IHE 2020

Density dependent groundwater flow in the coastal zone

Gualbert Oude Essink, PhD

Lecture set-up: 4*(45min, 15min break)

- PowerPoint sheets
- Lecture Notes
- Practicals numerical modelling

http://freshsalt.deltares.nl

Deltares
Unit Subsurface and Groundwater Systems
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17-18-22-24 June 2020

Curriculum Vitae

- Delft University of Technology, Civil Engineering: till 1997
  Ph.D.-thesis: Impact of sea level rise on groundwater flow regimes
- Utrecht University, Earth Sciences: till 2002
- Free University of Amsterdam, Earth Sciences: till 2004
- Deltares
- Utrecht University (Associate Professor): from 2014

Qualifications:

- Groundwater resources management
- Density-dependent groundwater flow and coupled solute transport
- Salt water intrusion in coastal aquifers
- Assessment of climate change on groundwater resources
- Numerical Modeling
- Teaching and training

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Colleagues at Deltares
Groundwater in the Coastal Zone

http://zoetzout.deltares.nl
http://freshsalt.deltares.nl

Gualbert Oude Essink
Joost Delsman
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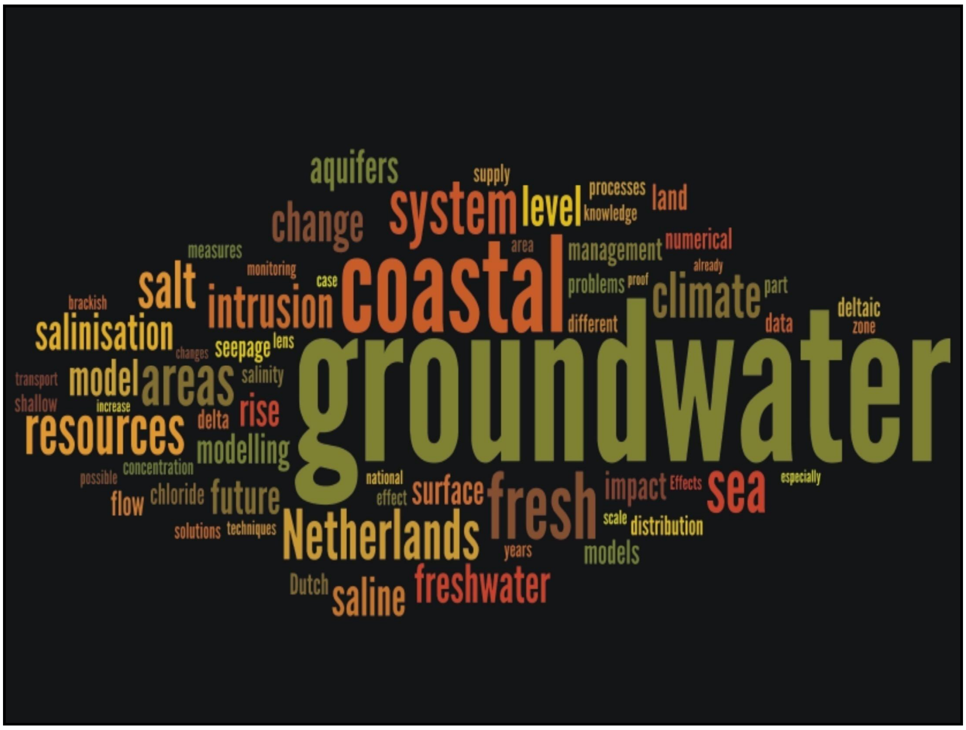
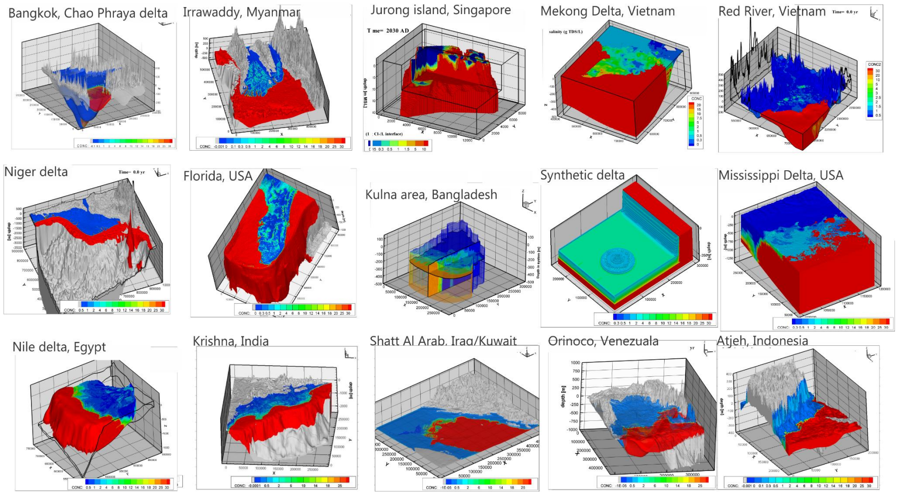
Esther van Baaren
Jarno Verkaik
Marta Faneca





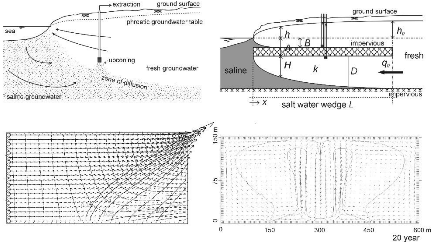
Research on groundwater in the coastal zone

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

Lecture notes, practicals and ppt on freshsalt.deltares.nl

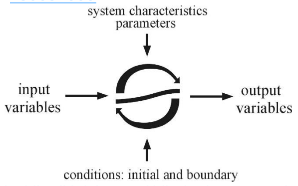
1. Density dependent groundwater flow

http://publicwiki.deltares.nl/download/attachments/22183944/gwm2.pdf?version=1&modificationDate=1268945548000



2. Groundwater modelling

http://publicwiki.deltares.nl/download/attachments/22183944/gwm1.pdf?version=1&modificationDate=1268750652000


system characteristics
parameters

input variables → → output variables

conditions: initial and boundary

http://publicwiki.deltares.nl/display/FRESHSALT/Upload

Introduction

Practicals numerical modelling

- PMWIN
- SEAWAT
- Cases:
  - Rotating sharp interface
  - Freshwater lens
  - Henry's case
  - (Elder's case)
- Setup practicals:
  - try to work together in teams, e.g. of two persons
  - short report of findings (make screenshots)
  - deliver within two weeks after finish last SWI lectures

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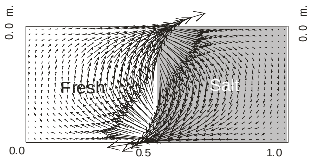
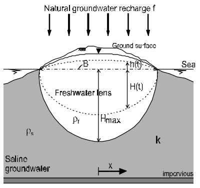
Practicals

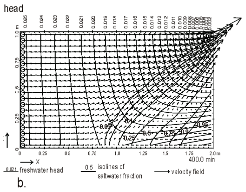
- Rotating sharp interface



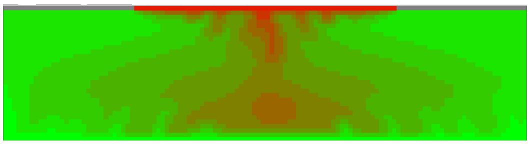
- Freshwater lens



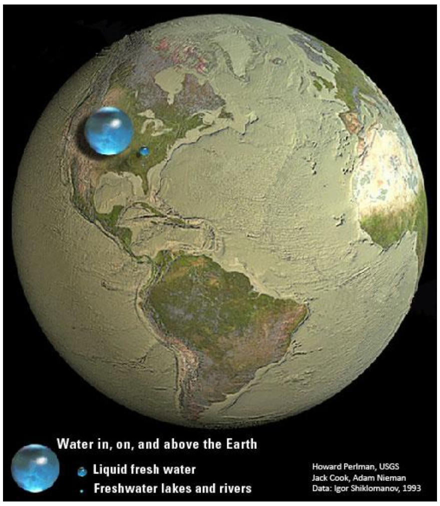
- Henry's case

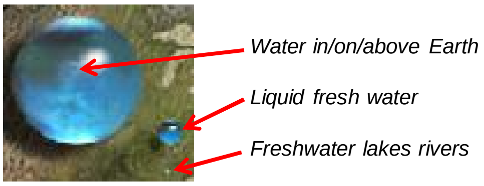


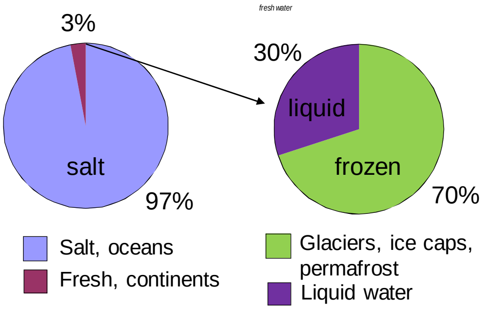
- (Elder's case)



Volumes of water on Earth: a scarce product



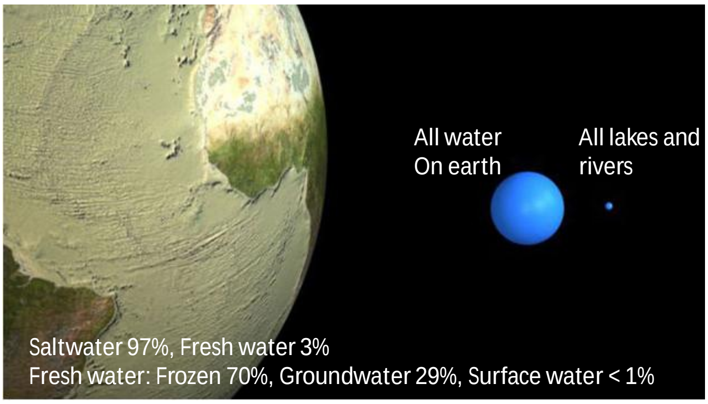




Source: Perlman, USGS; Shiklomanov, 1993

Water Energy Food Nexus
Global water scarcity

Fresh water is a scarce resource…

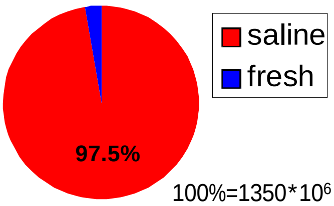


Saltwater 97%, Fresh water 3%
Fresh water: Frozen 70%, Groundwater 29%, Surface water < 1%

Introduction

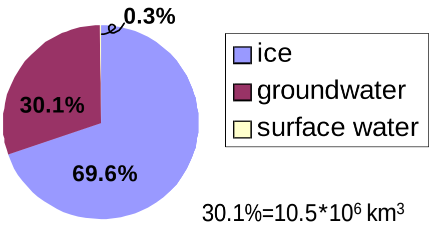
Water on Earth

Total water on Earth



$100\%=1350*10^6$ km^3

Total fresh water on Earth



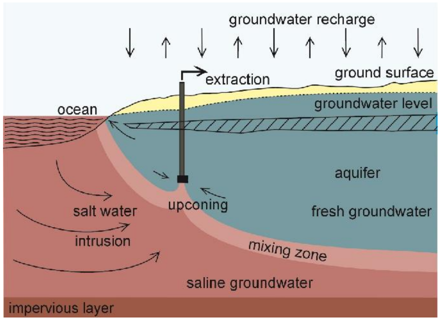
$30.1\%=10.5*10^6$ km^3

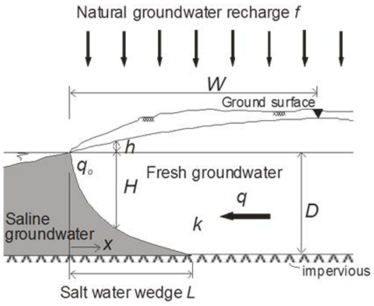
Demand for groundwater (now 30%) increases due to:

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

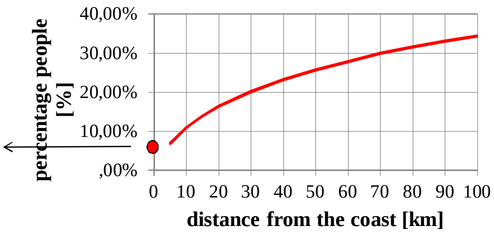
(Source: Cheng, 1998)

Groundwater in the coastal zone





500 million people in the first 5km from the coastline



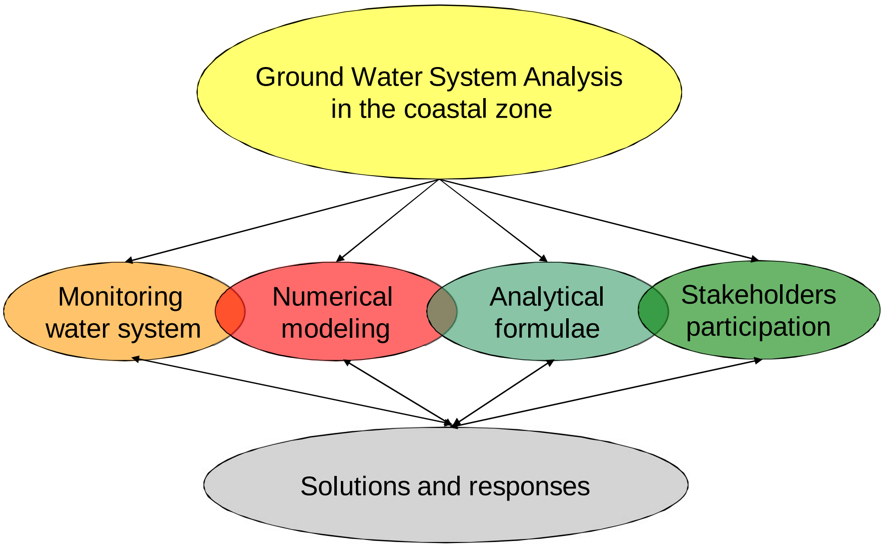
Introduction

Topics of density driven groundwater flow

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

Deltares
Enabling Delta Life

Work at Deltares



Ground Water System Analysis in the coastal zone

Monitoring water system

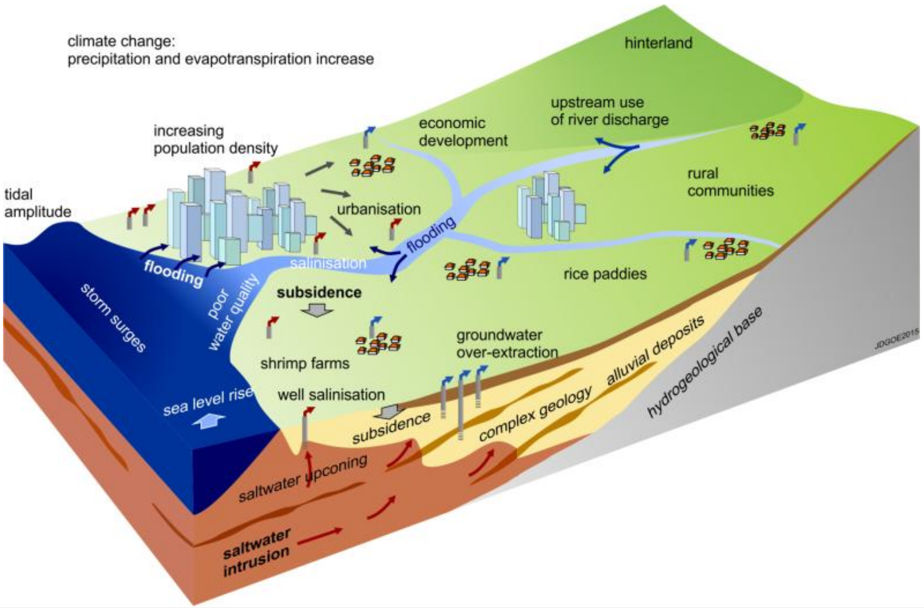
Numerical modeling

Analytical formulae

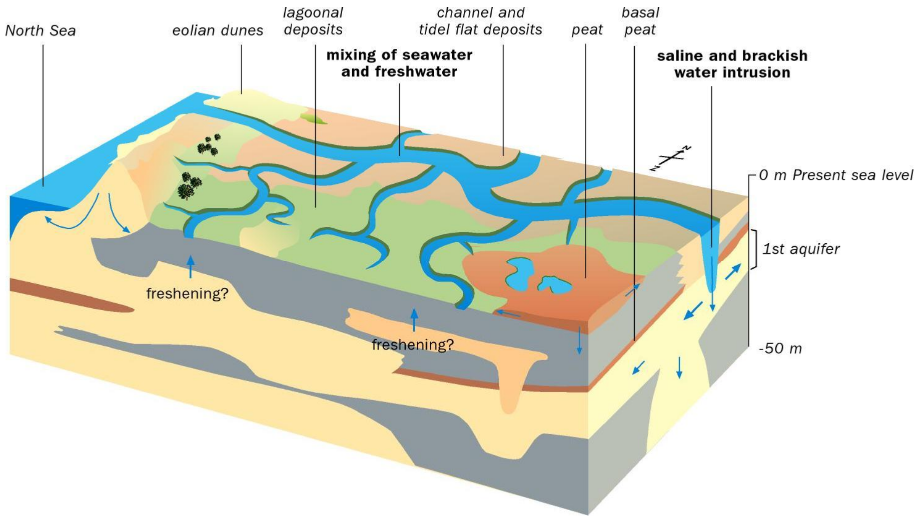
Stakeholders participation

Solutions and responses

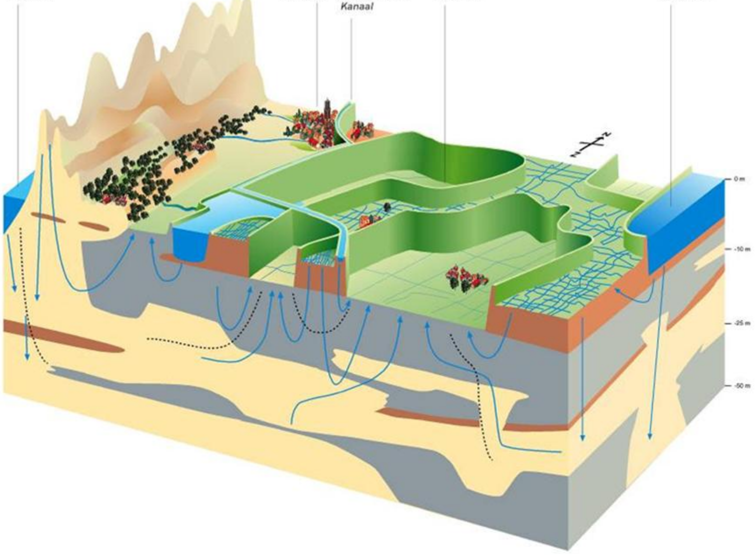
Groundwater issues in the coastal zone/deltaic areas



Past, before man



The polders in the Nederland



Groundwater in the future

We have to cope which...:

- We have to cope which...:
- Groundwater extractions
- Development energy use/production (heat-cold)
- Climate change
- Land subsidence
- Development spatial land use
- Politics, Policy & Watermanagement

Direct anthopogenic influence on groundwater is more important than climate effect

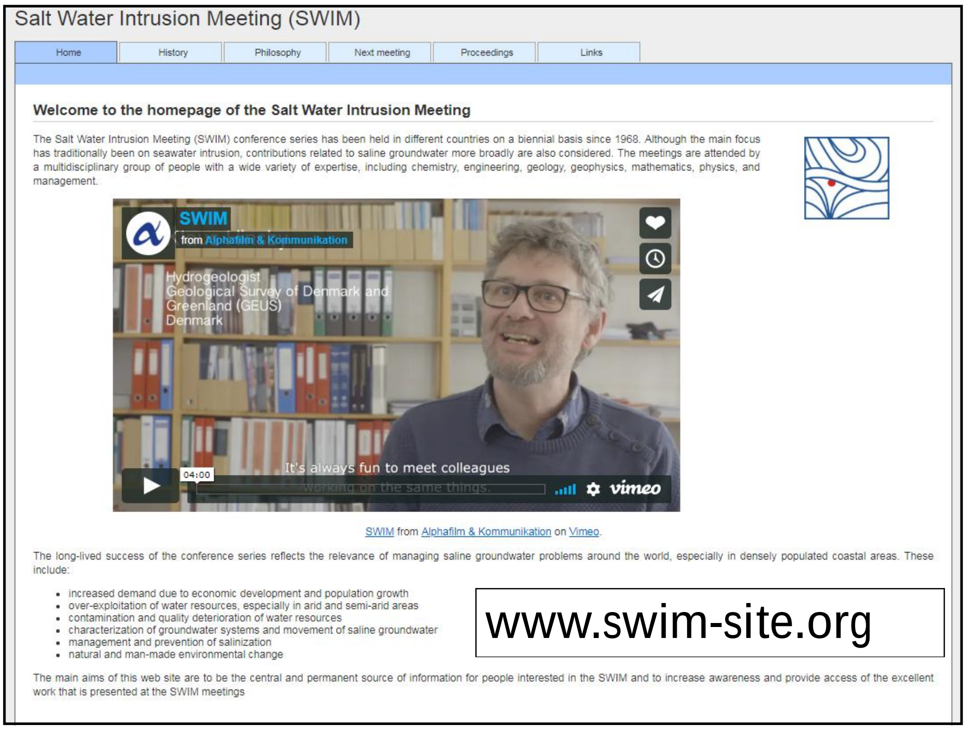
Salt Water Intrusion Meeting, since 1968

Salt Water Intrusion Meeting, since 1968

http://www.swim-site.org/

Themes

- Water systeem analysis
- Monitoring
- Modelling
- Effects
- Solutions



Salt Water Intrusion Meeting (SWIM)

Welcome to the homepage of the Salt Water Intrusion Meeting

The Salt Water Intrusion Meeting (SWIM) conference series has been held in different countries on a biennial basis since 1968. Although the main focus has traditionally been on seawater intrusion, contributions related to saline groundwater more broadly are also considered. The meetings are attended by a multidisciplinary group of people with a wide variety of expertise, including chemistry, engineering, geology, geophysics, mathematics, physics, and management.

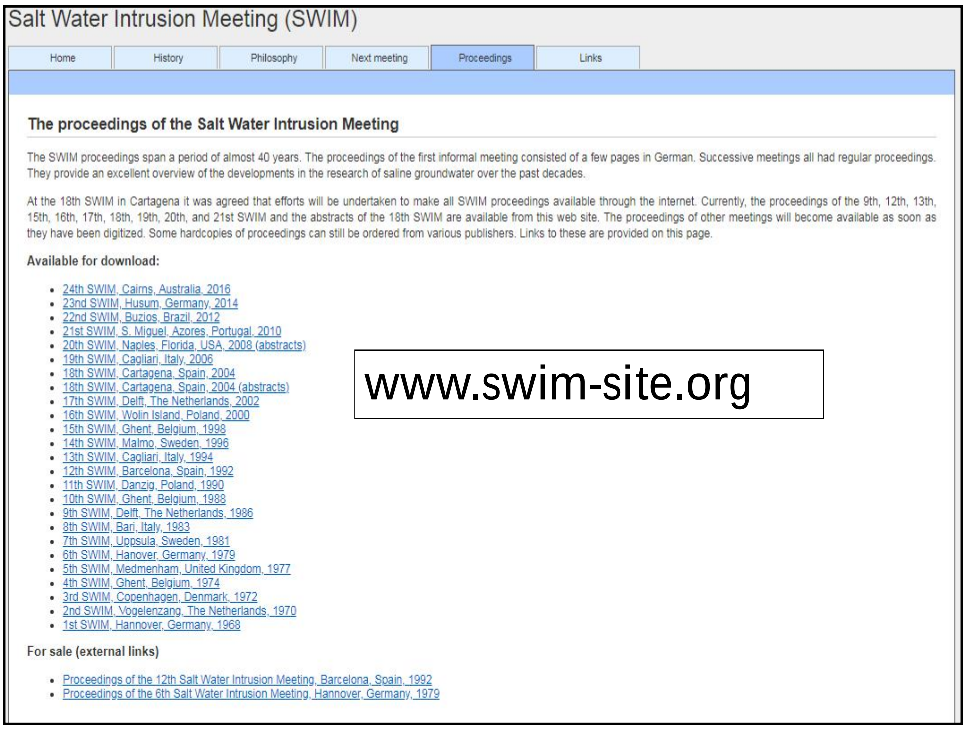
SWIM from Alphafilm & Kommunikation on Vimeo.

The long-lived success of the conference series reflects the relevance of managing saline groundwater problems around the world, especially in densely populated coastal areas. These include:

- increased demand due to economic development and population growth
- over-exploitation of water resources, especially in arid and semi-arid areas
- contamination and quality deterioration of water resources
- characterization of groundwater systems and movement of saline groundwater
- management and prevention of salinization
- natural and man-made environmental change

The main aims of this web site are to be the central and permanent source of information for people interested in the SWIM and to increase awareness and provide access of the excellent work that is presented at the SWIM meetings

www.swim-site.org



Salt Water Intrusion Meeting (SWIM)

The proceedings of the Salt Water Intrusion Meeting

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

At the 18th SWIM in Cartagena it was agreed that efforts will be undertaken to make all SWIM proceedings available through the internet. Currently, the proceedings of the 9th, 12th, 13th, 15th, 16th, 17th, 18th, 19th, 20th, and 21st SWIM and the abstracts of the 18th SWIM are available from this web site. The proceedings of other meetings will become available as soon as they have been digitized. Some hardcopies of proceedings can still be ordered from various publishers. Links to these are provided on this page.

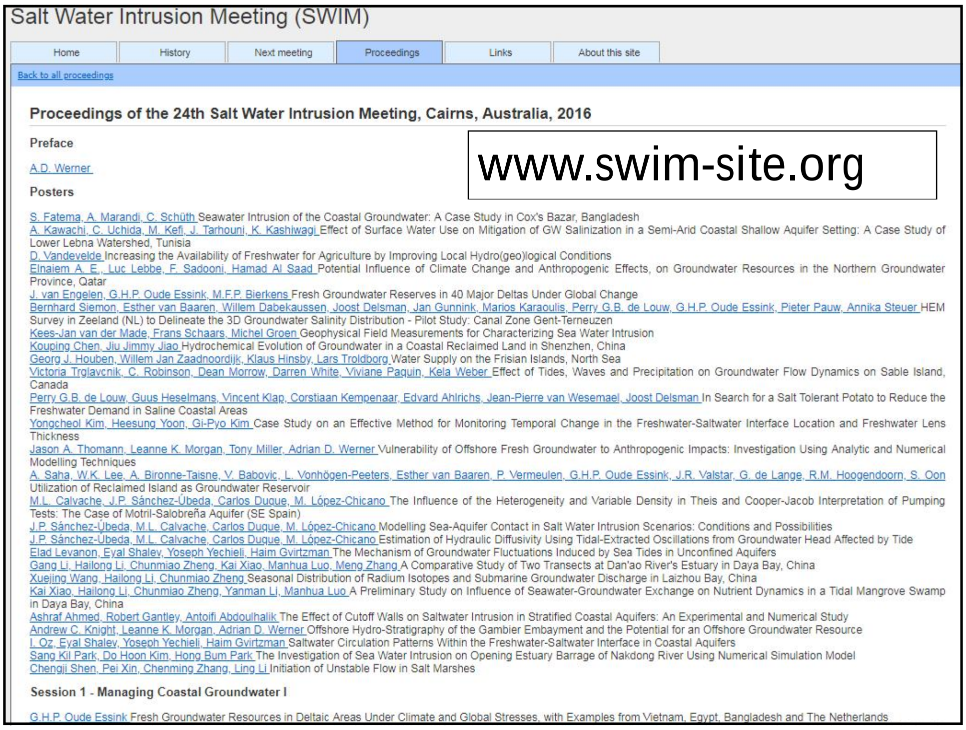
Available for download:

- 24th SWIM, Cairns, Australia, 2016
- 23nd SWIM, Husum, Germany, 2014
- 22nd SWIM, Buzios, Brazil, 2012
- 21st SWIM, S. Miguel, Azores, Portugal, 2010
- 20th SWIM, Naples, Florida, USA, 2008 (abstracts)
- 19th SWIM, Cagliari, Italy, 2006
- 18th SWIM, Cartagena, Spain, 2004
- 18th SWIM, Cartagena, Spain, 2004 (abstracts)
- 17th SWIM, Delft, The Netherlands, 2002
- 16th SWIM, Wolin Island, Poland, 2000
- 15th SWIM, Ghent, Belgium, 1998
- 14th SWIM, Malmo, Sweden, 1996
- 13th SWIM, Cagliari, Italy, 1994
- 12th SWIM, Barcelona, Spain, 1992
- 11th SWIM, Danzig, Poland, 1990
- 10th SWIM, Ghent, Belgium, 1988
- 9th SWIM, Delft, The Netherlands, 1986
- 8th SWIM, Bari, Italy, 1983
- 7th SWIM, Uppsula, Sweden, 1981
- 6th SWIM, Hanover, Germany, 1979
- 5th SWIM, Medmenham, United Kingdom, 1977
- 4th SWIM, Ghent, Belgium, 1974
- 3rd SWIM, Copenhagen, Denmark, 1972
- 2nd SWIM, Vogelenzang, The Netherlands, 1970
- 1st SWIM, Hannover, Germany, 1968

For sale (external links)

- Proceedings of the 12th Salt Water Intrusion Meeting, Barcelona, Spain, 1992
- Proceedings of the 6th Salt Water Intrusion Meeting, Hannover, Germany, 1979

www.swim-site.org



Proceedings of the 24th Salt Water Intrusion Meeting, Cairns, Australia, 2016

www.swim-site.org

Preface

A.D. Werner

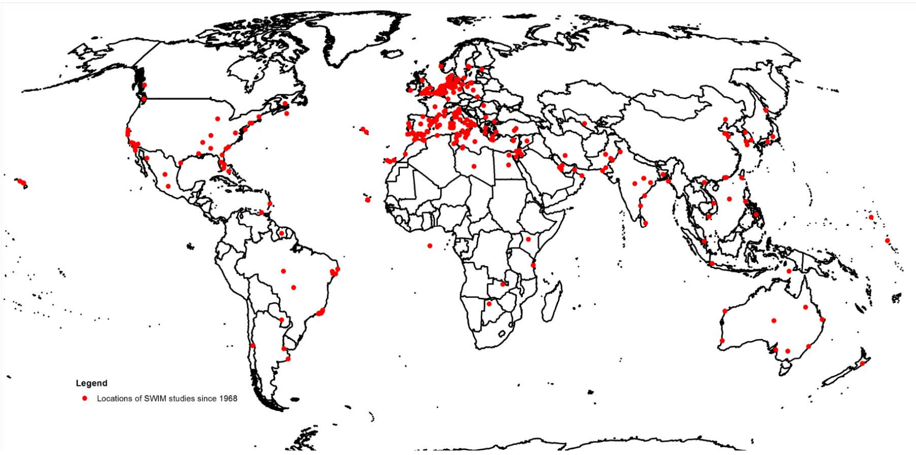
Posters

S. Fatema, A. Marandi, C. Schüth Seawater Intrusion of the Coastal Groundwater: A Case Study in Cox's Bazar, Bangladesh
A. Kawachi, C. Uchida, M. Kefi, J. Tarhouni, K. Kashiwagi Effect of Surface Water Use on Mitigation of GW Salinization in a Semi-Arid Coastal Shallow Aquifer Setting: A Case Study of Lower Lebna Watershed, Tunisia
D. Vandevelde Increasing the Availability of Freshwater for Agriculture by Improving Local Hydro(geo)logical Conditions
Elnaiem A. E., Luc Lebbe, F. Sadooni, Hamad Al Saad Potential Influence of Climate Change and Anthropogenic Effects, on Groundwater Resources in the Northern Groundwater Province, Qatar
J. van Engelen, G.H.P. Oude Essink, M.F.P. Bierkens Fresh Groundwater Reserves in 40 Major Deltas Under Global Change
Bernhard Siemon, Esther van Baaren, Willem Dabekaussen, Joost Delsman, Jan Gunnink, Marios Karaoulis, Perry G.B. de Louw, G.H.P. Oude Essink, Pieter Pauw, Annika Steuer HEM Survey in Zeeland (NL) to Delineate the 3D Groundwater Salinity Distribution - Pilot Study: Canal Zone Gent-Terneuzen
Kees-Jan van der Made, Frans Schaars, Michel Groen Geophysical Field Measurements for Characterizing Sea Water Intrusion
Kouping Chen, Jiu Jimmy Jiao Hydrochemical Evolution of Groundwater in a Coastal Reclaimed Land in Shenzhen, China
Georg J. Houben, Willem Jan Zaadnoordijk, Klaus Hinsby, Lars Troldborg Water Supply on the Frisian Islands, North Sea
Victoria Trglavcnik, C. Robinson, Dean Morrow, Darren White, Viviane Paquin, Kela Weber Effect of Tides, Waves and Precipitation on Groundwater Flow Dynamics on Sable Island, Canada
Perry G.B. de Louw, Guus Heselmans, Vincent Klap, Corstiaan Kempenaar, Edvard Ahlrichs, Jean-Pierre van Wesemael, Joost Delsman In Search for a Salt Tolerant Potato to Reduce the Freshwater Demand in Saline Coastal Areas
Yongcheol Kim, Heesung Yoon, Gi-Pyo Kim Case Study on an Effective Method for Monitoring Temporal Change in the Freshwater-Saltwater Interface Location and Freshwater Lens Thickness
Jason A. Thomann, Leanne K. Morgan, Tony Miller, Adrian D. Werner Vulnerability of Offshore Fresh Groundwater to Anthropogenic Impacts: Investigation Using Analytic and Numerical Modelling Techniques
A. Saha, W.K. Lee, A. Bironne-Taisne, V. Babovic, L. Vonhögen-Peeters, Esther van Baaren, P. Vermeulen, G.H.P. Oude Essink, J.R. Valstar, G. de Lange, R.M. Hoogendoorn, S. Oon Utilization of Reclaimed Island as Groundwater Reservoir
M.L. Calvache, J.P. Sánchez-Úbeda, Carlos Duque, M. López-Chicano The Influence of the Heterogeneity and Variable Density in Theis and Cooper-Jacob Interpretation of Pumping Tests: The Case of Motril-Salobreña Aquifer (SE Spain)
J.P. Sánchez-Úbeda, M.L. Calvache, Carlos Duque, M. López-Chicano Modelling Sea-Aquifer Contact in Salt Water Intrusion Scenarios: Conditions and Possibilities
J.P. Sánchez-Úbeda, M.L. Calvache, Carlos Duque, M. López-Chicano Estimation of Hydraulic Diffusivity Using Tidal-Extracted Oscillations from Groundwater Head Affected by Tide
Elad Levanon, Eyal Shalev, Yoseph Yechieli, Haim Gvirtzman The Mechanism of Groundwater Fluctuations Induced by Sea Tides in Unconfined Aquifers
Gang Li, Hailong Li, Chunmiao Zheng, Kai Xiao, Manhua Luo, Meng Zhang A Comparative Study of Two Transects at Dan'ao River's Estuary in Daya Bay, China
Xuejing Wang, Hailong Li, Chunmiao Zheng Seasonal Distribution of Radium Isotopes and Submarine Groundwater Discharge in Laizhou Bay, China
Kai Xiao, Hailong Li, Chunmiao Zheng, Yanman Li, Manhua Luo A Preliminary Study on Influence of Seawater-Groundwater Exchange on Nutrient Dynamics in a Tidal Mangrove Swamp in Daya Bay, China
Ashraf Ahmed, Robert Gantley, Antoifi Abdoulhalik The Effect of Cutoff Walls on Saltwater Intrusion in Stratified Coastal Aquifers: An Experimental and Numerical Study
Andrew C. Knight, Leanne K. Morgan, Adrian D. Werner Offshore Hydro-Stratigraphy of the Gambier Embayment and the Potential for an Offshore Groundwater Resource
I. Oz, Eyal Shalev, Yoseph Yechieli, Haim Gvirtzman Saltwater Circulation Patterns Within the Freshwater-Saltwater Interface in Coastal Aquifers
Sang Kil Park, Do Hoon Kim, Hong Bum Park The Investigation of Sea Water Intrusion on Opening Estuary Barrage of Nakdong River Using Numerical Simulation Model
Chengji Shen, Pei Xin, Chenming Zhang, Ling Li Initiation of Unstable Flow in Salt Marshes

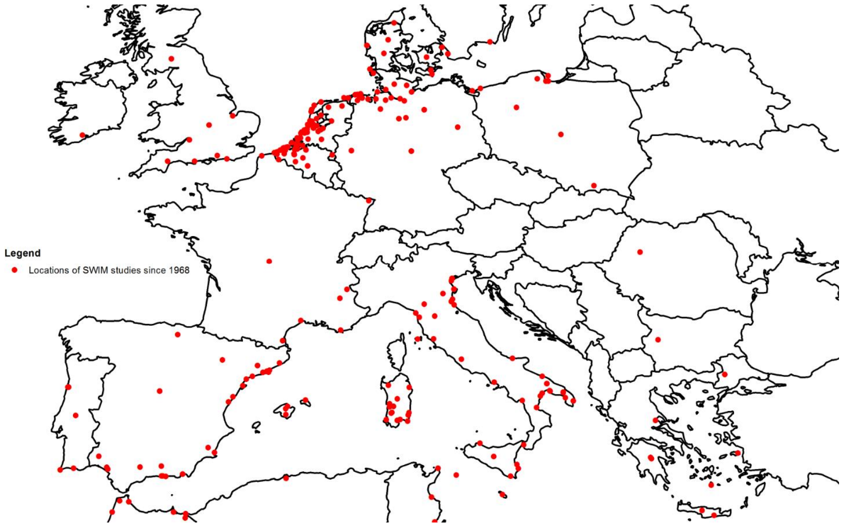
Session 1 - Managing Coastal Groundwater I

G.H.P. Oude Essink Fresh Groundwater Resources in Deltaic Areas Under Climate and Global Stresses, with Examples from Vietnam, Egypt, Bangladesh and The Netherlands

Location of SWIM studies since 1968



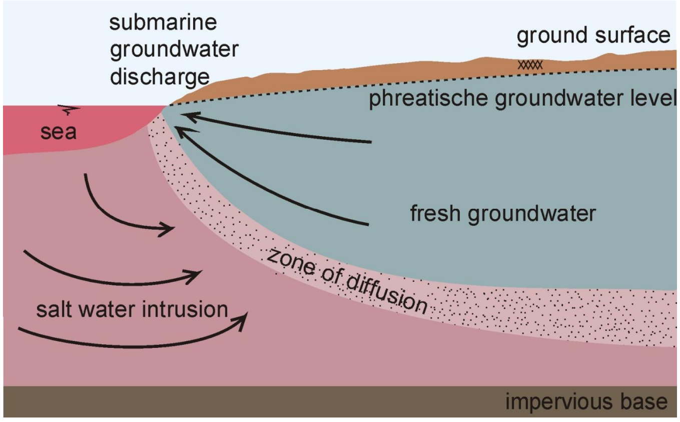
Location of SWIM studies since 1968



Introduction SWI

Definition of salt water intrusion

Inflow of saline water into an aquifer which contains fresh water



Origin of saline groundwater in the subsoil

Geological causes:

-marine deposits during geological times

-trans- and regressions in coastal areas (deltas)

-salt/brine dome

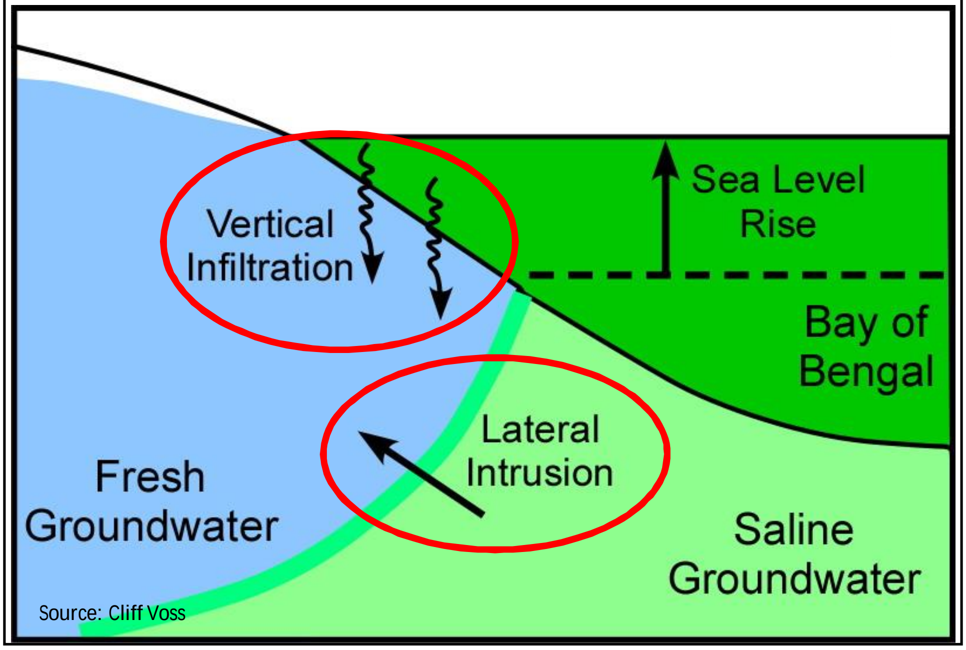
Anthropogenic causes:

-agriculture/irrigation (salt damage Middle East & Australia)

-upconing under extraction wells throughout the world

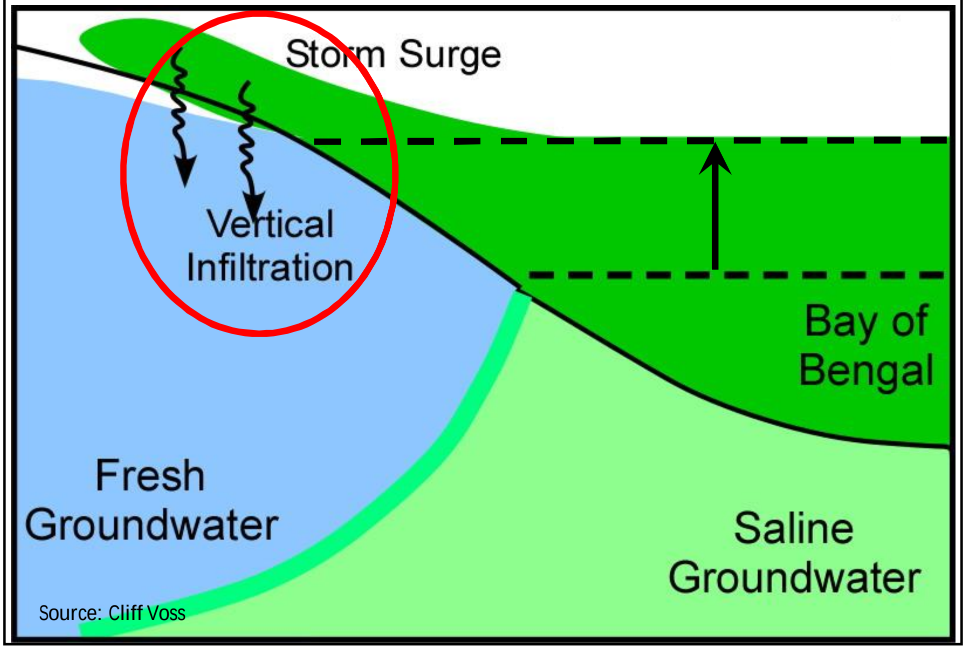
-upconing under low-lying areas (e.g. Dutch polders)

Modes of Salinization due to Sea-Level Rise



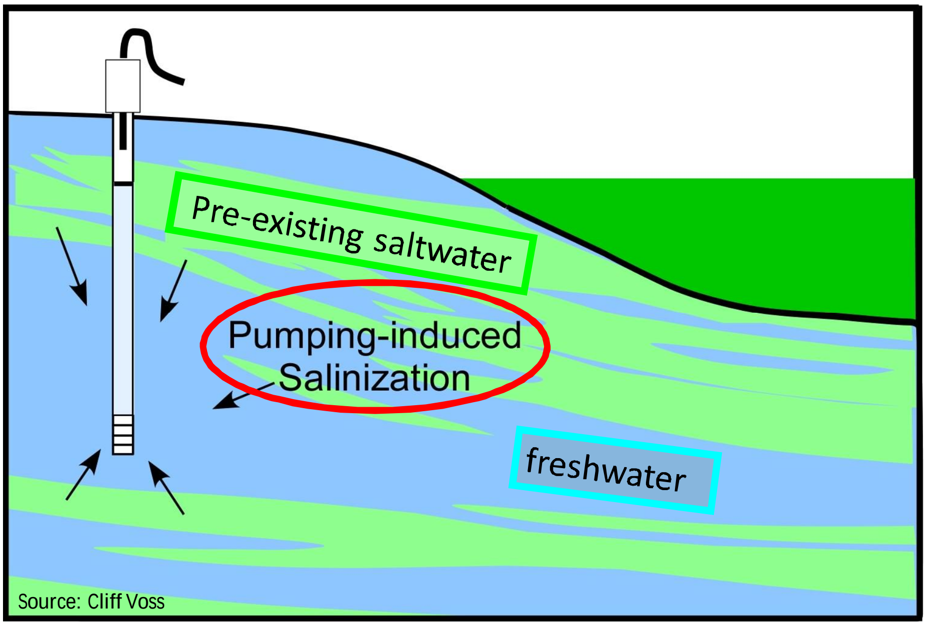
Source: Cliff Voss

Modes of Salinization due to Sea-Level Rise



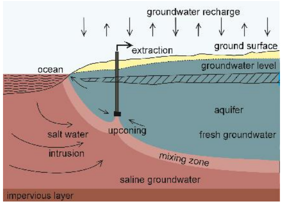
Source: Cliff Voss

Salinization due to Pumping

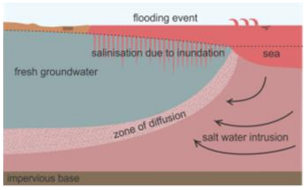


Source: Cliff Voss

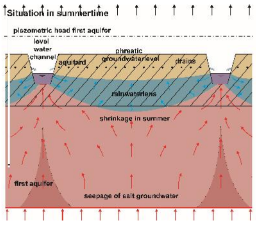
Salinisation processes at local scale



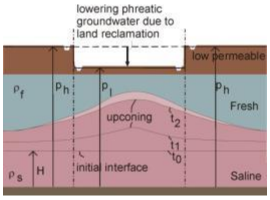
Salt water intrusion groundwater



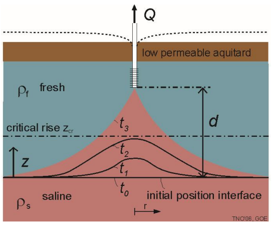
Inundation saline seawater



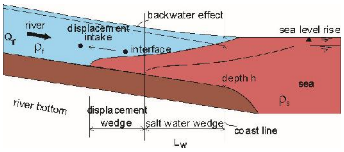
Shallow rainwaterlens



Upconing low-lying area

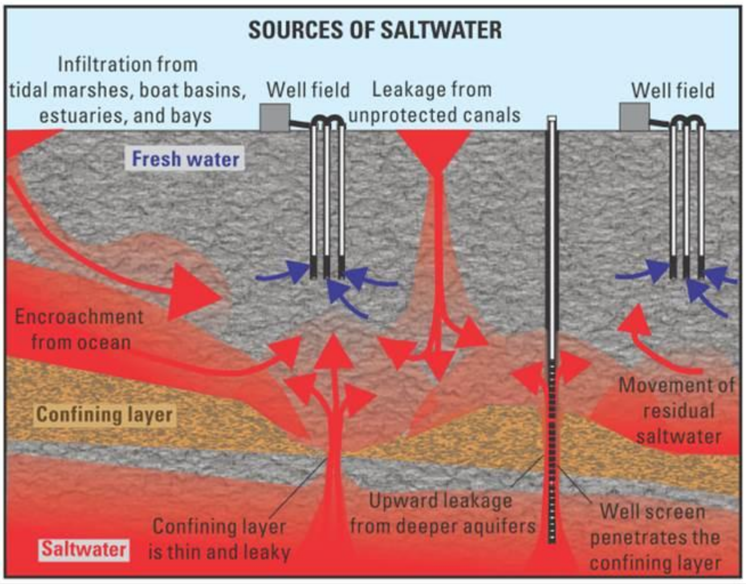


Upconing extraction



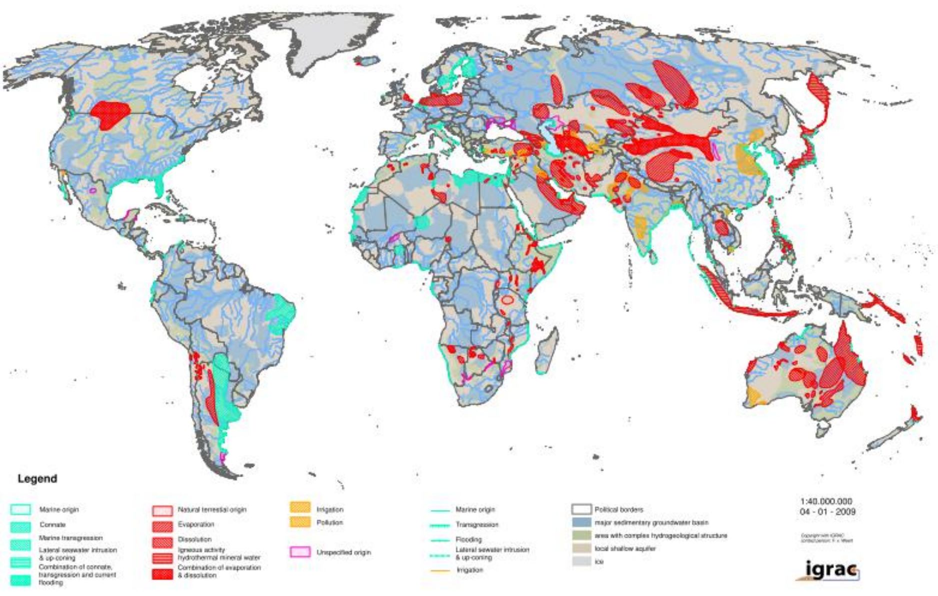
Salt water intrusion surface water

Salinization processes in the coastal zone: combination



GEUS

Regions with brackish and saline groundwater at shallow and intermediate depts



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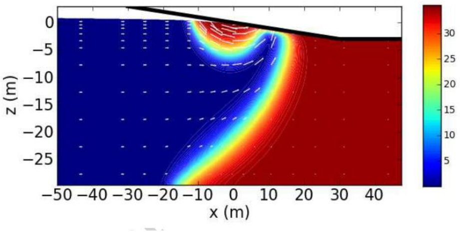
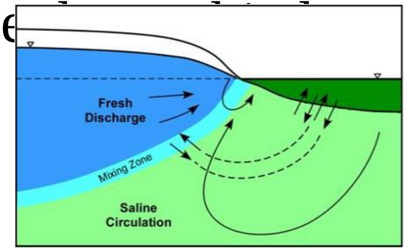
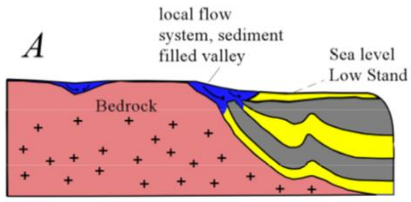
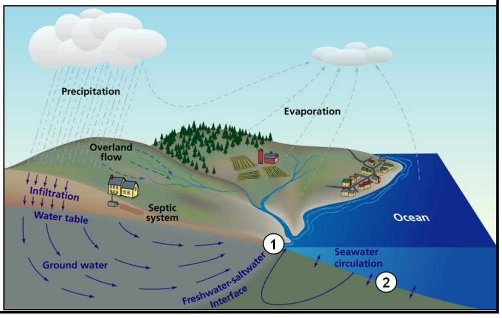
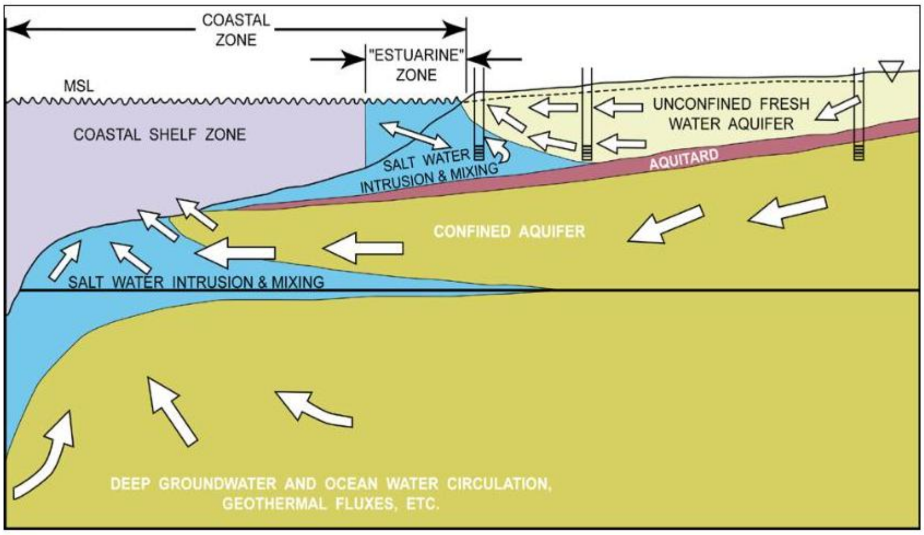




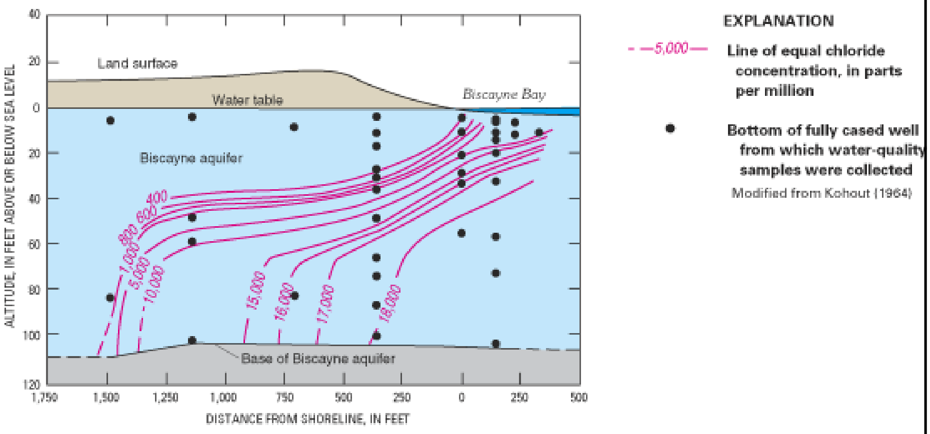


Source: Nature, 2013



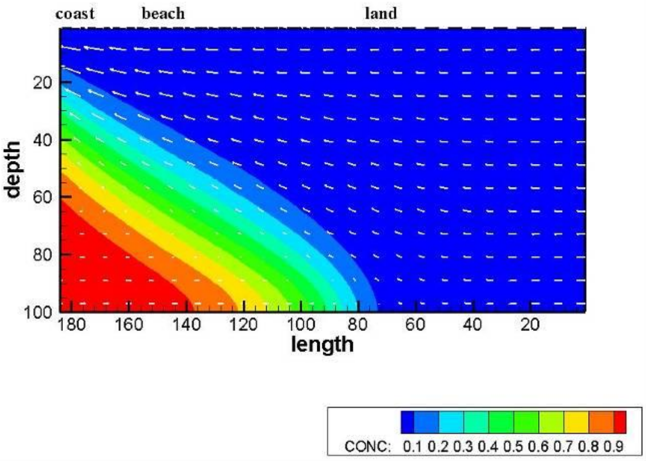


Biscayne aquifer, Florida USA: Henry’s case



Definition of salt water intrusion

Numerical model: Henry’s case



Definition of salt water intrusion

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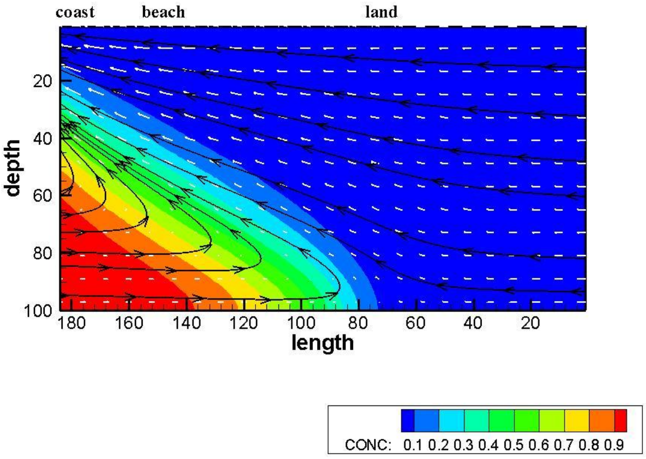
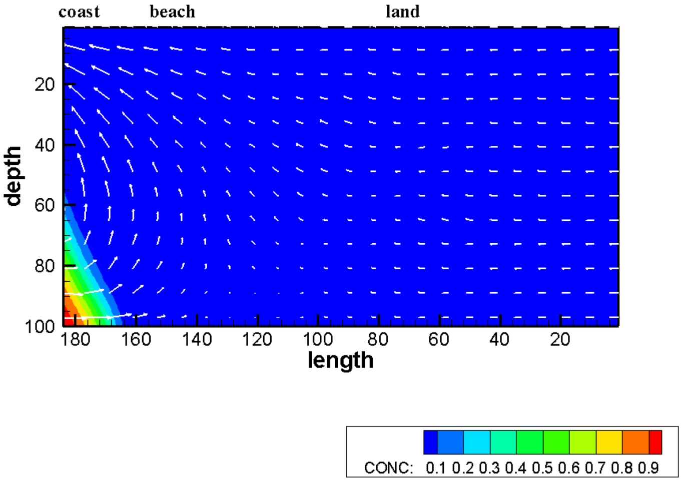
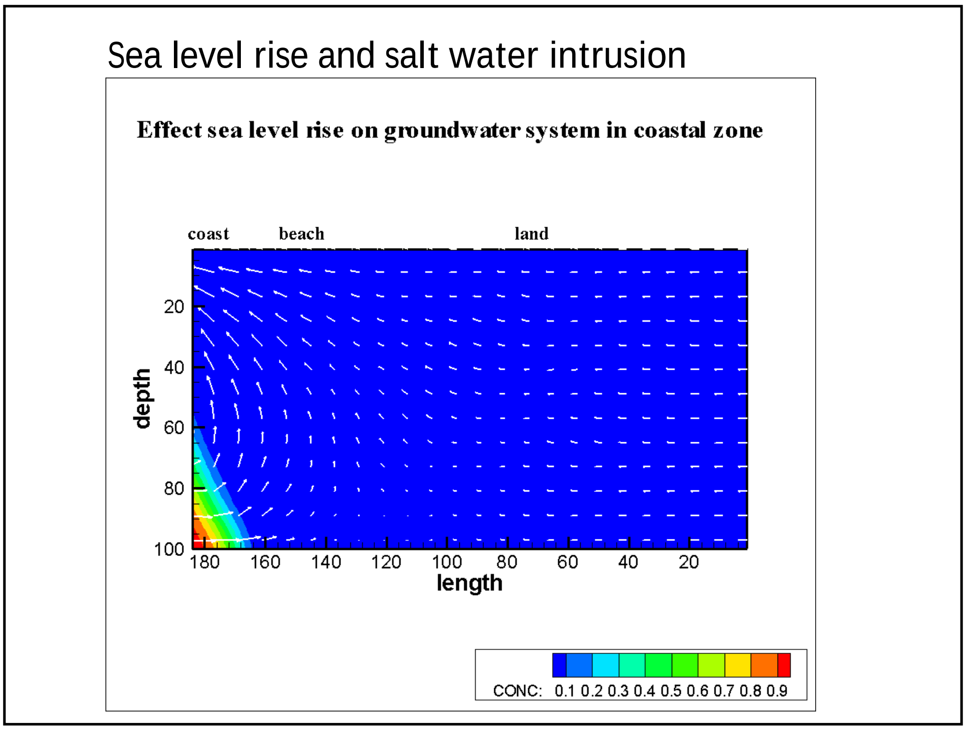


Sea level rise and salt water intrusion

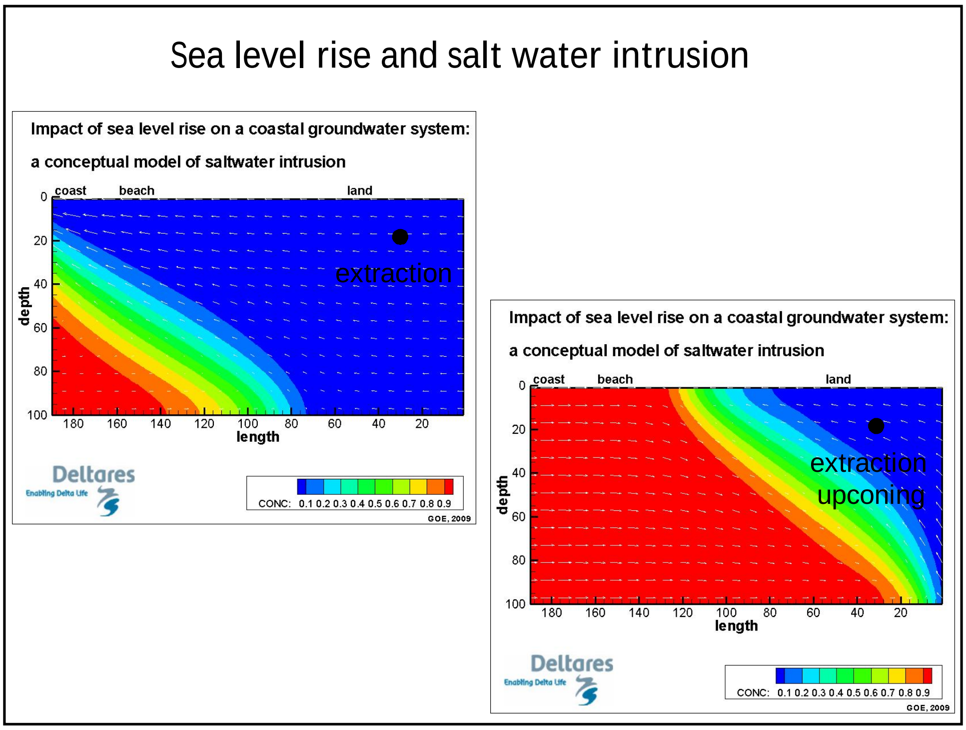
Effect sea level rise on groundwater system in coastal zone





Sea level rise and salt water intrusion

Effect sea level rise on groundwater system in coastal zone



Sea level rise and salt water intrusion

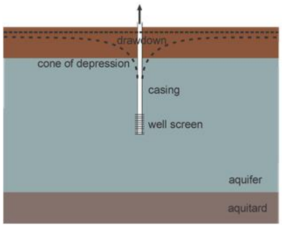
Impact of sea level rise on a coastal groundwater system:

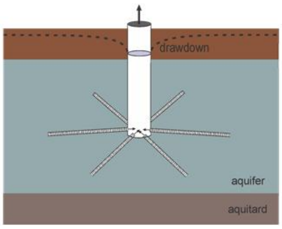
a conceptual model of saltwater intrusion

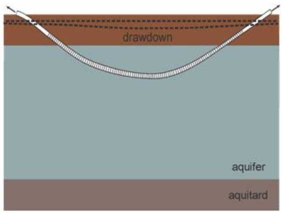
Impact of sea level rise on a coastal groundwater system:

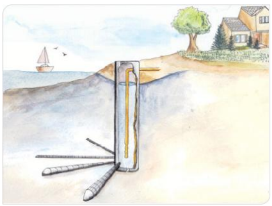
a conceptual model of saltwater intrusion

Types of extraction systems

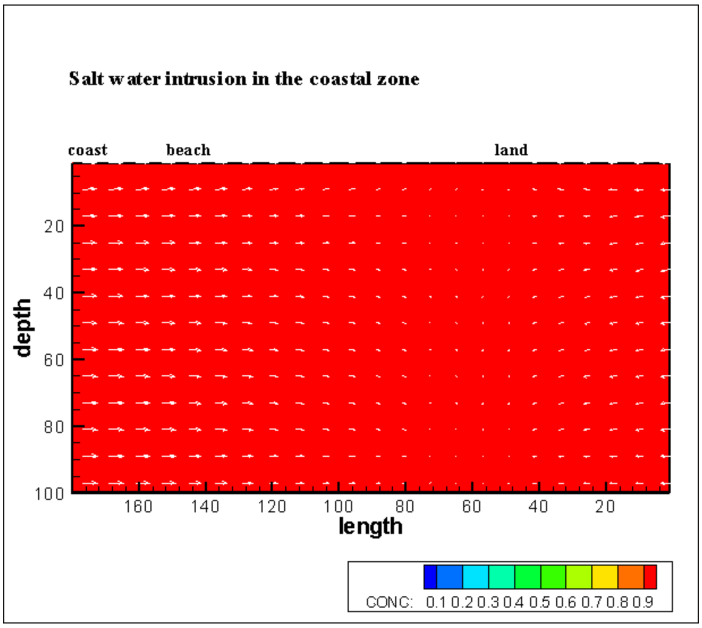








Salt water intrusion



Water on Earth

Some serious developments:

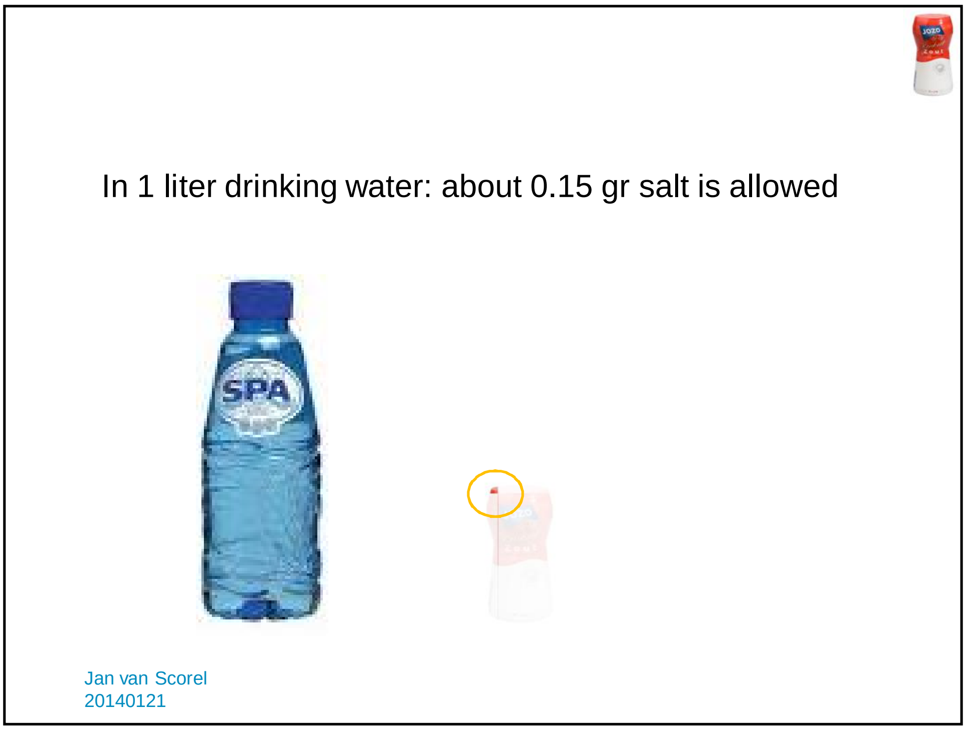
"*shortage of drinking water will be one of the biggest problems of the 21th century*"

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

In 1 liter ocean: about 35 gr salt

In 1 liter ocean: about 35 gr salt

In 1 liter Dead Sea water (Jordan/Israel) : about 280 gr salt

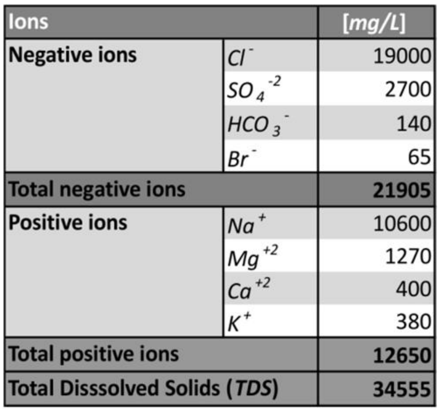


In 1 liter drinking water: about 0.15 gr salt is allowed

Jan van Scorel
20140121

Grass can grow well in water with a salt content equal to about 6.5 gr salt in 1 liter water

Fresh-brackish-saline groundwater



Ions		***[mg/L]***
Negative ions	Cl^-	19000
	SO_4^{-2}	2700
	HCO_3^-	140
	Br^-	65
Total negative ions		**21905**
Positive ions	Na^+	10600
	Mg^{+2}	1270
	Ca^{+2}	400
	K^+	380
Total positive ions		**12650**
Total Disssolved Solids (*TDS*)		**34555**

Definition fresh-brackish-saline groundwater

Main type of groundwater	Chloride concentration $[mg\ Cl^-/L]$
oligohaline	0 - 5
oligohaline-fresh	5 - 30
fresh	30 - 150
fresh-brackish	150 -300
brackish	300 - 1000
brackish-saline	1000 - 10.000
saline	10.000 - 20.000
hyperhaline or brine	≥20.000

Type	*[mS/cm]*	*[mg TDS/L]*	Drinking- or irrigation water
Non-saline or fresh water	<0.7	<500	Drinking and irrigation water
Slightly saline	0.7 - 2	500-1.500	Irrigation water
Moderately saline	2 - 10	1.500-7.000	Primary drainage water and groundwater
Highly saline	10 - 25	7.000-15.000	Secondary drainage water and groundwater
Very highly saline	25 - 45	15.000-35.000	Seawater is about 35000 *TDS mg/L*
Brine	>45	>35.000	n.a.

EOS

Examples of equations of state

Knudsen (1902)

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

T<15 ºC, S<20 ppt

Linear (concentration)

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

where a=relative density difference

Linear (temperature)

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

Exponential (temperature, pressure, salt)

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

Equation of state (SEAWAT)

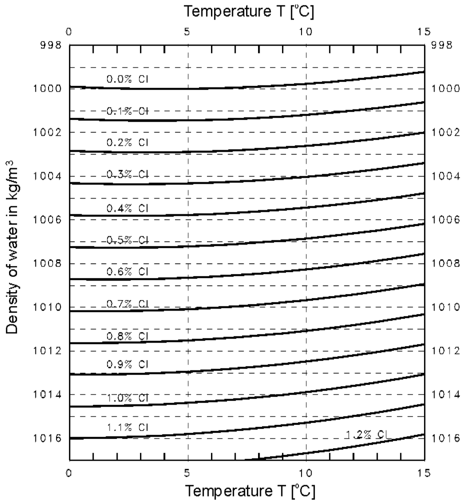
$$\rho_{i,j,k} = \rho_f + \frac{\partial \rho}{\partial C} C_{i,j,k}$$

e.g.:

1. conc=35 TDS g/l: DRHODC=0.7143
2. conc=19000 mg Cl-/l: DRHODC=0.001316
   (as 1025=1000+0.001316*19000)
3. conc=1: DRHODC=25 (example practicals)

EOS

Density depends on salinity and temperature

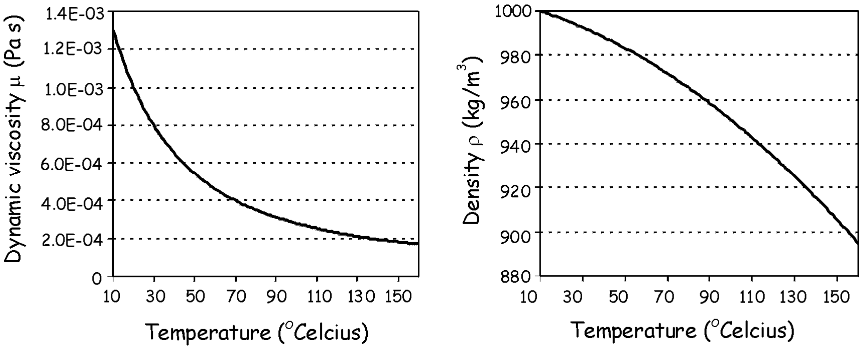


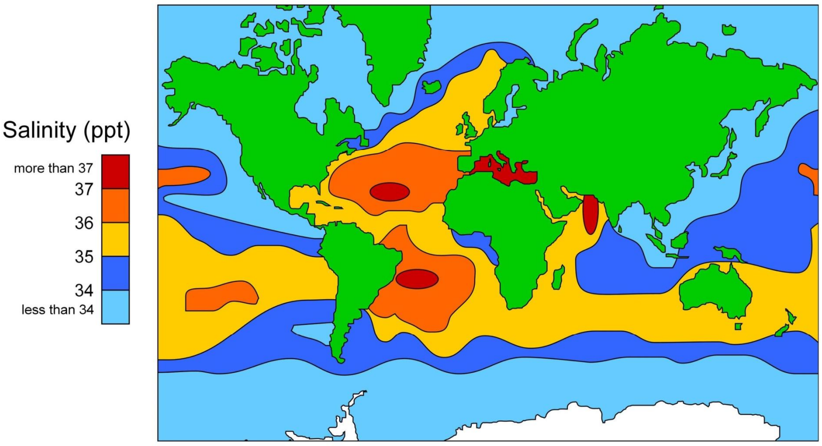
Accurate for T<15 °C and for Cl<1.1 %

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

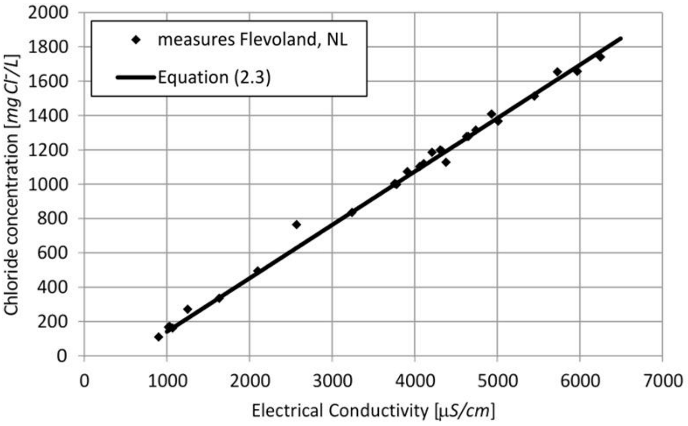
Density and viscosity depend on temperature

(10°C-160 °C)





Close relation between chloride concentration and Electrical Conductivity



$$Cl^{-}(mg\ /\ L) = EC_{w}(\mu S\ /\ cm)\cdot 0.305 - 137$$

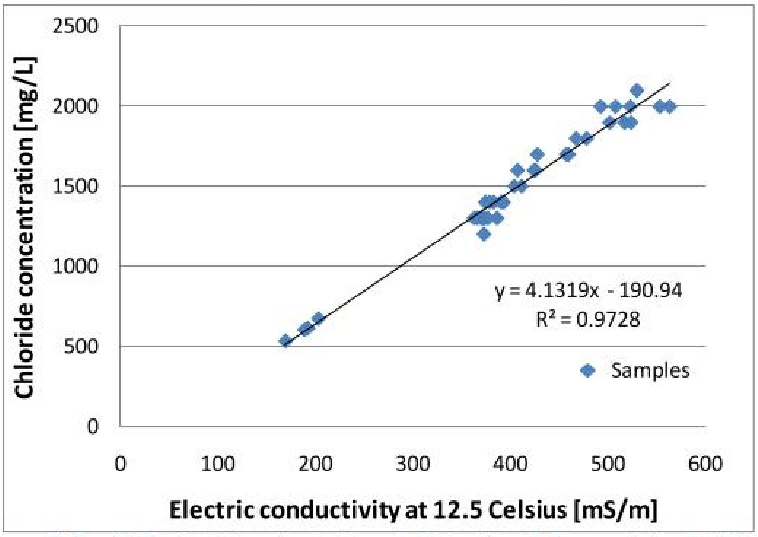
Close relation between chloride concentration and Electrical Conductivity

10^6 *µS/cm* = 10^3 *mS/cm* = 1 *S/cm*
1 *µS/cm* = 100 *µS/m*

ocean water:
~19000 *mg Cl-/L* or ~34555 *mg TDS/L*
~5 *S/m* or ~48 *mS/cm*

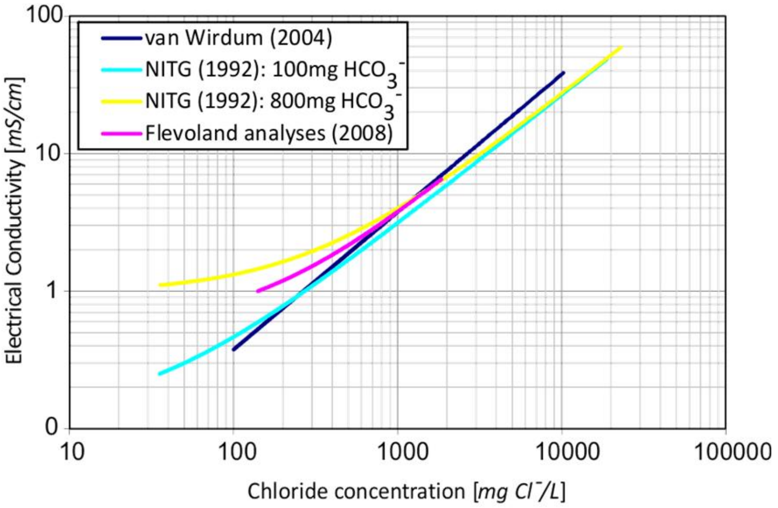
the ratio Cl^- over TDS equal to ~0.554, under stable normal seawater environments

A fresh-keeper for Noard Burgum
The new future for a salinated well field?



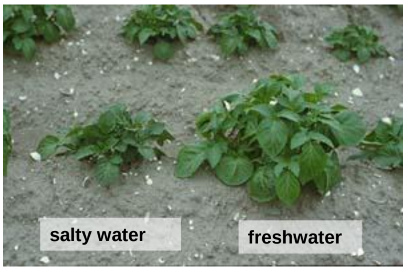
Appendix figure 11: Relation between the electric conductivity and the chloride concentration. For this relation samples from observation well B06D1114 and B06D1087 in between 23-sept-2009 and 9-okt-2010 were plotted.

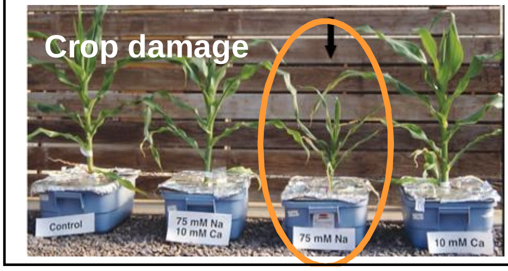
EC-Chloride



Salt in water is a problem

Drinking water





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

-drinking water:

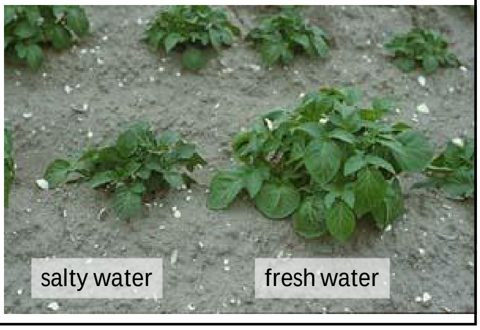
- taste (100-300 mg Cl^-/l)
- long term health effect
- norm: EC& WHO=150 mg Cl^-/l (live stock=1500 mg Cl^-/l)

-industry:

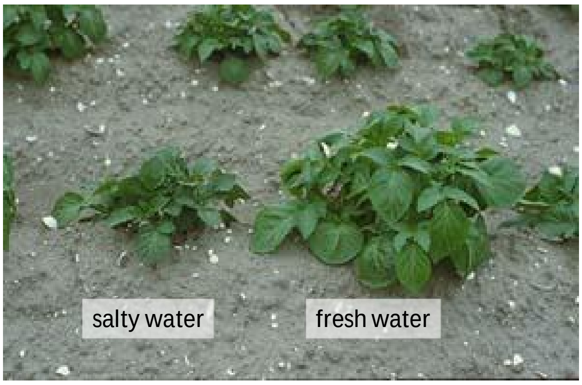
- corrosion pipes
- preparation food

-irrigation/agriculture:

- production crops
- salt damage



Effects salinisation: salt damage



Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

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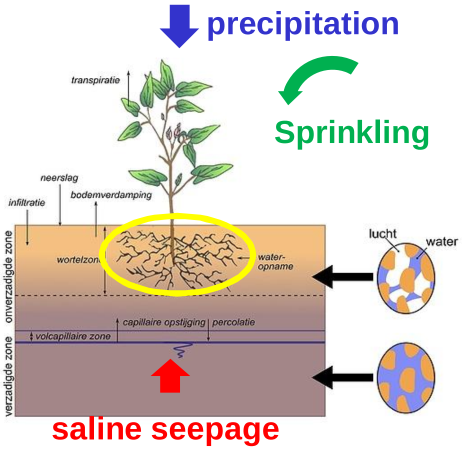
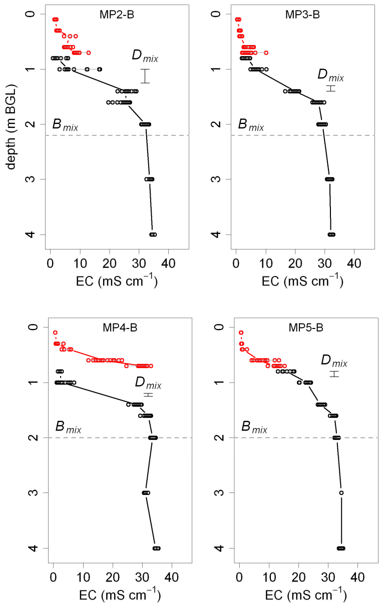
Salt-resistant crops





Important parameter:

Chloride concentration root zone
Land use
Sensitivity crops

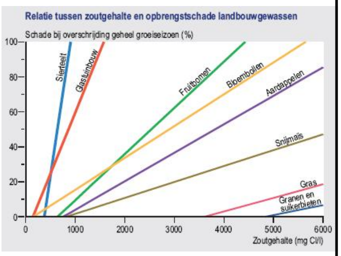
Salt damage to crops

Important parameters:

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

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

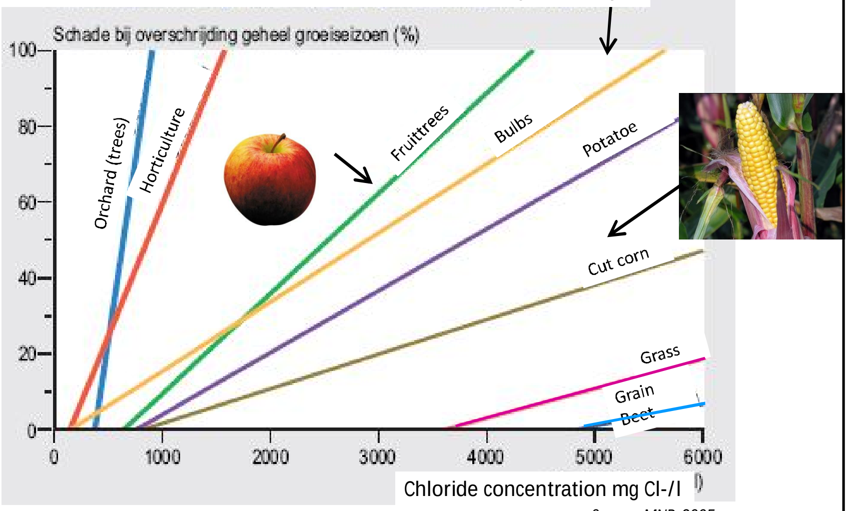
Source: Roest et al., 2003 en Haskoning



Source: MNP, 2005

Salt damage to crops

Relation between salt concentration and damage to crops

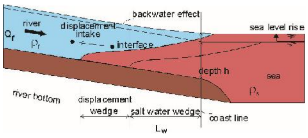


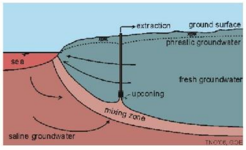
Source: MNP, 2005

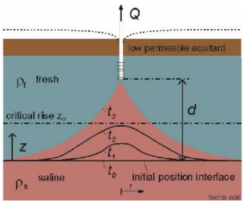
	Soil moisture		Irrigation water	
	Limi	Gradient	Limit	Gradient
Crop	mg/l Cl	%/mg/l Cl	mg/l Cl	%/mg/l Cl
Potatoe	756	0.0163	202	0.0610
Grass	3606	0.0078	962	0.0294
Sugar beat	4831	0.0057	1288	0.0212
Cut Corn	815	0.0091	217	0.0343
Grains	4831	0.0058	1288	0.0218
Fruit trees	642	0.0264	171	0.0991
Orchard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

Why is salinisation a pressing problem?

- 30% of world population lives <100 km from coastline
- economic and tourist activities increase
- enormous increase in extraction
- irreversible process
- increase saltwater intrusion problem world-wide:
    - upconing
    - salt water wedge
    - decrease outflow q_0
- climate change:
    - sea level rise
    - natural groundwater recharge







Processes that accelerate salt water intrusion:

- Sea level rise
- Land subsidence
- Human activities

Threats for:

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

2500 litres of water for 1 cotton shirt

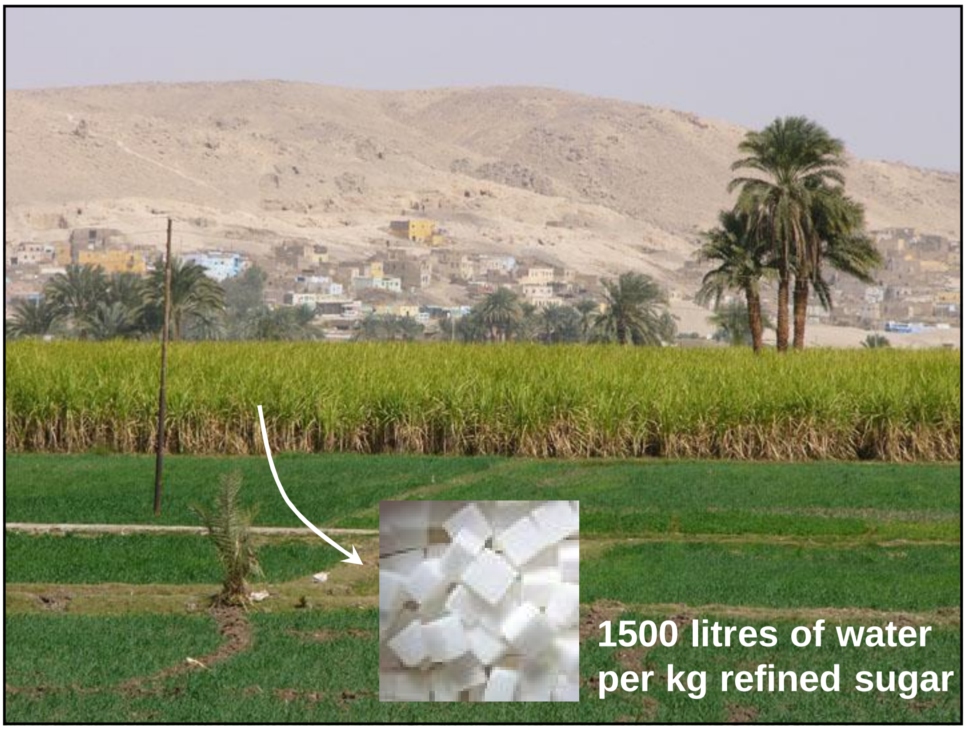
The water footprint of products

global averages

1 kg wheat	1 m^3 water
1 kg rice	3 m^3 water
1 kg milk	1 m^3 water
1 kg cheese	5 m^3 water
1 kg pork	5 m^3 water
1 kg beef	15 m^3 water

[Hoekstra & Chapagain, 2008]

40 litres of water
for 1 slice of bread



1500 litres of water
per kg refined sugar

2400 litres of water
for 1 hamburger

= 140 litres of water

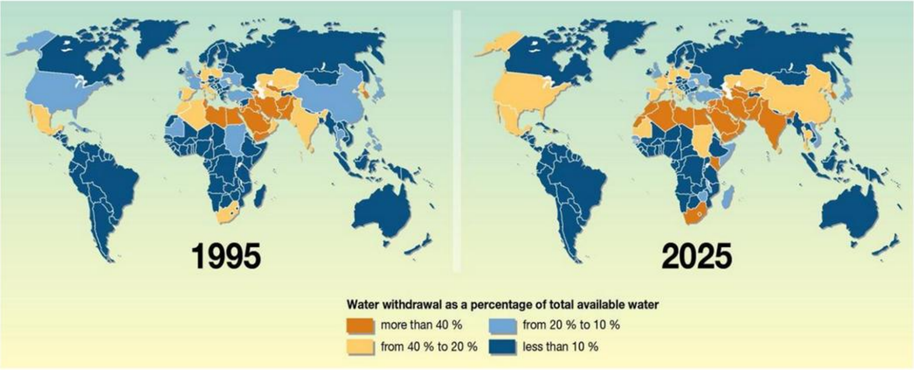
10 litres of water
for 1 sheet of A4-paper

Question:

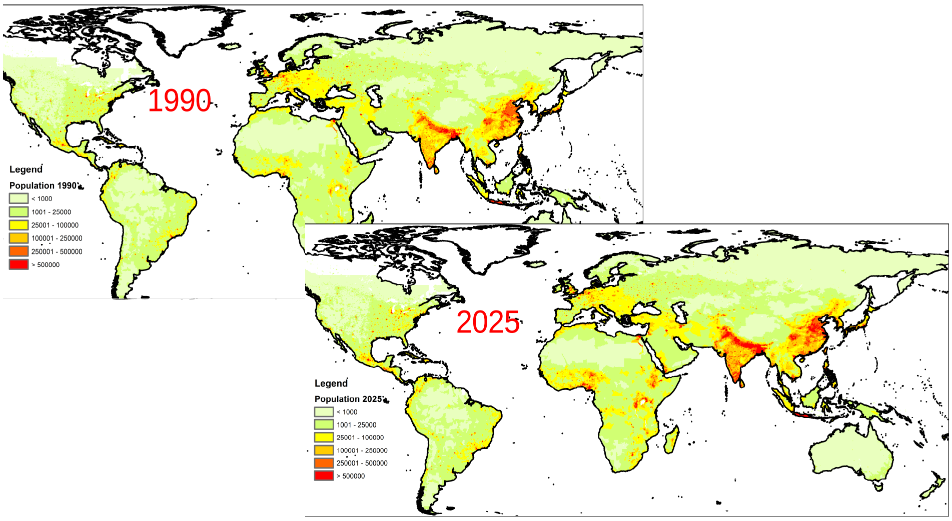
Demand fresh water per capita per day?:

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

Water withdrawal as % of total available water



Population growth 1990-2025



*Global 15 x 15 Minute Grids of the Downscaled Population Based on the SRES B2 Scenario, 1990 and 2025 (~28*28km2 at equator)*

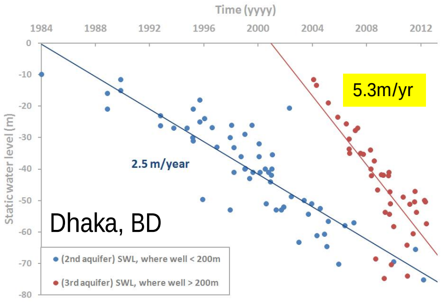
Introduction

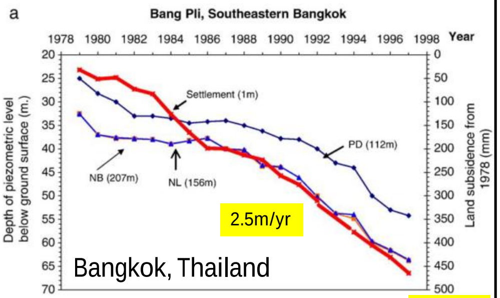
Reasons and drawbacks of using groundwater

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

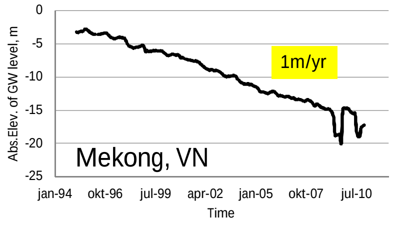
Disadvantage:
-high extraction costs
-local droughts
-high mineral content
-land subsidence….
-salt water intrusion !

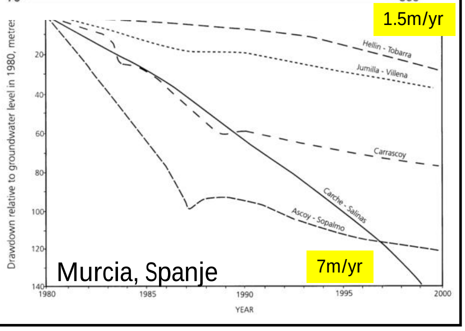
Serious overexploitation coastal aquifers worldwide





Elev. of GW level in aquifer n_2^1





What causes the land to subside?

Natural causes (geological processes):

- *Loading* of the earth's crust by ice sheets, sediment (delta's), the ocean/sea
- *Compaction* of older sediments after sedimentation

Anthropogenic causes (human-induced processes):

- Oil/gas *extraction* (usually relatively deep)
- Groundwater *extraction* (usually moderately deep)
- *Drainage* of soils ⇒ oxidation of peat, soil compaction

Why discriminating between human-induced and natural processes?

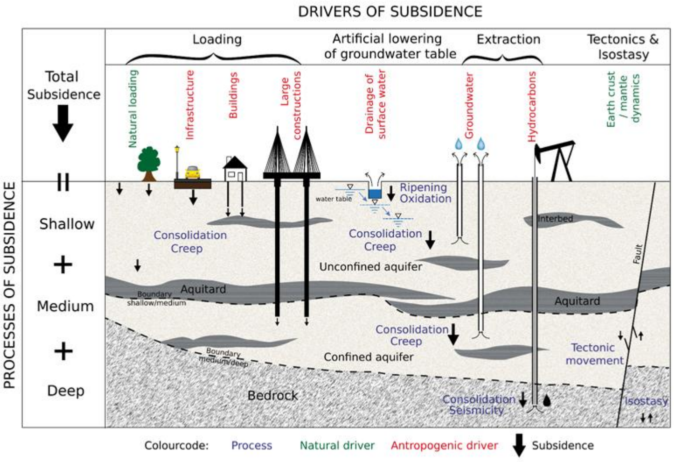
- Magnitude
- Cooping strategy (mitigation versus adaptation)

Possible causes of land subsidence in the Mekong

Land subsidence is natural process in deltas.

Land subsidence can be accelerated by human activities that increase physical loading or change the hydrogeological situation

Total subsidence is the cumulative effect of all processes.



