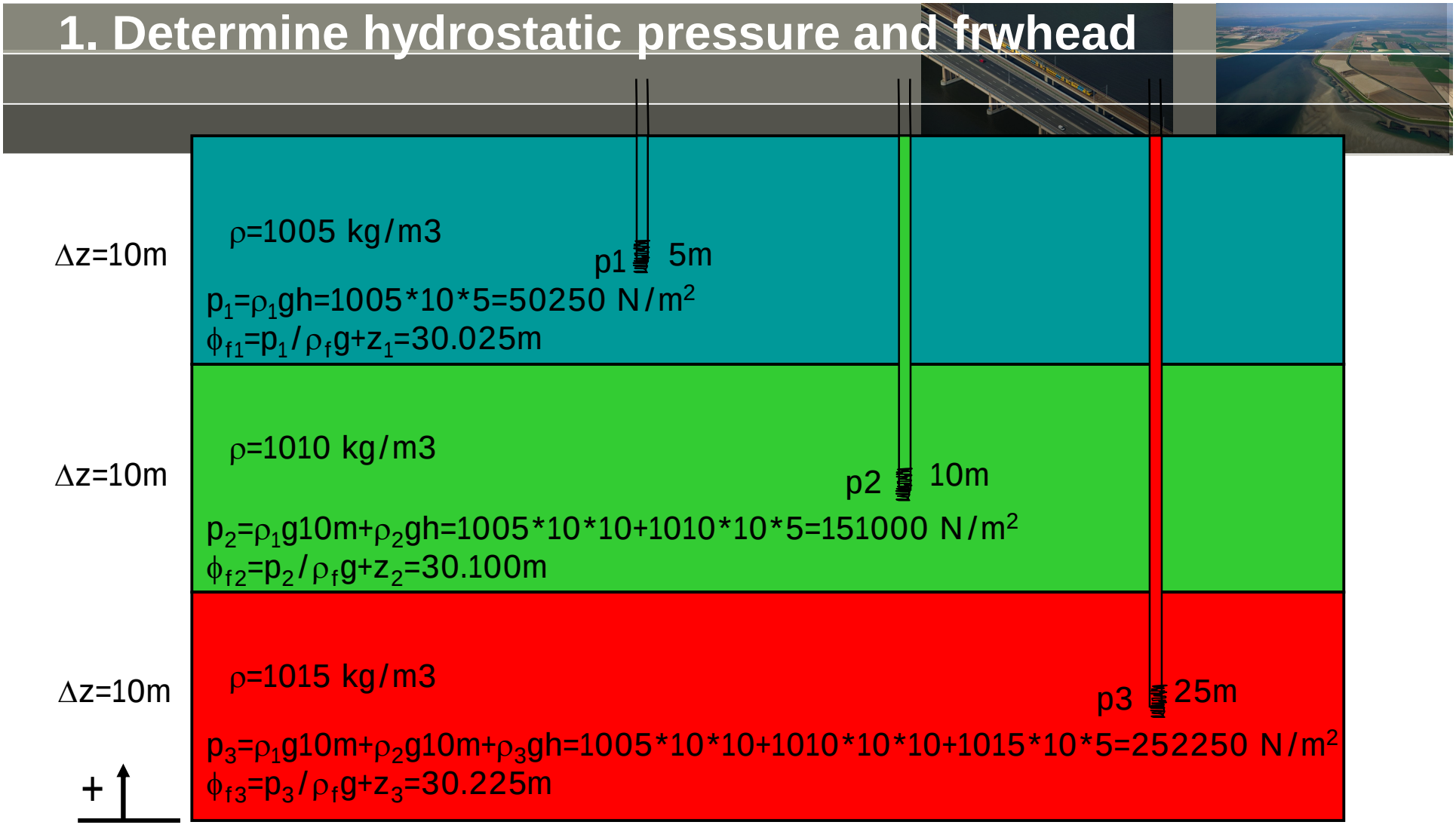
Deltares



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

Deltares

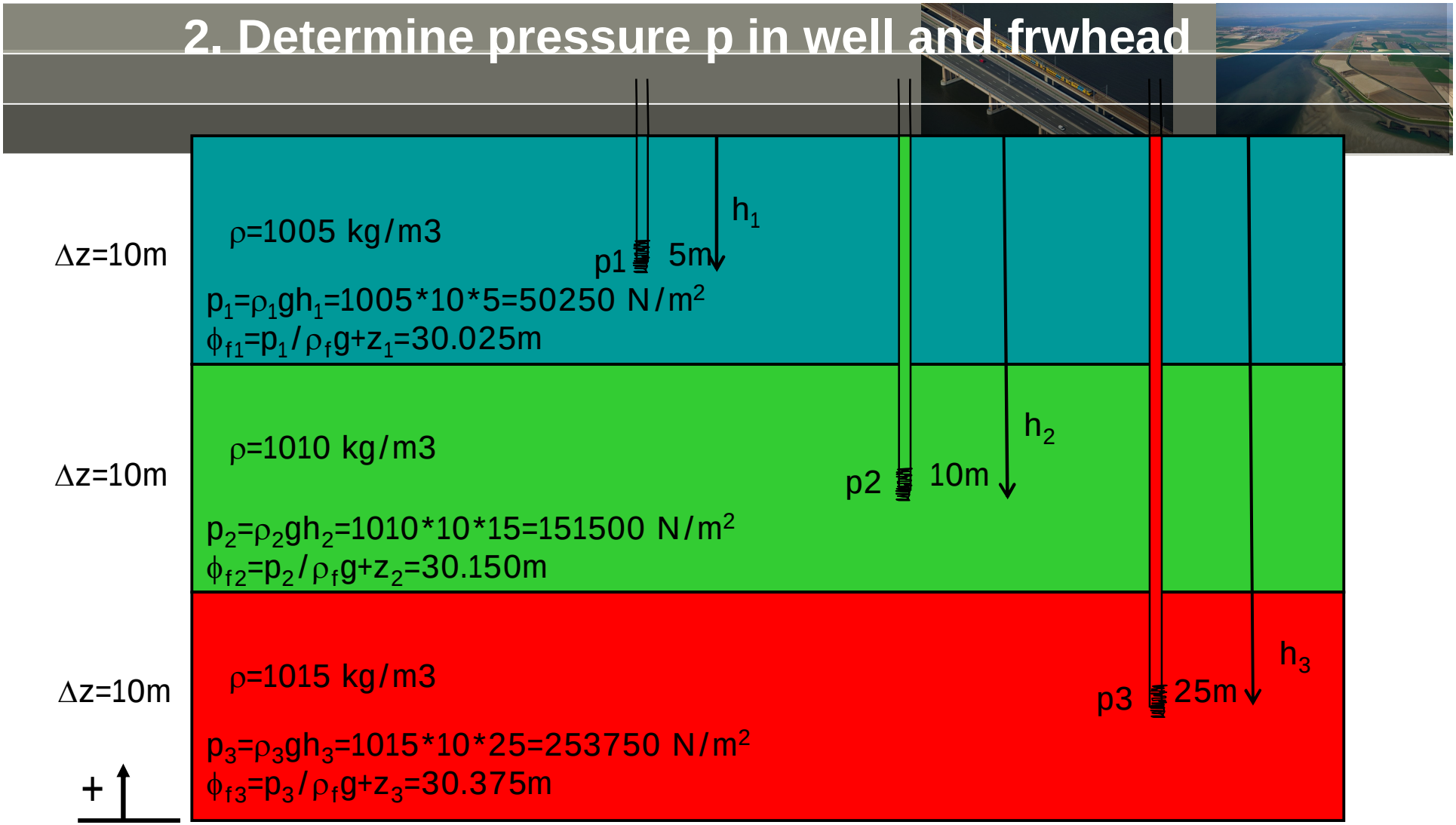
1. Determine hydrostatic pressure and frwhead



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

Deltares

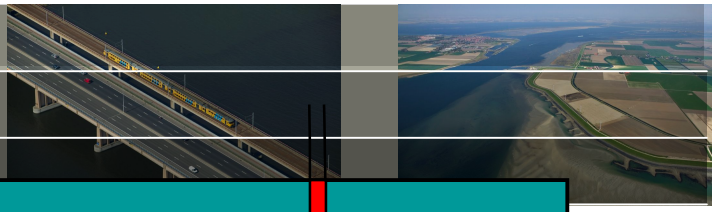
2. Determine pressure p in well and frwhead