Minderhoud et al. 2015

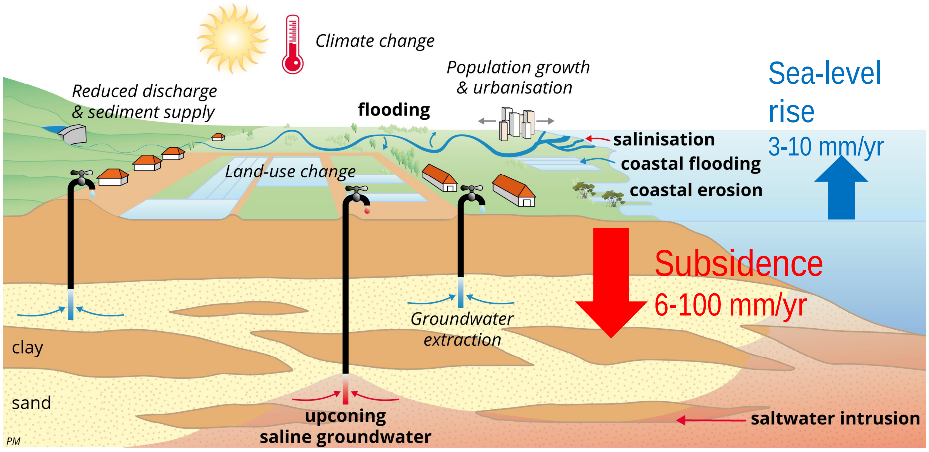
Impacts

Evidence of subsidence in the Mekong delta

Shallow subsidence, visible around founded bridges and buildings

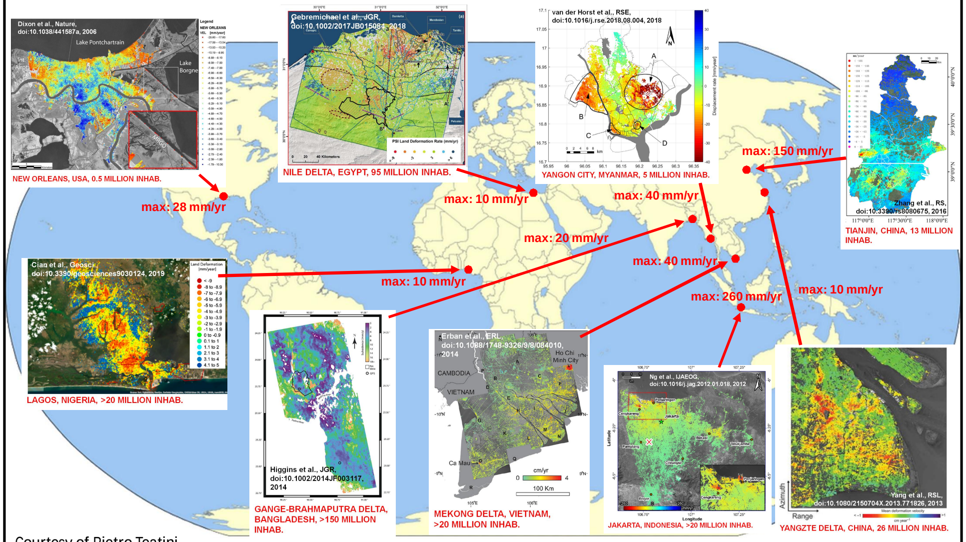
Deeper subsidence, visible by protruding pumping wells

Challenges deltaic areas



Minderhoud, 2019

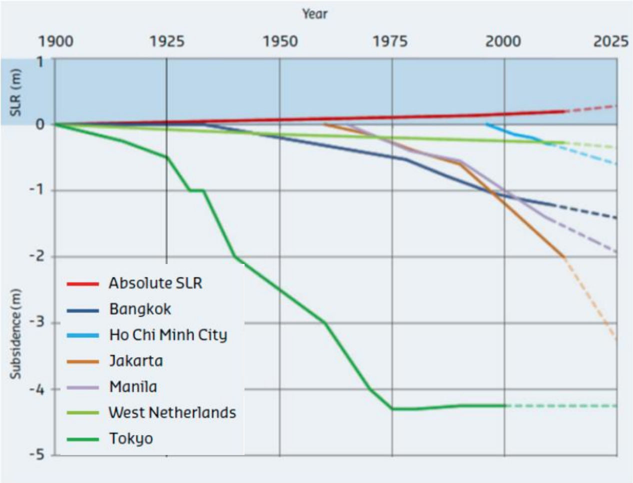
Land subsidence in deltas is a global problem



Courtesy of Pietro Teatini

Examples of some major coastal cities

The subsidence issue is underestimated



Relative
Sea-level
Rise
Tokyo
4,5 m!

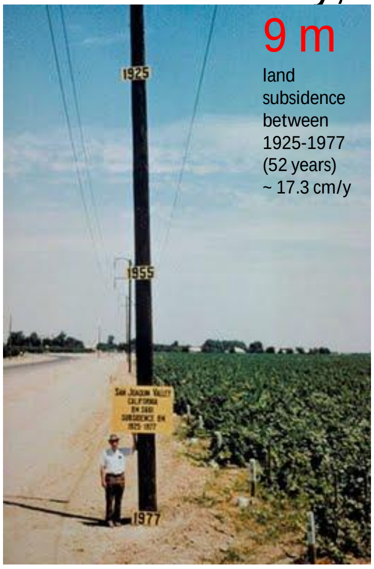
Megacity	Max. subsidence [m]	Date commenced
Shanghai	2.80	1921
Osaka	2.80	1935
Tianjin	2.60	1959
Jakarta	0.90	1978
Los Angeles	9.00	1930's

Four case studies

What lessons can we learn:

1. California, USA
2. Bangkok, Thailand: implementing policies to reduce extraction
   - Groundwater act (1977)
   - Mitigation of Groundwater Crisis and Land subsidence (1983)
   - Groundwater Tariff and Conservation Fee (1985)
3. Jakarta, Indonesia: until today no mitigation measures on groundwater extraction
4. Mekong Delta, Vietnam

Case 1: Land subsidence San Joachim Valley, CA, USA

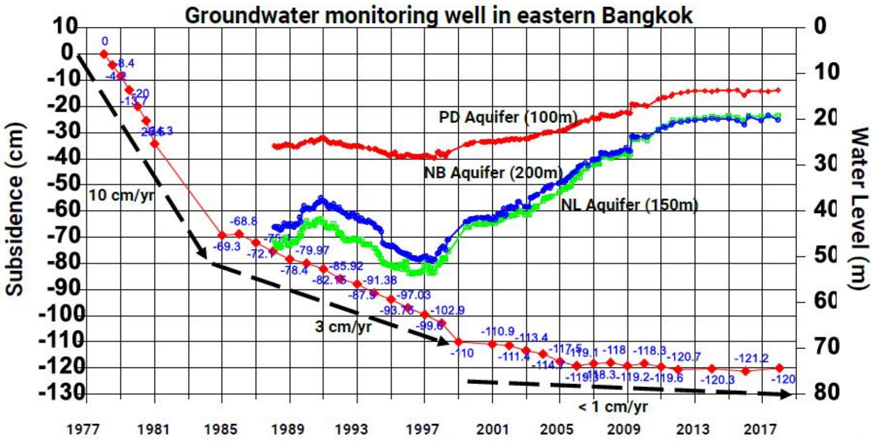


9 m

land subsidence between 1925-1977 (52 years) ~ 17.3 cm/y

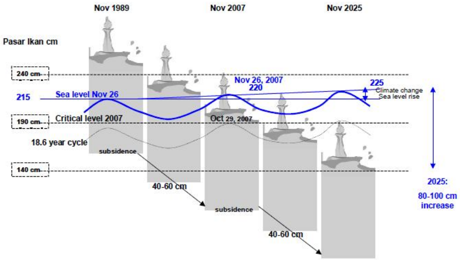
9 m since 1930s

Case 2: Bangkok



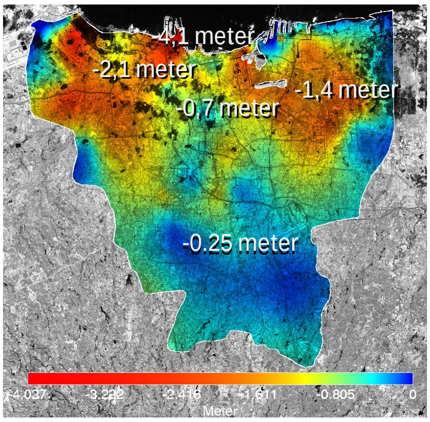
Courtesy: Chadaporn Busarakum

Case 3: Jakarta



Brinkman and Hartman, 2009

Cumulative subsidence map of Jakarta 1974-2010



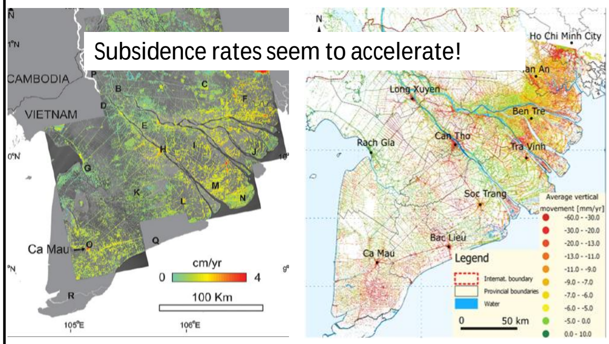
Subsidence rates: up to 25 cm/year

Case 4: Groundwater overexploitation in Mekong Delta

Aquaculture (shrimp farms) need an enormous quantity of fresh groundwater

The Mekong delta is sinking

Estimated InSAR-derived subsidence rates (cm/yr)

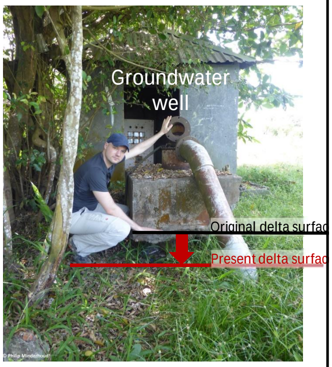


<u>2006-2010:</u>
Up to 4 cm/yr

<u>2014-2019:</u>
Up to 6 cm/yr

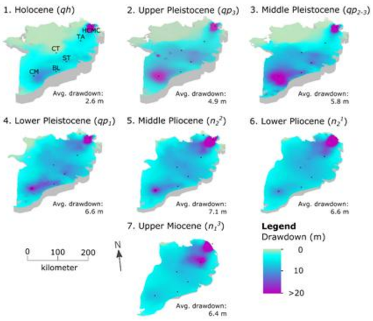
Erban et al., 2014. Environ. Res. Lett.

EU Copernicus EMSN062

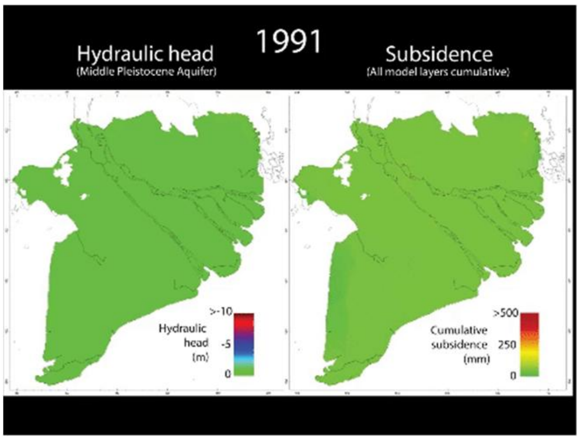


Evidence on the ground

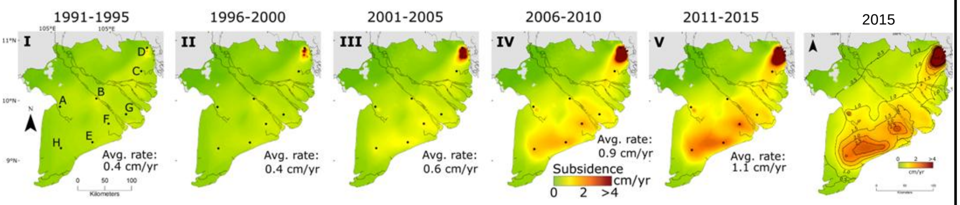
25 years of simulated groundwater extraction



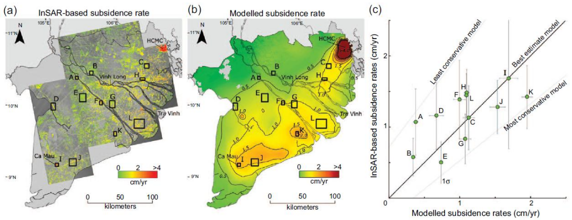
Groundwater extraction is much larger than groundwater recharge, and replenishment is very limited



Extraction-induced subsidence is accelerating!



Groundwater extraction-driven subsidence exceeds absolute sea-level rise by a magnitude!



Most/least conservative model: 60%/160% of the best estimate model rates

Sources of uncertainties in modeling results:

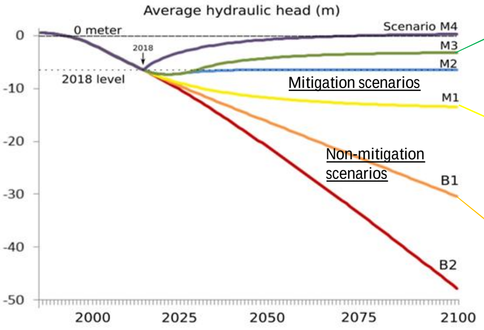
- Hydrogeology and geotechnical parameters
- Extraction data
- Geological schematization
- Layer discretization

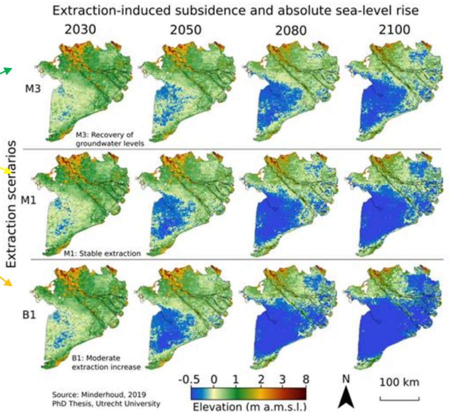
Minderhoud et al., 2017
Environmental Research Letters

The future of the Mekong delta?

The decisions of today, will determine tomorrow

Scenarios of future groundwater extraction pathways

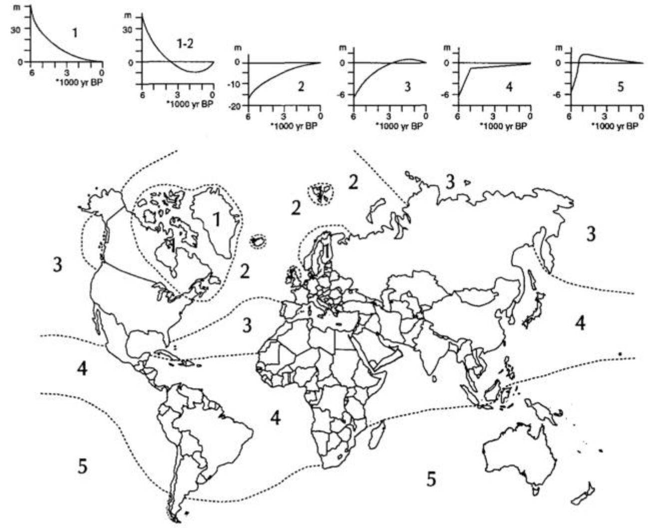




N.B. New InSAR measurements point to a potential underestimation of subsidence by the model

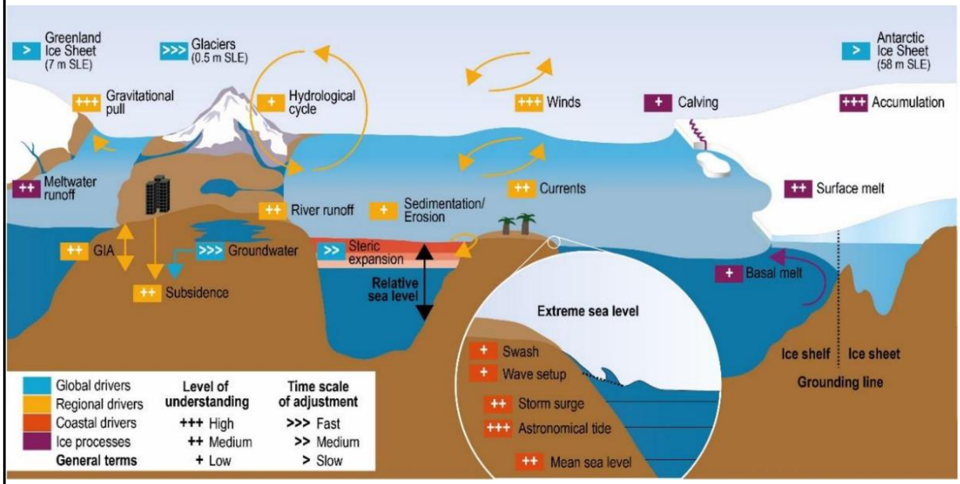
Minderhoud et al., in review

Regional distribution of Holocene Sea-level Changes

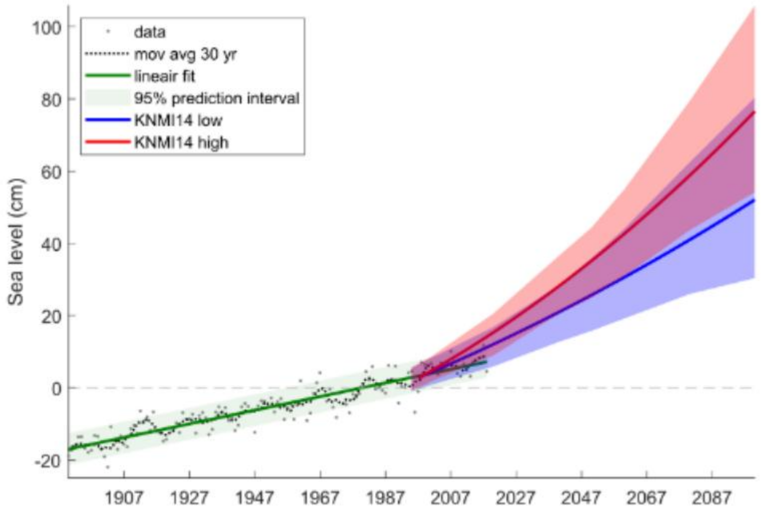


Source: Pirazzoli, P.A. & Pluet, J., 1991. World Atlas of Holocene Sea-level Changes. Elsevier Oceanography Series, Vol. 58

Illustration of climate and non-climate driven processes that influence sea level along coasts

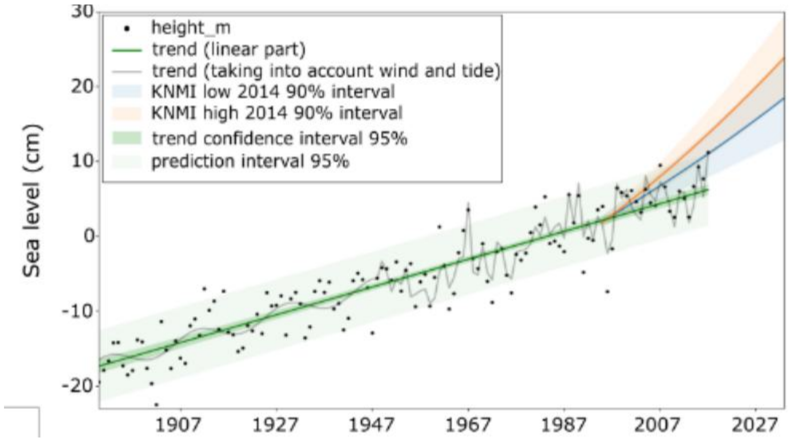


KNMI sea level projections and historic observations in the Zeespiegelmonitor

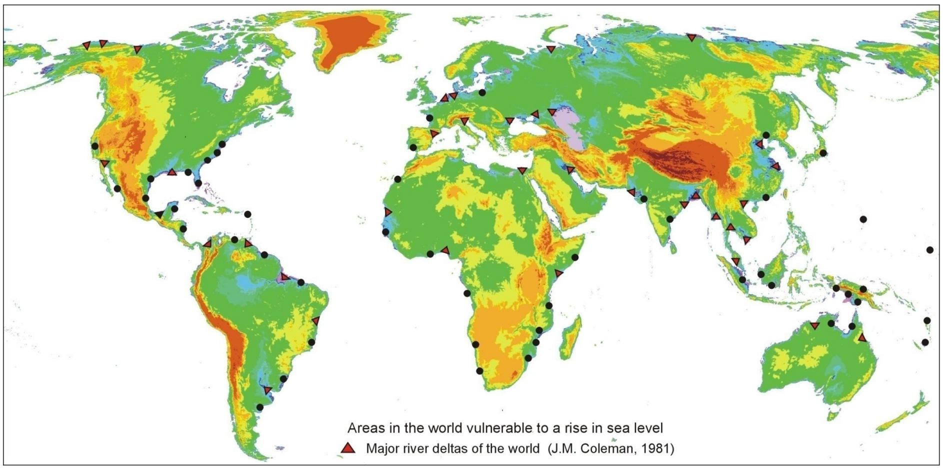


Hurk, B. van den, Geertsema, T., n.d. An assessment of present day and future sea level rise at the Dutch coast.

KNMI sea level projections and historic observations in the Zeespiegelmonitor



Areas vulnerable to sea level rise



Areas in the world vulnerable to a rise in sea level

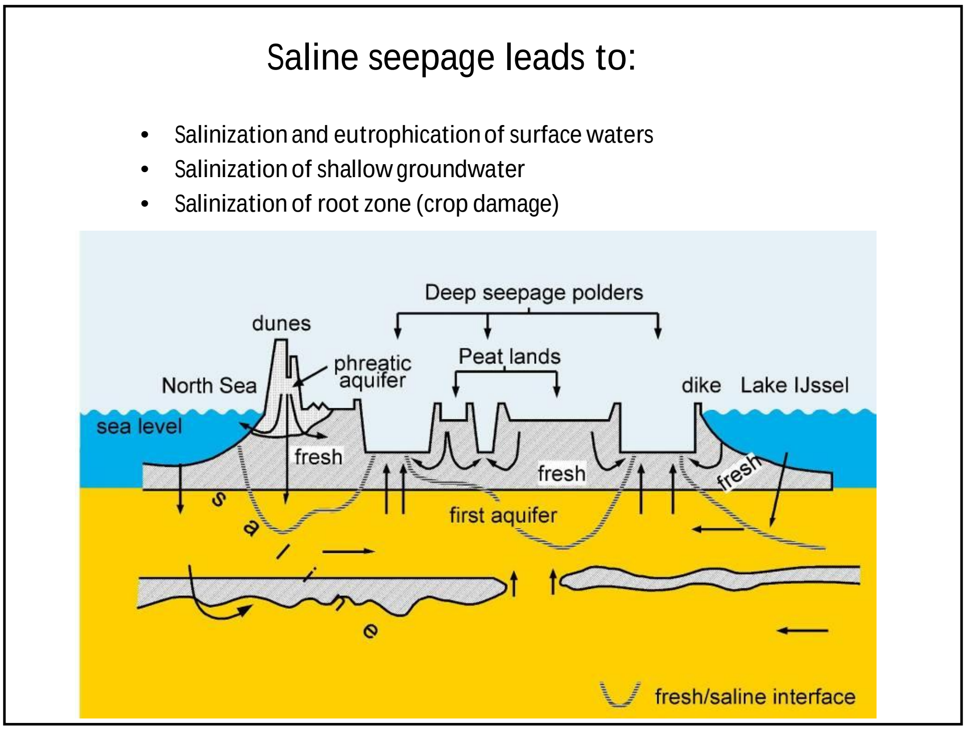
▲ Major river deltas of the world (J.M. Coleman, 1981)

The Netherlands: low-lying lands

Sea level rise: +2 m

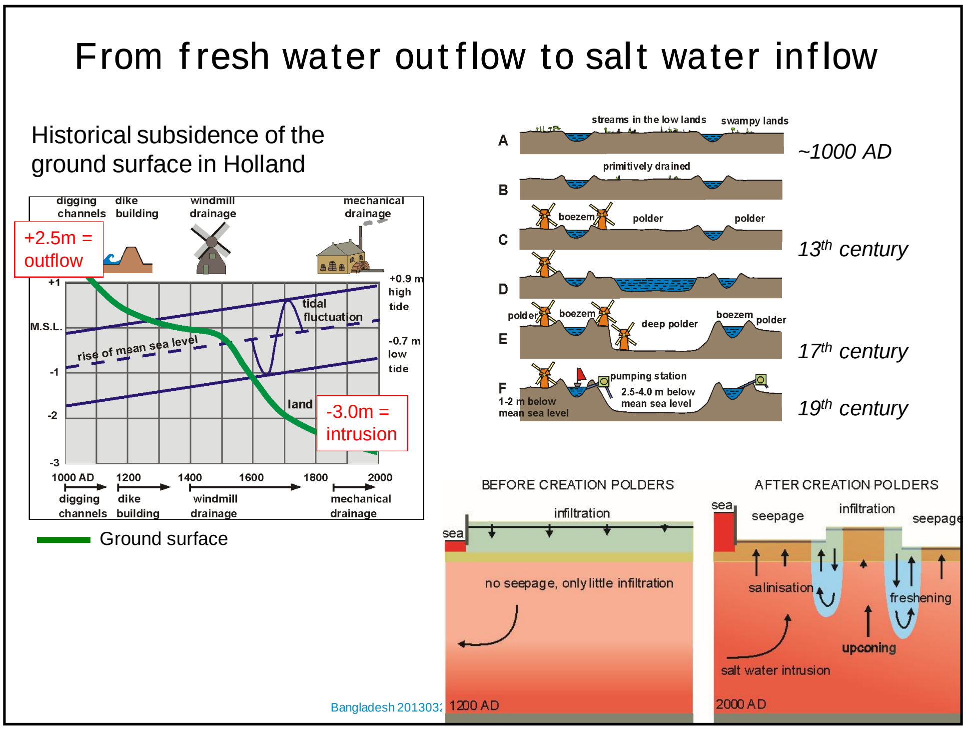
http://flood.firetree.net

~50km



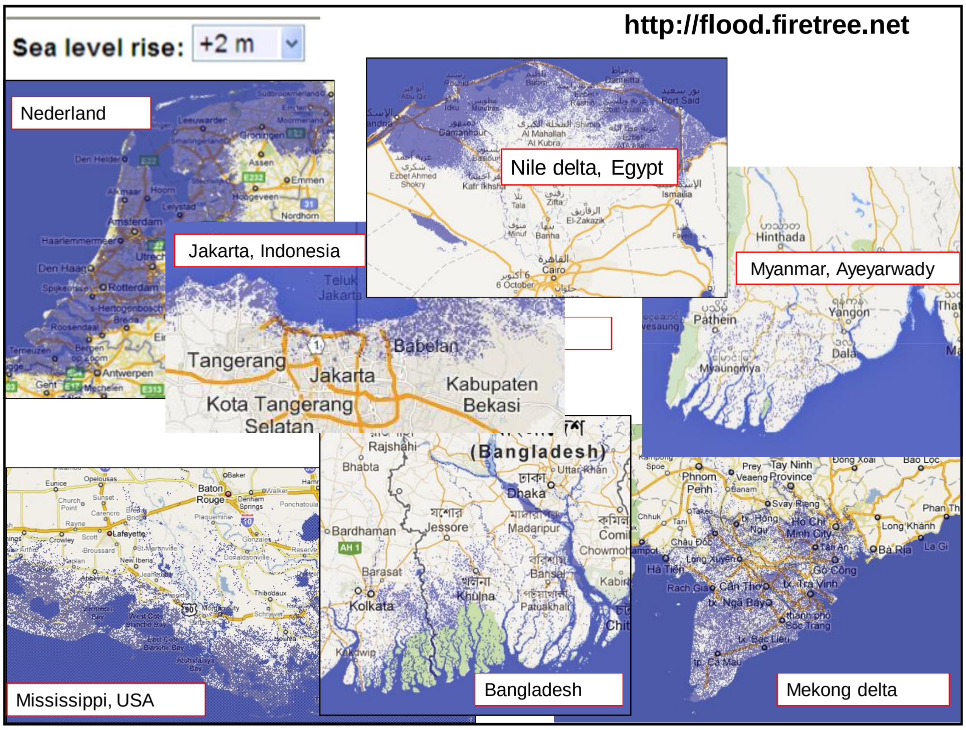
Saline seepage leads to:

- Salinization and eutrophication of surface waters
- Salinization of shallow groundwater
- Salinization of root zone (crop damage)

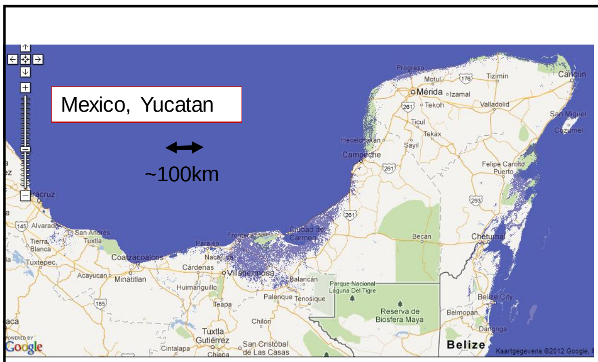


From fresh water outflow to salt water inflow

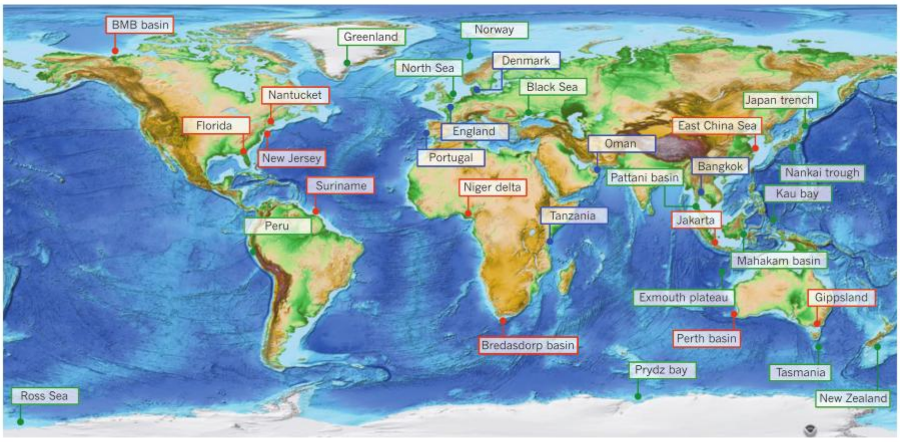
Historical subsidence of the ground surface in Holland



http://flood.firetree.net

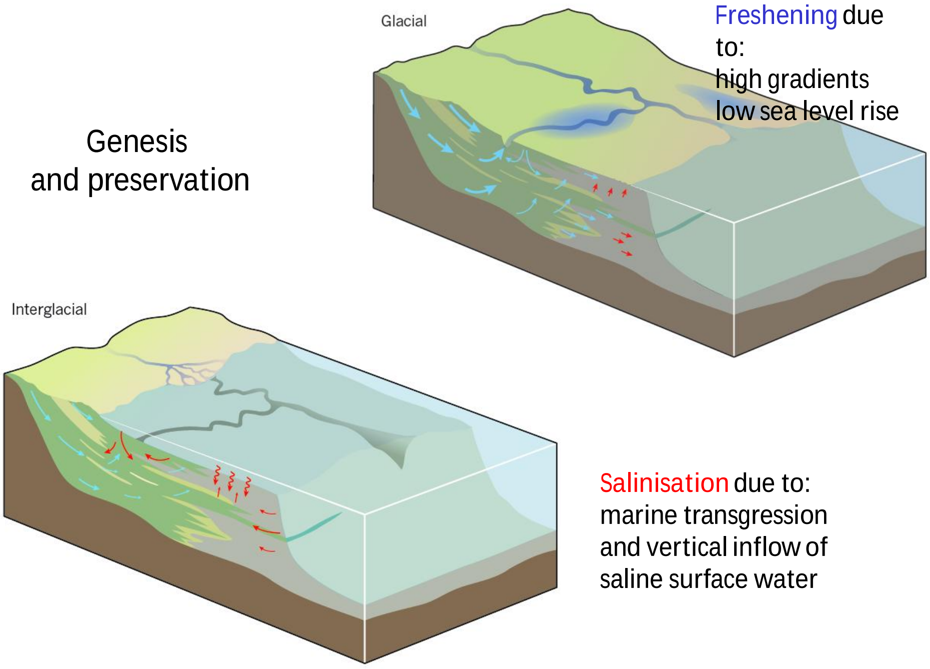


World map of topography and bathymetry showing known occurrences of fresh and brackish offshore groundwater



Post et al., Nature, 2013

Genesis
and preservation

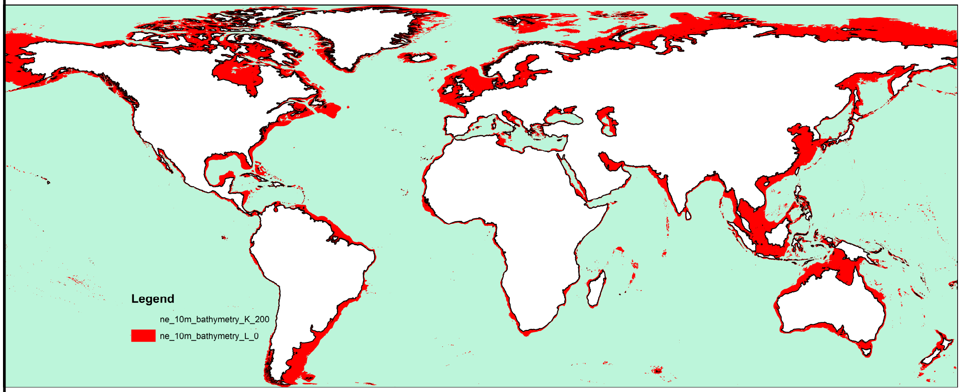


Freshening due to:
high gradients
low sea level rise

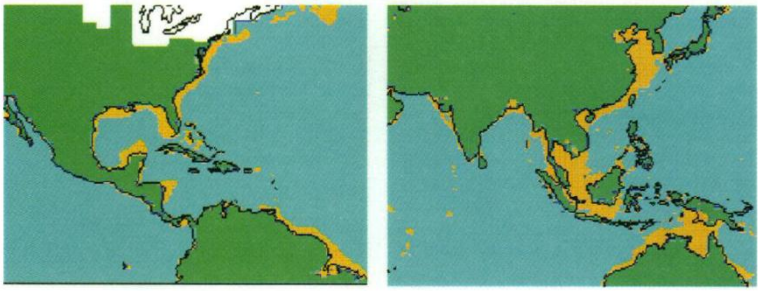
Salinisation due to:
marine transgression
and vertical inflow of
saline surface water

Source: Nature, 2013

Possible locations of offshore (submarine) groundwater

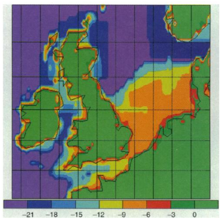


Coastal zone cases around the world
Occurrence related to dynamic sea-levels and coastlines

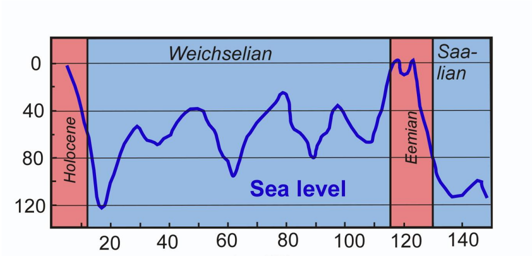


Exposed continental shelves

Peltier, *Science*, 1994

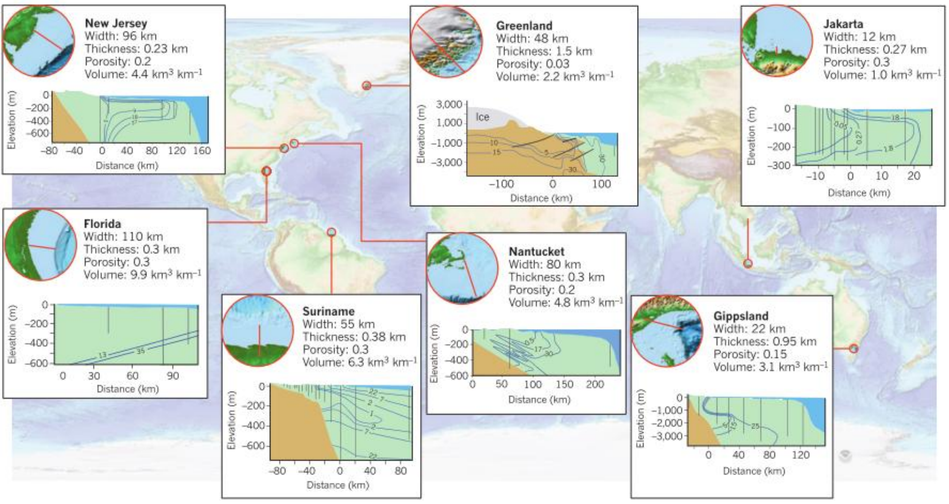


Inundated (kyr BP)



Linsley, Nature, 1996

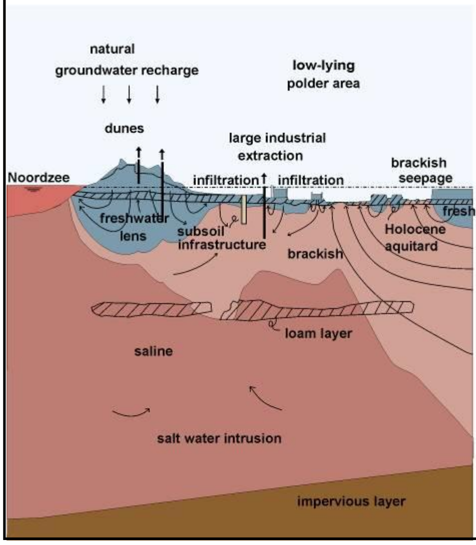
Global overview of inferred key metrics and cross sections of well-characterised vast meteoric groundwater reserves



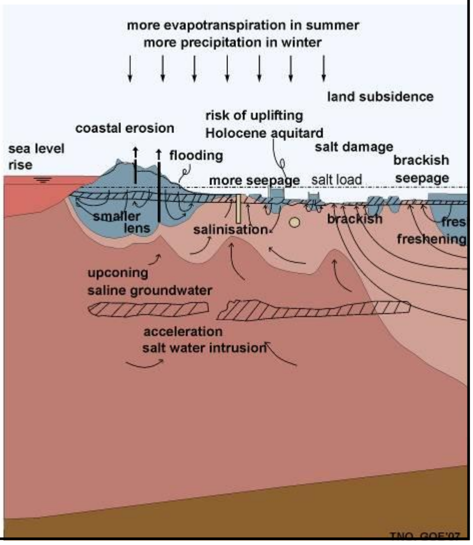
My first density dependent groundwater flow and solute transport model in 1990!

The Dutch groundwater system under stress

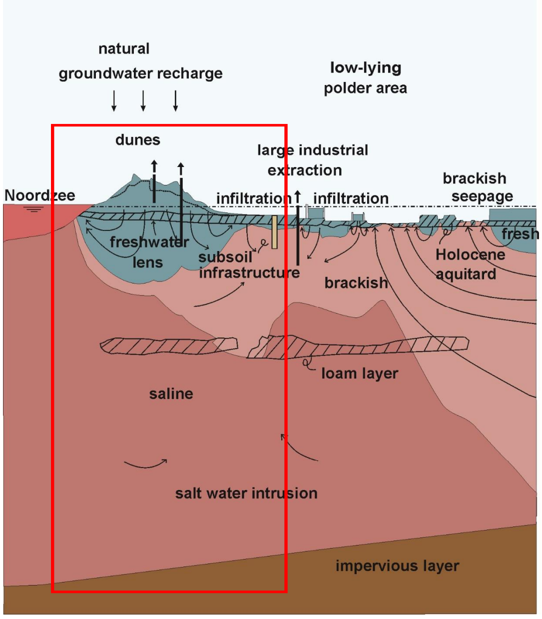
Present processes



Future changes

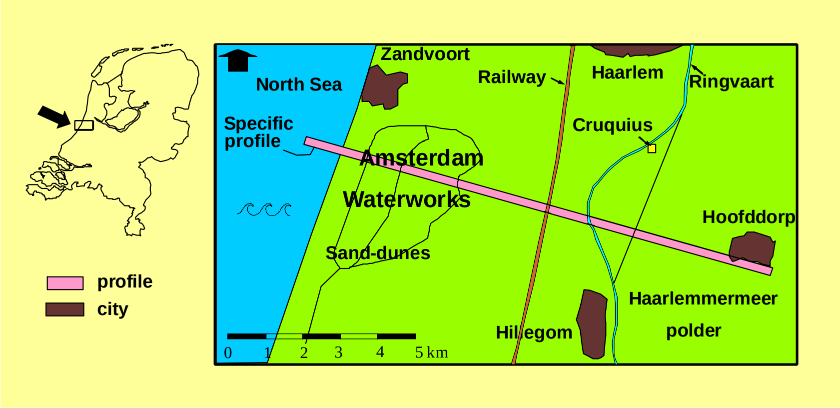


Saltwater intrusion in the Netherlands



Saltwater intrusion in the Dutch coastal zone

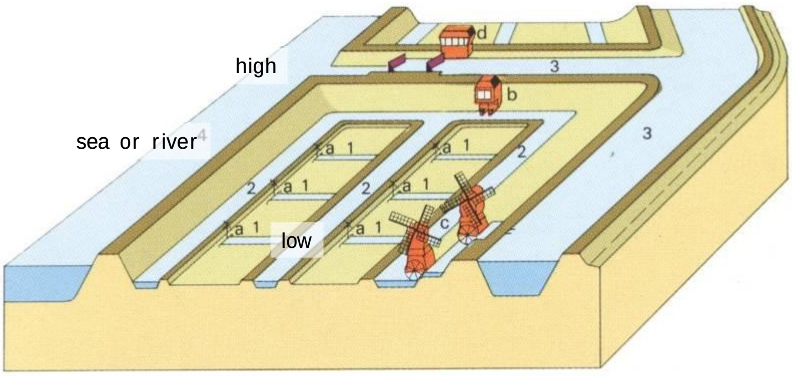
Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



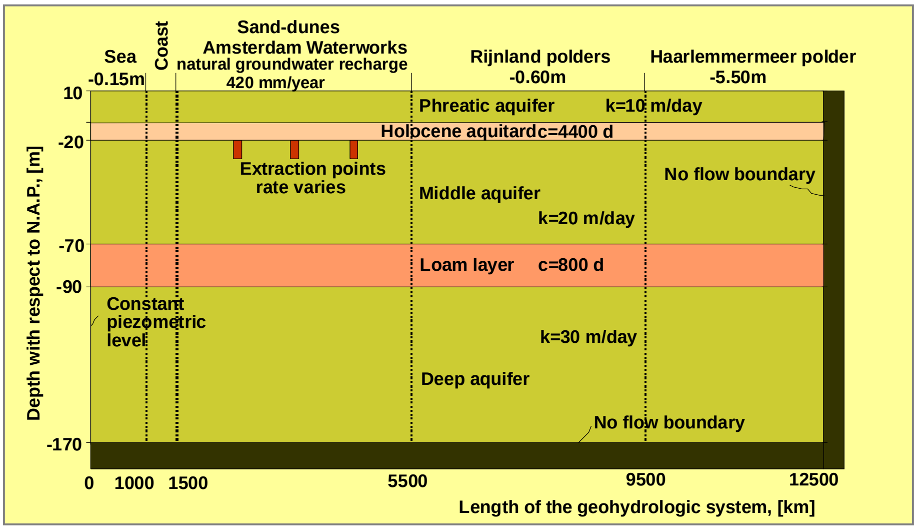
The polder system

A polder is:

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

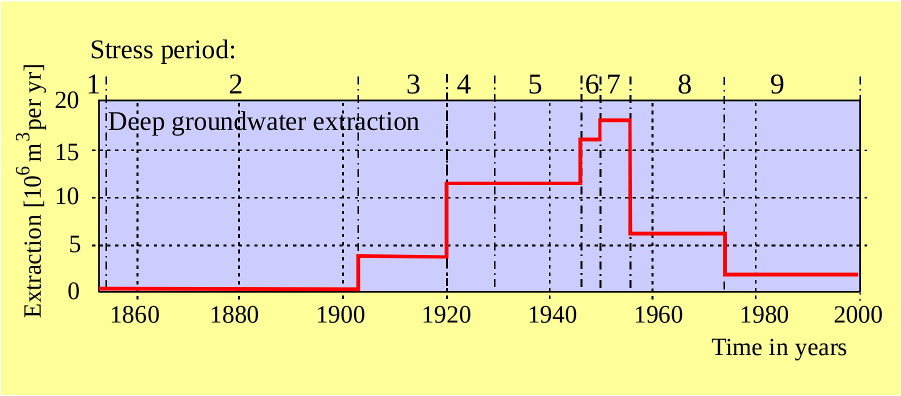


Geometry, subsoil parameters, boundary conditions

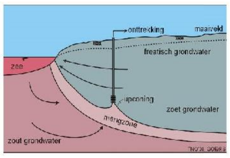


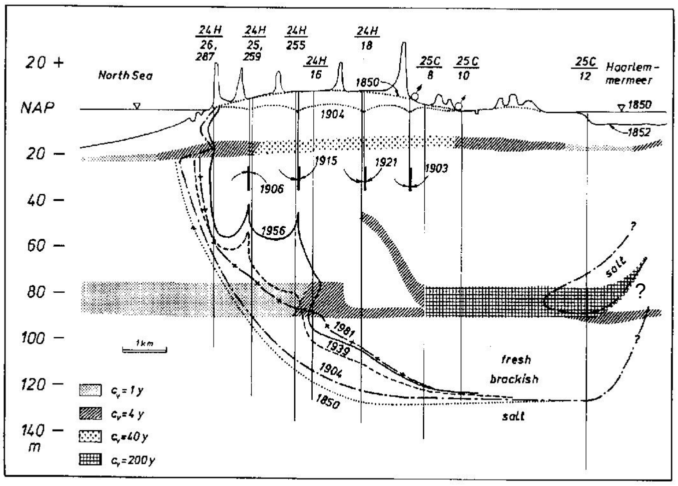
Saltwater intrusion in the Dutch coastal zone

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



Upconing of brackish-saline groundwater





Stuyfzand, 1993

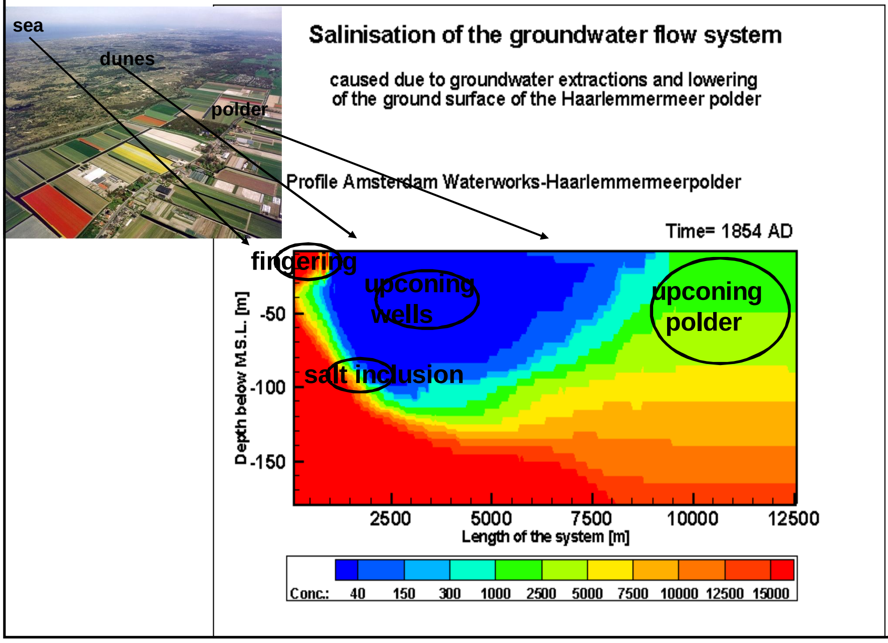
Saltwater intrusion in the Dutch coastal zone

Salinisation of the groundwater flow system

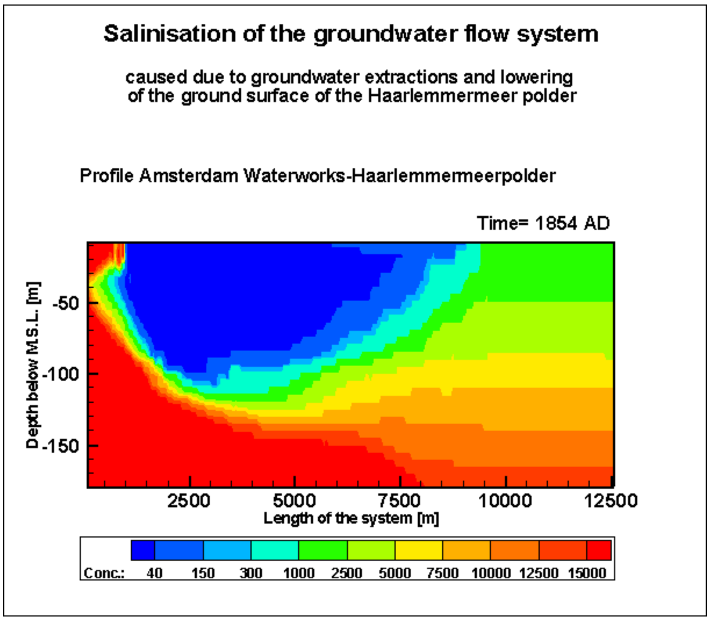
caused due to groundwater extractions and lowering of the ground surface of the Haarlemmermeer polder

Profile Amsterdam Waterworks-Haarlemmermeerpolder

Time= 1854 AD



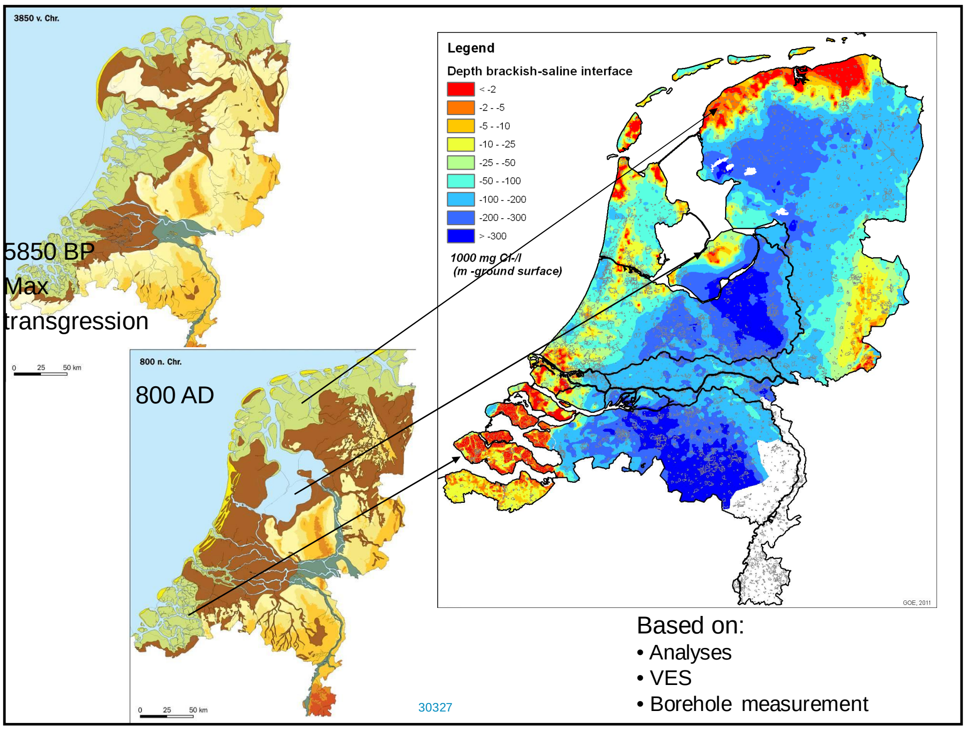
Saltwater intrusion in the Dutch coastal zone



Palaeo hydrogeological modelling

Palaeo-modeling salt water intrusion during the Holocene: an application to the Netherlands

J.R. Delsman, K. Hu-a-ng, P.C. Vos, P.G.B. de Louw, G.H.P. Oude Essink and M.F.P. Bierkens



5850 BP
Max
transgression

800 AD

Legend

Depth brackish-saline interface

- 🟥 < -2
- 🟧 -2 - -5
- 🟧 -5 - -10
- 🟨 -10 - -25
- 🟩 -25 - -50
- 🟦 -50 - -100
- 🟦 -100 - -200
- 🟦 -200 - -300
- 🟦 > -300

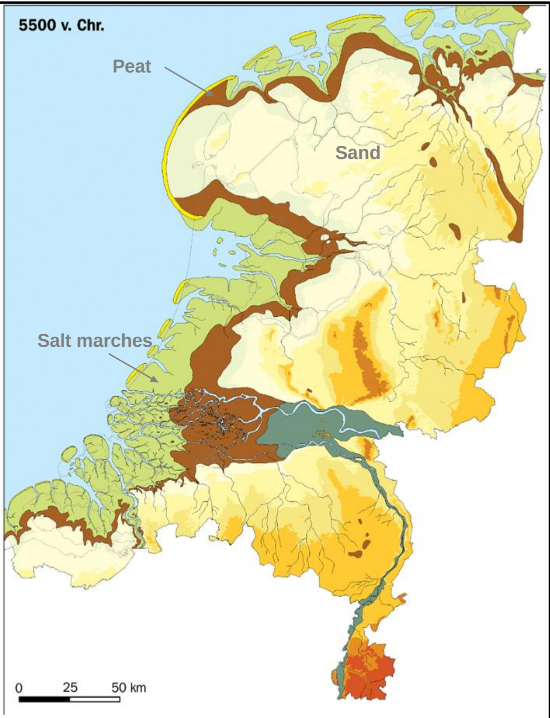
1000 mg Cl-/l
(m -ground surface)

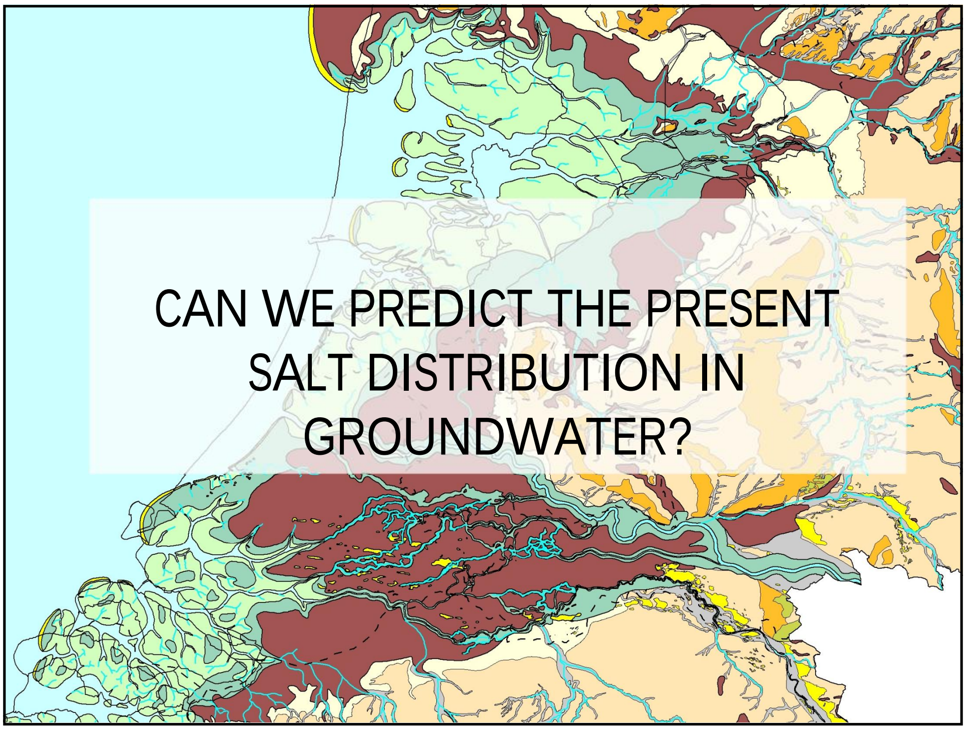
Based on:
- Analyses
- VES
- Borehole measurement

The Holocene transgressions

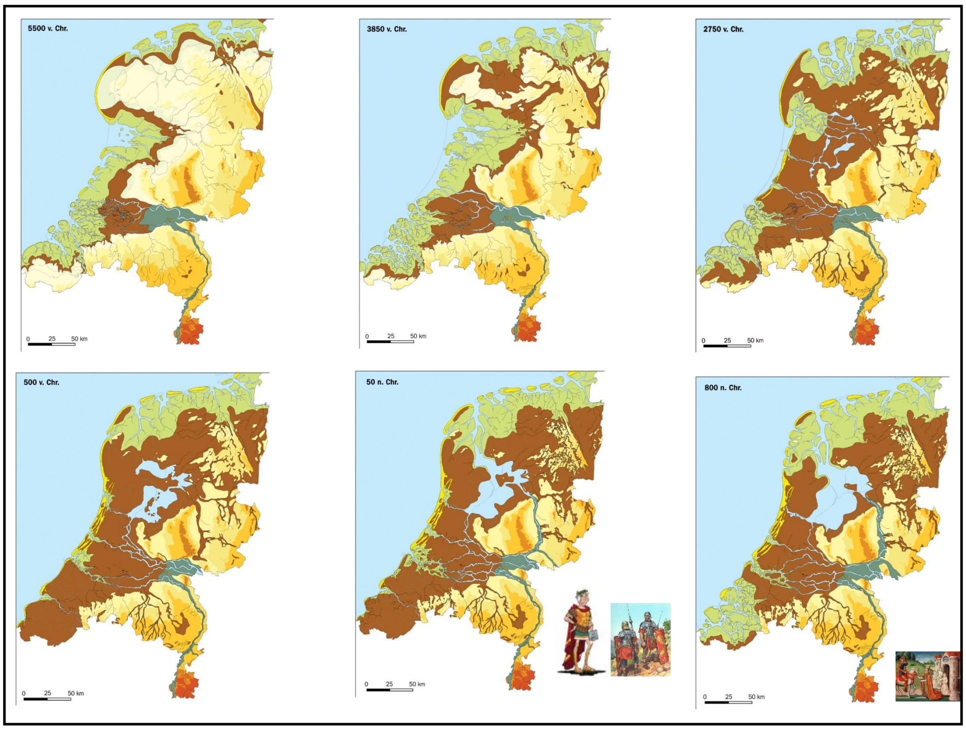
Major impact on present regional brackish groundwater systems

7500 BP



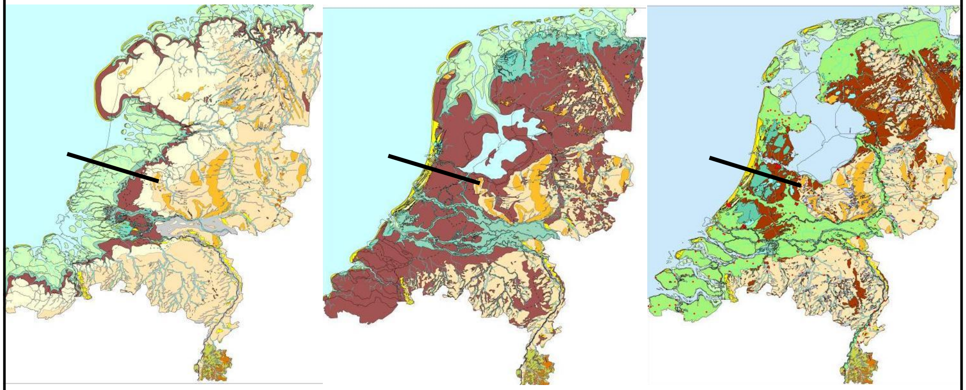


CAN WE PREDICT THE PRESENT SALT DISTRIBUTION IN GROUNDWATER?



Palaeogeographical development

5500 BC **100 AD** **1850 AD**



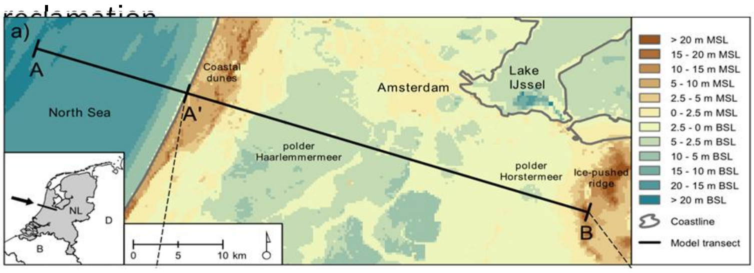
Maximal transgression **Peat development** **Reclaimed land, polder**

Delsman, J.R., Hu-a-ng, K.R.M., Vos, P.C., De Louw, P.G.B., Oude Essink, G.H.P., Stuyfzand, P.J. and Bierkens, M.F.P. 2013, Palaeo-modeling of coastal salt water intrusion during the Holocene: an application to the Netherlands, Hydrol. Earth Syst. Sci. Discuss., 10, 13707–13742

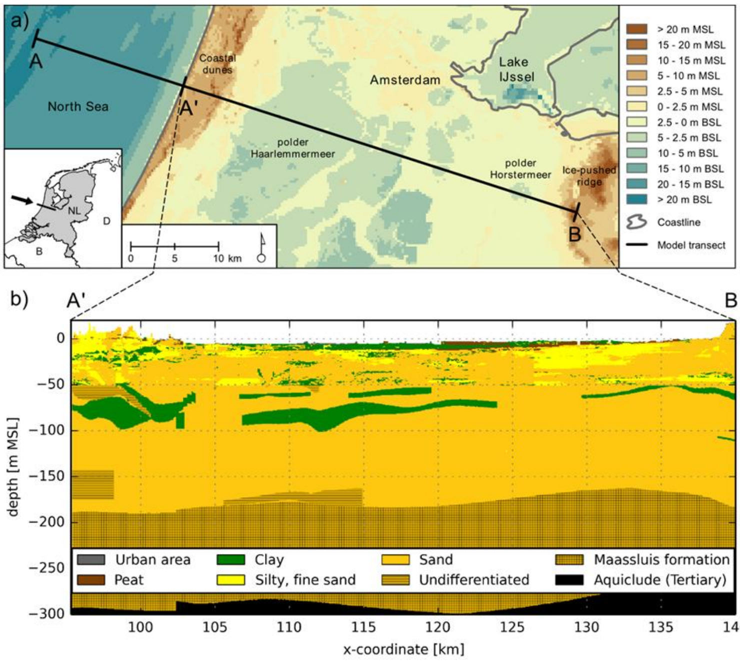
Atlas NL in het Holoceen (Vos et al, 2011)

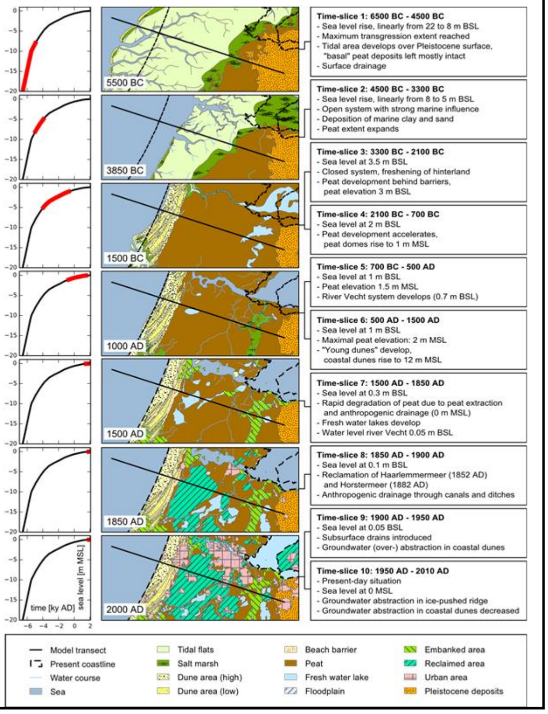
Occurrence of salt under the polder Haarlemmermeer

- Model profile Zandvoort - Hoofddorp – Hilversum
- Palaeogeographical development (Vos et al, 2011)
- 6500 BC - 2010 AD
- marine transgression
- Peat development, peat degradation, drainage, reclamation



Delsman et al., HESS, 2013





Time-slice 1: 6500 BC - 4500 BC
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage

Time-slice 2: 4500 BC - 3300 BC
- Sea level rise, linearly from 8 to 5 m BSL
- Open system with strong marine influence
- Deposition of marine clay and sand
- Peat extent expands

Time-slice 3: 3300 BC - 2100 BC
- Sea level at 3.5 m BSL
- Closed system, freshening of hinterland
- Peat development behind barriers, peat elevation 3 m BSL

Time-slice 4: 2100 BC - 700 BC
- Sea level at 2 m BSL
- Peat development accelerates, peat domes rise to 1 m MSL

Time-slice 5: 700 BC - 500 AD
- Sea level at 1 m BSL
- Peat elevation 1.5 m MSL
- River Vecht system develops (0.7 m BSL)

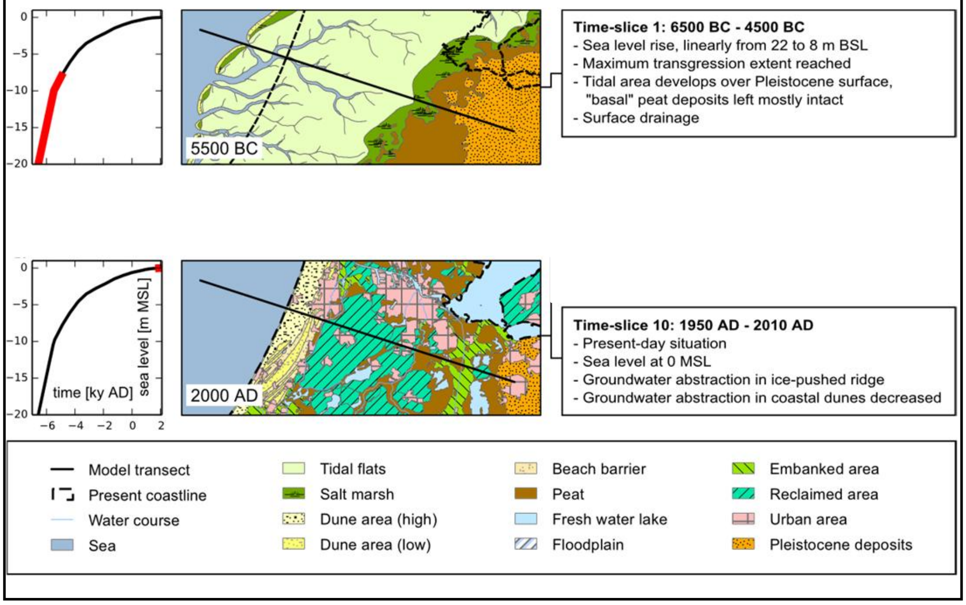
Time-slice 6: 500 AD - 1500 AD
- Sea level at 1 m BSL
- Maximal peat elevation: 2 m MSL
- "Young dunes" develop, coastal dunes rise to 12 m MSL

Time-slice 7: 1500 AD - 1850 AD
- Sea level at 0.3 m BSL
- Rapid degradation of peat due to peat extraction and anthropogenic drainage (0 m MSL)
- Fresh water lakes develop
- Water level river Vecht 0.05 m BSL

Time-slice 8: 1850 AD - 1900 AD
- Sea level at 0.1 m BSL
- Reclamation of Haarlemmermeer (1852 AD) and Horstermeer (1882 AD)
- Anthropogenic drainage through canals and ditches

Time-slice 9: 1900 AD - 1950 AD
- Sea level at 0.05 BSL
- Subsurface drains introduced
- Groundwater (over-) abstraction in coastal dunes

Time-slice 10: 1950 AD - 2010 AD
- Present-day situation
- Sea level at 0 MSL
- Groundwater abstraction in ice-pushed ridge
- Groundwater abstraction in coastal dunes decreased



Time-slice 1: 6500 BC - 4500 BC
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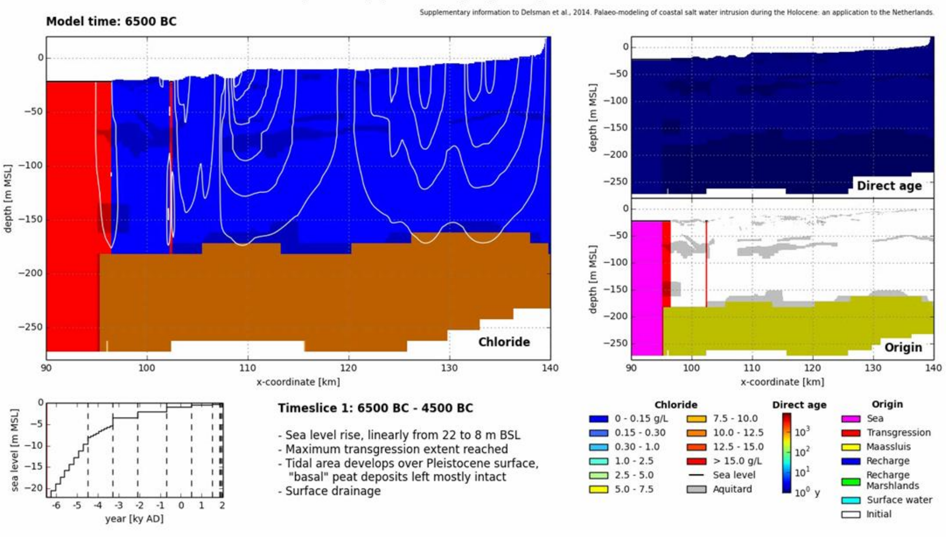
- Surface drainage

Time-slice 10: 1950 AD - 2010 AD
- Present-day situation
- Sea level at 0 MSL
- Groundwater abstraction in ice-pushed ridge
- Groundwater abstraction in coastal dunes decreased

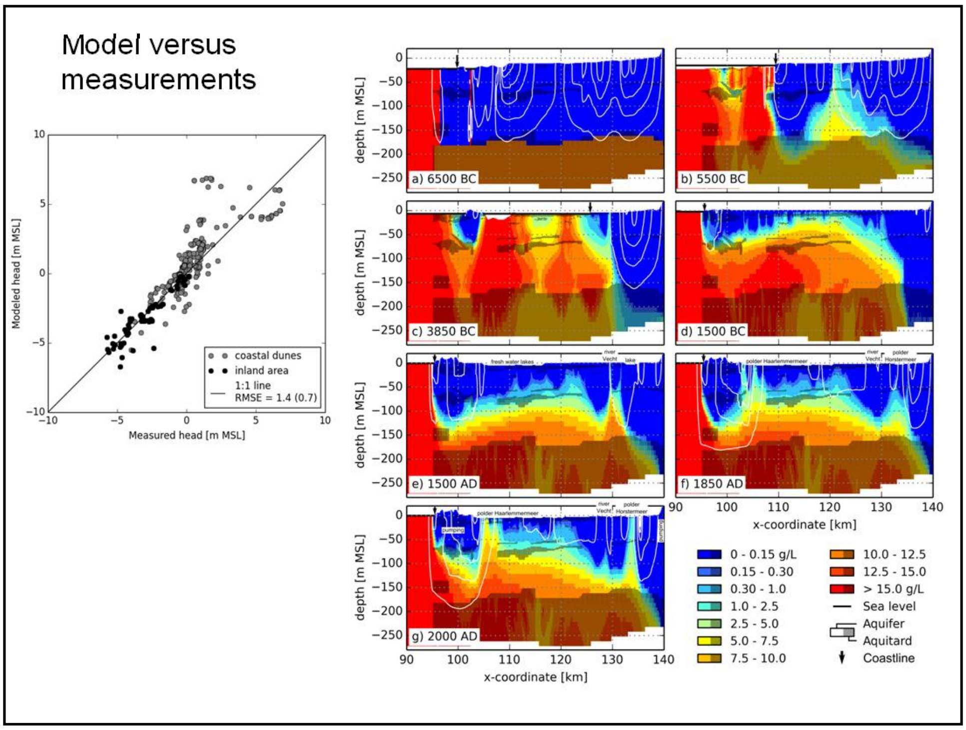
Development saline groundwater


Supplementary information to Delsman et al., 2014. Palaeo-modeling of coastal salt water intrusion during the Holocene: an application to the Netherlands.

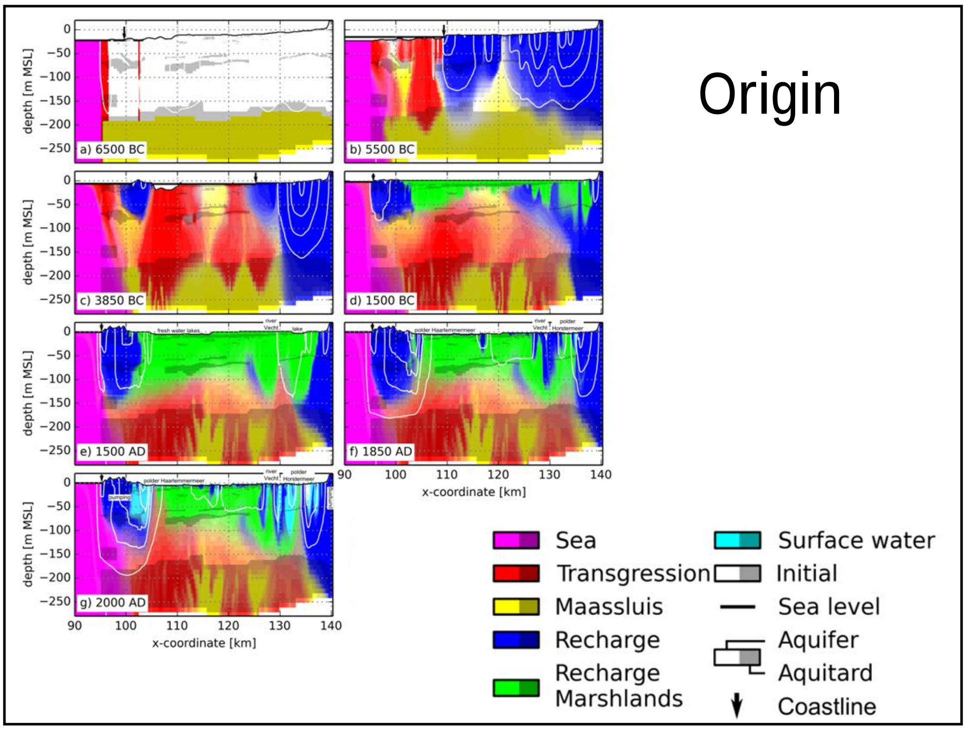
Model time: 6500 BC

Timeslice 1: 6500 BC - 4500 BC
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage

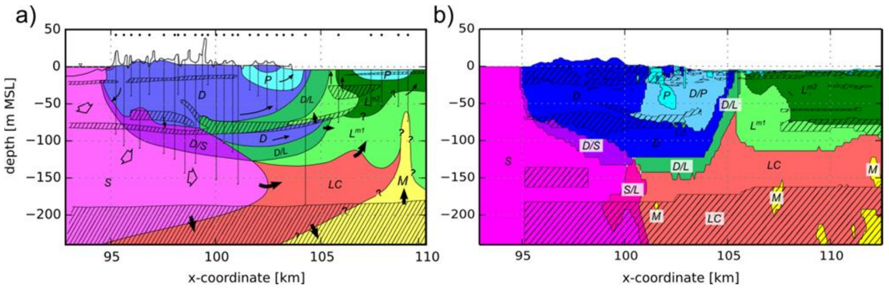
Delsman et al., HESSD, 2013

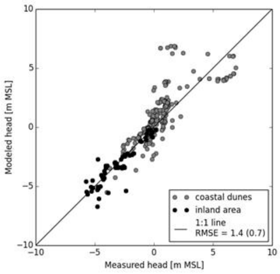


Model versus measurements

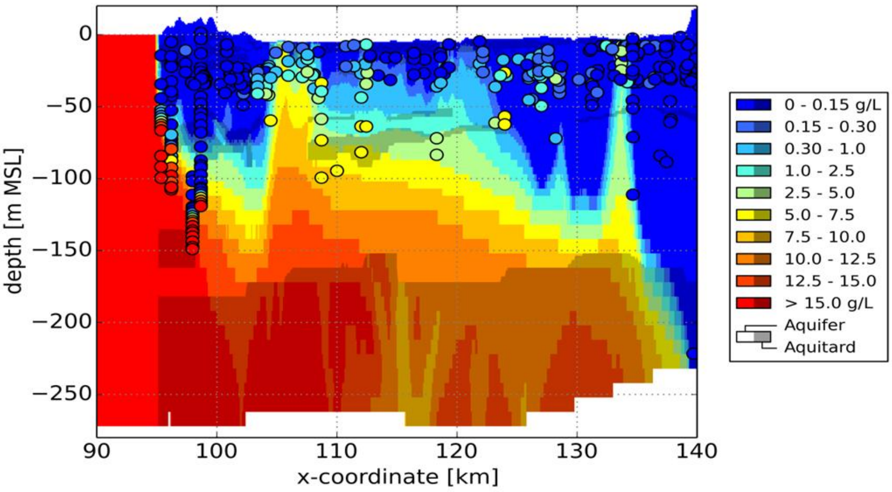


Origin





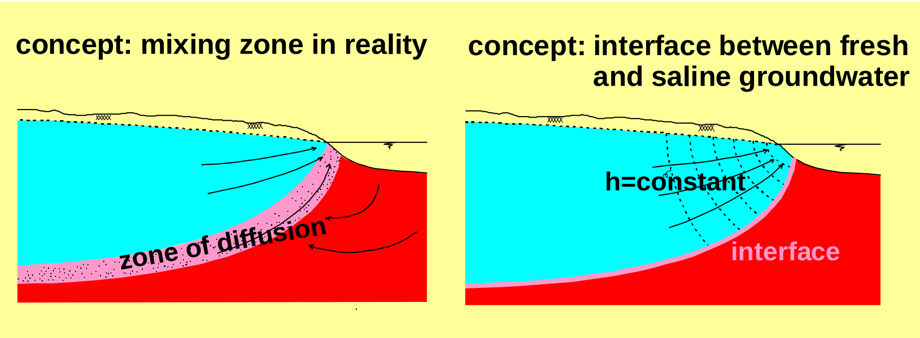
Model versus measurements



Sharp interface between fresh and saline groundwater

Badon Ghyben-Herzberg principle

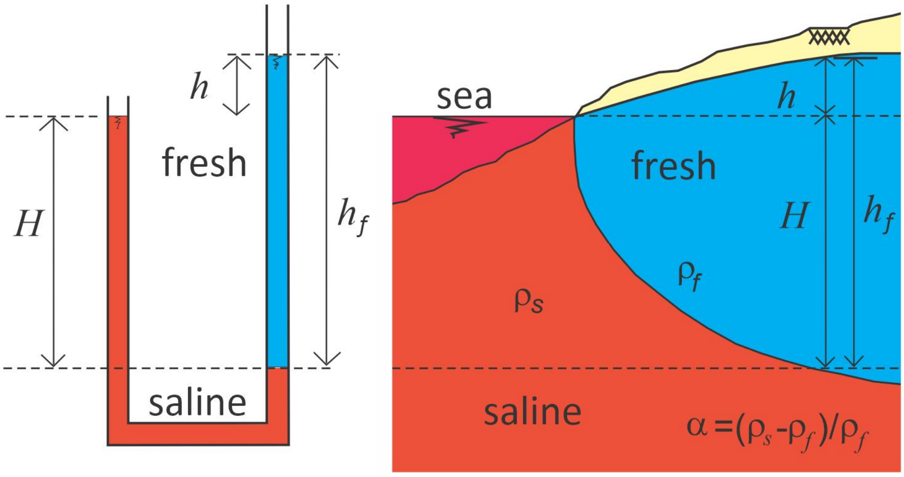
Difference between reality and Badon Ghyben-Herzberg approximation

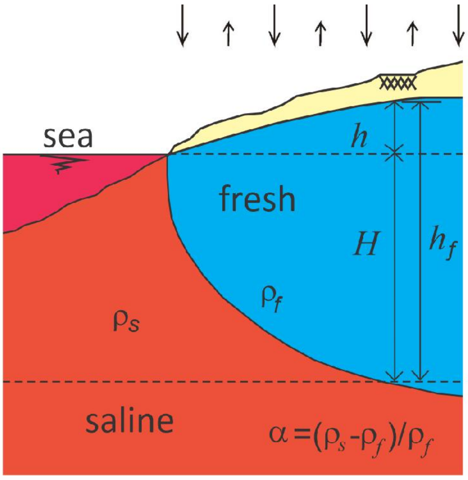


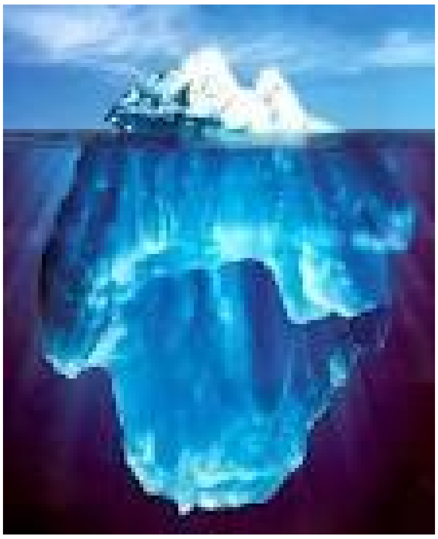
Badon Ghijben-Herzberg principle

The principle suggests an interface between fresh and saline groundwater

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





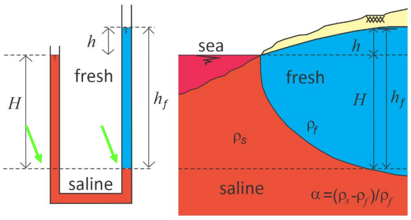


pressure saline groundwater=pressure fresh groundwater

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

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

$$h = \alpha H$$

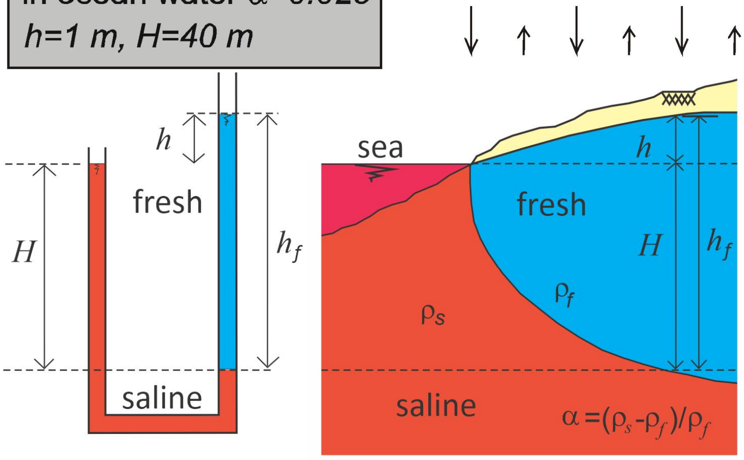


$$h = \alpha H \qquad h = \frac{\rho_s - \rho_f}{\rho_f} H \qquad h = \frac{1025 - 1000}{1000} H$$

h=α*H*

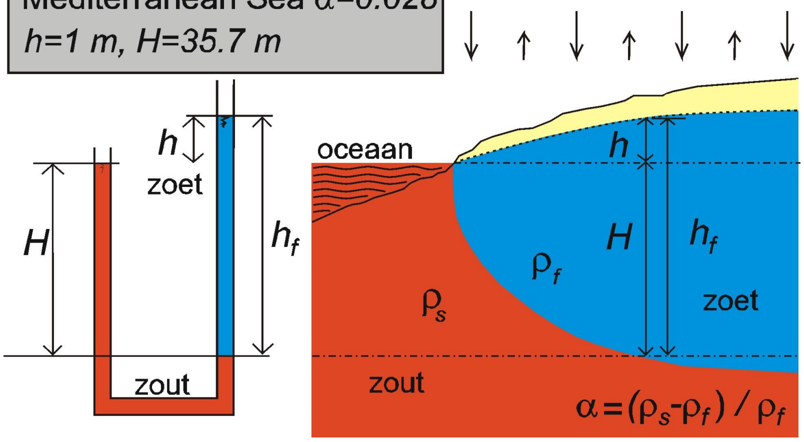
in ocean water α=*0.025*

h=1 m, H=40 m



$$h = \alpha H \qquad h = \frac{\rho_s - \rho_f}{\rho_f} H \qquad h = \frac{1028 - 1000}{1000} H$$

$h=\alpha H$
Mediterranean Sea $\alpha=0.028$
$h=1$ m, $H=35.7$ m



Badon Ghyben-Herzberg principle

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

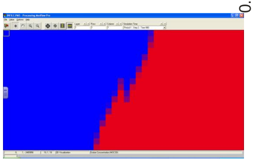
- interface is a simple approximation
- dispersion zone <10m
- relative simple geometries

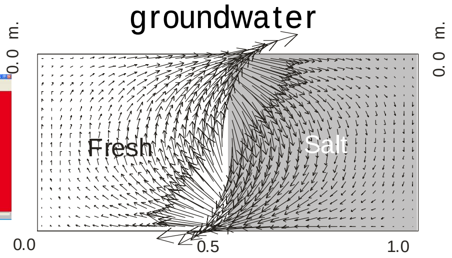
Badon Ghyben-Herzberg principle

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

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

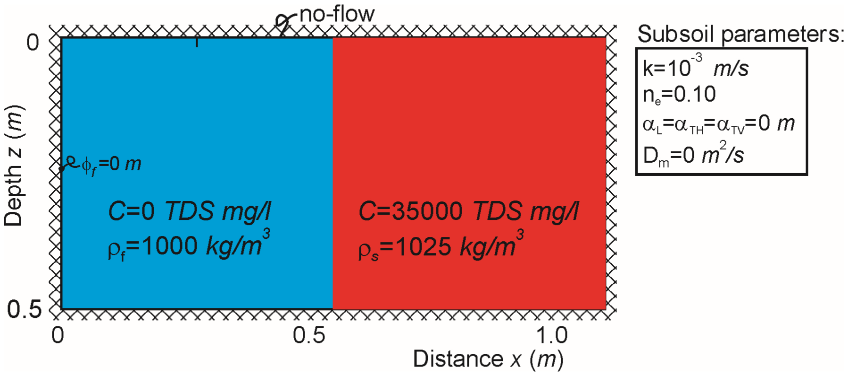
Case 1: Vertical interface between fresh and saline groundwater



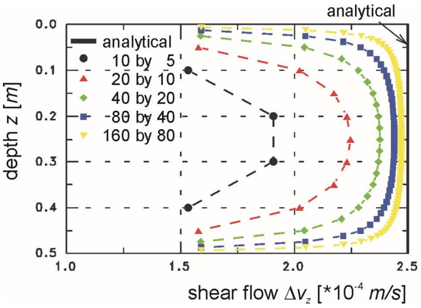


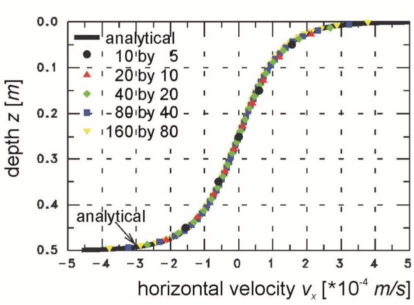
Parameters			
Layers	20	K_{hor}	$1\ 10^{-3}$ m/s
Rows	1	T	$2.5\ 10^{-5}$ m/s
Columns	40	Anisotropy K_{hor}/K_{ver}	1
Δx	0.025 m	n_e	0.1
Δy	1 m	α_L	0 m
Δz	0.025 m	α_T	0 m
Stress periods	15		
Initial concentration	0 and 35000 mg/l		
bouyancy	0.025		

Vertical interface



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

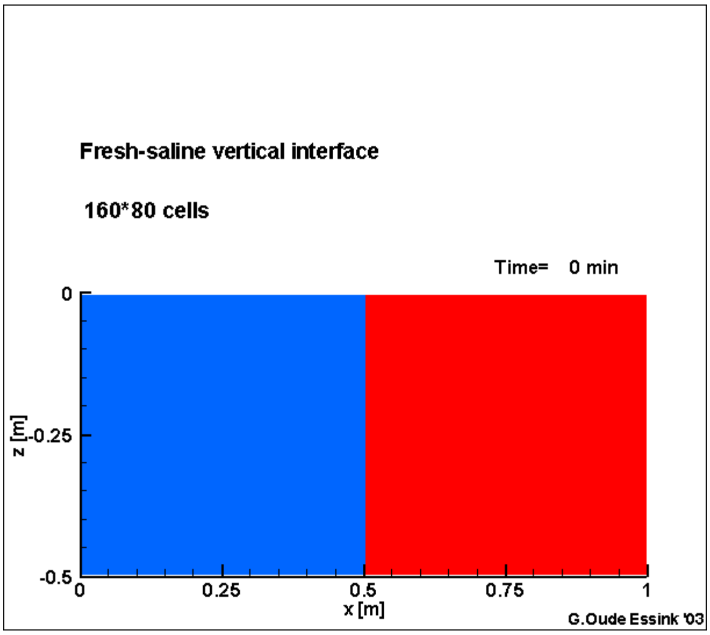




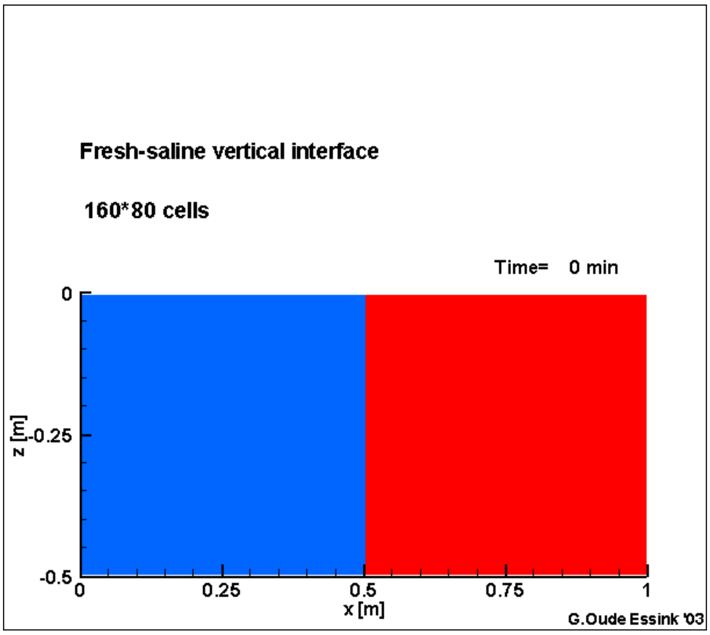
$$\Delta v_z = \frac{k}{n_e}\left(\frac{\rho_s - \rho_f}{\rho_f}\right)$$

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

Vertical interface



Vertical interface

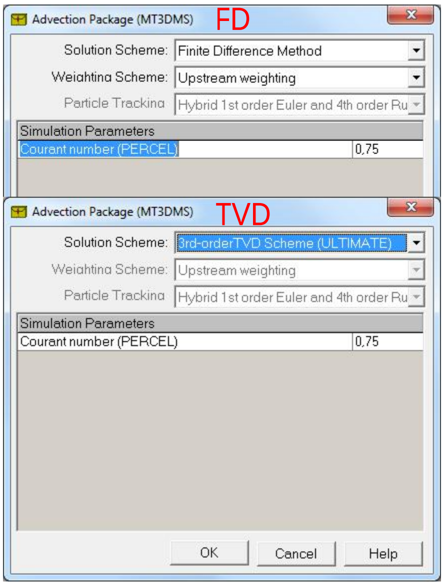


The effect of numerical solvers on the salt transport

Examples

EWRMP 201511

Default parameters solvers



FD

Solution Scheme: Finite Difference Method

Weiahtina Scheme: Upstream weighting

Particle Trackina: Hybrid 1st order Euler and 4th order Ru

Simulation Parameters	
Courant number (PERCEL)	0,75

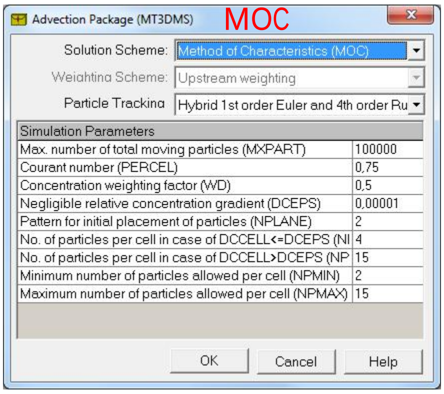
TVD

Solution Scheme: 3rd-orderTVD Scheme (ULTIMATE)

Weiahtina Scheme: Upstream weighting

Particle Trackina: Hybrid 1st order Euler and 4th order Ru

Simulation Parameters	
Courant number (PERCEL)	0,75



MOC

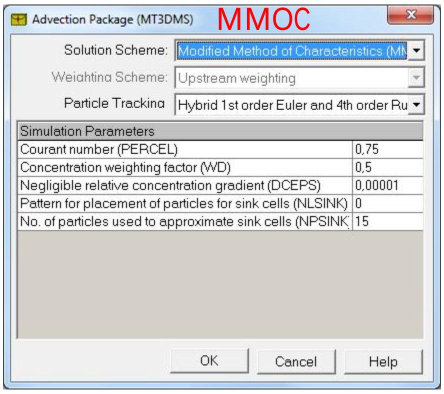
Solution Scheme: Method of Characteristics (MOC)

Weiahtina Scheme: Upstream weighting

Particle Trackina: Hybrid 1st order Euler and 4th order Ru

Simulation Parameters	
Max. number of total moving particles (MXPART)	100000
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for initial placement of particles (NPLANE)	2
No. of particles per cell in case of DCCELL<=DCEPS (NI	4
No. of particles per cell in case of DCCELL>DCEPS (NP	15
Minimum number of particles allowed per cell (NPMIN)	2
Maximum number of particles allowed per cell (NPMAX)	15

Default parameters solvers



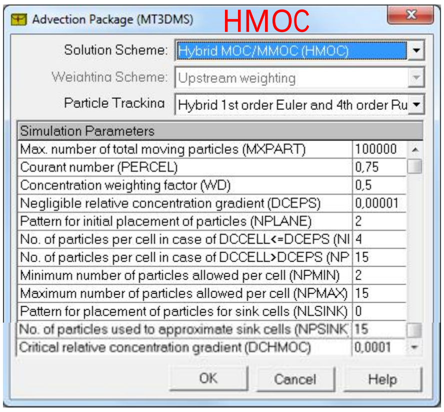
MMOC

Solution Scheme: Modified Method of Characteristics (MM

Weighting Scheme: Upstream weighting

Particle Tracking: Hybrid 1st order Euler and 4th order Ru

Simulation Parameters	
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for placement of particles for sink cells (NLSINK)	0
No. of particles used to approximate sink cells (NPSINK	15



HMOC

Solution Scheme: Hybrid MOC/MMOC (HMOC)

Weighting Scheme: Upstream weighting

Particle Tracking: Hybrid 1st order Euler and 4th order Ru

Simulation Parameters	
Max. number of total moving particles (MXPART)	100000
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for initial placement of particles (NPLANE)	2
No. of particles per cell in case of DCCELL<=DCEPS (NI	4
No. of particles per cell in case of DCCELL>DCEPS (NP	15
Minimum number of particles allowed per cell (NPMIN)	2
Maximum number of particles allowed per cell (NPMAX)	15
Pattern for placement of particles for sink cells (NLSINK)	0
No. of particles used to approximate sink cells (NPSINK	15
Critical relative concentration gradient (DCHMOC)	0,0001

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.

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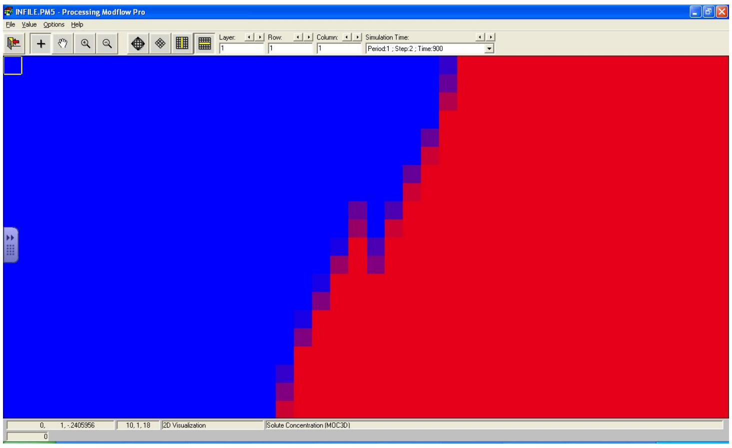
1 particle per cell



Layer: 1

Row: 1

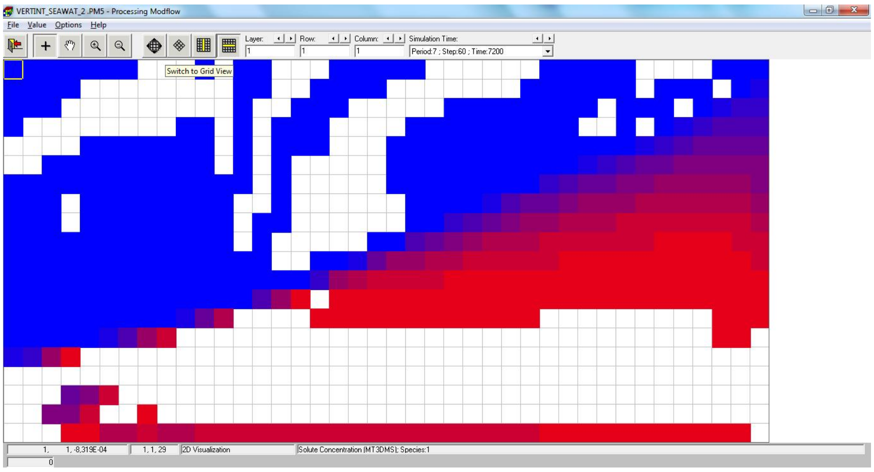
Column: 1

Simulation Time: Period:1 ; Step:2 ; Time:900

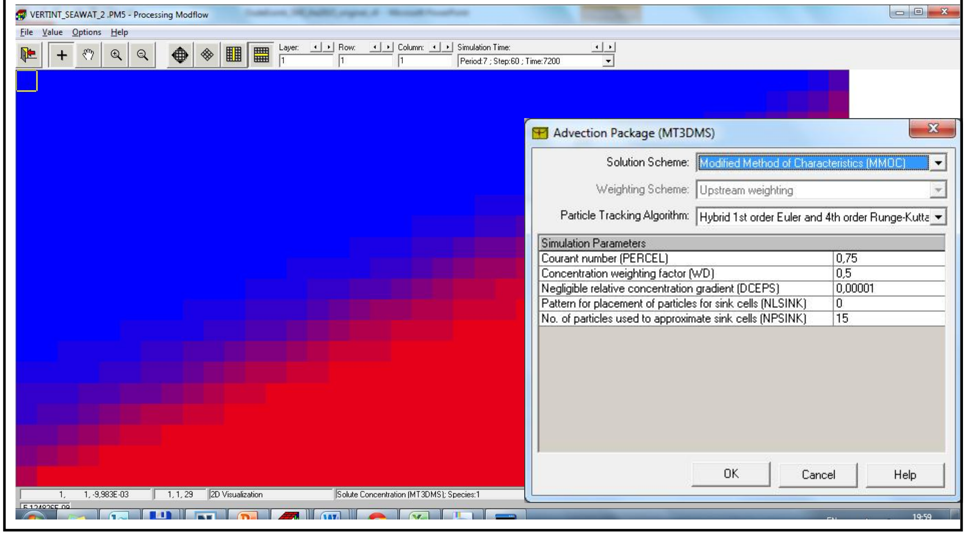
0, 1, -.2405956 | 10, 1, 18 | 2D Visualization | Solute Concentration (MOC3D)

0

ULTIMATE



MMOC, NPLANE=0



Advection Package (MT3DMS)

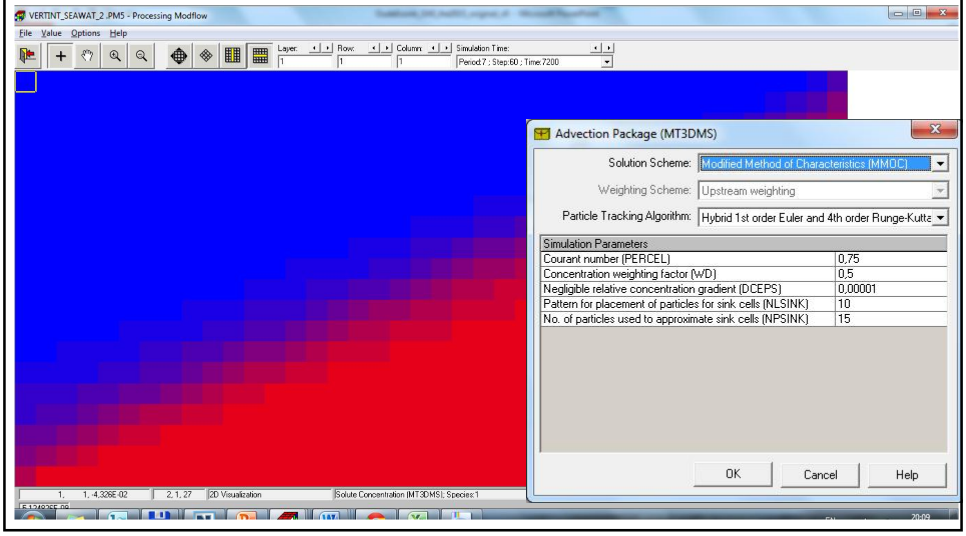
Solution Scheme: Modified Method of Characteristics (MMOC)

Weighting Scheme: Upstream weighting

Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta

Simulation Parameters	
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for placement of particles for sink cells (NLSINK)	0
No. of particles used to approximate sink cells (NPSINK)	15

MMOC, NPLANE=10



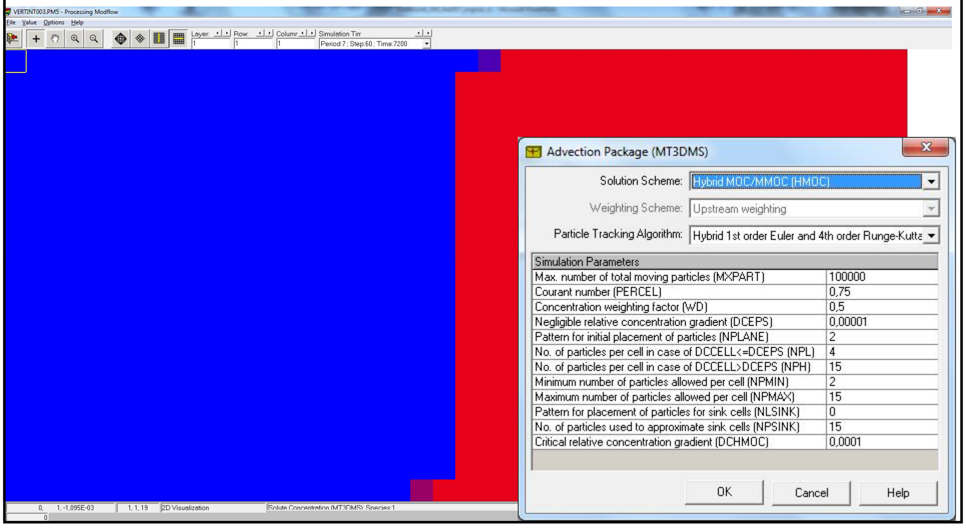
Solution Scheme: Modified Method of Characteristics (MMOC)

Weighting Scheme: Upstream weighting

Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta

Simulation Parameters	
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for placement of particles for sink cells (NLSINK)	10
No. of particles used to approximate sink cells (NPSINK)	15

HMOC



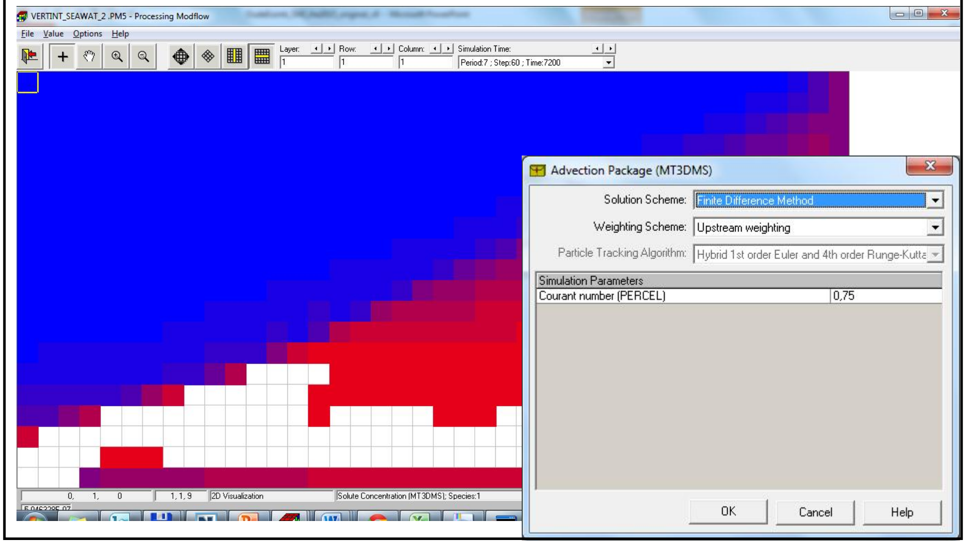
Solution Scheme: Hybrid MOC/MMOC (HMOC)

Weighting Scheme: Upstream weighting

Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta

Simulation Parameters	
Max. number of total moving particles (MXPART)	100000
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for initial placement of particles (NPLANE)	2
No. of particles per cell in case of DCCELL<=DCEPS (NPL)	4
No. of particles per cell in case of DCCELL>DCEPS (NPH)	15
Minimum number of particles allowed per cell (NPMIN)	2
Maximum number of particles allowed per cell (NPMAX)	15
Pattern for placement of particles for sink cells (NLSINK)	0
No. of particles used to approximate sink cells (NPSINK)	15
Critical relative concentration gradient (DCHMOC)	0,0001

Finite Difference Method

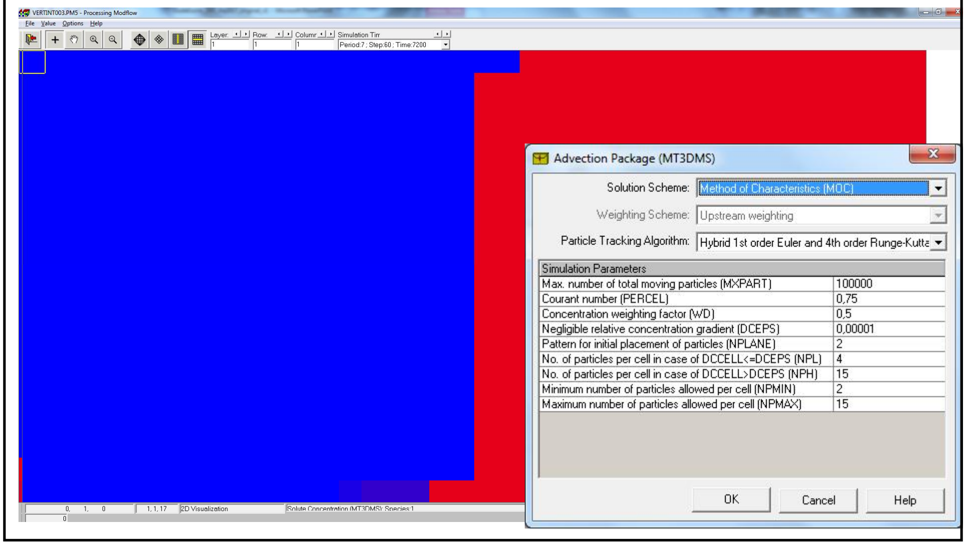


Advection Package (MT3DMS)

Solution Scheme: Finite Difference Method
Weighting Scheme: Upstream weighting
Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta

Simulation Parameters	
Courant number (PERCEL)	0,75

MOC

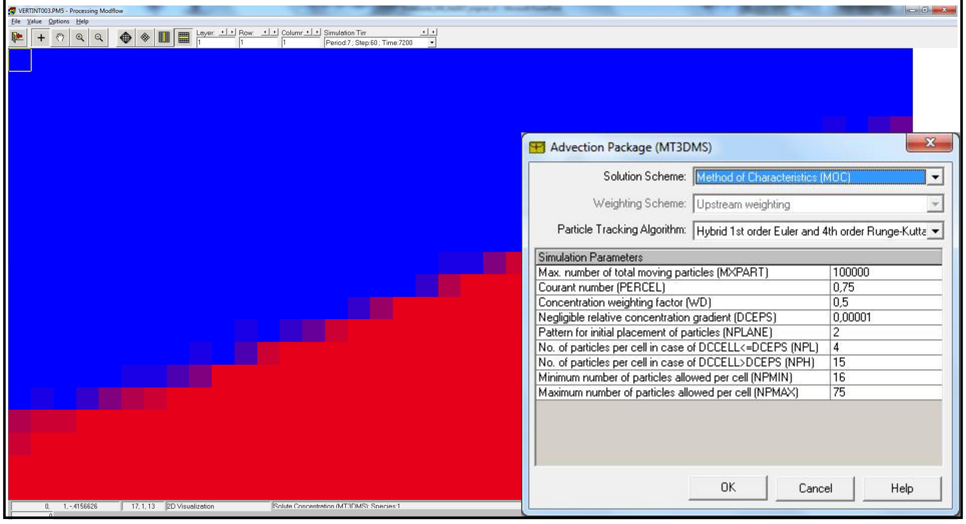


Advection Package (MT3DMS)

Solution Scheme: Method of Characteristics (MOC)
Weighting Scheme: Upstream weighting
Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta

Simulation Parameters	
Max. number of total moving particles (MXPART)	100000
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for initial placement of particles (NPLANE)	2
No. of particles per cell in case of DCCELL<=DCEPS (NPL)	4
No. of particles per cell in case of DCCELL>DCEPS (NPH)	15
Minimum number of particles allowed per cell (NPMIN)	2
Maximum number of particles allowed per cell (NPMAX)	15

MOC



Advection Package (MT3DMS)

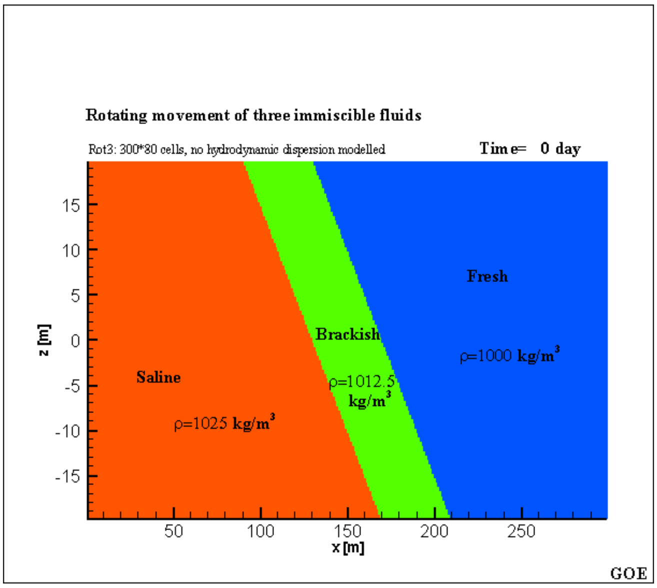
Solution Scheme: Method of Characteristics (MOC)

Weighting Scheme: Upstream weighting

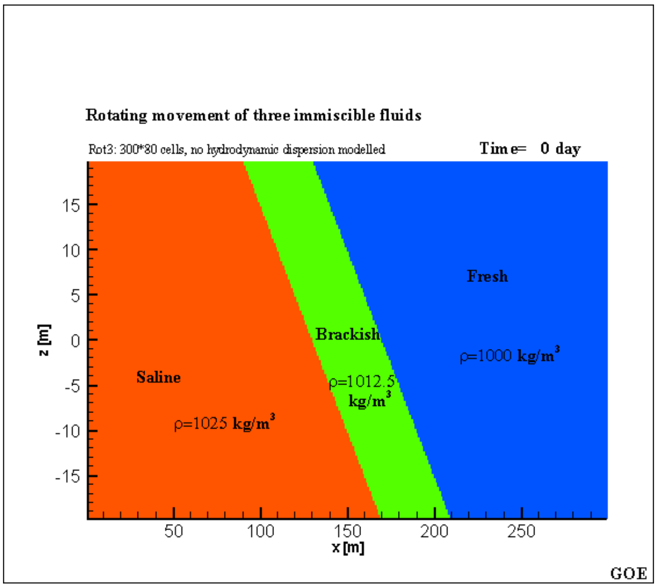
Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta

Simulation Parameters	
Max. number of total moving particles (MXPART)	100000
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for initial placement of particles (NPLANE)	2
No. of particles per cell in case of DCCELL<=DCEPS (NPL)	4
No. of particles per cell in case of DCCELL>DCEPS (NPH)	15
Minimum number of particles allowed per cell (NPMIN)	16
Maximum number of particles allowed per cell (NPMAX)	75

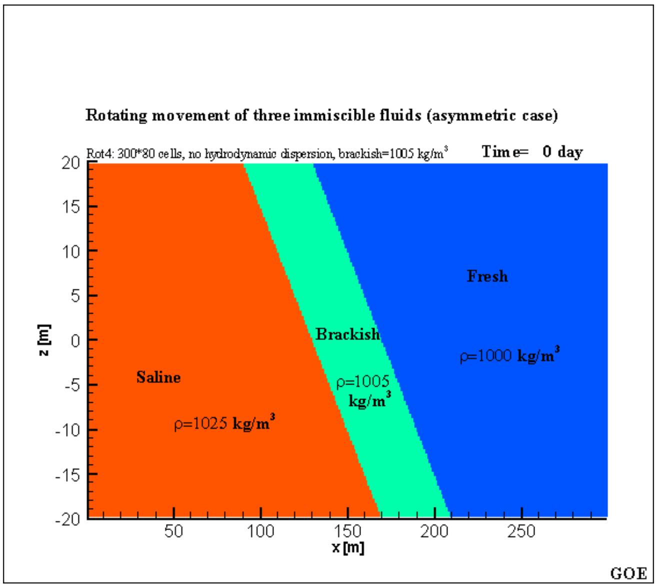
Rotating immiscible interfaces



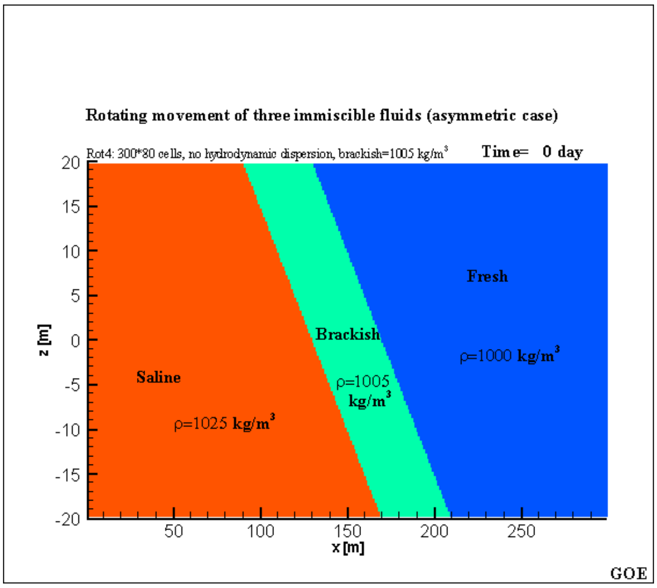
Rotating immiscible interfaces



Rotating immiscible interfaces (asymmetric)

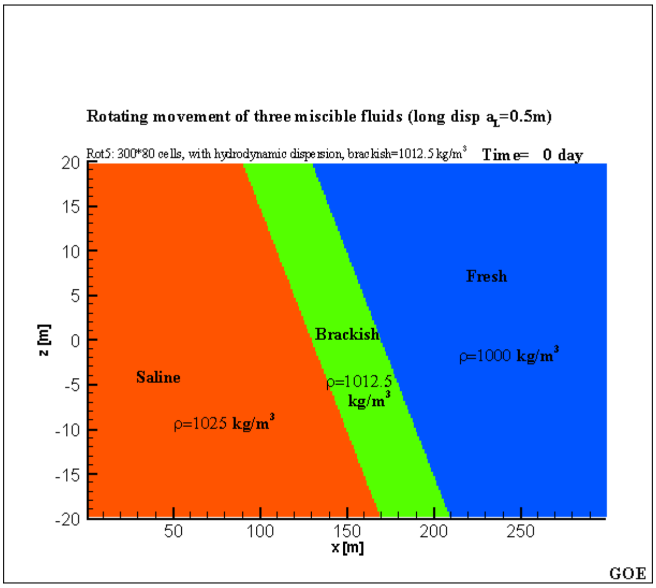


Rotating immiscible interfaces (asymmetric)

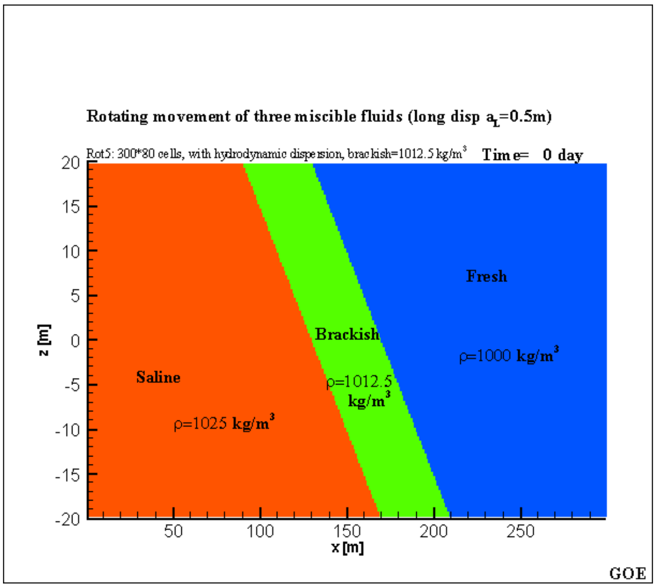


Bakker, M., Oude Essink, G.H.P. & Langevin, C. 2004. The rotating movement of three immiscible fluids, J. of Hydrology 287, 270-278

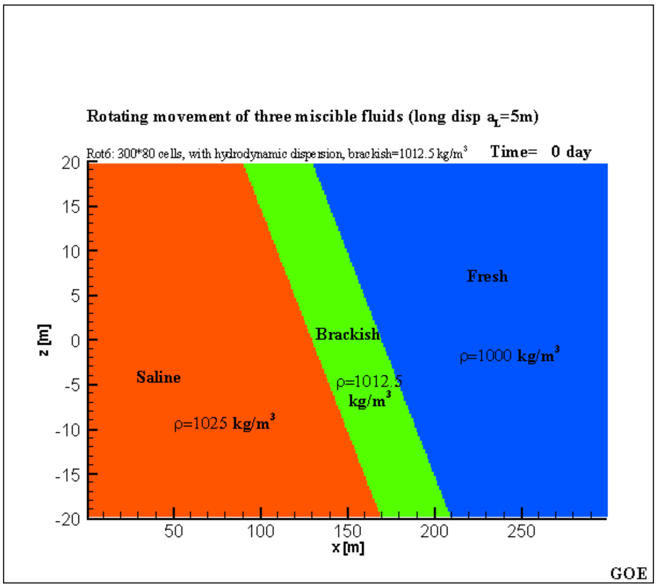
Rotating interfaces with dispersion α_L=0.5m



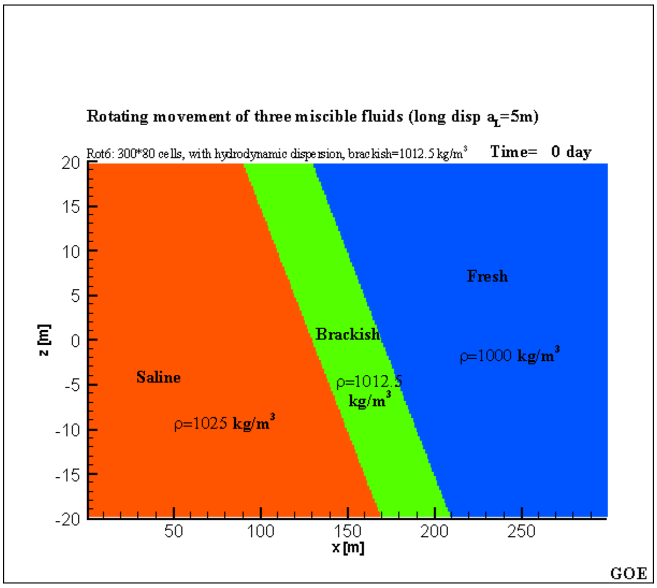
Rotating interfaces with dispersion α_L=0.5m



Rotating interfaces with dispersion α_L=5m



Rotating interfaces with dispersion α_L=5m

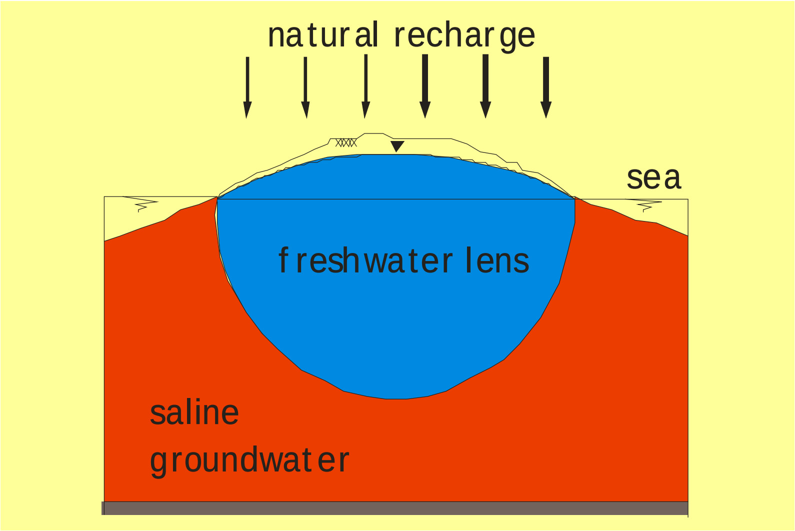


Rotating immiscible interfaces

Conclusion:

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

Evolution of a freshwater lens



Question:

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

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

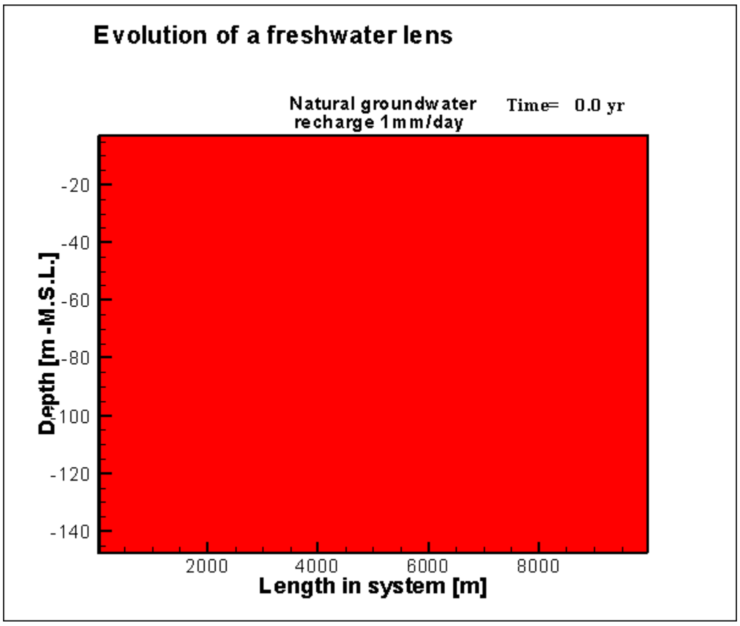
T = specific time scale

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

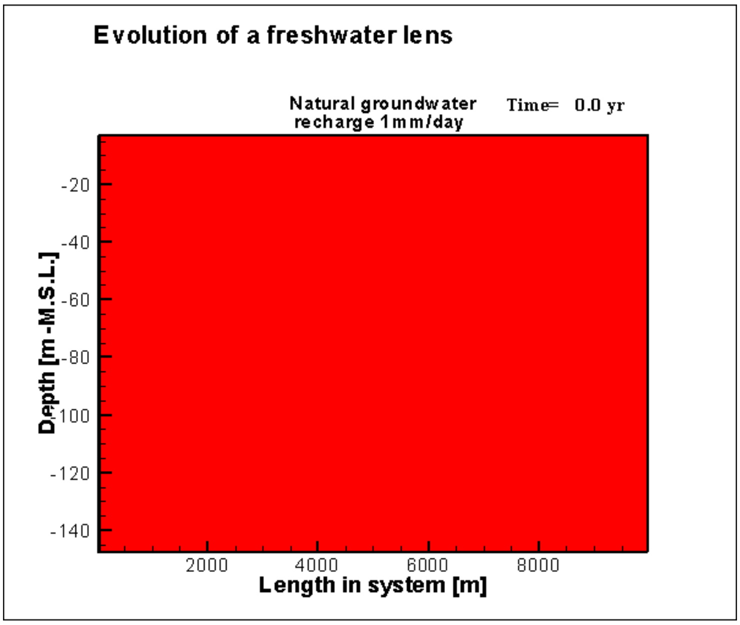
In the Netherlands: T = 75-200 jaar,

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

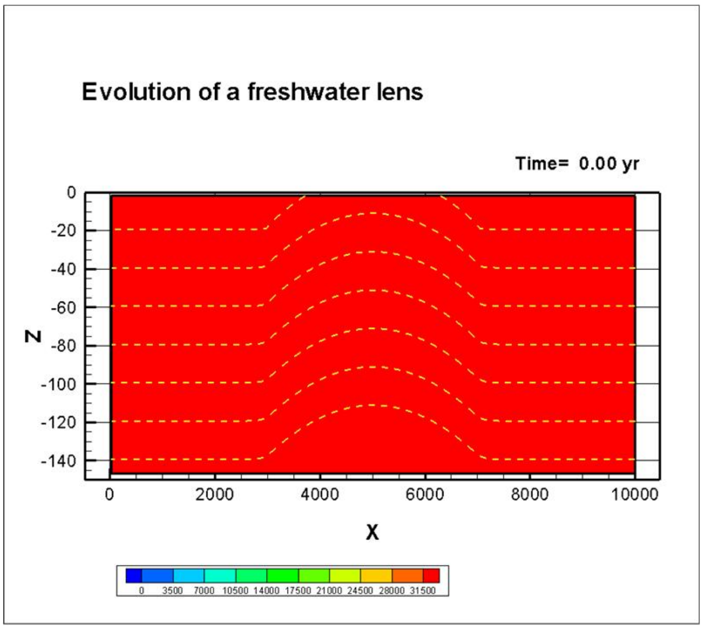
Concept: evolution freshwater lens (not Griend!)



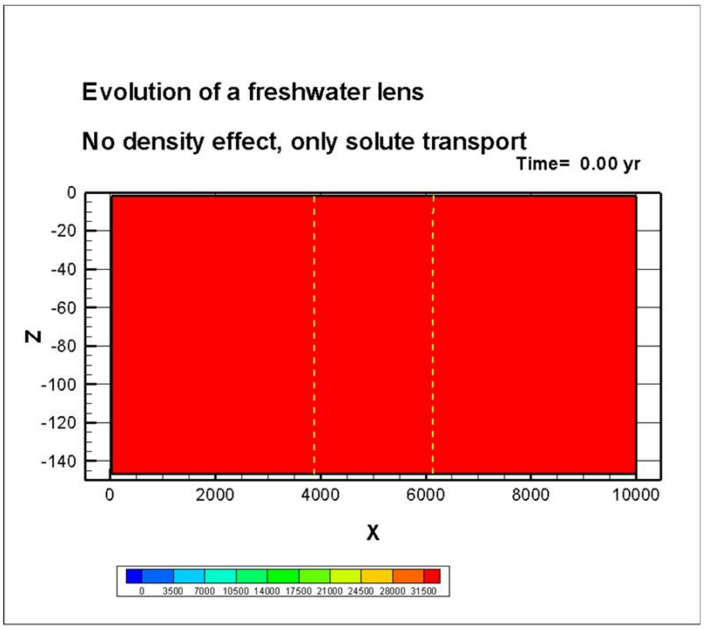
Concept: evolution freshwater lens (not Griend!)



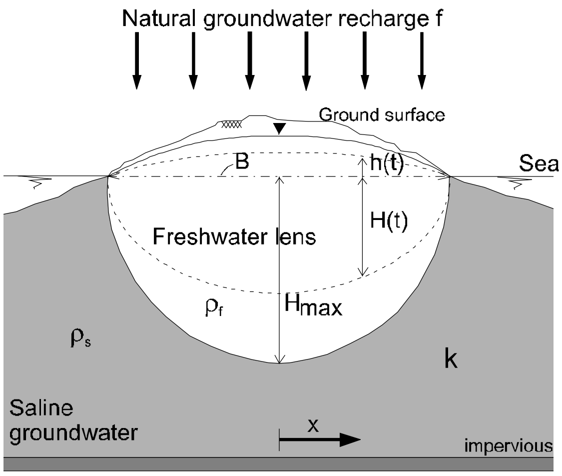
Evolution freshwater lens



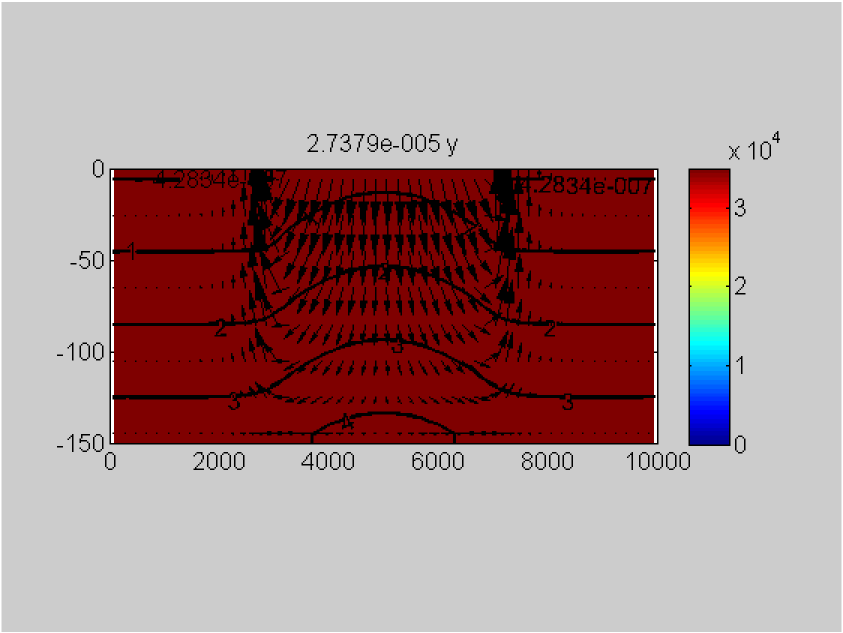
Evolution freshwater lens: no density effects



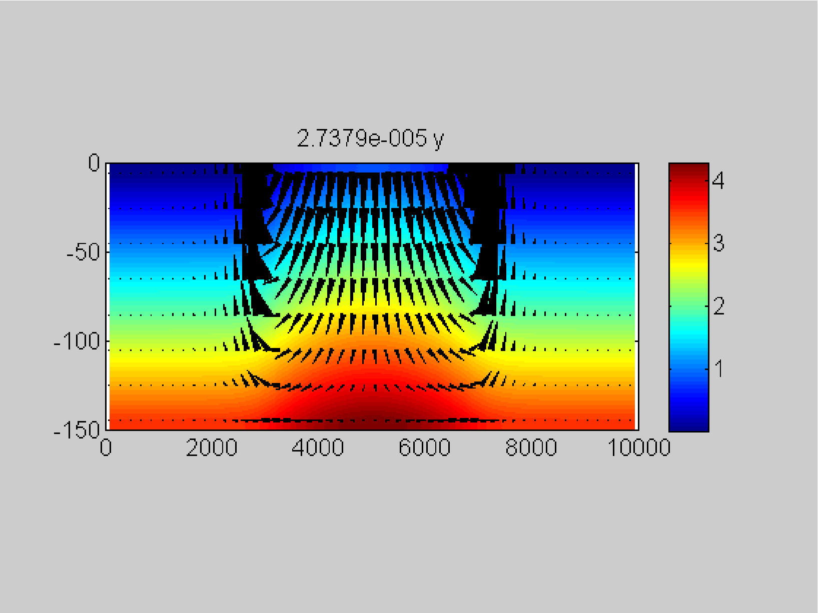
Case 2: Development of a freshwater lens



Evolution lens



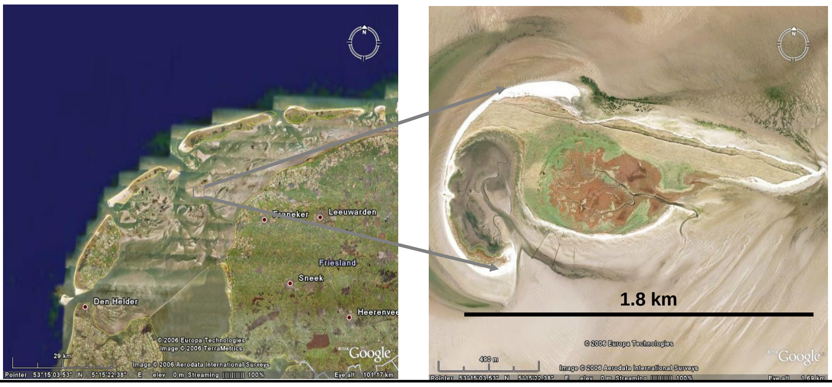
Evolution freshwater head



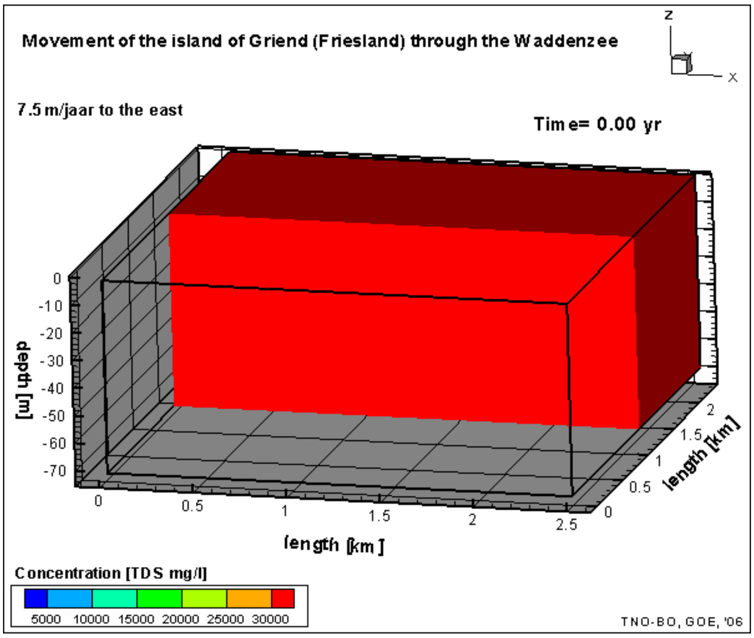
The island of Griend

Issues:

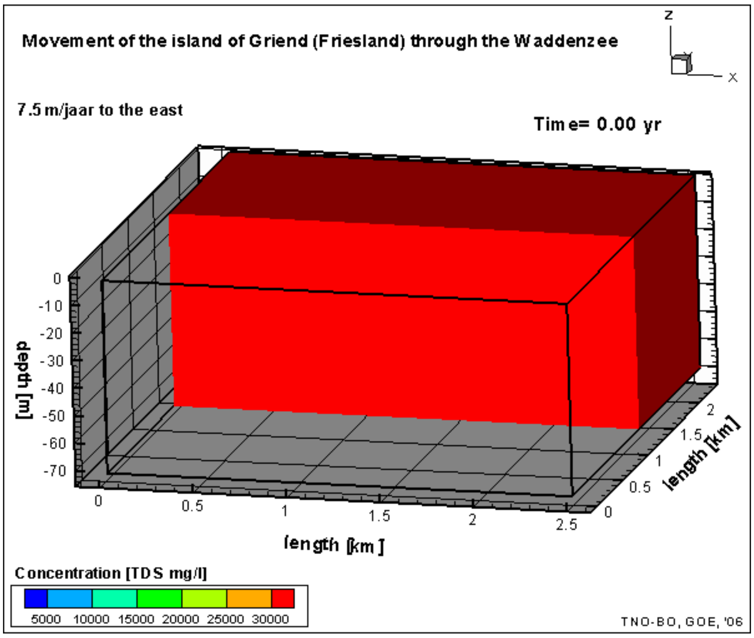
1. Small island moves ~7.5m per year to the east
2. Effect on the volume of the freshwater lens:
    - Can a lens be developed?
    - What is the thickness of the lens?



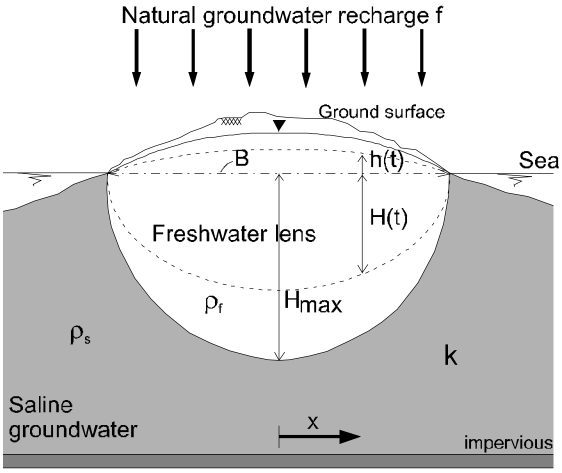
Movement of De Griend and creation of the lens



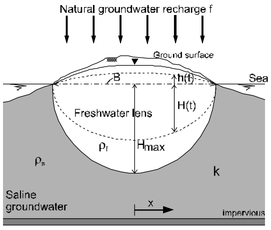
Movement of De Griend and creation of the lens



Case 2: Development of a freshwater lens

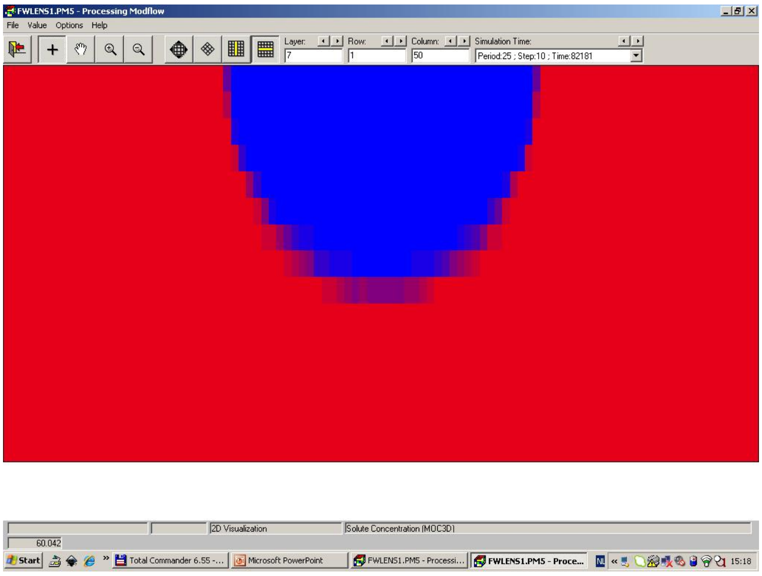


Case 2: Development of a freshwater lens



Parameters			
Layers	15	K_{hor}	20 m/d
Rows	1	T	200 m/d
Columns	100	Anisotropy K_{hor}/K_{ver}	10
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		

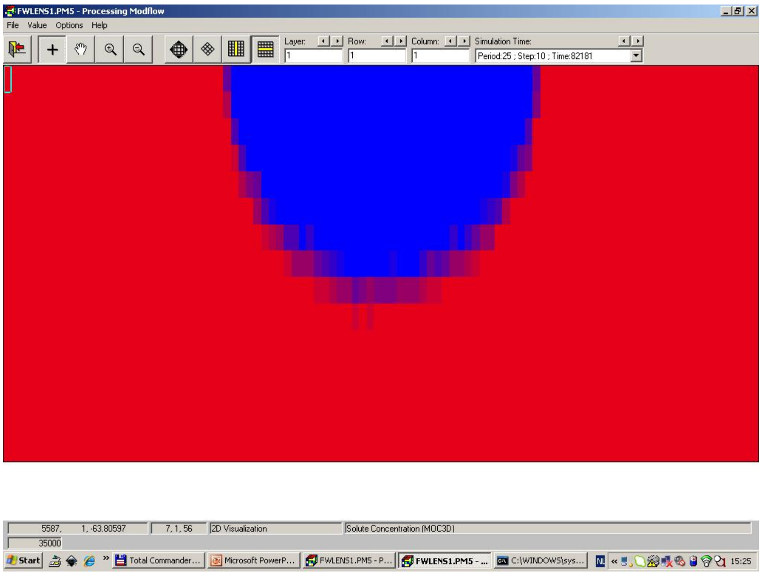
MOCDENS3D, no disp, 16part



Layer: 7 Row: 1 Column: 50 Simulation Time: Period:25 ; Step:10 ; Time:82181

60.042 | 2D Visualization | Solute Concentration (MOC3D)

MOCDENS3D, no disp, 4part

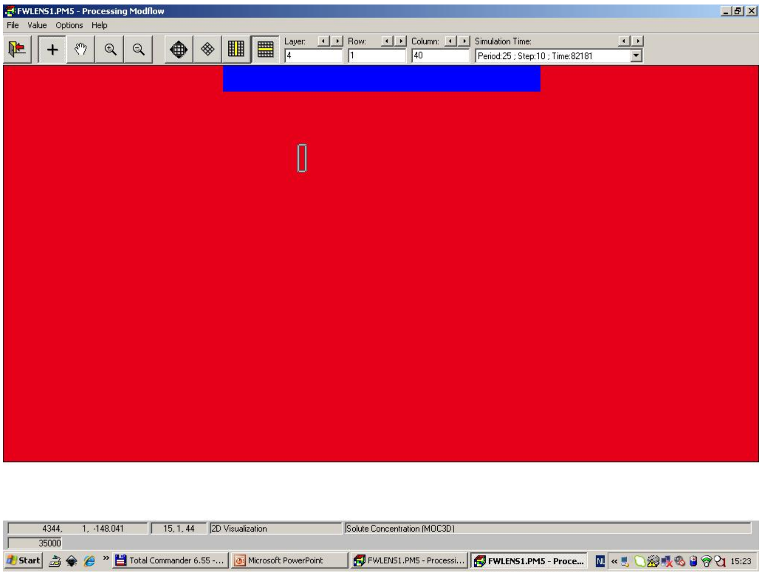


Layer: 1 Row: 1 Column: 1 Simulation Time: Period:25 ; Step:10 ; Time:82181

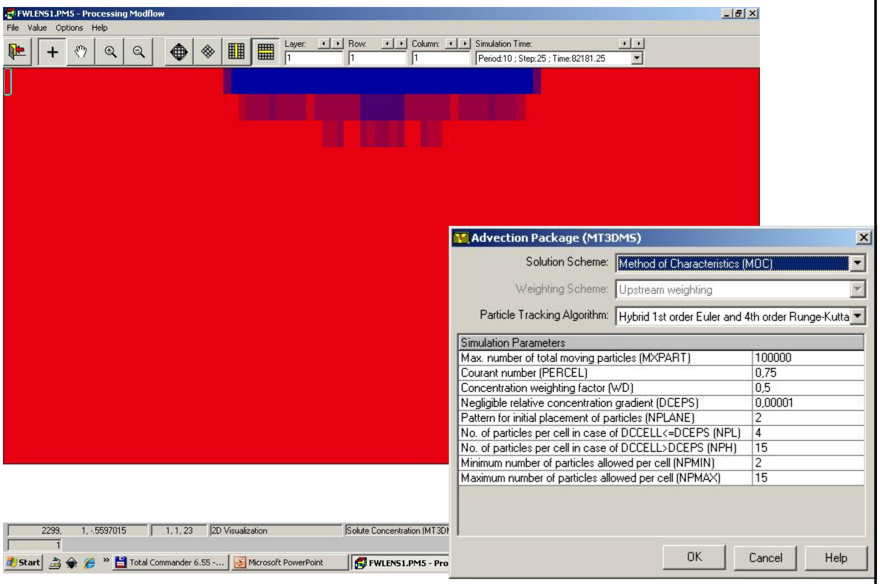
5587, 1, -63.80597 | 7, 1, 56 | 2D Visualization | Solute Concentration (MOC3D)

35000

MOCDENS3D, no disp, 1part



SEAWAT, MOC, NPLANE=2



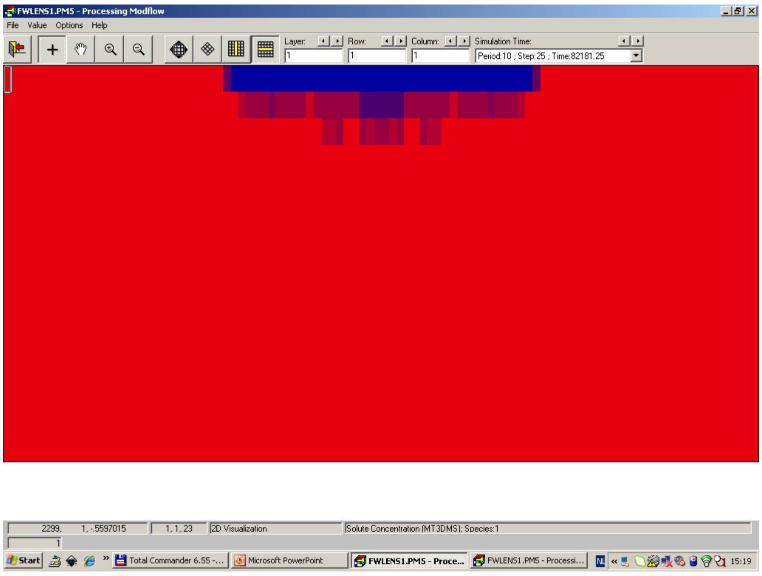
Solution Scheme: Method of Characteristics (MOC)

Weighting Scheme: Upstream weighting

Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta

Simulation Parameters	
Max. number of total moving particles (MXPART)	100000
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for initial placement of particles (NPLANE)	2
No. of particles per cell in case of DCCELL<=DCEPS (NPL)	4
No. of particles per cell in case of DCCELL>DCEPS (NPH)	15
Minimum number of particles allowed per cell (NPMIN)	2
Maximum number of particles allowed per cell (NPMAX)	15

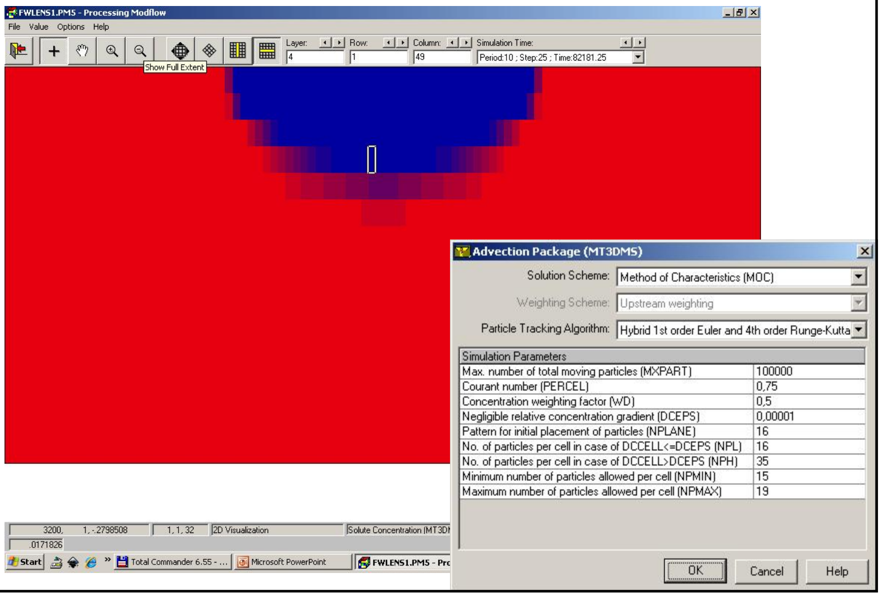
SEAWAT, MOC, 4.NPLANE=16



Layer: 1
Row: 1
Column: 1
Simulation Time: Period:10 ; Step:25 ; Time:82181.25

2299, 1, -.5597015
1, 1, 23
2D Visualization
Solute Concentration (MT3DMS); Species:1
1

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



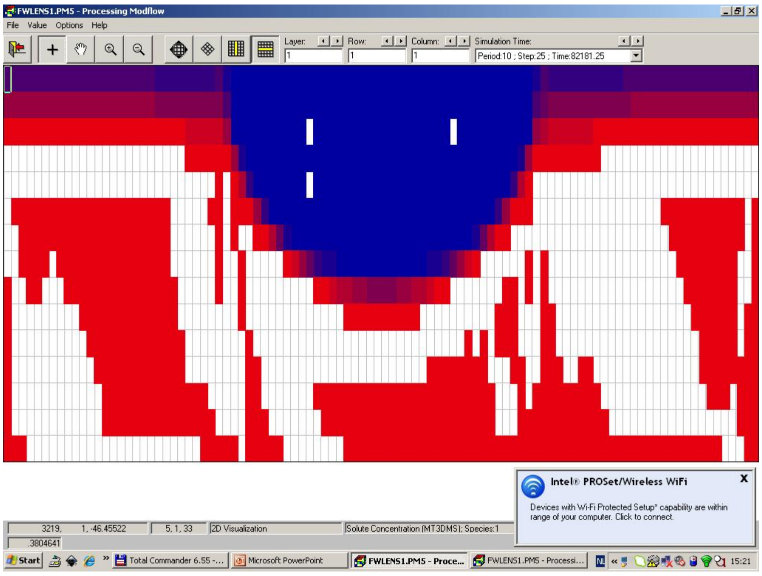
Layer: 4
Row: 1
Column: 49
Simulation Time: Period:10 ; Step:25 ; Time:82181.25

3200, 1, -.2798508
1, 1, 32
2D Visualization
Solute Concentration (MT3D
.0171826

Solution Scheme: Method of Characteristics (MOC)
Weighting Scheme: Upstream weighting
Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta

Simulation Parameters	
Max. number of total moving particles (MXPART)	100000
Courant number (PERCEL)	0,75
Concentration weighting factor (WD)	0,5
Negligible relative concentration gradient (DCEPS)	0,00001
Pattern for initial placement of particles (NPLANE)	16
No. of particles per cell in case of DCCELL<=DCEPS (NPL)	16
No. of particles per cell in case of DCCELL>DCEPS (NPH)	35
Minimum number of particles allowed per cell (NPMIN)	15
Maximum number of particles allowed per cell (NPMAX)	19

SEAWAT, ULTIMATE, 16.56sec



Layer: 1 Row: 1 Column: 1 Simulation Time: Period:10 ; Step:25 ; Time:82181.25

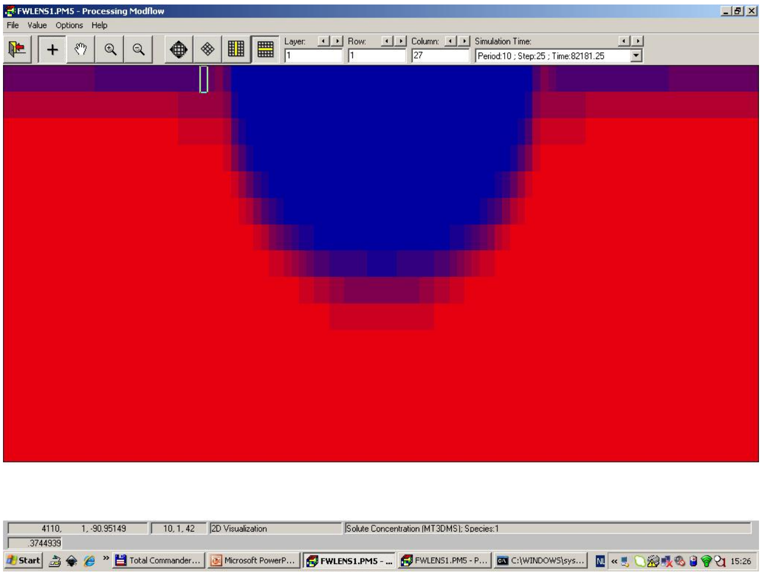
Intel® PROSet/Wireless WiFi

Devices with Wi-Fi Protected Setup* capability are within range of your computer. Click to connect.

3219, 1, -46.45522 | 5, 1, 33 | 2D Visualization | Solute Concentration (MT3DMS); Species:1

3804641

SEAWAT, MMOC, 8.5sec

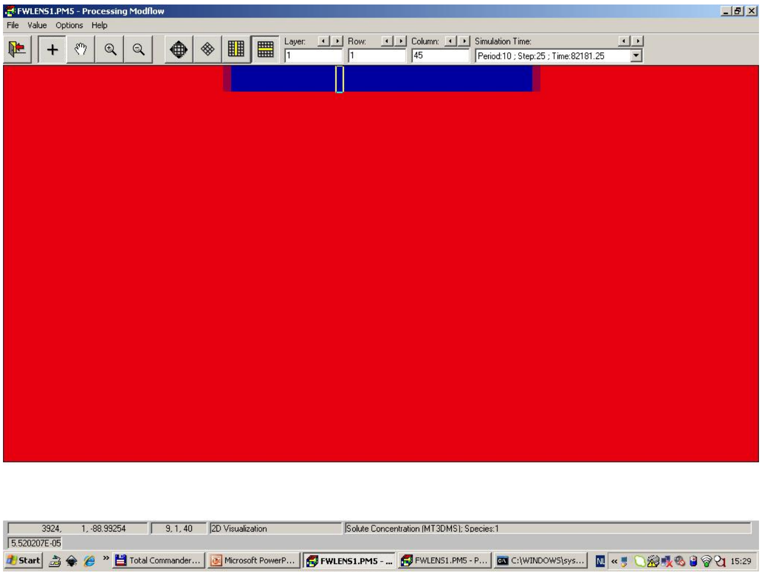


Layer: 1 Row: 1 Column: 27 Simulation Time: Period:10 ; Step:25 ; Time:82181.25

4110, 1, -90.95149 | 10, 1, 42 | 2D Visualization | Solute Concentration (MT3DMS); Species:1

3744939

SEAWAT, HMOC, 6.8sec



Layer: 1

Row: 1

Column: 45

Simulation Time: Period:10 ; Step:25 ; Time:82181.25

3924, 1, -88.99254

9, 1, 40

2D Visualization

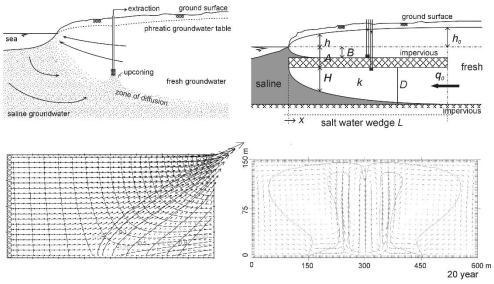
Solute Concentration (MT3DMS); Species:1

5.520207E-05

Analytical solutions

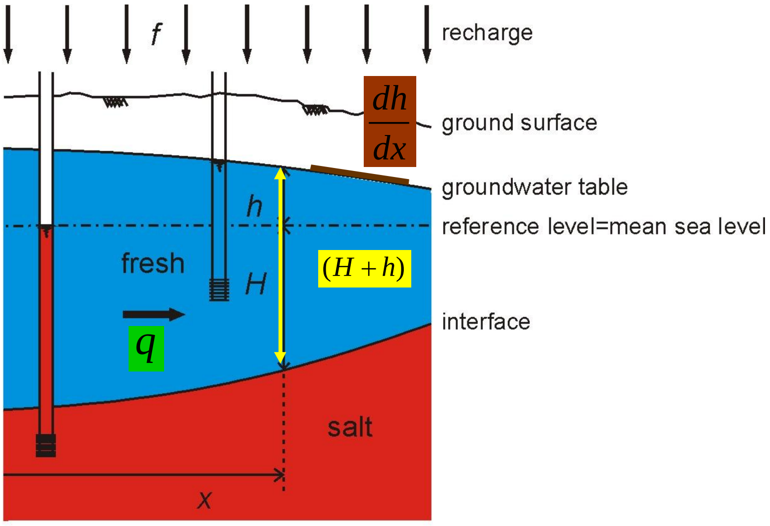
Analytical solutions

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



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

Unconfined aquifer (1D situation)



Unconfined aquifer (1D situation)

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

(II) Continuity $dq = fdx$

(III) BGH $h = \alpha H$

Unconfined aquifer (1D situation)

$dq = fdx$ integration gives $q = fx + C1$

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

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

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

Unconfined aquifer (1D situation)

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

integration gives

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

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

Unconfined aquifer (1D situation)

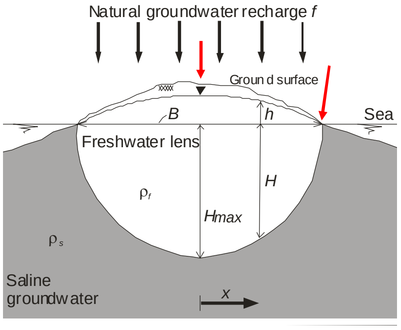
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}}$$

$$h = \alpha H$$

$$q = fx + C1$$

Example 1: Elongated island

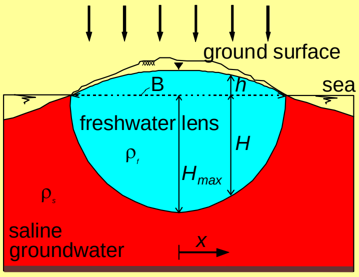
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}} \qquad q = fx + C1$$



Boundary conditions

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

Example of analytical solutions (I)



Depth of fresh-saline interface H

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

$$h = \alpha H$$

Maximal thickness lens

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

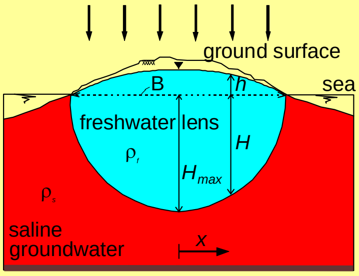
Volume lens

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

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

Lecture notes p. 32

Example of analytical solutions (I)



Depth of fresh-saline interface H

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

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

$$n_e = 0.35$$

Maximal thickness lens

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

Volume lens (wrong in lectures notes)

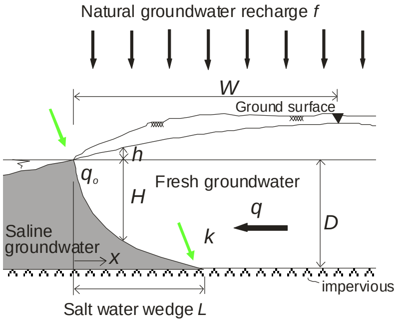
$$V = 35203\text{m}^3/\text{m}'$$

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

Lecture notes p. 32

Example 2: salt water wedge

$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}} \qquad q = fx + C1$$



Boundary conditions

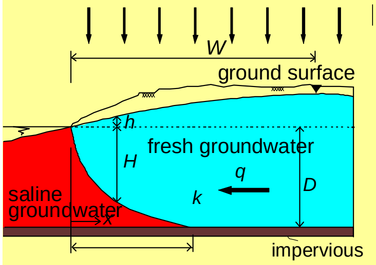
$$x = 0 : q = q_0 \rightarrow q_0 = -fW \rightarrow C1 = q_0$$

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

Length of salt water wedge

$$x = L : H = D$$

Example of analytical solutions (II)



Salt water wedge *L*

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

$$q_0 = -fW$$

$$h = \alpha H$$

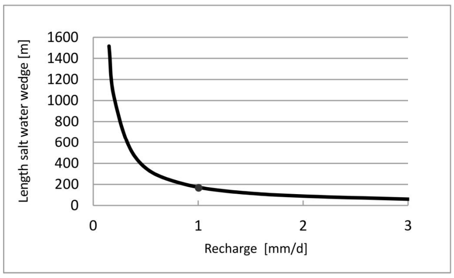
Example:

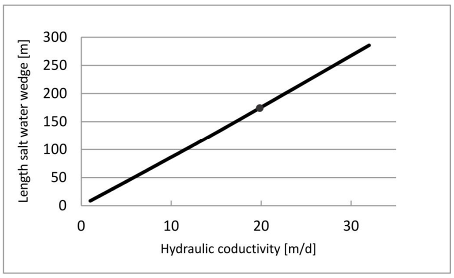
$$W = 3000\text{m}, f = 0.001\text{m/day}, \alpha = 0.020, k = 20\text{m/day}, D = 50\text{m}$$

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

Lecture notes p. 33

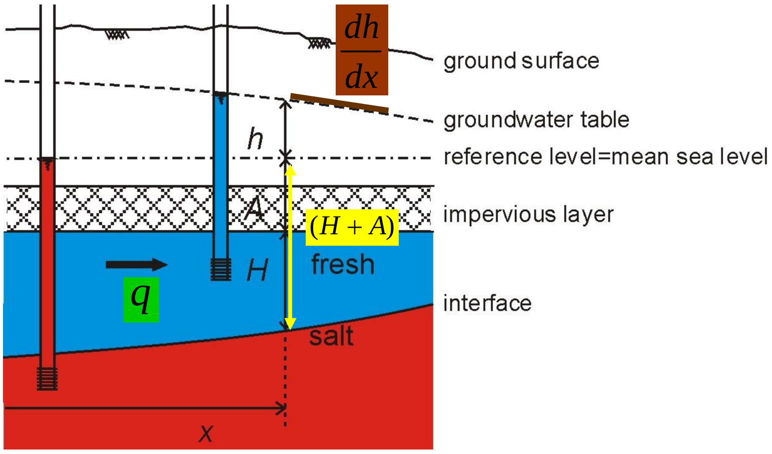
Length of the salt water wedge as a function of a. recharge and b. hydraulic conductivity





the dots resample with the example mentioned above

Confined aquifer (1D situation)



Confined aquifer (1D situation)

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

(II) Continuity $$q = q_o$$

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

Confined aquifer (1D situation)

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

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

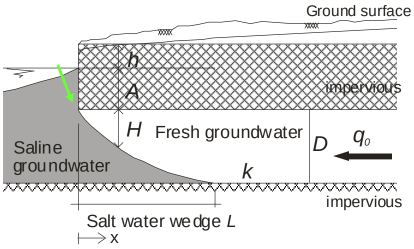
integration gives

$$\frac{1}{2}H^2=\frac{q_0x}{k\alpha}+C$$

$$H=\sqrt{-\frac{2q_0x}{k\alpha}+2C}$$

Example 3: salt water wedge confined aquifer

$$H=\sqrt{-\frac{2q_0x}{k\alpha}+2C}$$



Boundary condition

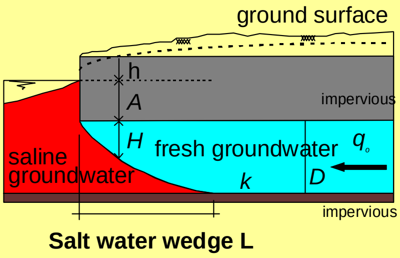
$$x=0:H=0\rightarrow C=0$$

$$H=\sqrt{-\frac{2q_0x}{k\alpha}}$$

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

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

Example of analytical solutions (III)



Length of salt water wedge

$$H = \sqrt{-\frac{2q_0x}{k\alpha}}$$

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

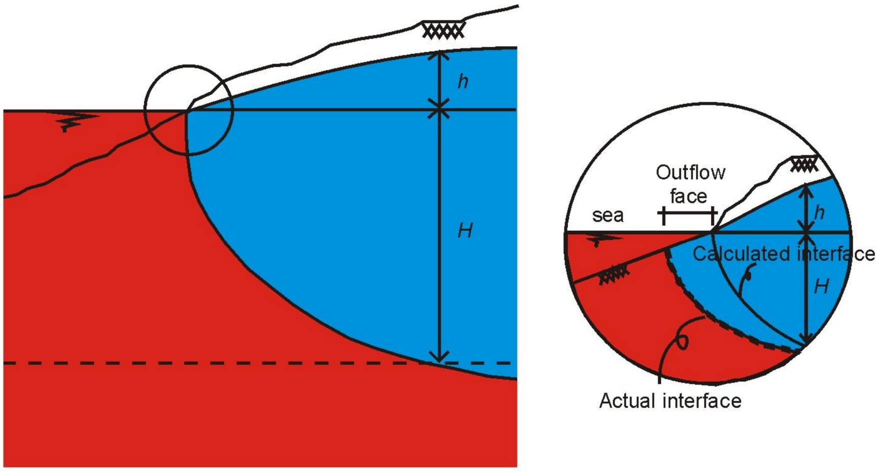
Example:

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

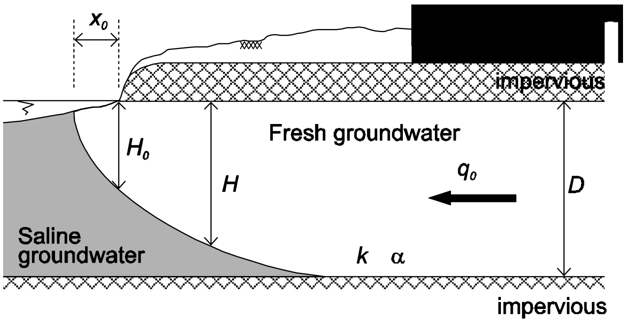
$$L = 250\text{m}$$

Lecture notes p. 35-36

Outflow face (Submarine Groundwater Discharge)



Outflow face (Submarine Groundwater Discharge)

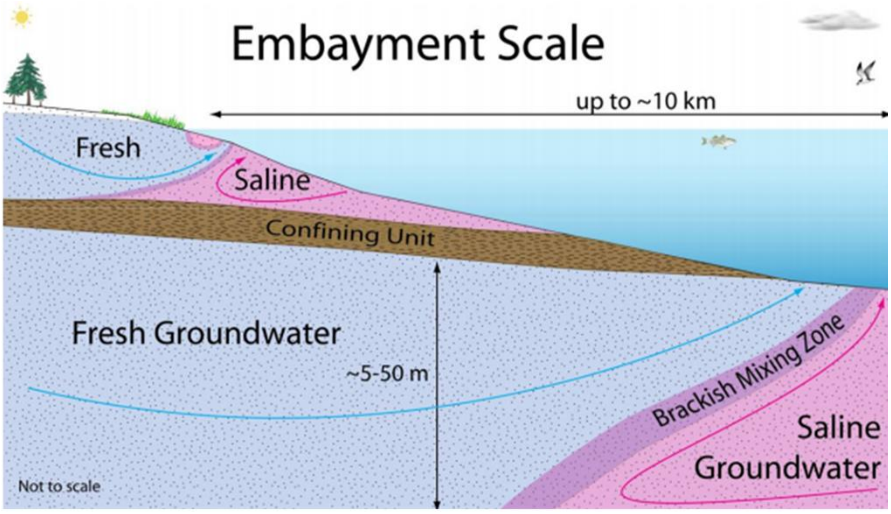


$$x_0 = \frac{q_0}{2k\alpha} \qquad H_0 = \frac{q_0}{k\alpha}$$ Glover (1959)

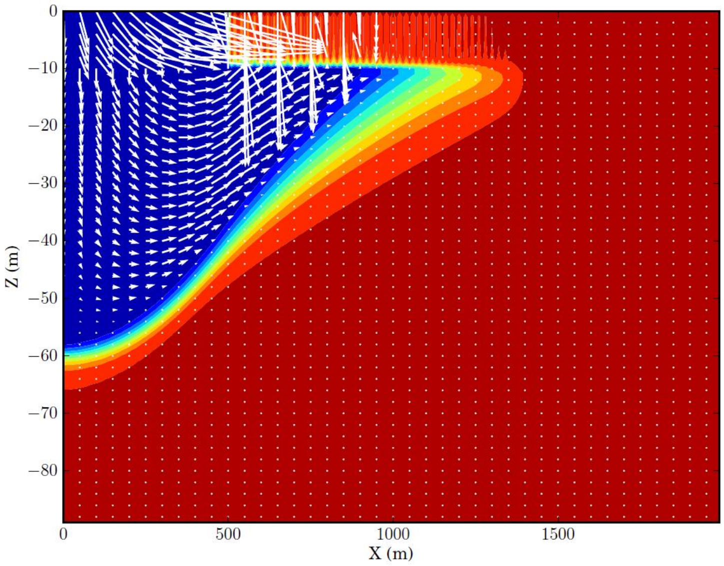
Example:
x_0= f*L/(2ka) = 0.001m/d*20000m/(2*20*0.025) = 20m (only!)

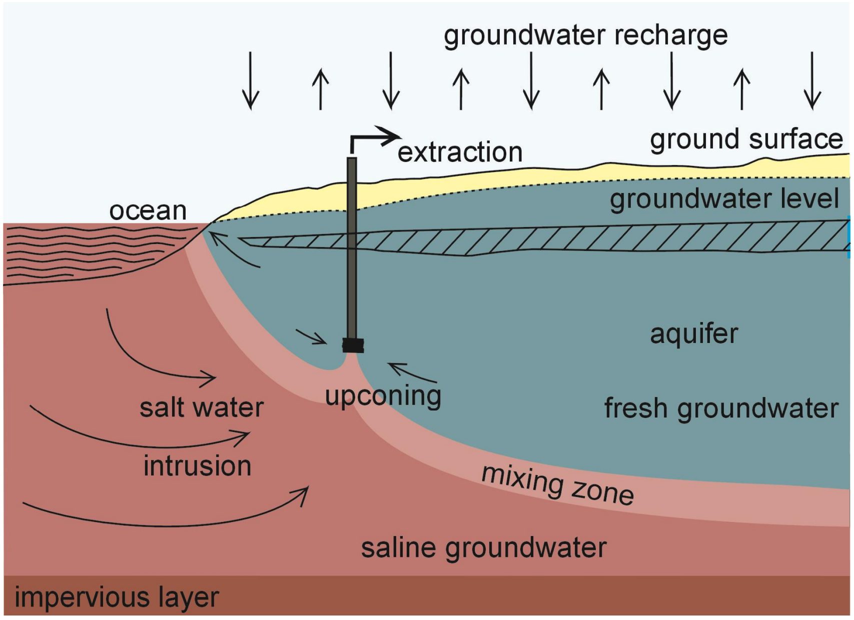
Note: no resistance layer offshore

Outflow face (Submarine Groundwater Discharge)

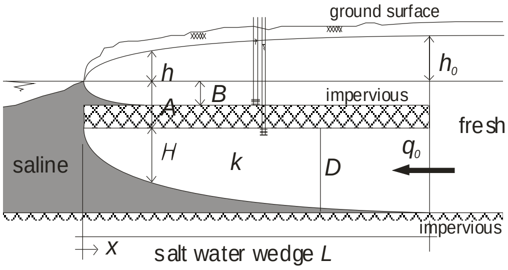


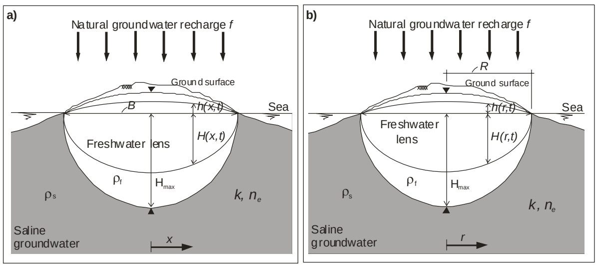
Outflow face (Submarine Groundwater Discharge)





See the lectures for more cases



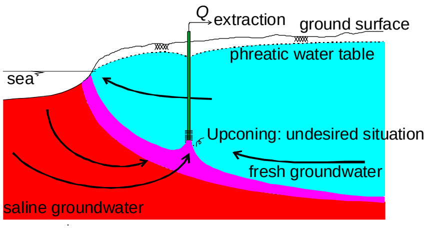


Upconing processes

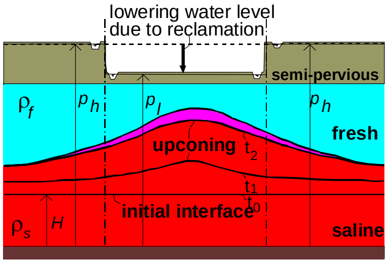
Introduction

Upconing of saline groundwater

Under an extraction well



Under a low-lying polder area



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

‘Solutions’: reduce extraction rate, abandon well, inundate polder

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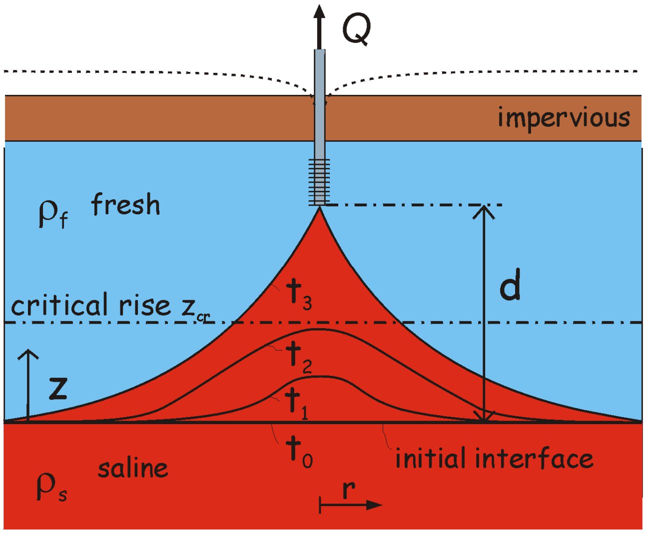
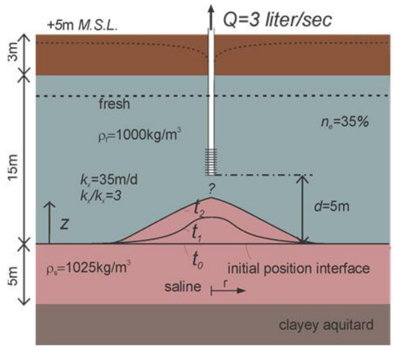
Examples of analytical solutions (IV)

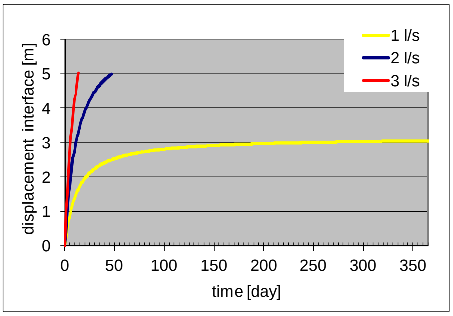
Upconing of saline groundwater under an extraction well



Lecture notes p. 44

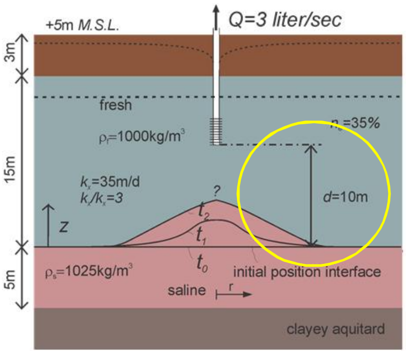
Situation Jurong Island: pilot extraction well

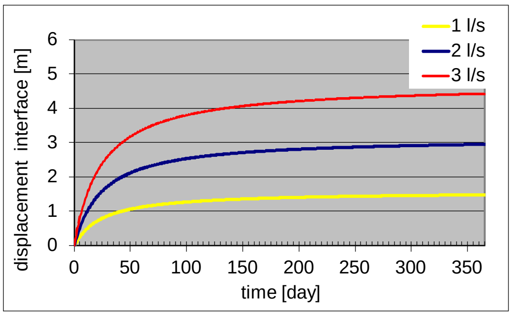




- Distance between well screen and initial interface: 5m
- Rapid upconing of interface, depending on extraction rate
- No saline groundwater in extraction well with scenario 1 l/s
- Good set-up for testing system

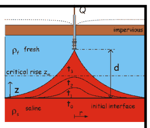
Situation Jurong Island: pilot extraction well: d=10m!





- Distance between well screen and initial interface: not 5 but 10m
- No saline groundwater in extraction well with all three scenarios
- Less interesting for testing system

Examples of analytical solutions (IV)



Upconing of saline groundwater under an extraction well

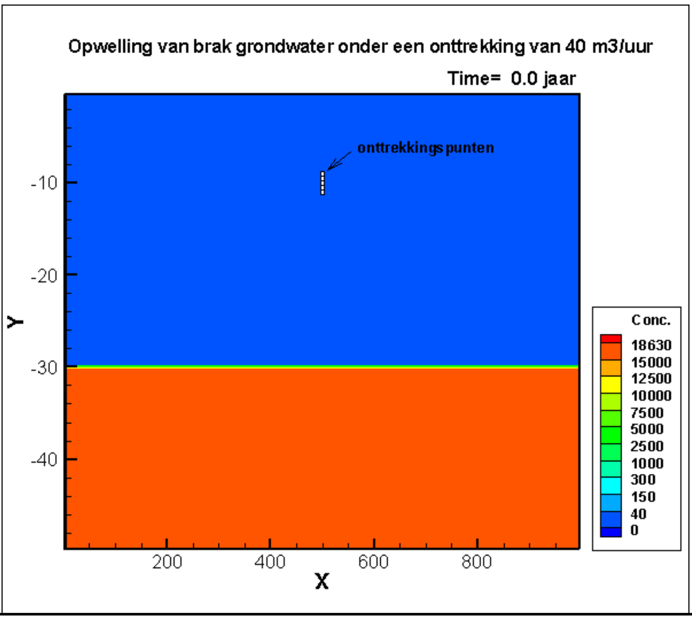
$$z(r,t) = \frac{Q}{2\pi\alpha k_x d}\left[\frac{1}{(1+R'^2)^{1/2}} - \frac{1}{[(1+\gamma')^2+R'^2]^{1/2}}\right]$$

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

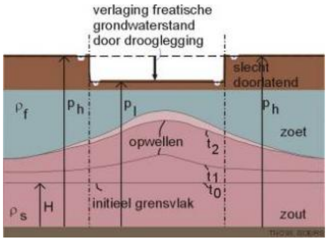
Dagan & Bear, 1968, J. Hydraul. Res 6, 1563-1573

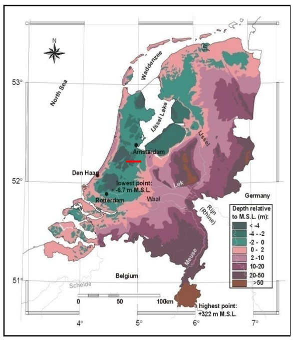
Lecture notes p. 44

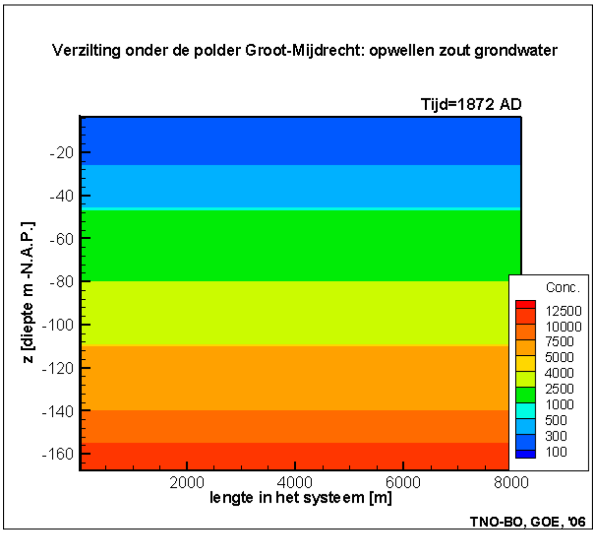
Upconing of salt under an extraction



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

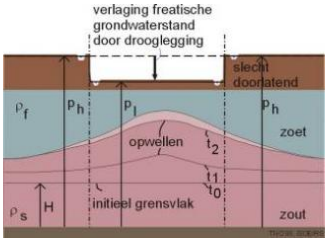


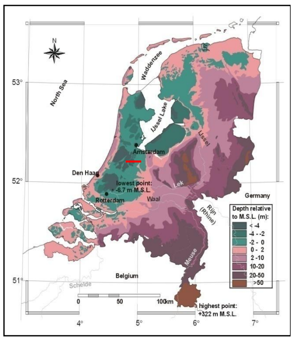


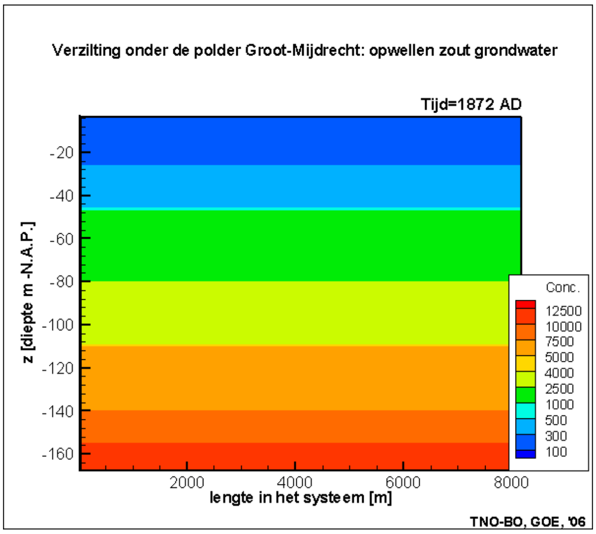

Verzilting onder de polder Groot-Mijdrecht: opwellen zout grondwater

TNO-BO, GOE, '06

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

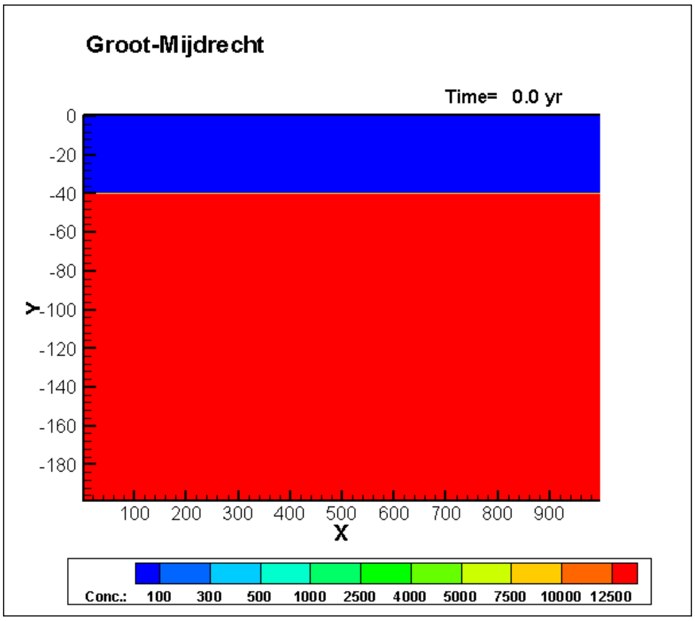




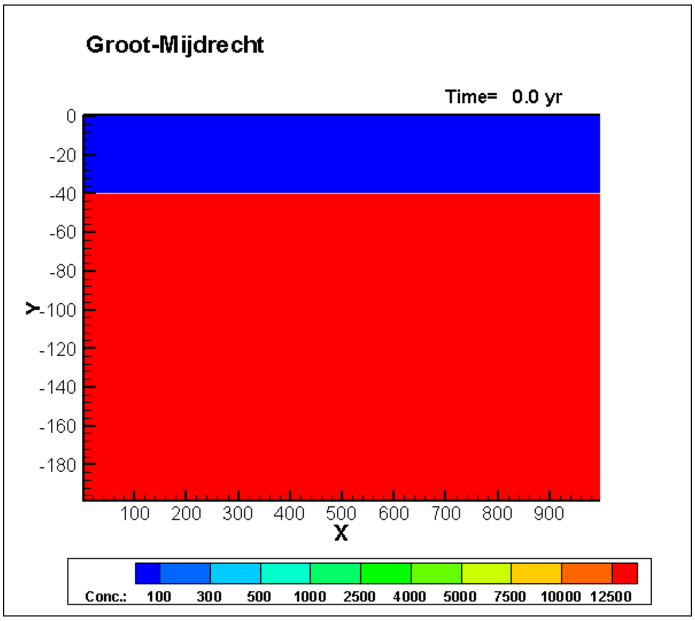

Verzilting onder de polder Groot-Mijdrecht: opwellen zout grondwater

TNO-BO, GOE, '06

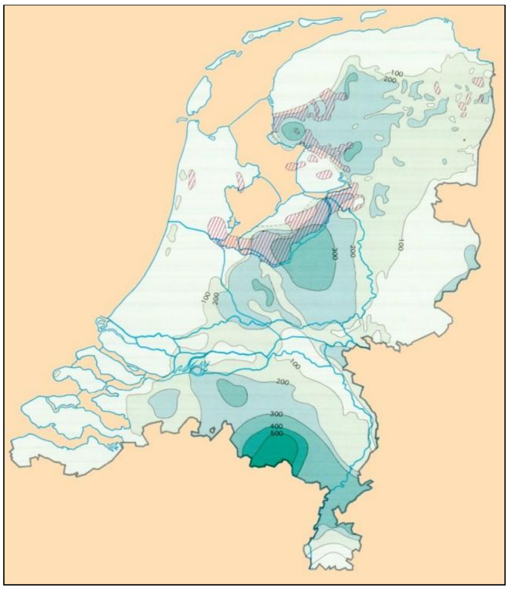
Upconing under a low-lying polder (Groot-Mijdrecht)



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

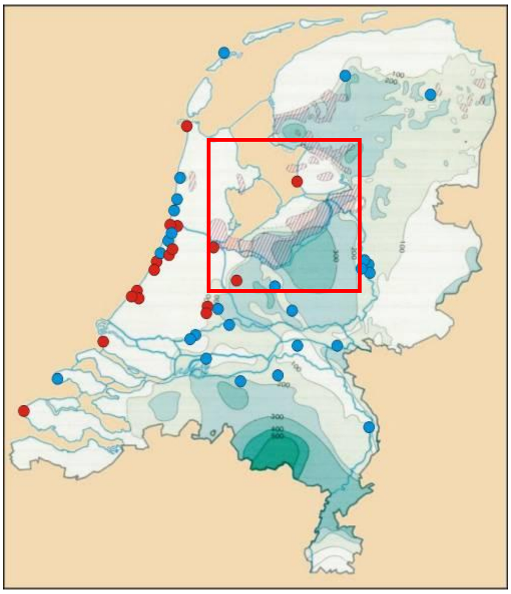


Fresh-salt interface (150 mg Cl^-/l)



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

Availability of fresh groundwater

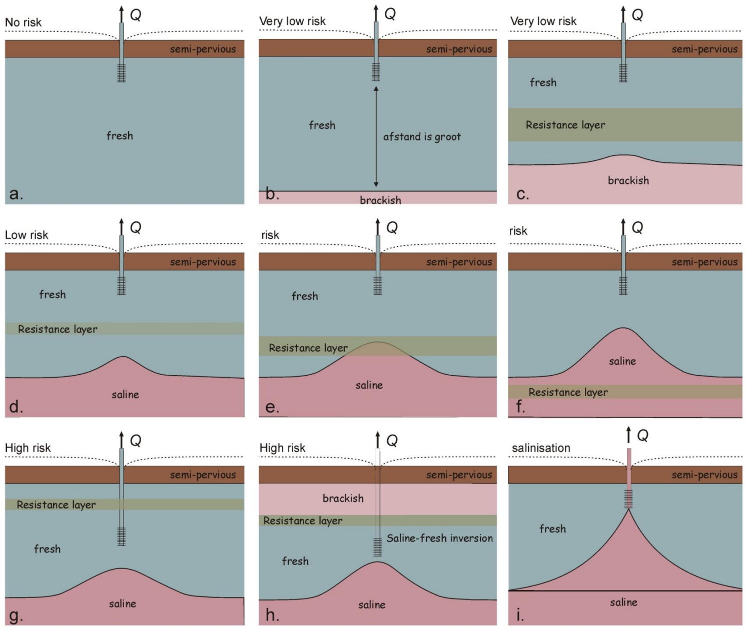


- 🟩 <100 m
- 🟩 100-200 m
- 🟩 200-300 m
- 🟩 300-400 m
- 🟩 400-500 m
- 🟩 >500 m
- ▨ >inversion (salt above fresh)

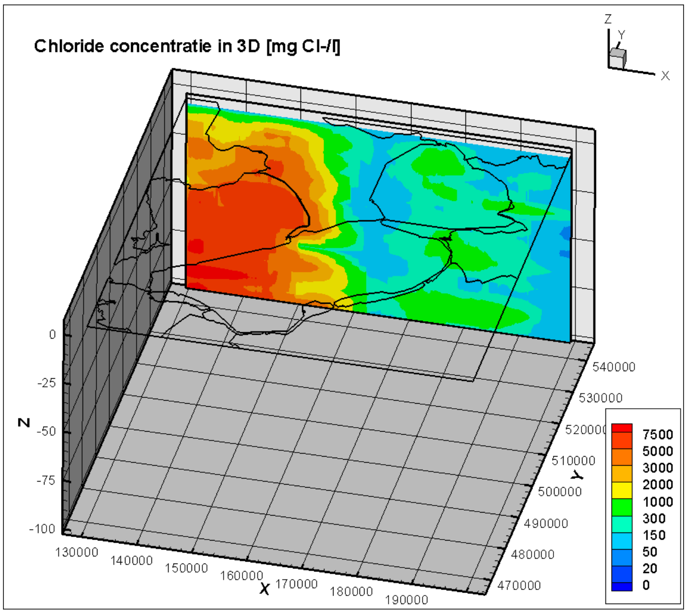
● Pumping stations with salinisation

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

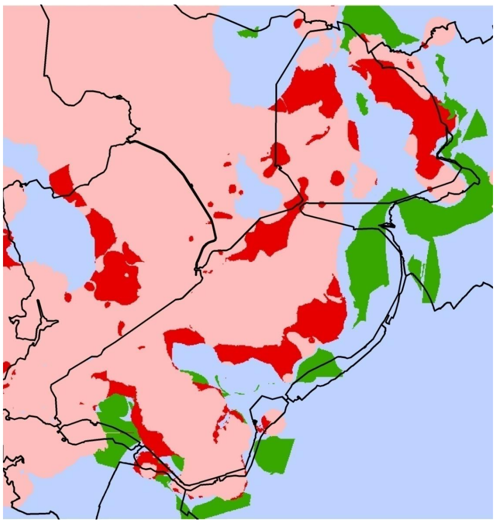
Different risks of upconing saline groundwater



Animation 3D Chloride concentration



Upconing in Flevoland



Risk depends on:

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

🟥 High risk

🟩 Low risk

🟦 Very low risk

Compensating measures

Possible solutions to stop salt water intrusion:

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

Tools to understand salt water intrusion:

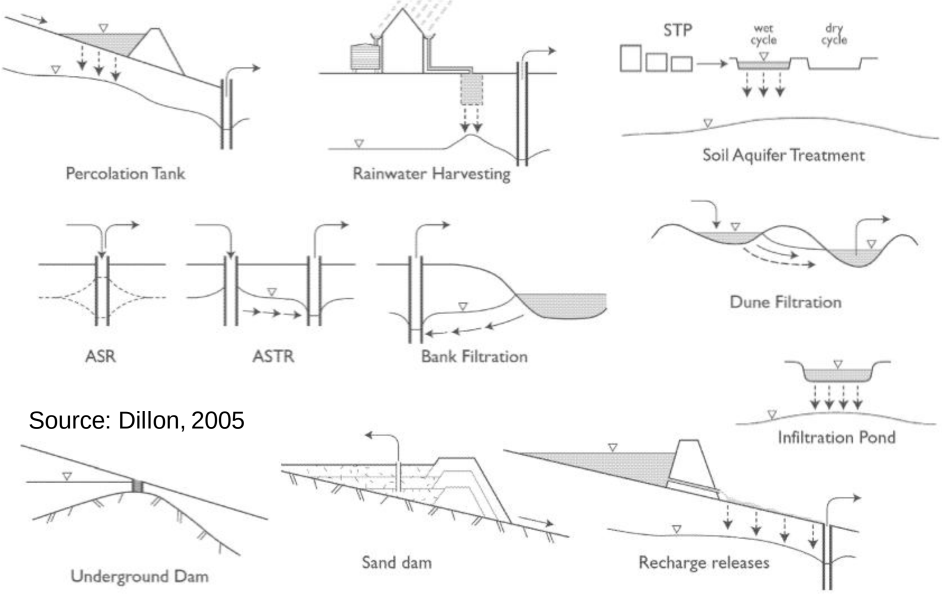
- Monitoring of salinities and piezometric levels
- Numerical modelling of salt water intrusion

Measures to compensate salt water intrusion

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

Aquifer Storage and Recovery

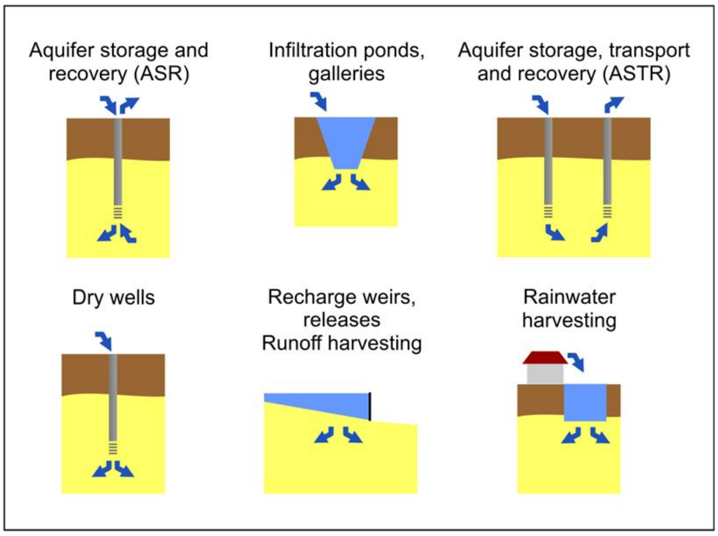
“potential to be a major contribution to UN Millennium Goals for Water Supply”



Source: Dillon, 2005

Aquifer Storage and Recovery / Managed Aquifer Recharge

“potential to be a major contribution to UN Millennium Goals for Water Supply”



Aquifer storage and recovery (ASR)

Infiltration ponds, galleries

Aquifer storage, transport and recovery (ASTR)

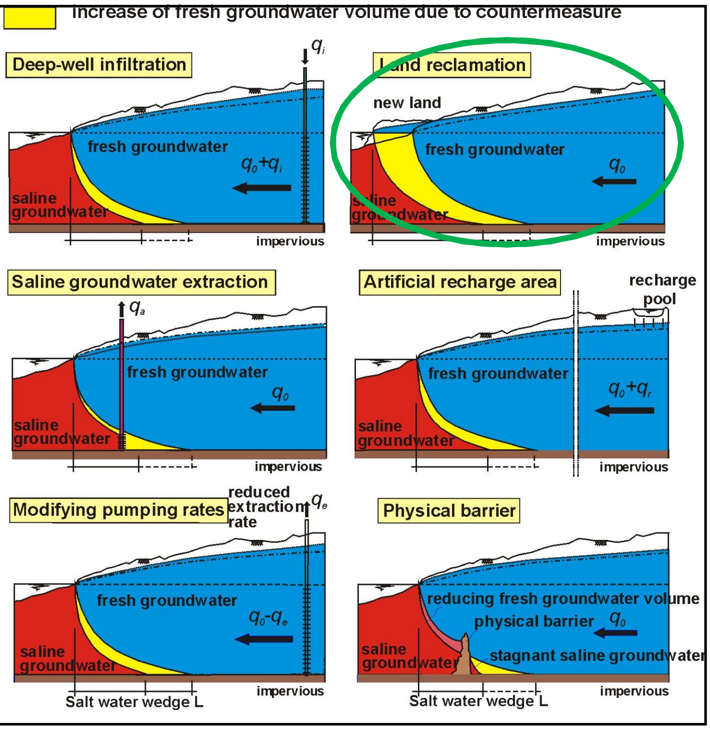
Dry wells

Recharge weirs, releases
Runoff harvesting

Rainwater harvesting

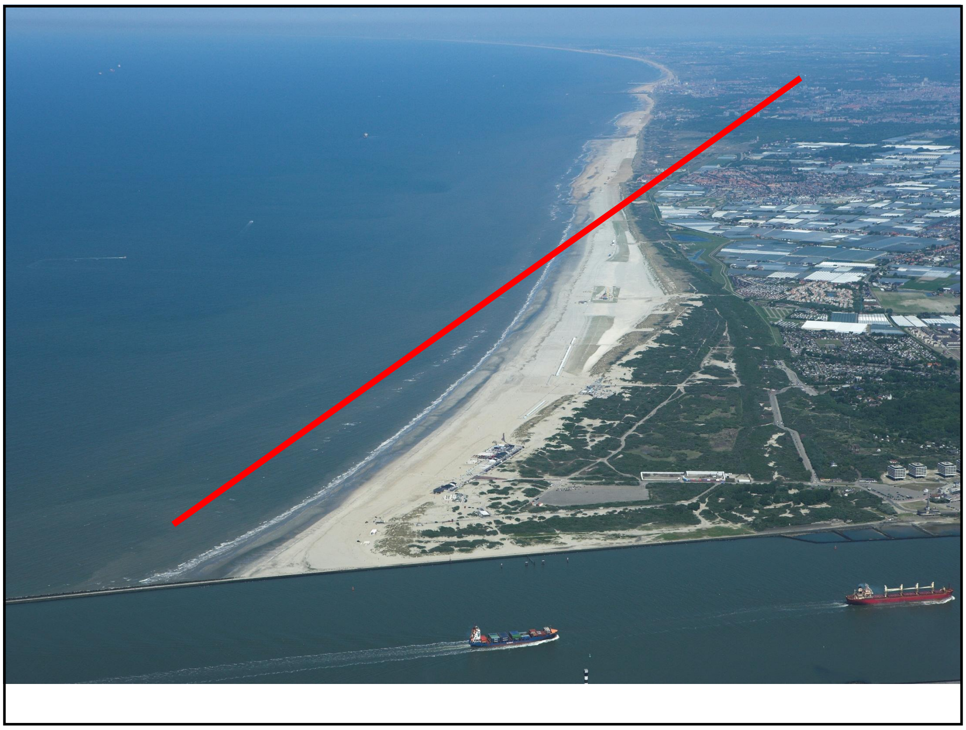
Source: Dillon, 2005

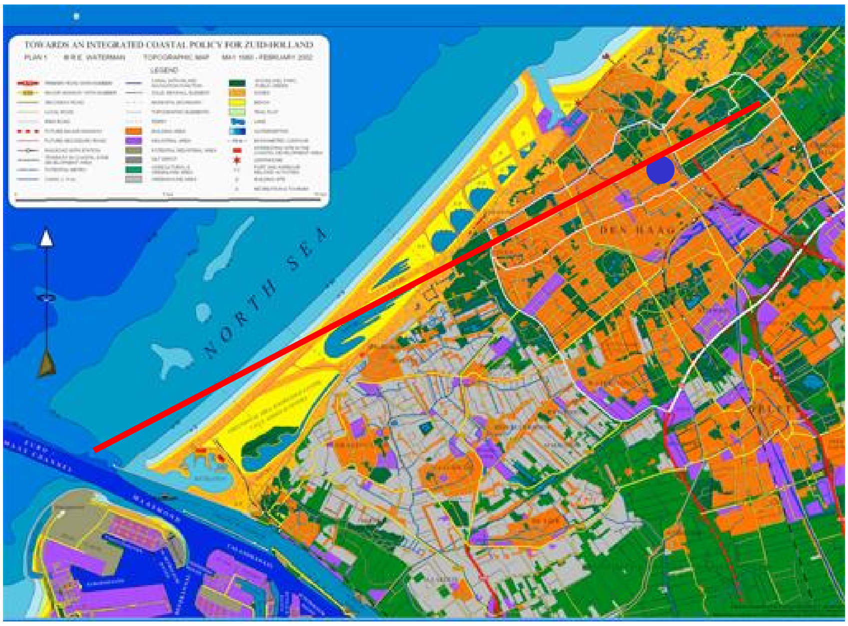
Technical
measures
to
compensate
salt
water
intrusion



Land reclamation

The Zandmotor: effects at the hinterland?