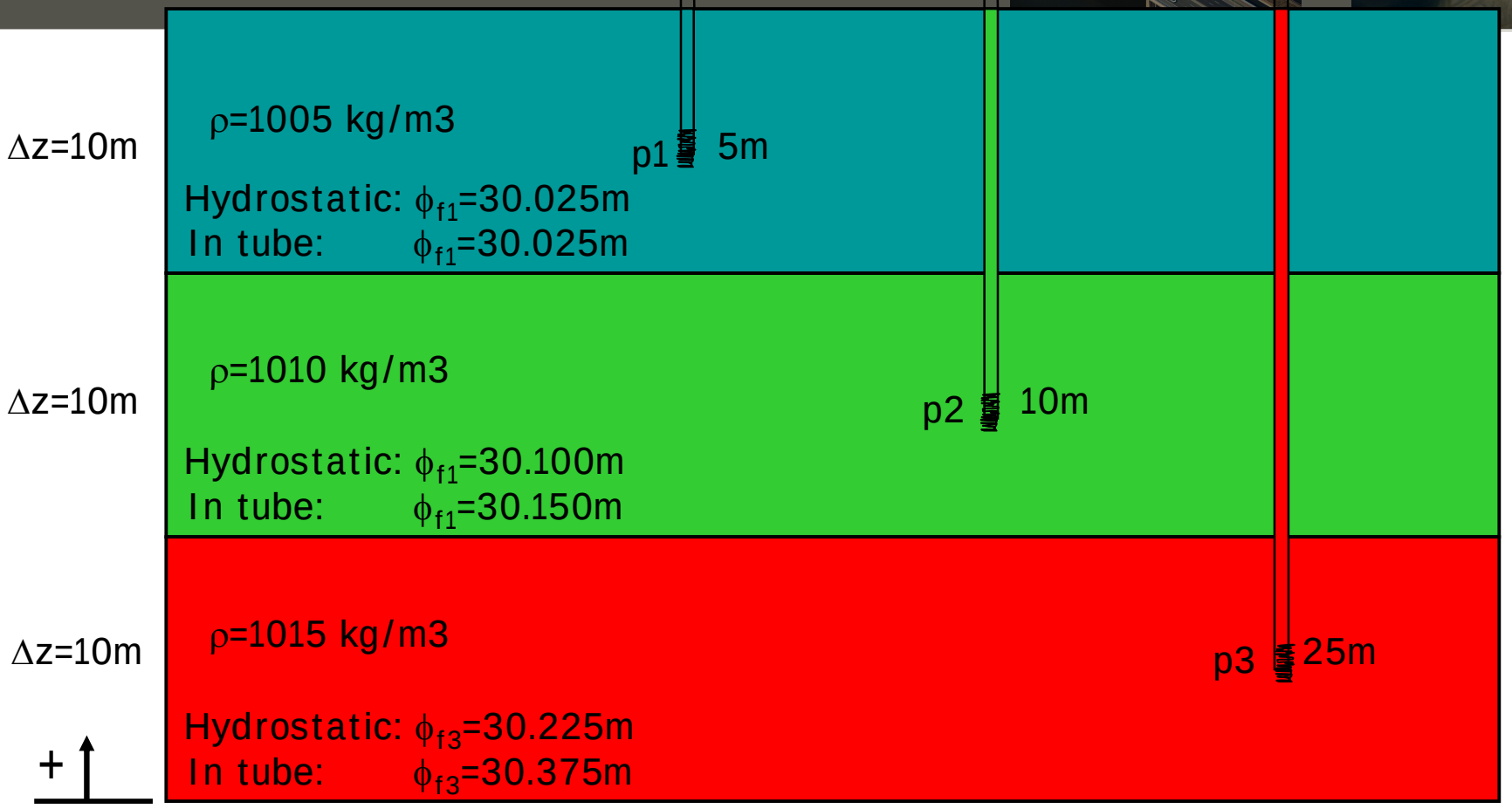


1. Determine hydrostatic pressure (and freshwater head f_f)
2. Determine pressure p <u>in</u> well! (and freshwater head f_f)