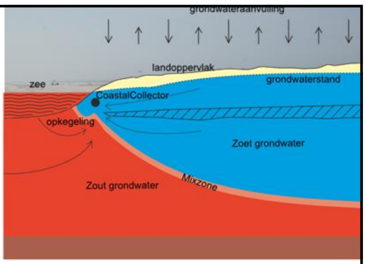


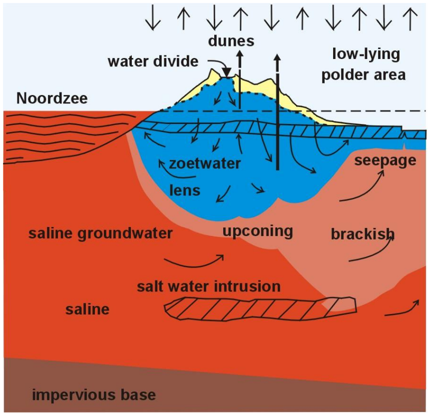

TOWARDS AN INTEGRATED COASTAL POLICY FOR ZUID-HOLLAND
PLAN 1
TOPOGRAPHIC MAP
LEGEND
NORTH SEA
DEN HAAG

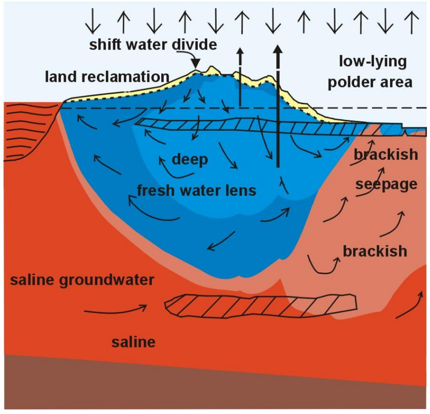
The Zandmotor: effects at the hinterland?

The Zandmotor

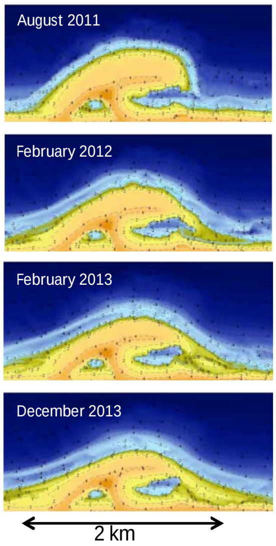
storage extra
fresh water?



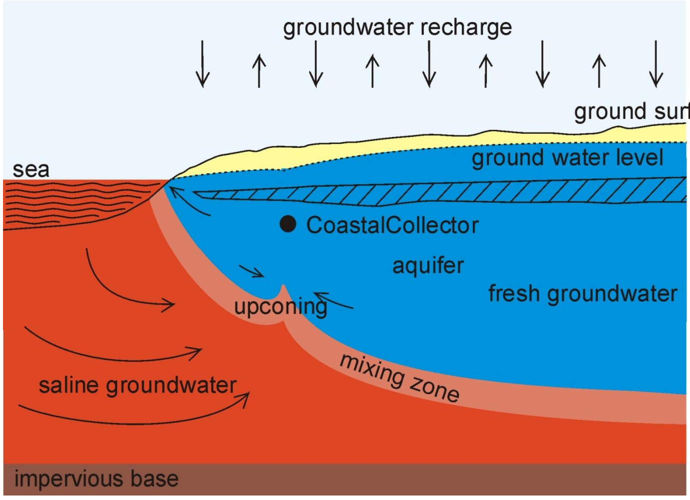




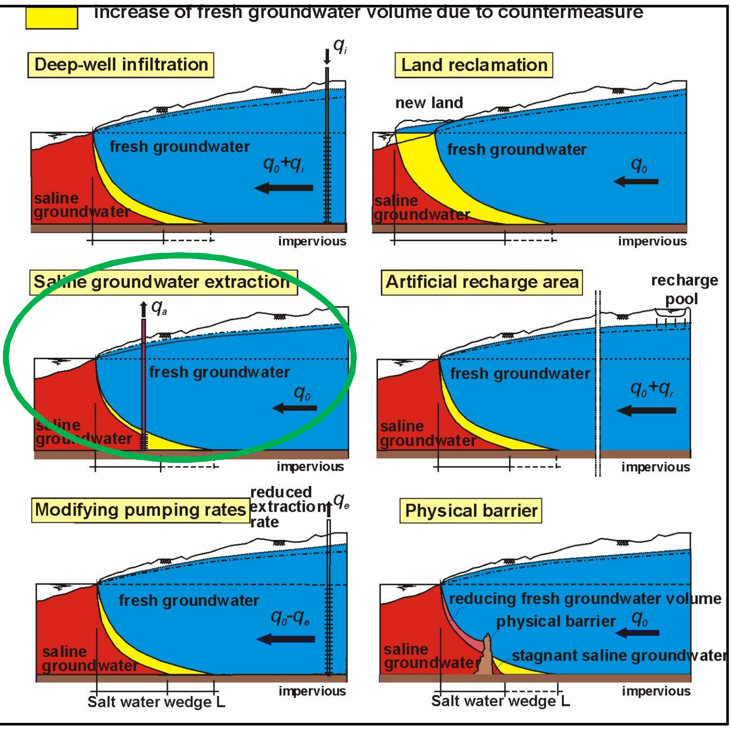

Jul 2011
Development of the Sand Motor
0 years
5 years
10 years
20 years


August 2011
February 2012
February 2013
December 2013
2 km

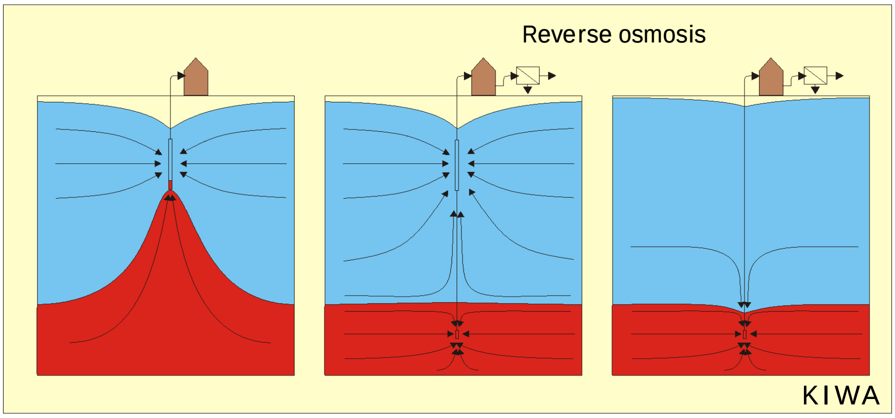
The Coastal Collector



Technical measures to compensate salt water intrusion



Solution: The Fresh Holder

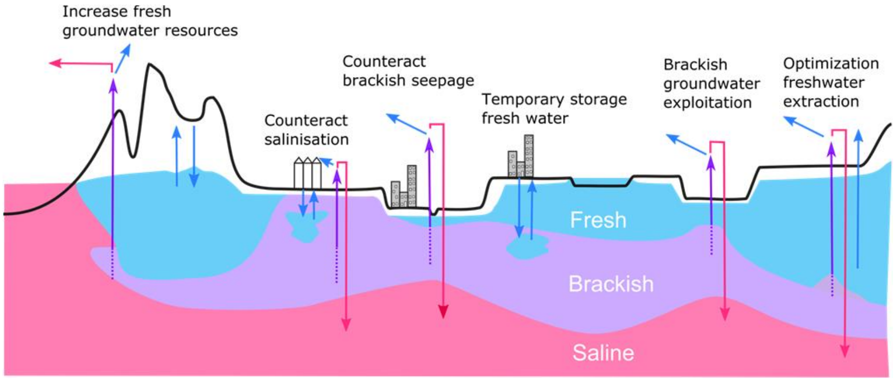


Upconing can be prevented by the extraction of brackish groundwater

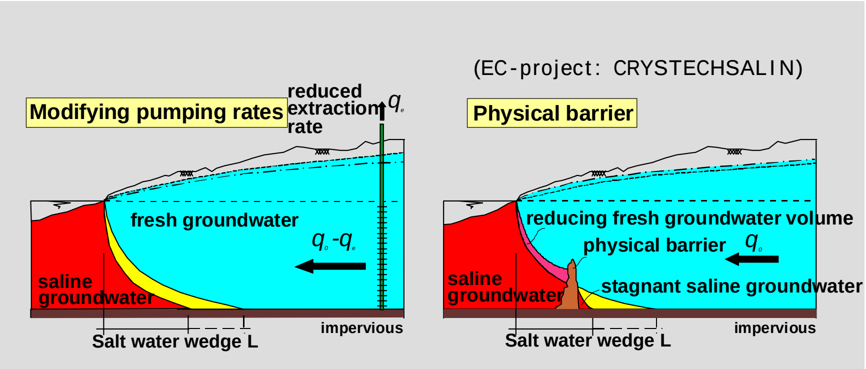
This brackish groundwater can be transformed to water of agricultural water quality by using the membrane filtration technique

---

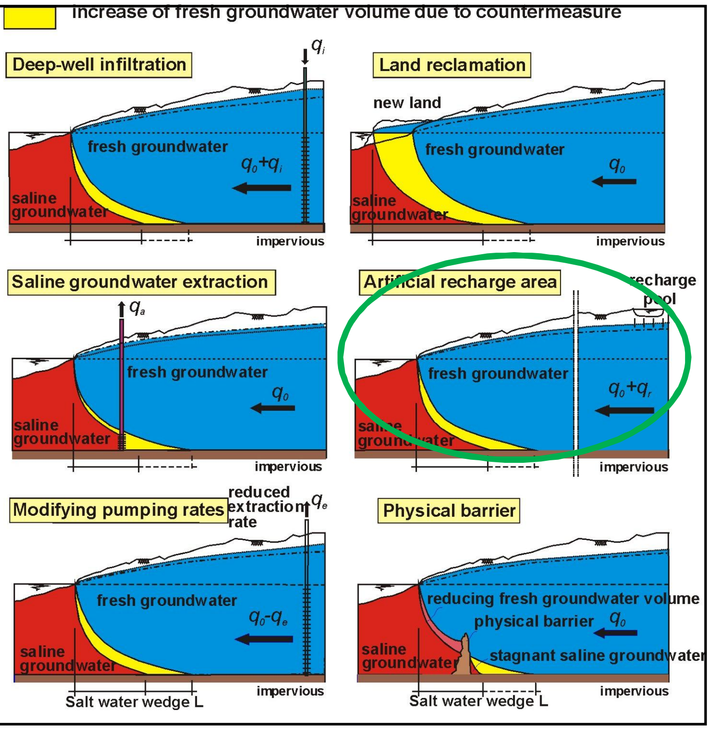
COASTAR: COastal Aquifer STorage And Recovery



Countermeasures of salt water intrusion



Technical measures to compensate salt water intrusion

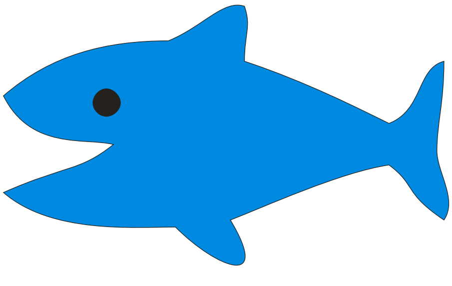


Base idea

Many local solutions for fresh groundwater supply can have regional impact

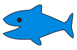
Starring

solution fresh groundwater supply



Starring

Local solution fresh groundwater supply



Starring

climate and global change

Starring

climate and global change

Solutions and responses

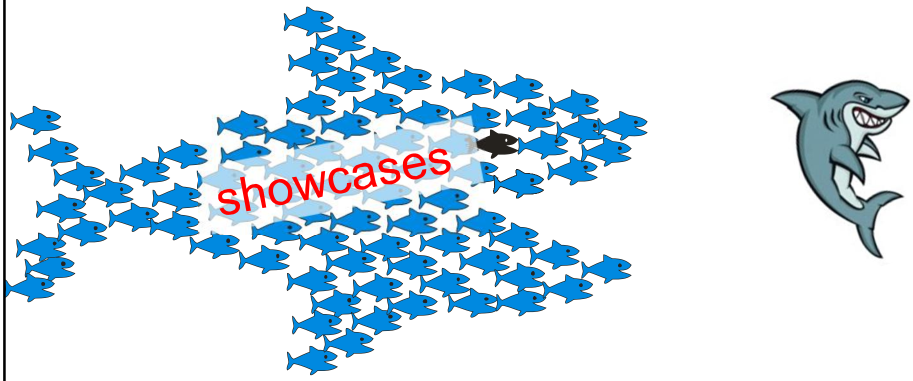
Local solution fresh
groundwater supply

climate and global change

What should be the response?

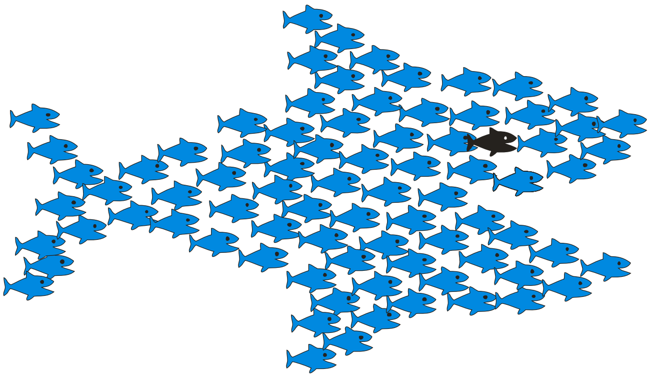
Many local solutions fresh groundwater supply

climate and global change



Many local solutions for fresh groundwater supply can have regional impact!

-upscaling local cases to regional strategy
-assess economical feasibility
-increase impact: communicate our showcases
-working together

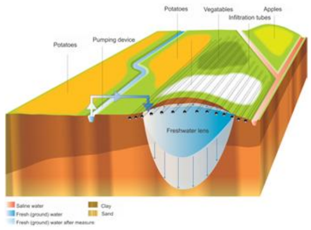


Aquifer Storage and Recovery in the coastal zone

www.go-fresh.info

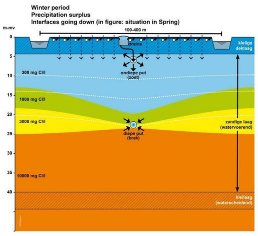
Goal:
Increase fresh groundwater resources in saline seepage areas in the southwestern part of the Dutch Delta
Methods:
3 pilot studies: infiltration of fresh water in times of water excess and extraction in times of droughts

Many small local solutions together can be enough for a regional fresh water supply



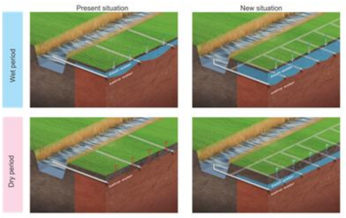
Creekridge Infiltration Test

Increase fresh water in creek ridge by injection of fresh surface water and extraction of saline groundwater



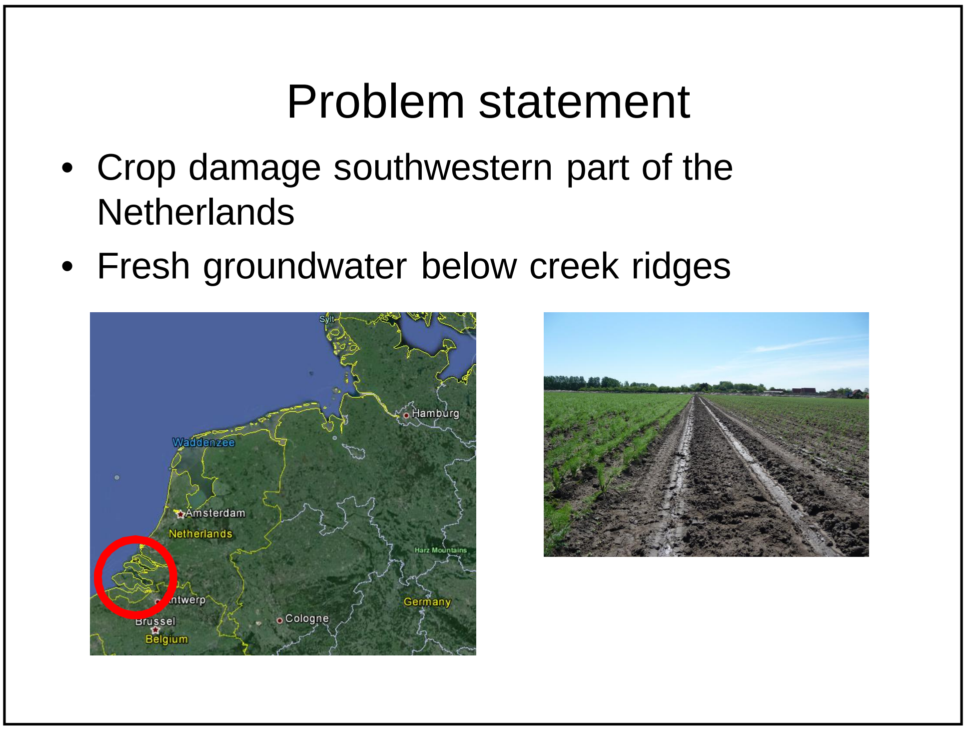
The Freshmaker

Increase fresh water volume in creek ridge by passive infiltration via drainage



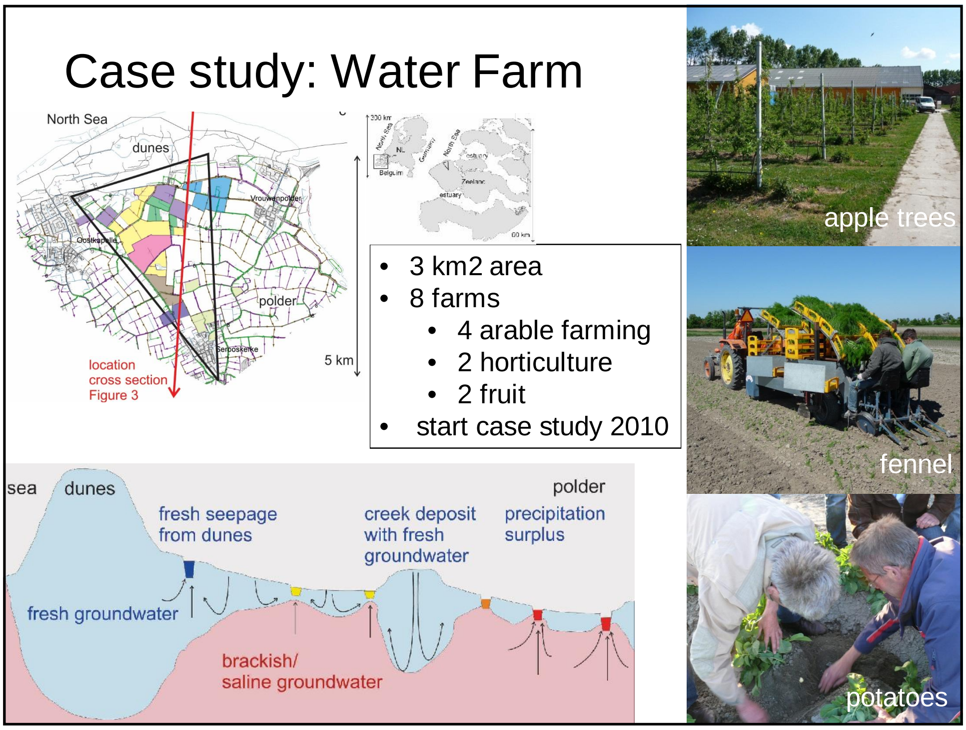
Drains2Buffer

Maintain fresh water volume in shallow rainwater lenses by smart deep controlled drainage



Problem statement

- Crop damage southwestern part of the Netherlands
- Fresh groundwater below creek ridges

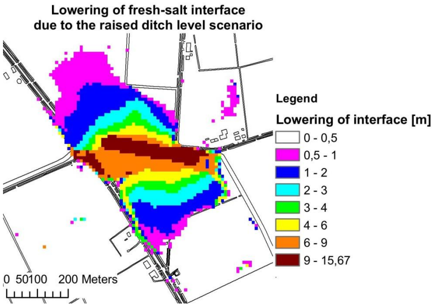


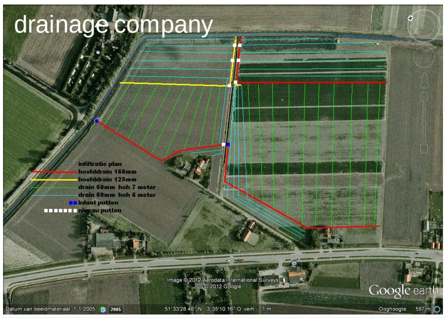
Case study: Water Farm

- 3 km2 area
- 8 farms
  - 4 arable farming
  - 2 horticulture
  - 2 fruit
- start case study 2010

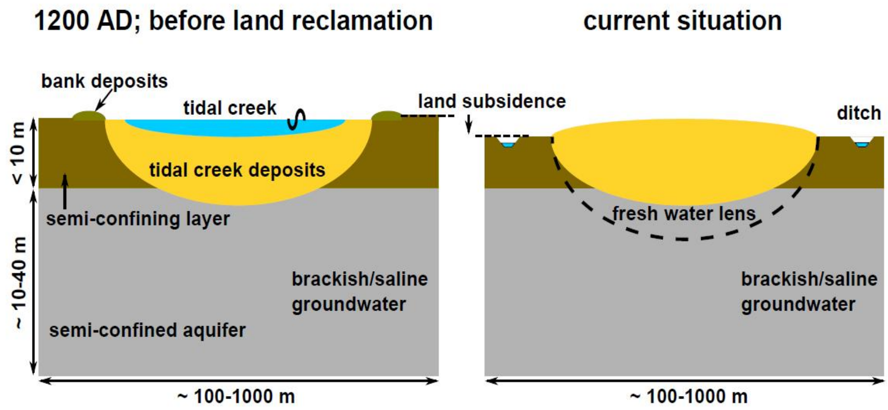
- measures
- communication to outside world

Researchers: scenario analysis



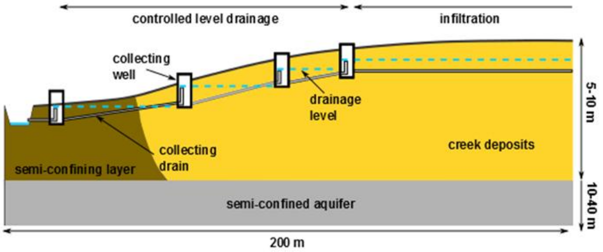


Creek ridges

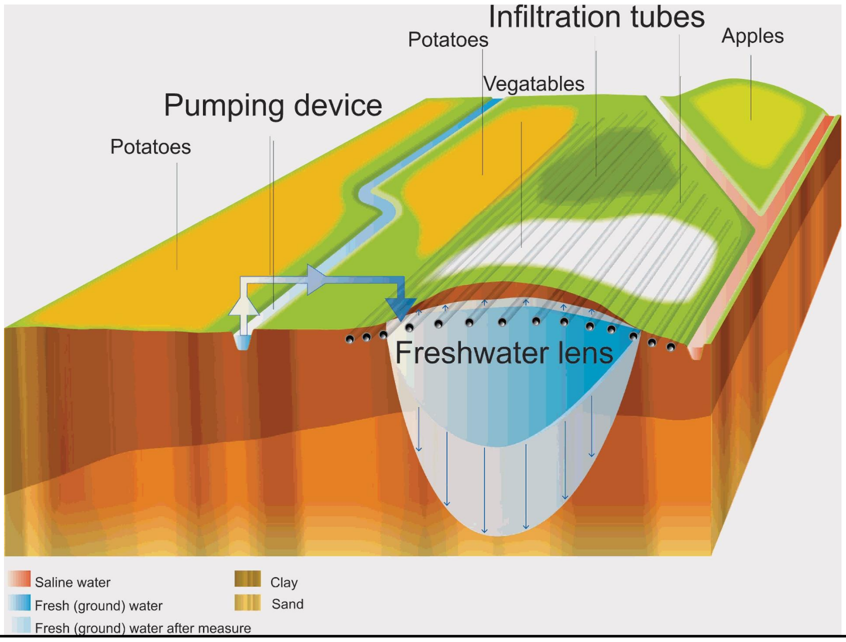


Measure

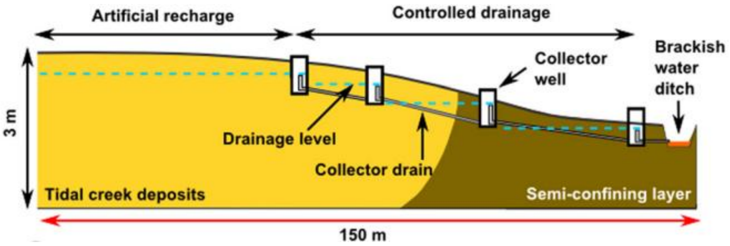
- Controlled level drainage
- Increase groundwater level

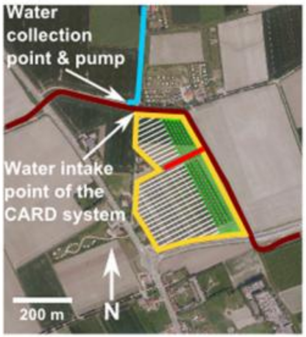


Creekridge Infiltration System



Concept of CARD and pilot layout



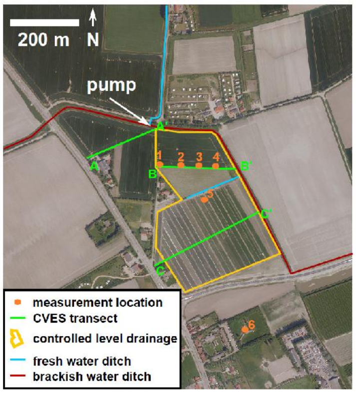


Legend

- 🟨 Extent CARD system
- 🟥 Location of the cross section show in a
- 🟦 Fresh water ditch
- 🟥 Brackish/saline water ditch
- ▨ Artificial recharge
- 🟩 Controlled drainage

20170615:

Installation of drainage and monitoring network

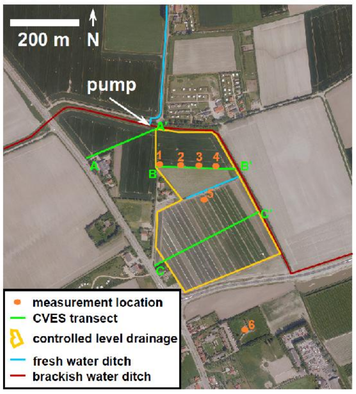


various types of field measurements

Different types of field measurements applied

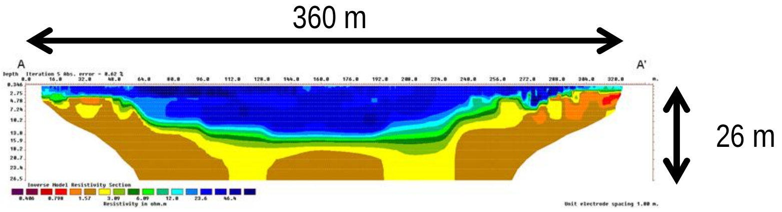
Measurement type	Purpose
Pressure transducers[a]	Groundwater levels
Sampling using piezometer nest	EC_{w20}
SLIMFLEX[b]	EC_{bulk}
CPT[c]	Lithology and EC_{bulk}
CVES[d]	EC_{bulk}
SMD[e]	EC_{bulk}

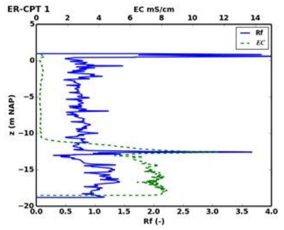
- a. Schlumberger, The Netherlands (type ‘ Diver ’)
- b. Deltares, The Netherlands
- c. Fugro, The Netherlands
- d. ABEM, Sweden
- e. Imageau, France



Key field observations (1)

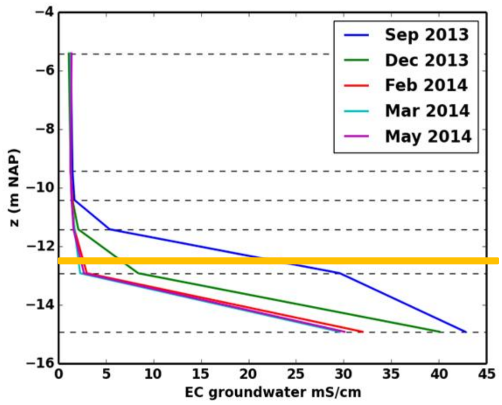
- Fresh groundwater up to -12 m NAP





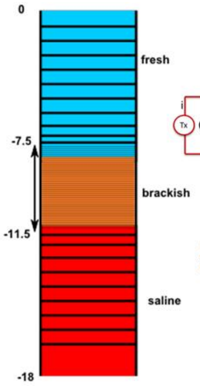
Key field observations (2)

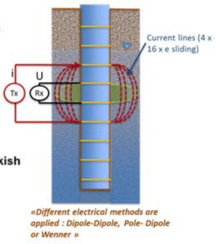
- Freshening up to 2m



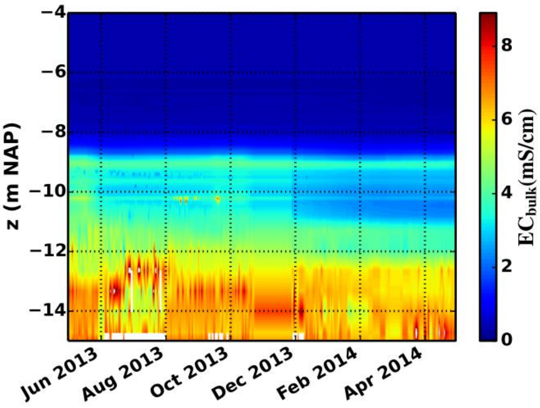
thin, low permeable layer

Subsurface Monitoring Device (SMD): Monitoring salinities



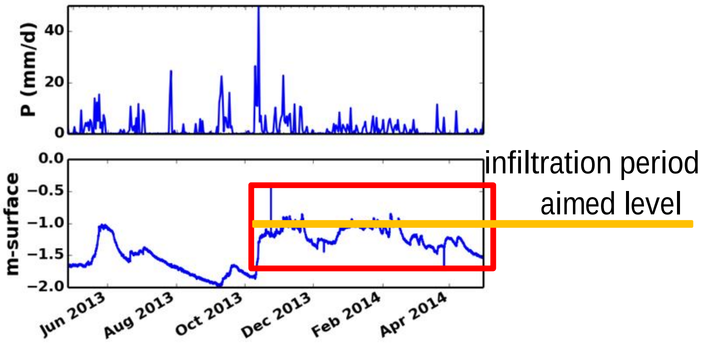


«Different electrical methods are applied : Dipole-Dipole, Pole- Dipole or Wenner »



Key field observations (3)

- Groundwater levels and precipitation

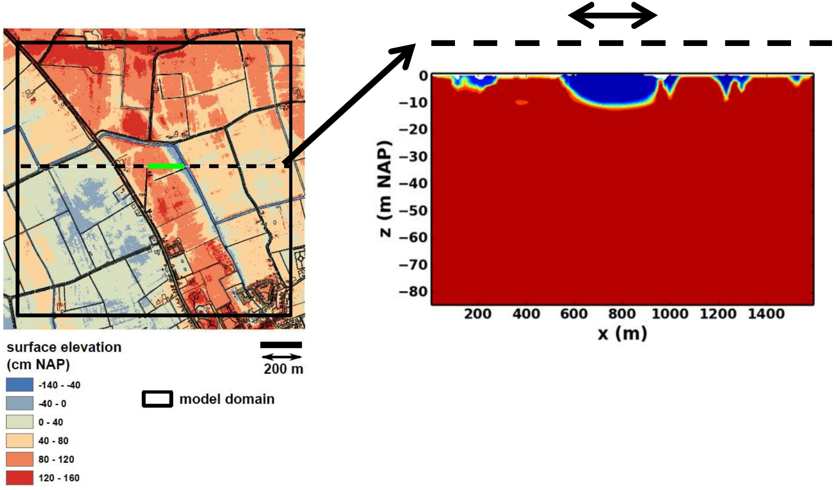


infiltration period

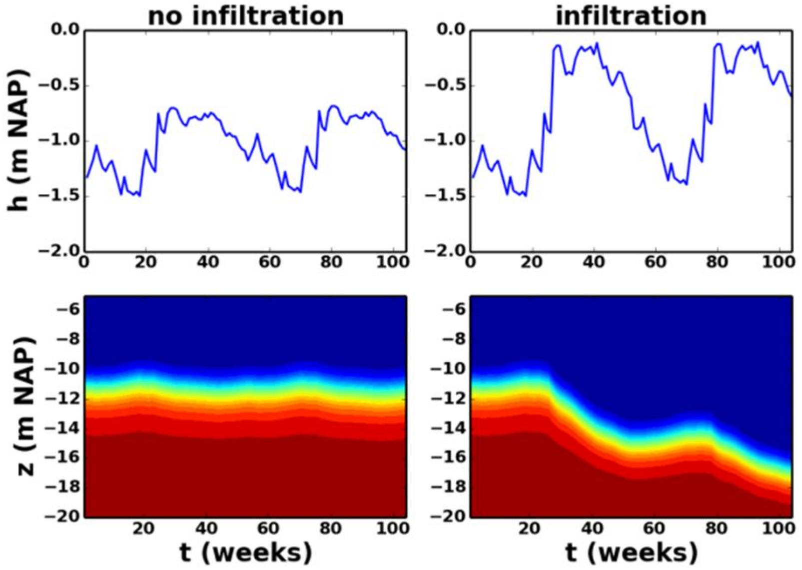
aimed level

Modeling

creek ridge



Influence of infiltration



Example NL:
Salt resistant crops on salty boils

Cl-conc seepage:

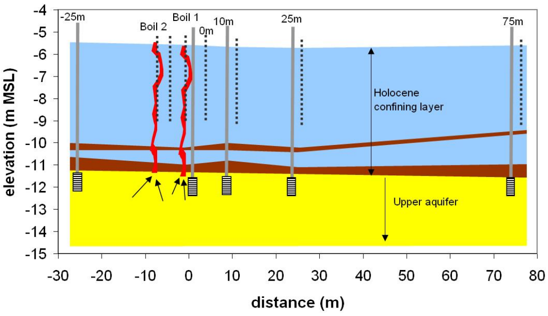
(Polder Noordplas)

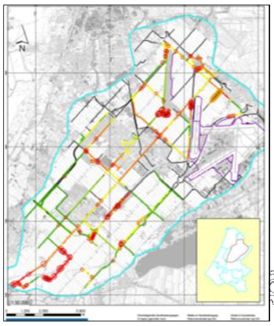
Diffuse : 100 mg/l

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

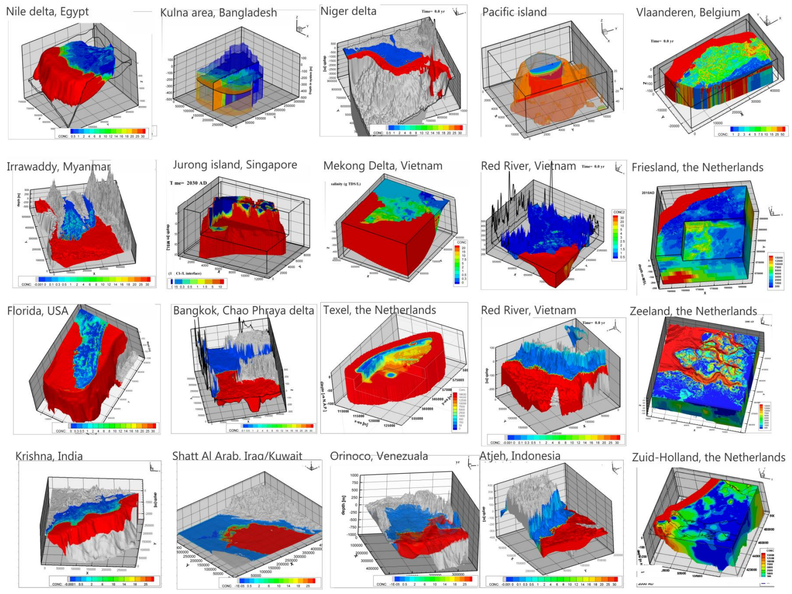
Type:

- sharp interface models
- solute transport models

State of the art:

- three-dimensional
- solute transport
- transient

3D numerical models groundwater coastal zone



Nile delta, Egypt
Kulna area, Bangladesh
Niger delta
Pacific island
Vlaanderen, Belgium
Irrawaddy, Myanmar
Jurong island, Singapore
Mekong Delta, Vietnam
Red River, Vietnam
Friesland, the Netherlands
Florida, USA
Bangkok, Chao Phraya delta
Texel, the Netherlands
Red River, Vietnam
Zeeland, the Netherlands
Krishna, India
Shatt Al Arab, Iraq/Kuwait
Orinoco, Venezuala
Atjeh, Indonesia
Zuid-Holland, the Netherlands

modelling

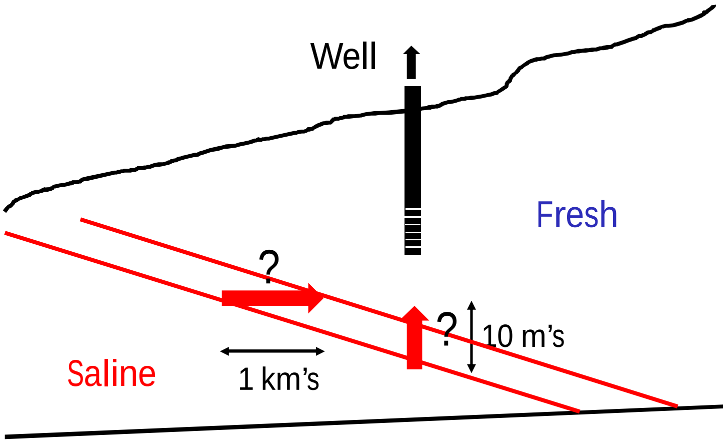
Some existing 3D codes which simulate variable density groundwater flow in porous media:

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)

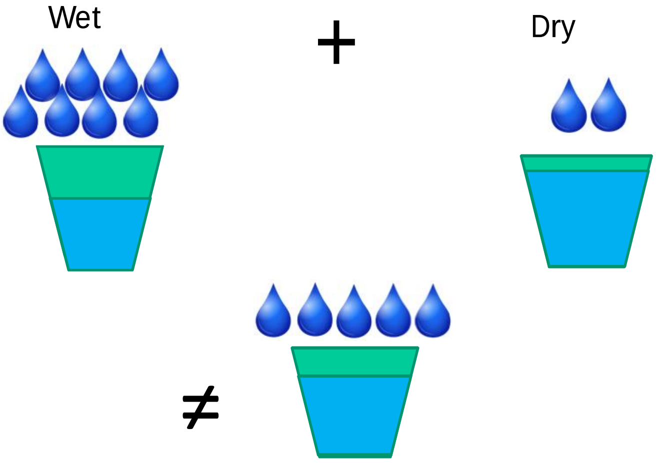
Fresh-salt groundwater modelling issues

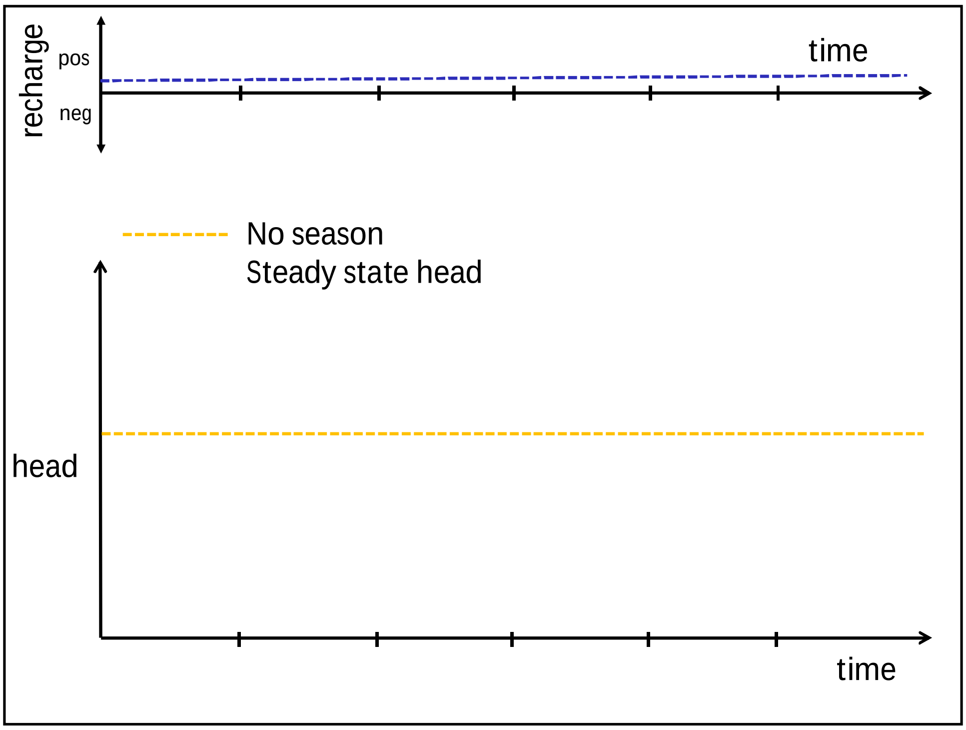
1. Grid convergence
2. Vert-hor displacement interface
3. Transient versus Steady-state
4. Salt BC: e.g. far enough for the area of interest, BC zz 3D model
5. Do not trust solvers default: e.g. Case Nile delta
6. Rotation mixing, effect of dispersion
7. Big delta systems and drain-river packages: there is always a drainage system around
    a. Conductance for large cells
    b. Sof okay, but check it
8. Rule of Thumb: Lambda (GHB)
9. Animation over more times than just Stress Periods
10. Focus velocity field, including high DEM contrast!

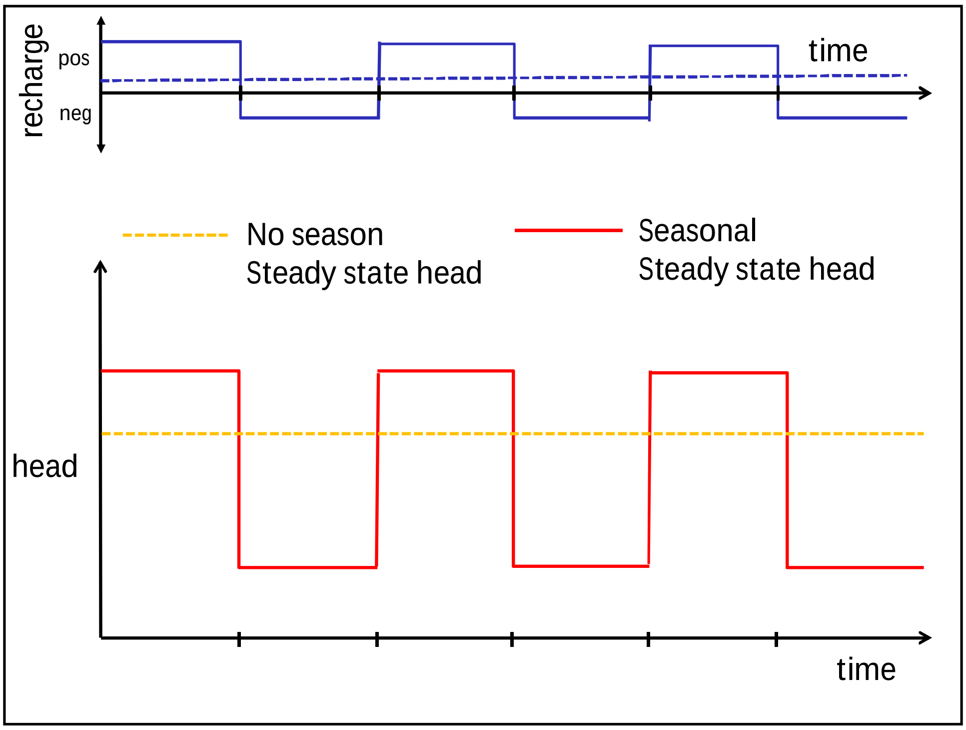
Movement of interface: hor. of vert.?



Acknowledge non-stationarity

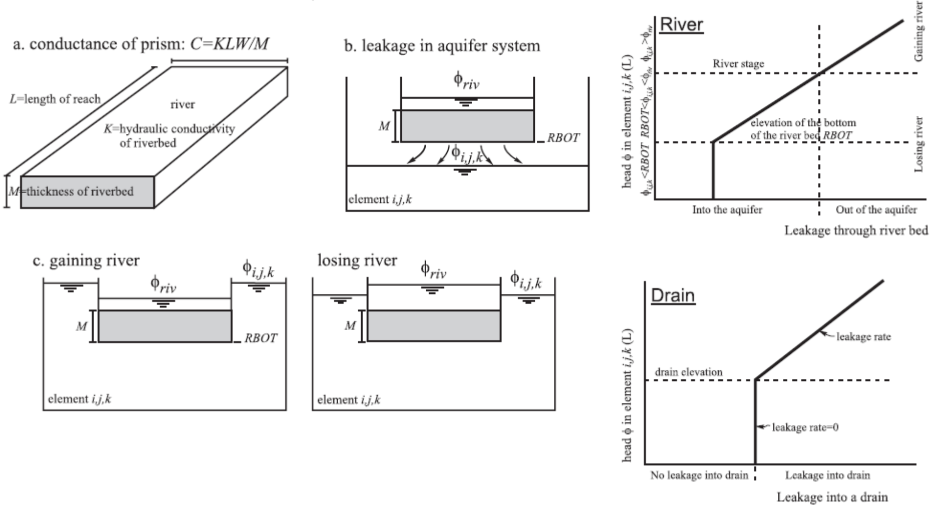


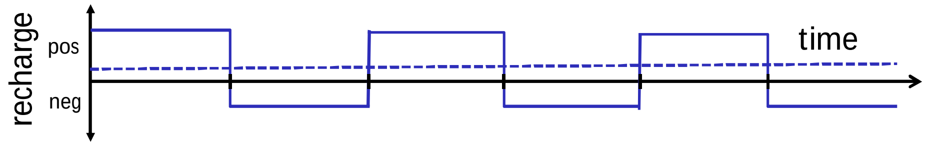

recharge
pos
neg
time
No season
Steady state head
head
time


recharge
pos
neg
time
No season
Steady state head
Seasonal
Steady state head
head
time

Non-linearity discharge systems, e.g. rivers

During high recharge fluxes, more water is discharged, and head is less high

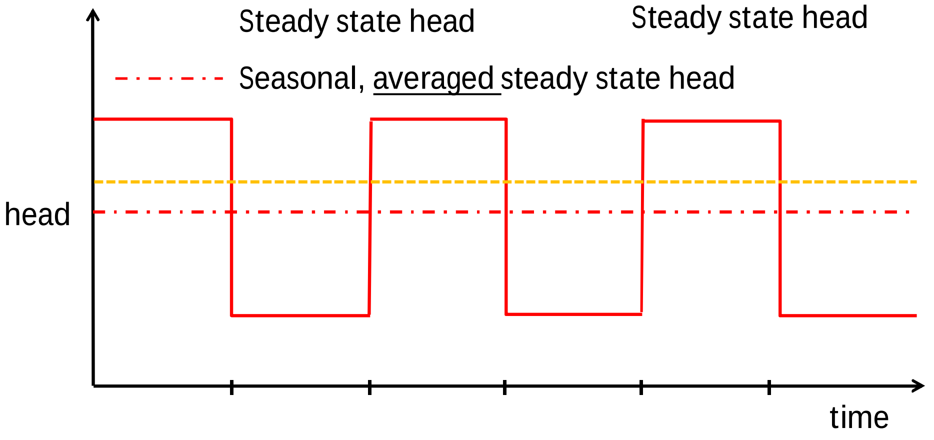


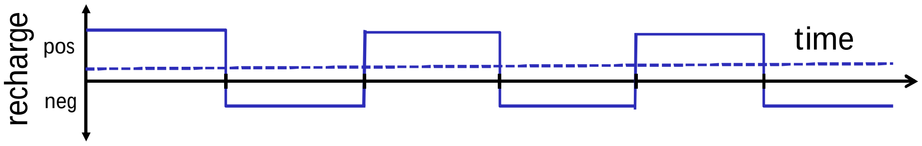


No season Steady state head

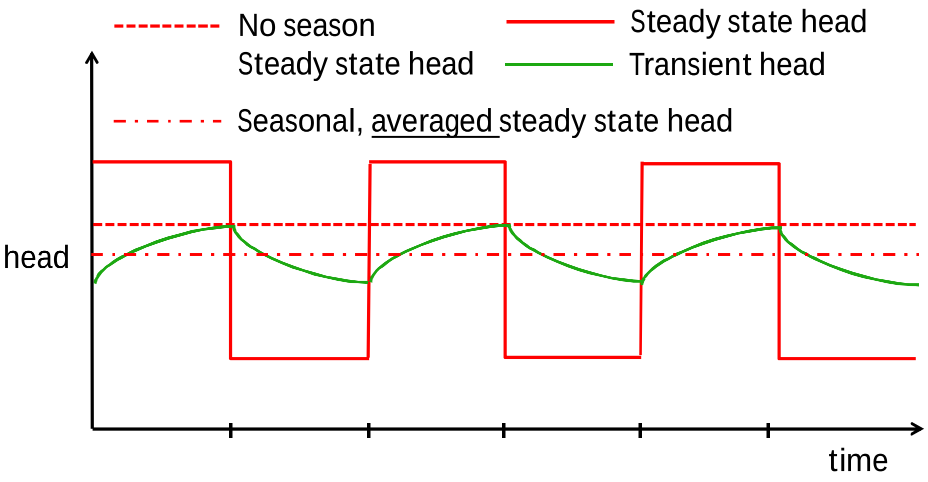
Seasonal Steady state head

Seasonal, averaged steady state head

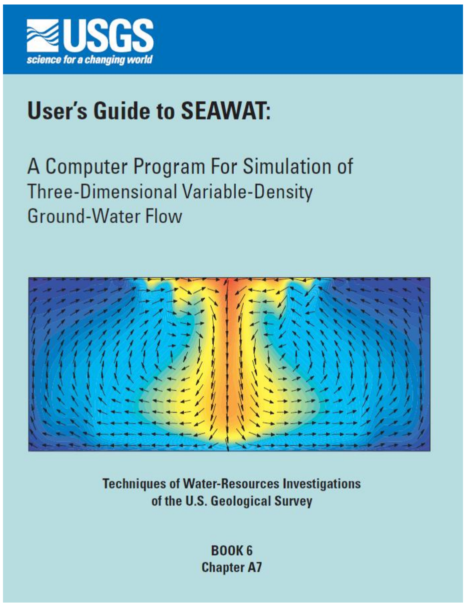




Extra issue: with smaller effective velocities, hydrodynamic disp. is smaller too



2002



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science for a changing world

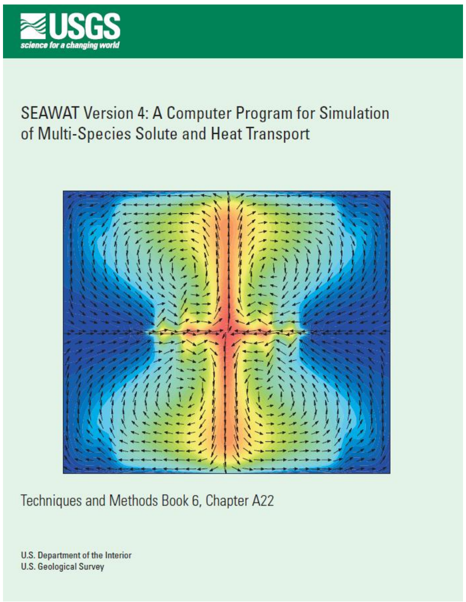
User's Guide to SEAWAT:

A Computer Program For Simulation of
Three-Dimensional Variable-Density
Ground-Water Flow

Techniques of Water-Resources Investigations
of the U.S. Geological Survey

BOOK 6
Chapter A7

2007/2008



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SEAWAT Version 4: A Computer Program for Simulation
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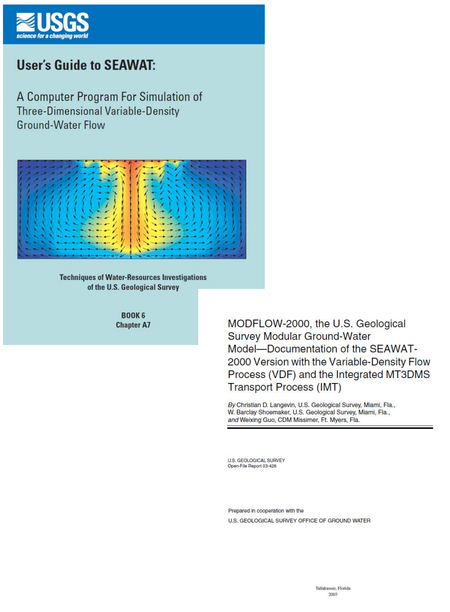
Techniques and Methods Book 6, Chapter A22

U.S. Department of the Interior
U.S. Geological Survey

2002/2003



User's Guide to SEAWAT:

A Computer Program For Simulation of
Three-Dimensional Variable-Density
Ground-Water Flow

Techniques of Water-Resources Investigations
of the U.S. Geological Survey

BOOK 6
Chapter A7

MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model—Documentation of the SEAWAT-2000 Version with the Variable-Density Flow Process (VDF) and the Integrated MT3DMS Transport Process (IMT)

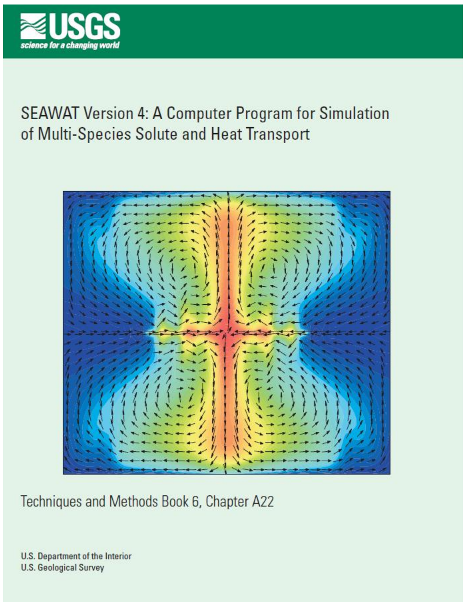
By Christian D. Langevin, U.S. Geological Survey, Miami, Fla.,
W. Barclay Shoemaker, U.S. Geological Survey, Miami, Fla.,
and Weixing Guo, CDM Missimer, Ft. Myers, Fla.

U.S. GEOLOGICAL SURVEY
Open-File Report 03-426

Prepared in cooperation with the
U.S. GEOLOGICAL SURVEY OFFICE OF GROUND WATER

Tallahassee, Florida
2003

2007/2008



SEAWAT Version 4: A Computer Program for Simulation
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Techniques and Methods Book 6, Chapter A22

U.S. Department of the Interior
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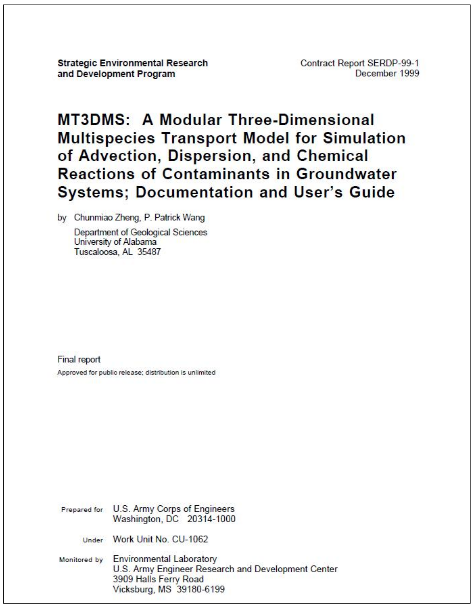
MT3D 1999



**Strategic Environmental Research
and Development Program**

Contract Report SERDP-99-1
December 1999

MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide

by Chunmiao Zheng, P. Patrick Wang
Department of Geological Sciences
University of Alabama
Tuscaloosa, AL 35487

Final report

Approved for public release; distribution is unlimited

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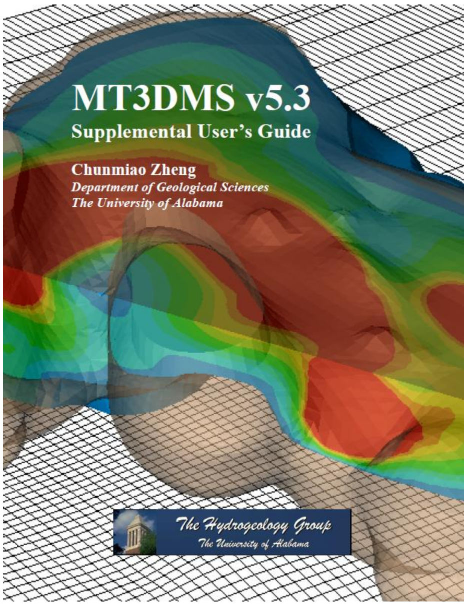
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Supplement 2010



MT3DMS v5.3
Supplemental User's Guide

Chunmiao Zheng
Department of Geological Sciences
The University of Alabama

The Hydrogeology Group
The University of Alabama

Visualisation tools

- Tecplot https://www.tecplot.com/
- Paraview https://www.paraview.org/
- iMOD https://oss.deltares.nl/web/imod
- Flopy https://www.usgs.gov/software/flopy-python-package-creating-running-and-post-processing-modflow-based-models
- Modelviewer https://www.usgs.gov/software/model-viewer-a-program-three-dimensional-visualization-ground-water-model-results

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SEAWAT

$$\nabla\cdot\left[\rho K_o\left(\nabla h_f+\frac{\rho-\rho_f}{\rho_f}\nabla z\right)\right]=\rho S_s\frac{\partial h_f}{\partial t}+\theta\frac{\partial\rho}{\partial C}\frac{\partial C}{\partial t}-\rho_{ss}q_{ss}$$

where ρ is the density of the groundwater (M L^{-3}); K_0 is the hydraulic conductivity tensor (L T^{-1}); h_f is the freshwater head (L); z is the vertical coordinate (L); ρ_f is the density of fresh groundwater (M L^{-3}); S_s is the specific storage coefficient (L^{-1}); t is the time (T); ϕ is the effective porosity (-); C is the concentration (M L^{-3}); ρ_{ss} is the density of the sink or source (T^{-1}); and q_{ss} is the sink and source term (T^{-1}).

$$\rho=\rho_f+\frac{\partial\rho}{\partial C}C$$

$$\frac{\partial\left(\theta C\right)}{\partial t}=\nabla\cdot\left(\theta D\cdot\nabla C\right)-\nabla\cdot\left(qC\right)-q_{ss}C_{ss}$$

where D is the hydrodynamic dispersion tensor (L^2 T^{-1}); q is the specific discharge vector (L T^{-1}) and C_{ss} is the source and sink concentration (M L^{-3}).

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

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  - -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

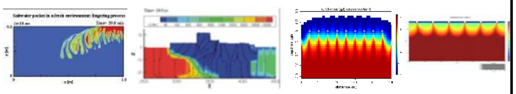
solution is 64 bits computer

- the numerical dispersion problem:
  - -numerical dispersion is large in case of coarse grid

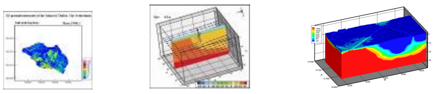
solution is better solvers

Modelling fresh-salt groundwater on different scales

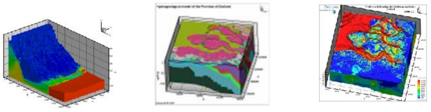
Sub-local: fingering, salty sand boils
Sri Lanka (Tsunami 2004),
Zandmotor
cell size=1cm-1m



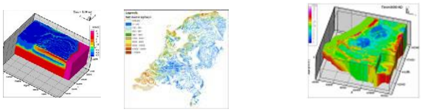
Local: rainwaterlenses, heat-cold
Tholen, Schouwen-Duiveland
cell size=5-25m



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

---

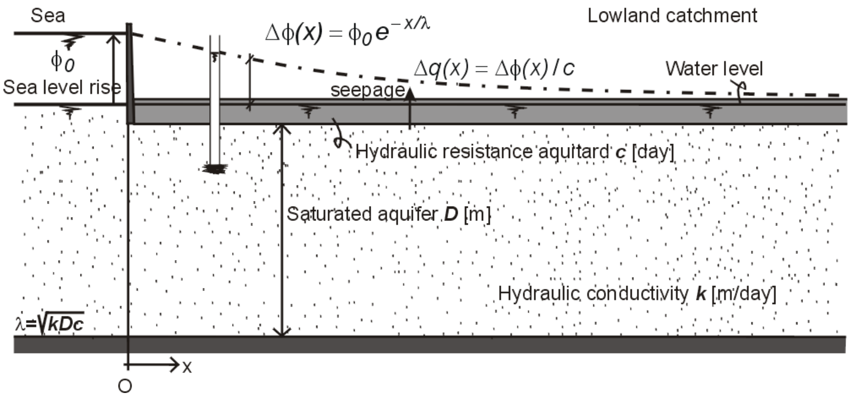
Boundary Conditions

Dirichlet: head
- fixed head (DEM minus unsaturated zone)

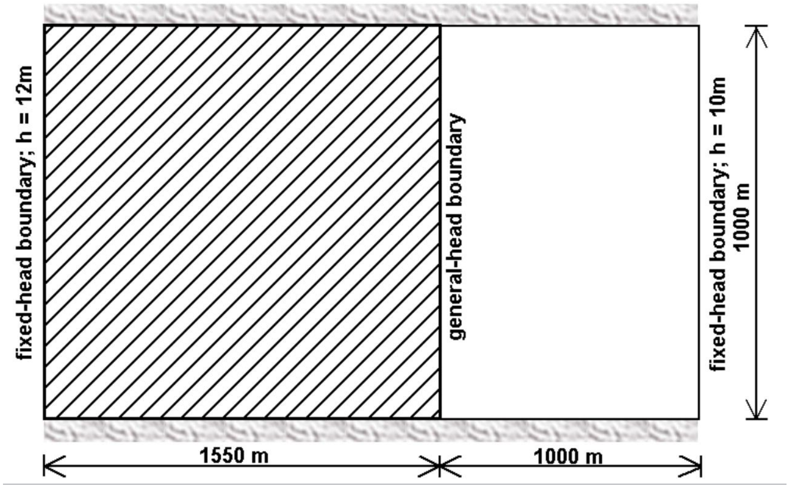
Neumann: flux
- Zero = no-flow
- Constant

Robin / Cauchy: mixed
- Like General Head Boundary!

Formula of Mazure, zone of influence head



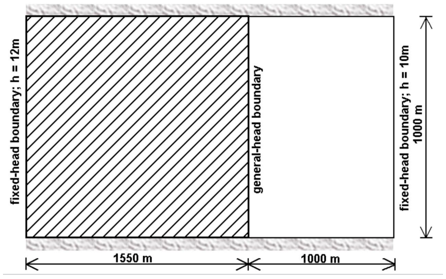
Using the GHB for the head BC



Using the GHB for the head BC

$\text{Conductance}_{GHB} = K_{GHB} \cdot A/L$

- K_{GHB} is the (horizontal) hydraulic conductivity,
- L is the distance from the actual fixed-head boundary to the modeled GHB cell,
- A is the area of the cell face, which is perpendicular to the groundwater flow in the unmodeled area.

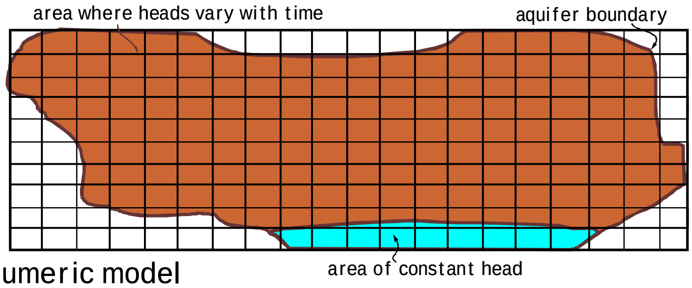


MODFLOW

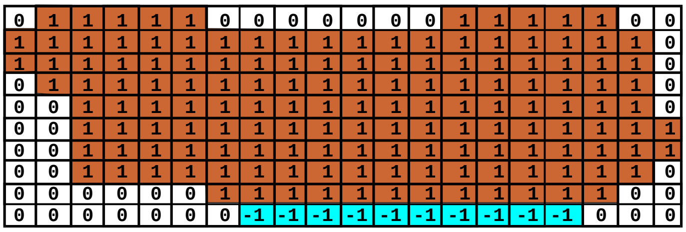
MODFLOW

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

MODFLOW

Boundary conditions in MODFLOW (II)

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

Packages in MODFLOW

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

---

1. Well package

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

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

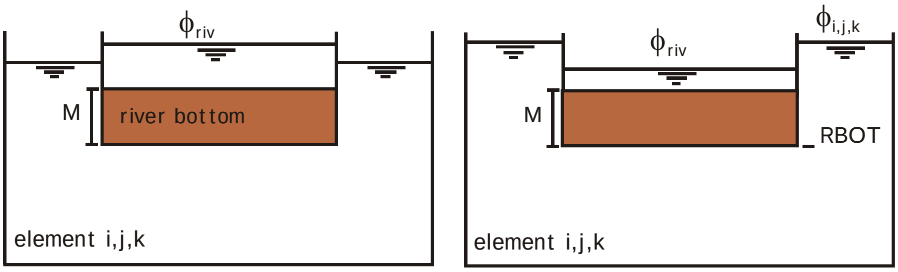
$$Q_{ext,i,j,k} = P_{i,j,k}\phi^{t+\Delta t}_{i,j,k} + Q'_{i,j,k}$$

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

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

MODFLOW

2. River package (I)


river loses water

river gains water

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

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

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:

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

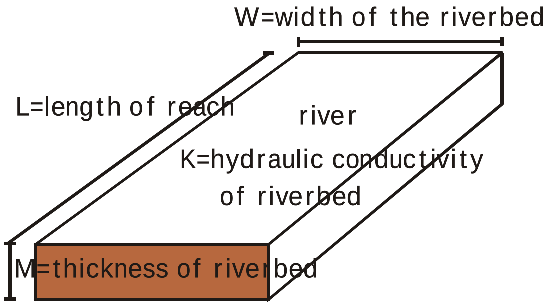
$$Q_{ext,i,j,k} = 20\left(3 - \phi_{i,j,k}\right)$$

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

MODFLOW

2. River package (III)

Determine the conductance of the river in one element:

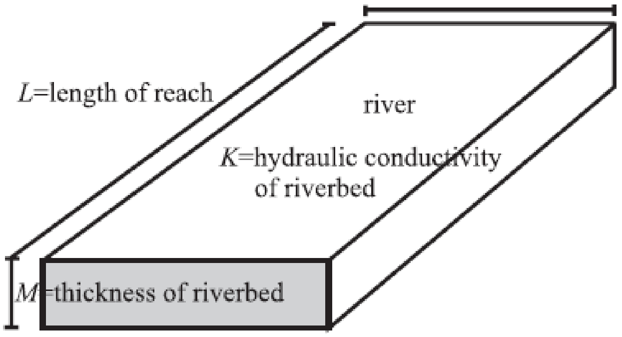


where $C_{riv} = \frac{KLW}{M}$ is the conductance [L^2/T] of the river

---

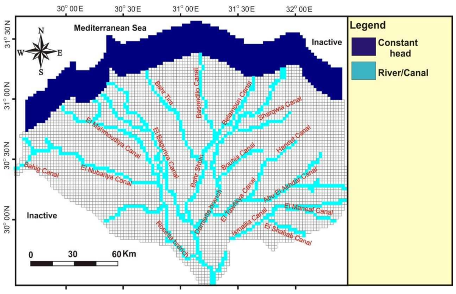
CONDUCTANCE

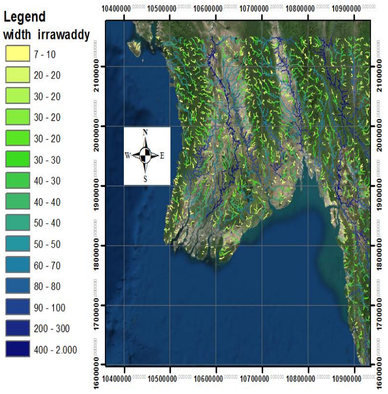
conductance of prism: $C=KLW/M$



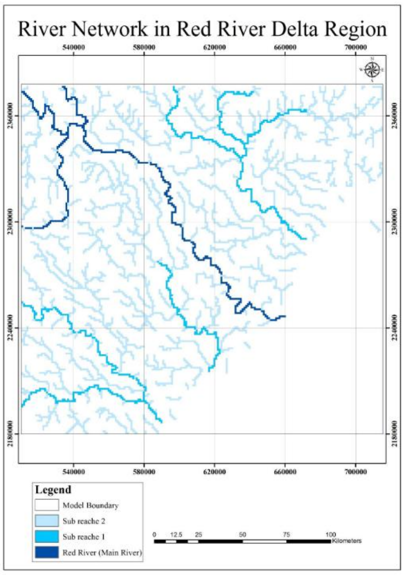
River Package: water courses

1. Location of watercourses
2. Water level; different approach per type of watercourse
3. Drainage resistance (conductance)
4. Chloride concentration surface water





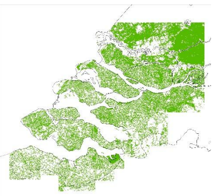
Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS)

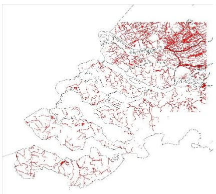


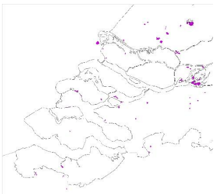
River types, model Zeeland

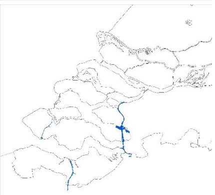
Watercourse type	**Type**	**Indeling Waterboard**
1	*Sloot*=ditch (top10)	Primaire waterloop / secundaire waterloop
2	*Rivier*=river (top10)	Primaire waterloop
3	*Meer*=lake (top10)	
4	*Kanaal*=canal (top10)	
5	*Greppel*=trench (top10)	Secundaire waterloop/ tertiare waterloop
6	*Zee*=sea or *binnenwater*=innersea	

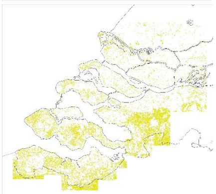
River types, model Zeeland


Waterloop type 1: sloot


Waterloop type 2: rivier


Waterloop type 3: meer

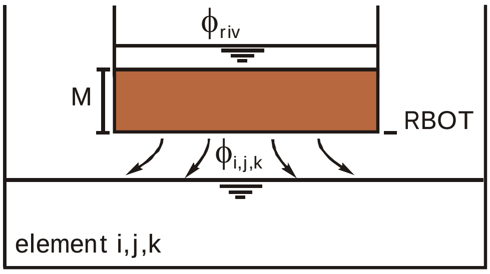

Waterloop type 4: kanaal


Waterloop type 5: greppel


Waterloop type 6:
binnenwater en zee

2. River package (IV)

Leakage to the groundwater system

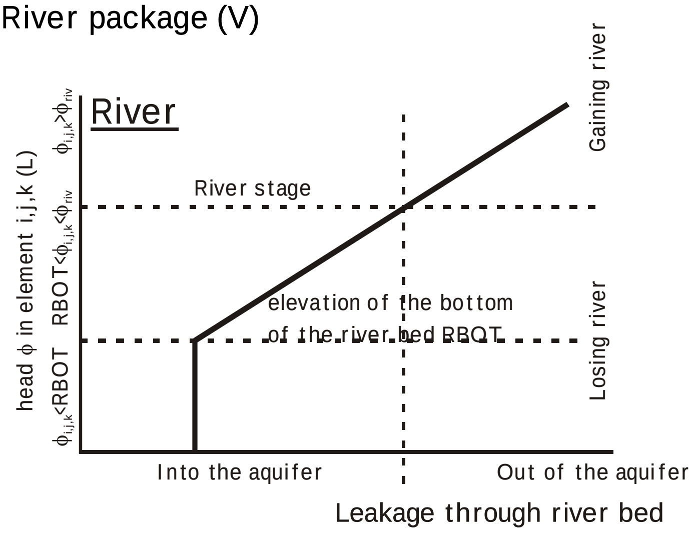


Special case:

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

---

2. River package (V)



3. Recharge package

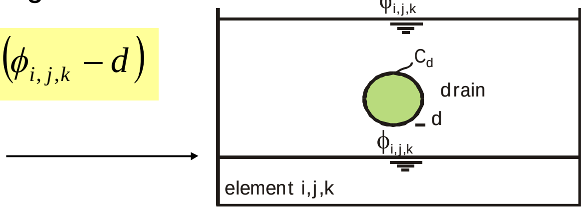
$$Q_{rec} = I\Delta x\Delta y$$

---

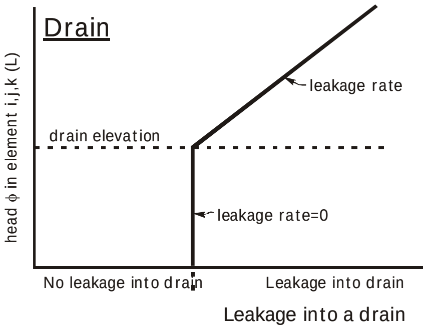
4. Drain package

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

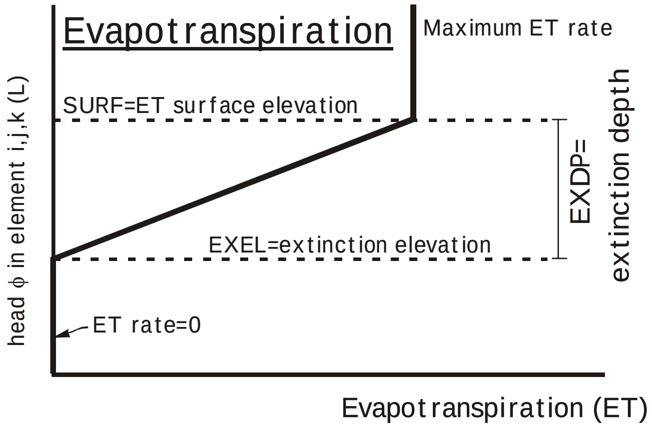
Special case:



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



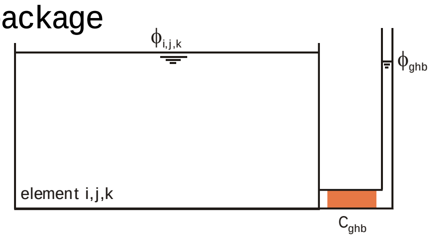
5. Evapotranspiration package

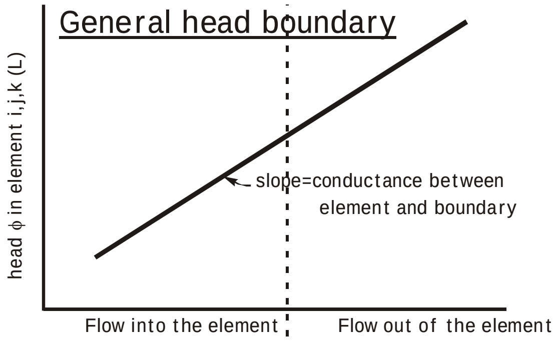


---

6. General head boundary package

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



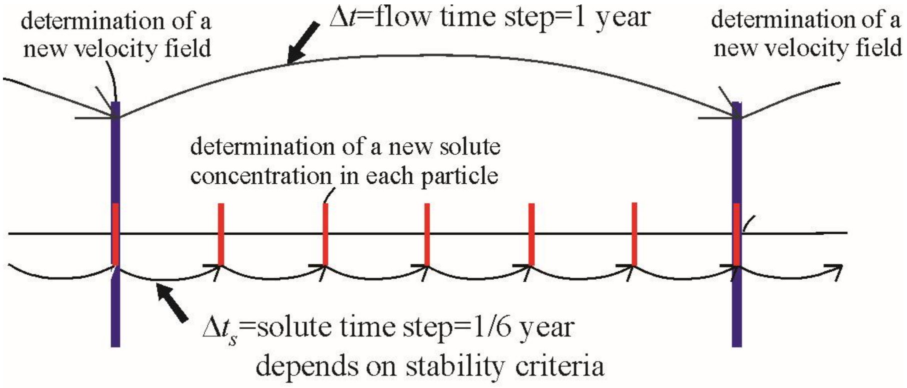


Flow to a general head boundary

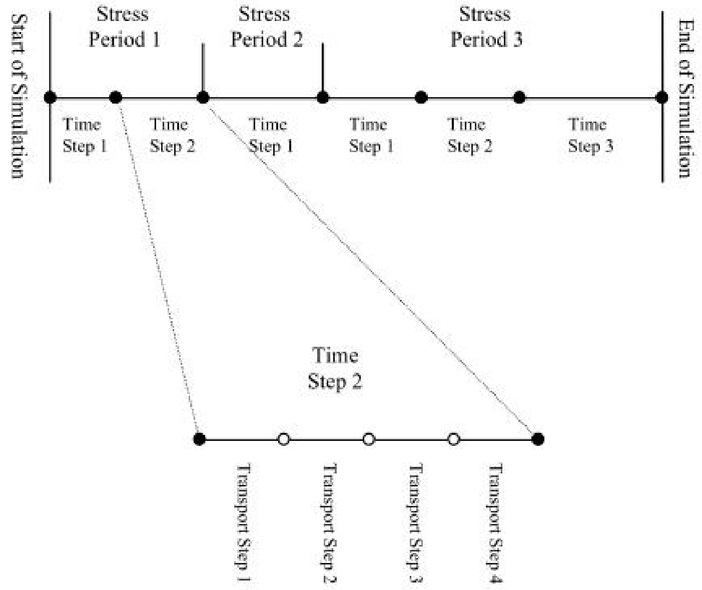
Time indication MODFLOW

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

Flow time step and solute time step



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



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:

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

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)

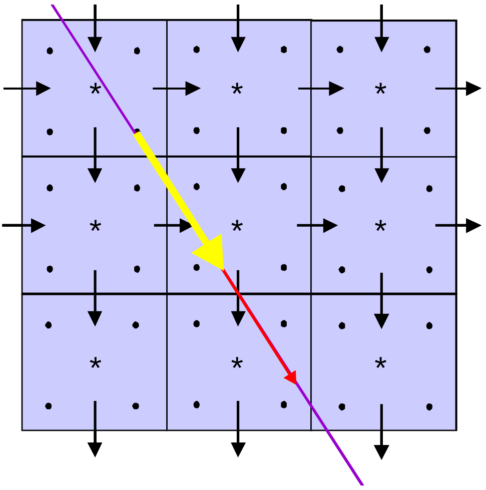
3. Courant criterion:

$0<\xi<=\sim 1$

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

Stability criteria (III)

3. Courant criterium



- * Node element
- • Particle

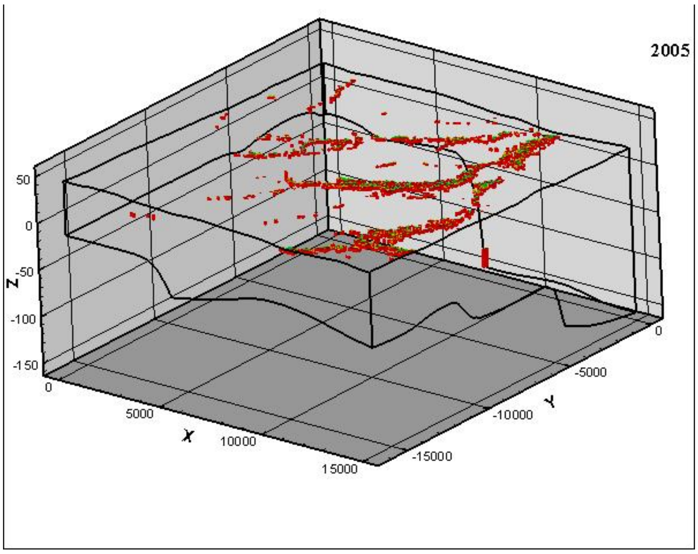
Velocity direction

Movement particles

0<x<=~1

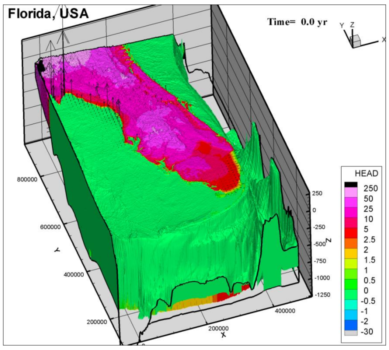
$$\Delta t_s \leq \frac{\xi \Delta x}{V_{x,\max}} \qquad \Delta t_s \leq \frac{\xi \Delta y}{V_{y,\max}} \qquad \Delta t_s \leq \frac{\xi \Delta z}{V_{z,\max}}$$

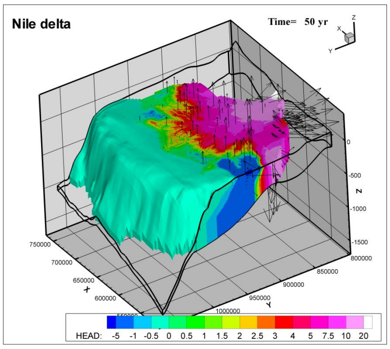
Courant criterion: places where timestep is smaller than 40 days

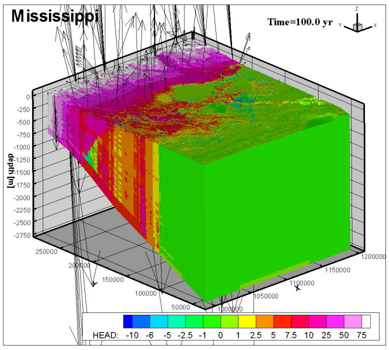


Check the velocity field!

Tool: tecplot / paraview

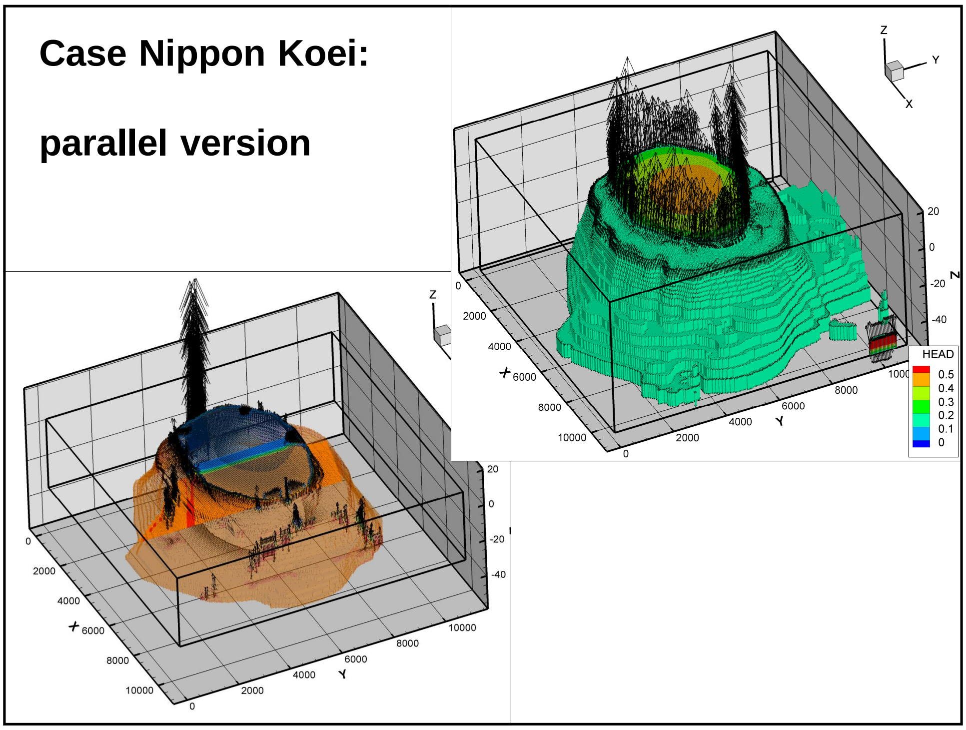






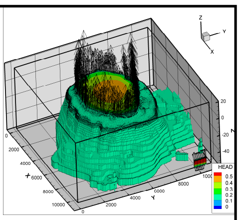
Case Nippon Koei:

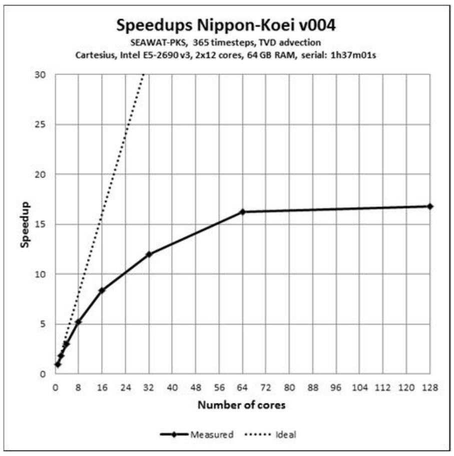
parallel version

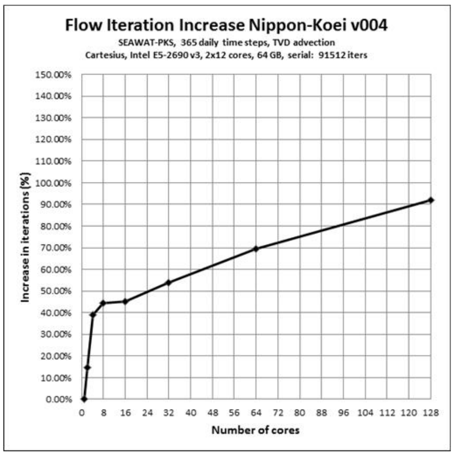


Case Nippon Koei:

parallel version

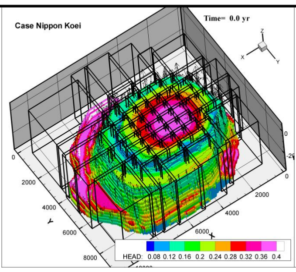


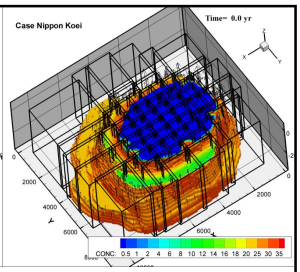




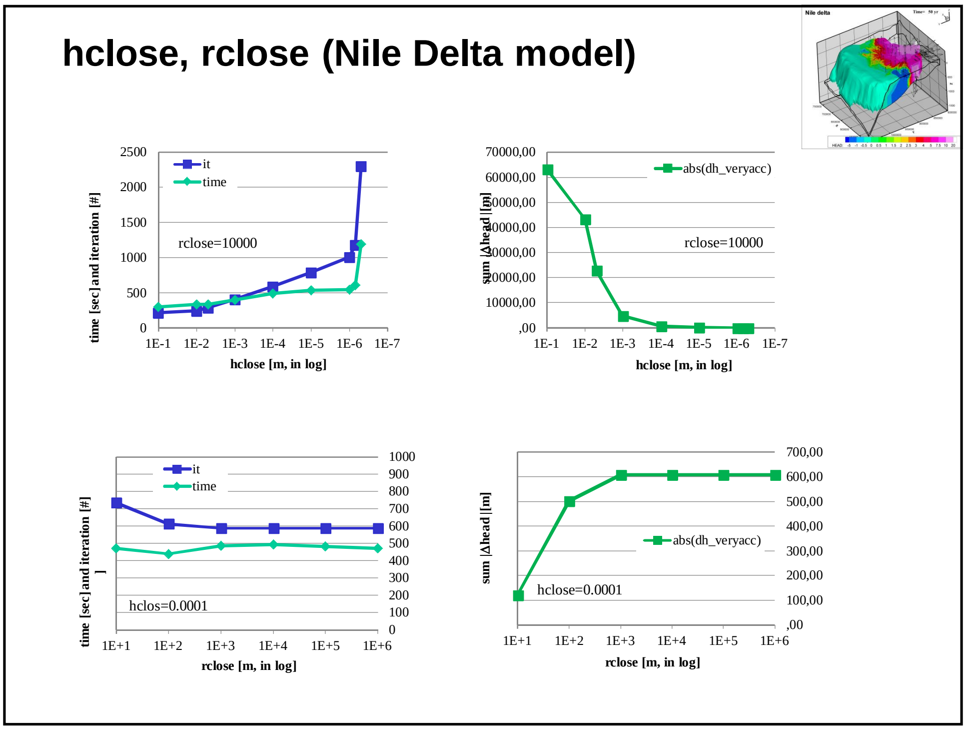
Case Nippon Koei:

parallel version

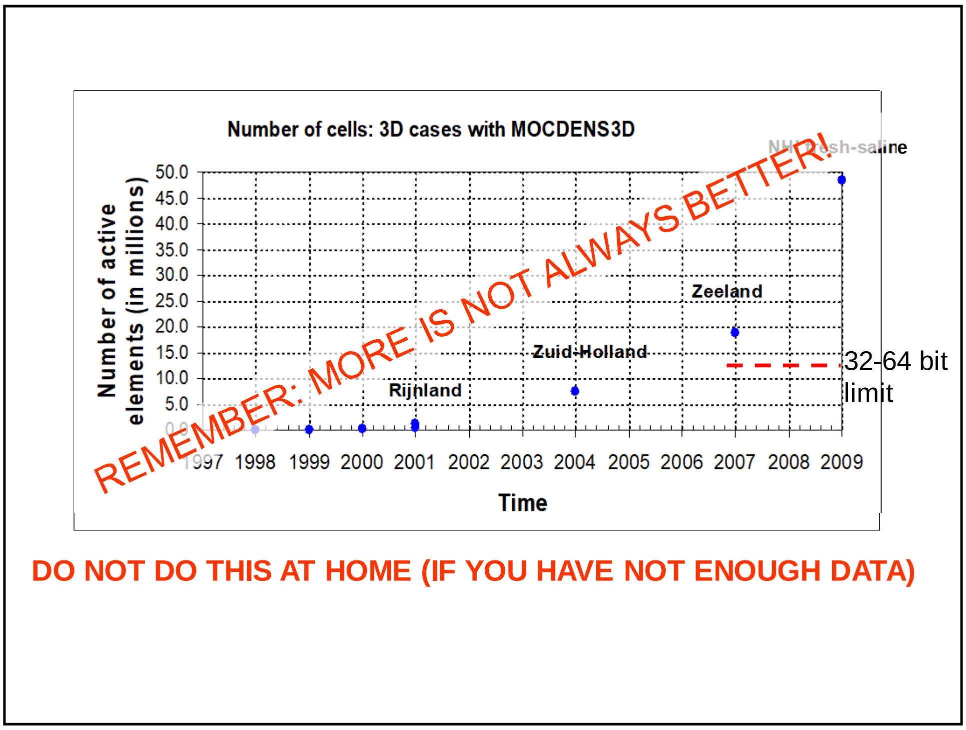




Name	seawat005_gv23	seawat006_gv23	seawat-3-004	seawat-3-004	seawat-3-004
parallel	no	no	no	yes	yes
name ‘nam’ file	gv23	gv23	gv23	gv23	gv23
software	SEAWAT	SEAWAT	SEAWAT	iMOD-SEAWAT	iMOD-SEAWAT
computer	Quad 2.60 GHz	Quad 2.60 GHz	Quad 2.60 GHz	Cartesius 1 core	Cartesius 64 cores
date input data	21-11-17	08-12-17	21-12-2017	21-12-2017	21-12-2017
calc.time	5d0h36m43s	0d10h2m52s	0d6h41m14s	~0d1h30m0s	0d0h5m59s
speedup factor	1	12.0	18.0	44.0	1209.5



hclose, rclose (Nile Delta model)



REMEMBER: MORE IS NOT ALWAYS BETTER!

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

Modelling effect climate change on fresh-salt groundwater

Modelling:

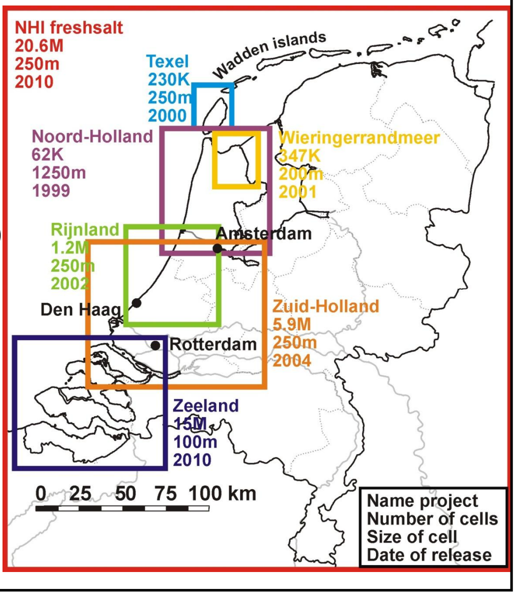
- variable-density
- 3D, non-steady
- groundwater flow
- coupled solute transport

Code:

MOCDENS3D (MODFLOW family)
similar to SEAWAT

Assessing effects:

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



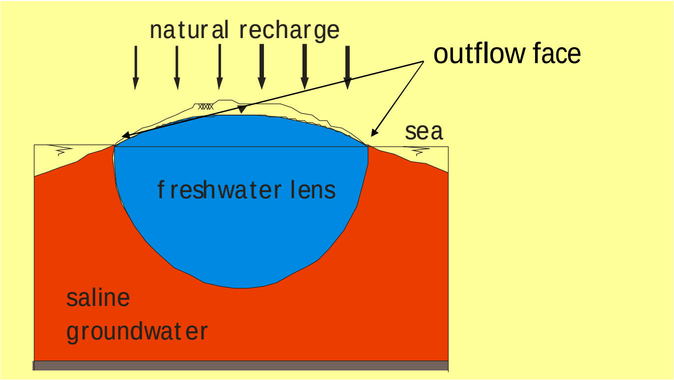
Fields of application of fresh-saline groundwater models

- 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

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

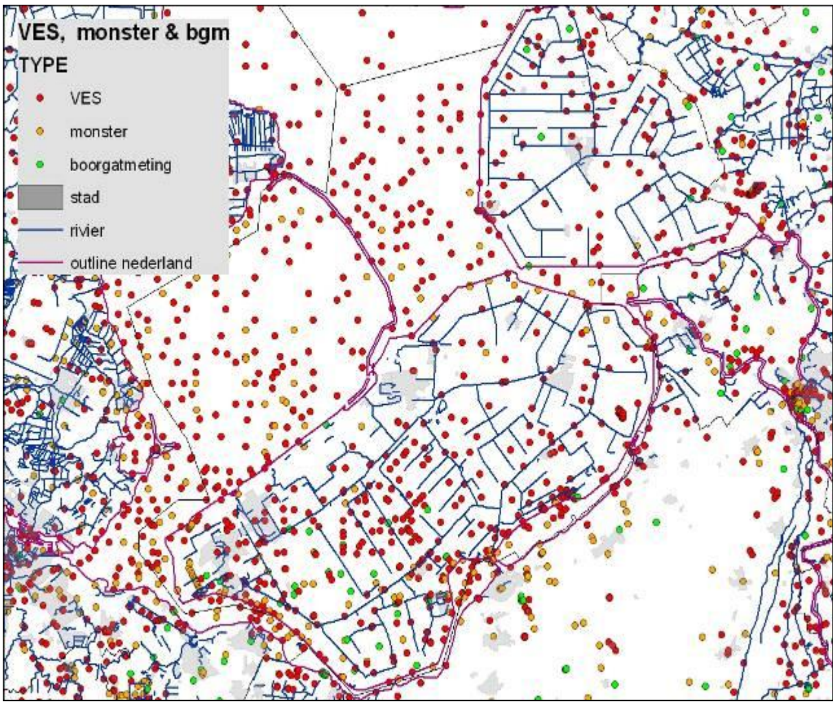
A good initial density distribution is essential

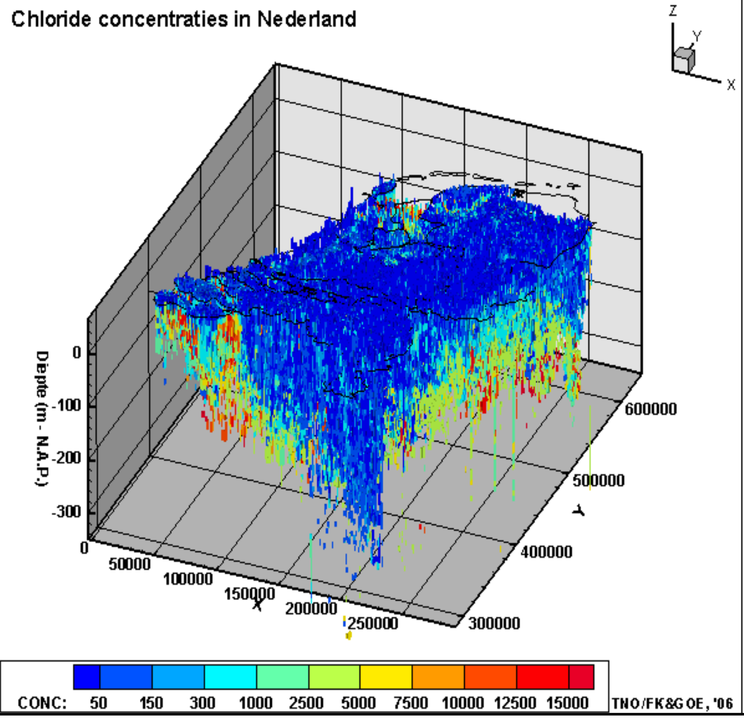
- Because groundwater and solute transport are coupled, the density influences grondwater velocities
- Numerous density measurements are necessary to get a reliable 3D density matrix

---

‘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



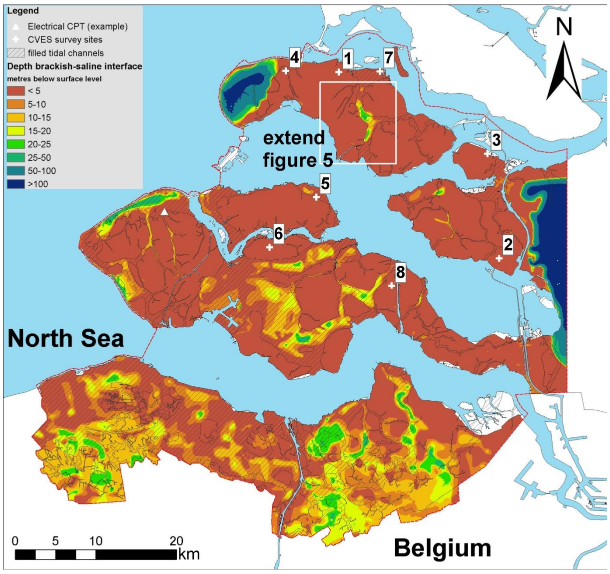

Chloride concentraties in Nederland

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**		

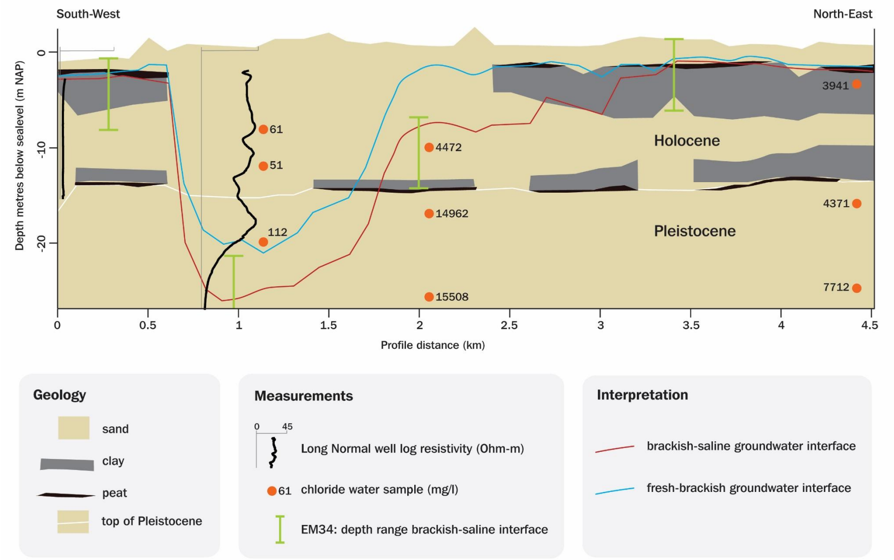
Mapping brackish-saline interface



Goes et al, 2009

Mapping brackish-saline interface

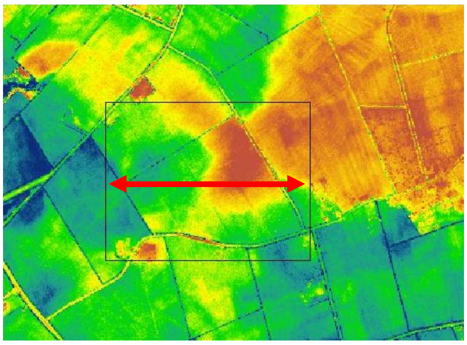
Combining different types of data sources

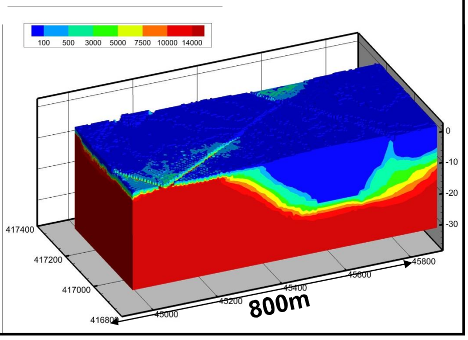


Use variable-density groundwater flow modelling

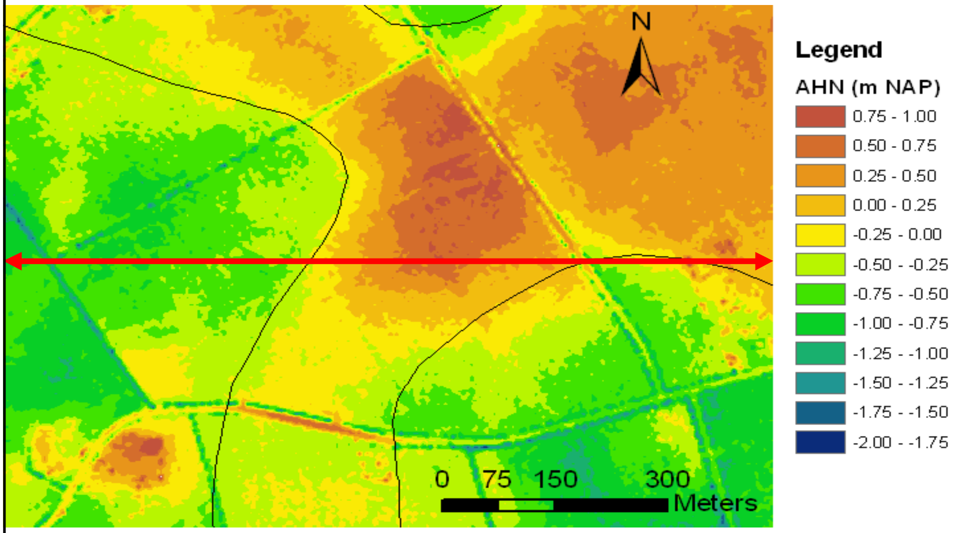
Why a model?

- variation in ground surface directly affects fresh-saline disribution





Use variable-density groundwater flow modelling

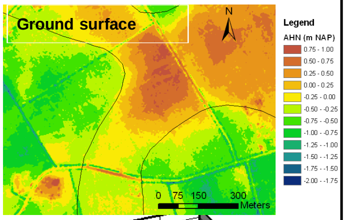


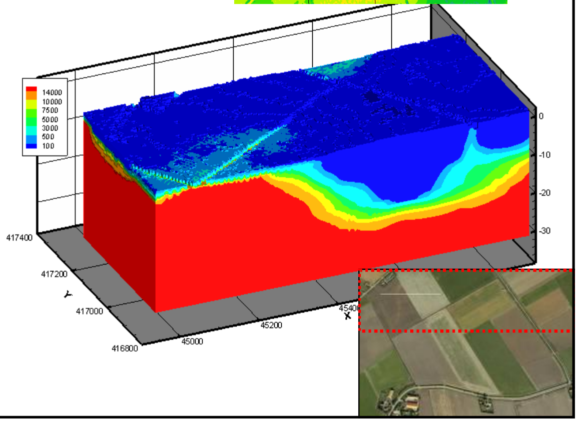
Local 3D model of the agricultural plot

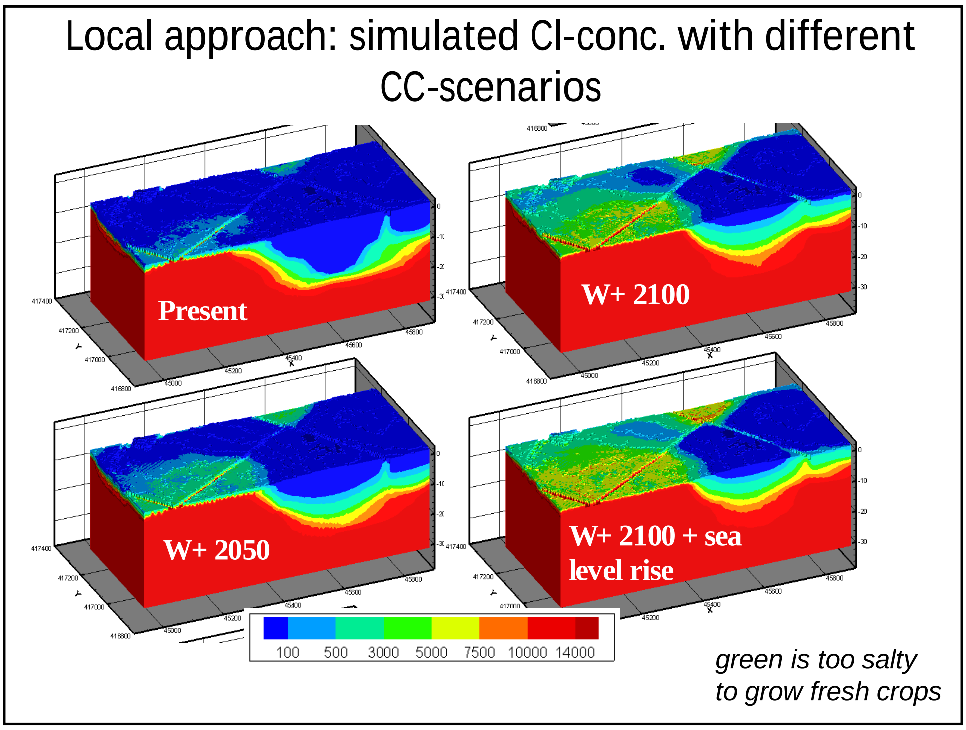
Modelling:
- variable-density
- 3D, non-steady
- groundwater flow & coupled solute transport
- model cell size: 5*5m^2

Code:
MOCDENS3D

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

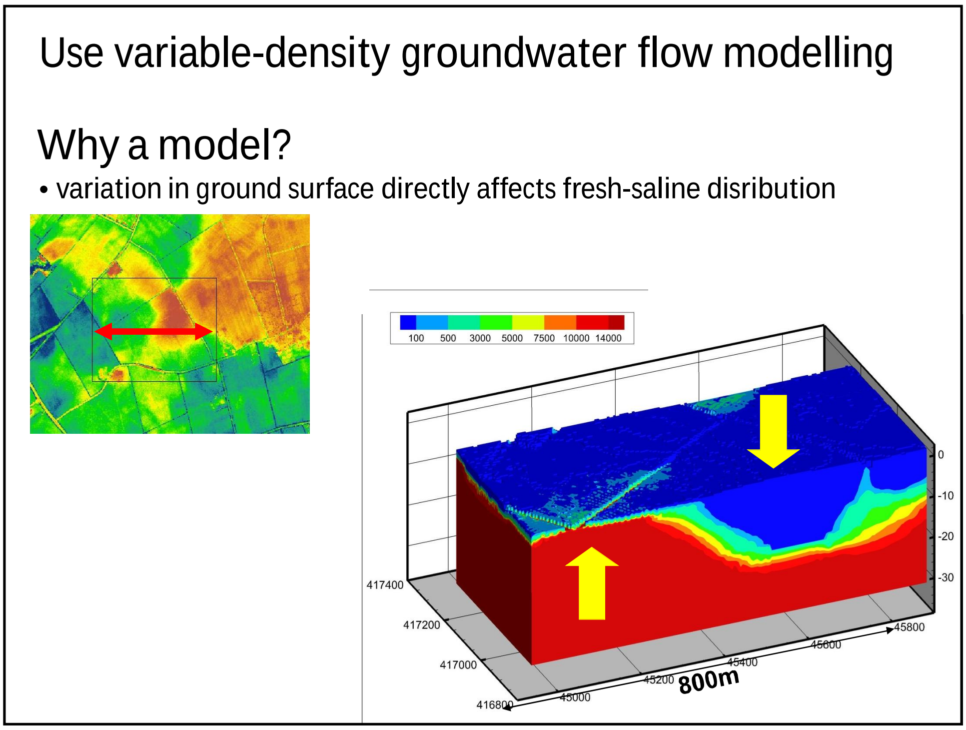






Local approach: simulated Cl-conc. with different CC-scenarios

green is too salty to grow fresh crops

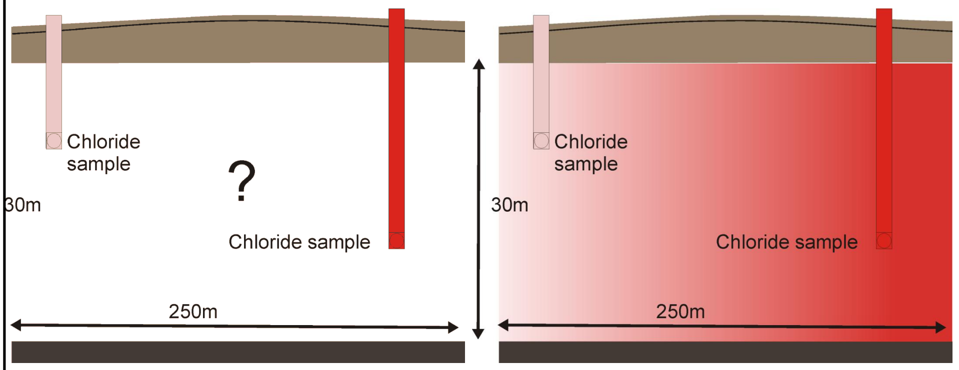


Use variable-density groundwater flow modelling

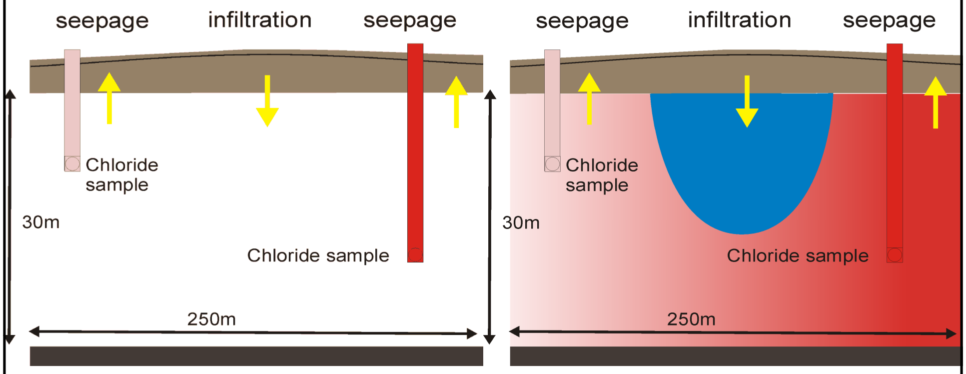
Why a model?

- variation in ground surface directly affects fresh-saline disribution

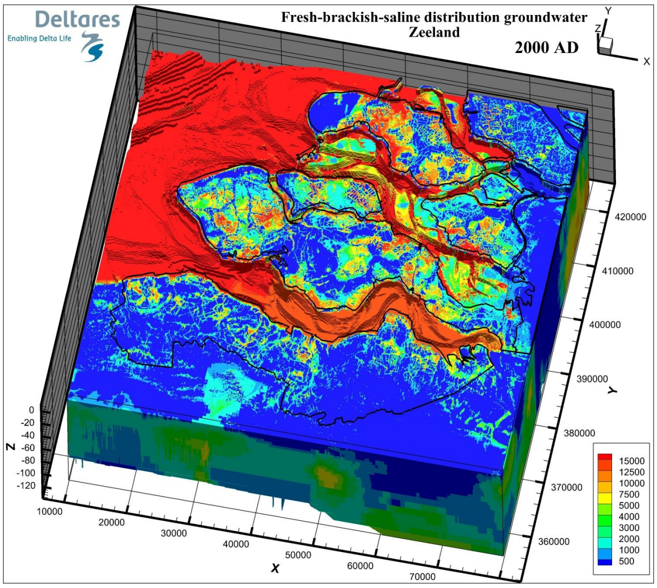
Interpolation chloride



Using flow model for better interpolate chloride

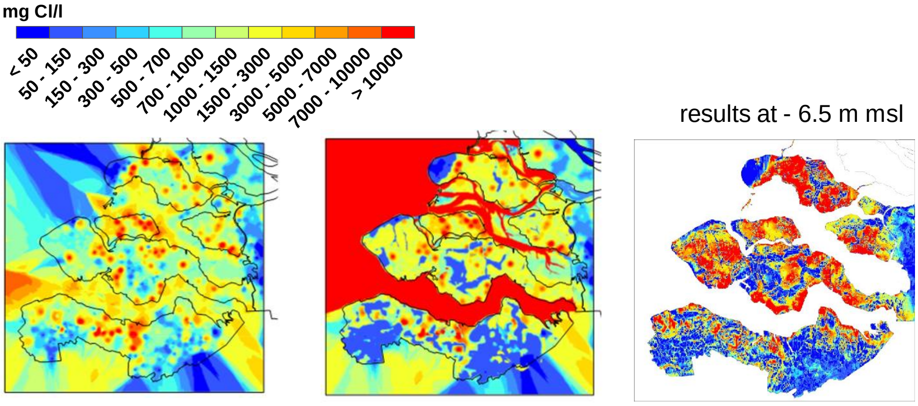


3D fresh-saline groundwater distribution



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*

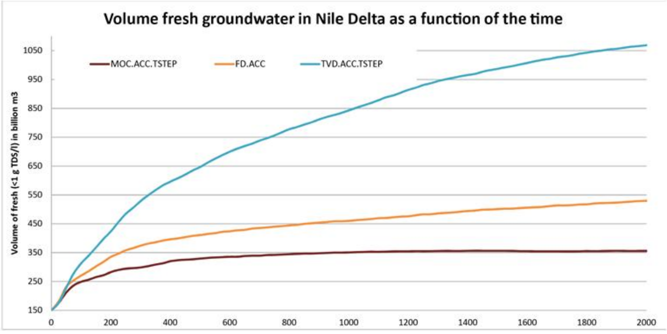
Step 3:
model result 2010:

- *Model as interpolator*

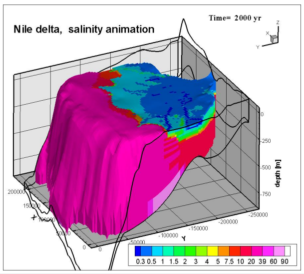
Examples of variable-density groundwater flow

- 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

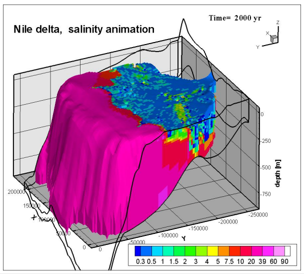
Case Nile delta, effect of solvers



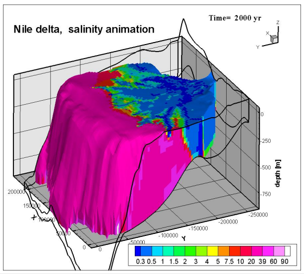
MOC.ACC.TSTEP



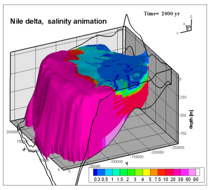
FD.ACC



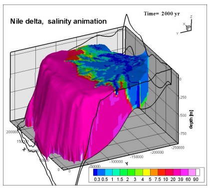
TVD.ACC.TSTEP

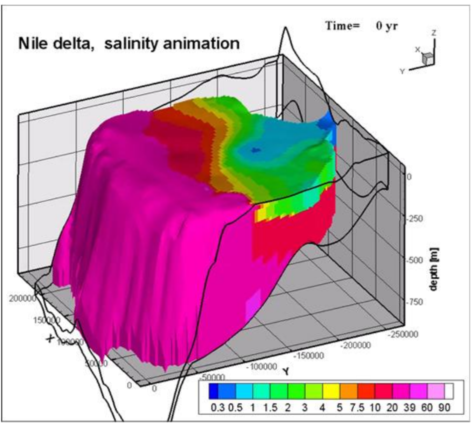


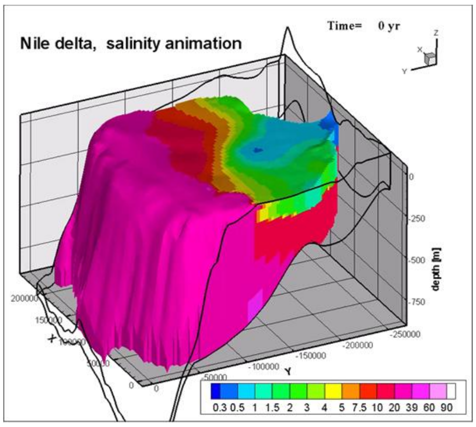
MOC.ACC.TSTEP



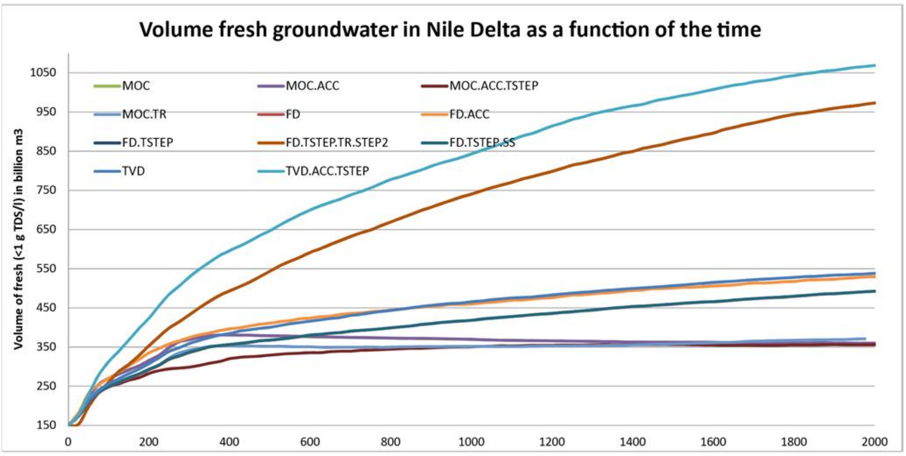
TVD.ACC.TSTEP



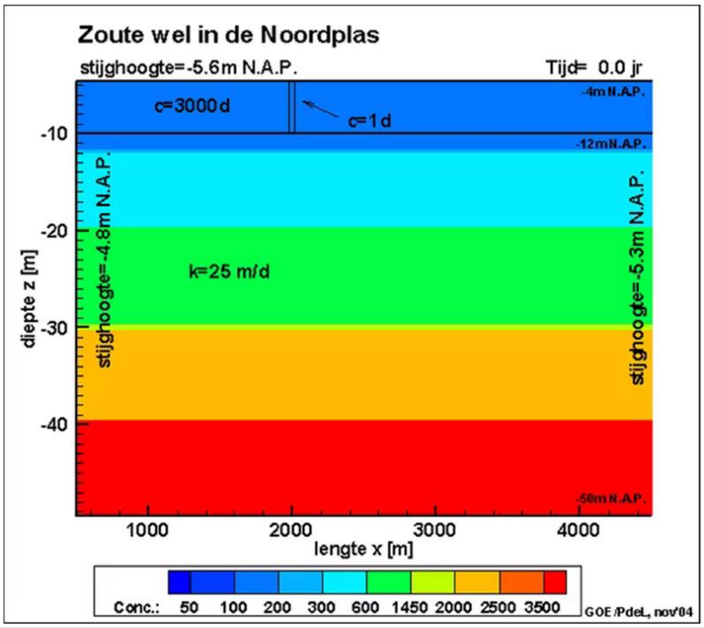




Case Nile delta, effect of solvers, and different settings (e.g. Courant number, number of time steps, SS/TR)



Find the two errors!



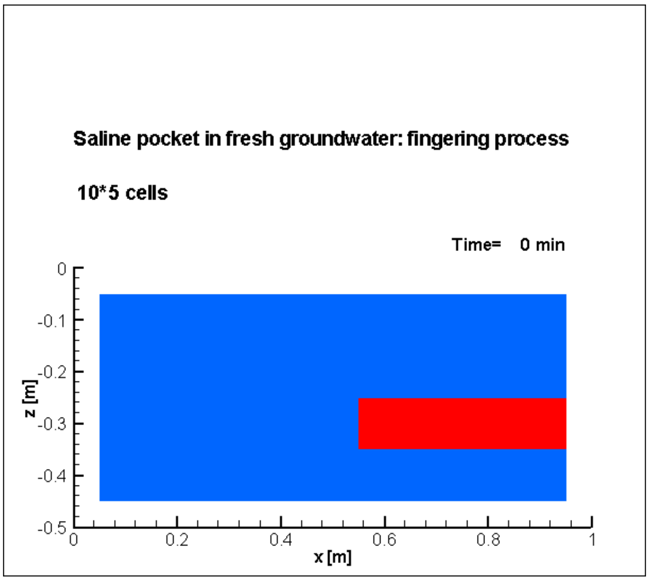
Salt water pocket in a fresh environment

Grid convergence

Time step

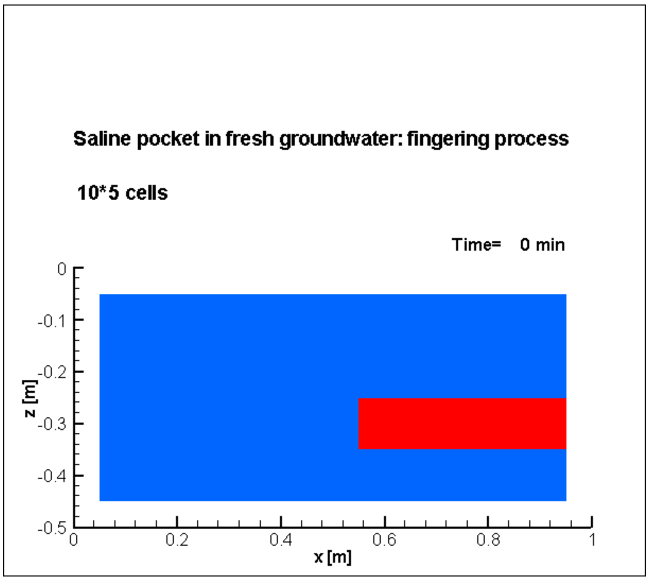
Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



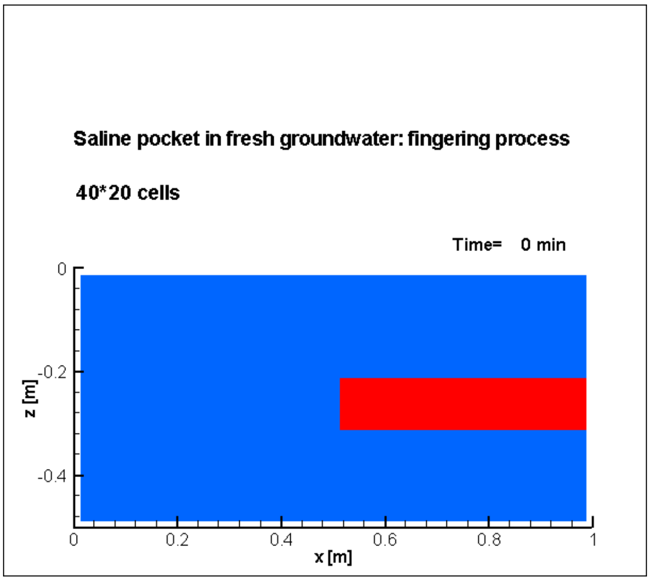
Salt water pocket in a fresh environment (I)

Effect of discretisation on a ‘salt lake problem’



Salt water pocket in a fresh environment (II)

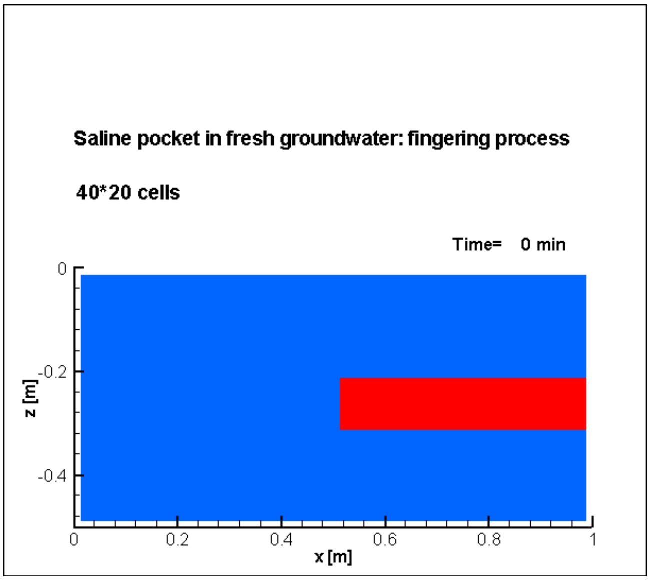
Effect of discretisation



cases

Salt water pocket in a fresh environment (II)

Effect of discretisation



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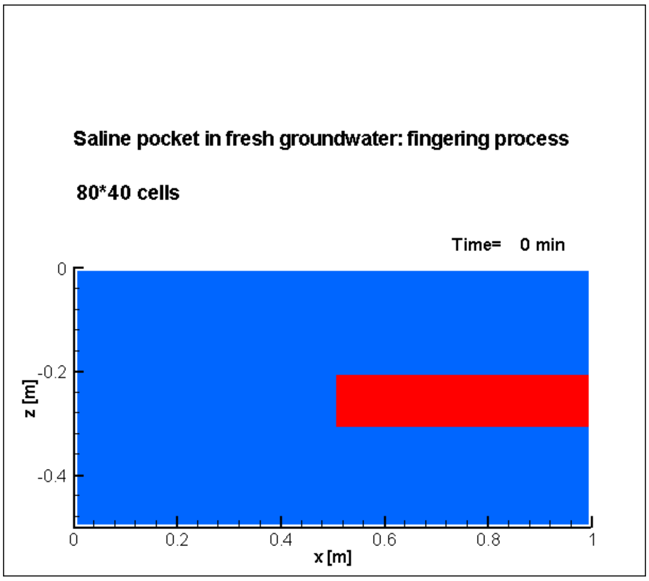
cases

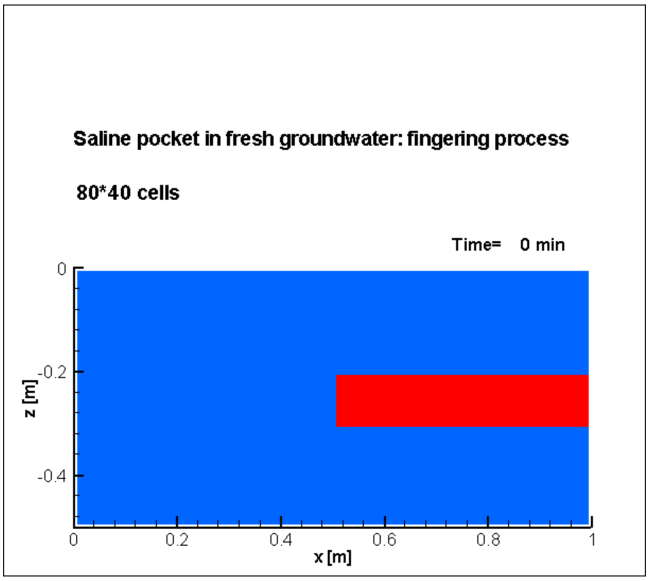
Salt water pocket in a fresh environment (III)

Effect of discretisation



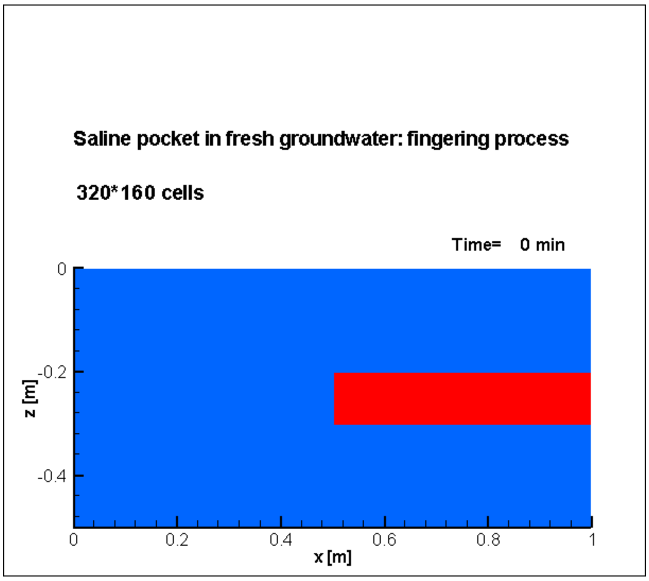
Salt water pocket in a fresh environment (III)

Effect of discretisation



Salt water pocket in a fresh environment (IV)

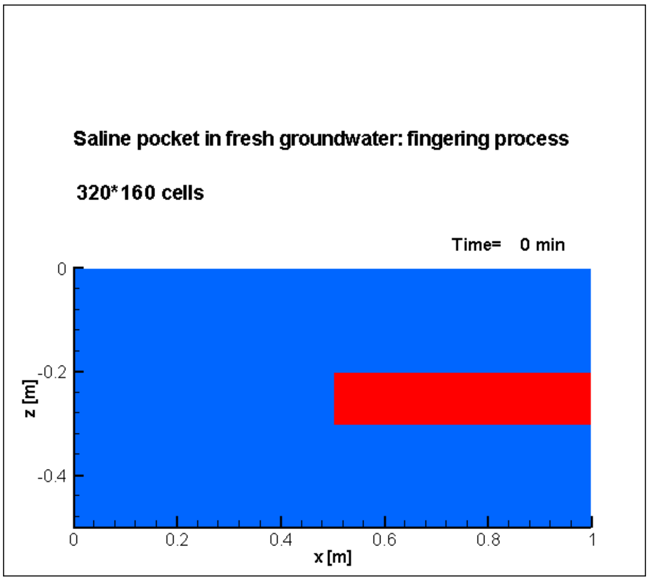
Effect of discretisation



cases

Salt water pocket in a fresh environment (IV)

Effect of discretisation



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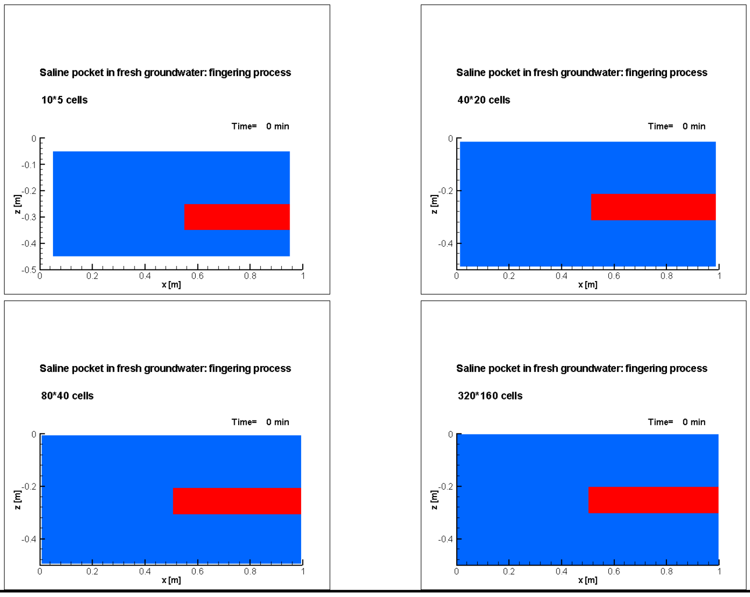
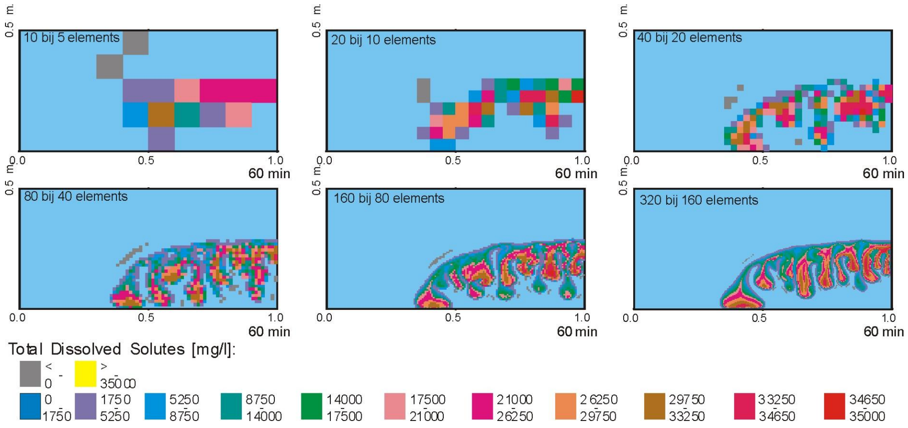
cases

Salt water pocket in a fresh environment (V)

Effect of discretisation

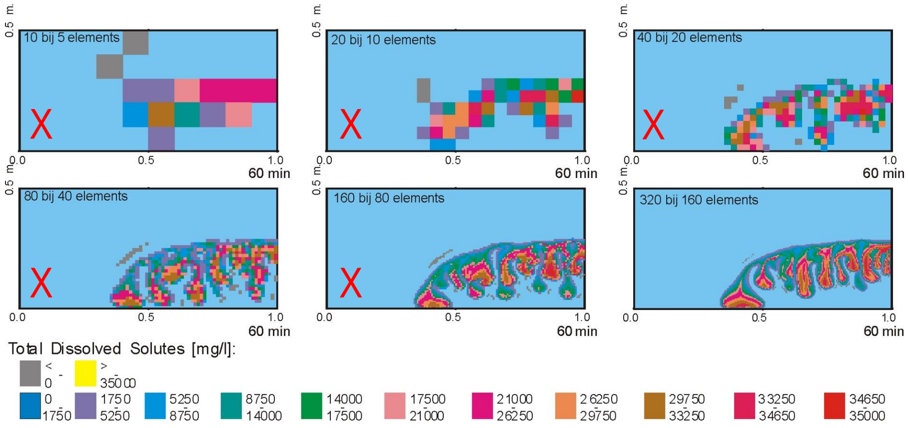


Effect of size model cell on physical process



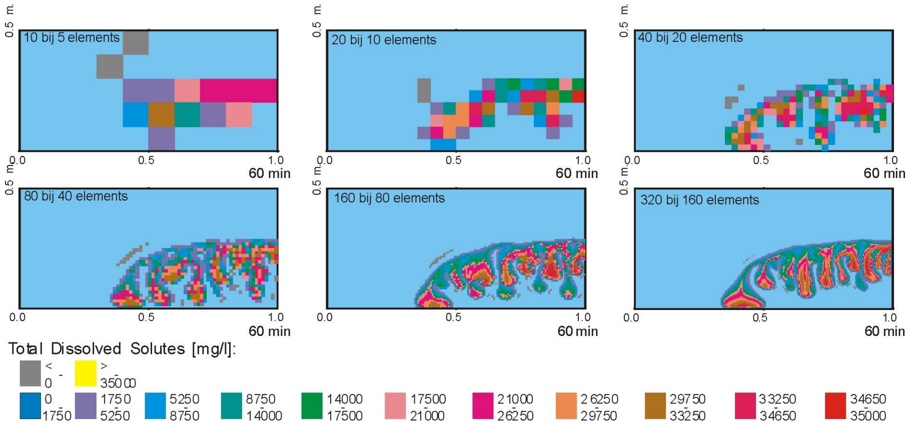
Size of cell has a large effect on modelling result!

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



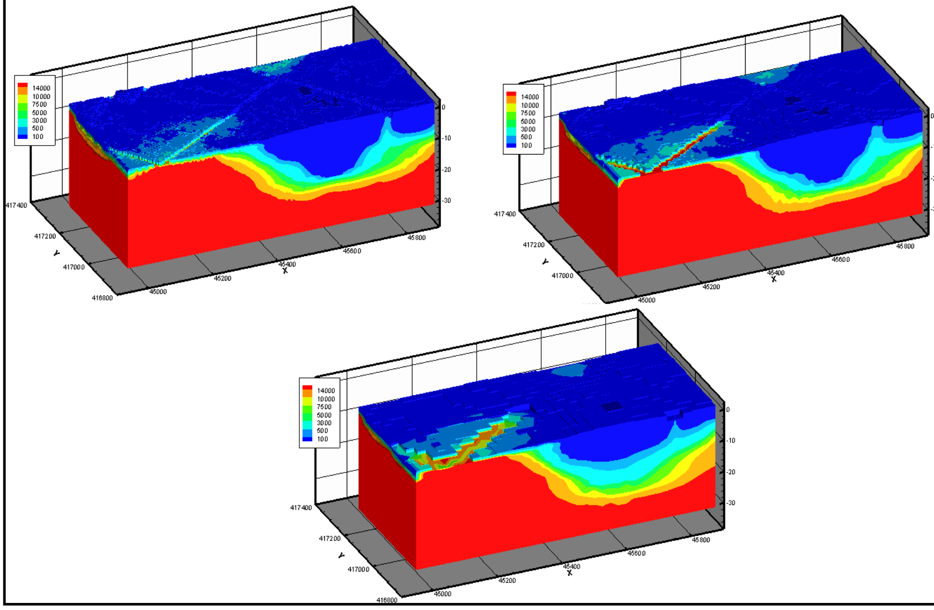
BUT: all models are GOOD for predicting the moment of touching the base!

Salt water pocket in a fresh environment (VI)

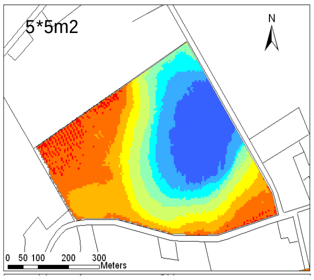
Conclusion:

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

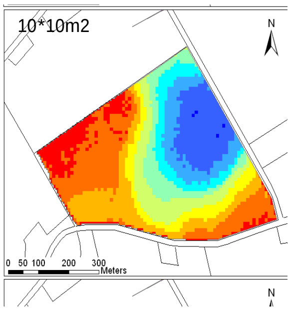
Different model scales: 5, 10, 25m2

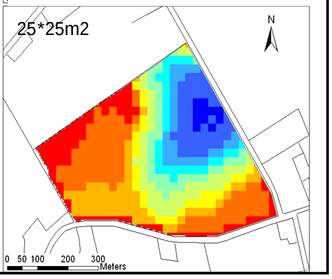


Different model scales

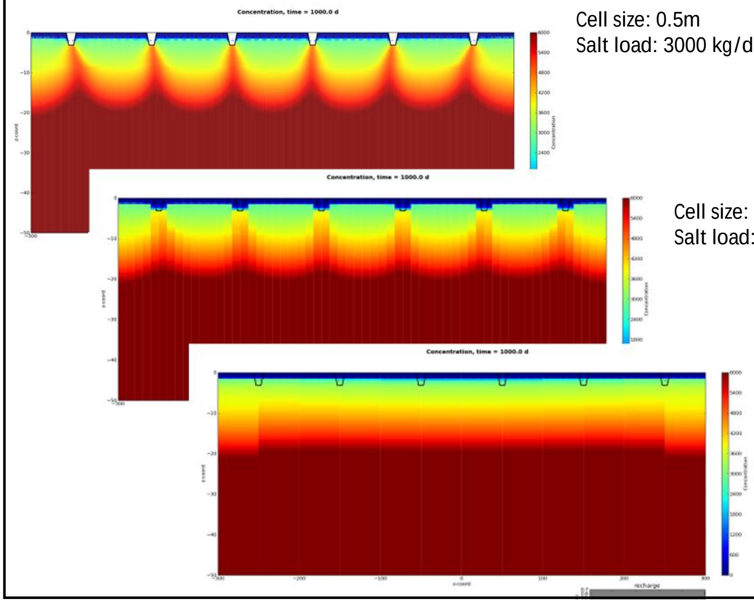


Which one is good enough?





Upscaling issues: upconing under ditch



Cell size: 0.5m
Salt load: 3000 kg/d

Cell size: 10m
Salt load: 1750 kg/d

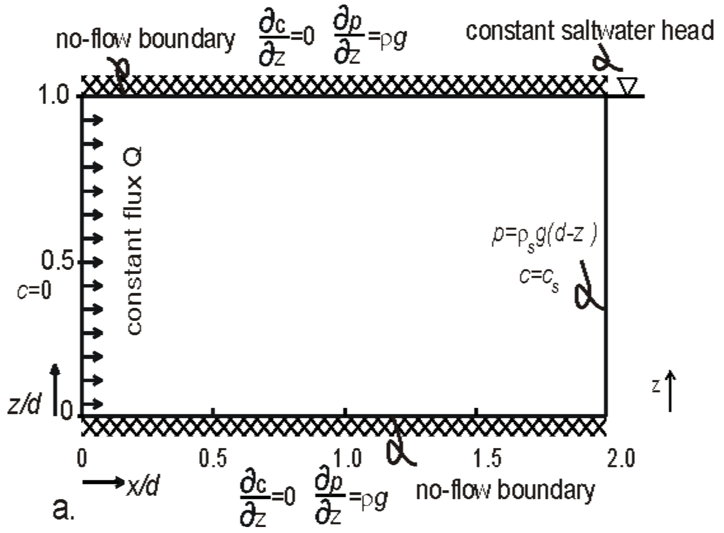
Cel size: 50m
Salt load: 2000 kg/d

a_L=0.01m

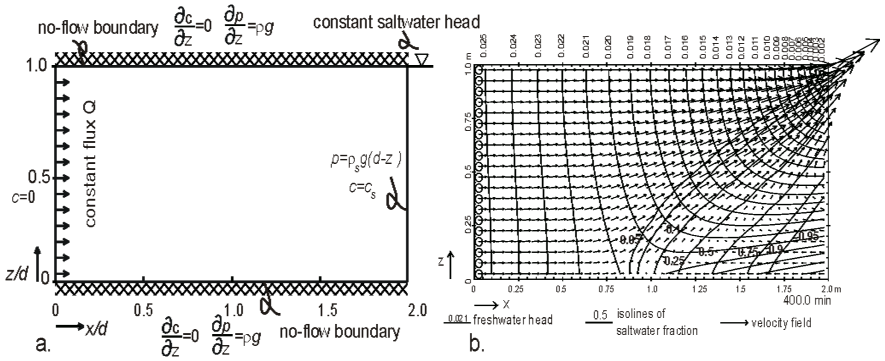
---

cases

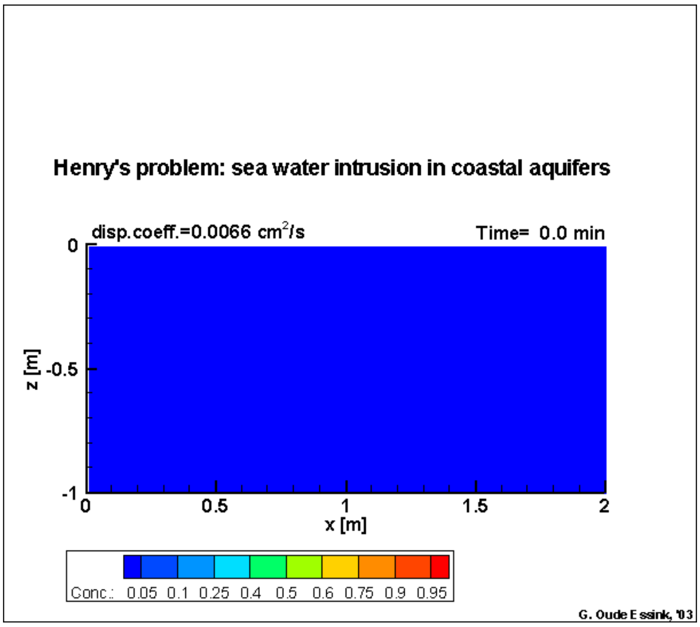
Henry’s problem (1964)



Henry’s problem



Henry’s problem

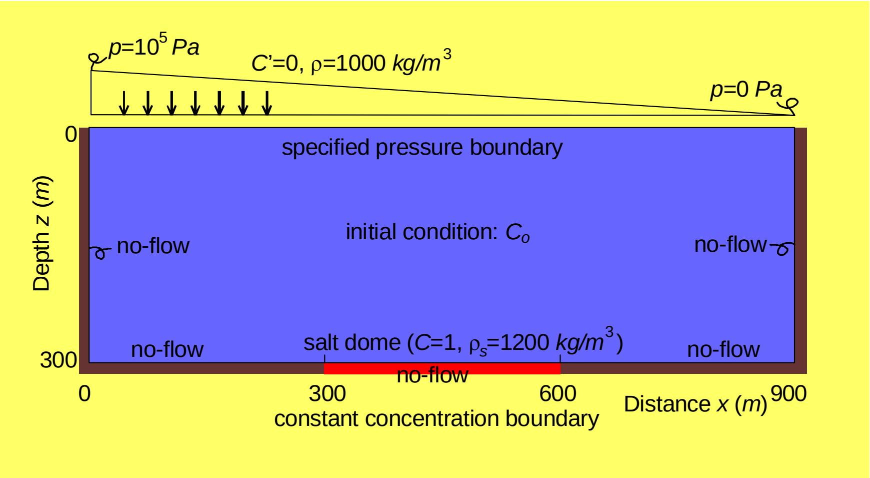


Henry’s problem

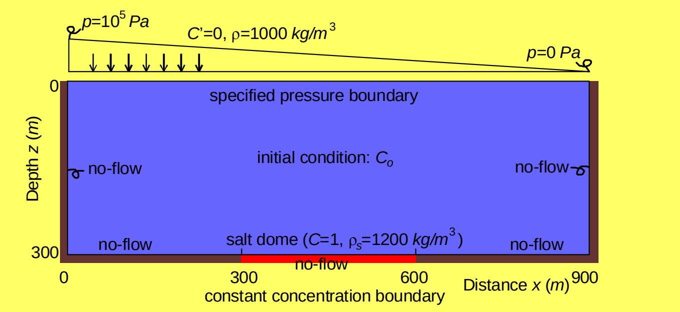
Don’t use the Henry problem as a variable-density benchmark, because even with a constant density model, the results are more or less the same!

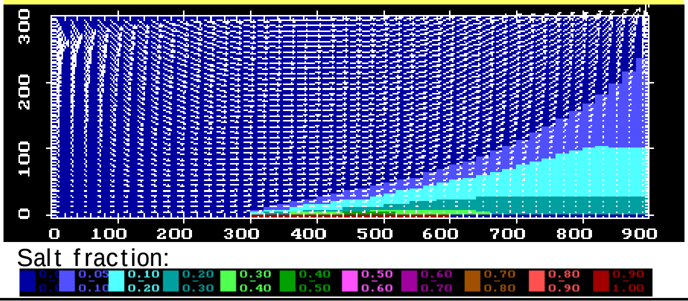
Hydrocoin:

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



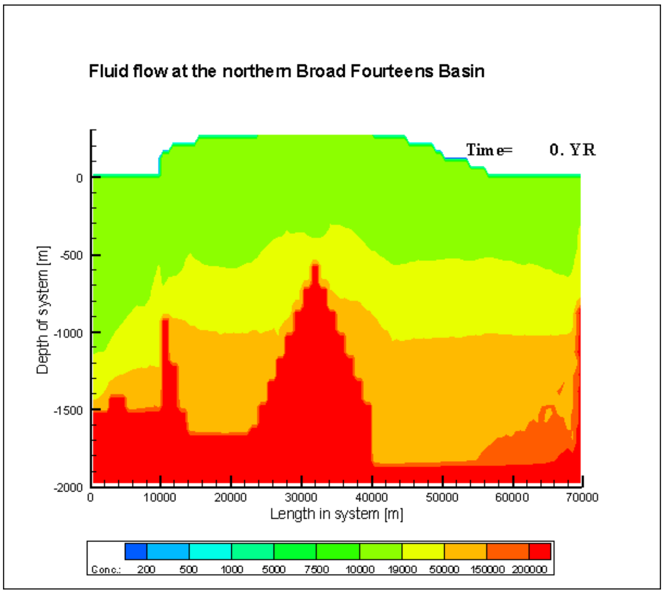
Hydrocoin:
groundwater movement near salt domes





Broad 14 Basin, North Sea

Geofluids'03, with L. Bouw

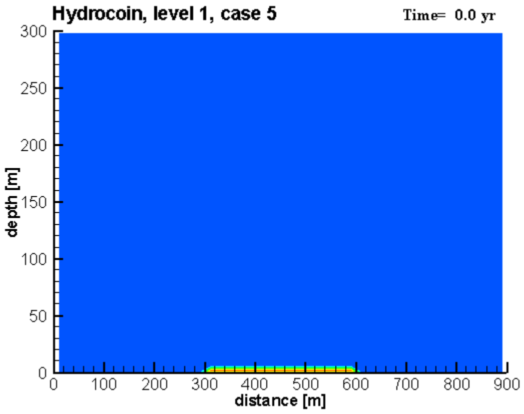


Bouw, L. & Oude Essink, G.H.P. 2003. Development of a freshwater lens in the inverted Broad Fourteens Basin, Netherlands offshore, J. of Geochemical Exploration (78-79), 321-325.

cases

Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

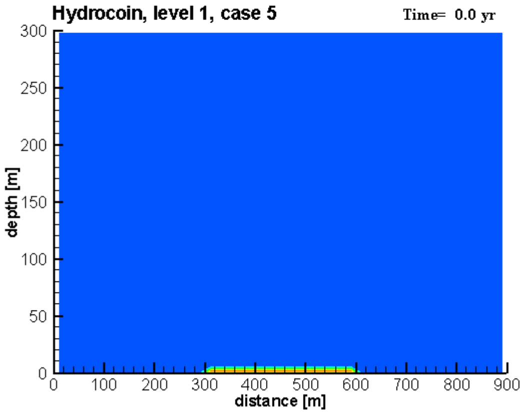


recirculation type

cases

Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

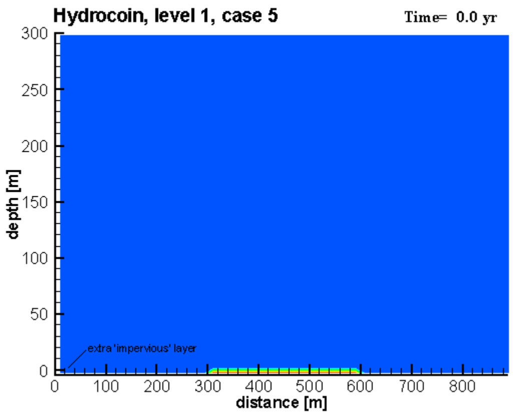


recirculation type

cases

Hydrocoin: effect of boundary condition (II)

supply of brine through only hydrodynamic dispersion



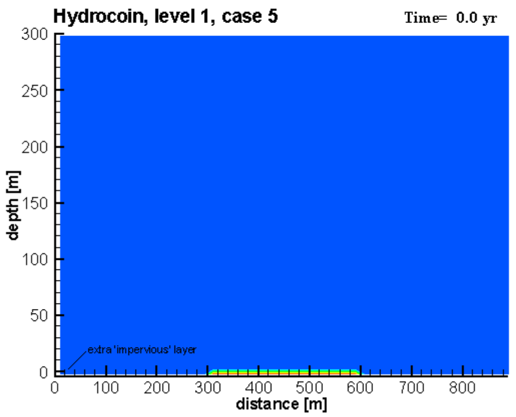
swept-forward type

---

cases

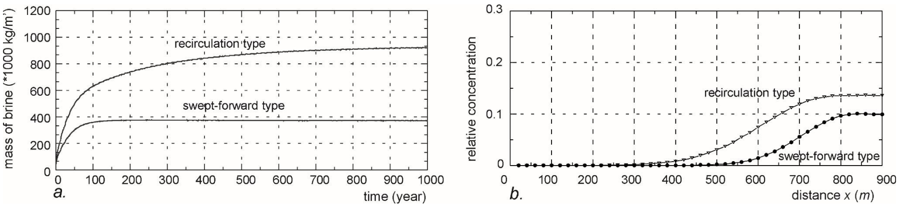
Hydrocoin: effect of boundary condition (II)

supply of brine through only hydrodynamic dispersion



swept-forward type

Hydrocoin: difference recirculation vs swept forward

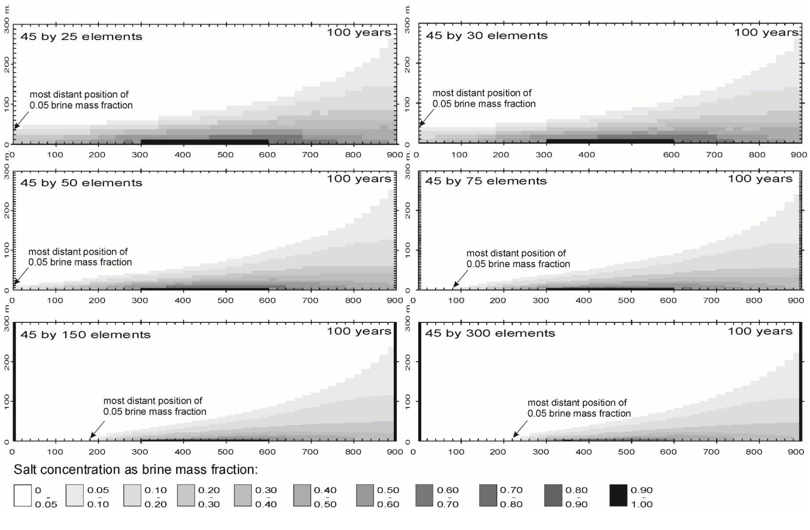


total mass of brine

brine conc at depth=200m

Lecture notes, p. 86-91

Hydrocoin: effect of vertical grid size

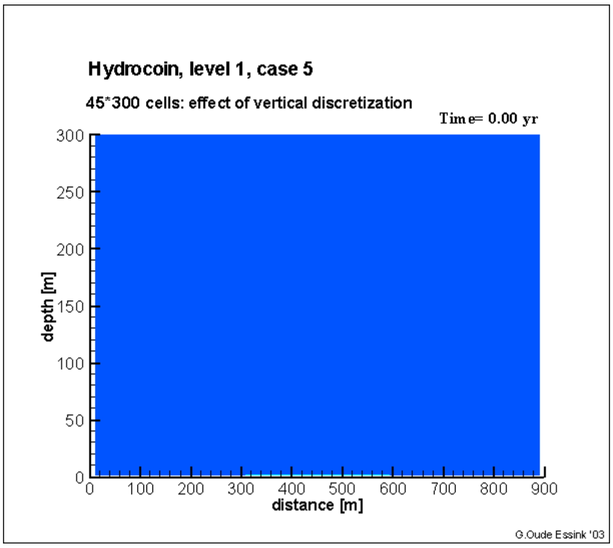


Recirculation type

cases

Hydrocoin: effect of vertical discretization (III)

more vertical cells give better solution

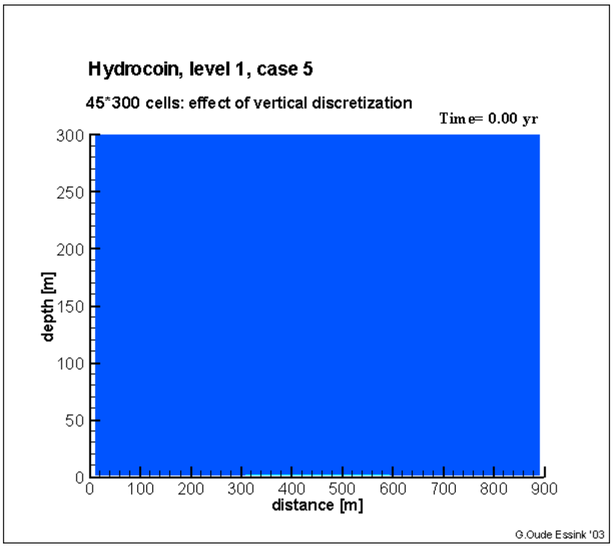


like the swept-forward type

cases

Hydrocoin: effect of vertical discretization (III)

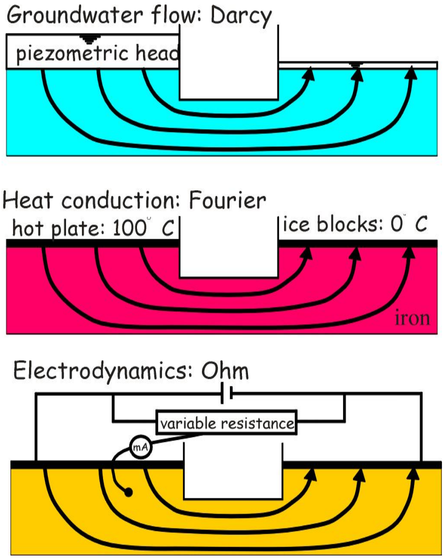
more vertical cells give better solution



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 ^{o}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 ^{o}C)]

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

Analogy solute and heat transport

Solute: advection-dispersion equation

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

Heat: convection-conduction equation

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

Analogy heat and solute transport

Heat transport

Convection-conduction equation

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

Equation of state: relation density & temperature

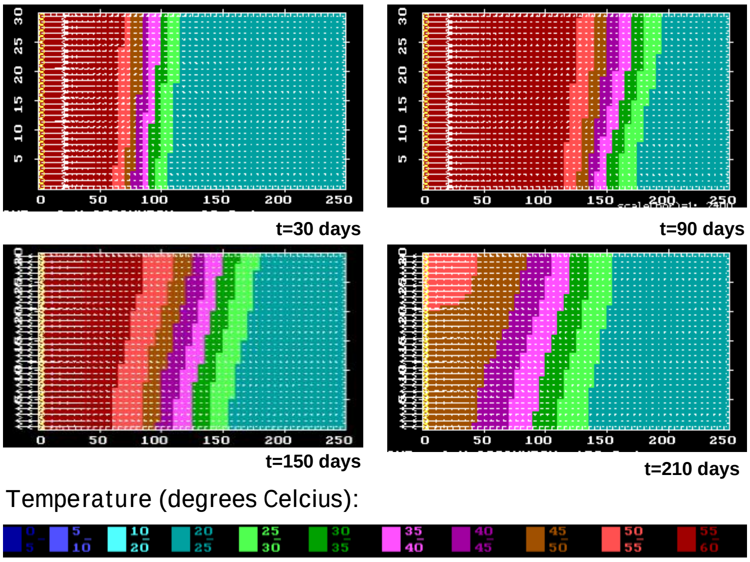
$$\rho_{\mathrm{i,j,k}} = \rho_f(1-\alpha_f T_{i,j,k})$$

Analogy between solute and heat transport

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

Heat transport

Energy storage in geothermal reservoirs



t=30 days

t=90 days

t=150 days

t=210 days

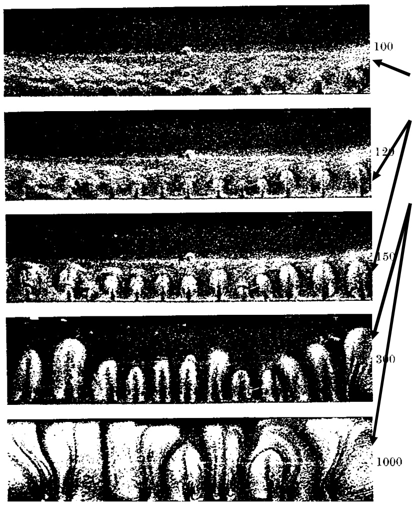
Temperature (degrees Celcius):

---

cases

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

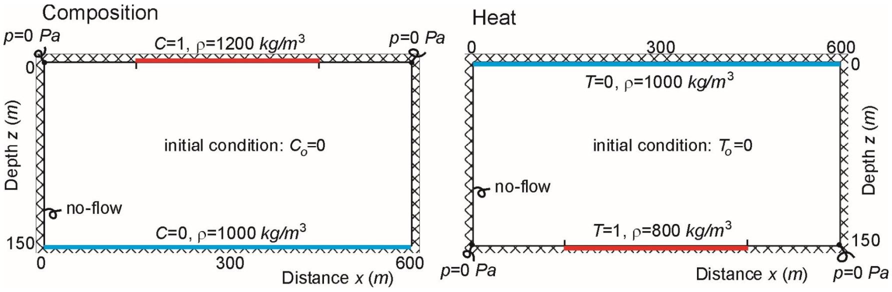
Convection of heat occurs when:

Rayleigh number > $4\pi^2$

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

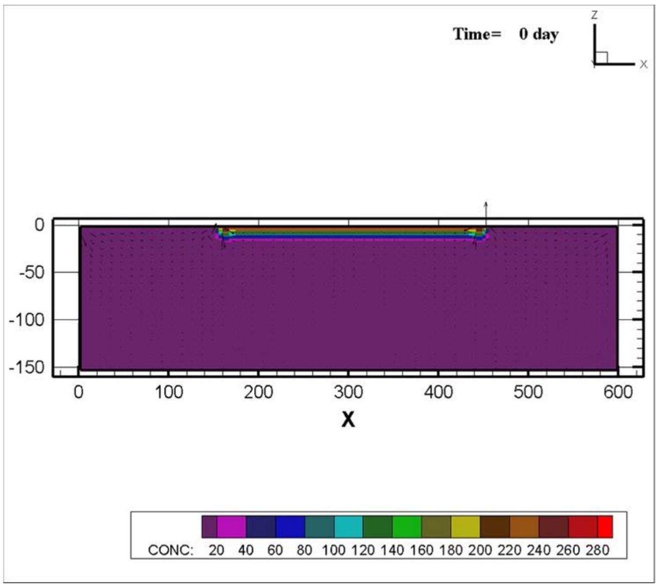
Elder problem (II)

Anology composition and heat



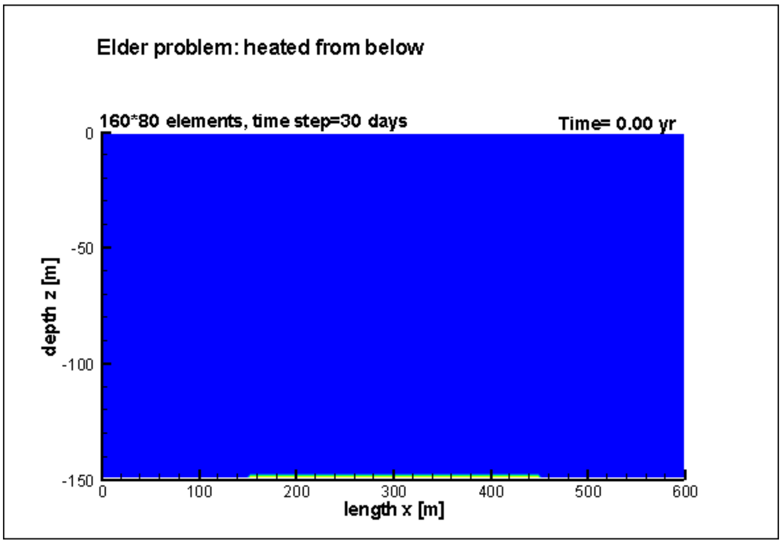
Lecture notes, p. 91-96

Case Elder, salt-fresh



Elder problem (III)

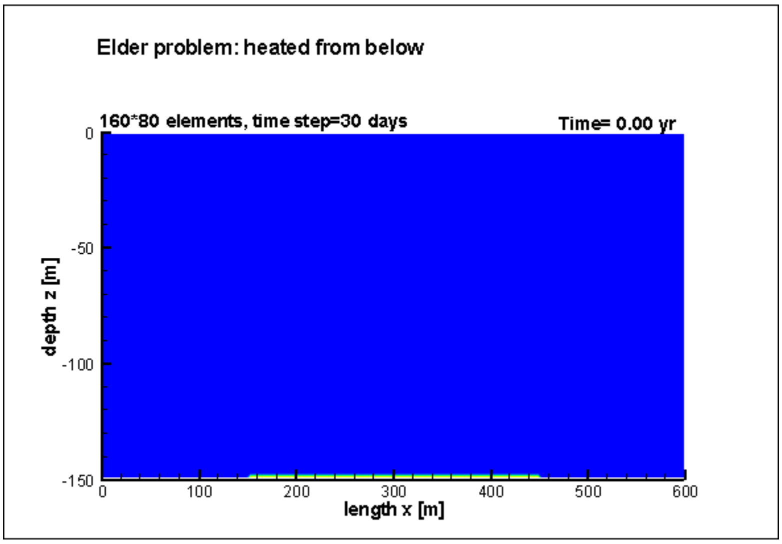
Development of convection cells (Rayleigh number=400)



cases

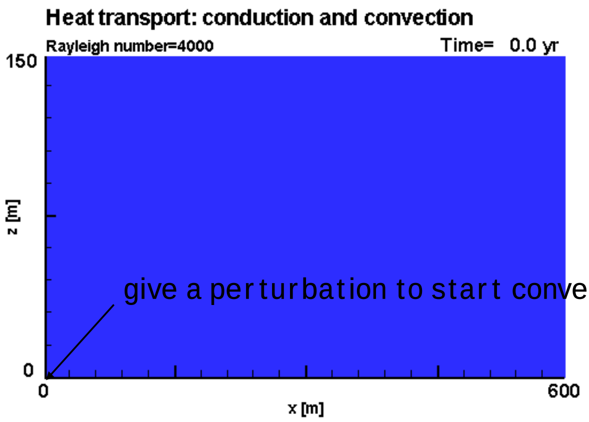
Elder problem (III)

Development of convection cells (Rayleigh number=400)



cases

Heat transport (Rayleigh number=4000)



give a perturbation to start convection

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

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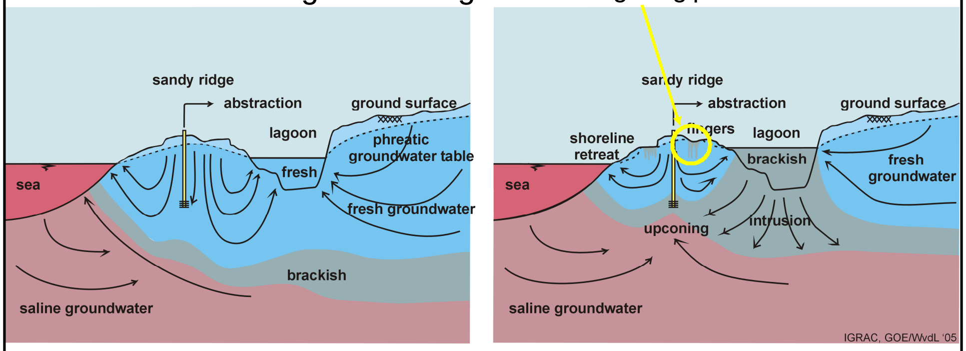
Concept 1: Fingering processes in the subsoil

Case Sri Lanka: lagoon setting

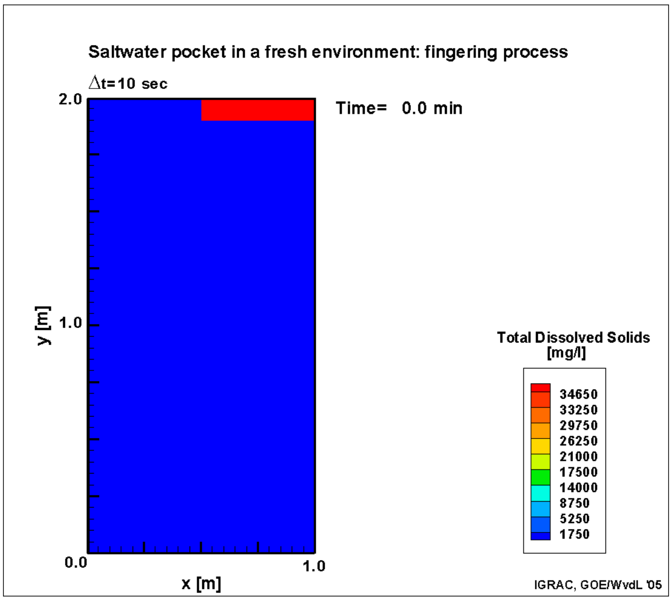
fingering processes



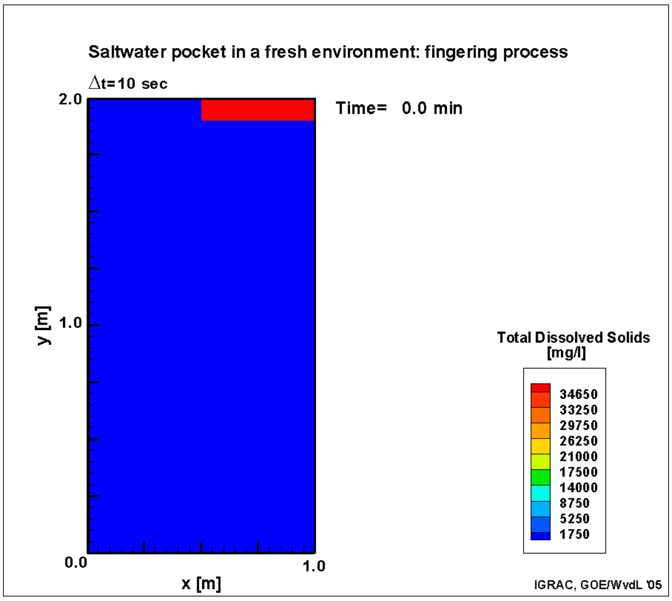
Before the Tsunami

After the Tsunami

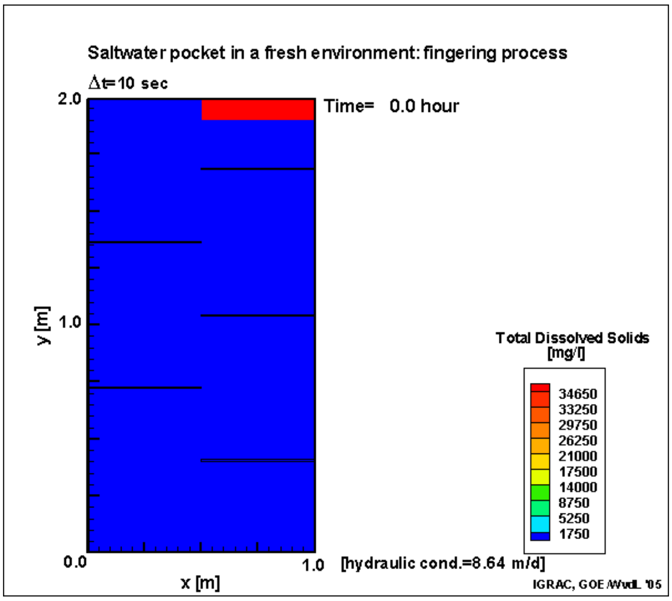
Concept 1: Fingering processes in the subsoil



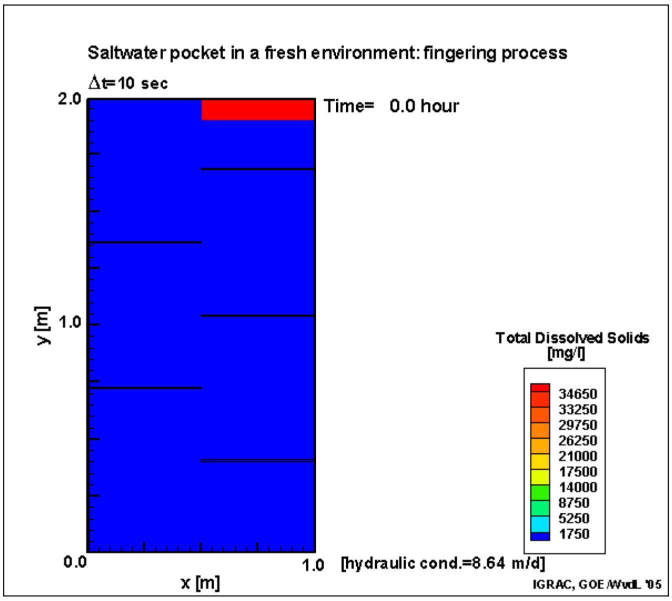
Concept 1: Fingering processes in the subsoil



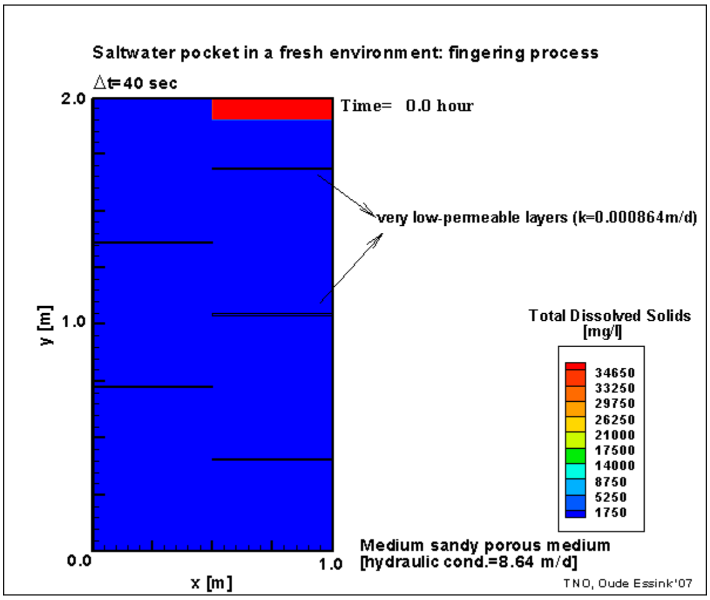
Concept 1: Fingering processes in the subsoil



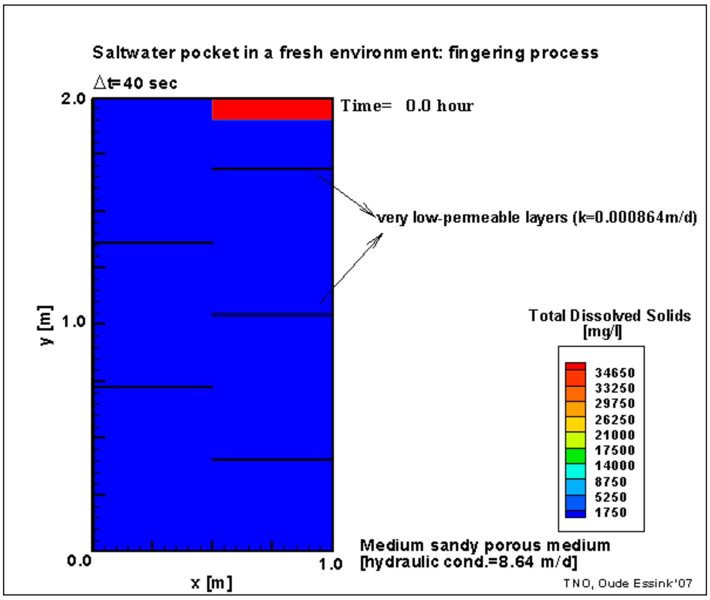
Concept 1: Fingering processes in the subsoil



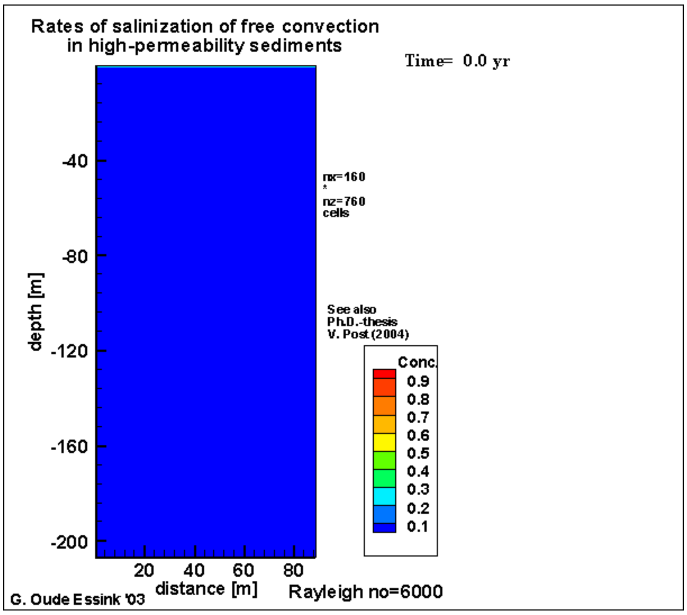
Concept 1: Fingering processes in the subsoil



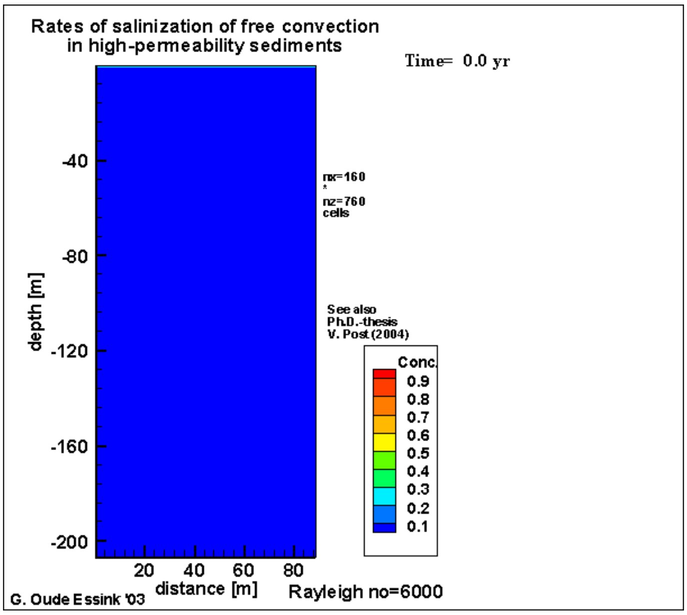
Concept 1: Fingering processes in the subsoil



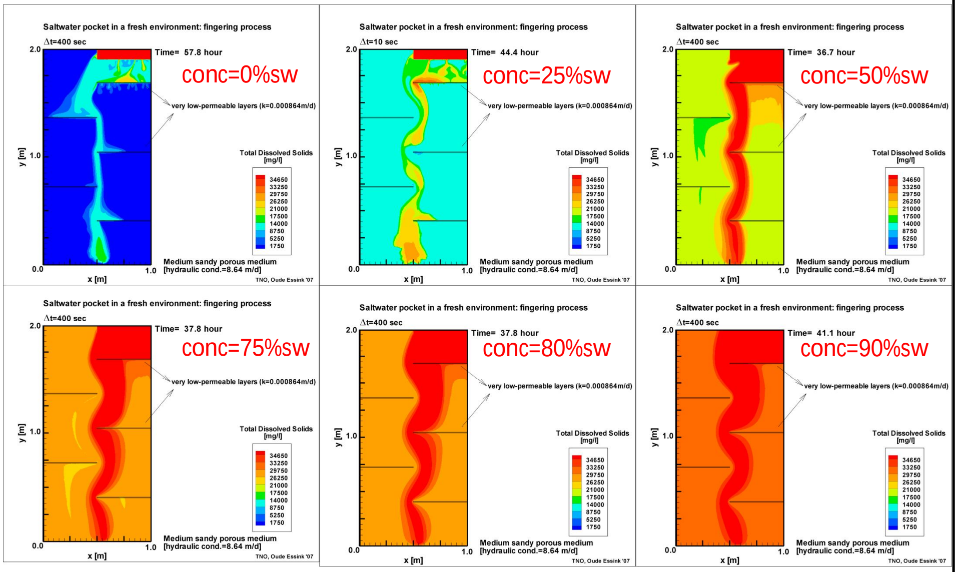
Concept 1: Fingering processes in the subsoil