Deltares

Comparison

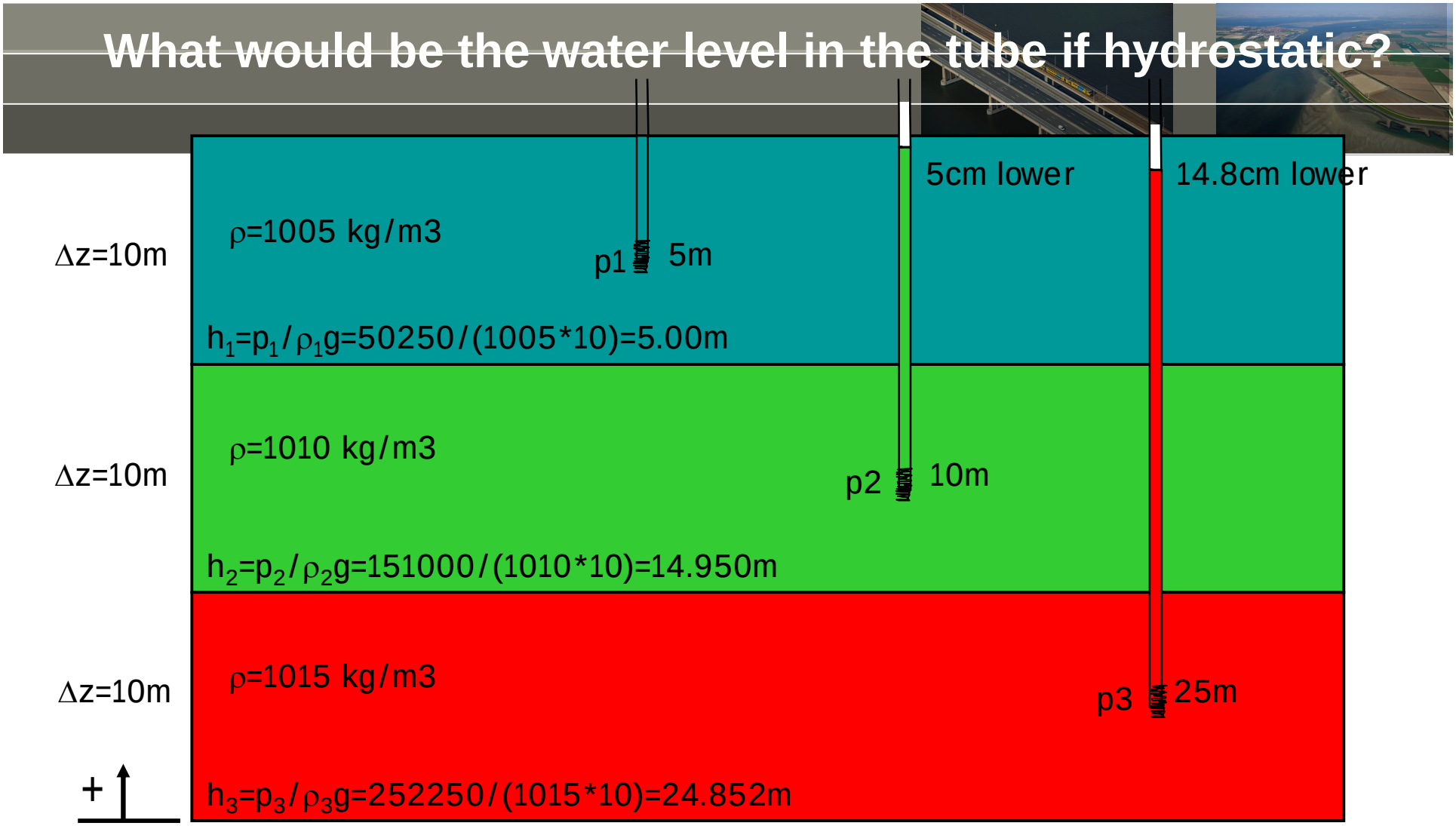




Conclusion: freshwater head not equal, so vertical upward flow!