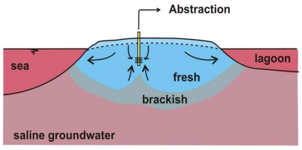
Concept 1: Fingering processes in the subsoil



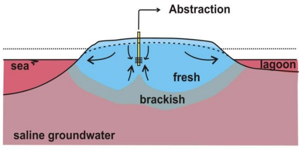
Fingering processes in the subsoil



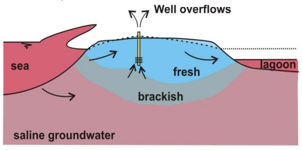
Concept 2: Evolution of a freshwater lens after flooding



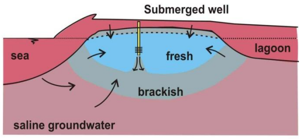
1. Before the Tsunami



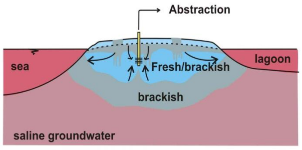
2. Just before the Tsunami:
Lowering of sea- and lagoonwater level



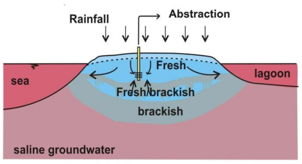
3. Just before the Tsunami:
Subsurface pressure wave precedes surface wave



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

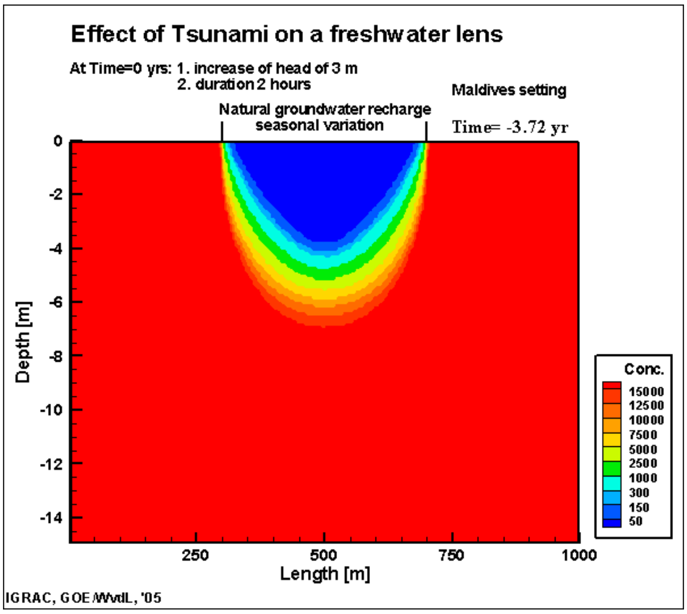


5. After the Tsunami
Freshwater mixed with brackish water

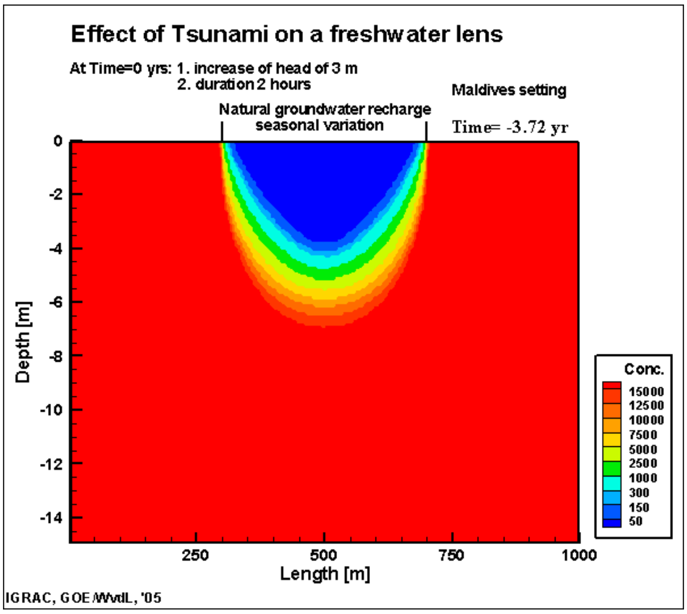


6. After the Tsunami
Recharge by rainfall replaces brackish water

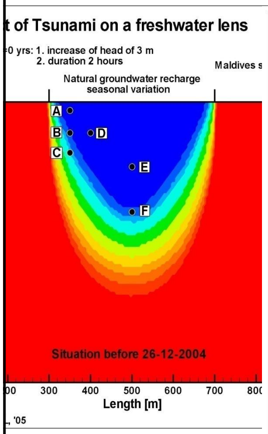
Concept 2: Evolution of a freshwater lens after flooding

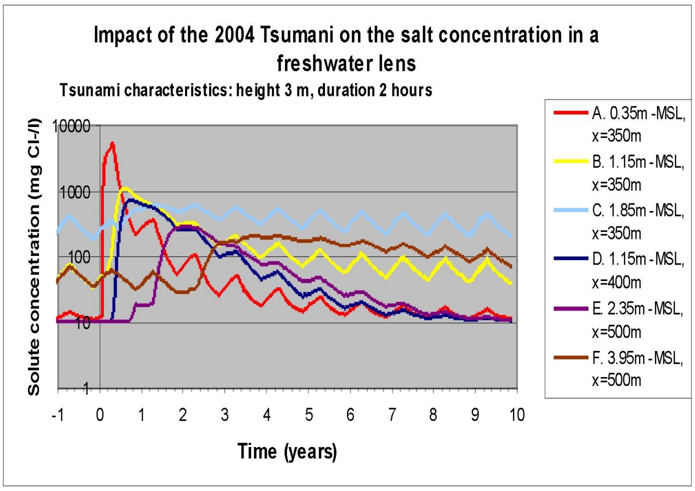


Concept 2: Evolution of a freshwater lens after flooding



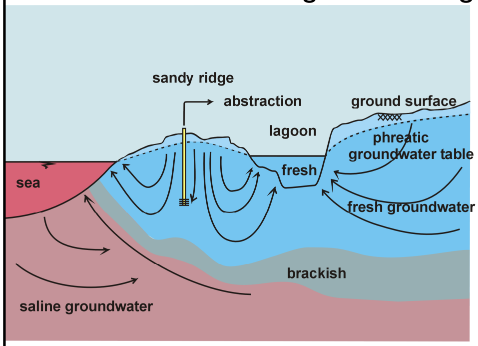
Concept 2: Evolution of a freshwater lens after flooding



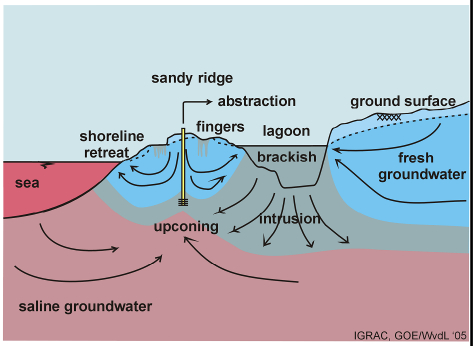


Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

Case Sri Lanka: lagoon setting

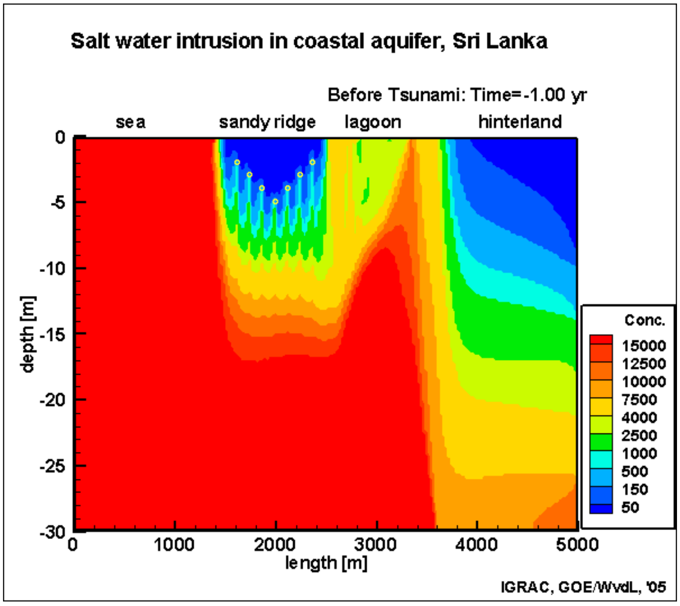


Before the Tsunami



After the Tsunami

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

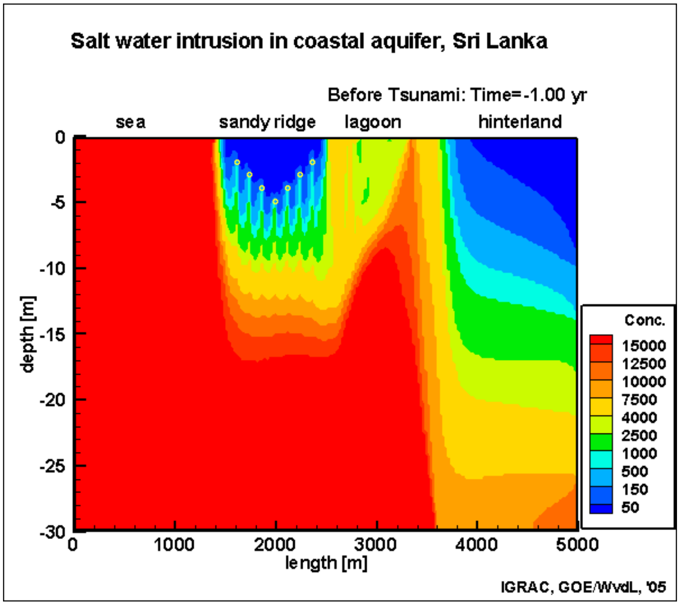


Salt water intrusion in coastal aquifer, Sri Lanka

Before Tsunami: Time=-1.00 yr

IGRAC, GOE/WvdL, '05

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

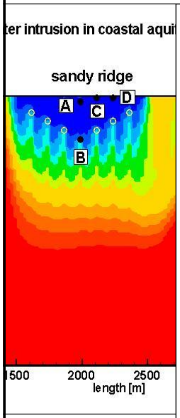


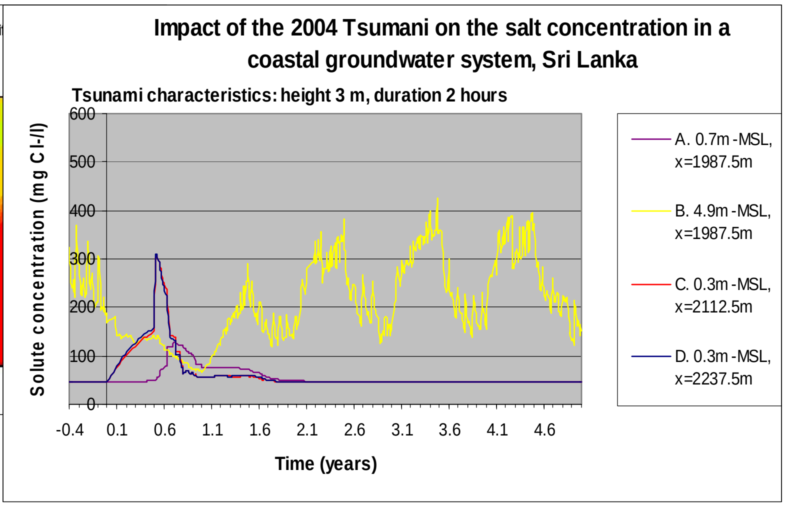
Salt water intrusion in coastal aquifer, Sri Lanka

Before Tsunami: Time=-1.00 yr

IGRAC, GOE/WvdL, '05

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




Impact of the 2004 Tsumani on the salt concentration in a coastal groundwater system, Sri Lanka

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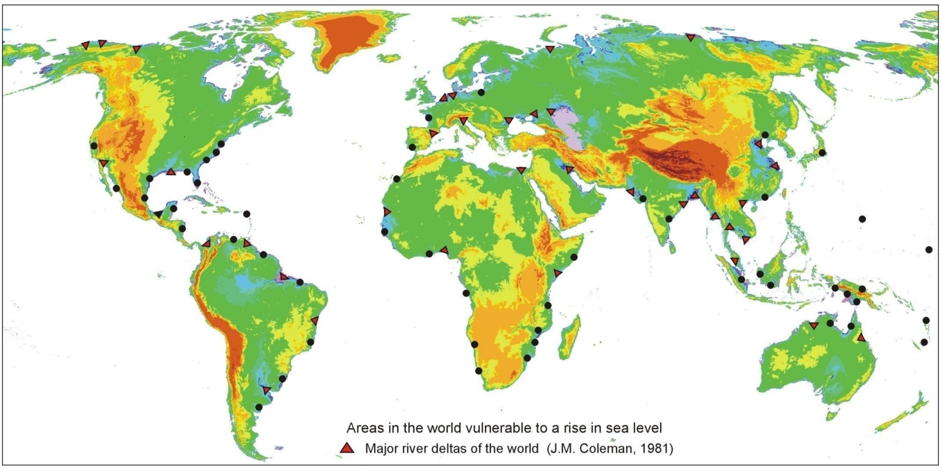
Effect sea level rise

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

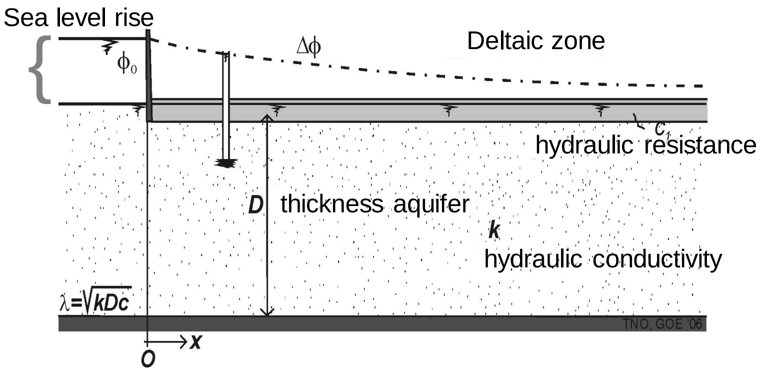


Areas in the world vulnerable to a rise in sea level

▲ Major river deltas of the world (J.M. Coleman, 1981)

Digital Elevation Model (DEM)

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



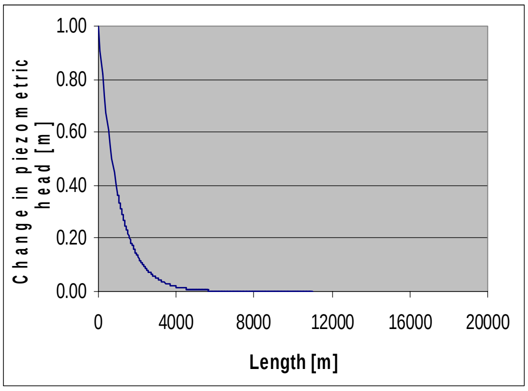
$$\Delta\phi(x)=\phi_0 e^{-x/\lambda}$$

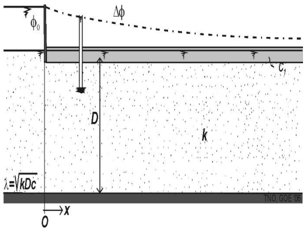
$$\lambda = \sqrt{\mathrm{kDc}}$$

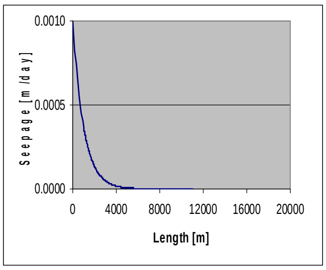
- Zone of influence is equal to sqrt(kDc)
- At x=3λ, only 5% of sea level rise is detactable

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

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



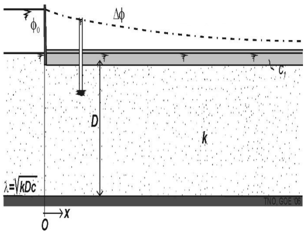


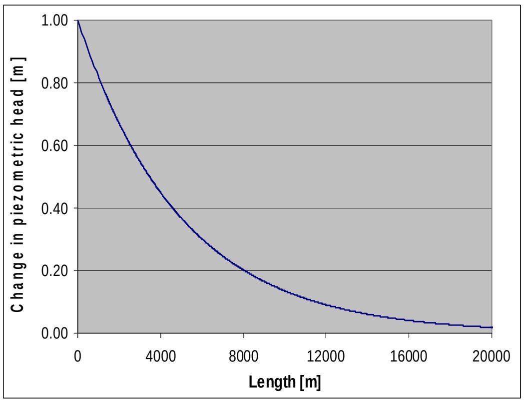


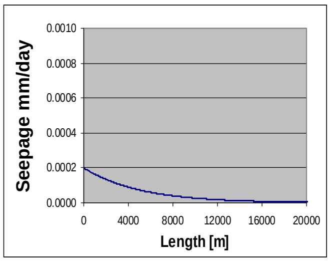
Effect of sea level rise:

Case 2 with Dutch subsoil parameters

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

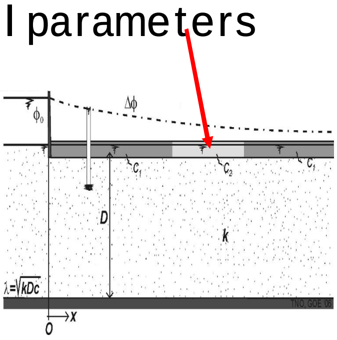


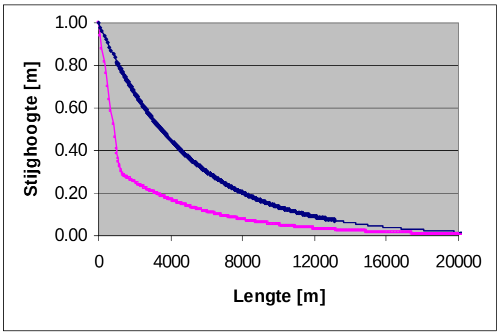


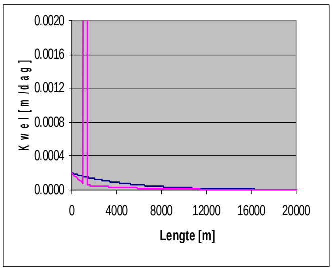


Case 3 with Dutch subsoil parameters

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

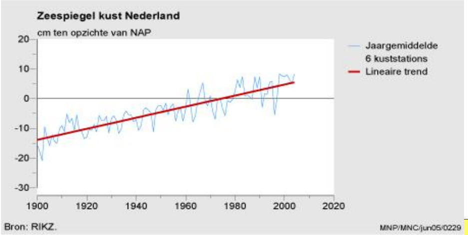


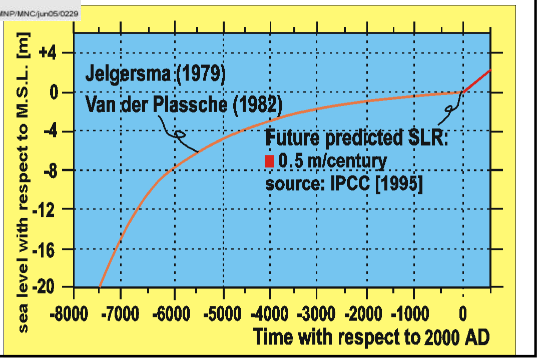




Climate change is HOT!

Past and future sea level rise in the Netherlands



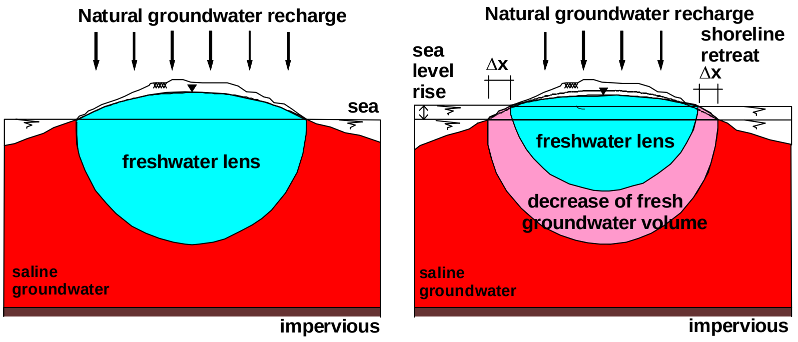


Implementing new KNMI06 climate scenarios

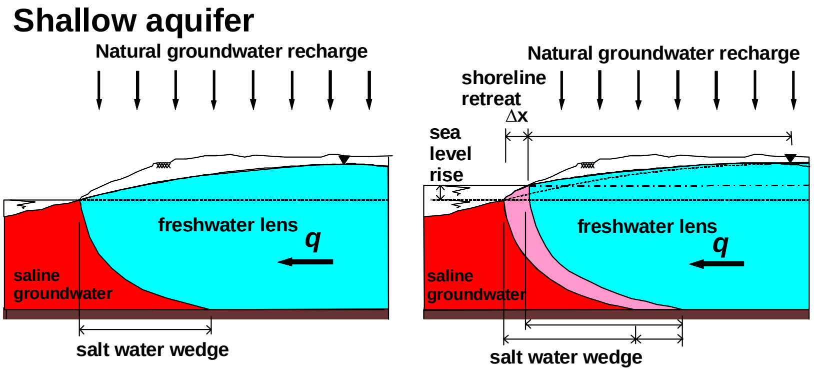
2100		G	G+	W	W+	C	C+
Worldwide temperature rise in 2050		**+1°C**	**+1°C**	**+2°C**	**+2°C**	**+3°C**	**+3°C**
Worldwide temperature rise in 2100		**+2°C**	**+2°C**	**+4°C**	**+4°C**	**+6°C**	**+6°C**
Change in airstream pattern Western Europa		**no**	**yes**	**no**	**yes**	**no**	**yes**
Winter	**Average 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):

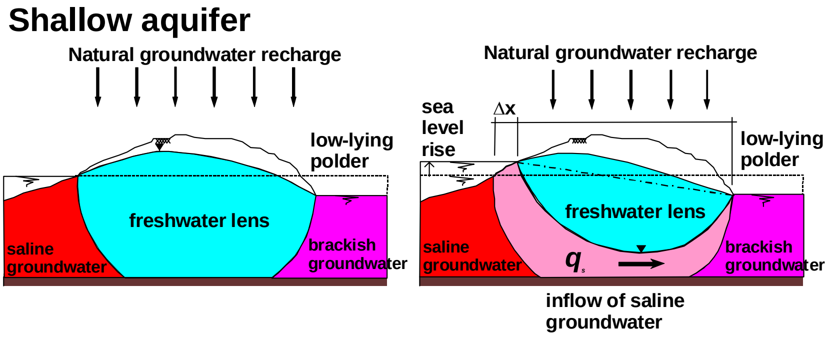
Deep aquifer



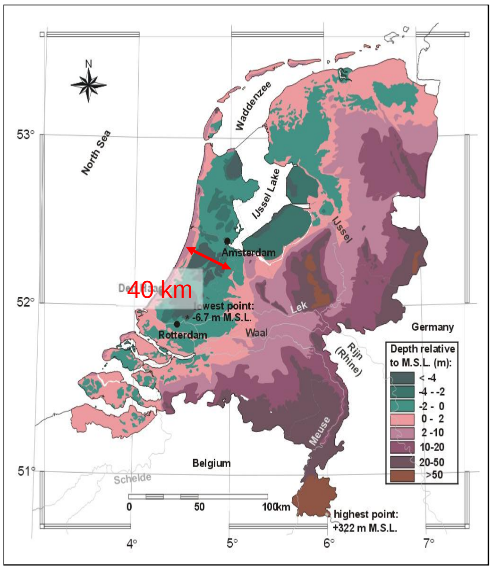
Effect of a relative sea level rise (2):

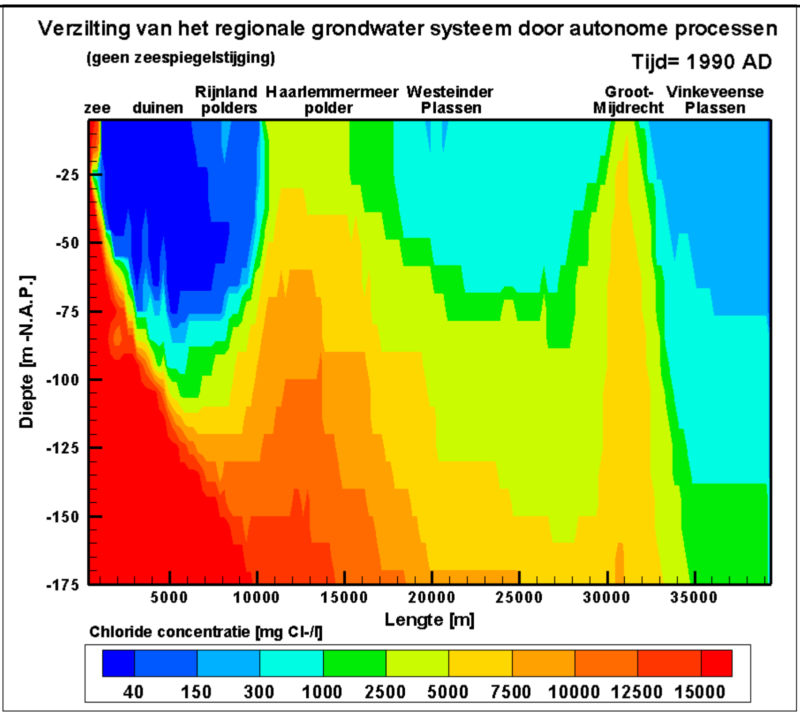


Effect of a relative sea level rise (3):



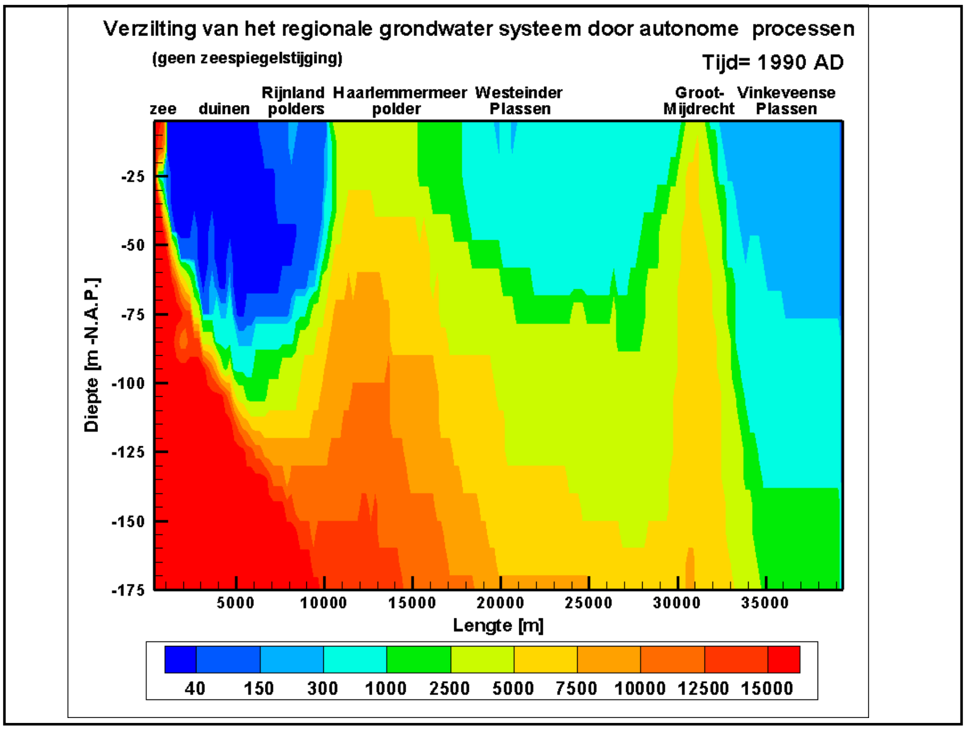
2D Profile and effect sea level rise

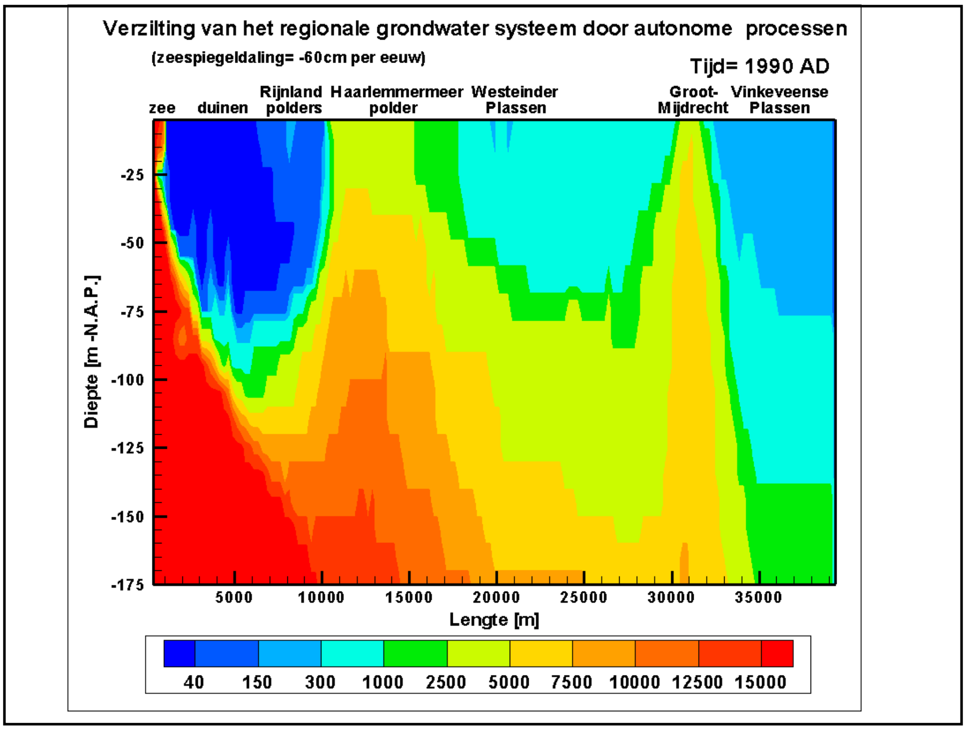



Verzilting van het regionale grondwater systeem door autonome processen

(geen zeespiegelstijging)

Tijd= 1990 AD


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
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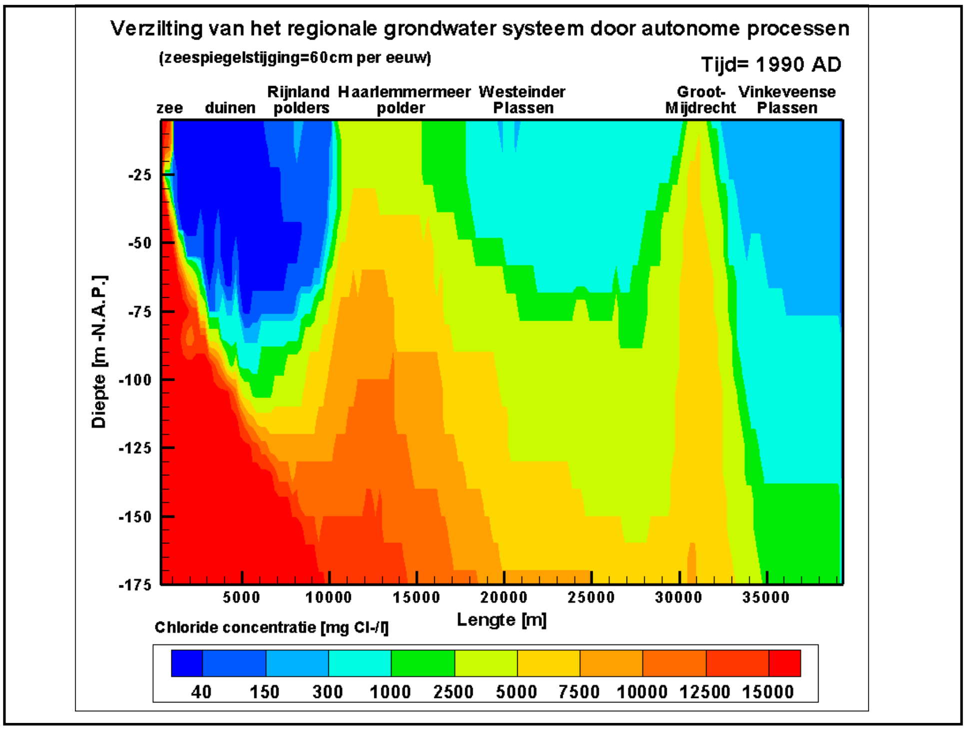
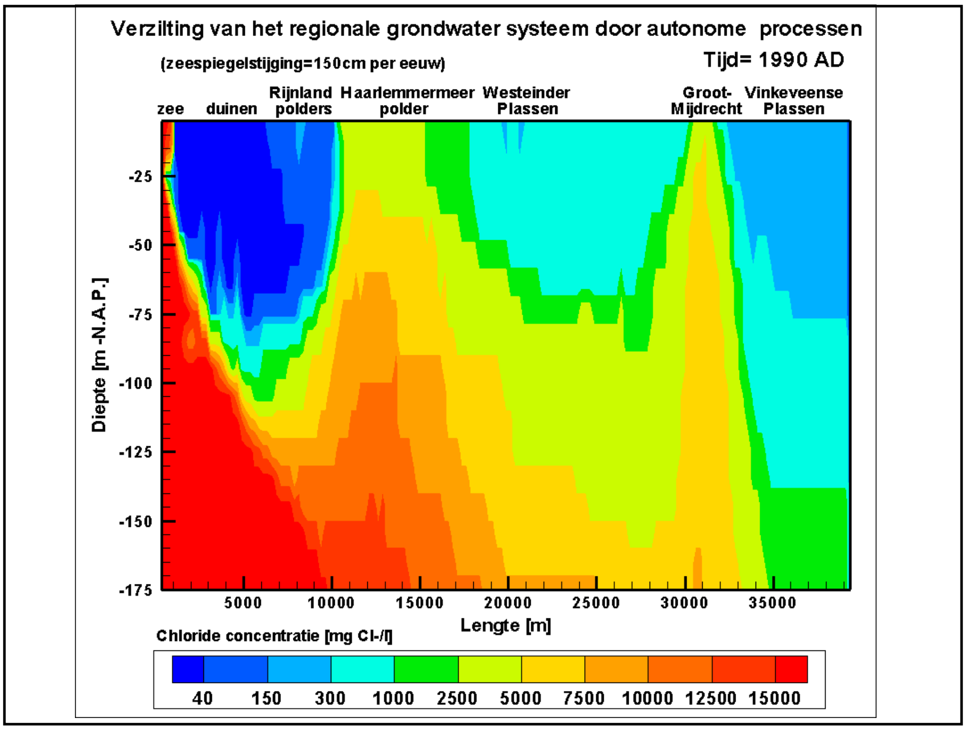
5000
7500
10000
12500
15000



Verzilting van het regionale grondwater systeem door autonome processen

(zeespiegelstijging=60cm per eeuw)

Tijd= 1990 AD



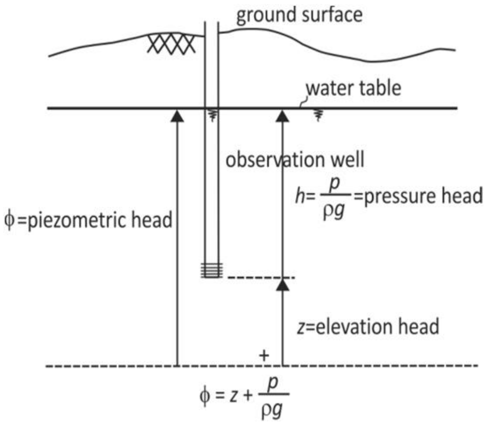
Verzilting van het regionale grondwater systeem door autonome processen

(zeespiegelstijging=150cm per eeuw)

Tijd= 1990 AD

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

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

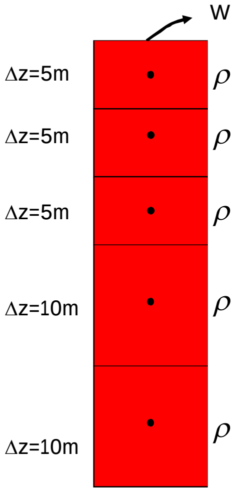
$$\partial \phi_f = -\frac{\rho - \rho_f}{\rho_f}\partial z$$

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

$\downarrow$ +

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

Hydrostatic boundary condition at the sea



Water level=+0m MSL

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

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

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

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

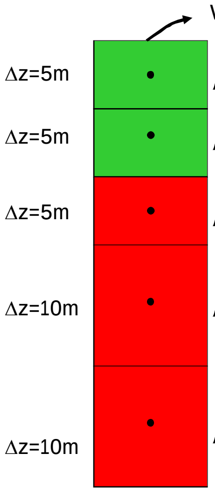
$\phi_{f4} = 0.3125 + 0.025*(2.5\text{m} + 5\text{m}) = 0.50\text{m}$

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

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

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

Hydrostatic boundary condition at the sea



Water level=+0m MSL

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

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

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

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

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

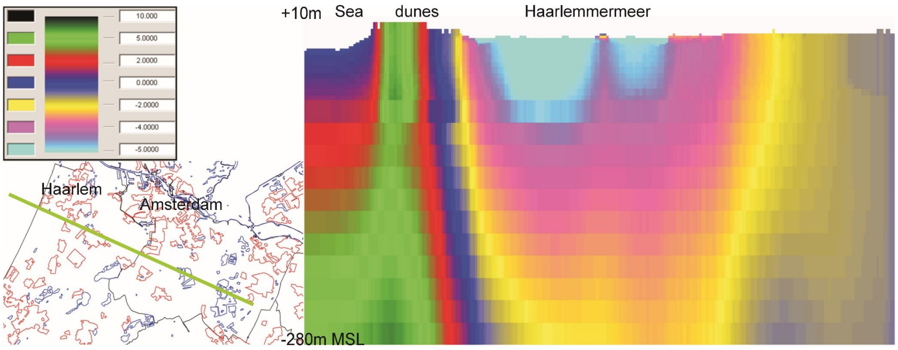
$$\phi_{f4} = 0.1625 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.35\text{m}$$

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

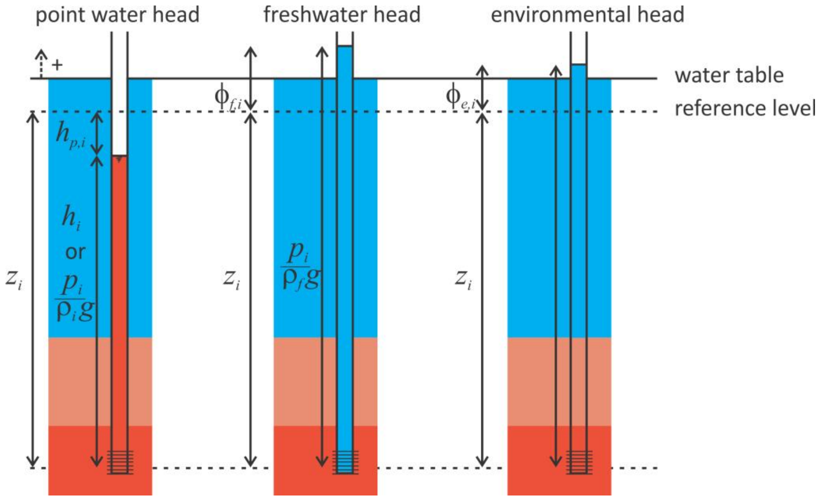
$$\phi_{f5} = 0.35 + 0.025 * (5\text{m} + 5\text{m}) = 0.60\text{m}$$

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

Example 2D profile NHI model freshwater head ϕ_f



Which one is useful?



Post, Kooi and Simmons, 2007, Ground Water

Point water head

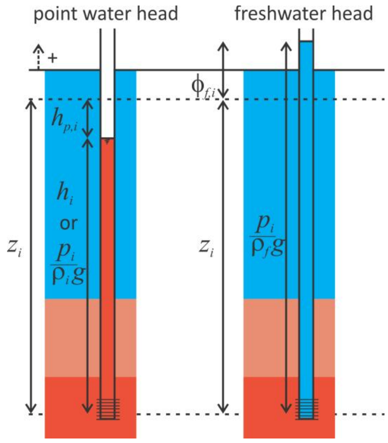
$$h_{p,i} = z_i + h_i \longleftrightarrow h_i = h_{p,i} - z_i$$

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

Freshwater head

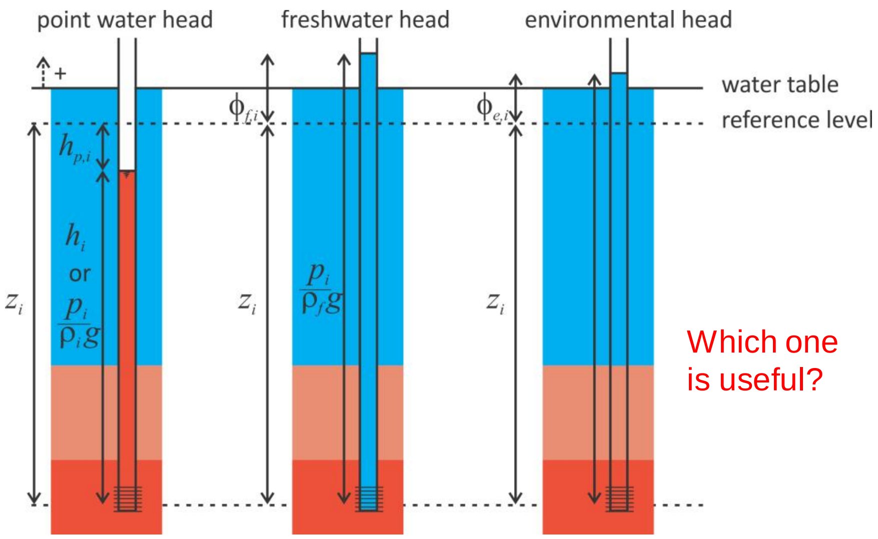
$$\phi_{f,i} = z_i + \frac{p_i}{\rho_f g} \longleftrightarrow \phi_{f,i} = z_i + \frac{h_i \rho_i}{\rho_f}$$

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



Post, Kooi and Simmons, 2007, Ground Water

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



Which one
is useful?

Post, Kooi and Simmons, 2007, Ground Water

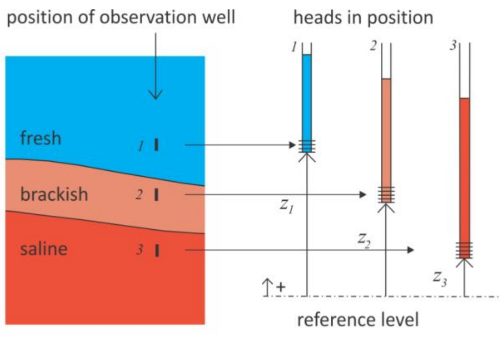
Point water head

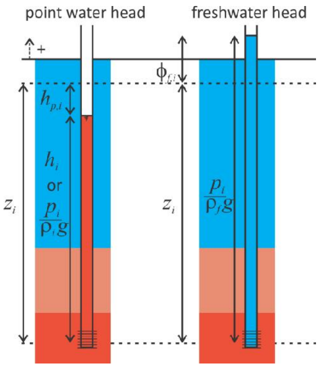
Freshwater head

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*.

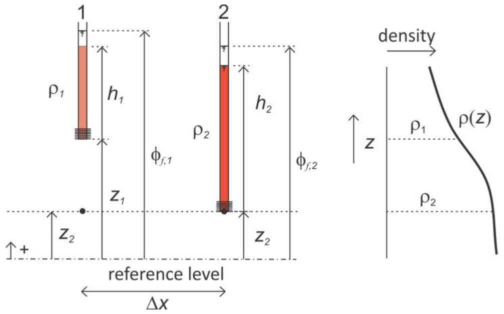
Example 2: $h_{p,i}$=0 *m MSL*, ρ_i =1025 *kg/m*$^{-3}$, z_i=-10*m MSL*: $\phi_{f,i}$=0.25*m MSL*.

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?

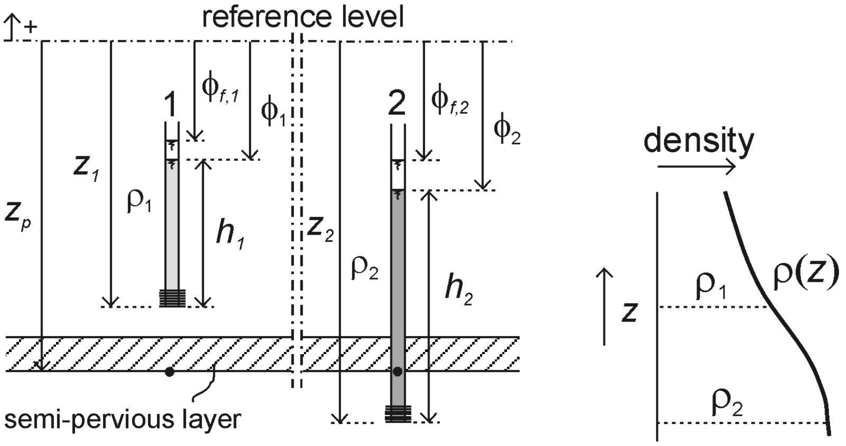


$$p_1^{at\ z=z_2} = \rho_1 g h_1 + \int_{z_2}^{z_1} \rho(z) g dz \qquad \phi_{f,1}^{at\ z=z_2} = z_2 + \frac{\rho_1}{\rho_f} h_1 + \frac{1}{\rho_f g} \int_{z_2}^{z_1} \rho(z) g dz$$

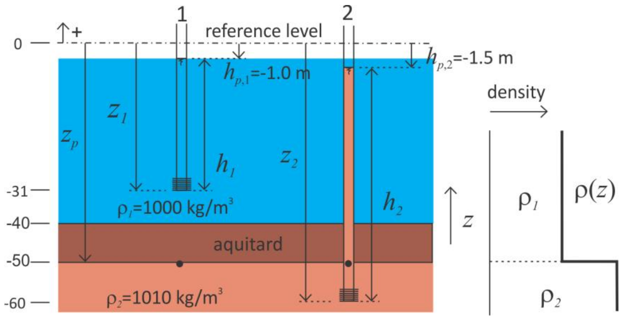
$$p_2^{at\ z=z_2} = \rho_2 g h_2 \qquad \phi_{f,2}^{at\ z=z_2} = z_2 + \frac{\rho_2}{\rho_f} h_2$$

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

Freshwater head ϕ_f : vertical flow?

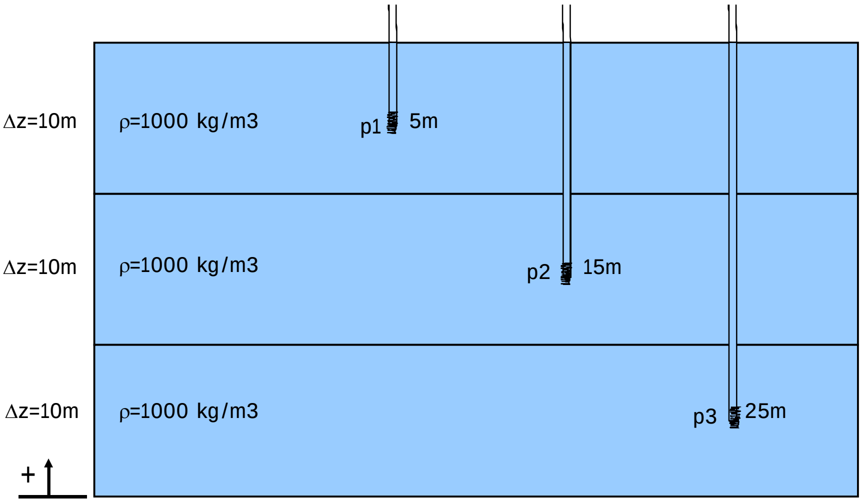


Freshwater head ϕ_f

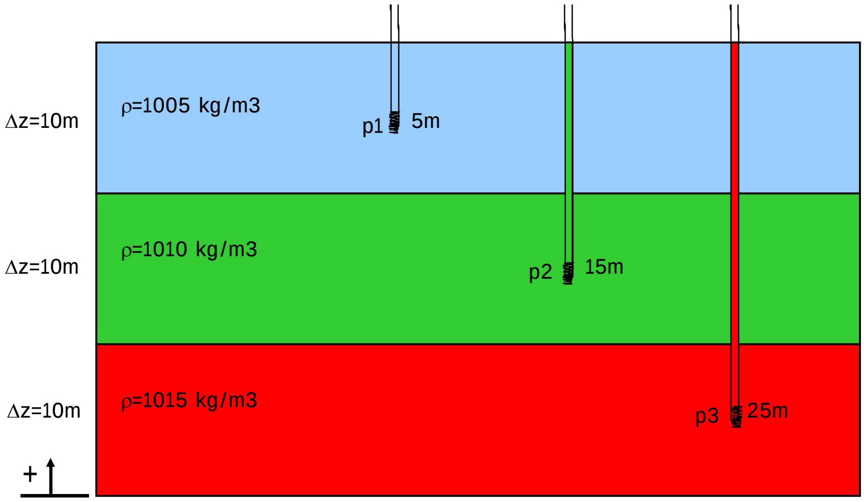


$$\phi_{f,1}^{z=-50} = -50 + \frac{1000}{1000}30 + \frac{1}{1000g}\int_{-50}^{-31}1000gdz = -50+30+19 = -1.0$$

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

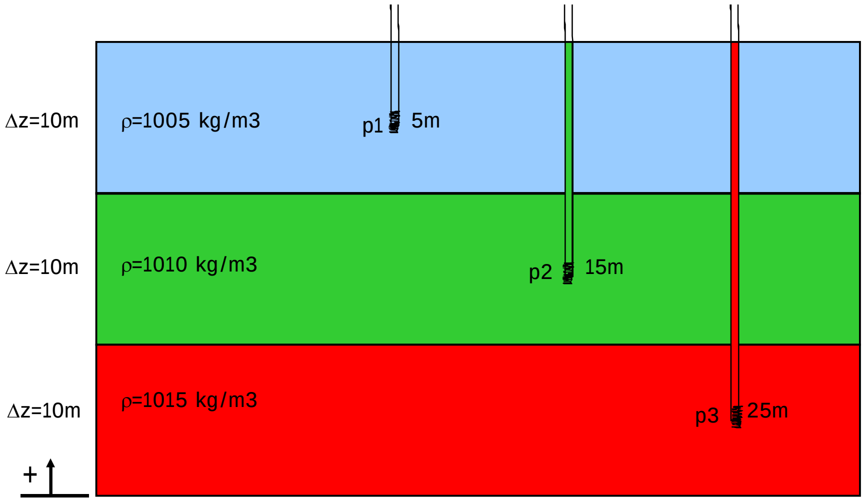


No flow



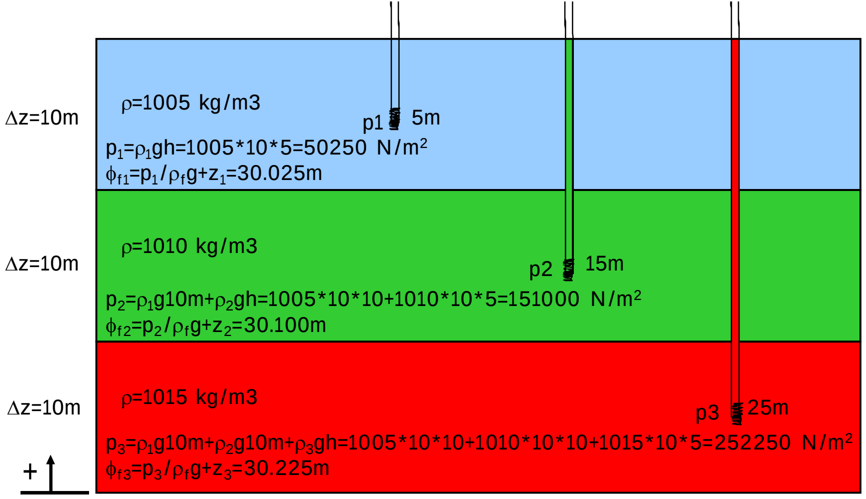
Flow or no flow? (if p≠hydrostatic than flow)

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



ρ=1005 kg/m3

$p_1=\rho_1 gh=1005*10*5=50250$ N/m^2

$\phi_{f1}=p_1/\rho_f g+z_1=30.025$m

ρ=1010 kg/m3

$p_2=\rho_1 g10m+\rho_2 gh=1005*10*10+1010*10*5=151000$ N/m^2

$\phi_{f2}=p_2/\rho_f g+z_2=30.100$m

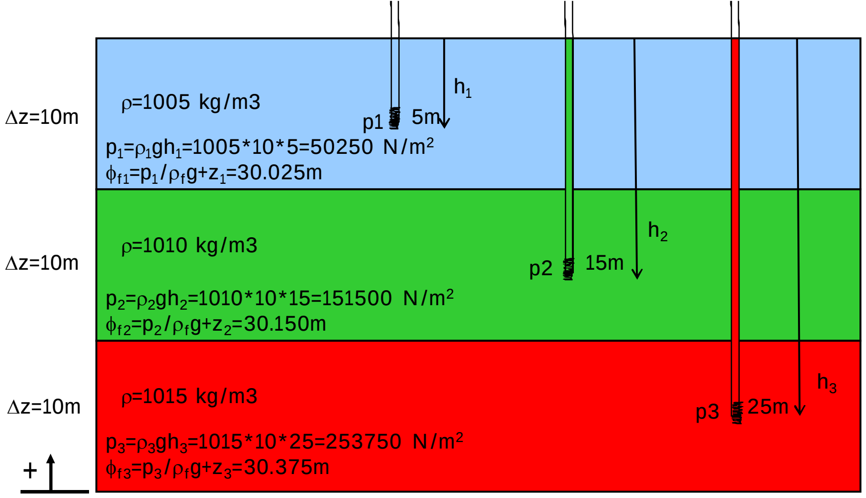
ρ=1015 kg/m3

$p_3=\rho_1 g10m+\rho_2 g10m+\rho_3 gh=1005*10*10+1010*10*10+1015*10*5=252250$ N/m^2

$\phi_{f3}=p_3/\rho_f g+z_3=30.225$m

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



ρ=1005 kg/m3

$p_1=\rho_1 gh_1=1005*10*5=50250$ N/m^2

$\phi_{f1}=p_1/\rho_f g+z_1=30.025$m

ρ=1010 kg/m3

$p_2=\rho_2 gh_2=1010*10*15=151500$ N/m^2

$\phi_{f2}=p_2/\rho_f g+z_2=30.150$m

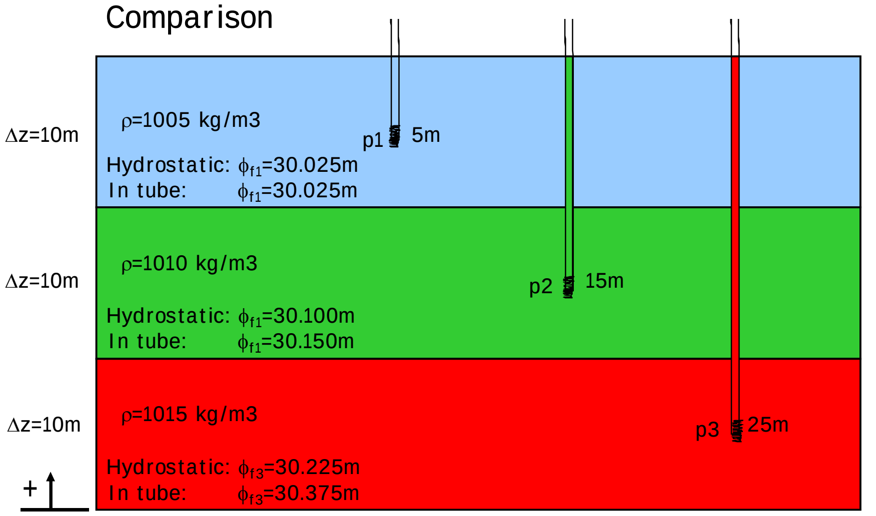
ρ=1015 kg/m3

$p_3=\rho_3 gh_3=1015*10*25=253750$ N/m^2

$\phi_{f3}=p_3/\rho_f g+z_3=30.375$m

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

Comparison



Δz=10m

ρ=1005 kg/m3

p1 5m

Hydrostatic: ϕ_{f1}=30.025m
In tube: ϕ_{f1}=30.025m

Δz=10m

ρ=1010 kg/m3

p2 15m

Hydrostatic: ϕ_{f1}=30.100m
In tube: ϕ_{f1}=30.150m

Δz=10m

ρ=1015 kg/m3

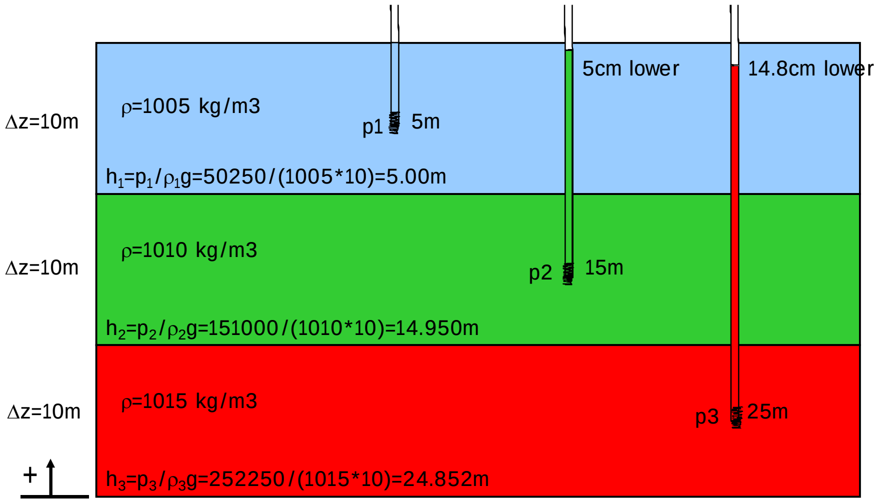
p3 25m

Hydrostatic: ϕ_{f3}=30.225m
In tube: ϕ_{f3}=30.375m

+

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

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



5cm lower

14.8cm lower

Δz=10m

ρ=1005 kg/m3

p1 5m

$h_1=p_1/\rho_1 g$=50250/(1005*10)=5.00m

Δz=10m

ρ=1010 kg/m3

p2 15m

$h_2=p_2/\rho_2 g$=151000/(1010*10)=14.950m

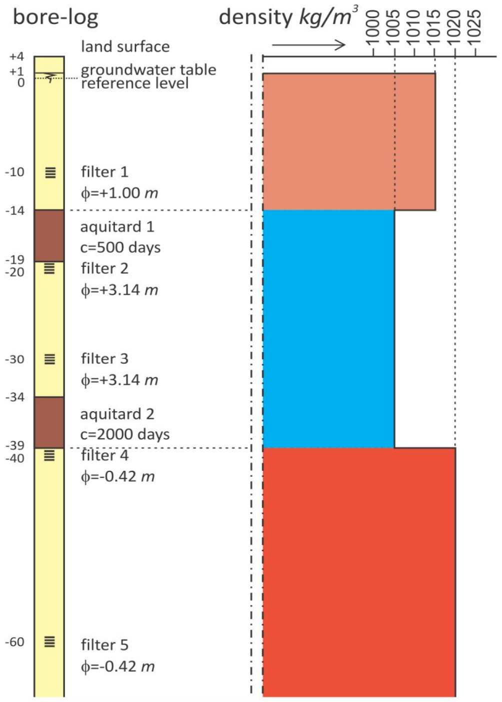
Δz=10m

ρ=1015 kg/m3

p3 25m

+

$h_3=p_3/\rho_3 g$=252250/(1015*10)=24.852m

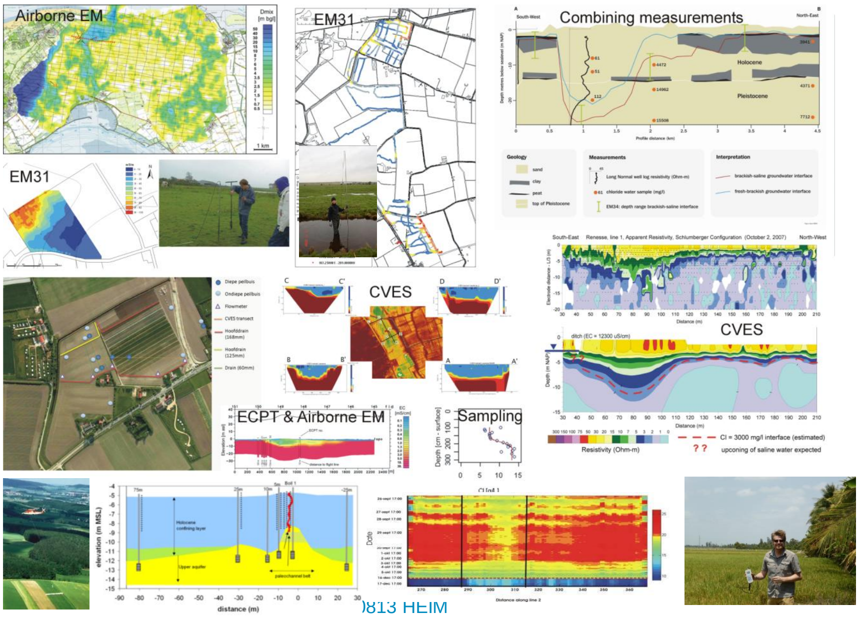


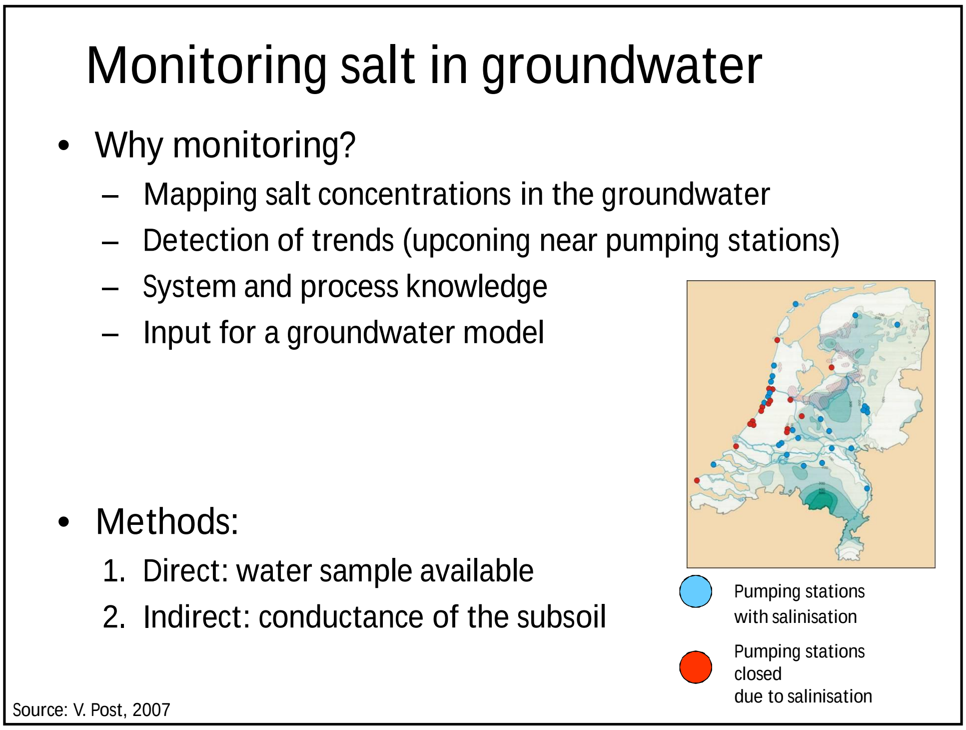
Take home message

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

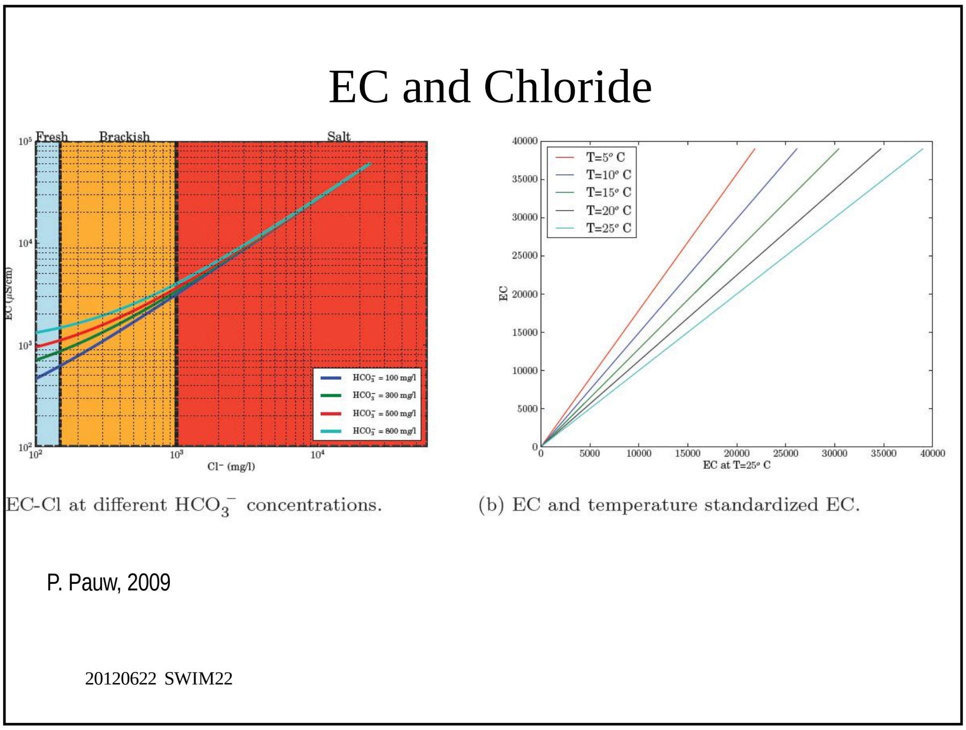
- Why monitoring?
  - Mapping salt concentrations in the groundwater
  - Detection of trends (upconing near pumping stations)
  - System and process knowledge
  - Input for a groundwater model

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

● Pumping stations with salinisation

● Pumping stations closed due to salinisation

Source: V. Post, 2007



EC and Chloride

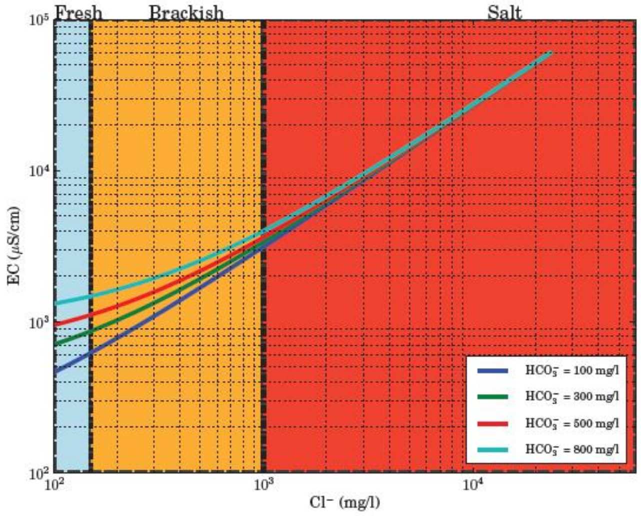
EC-Cl at different HCO_3^- concentrations.

(b) EC and temperature standardized EC.

P. Pauw, 2009

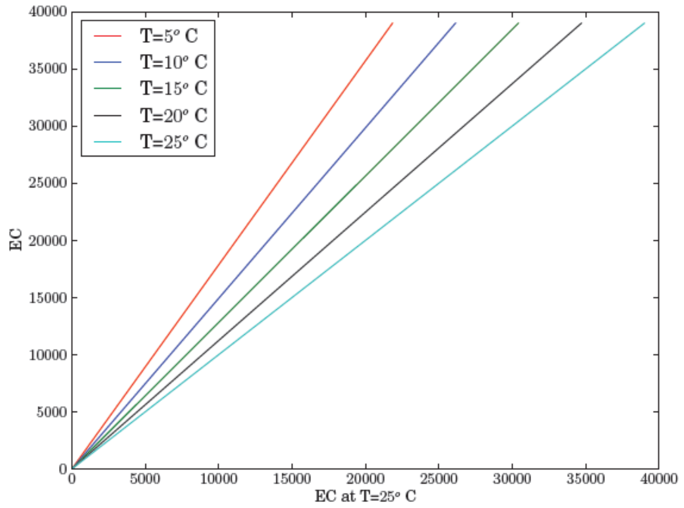
20120622 SWIM22

EC and Chloride

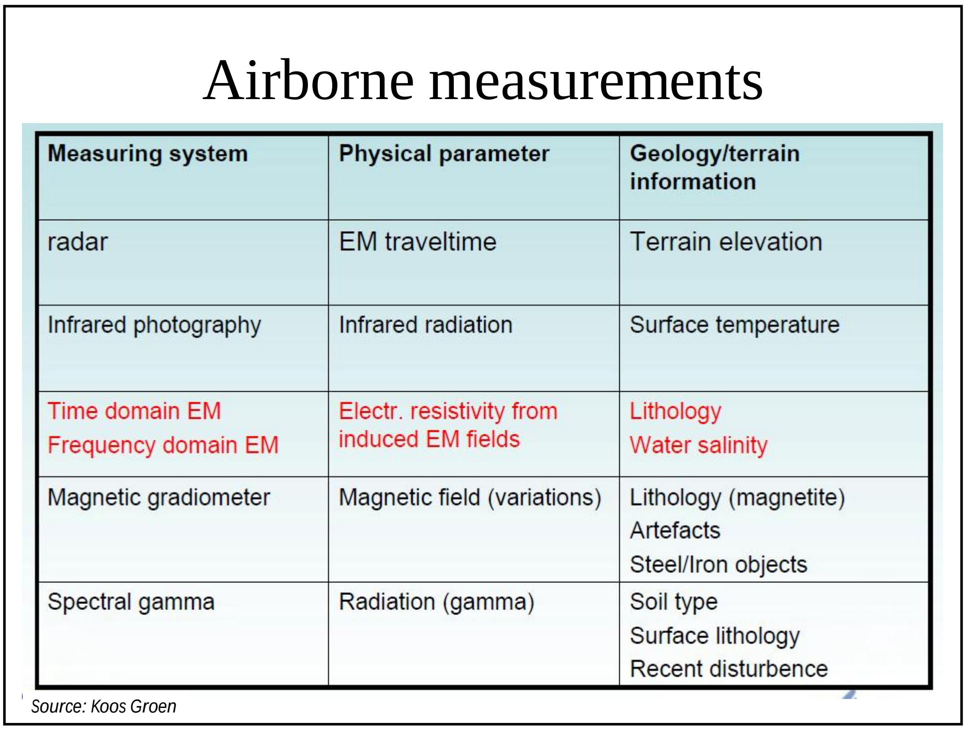


20120 EC-Cl at different HCO_3^- concentrations.

EC and Chloride



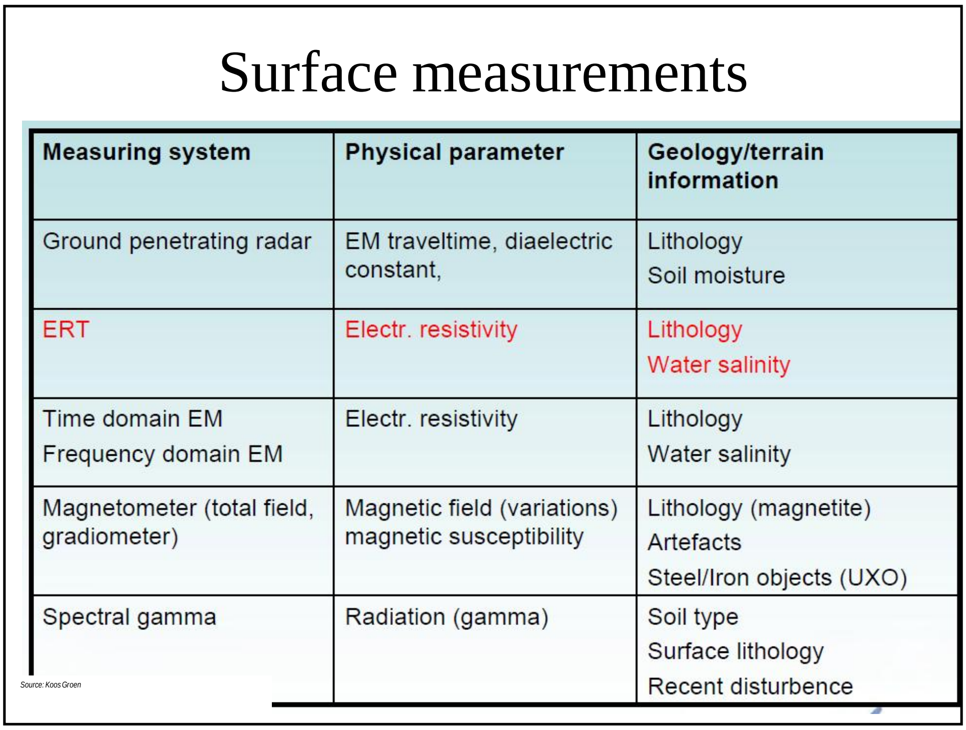
2 (b) EC and temperature standardized EC.



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

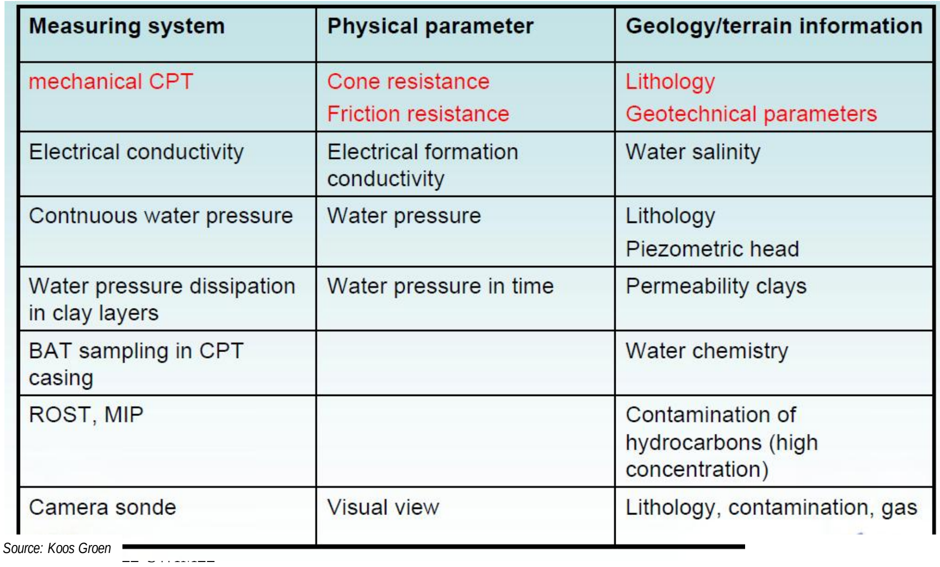


Surface measurements

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



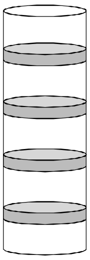
Measuring system	Physical parameter	Geology/terrain information
mechanical CPT	Cone resistance Friction resistance	Lithology Geotechnical parameters
Electrical conductivity	Electrical formation conductivity	Water salinity
Contnuous water pressure	Water pressure	Lithology Piezometric head
Water pressure 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

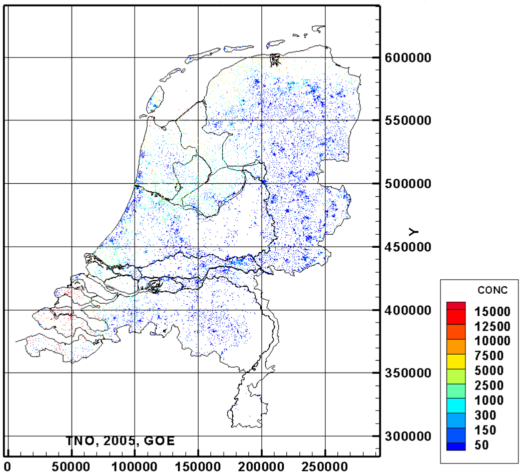
Method	**Advantages**	**Disadvantages**
1. Electrical conductance measurements	•High resolution (3D) •Depth ~200 m	•Time consuming
2. Electromagnetic measurements	•Fast	•Limited vertical resolution •Sensitive for underground conductors (pipes)
3. Satellites	•Suitable for large areas	•Small vertical resolution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

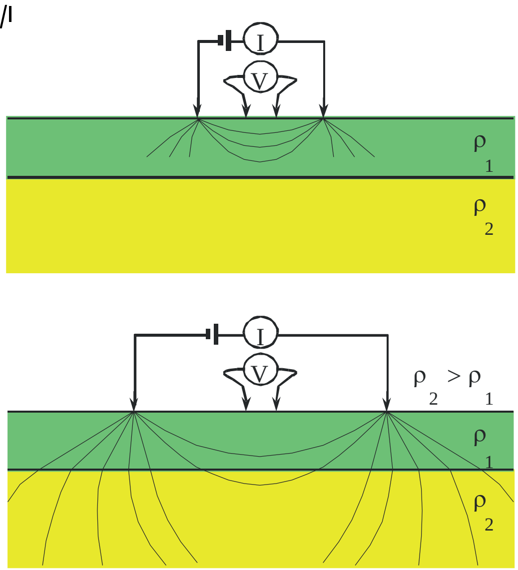
Source: Vitens

Source: V. Post, 2007

Principle geo-elektrical measurement

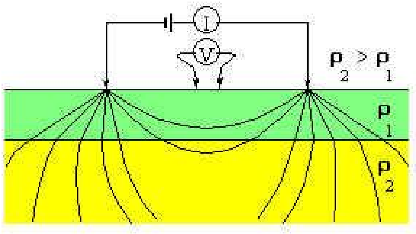
I: currentelektrode, V: potentialelektrodes, Ra: appearant elektrical resistiuvity

Ra = constant * V/I

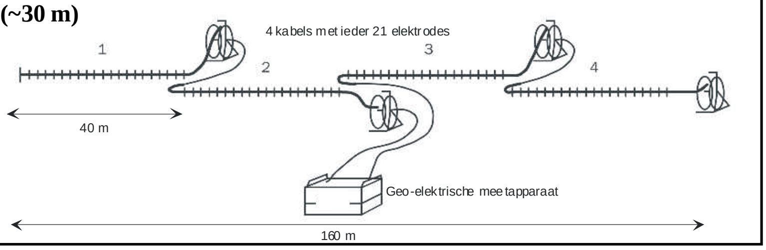


Types geo-electrical measurements

- 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)**

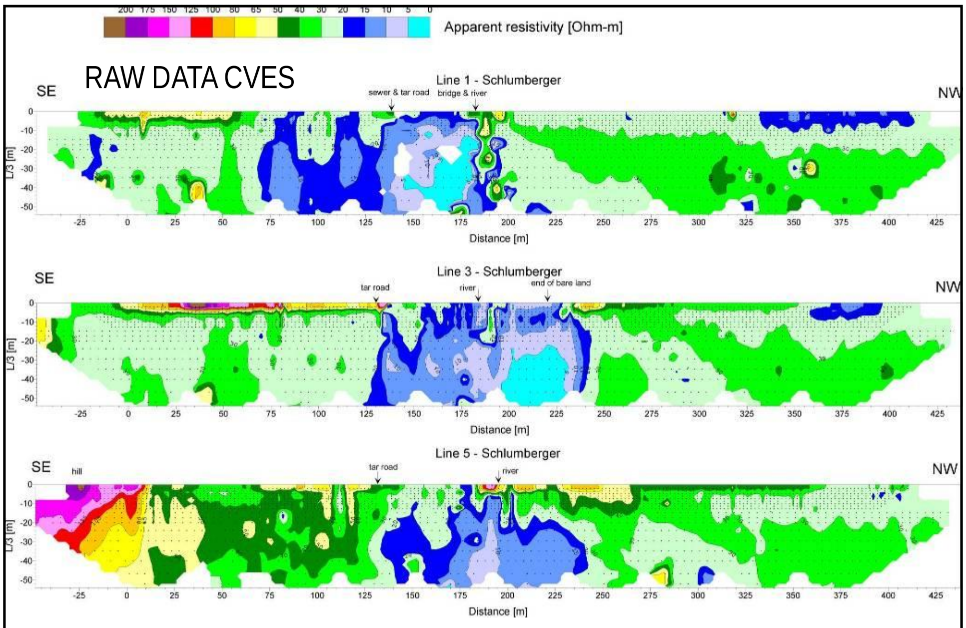


20120622 SW

VES measurement end 1950s/begin 1960s

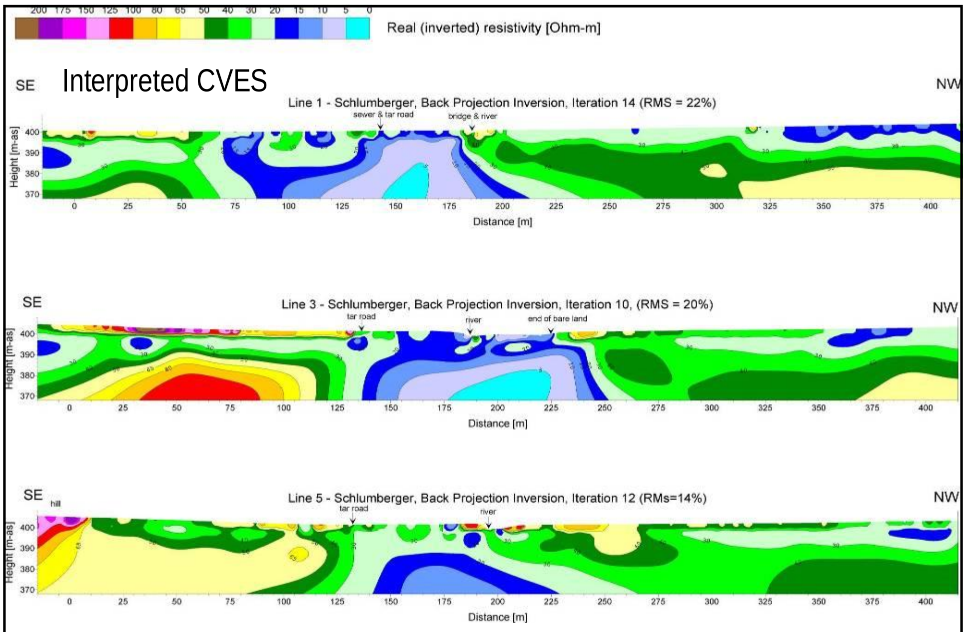
CVES
measurements 2010s

RAW DATA CVES



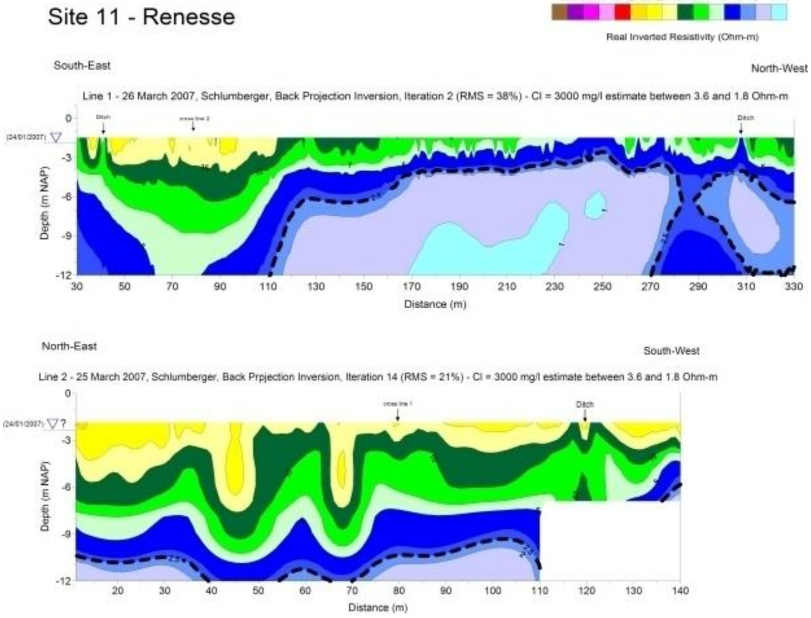
water met hoge EC (lage weerstand)

Interpreted CVES



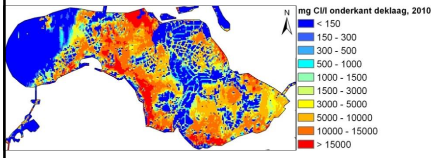
water met hoge EC (lage weerstand)

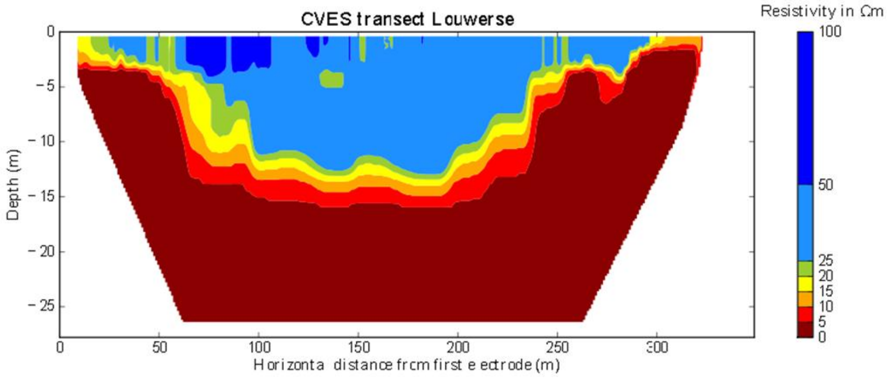
Site 11 - Renesse



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**

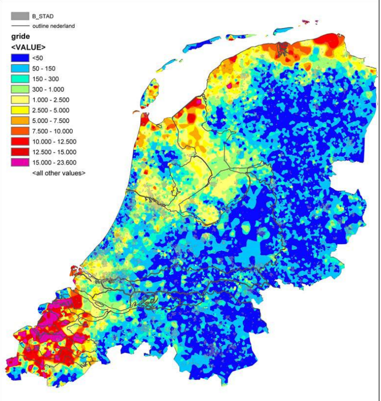
F varies with the resistance of the groundwater

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

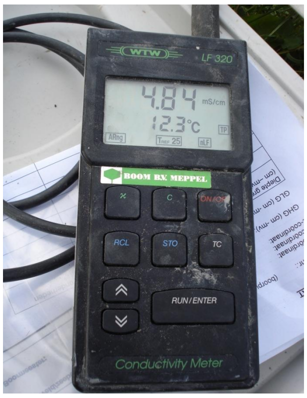
Result: chloride concentration bottom Holocene toplayer



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

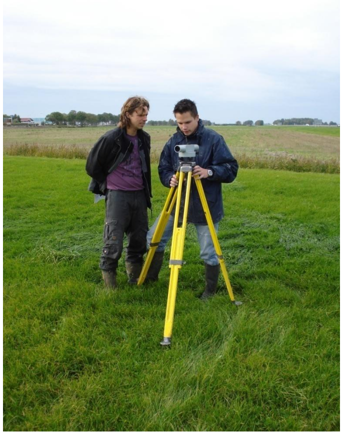
The Interreg IVB North Sea Region Programme

WETTERSKIP FRYSLÂN

provinsje fryslân
provincie fryslân

T EC fieldwork

Altitude measurements



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North Sea Region
Programme

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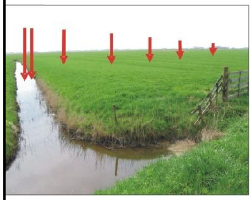
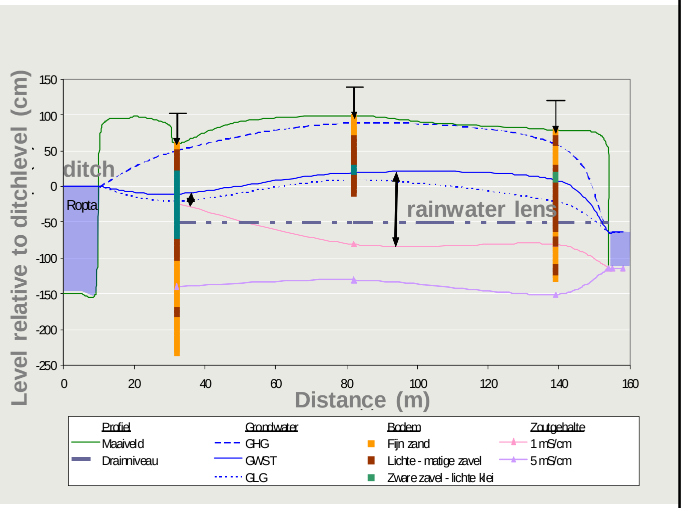
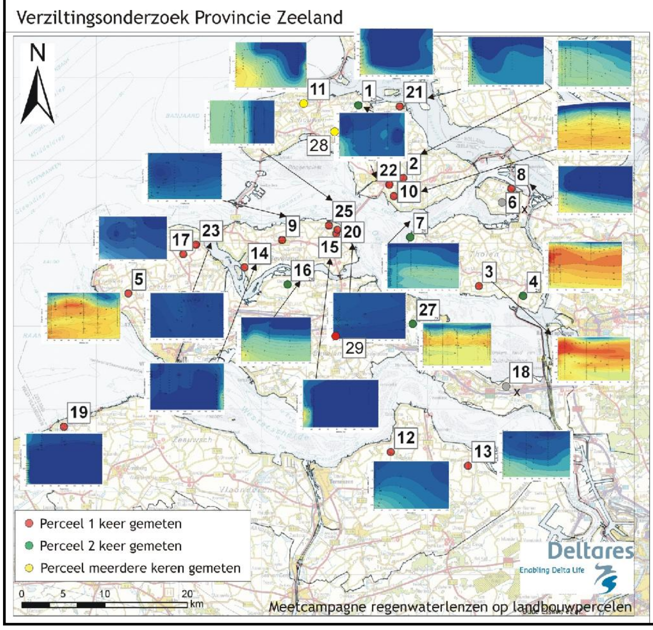
Use field measurements to understand the process





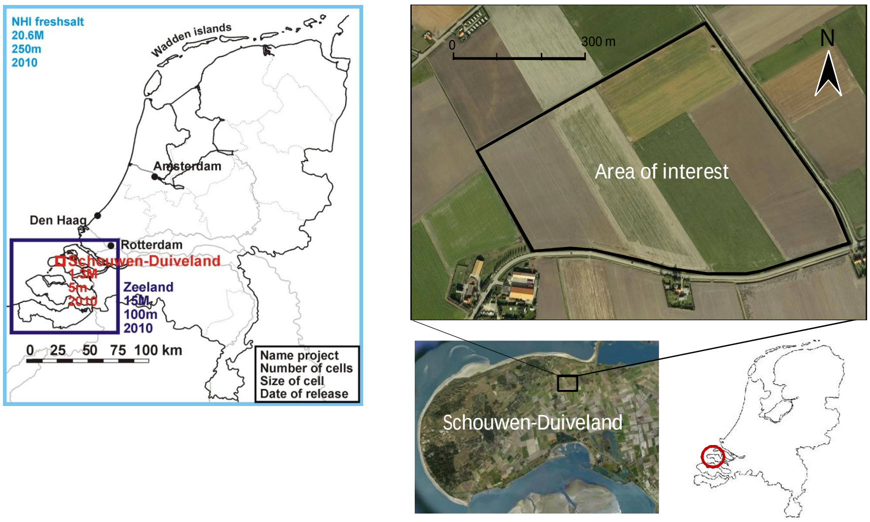
TEC-probe Monitoring campaign 2005-2009



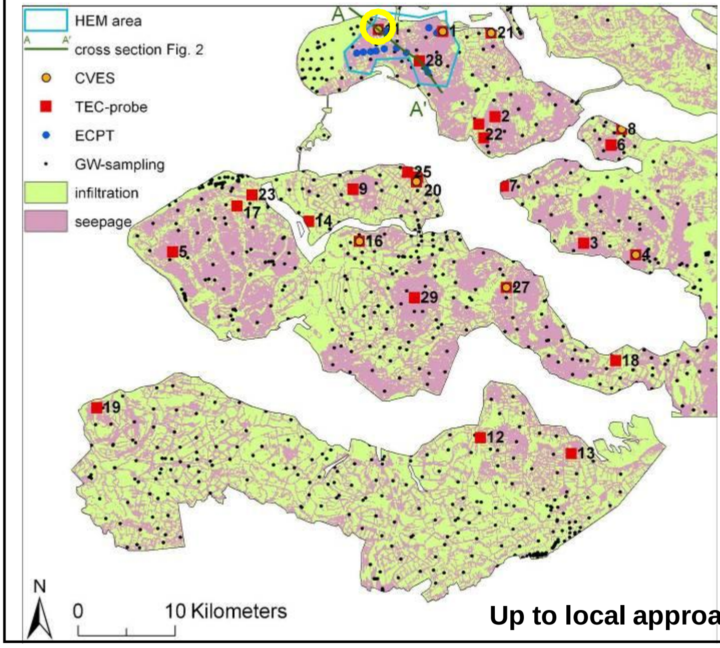
CliWat www.cliwat.eu

- 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



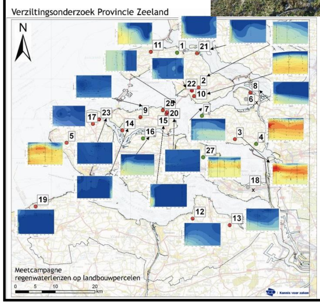
Up to local approach

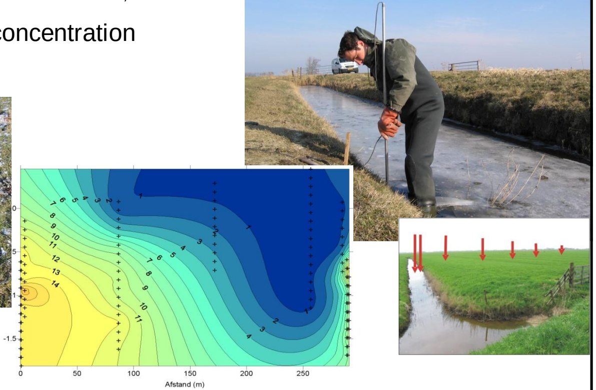
Example: Assessing effect of climate change on salt water intrusion

Source: Oude Essink, 2009

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

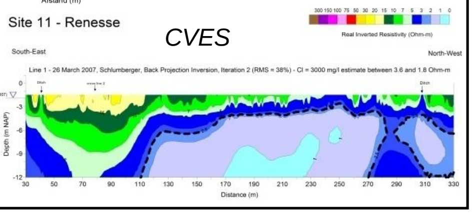
TEC probe



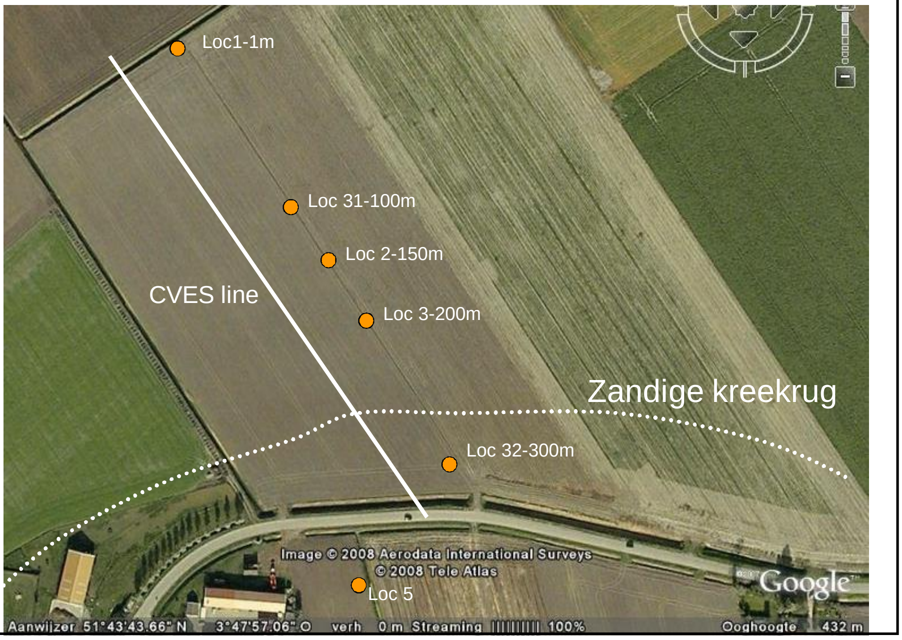


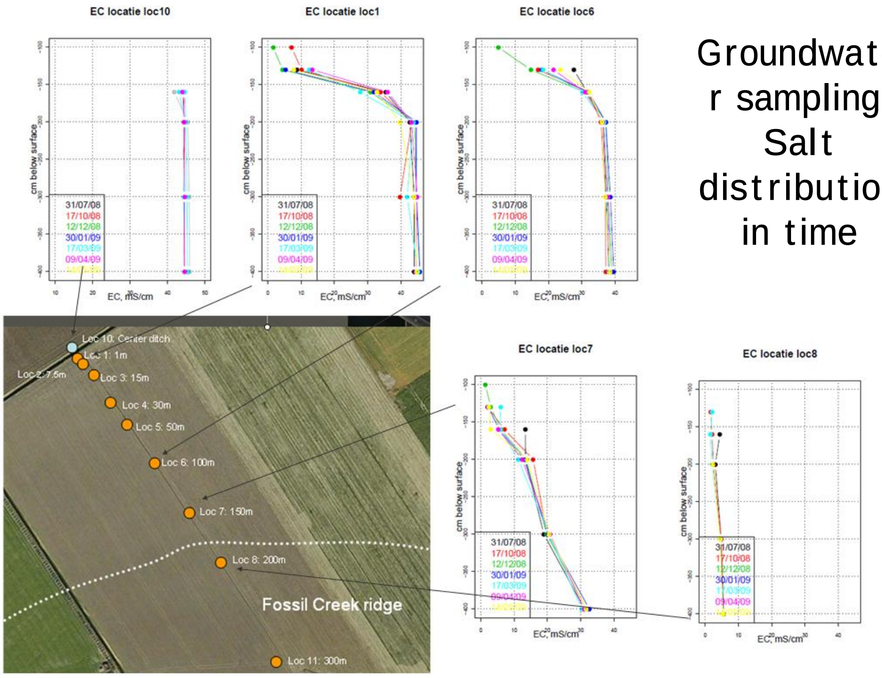
Site 11 - Renesse

CVES



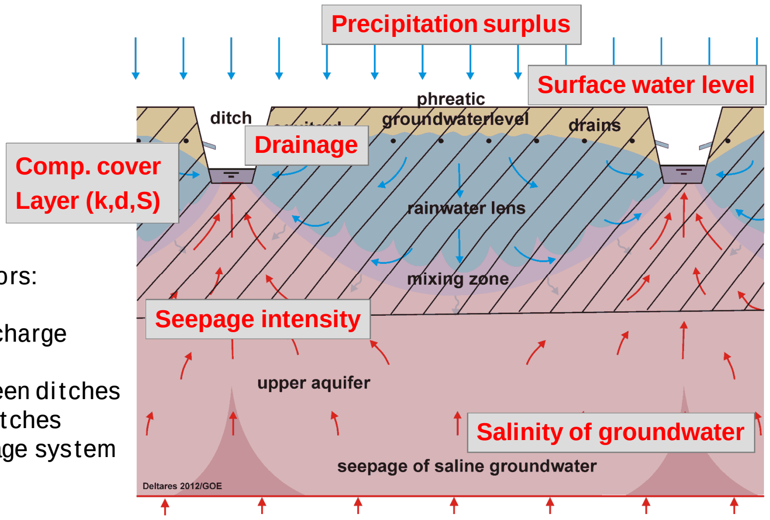
Site 11: from infiltration to seepage





Groundwater sampling: Salt distribution in time

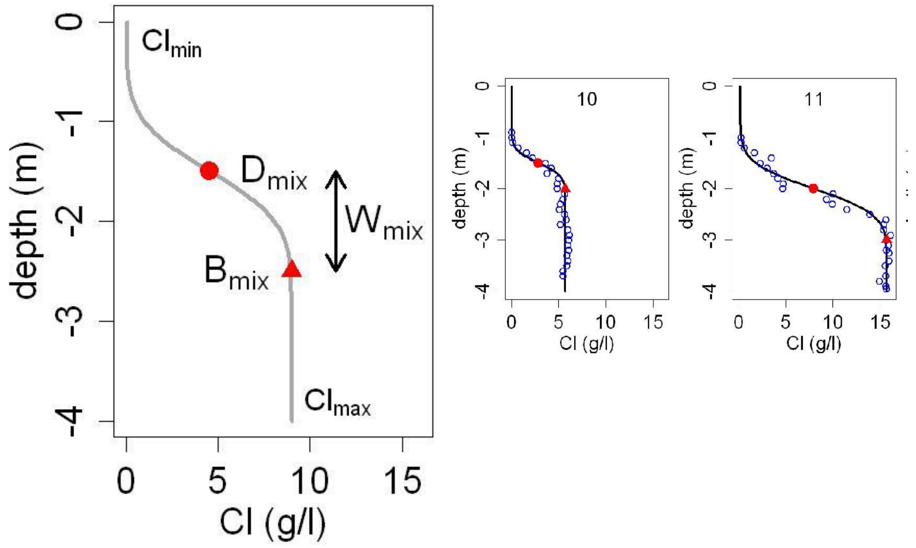
Factors controlling fresh-salt interface



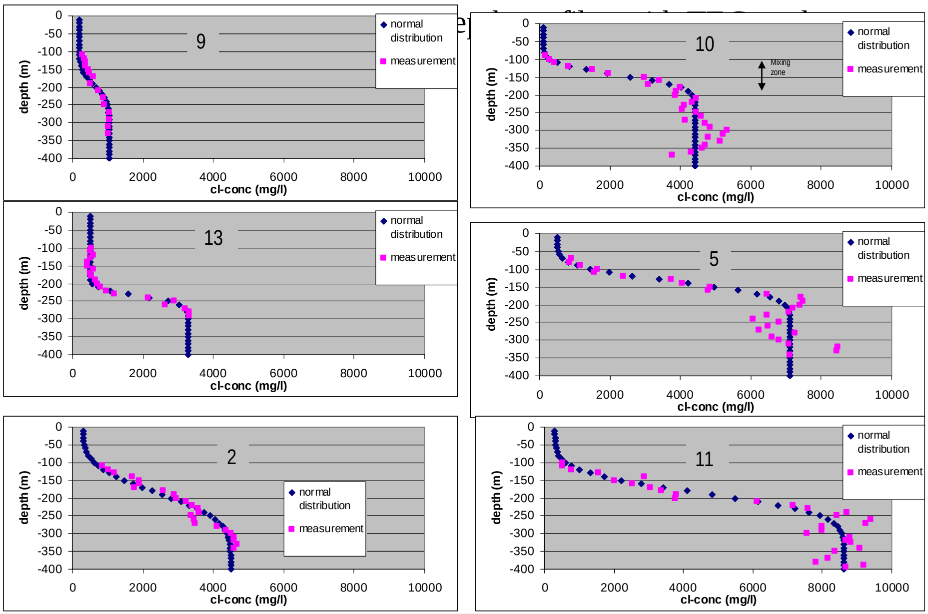
Important factors:

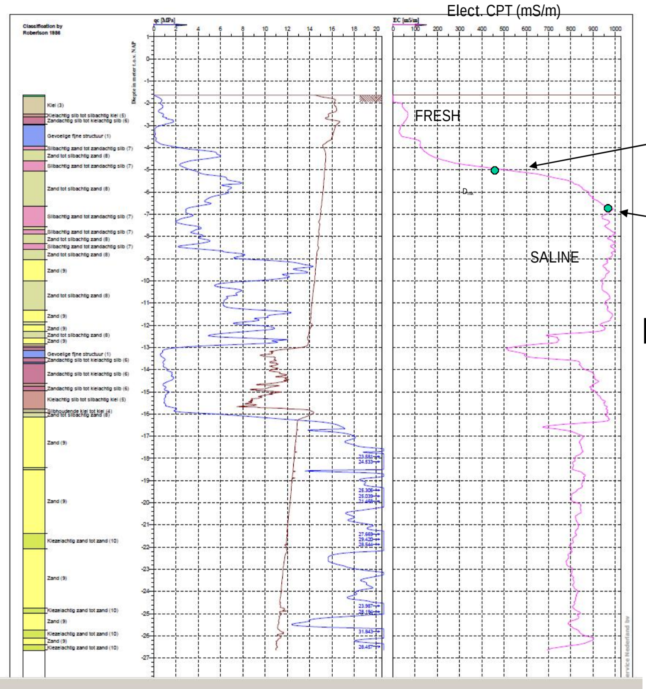
- natural grw recharge
- geology
- distance between ditches
- water levele ditches
- capacity drainage system

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.





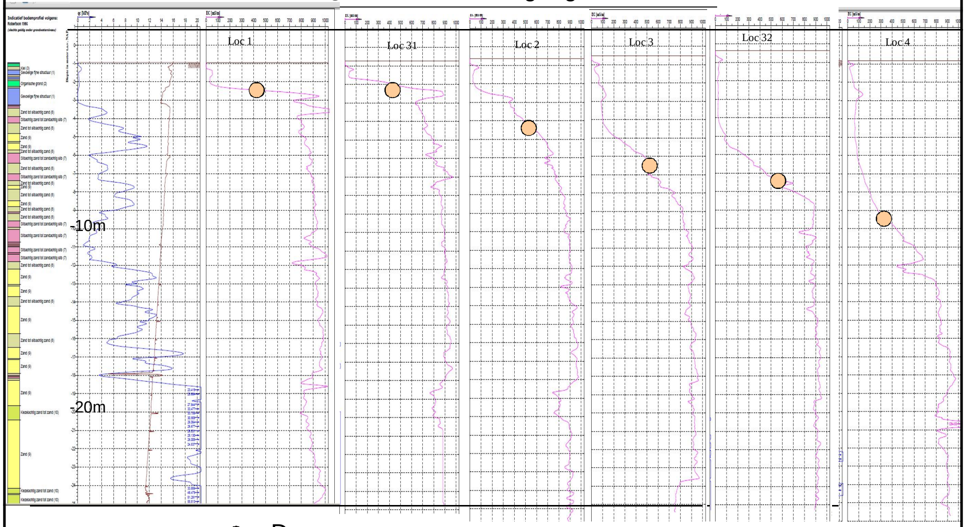
a) Depth of transition, D_{mix}, zone between 2 types of groundwater (fresh-saline)

b) Start of transition, S_{mix},

Electrical CPT

Results from ECPT's (soundings)

kwelgebied ⟷ overgang ⟷ infiltratie ⟶

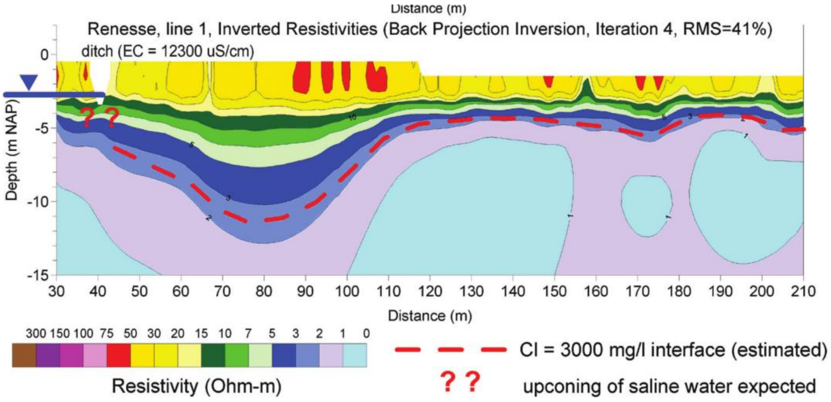


○ = D_{mix}

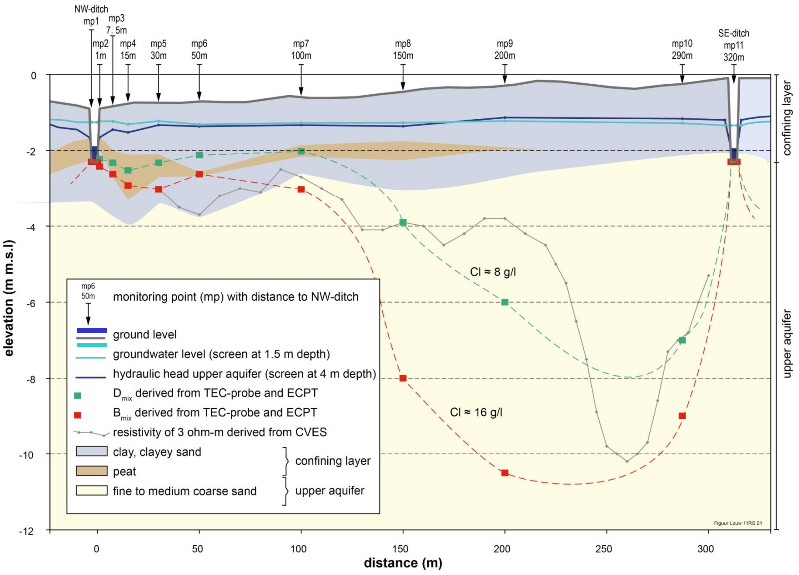
ECPT = electrical cone penetration test

CVES

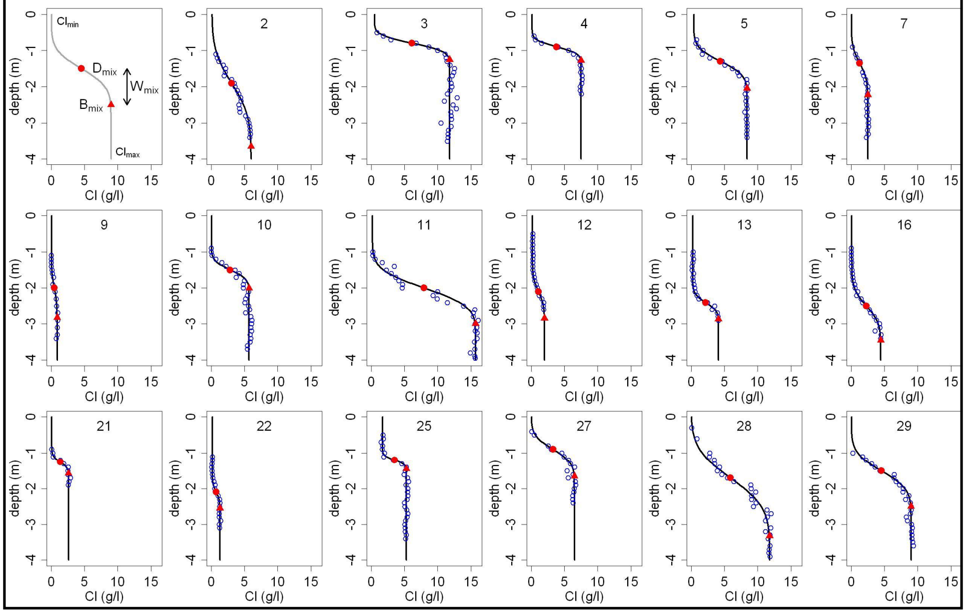
CVES: continuous vertical eletrical sounding



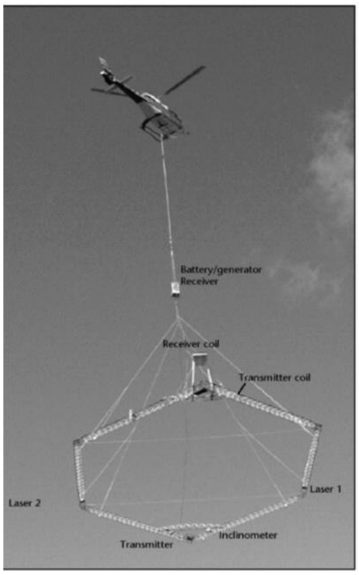
Seepage / infiltration determines thickness rainwaterlens



TEC-probe results

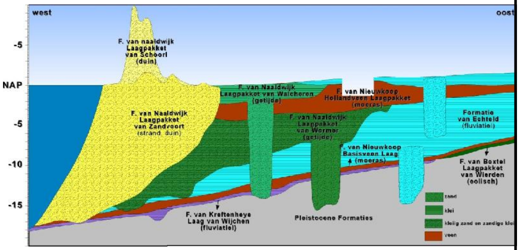


Electrical conductance measurements



10 juni 2013

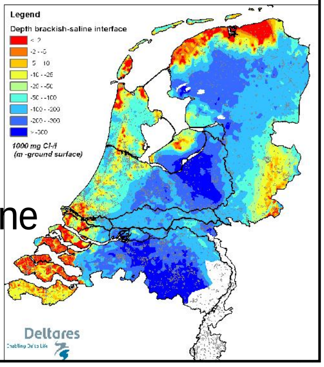
From bulk to groundwater resistivity



EC^{bulk}

EC lithology

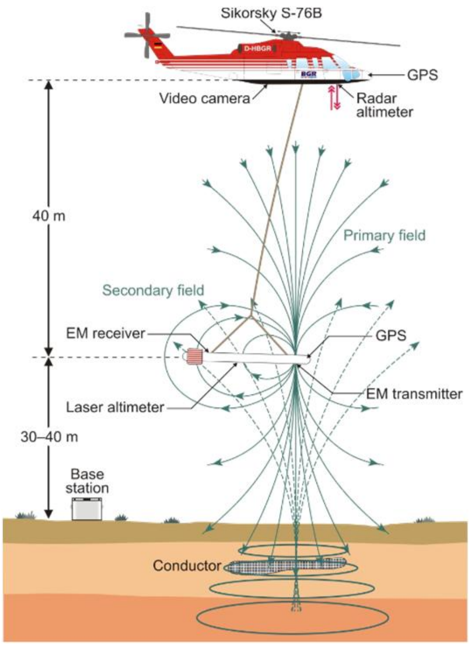
EC groundwater
→ fresh-brackish-saline



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

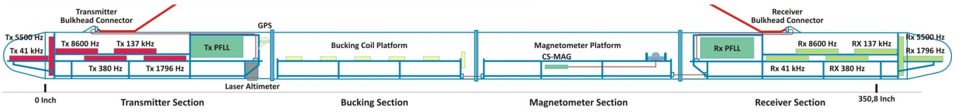


Meeting in Utrecht Feb. 25th 2014

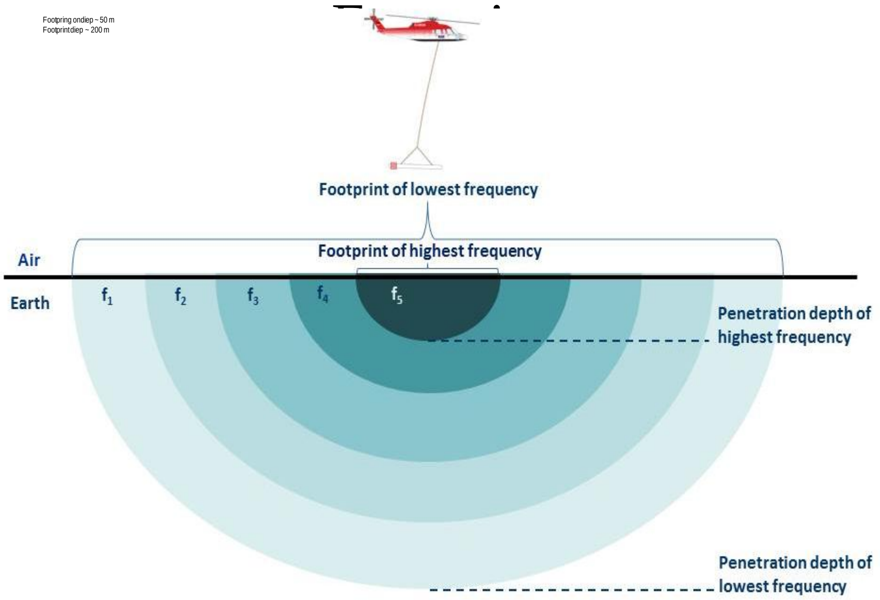
BGR helicopter-borne geophysical system

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

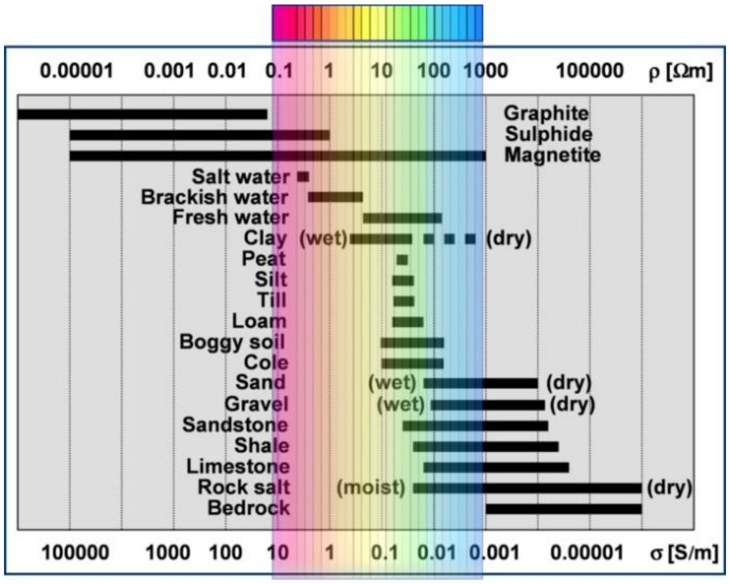
Ondiep voor hoge frequenties en/of hoge geleidbaarheid



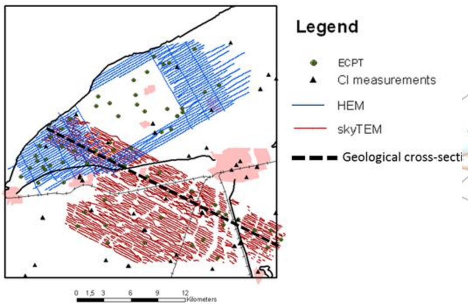
Footpring ondiep ~ 50 m
Footprintdiep ~ 200 m

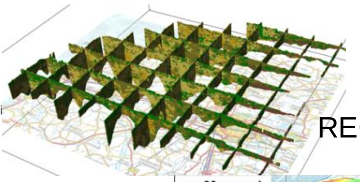


Typical resistivities / conductivities

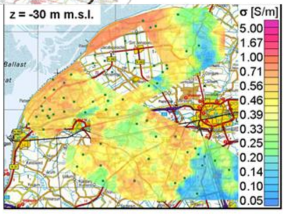


Case Wetterskip Fryslân

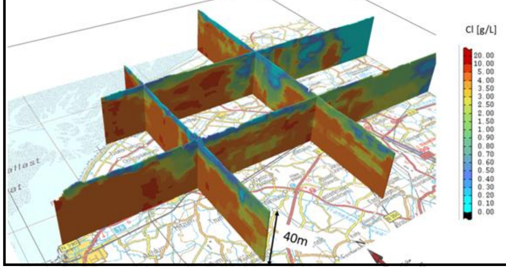




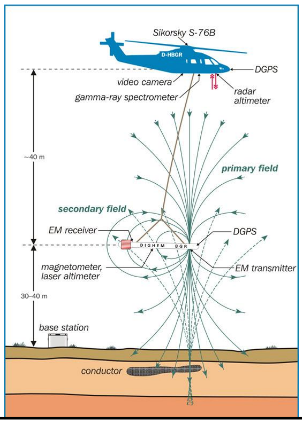
REGIS

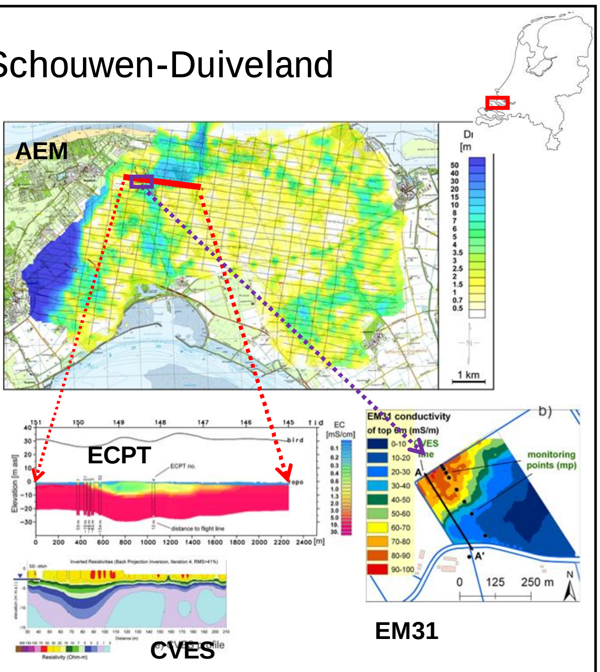


3D fresh-saline distribution



Case Schouwen-Duiveland





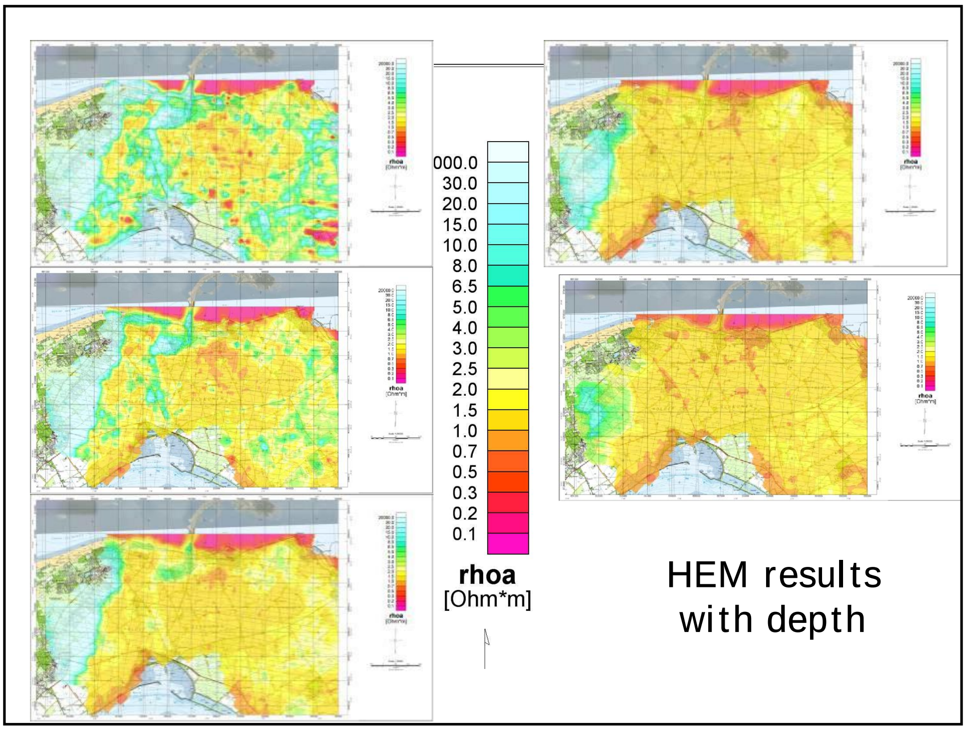
AEM

ECPT

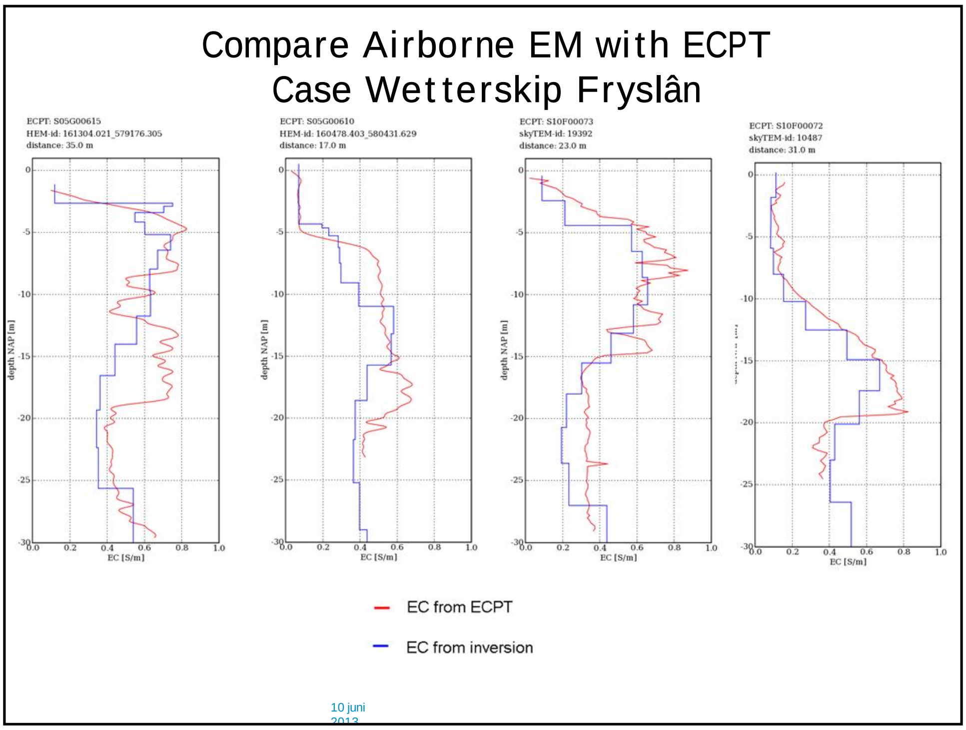
EM31

CVES

conventional monitoring techniques



HEM results with depth



Compare Airborne EM with ECPT
Case Wetterskip Fryslân

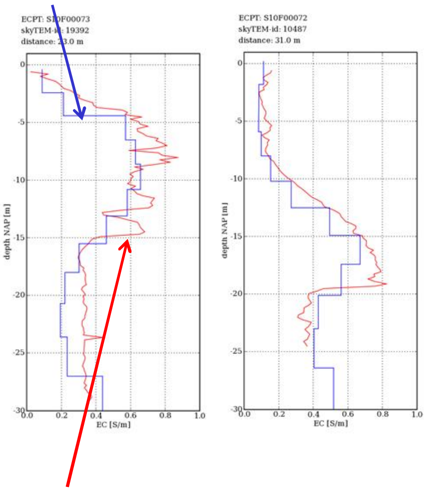
- EC from ECPT
- EC from inversion

10 juni 2013

3D characterising fresh-saline groundwater

How much samples in 1 week on 900km^2?

AEM: 80000 data points

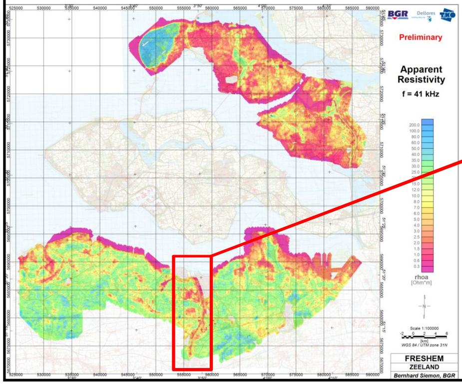


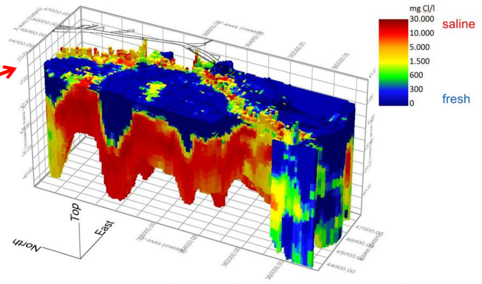
In-situ: >100 data points

3D Characterisation of the subsoil

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

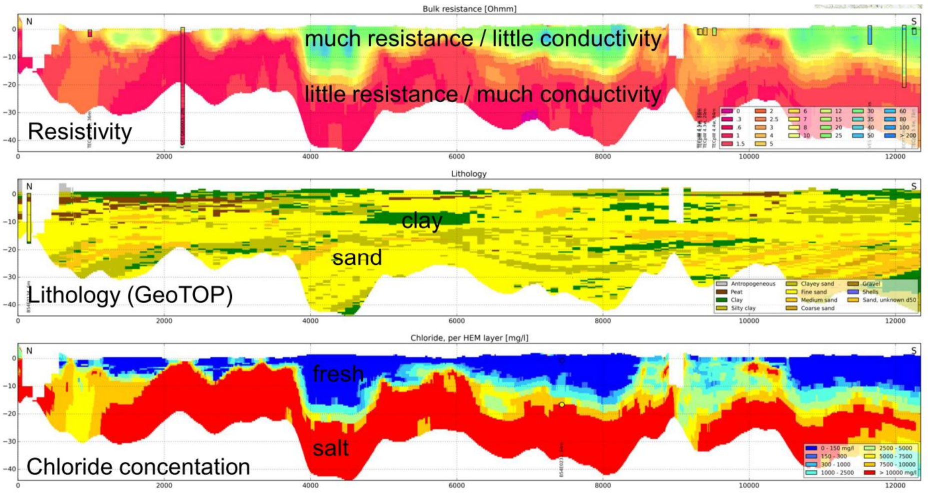
TNO innovation for life   BGR   Deltares Enabling Delta Life





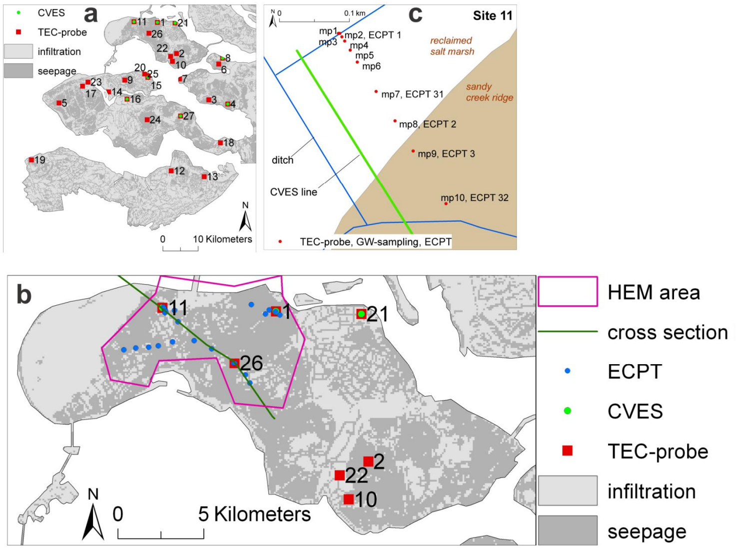
FRESHEM pilot Canal zone, visualization in iMOD

Example NL, Zeeland, project FRESHEM



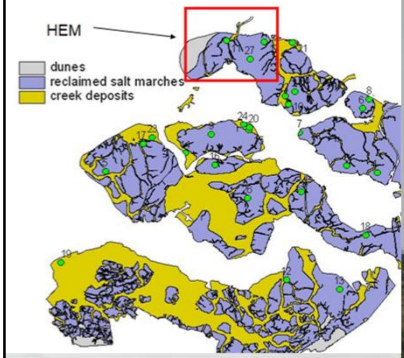
20160524 Ara Sul

Combining monitoring techniques



10 juni 2013

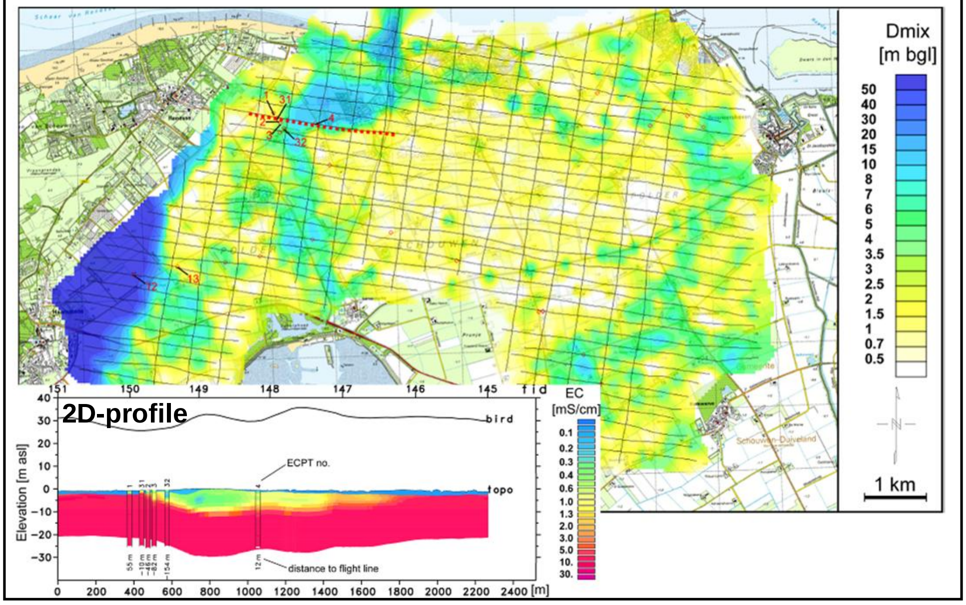
Helicopter-EM data for mapping fresh-saline groundwater



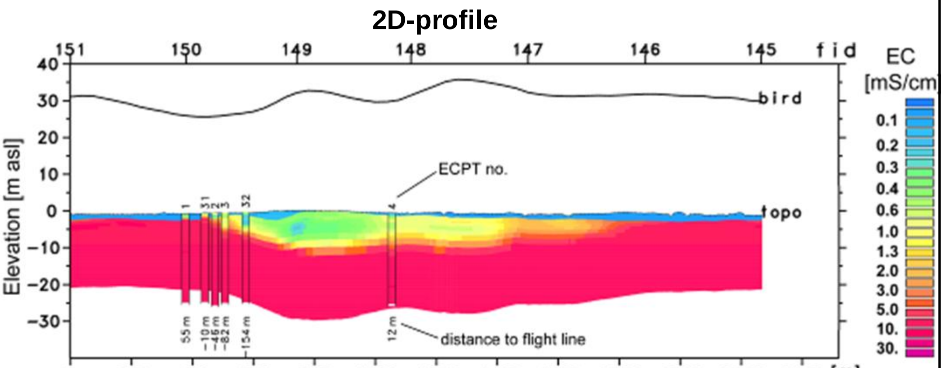
Interreg IV-B

CLIWAT
CLIMATE & WATER

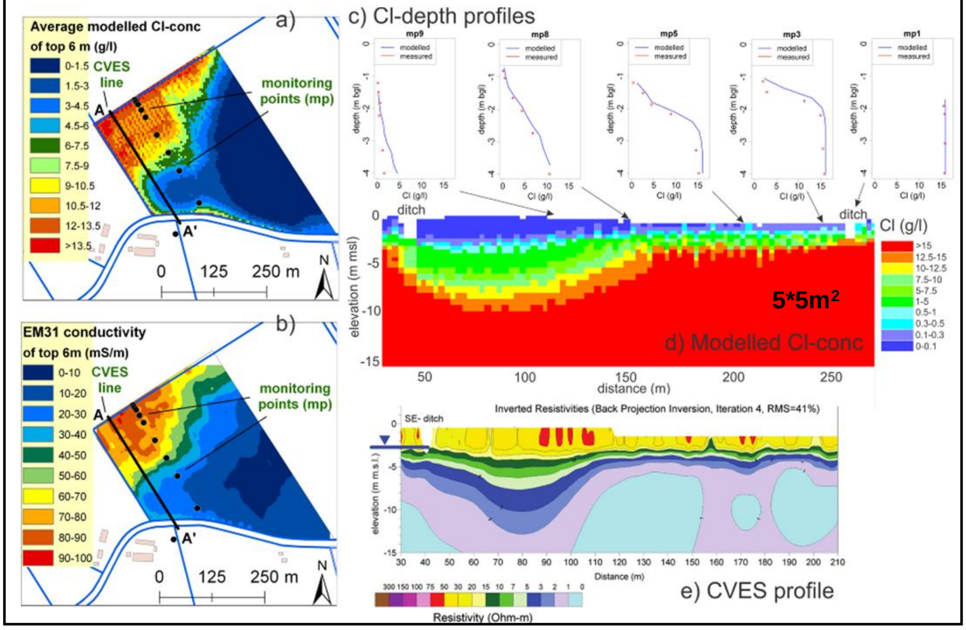
Thickness rainwater lens (D_{mix}) by HEM



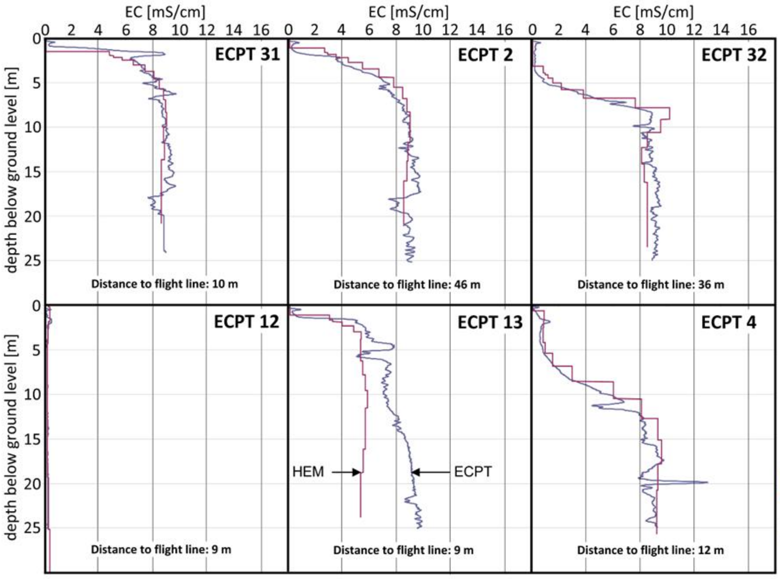
Thickness rainwater lens (D_{mix}) by HEM



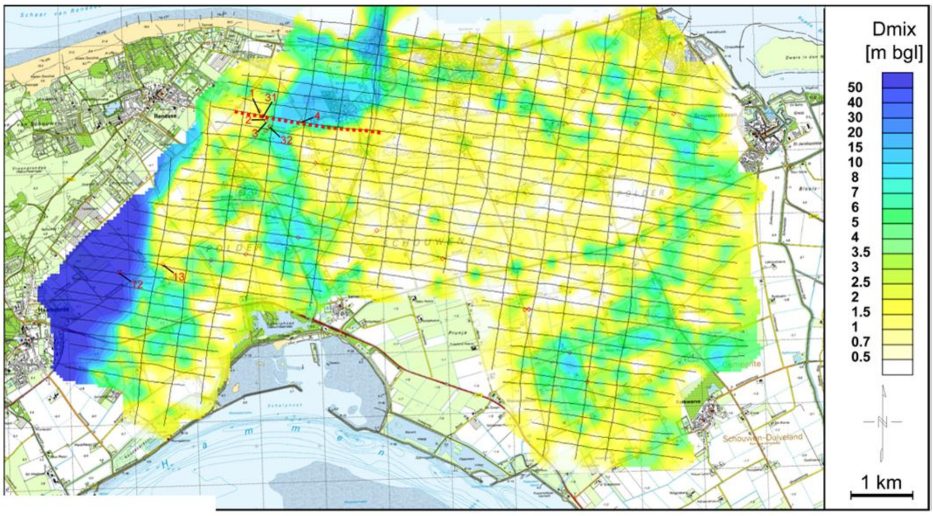
Comparison monitoring data with model results



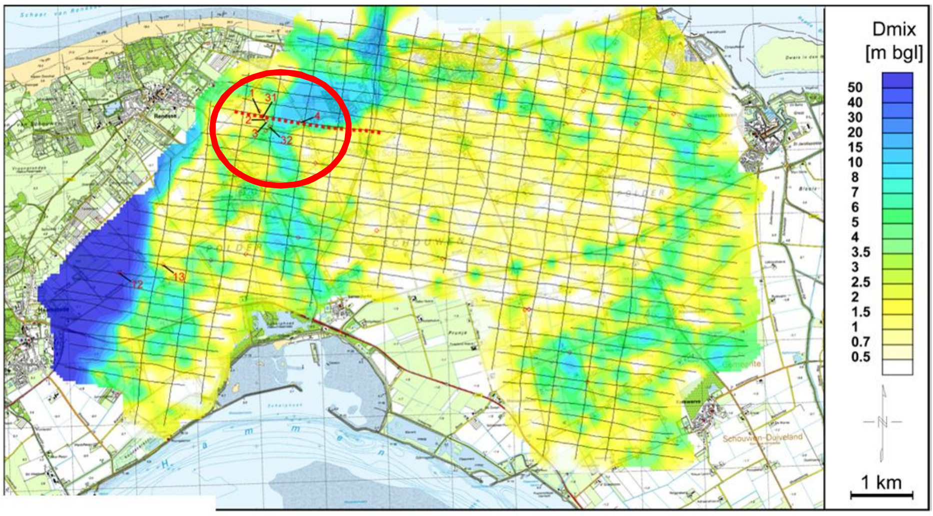
Comparison HEM – ECPT



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



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

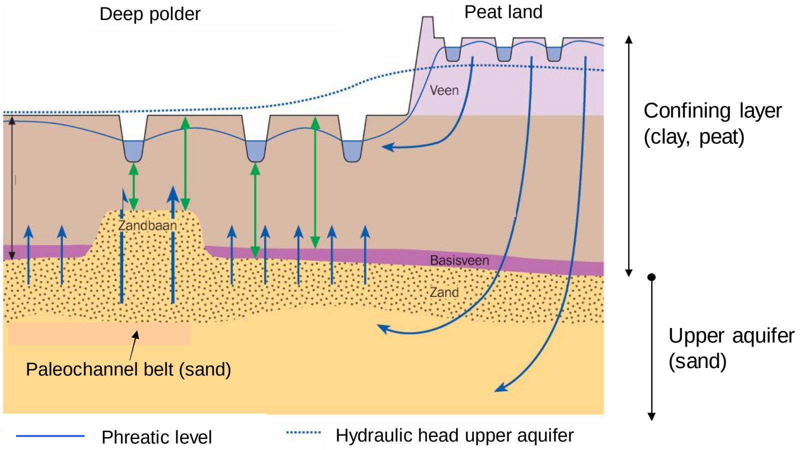


BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER

Salty boils

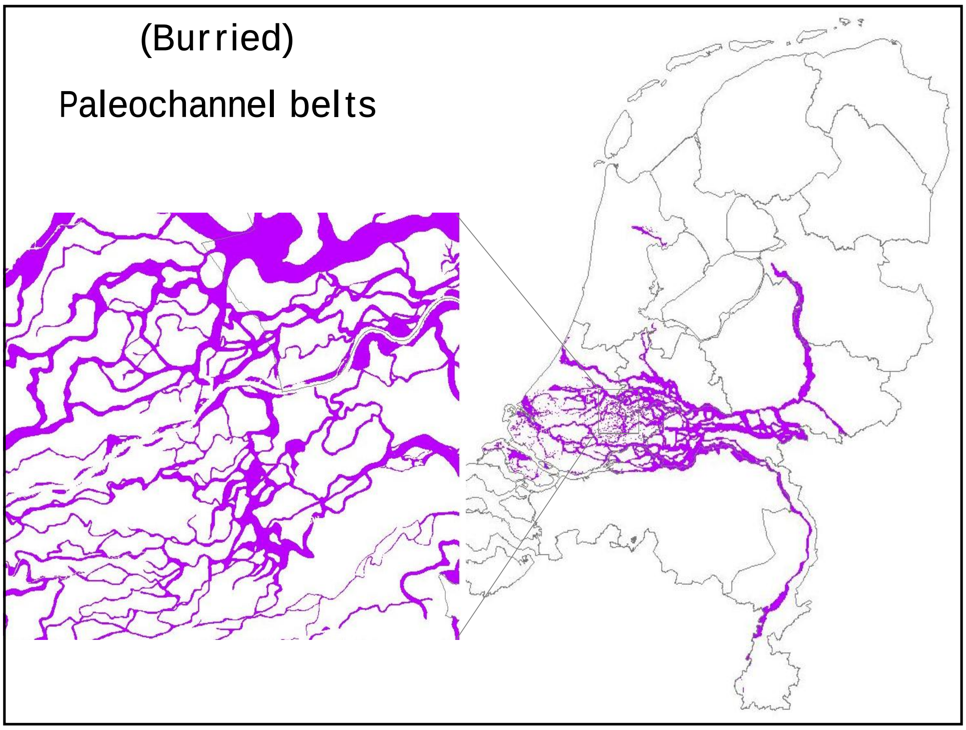
Louw, P.G.B., de, Oude Essink, G.H.P., Stuyfzand, P.J., Zee, van der, S.E.A.T.M., 2010, Upward groundwater flow in boils as the dominant mechanism of salinization in deep polders, The Netherlands, J. Hydrol. 394, 494-506.

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

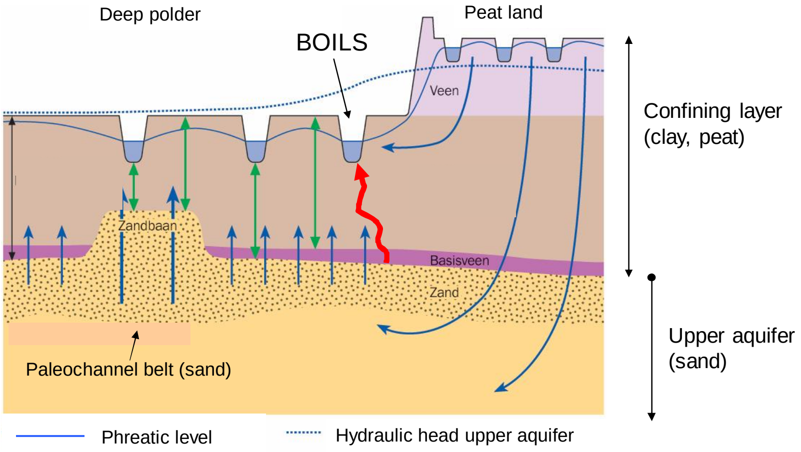


(Burried)

Paleochannel belts

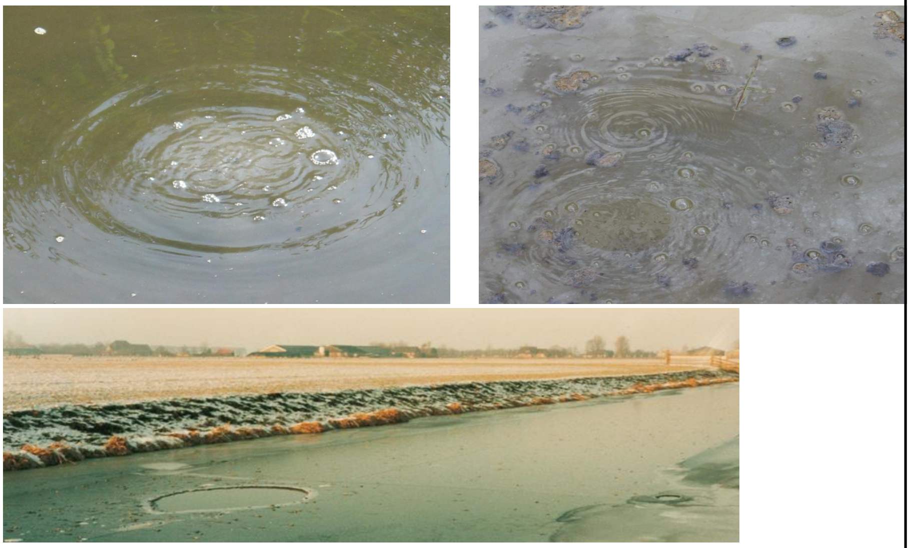


Preferential seepage via boils

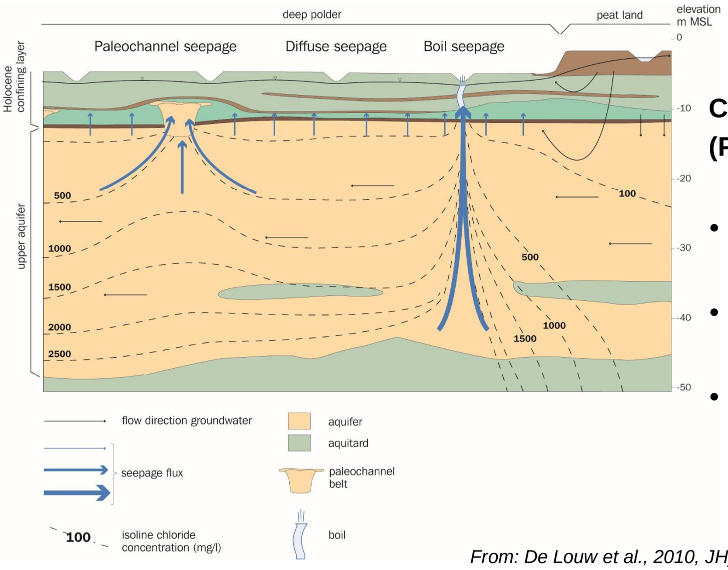


Preferential saline seepage via boils

Preferential saline seepage via boils



Three types of upward groundwater seepage

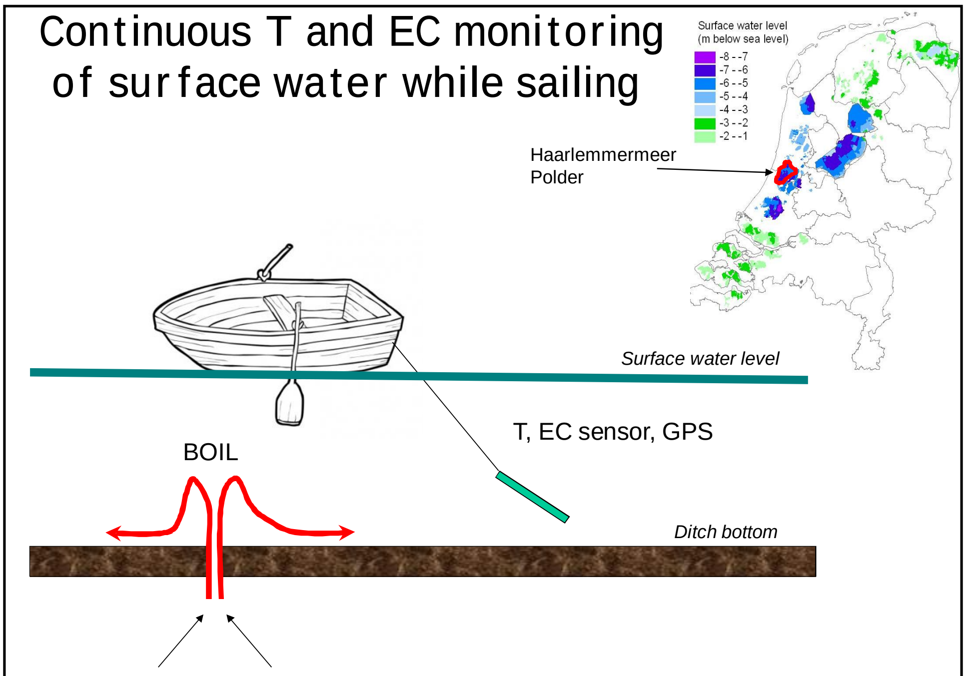


Cl-conc seepage:
(Polder Noordplas)

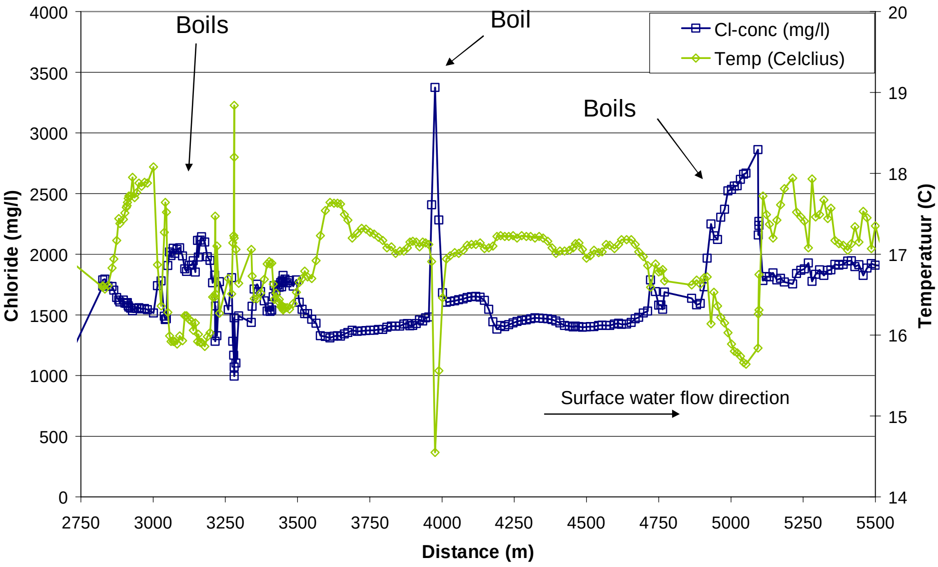
- Diffuse : 100 mg/l
- Paleochannel : 600 mg/l
- Boils : 1100 mg/l

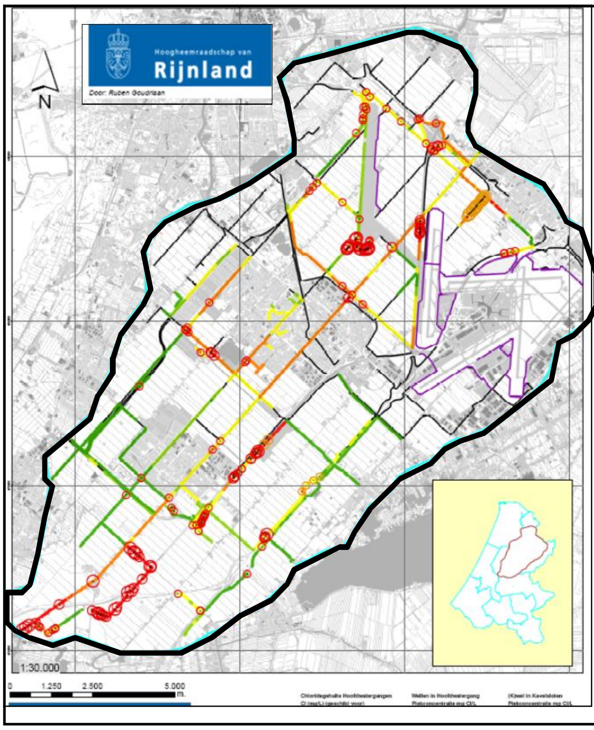
From: De Louw et al., 2010, JHydr.

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

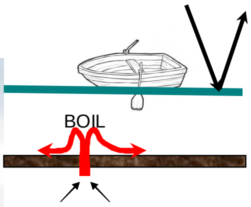
- ○ Cl = 500 -2000 mg/l
- ◯ Cl > 2000 mg/l

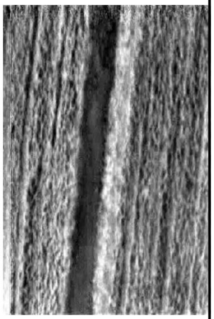
Cl-conc surface water

- 🟩 0-300 mg/l
- 🟨 300-600 mg/l
- 🟧 600-1000 mg/l
- 🟥 > 1000 mg/l

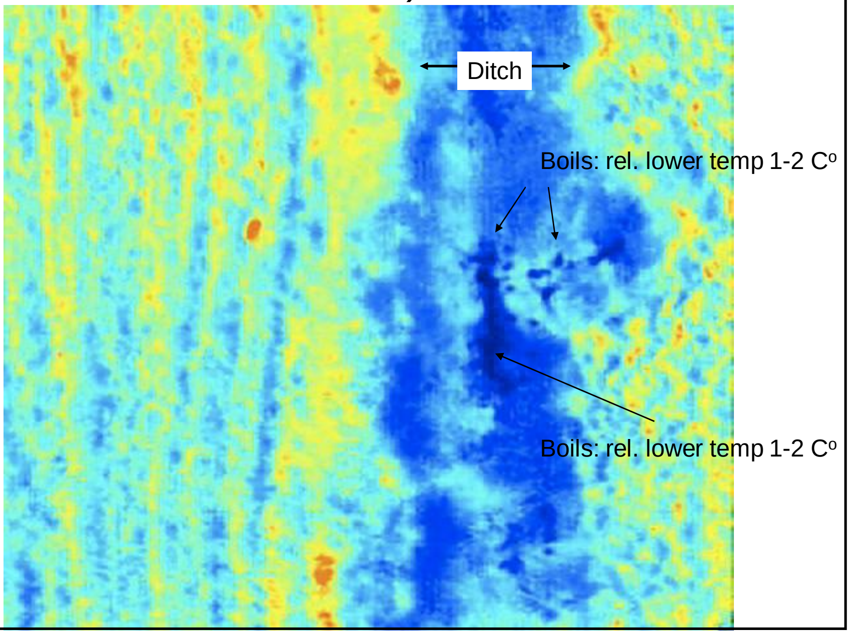
LARS technology (TNO Industry):
Thermal Infra-red

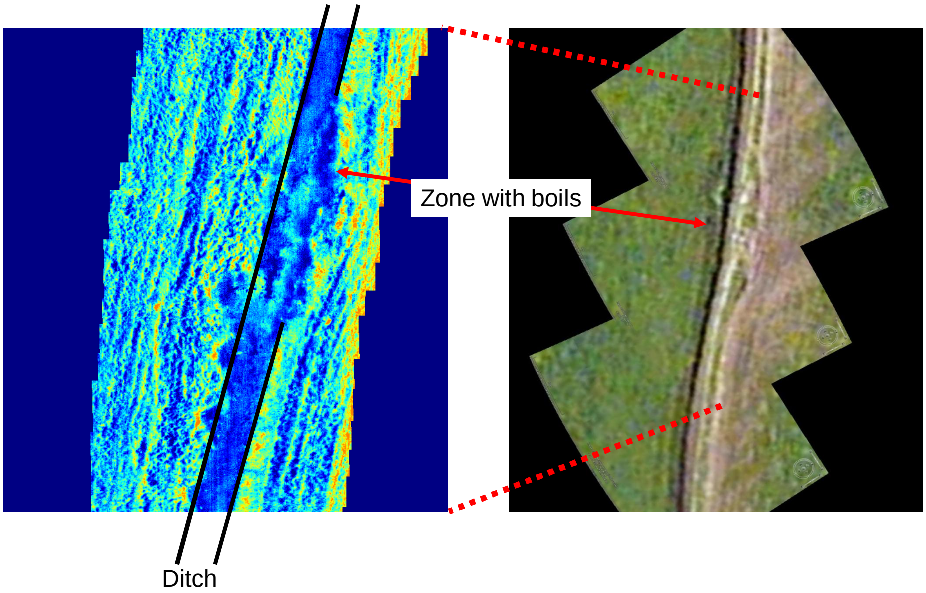
- Altitude: 0-150 m
- Temp-detection using Thermal Infra Red sensors (only surface !)





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

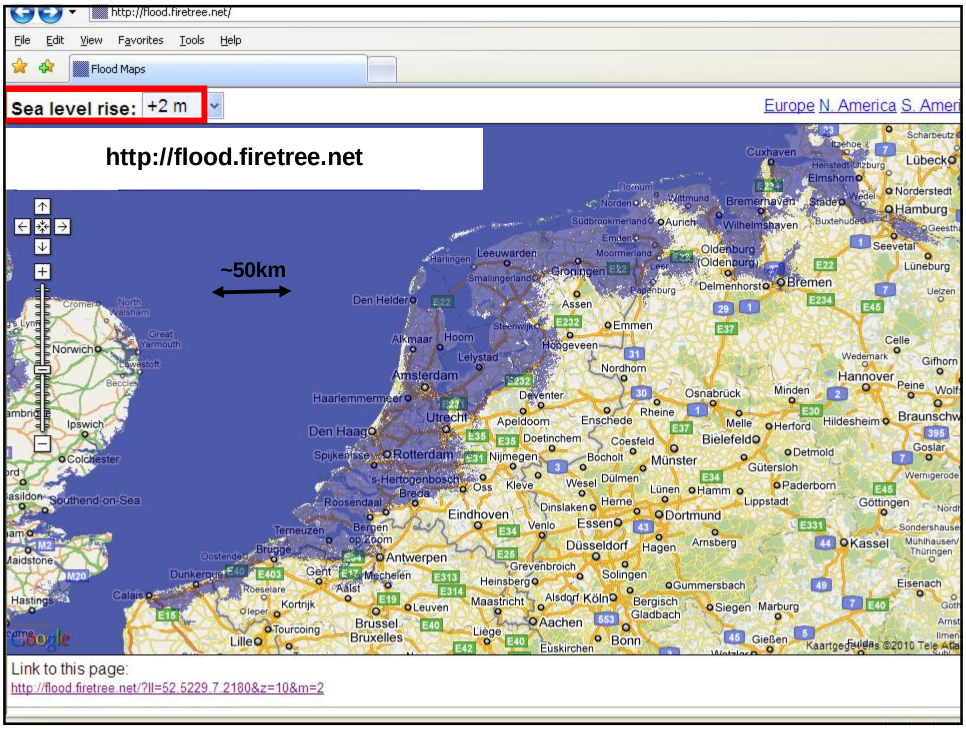




To get an idea about the possible future effects of sea level rise and climate change in your delta ...

evaluate of the past water management in the Dutch delta

Salt water intrusion in the Netherlands



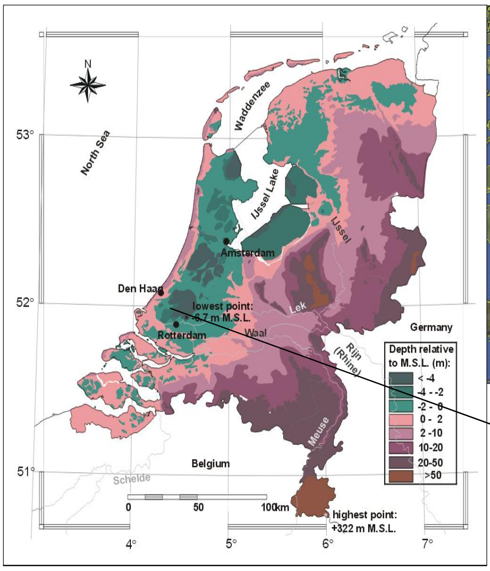
Sea level rise: +2 m

http://flood.firetree.net

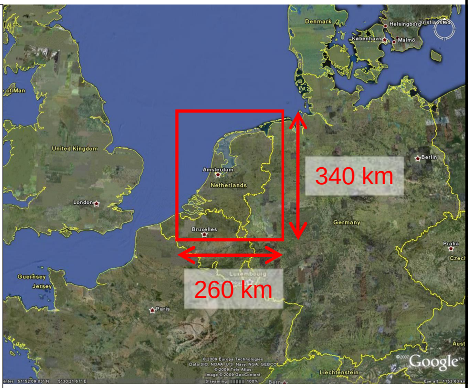
~50km

Link to this page:
http://flood.firetree.net/?ll=52.5229,7.2180&z=10&m=2

The 'low-lying' lands: Netherlands



Depth relative to M.S.L. (m):
< -4
-4 - -2
-2 - 0
0 - 2
2 -10
10-20
20-50
>50



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

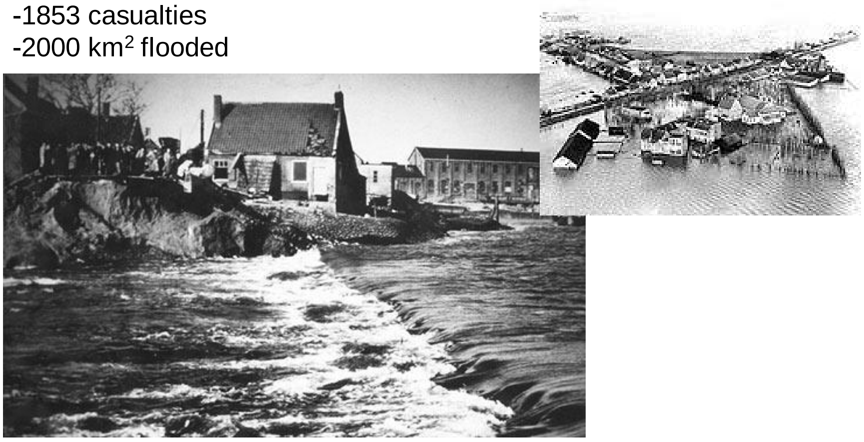
The facts:

- 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

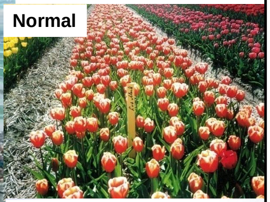


Infrastructure to protect our low-lying land from flooding


ANP-Foto

River flooding in 1995

Combination of heavy rains upstream the catchment
& short retention time



Normal

Too wet

Dike collapse 2003

Combination of peat dike instability and very dry summer

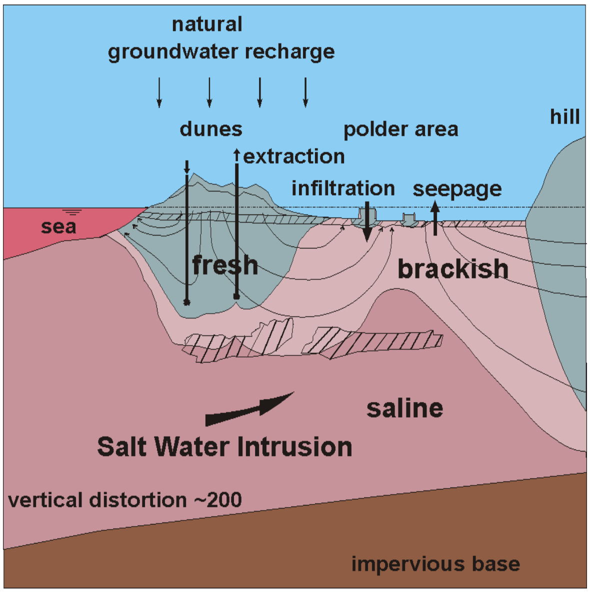
Estimated water management costs
‘to keep our feet dry’

Costs up till 2050 in billion euros:

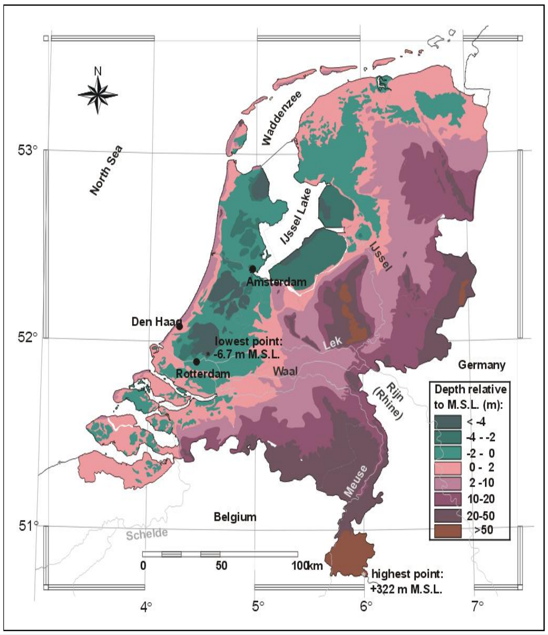
rivers: upper part	5.7
rivers: lower part	5.6
low-lands	1.7
coastal zone	8.0
infrastructure	3.5
purchase of ground	2.0
	-----+
	26.5 billion euros

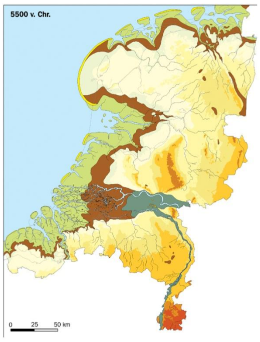
Dutch setting

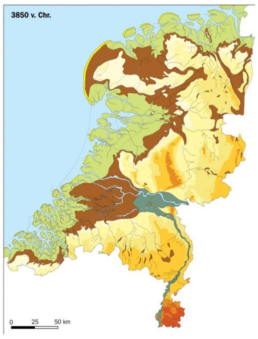
Salt water intrusion in the Netherlands

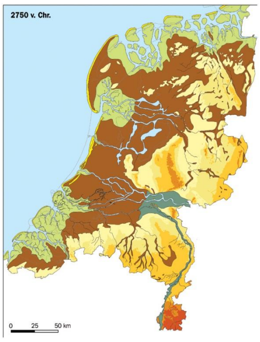


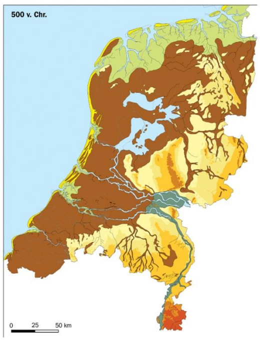
Present ground surface in the Netherlands

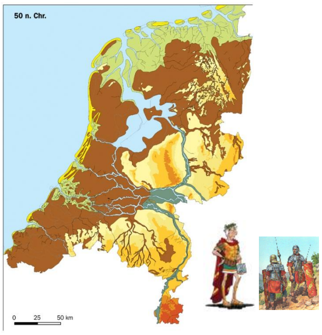


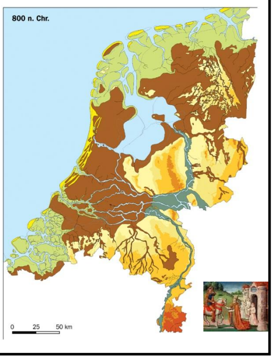


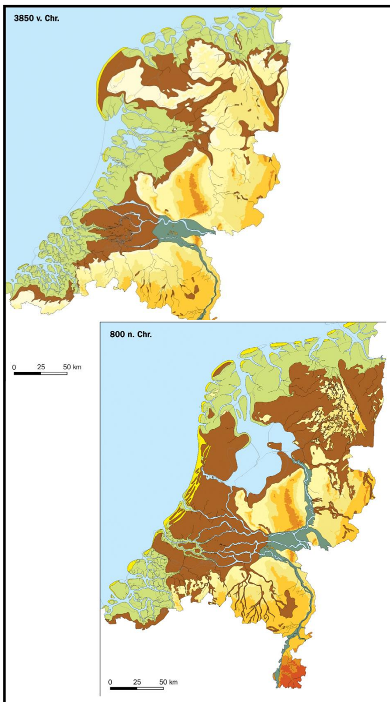


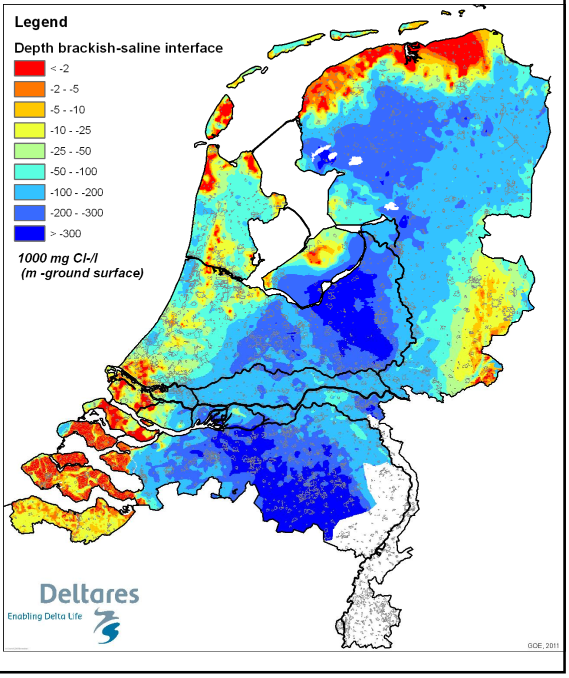




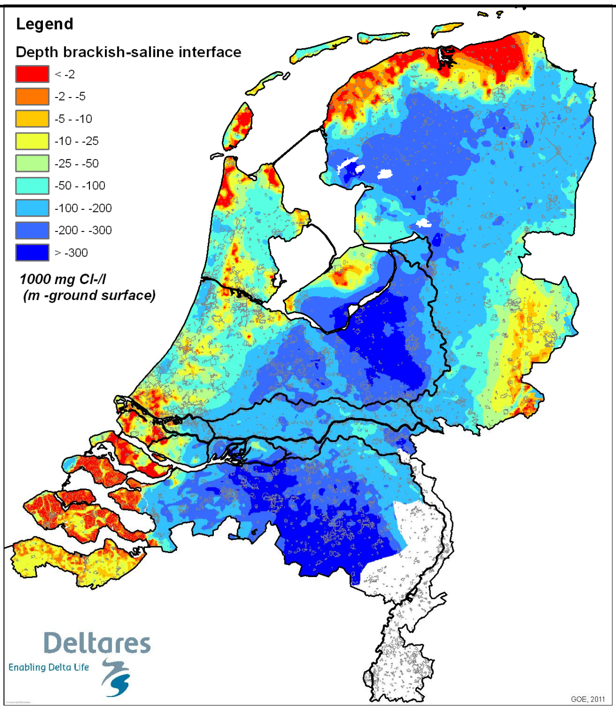




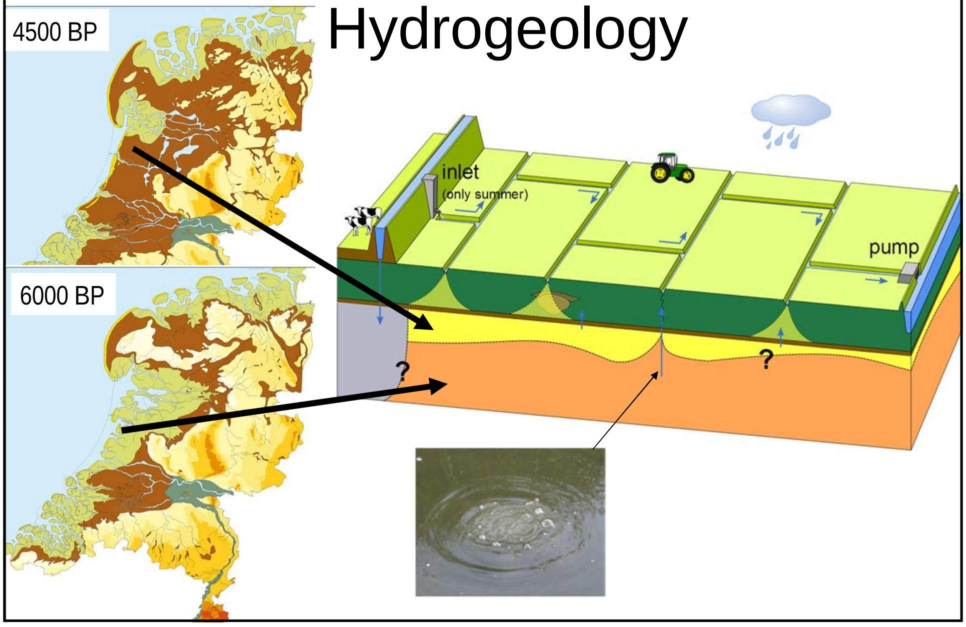




Fresh-Salt interface



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

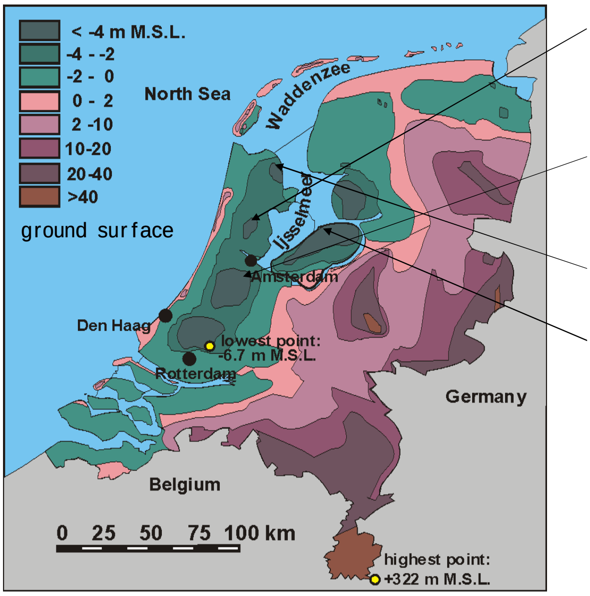
Anthropogenic causes:

- land subsidence
- polder level lowering
- groundwater extractions

Future developments (climate change):

- sea level rise
- changes in recharge

Abrupt land subsidence



position polders:

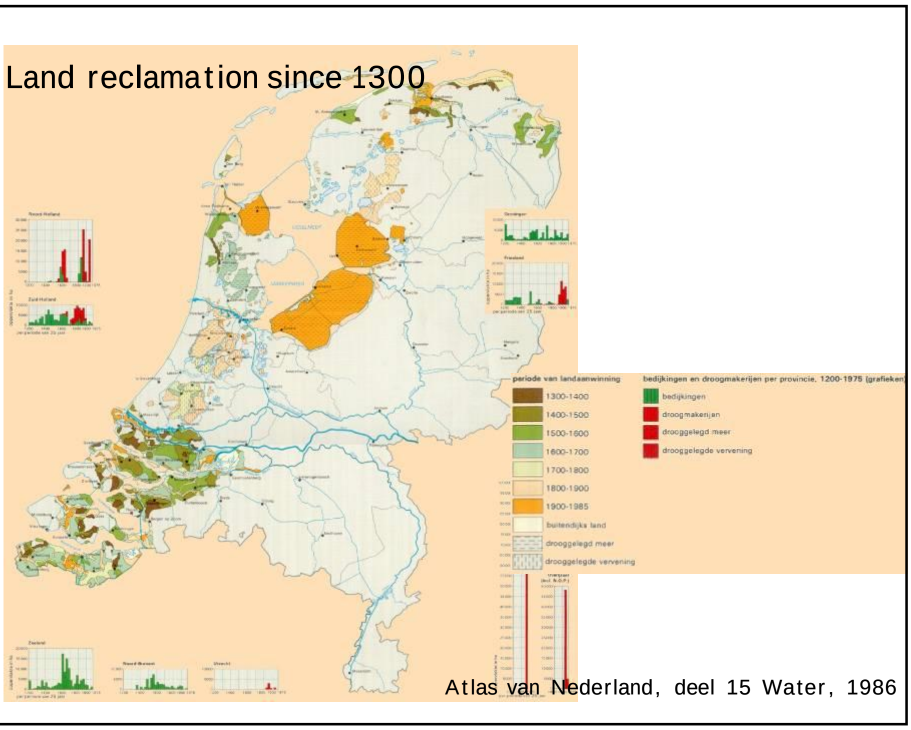
Beemster	1608-1612
Wormer	1625-1626
Schermer	1633-1635
Purmer	1618-1622

Haarlemmermeer polder 1850-1852

Wieringermeer polder ~1930

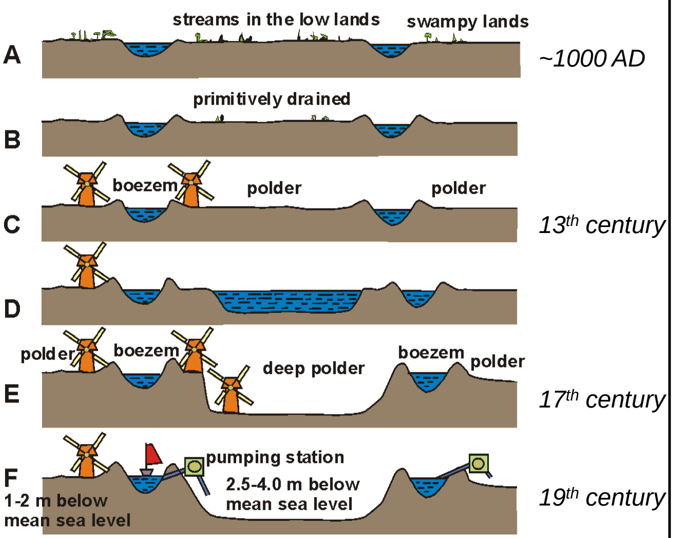
Flevo polders 1950-60s

Land reclamation since 1300



Atlas van Nederland, deel 15 Water, 1986

Development of the Dutch 'Polder' Landscape



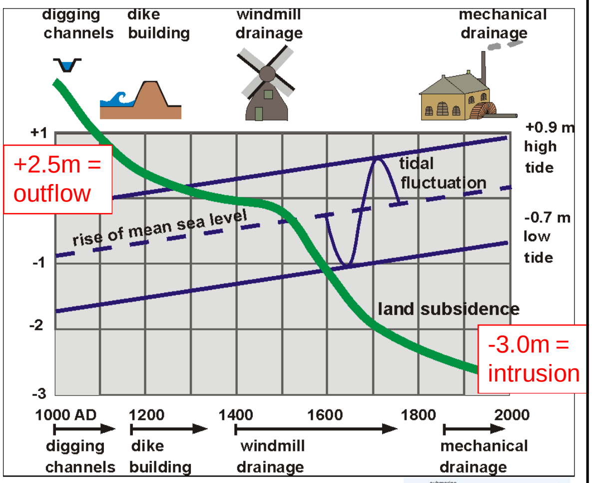
From fresh water outflow to salt water inflow

Causes:

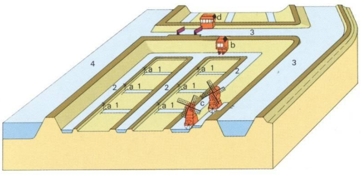
- Autonomous processes
- Land subsidence
- Abrupt land reclamation

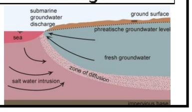
- Climate change
- Sea level rise
- Change in net recharge

Historical subsidence of the ground surface in Holland

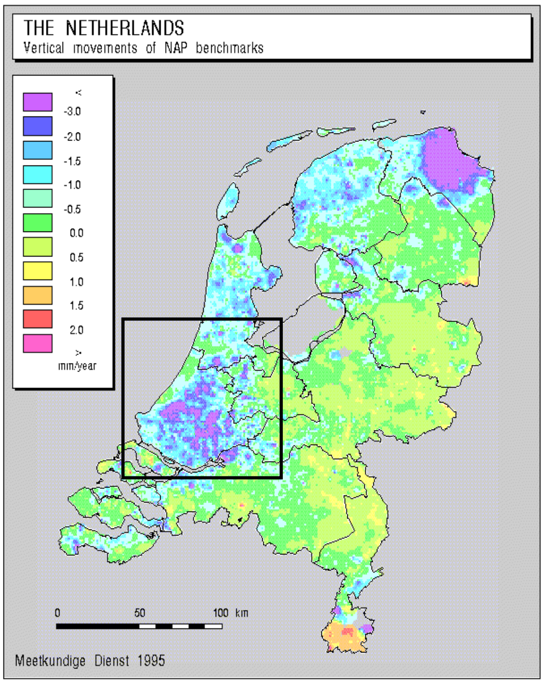


🟩 Ground surface





Land subsidence related to M.S.L.



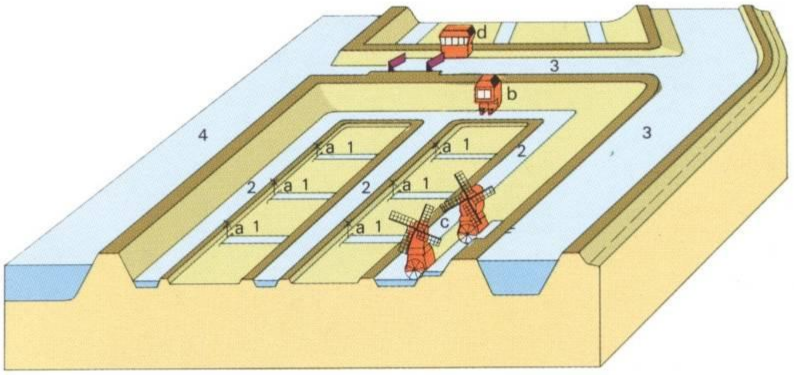
Land subsidence

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

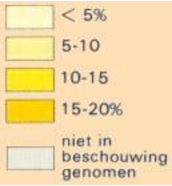
Many agricultural plots with different water levels throughout the season

The polder system

The polder system

Bulb farms at the landside of the sand dunes

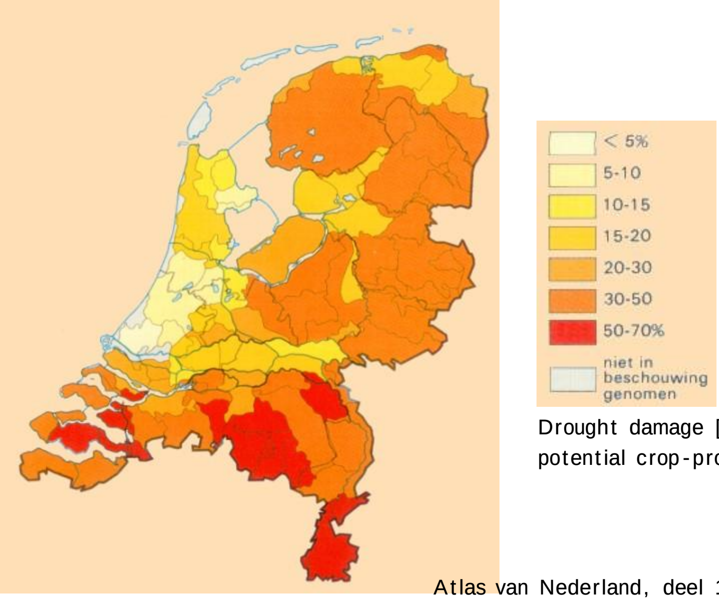
Salt damage in 1976 (very dry year)



Salt damage [percentage] in potential crop-production

Atlas van Nederland, deel 15 Water, 1986

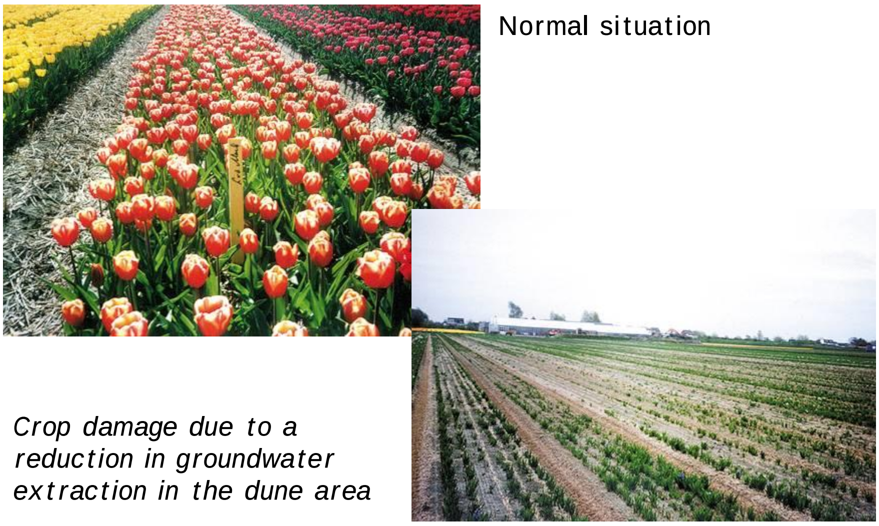
Drought damage in 1976 (very dry year)



Drought damage [percentage] in potential crop-production

Atlas van Nederland, deel 15 Water, 1986

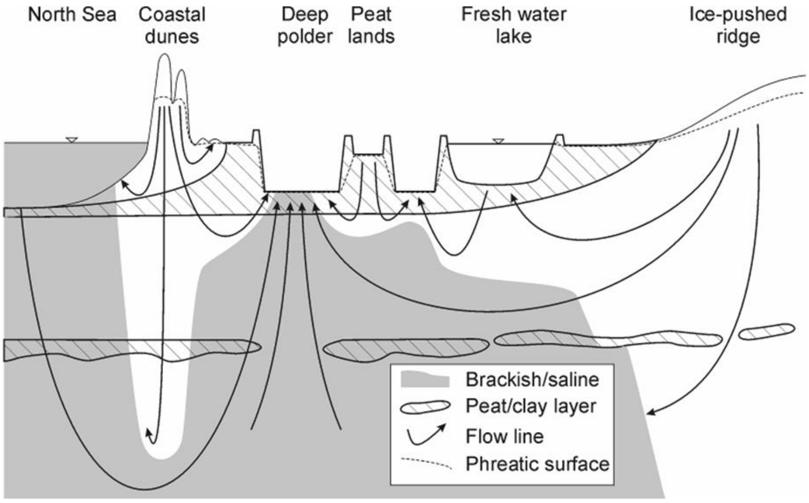
‘Wetting’ damage



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:

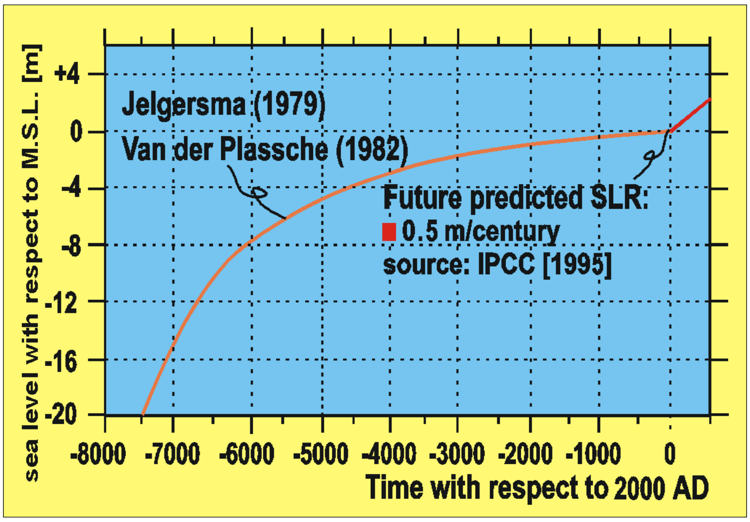
Short term threats:
-flooding
-dike collapse
-drought

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

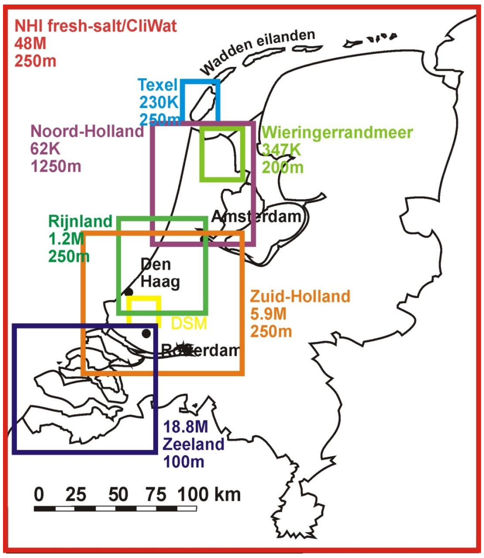


Numerical variable density models at Deltares

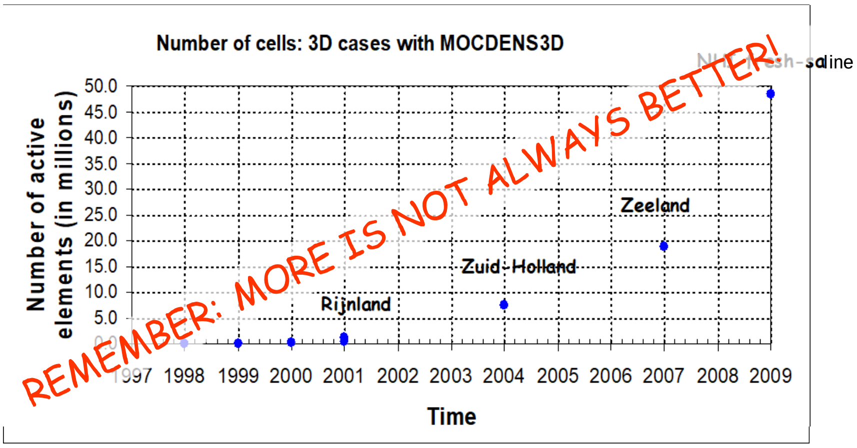
Characteristics:
- variable-density groundwater
- fresh, brackish and saline
- 3D, non-steady
- coupled solute transport

Code (MODFLOW family):
MOCDENS3D
SEAWAT

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



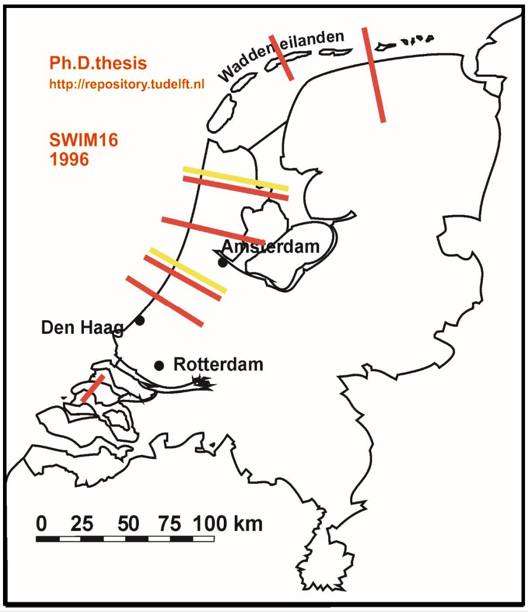
'DO NOT DO THIS AT HOME!' (DATA PROBLEM)



REMEMBER: MORE IS NOT ALWAYS BETTER!