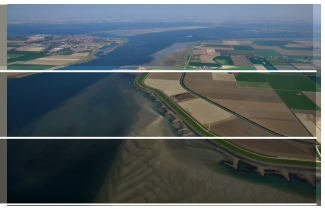
Deltares

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



Deltares

Hydrostatic pressure: q_z=0



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

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

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

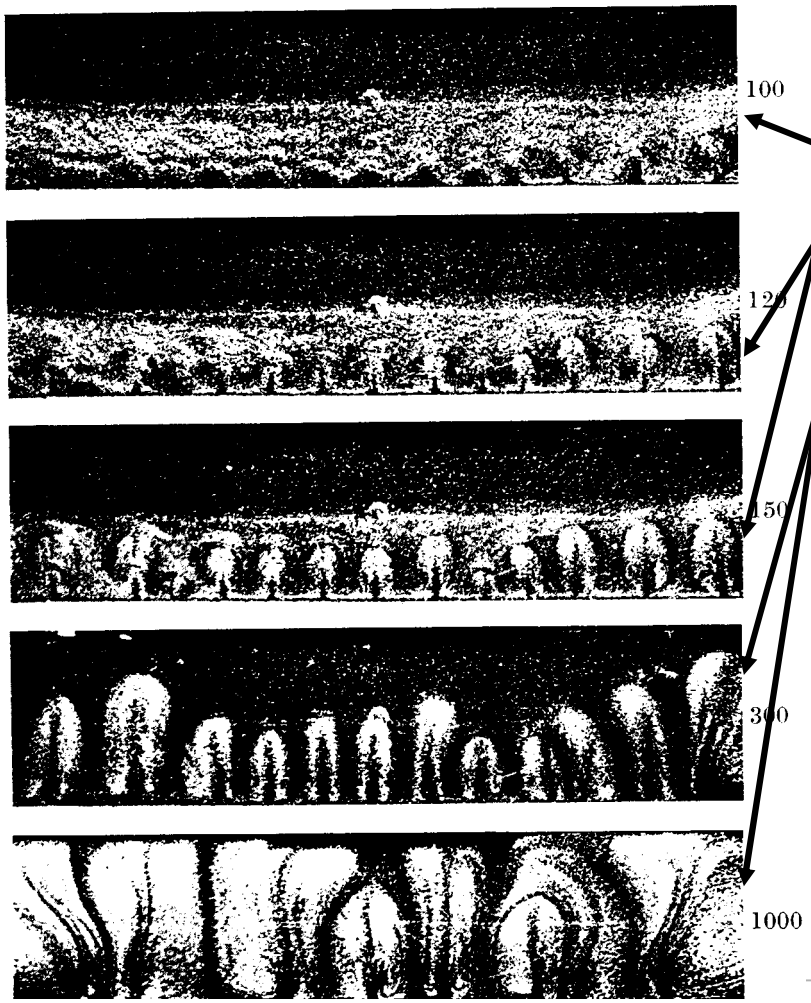
$$\phi_{f2} = \phi_{f1} - \frac{\rho - \rho_f}{\rho_f}(z2 - z1)$$

+

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

Deltares

It is originally a heat transport problem



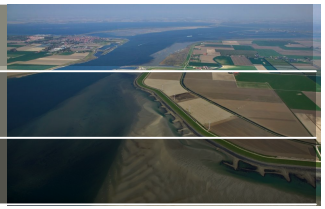
Phases:

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

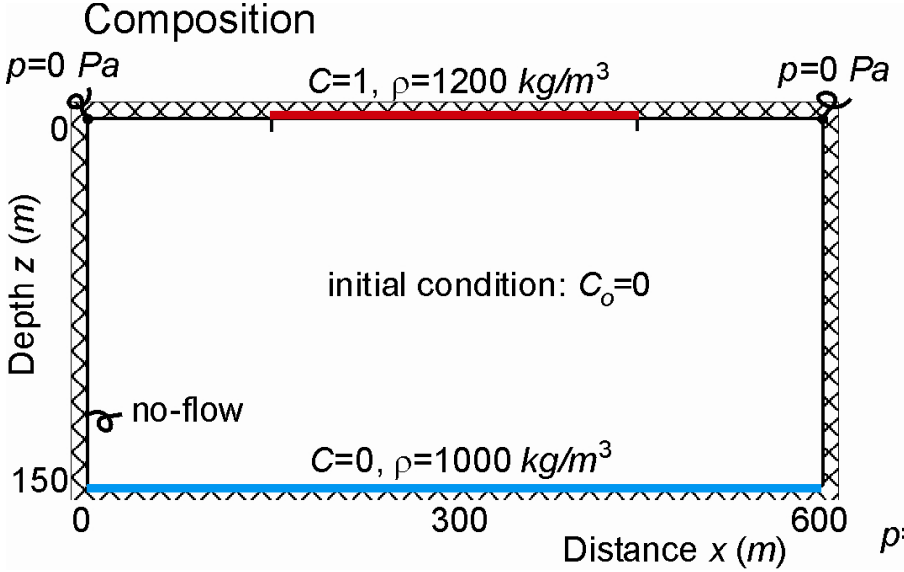
Convection of heat occurs when:

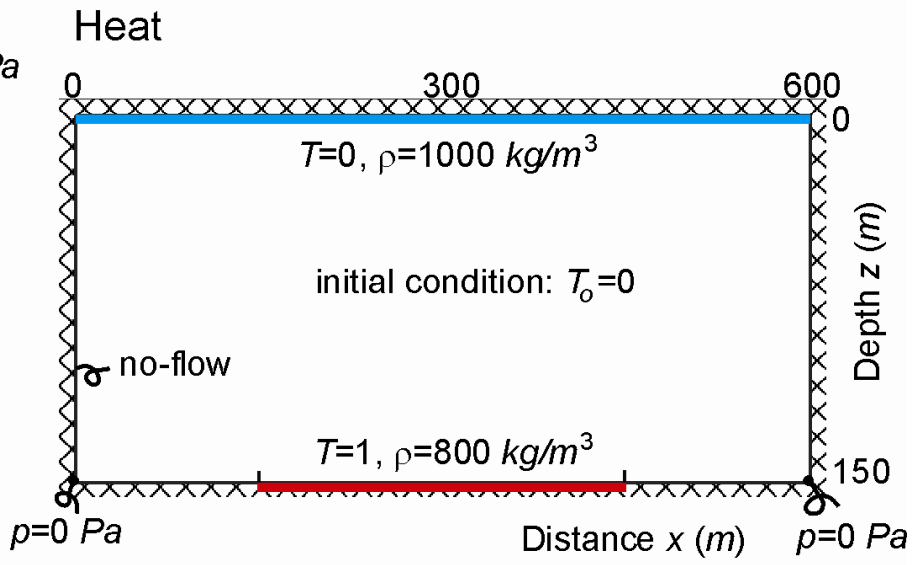
Rayleigh number > $4\pi^2$

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



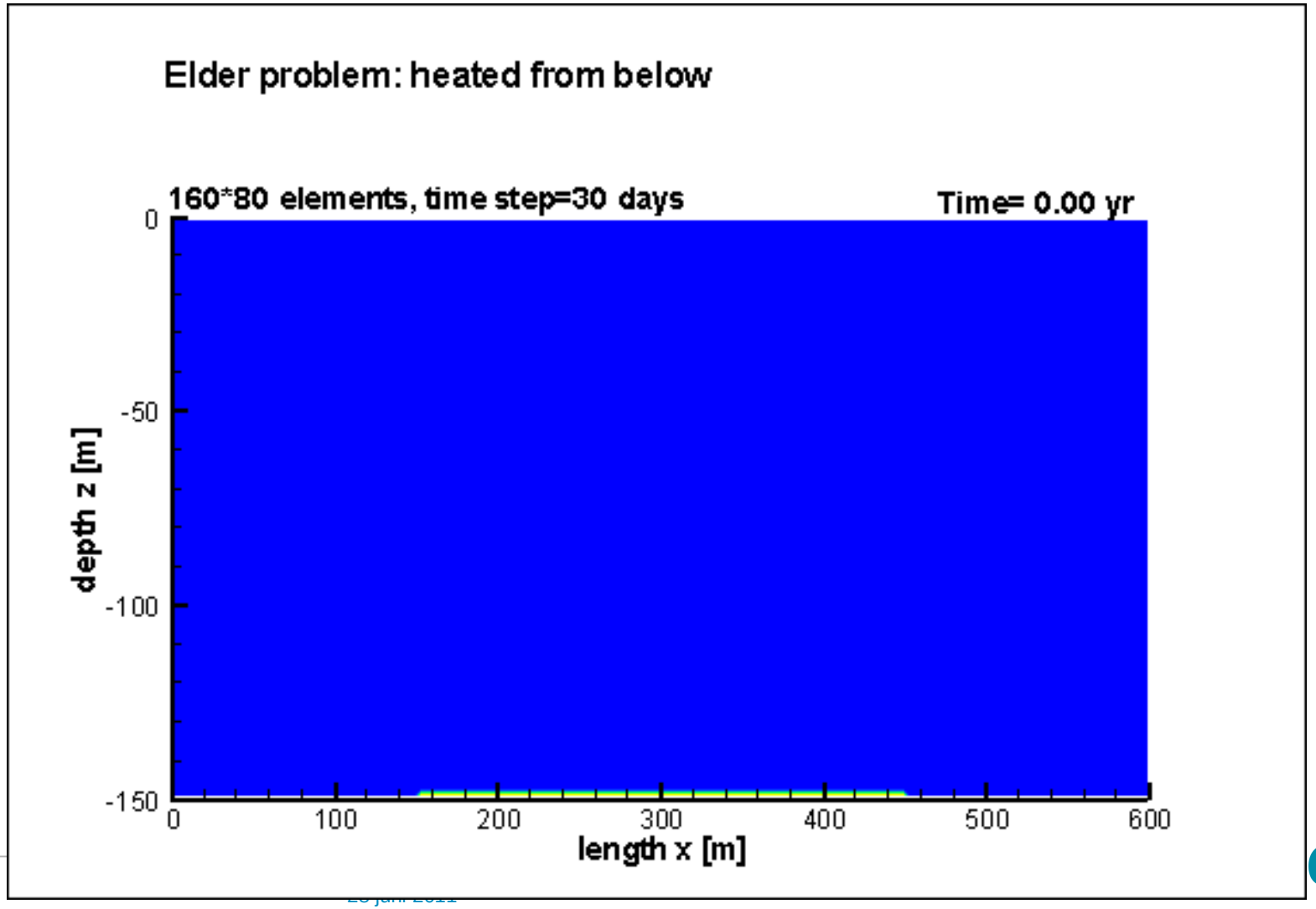
Anology composition and heat



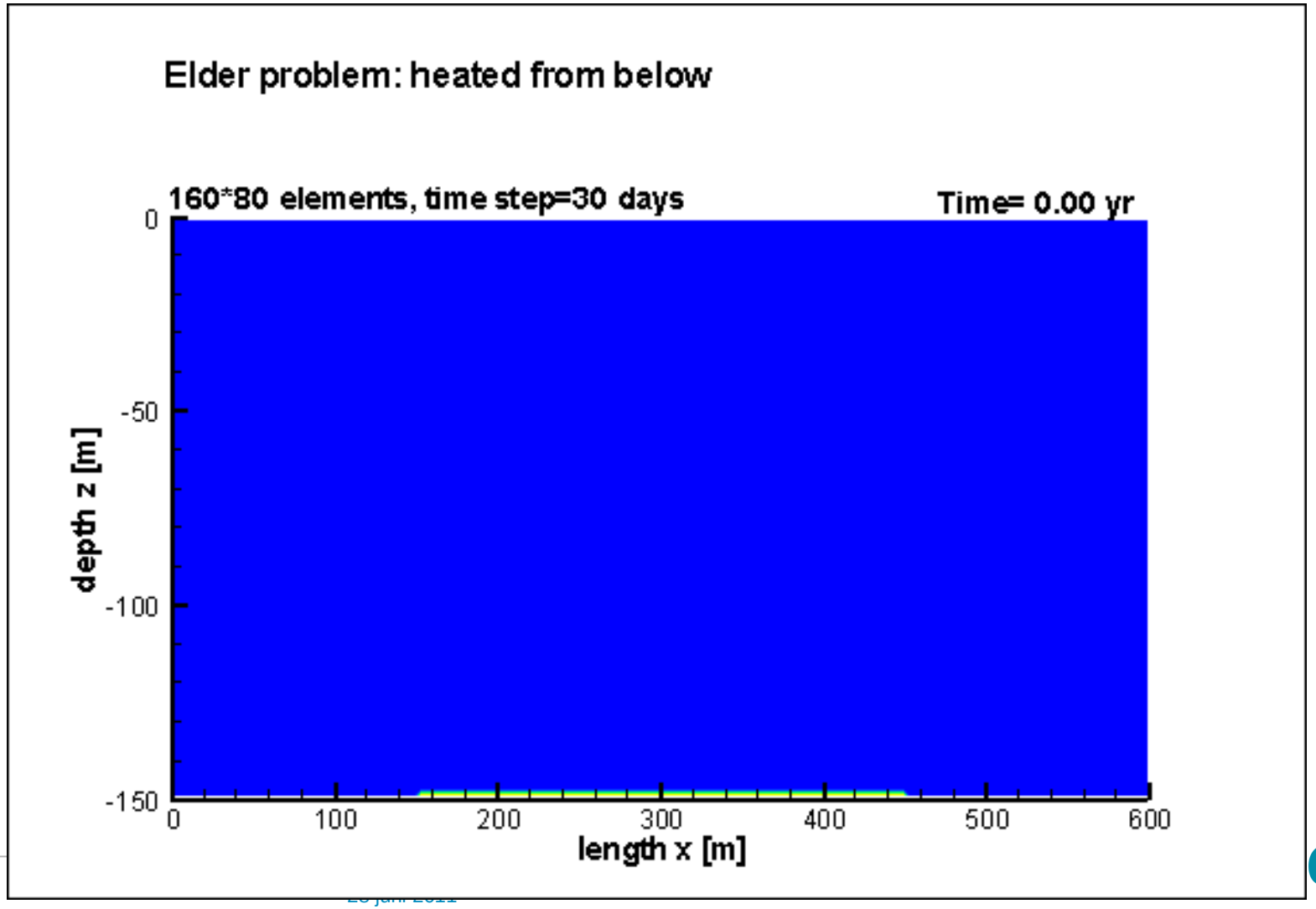


Lecture notes, p. 91-96

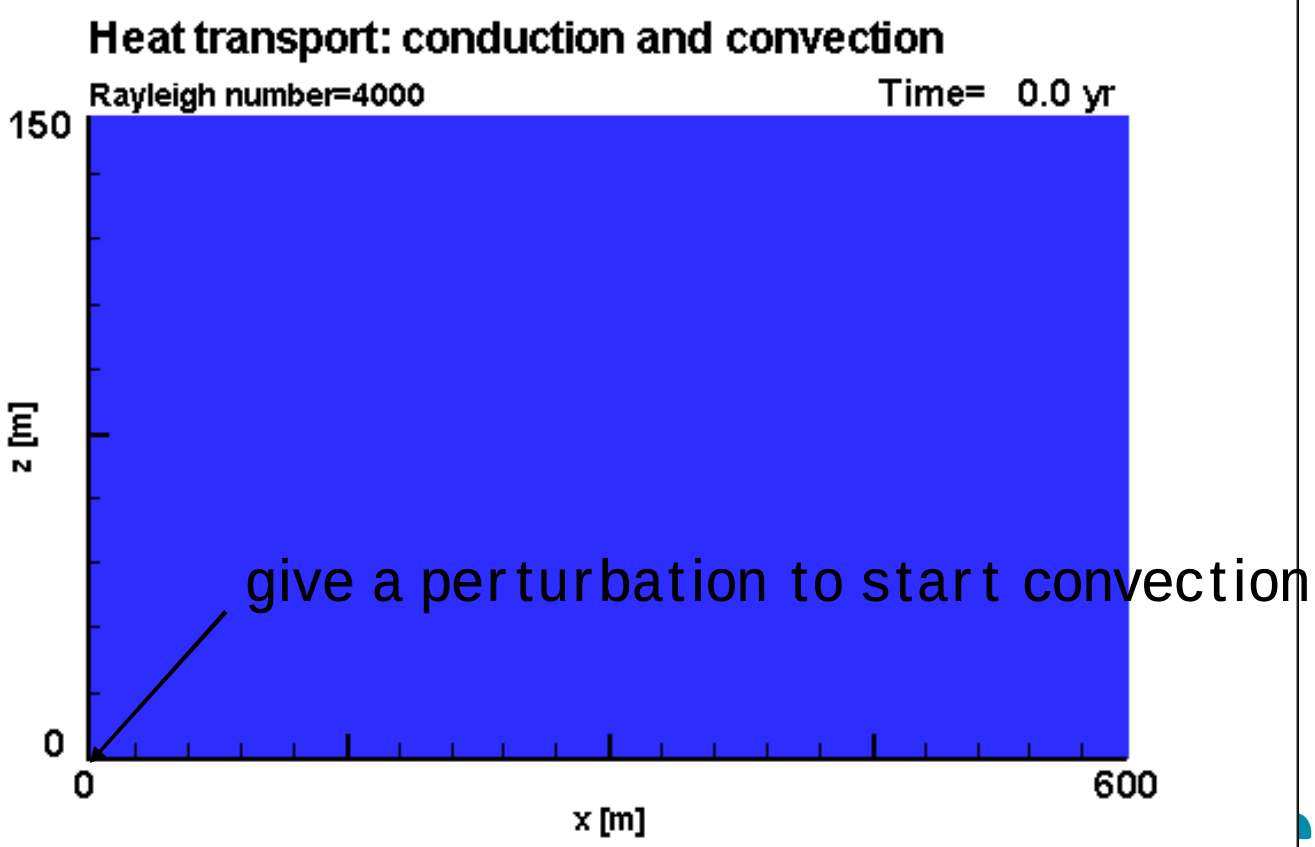
Development of convection cells (Rayleigh number=400)



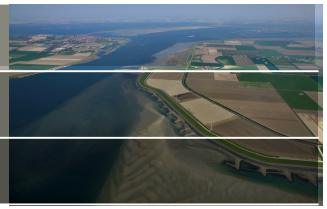
Development of convection cells (Rayleigh number=400)



Heat transport (Rayleigh number=4000)



Conclusies



1. In kustgebieden kunnen dichtheidsverschillen een belangrijke rol spelen
2. Autonome proces heeft een grotere invloed op de verzilting van Nederland dan klimaatverandering
3. Het verschil tussen de gevolgen van de klimaatscenario's is klein voor het grondwater systeem
4. Regenwaterlenzen zijn kwetsbare systemen
5. Te weinig metingen kwaliteit in het kustgebied