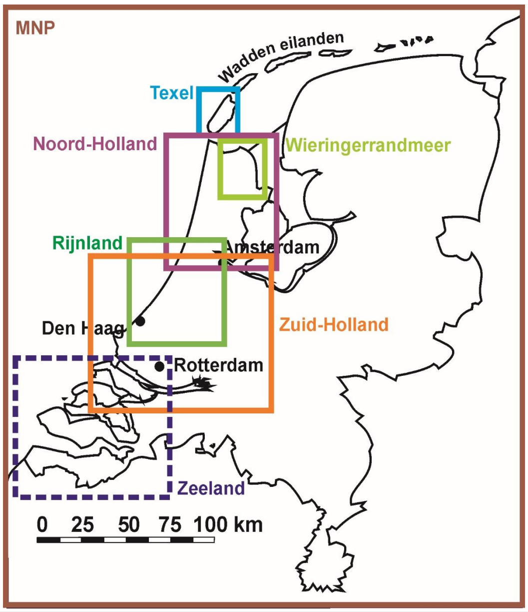
Modelling effect sea level rise on salt water intrusion

2D models



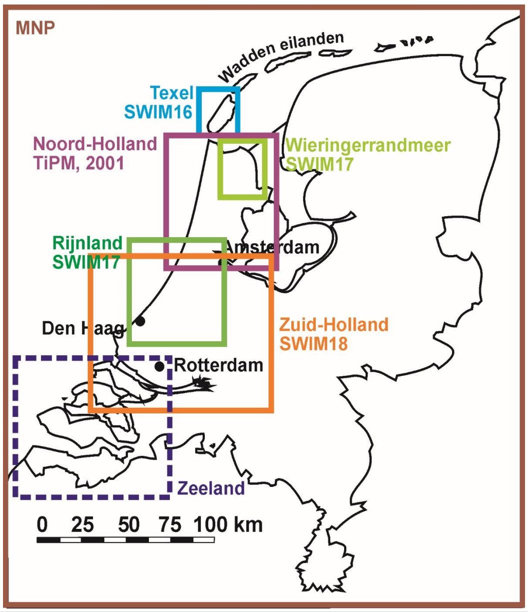
Modelling effect sea level rise on salt water intrusion

3D models



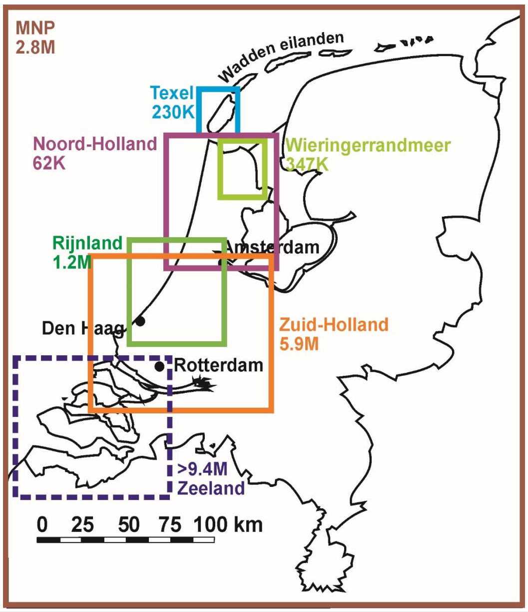
Modelling effect sea level rise on salt water intrusion

3D models
SWIM



Modelling effect sea level rise on salt water intrusion

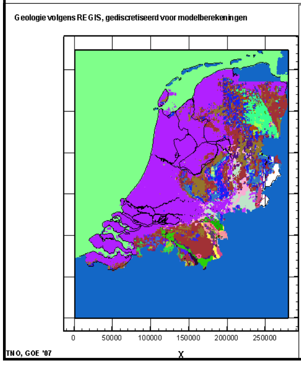
3D models number cells

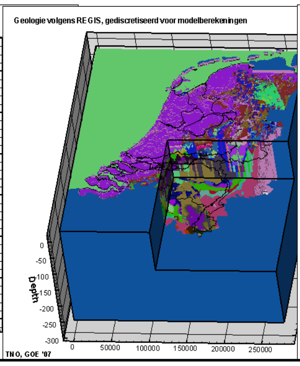


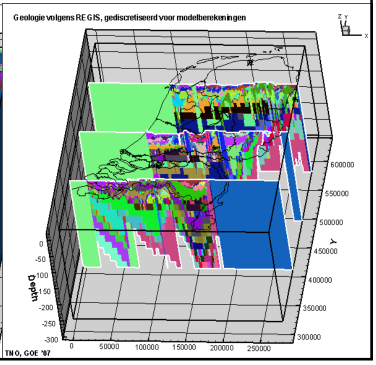
Recent model study for the whole Netherlands on the effect of sea level rise of water management (1)

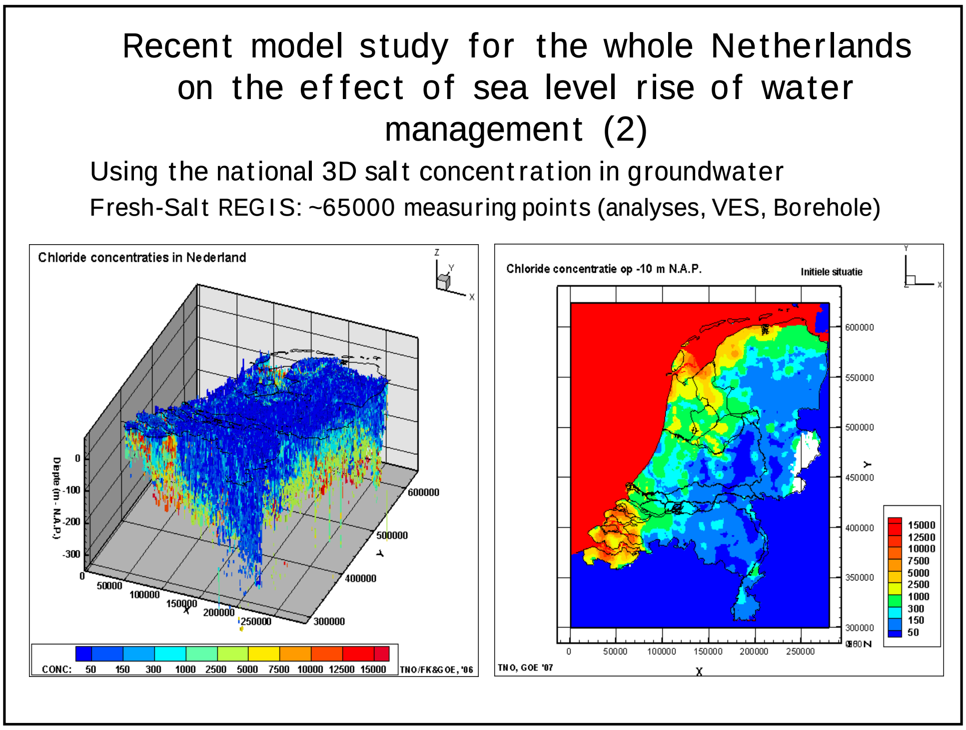
Using the national subsoil parametrisation

- 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)





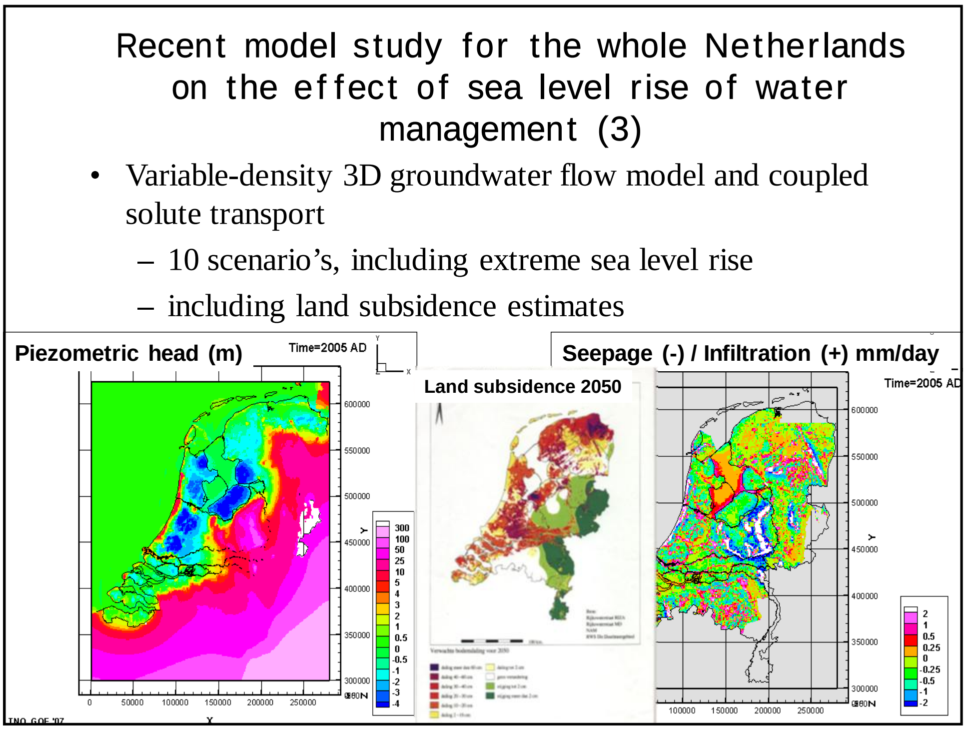




Recent model study for the whole Netherlands on the effect of sea level rise of water management (2)

Using the national 3D salt concentration in groundwater

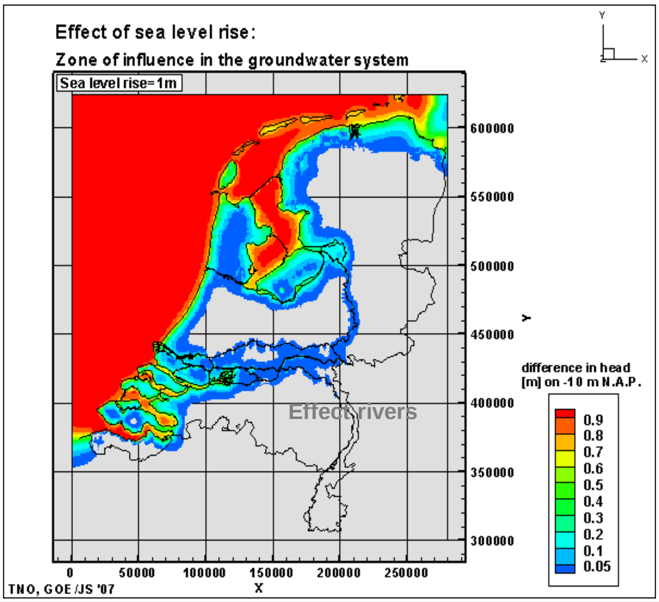
Fresh-Salt REGIS: ~65000 measuring points (analyses, VES, Borehole)



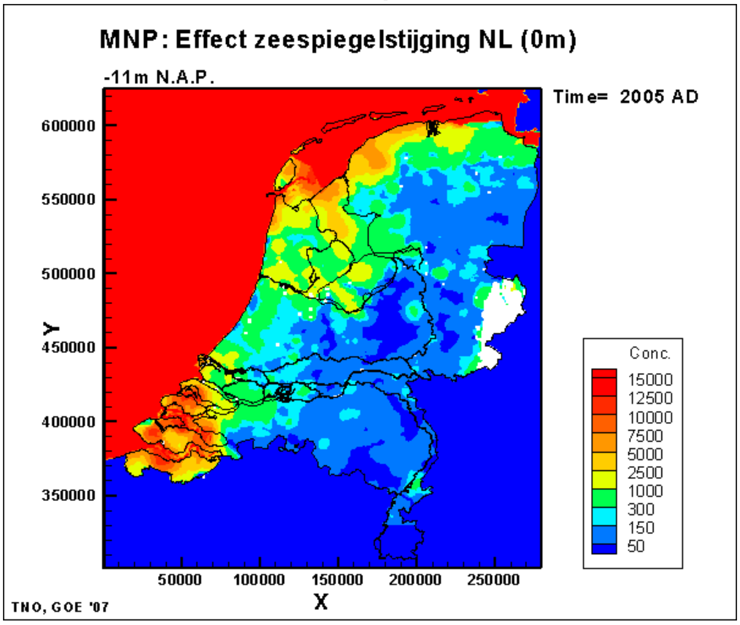
Recent model study for the whole Netherlands on the effect of sea level rise of water management (3)

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

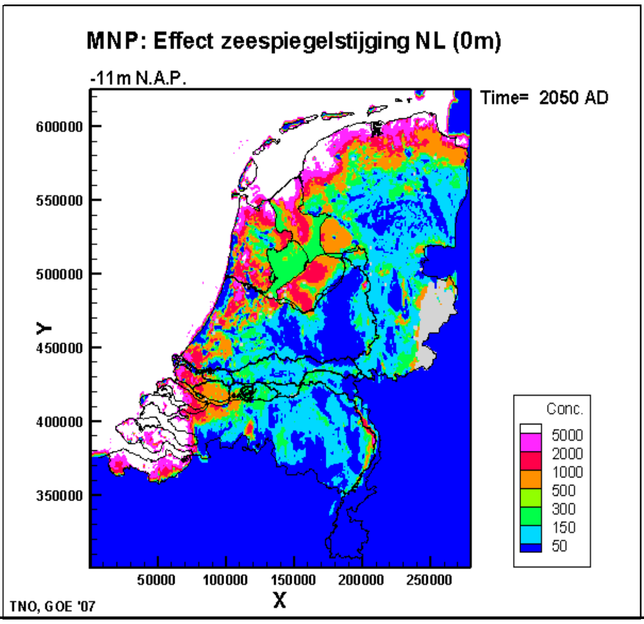
Results: zone of influence 1m sea level rise



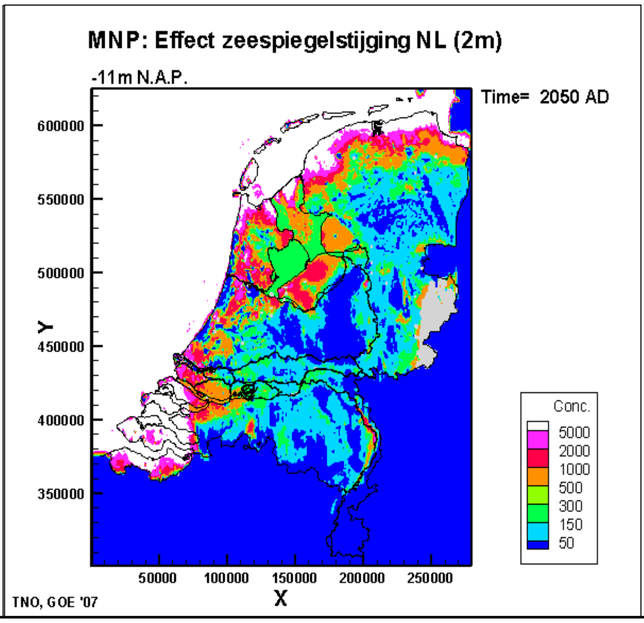
Salinisation over the period 2000-2050



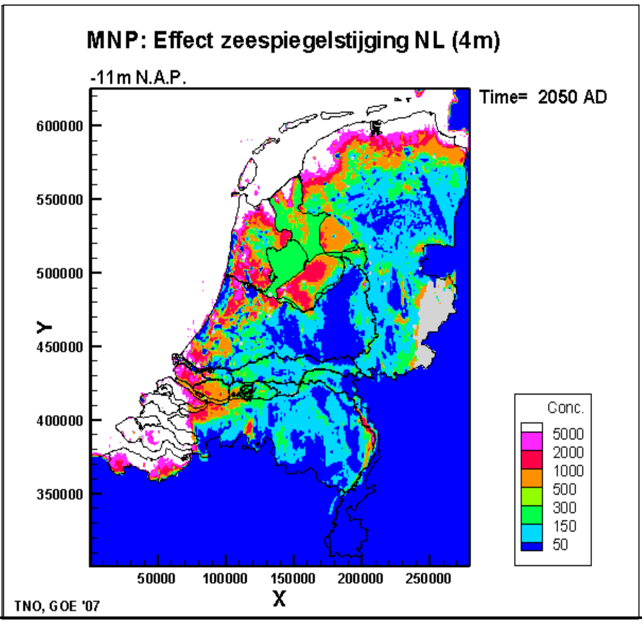
Salinisation subsoil at 0m sea level rise in 2050



Salinisation subsoil at 2m sea level rise in 2050

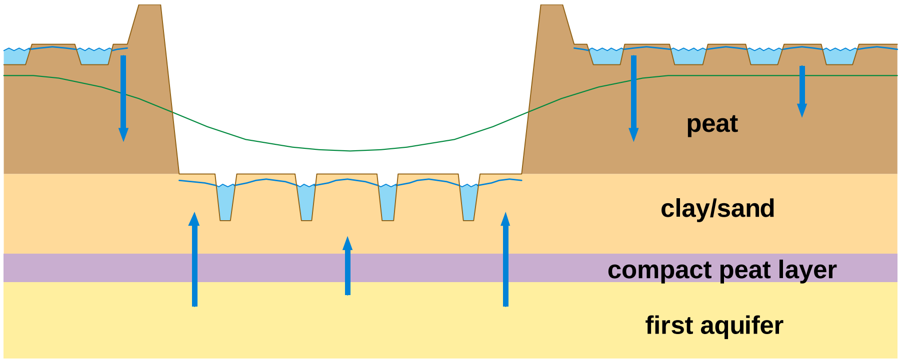


Salinisation subsoil at 4m sea level rise in 2050

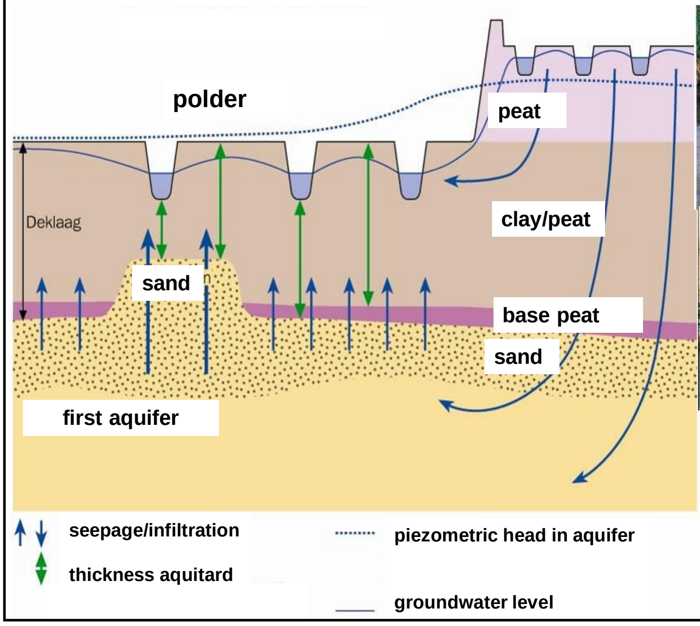


Salty wells

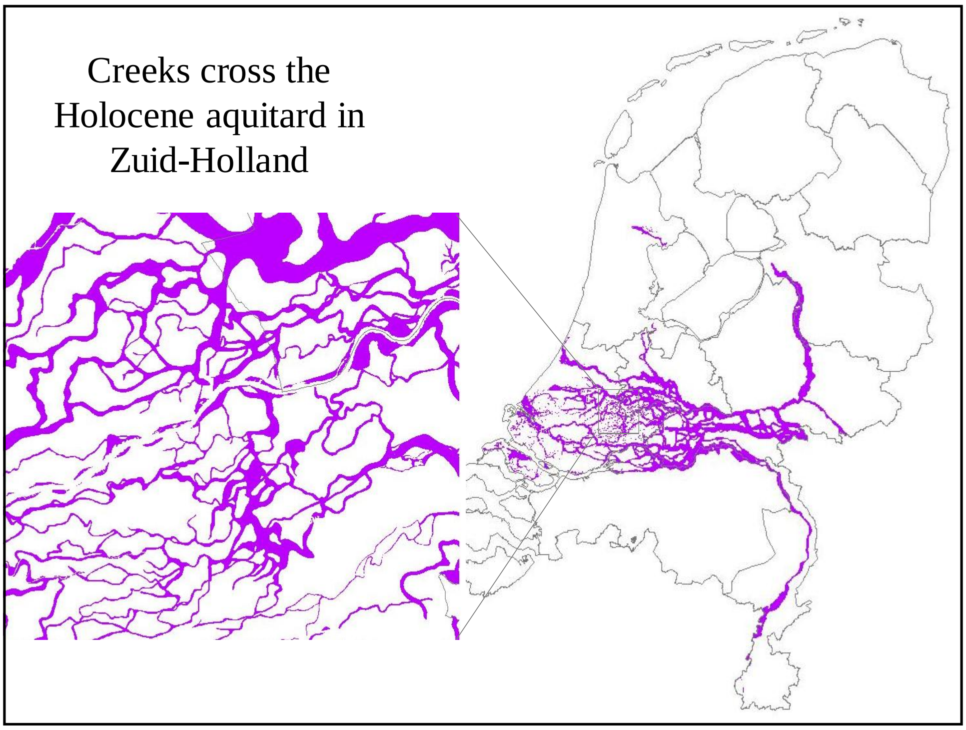
Seepage and infiltration situation around deep polders



Risk of instable Holocene aquitards (1)

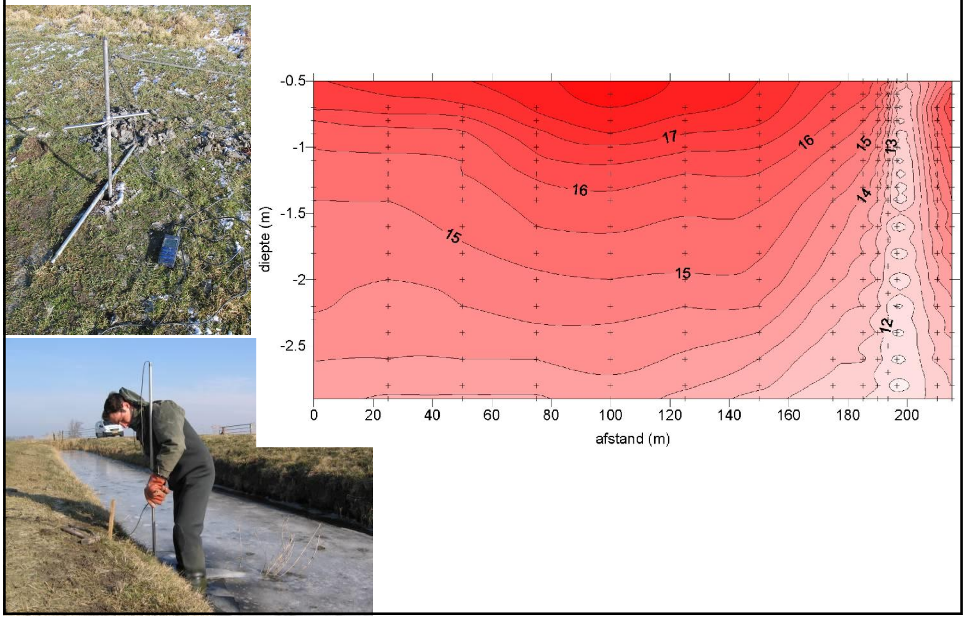


Creeks cross the Holocene aquitard in Zuid-Holland

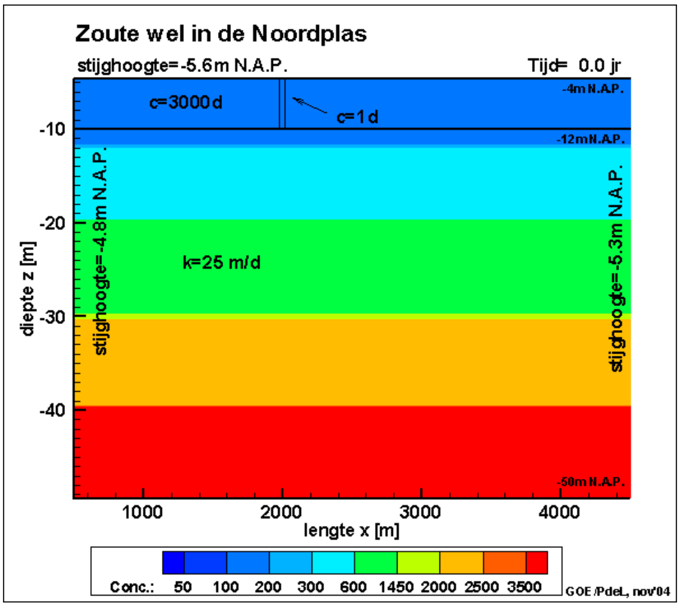


‘*Wells*’ (weak spots in Holocene layer)

Temperature measurements

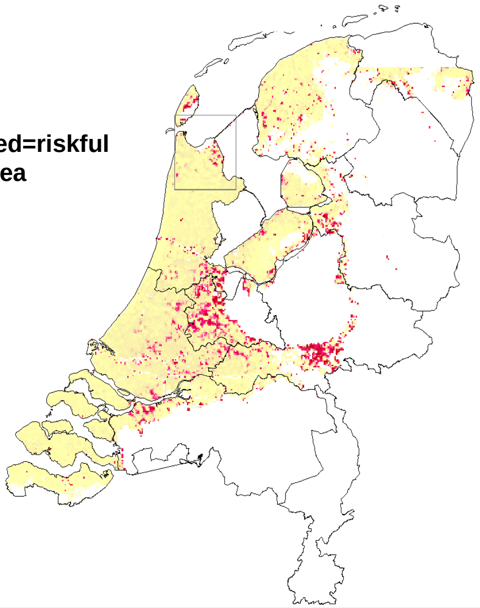


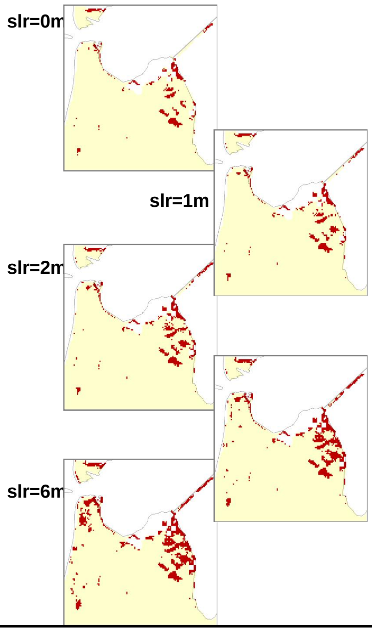
Simulation of salt groundwater towards *wells*



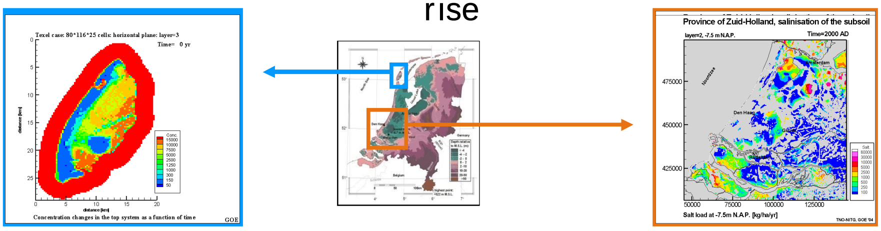
Risk of instable Holocene aquitards (2)

Red=riskful area





Quantification hydrogeological impacts of sea level rise



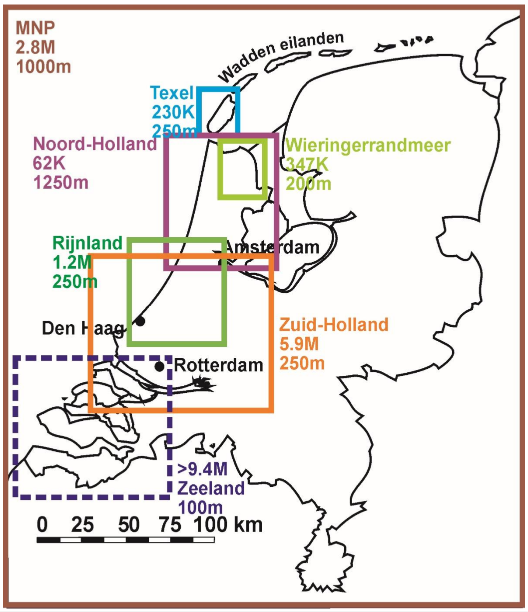
Situation at 2100 AD with sea level rise of 0.5m/century,

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*	$\lvert\Delta\phi\rvert$=0.24 m σ=0.77 m	$\lvert\Delta\phi\rvert$=0.34 m σ=0.21 m	$\lvert\Delta\phi\rvert$=0.60 m σ=0.77 m

* calibration with seepage & salt load in polders

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

Characteristics 3D Cases (II): model parameters

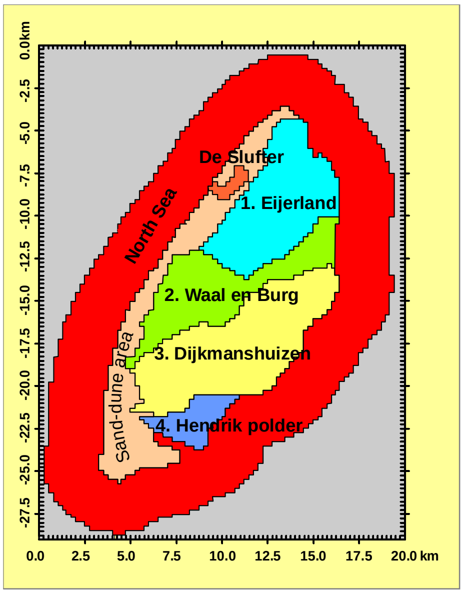
Case	Kop van Noord-Holland	Texel	Wieringer-meerpolder	Rijnland (=391 EM RAM)
horizontal cell size [m]	1250*1250	250*250	200*200	250*250
vertical cell size [m]	10	1.5 to 20	2 to 70	5 to 10
total # active cells	~40.000	~126.000	~312.000	~1.200.000
# cells	41*52*29	80*116*23	116*136*22	209*241*24
# particles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

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

Model of the island of Texel

Texel

Characteristics of the island of Texel (I)



•Tourist island in summer time

•Land surface: 130 km^2

•Polder areas:

🟦 1. Eijerland
🟩 2. Waal en Burg
🟨 3. Dijkmanshuizen
🟦 4. Hendrik polder

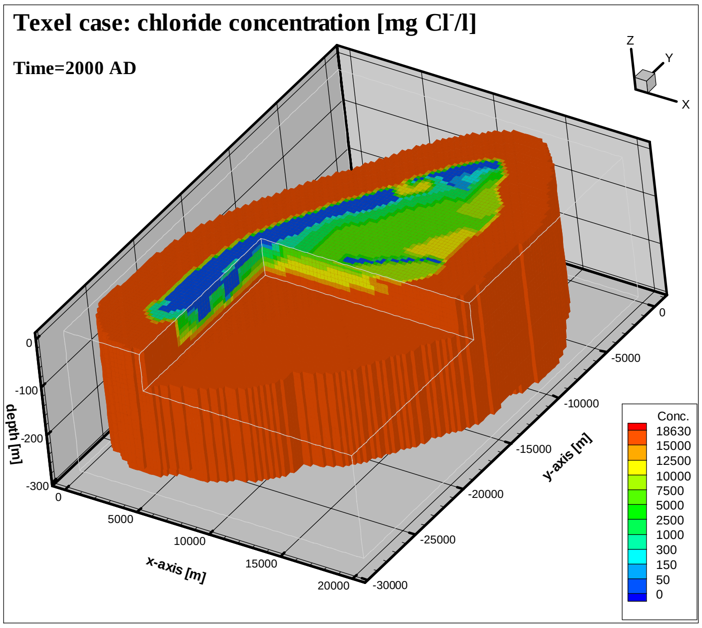
🟧 Sand-dune area at western side

🟧 'De Slufter' is a tidal salt-marsh

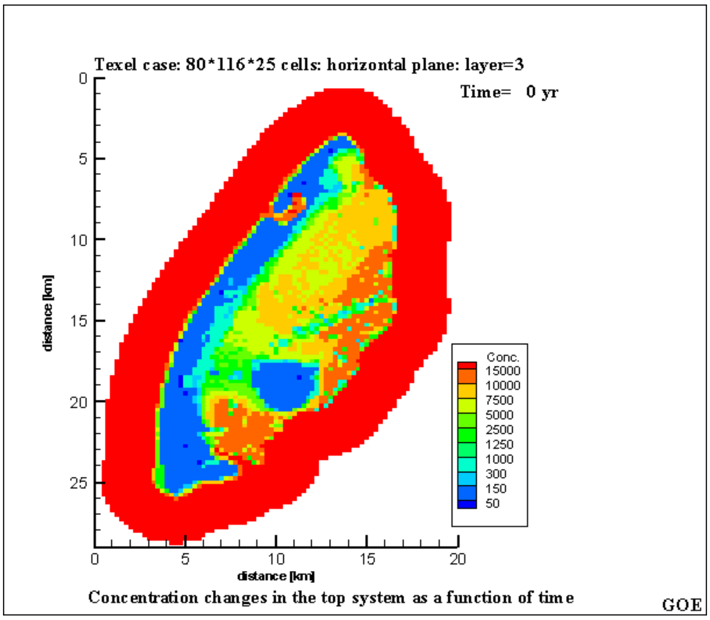
🟥 North Sea surrounds the island

Texel

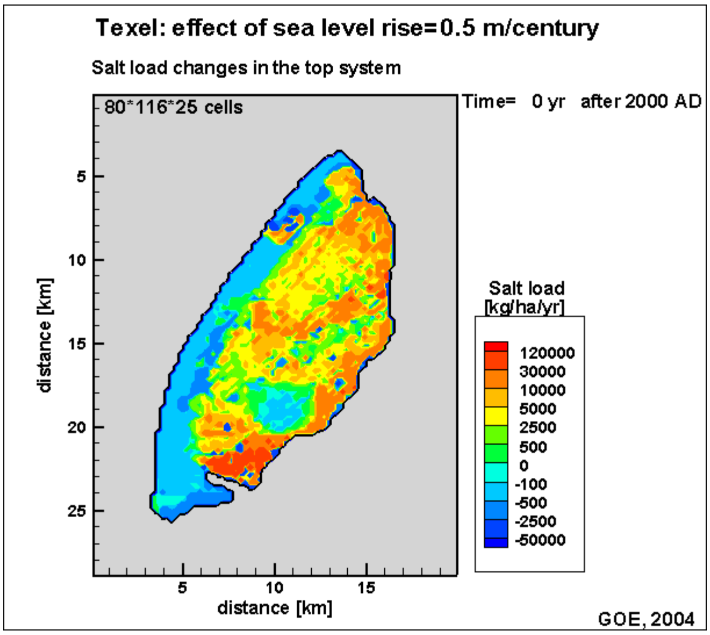
Texel: present 3D chloride distribution



Texel: reference case=autonomous development

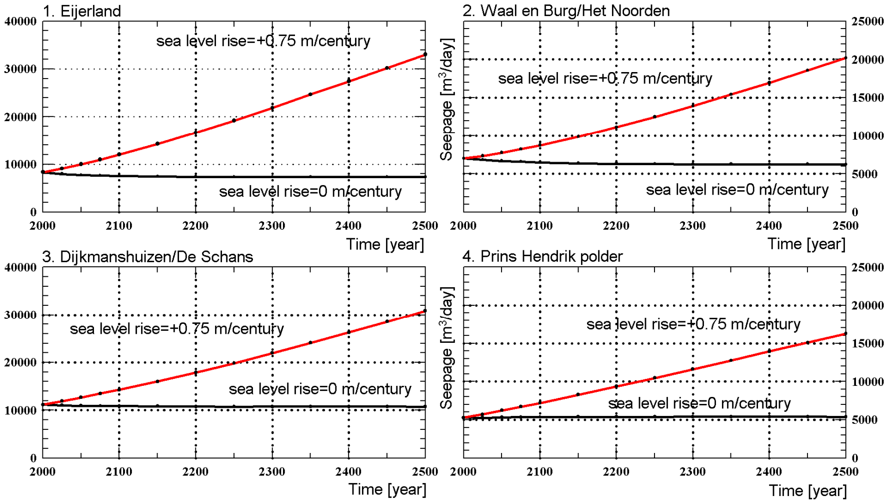


Texel: effect of sea level rise on salt load



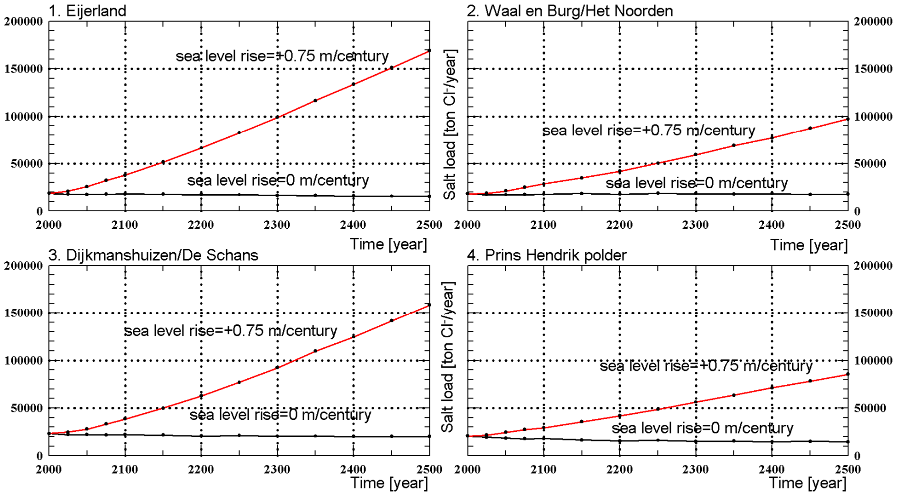
Texel

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“

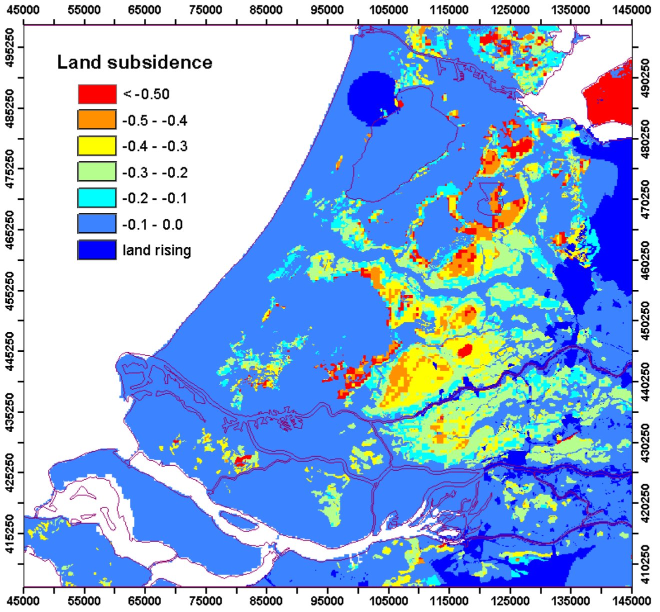
Identification of all fresh groundwater bodies in the province

How fast is the salinisation process?

More seepage, more salt load?

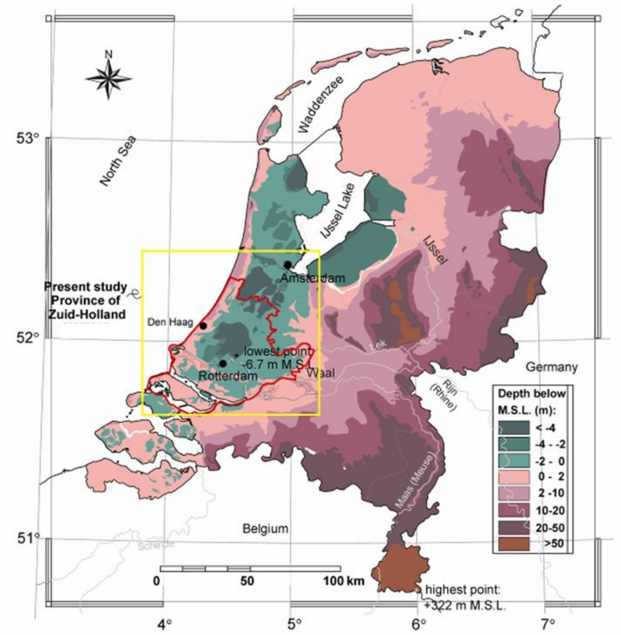
Land subsidence

2050



Source: RIZA

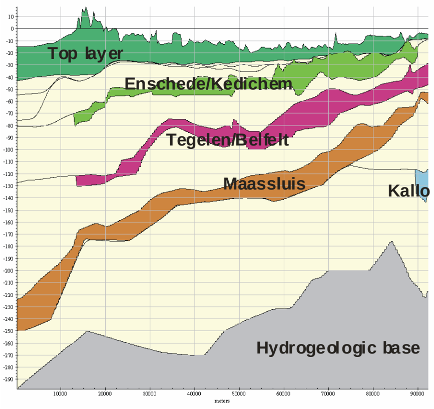
Location of the Province of Zuid-Holland

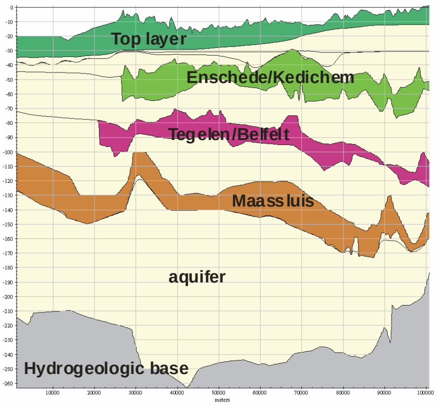


Numerical model description

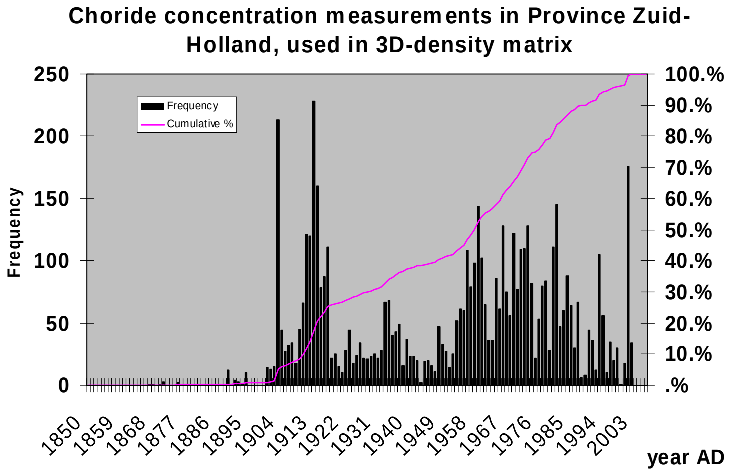
- variable-density groundwater flow
- coupled solute transport
- MOCDENS3D
- area: 100km * 92.5km * 300m depth
- 400 *370 cells, 40 layers
- ~4 million active cells
- uses most accurate Dutch 3D subsurface schematization available
- 9 aquifers and aquitards
- uses 5772 chloride concentration measurements

Position and name of aquitards





3D interpolation of chloride-concentration


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

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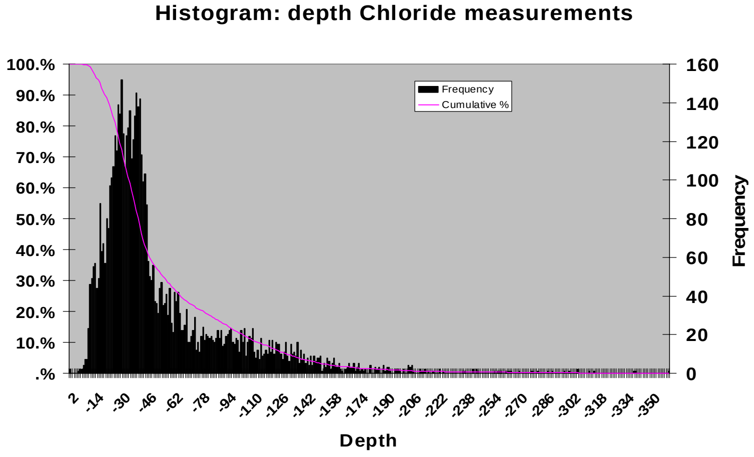
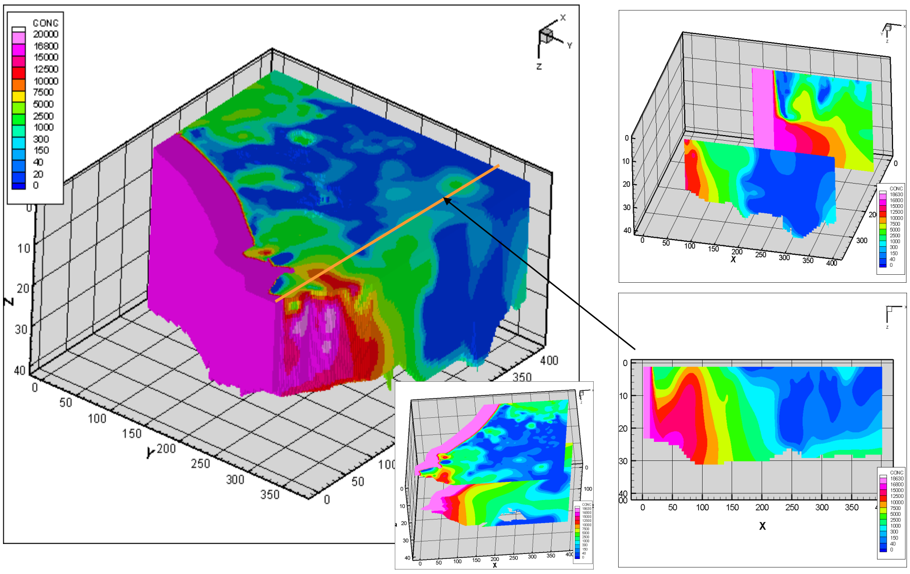
3D interpolation of chloride-concentration


Histogram: depth Chloride measurements

Initial chloride distribution

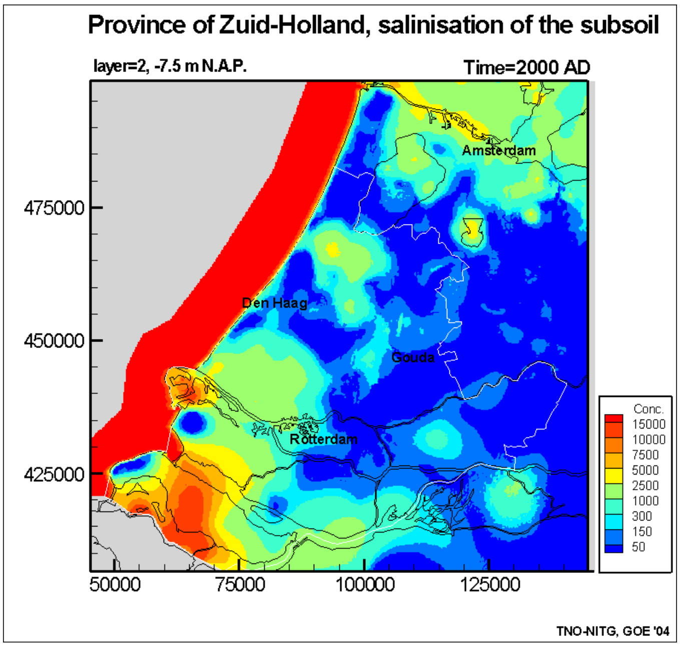


Present freshwater volume

27 billion m^3

36% fresh, 14% brackish, 50% saline

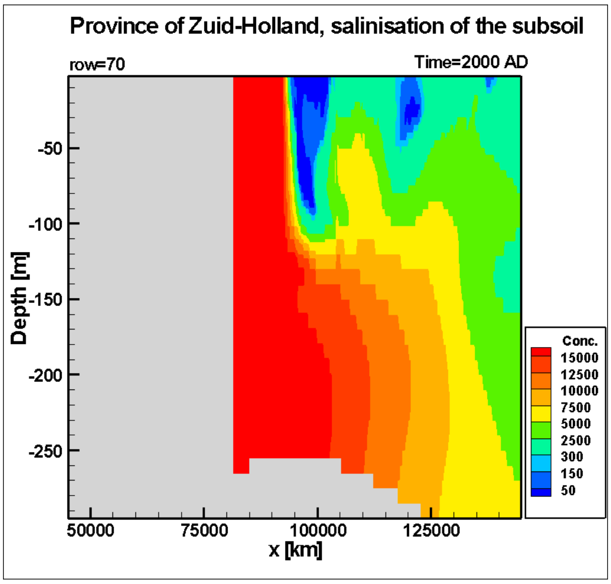
Results: Chloride conc. in 200 yrs



Province of Zuid-Holland, salinisation of the subsoil

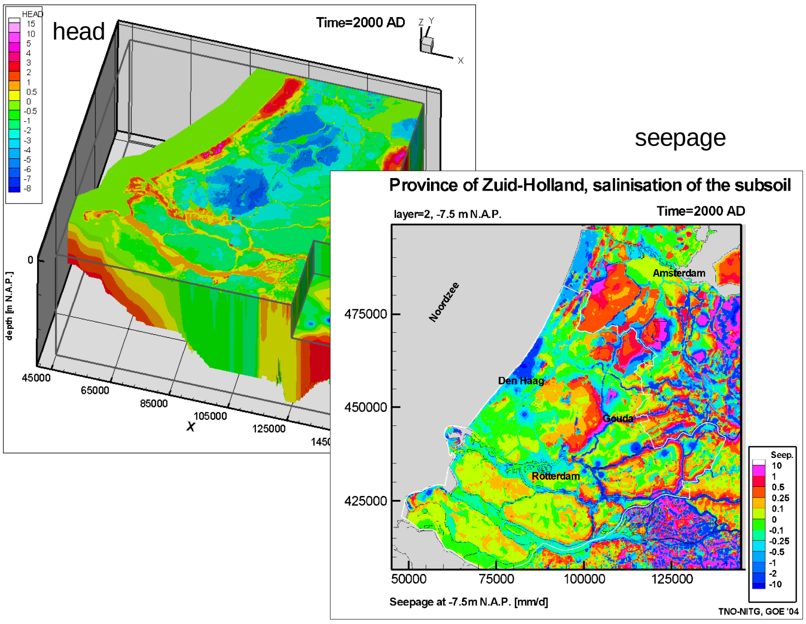
TNO-NITG, GOE '04

Results: Chloride conc. in 200 yrs



Province of Zuid-Holland, salinisation of the subsoil

Results: freshwater head and seepage at 2000 AD



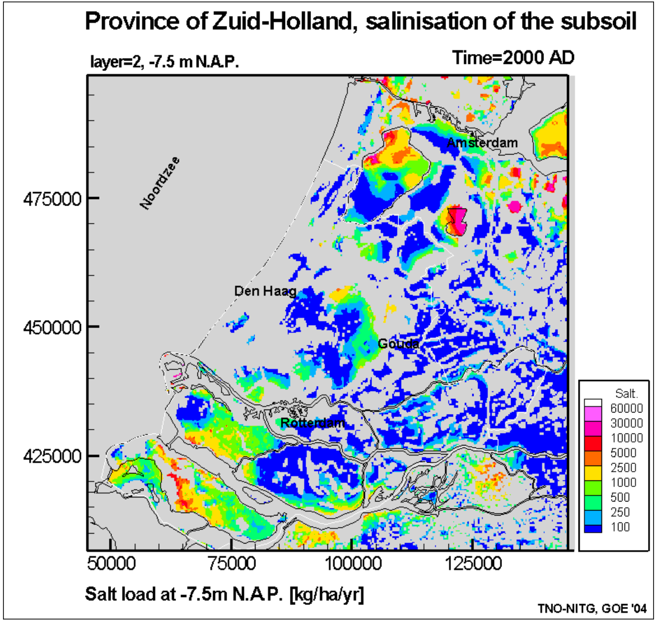
Province of Zuid-Holland, salinisation of the subsoil

layer=2, -7.5 m N.A.P. Time=2000 AD

Seepage at -7.5m N.A.P. [mm/d]

TNO-NITG, GOE '04

Results: Salt load in 200 yrs



Province of Zuid-Holland, salinisation of the subsoil

layer=2, -7.5 m N.A.P. Time=2000 AD

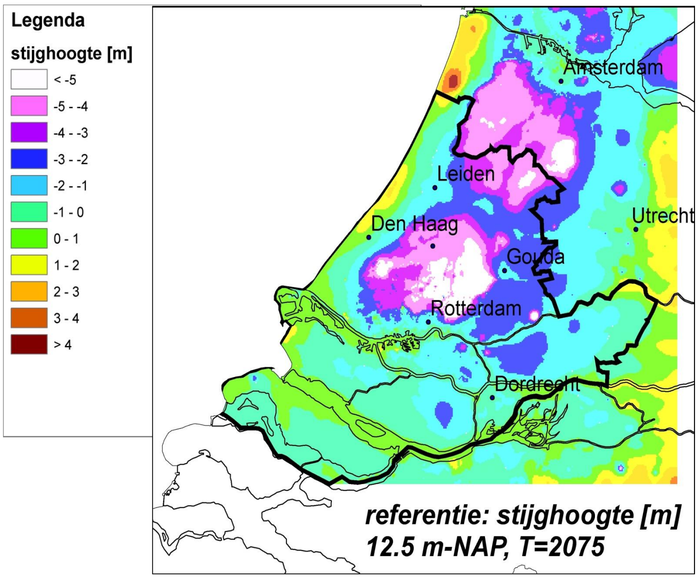
Salt load at -7.5m N.A.P. [kg/ha/yr]

TNO-NITG, GOE '04

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

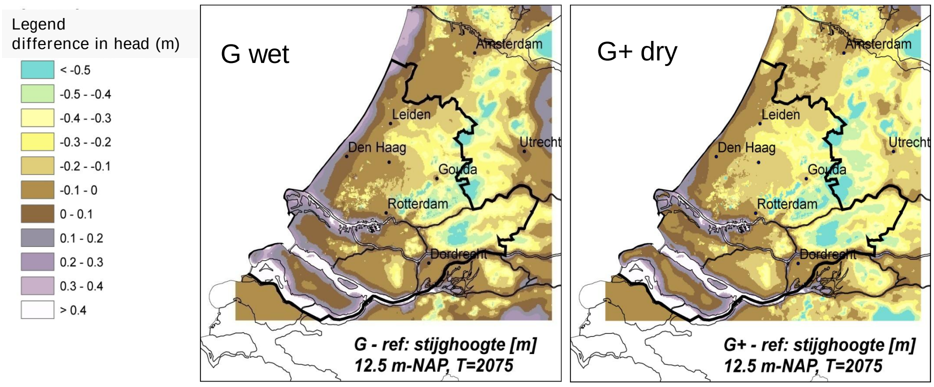
Some regional modelling results

Freshwater head at -12.5 M.S.L.



referentie: stijghoogte [m]
12.5 m-NAP, T=2075

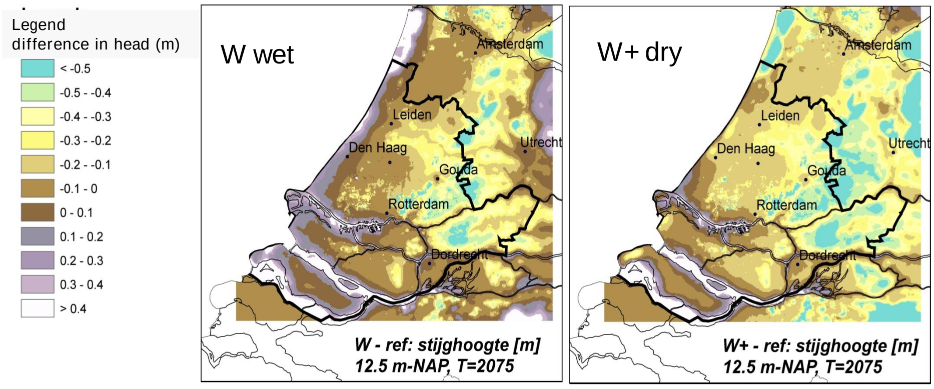
Difference in freshwater head on op -12.5 N.A.P.: G scenarios



Sea level rise is 60 cm

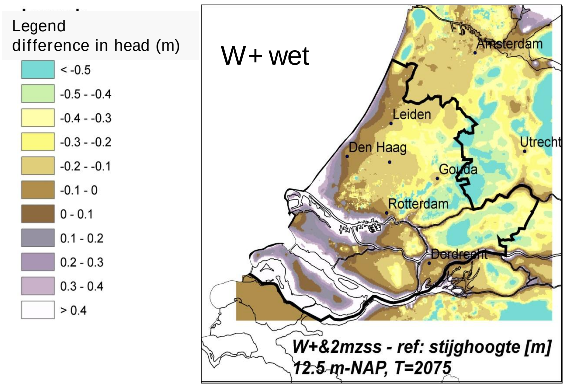
Including change in natural groundwater recharge

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



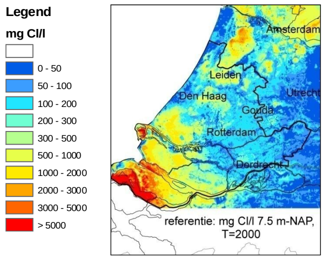
Sea level rise is 85 cm

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



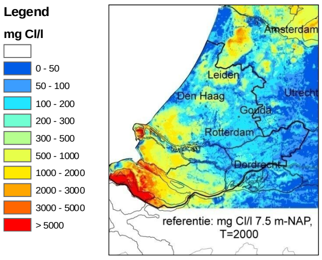
Sea level rise is 200 cm

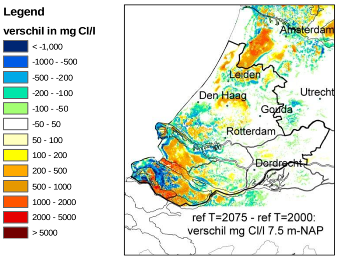
Salinisation/freshening Netherlands?: Present situation



modelstudy

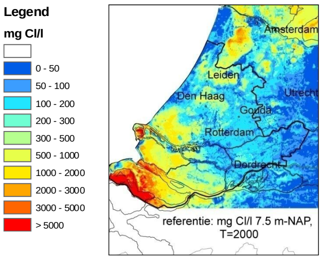
Salinisation/freshening Netherlands?: Autonomous processes

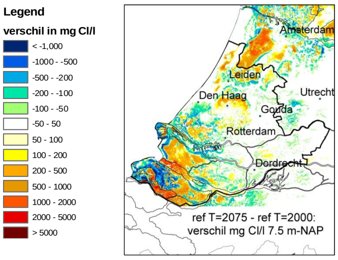


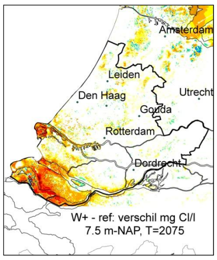


modelstudy

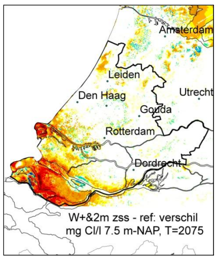
Salinisation/freshening Netherlands?: climate change







85 cm sea level rise

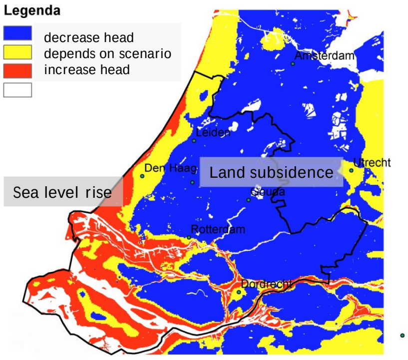


200 cm sea level rise

modelstudy

Effect climate scenarios in 2075 on

freshwater head

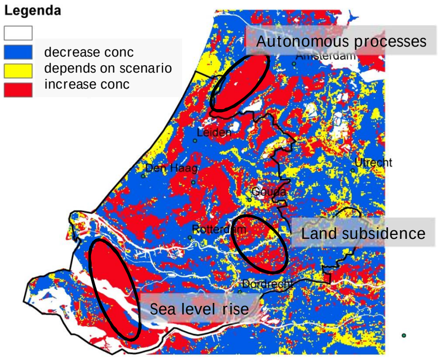


Land subsidence

Sea level rise

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

salinisation



Autonomous processes

Land subsidence

Sea level rise

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

Modelstudie PZH

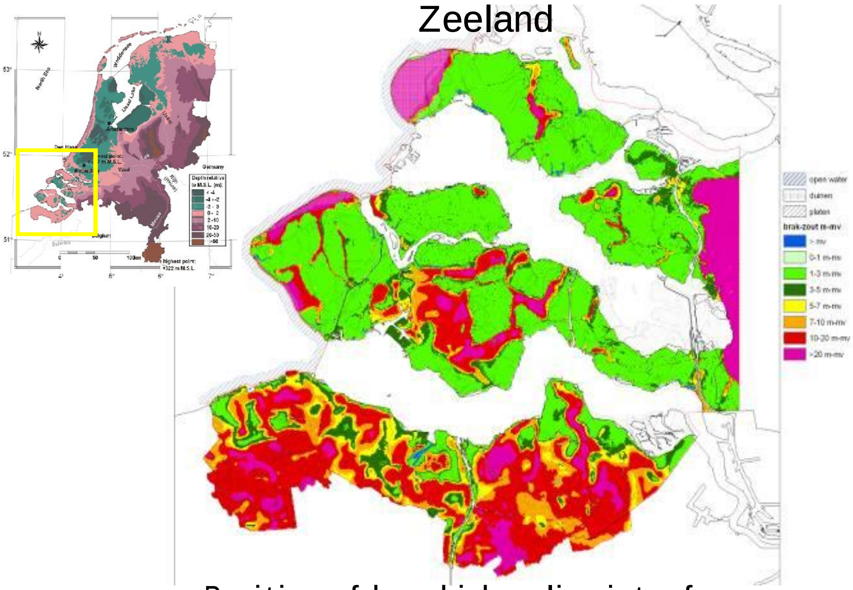
Rainwater lens

Rainwater lenses in an agricultural setting

Shallow dynamic freshwater bodies flowing upon brackish-saline groundwater

- density dependent
- dynamics: seasonal & long-year

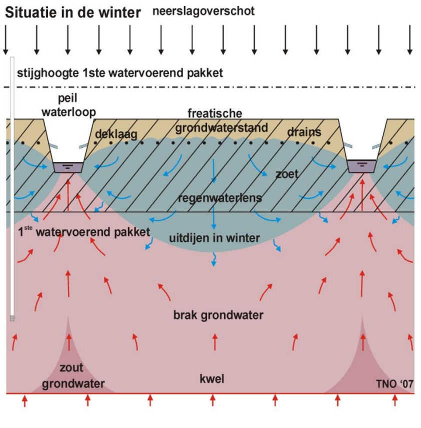
Salinisation of the phreatic groundwater in Zeeland



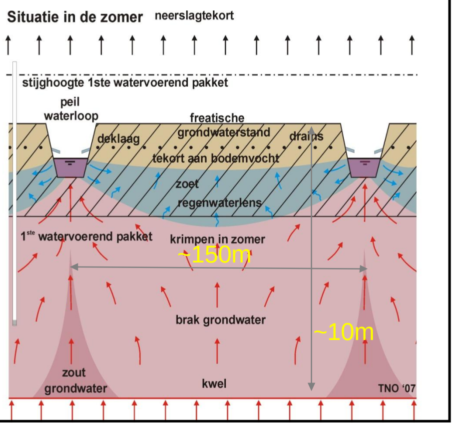
Position of brackish-saline interface

Salinisation of the phreatic groundwater in Zeeland

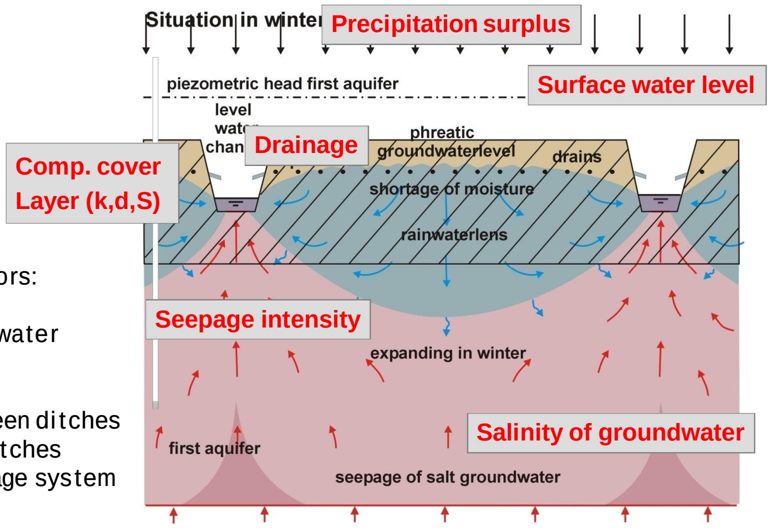
Dynamic rainwater lenses floating on saline groundwater



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



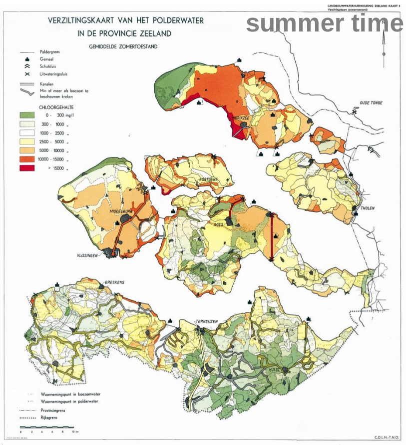
Factors controlling fresh-salt interface

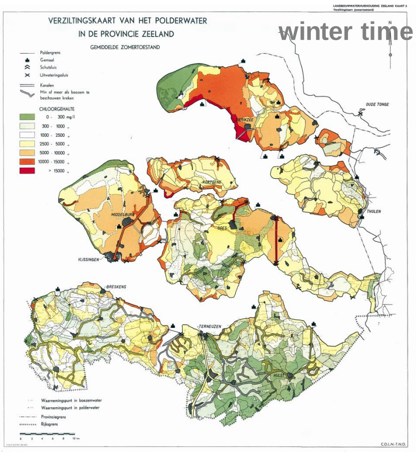


Important factors:

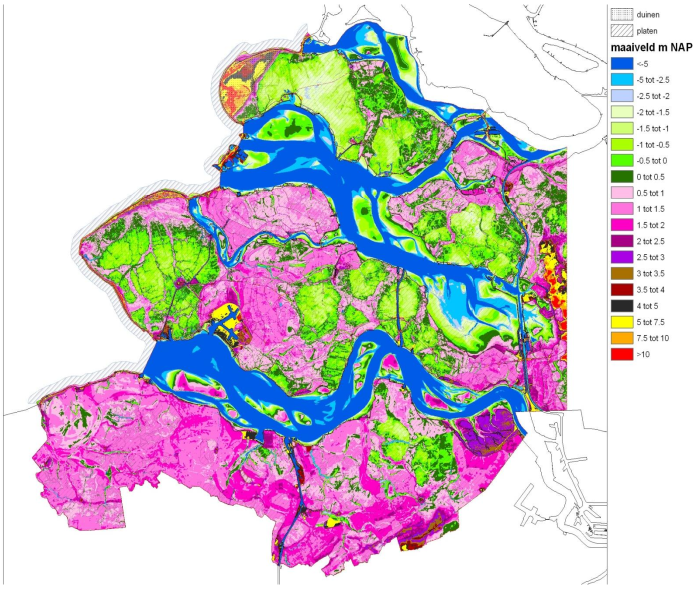
- natural groundwater recharge
- geology
- distance between ditches
- water levele ditches
- capacity drainage system

Salinisation surface water

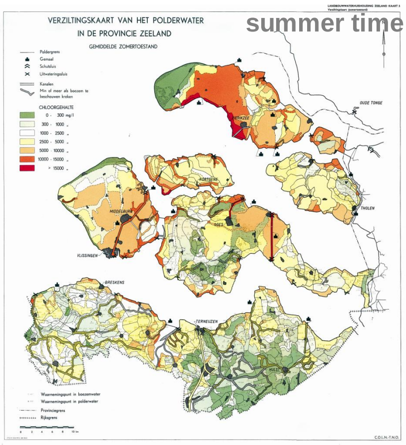


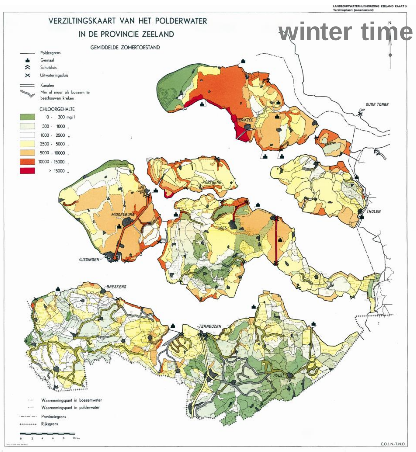


Position of the ground surface



Salinisation surface water





Problem definition dynamic freshwater lenses

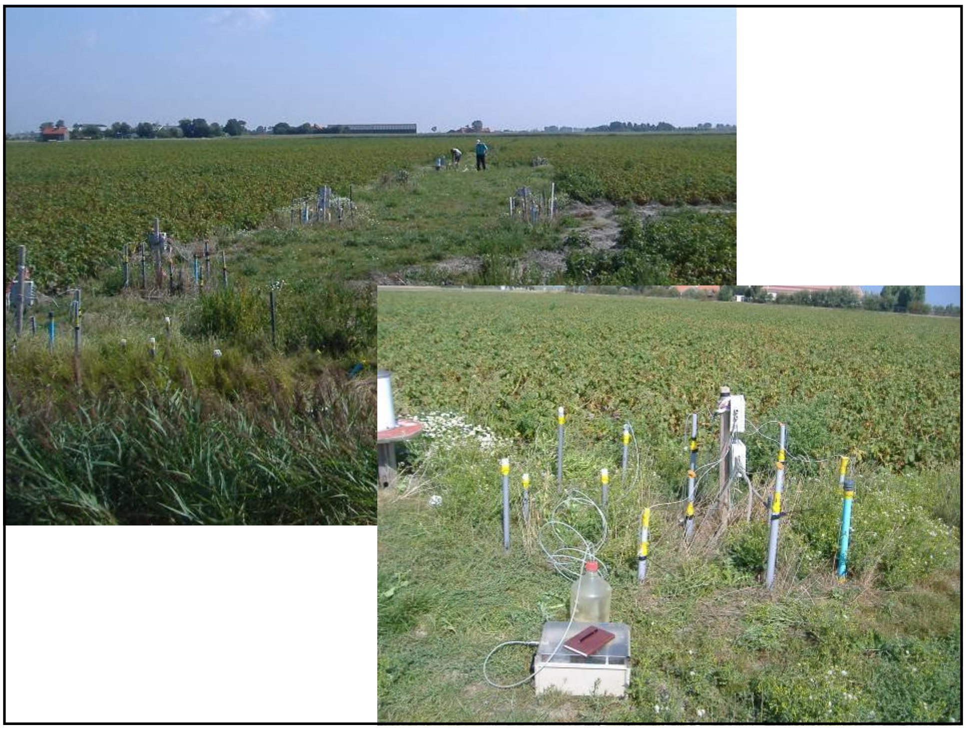
Salt in the agricultural plots originates from:
- surface water system (irrigation water)
- groundwater system (salt load to the root zone)

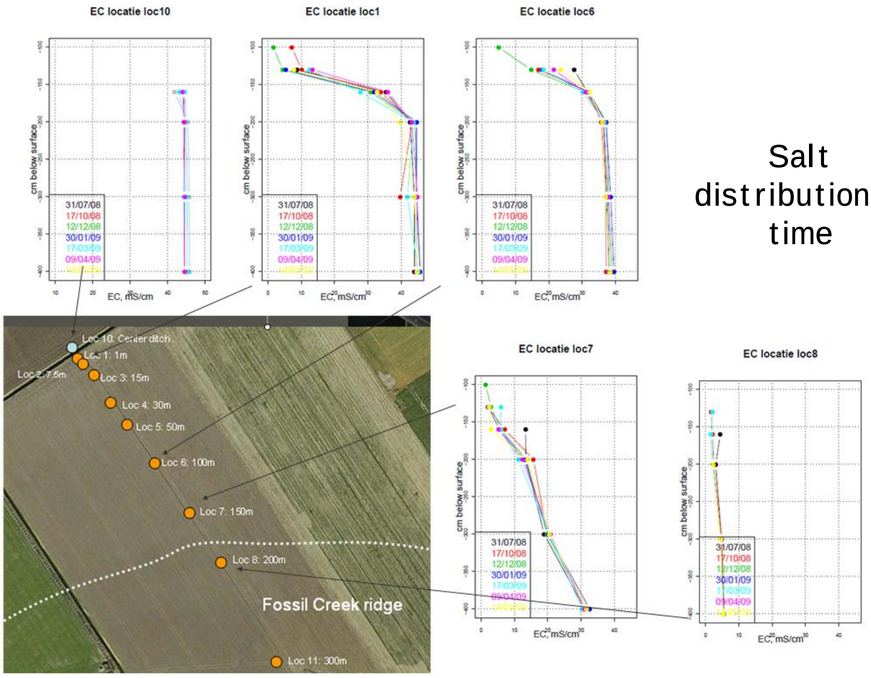
The salinisation will increase due to:
- sea level rise
- climate change
- water level management

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

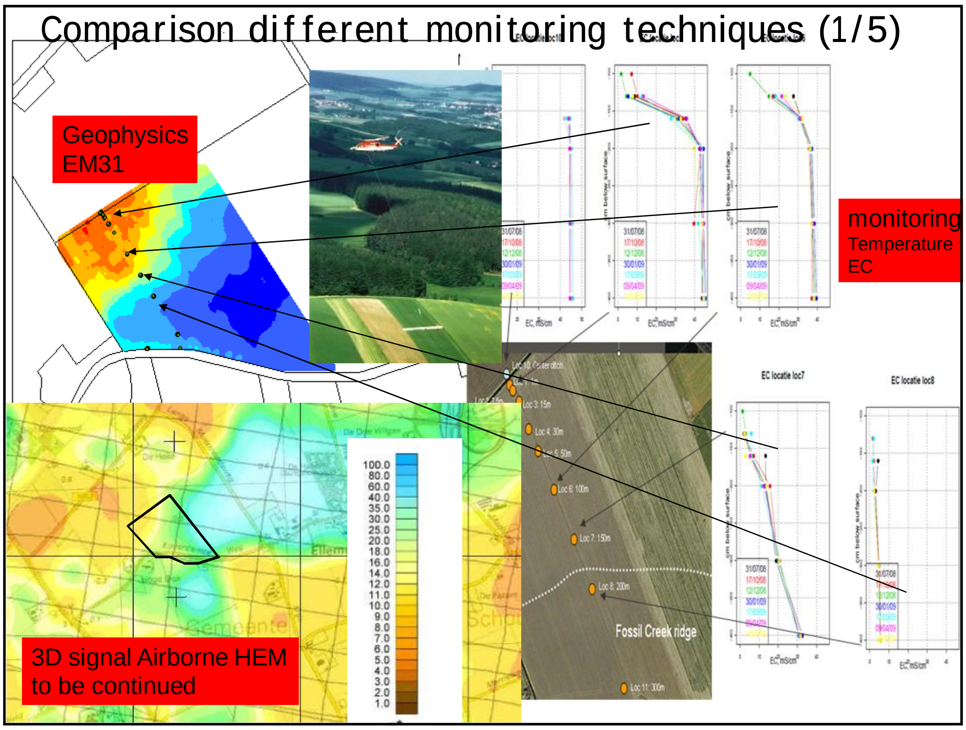




Salt distribution in time

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

Comparison different monitoring techniques (1/5)



Geophysics
EM31

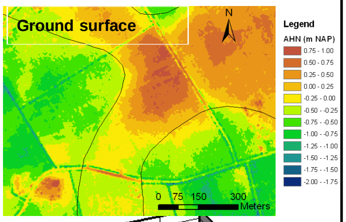
monitoring
Temperature
EC

3D signal Airborne HEM
to be continued

Local 3D model of the agricultural plot

Modelling:

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

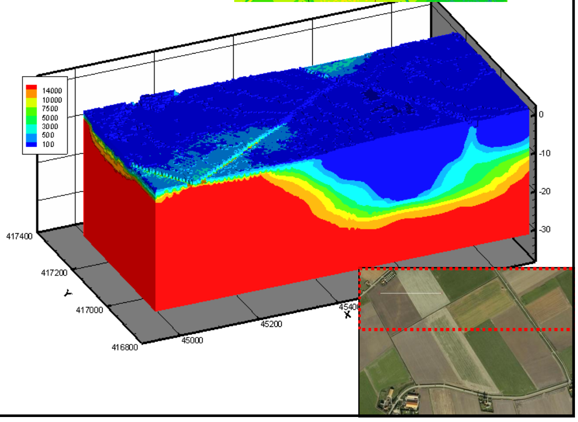


Code:

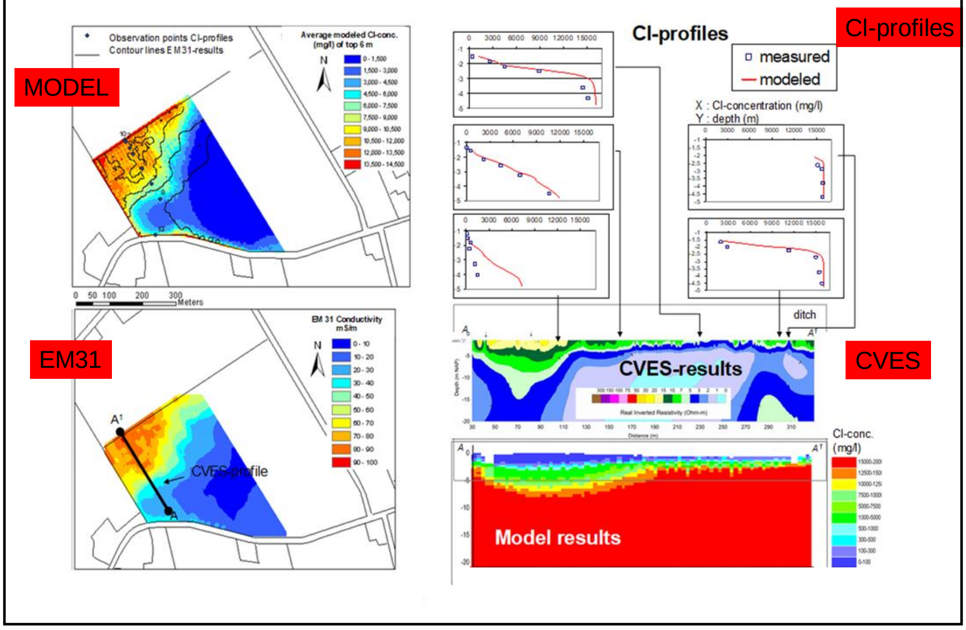
MOCDENS3D

Assessing effects:

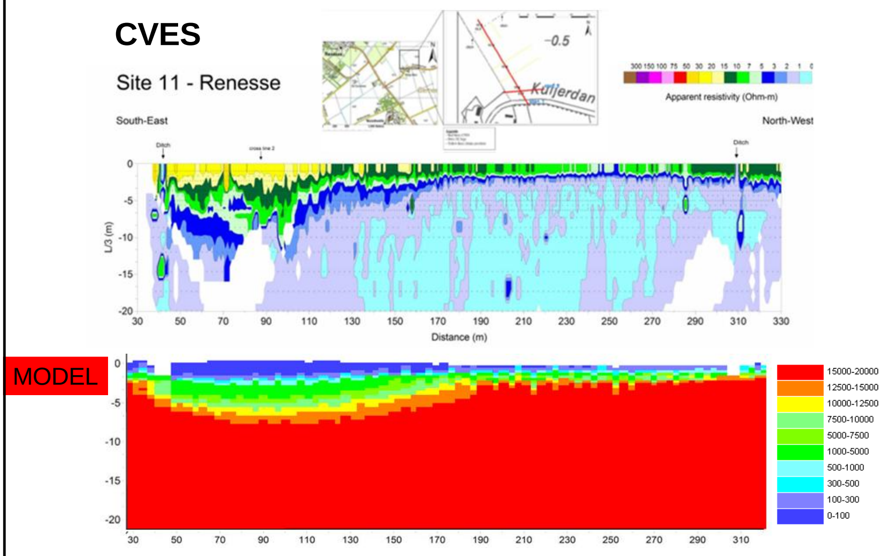
- autonomous salinisation
- sea level rise
- changing recharge pattern
- (adaption measures)



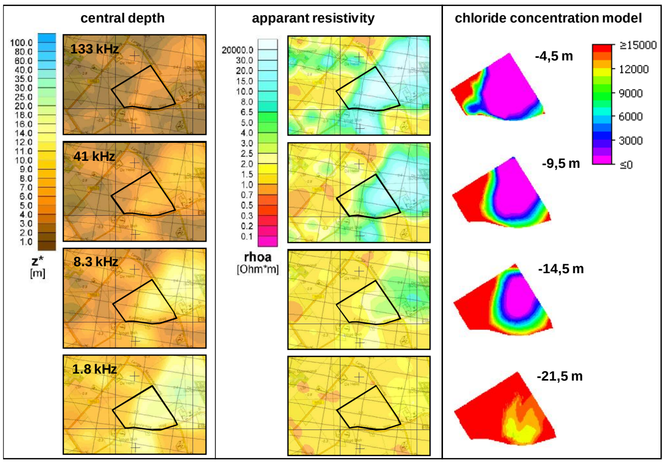
Comparison model with EM31, CVES, profiles



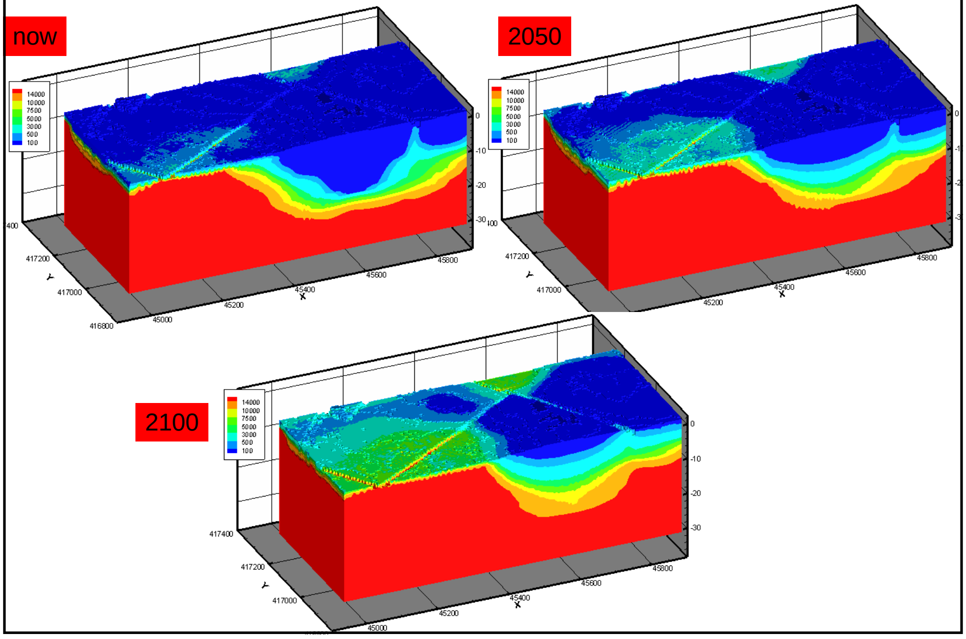
Comparison 3D model and CVES



HEM data



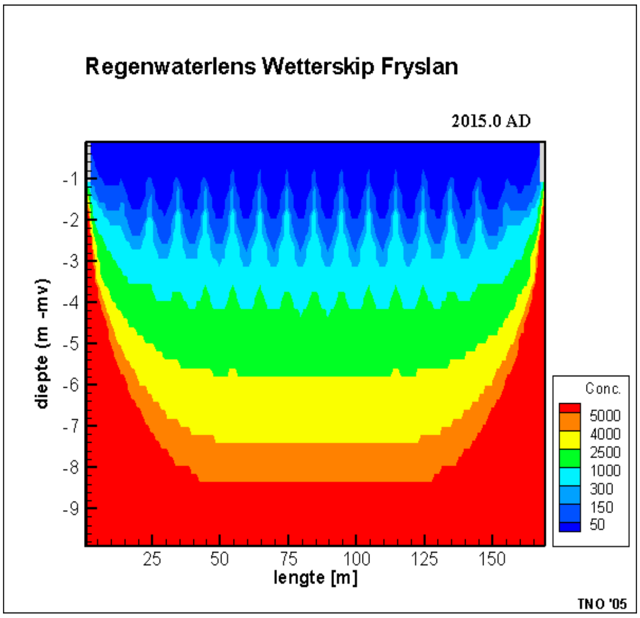
Climate change scenario (dry): model result



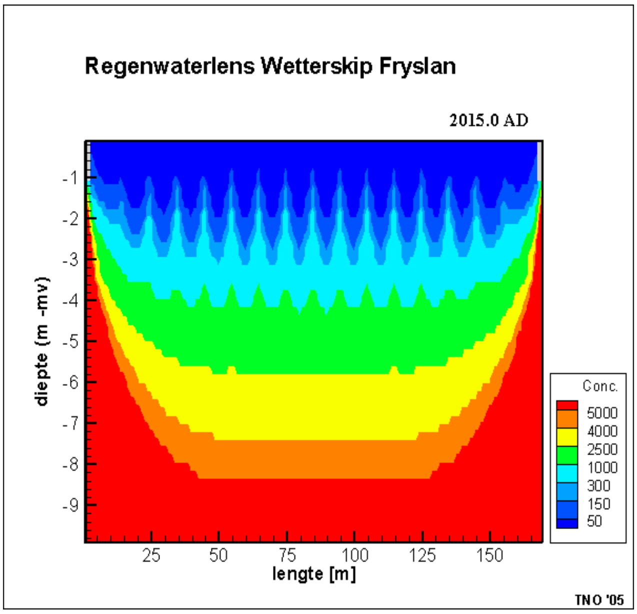
To be continued…

- 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

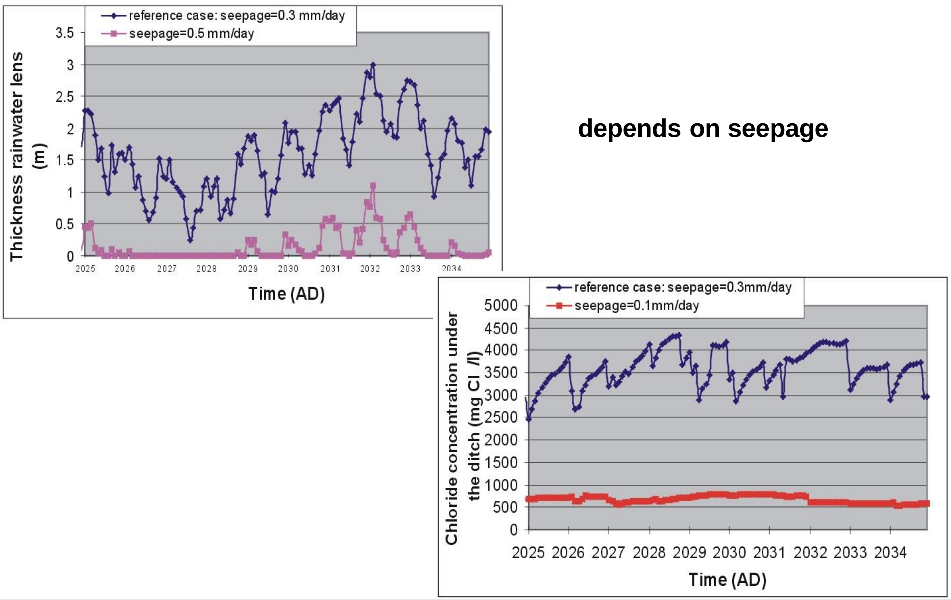
Model the dynamics of fresh-brackish-salt interface



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

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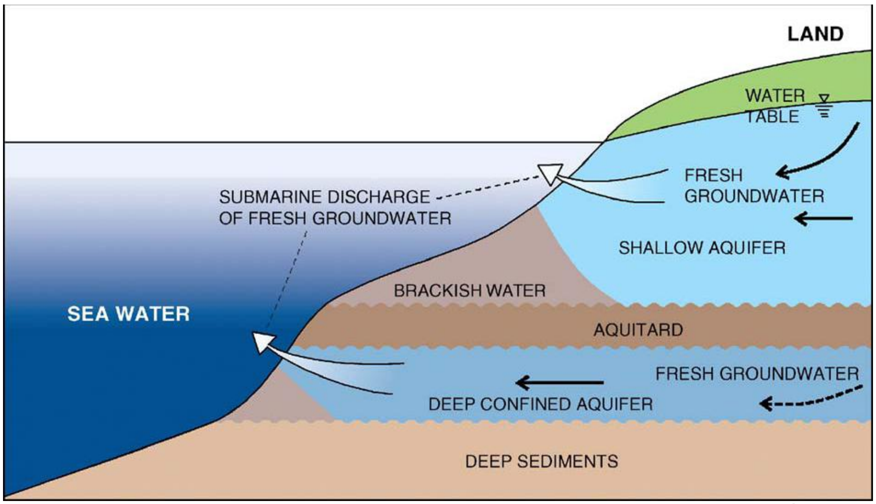
What is Submarine Groundwater Discharge (SGD)?

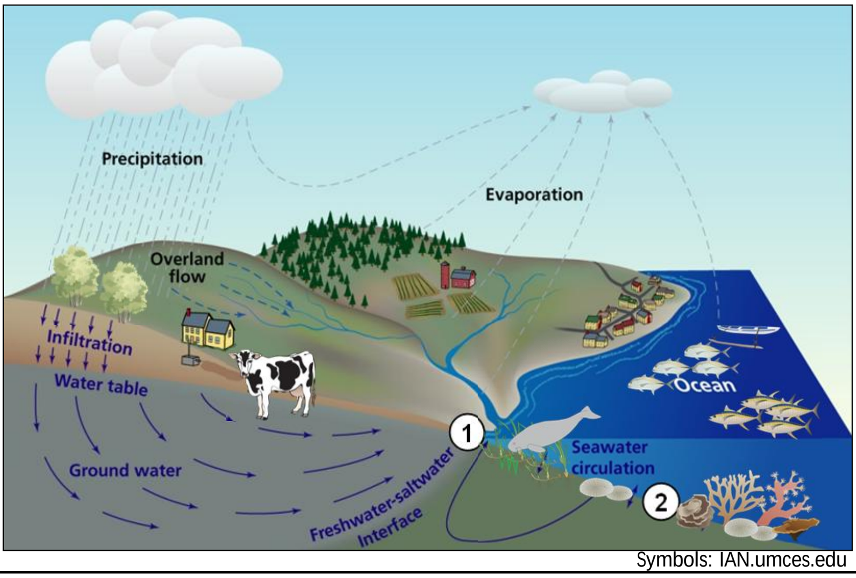
any flow of water out across the sea floor



Burnett et al, 2006

Why study SGD?

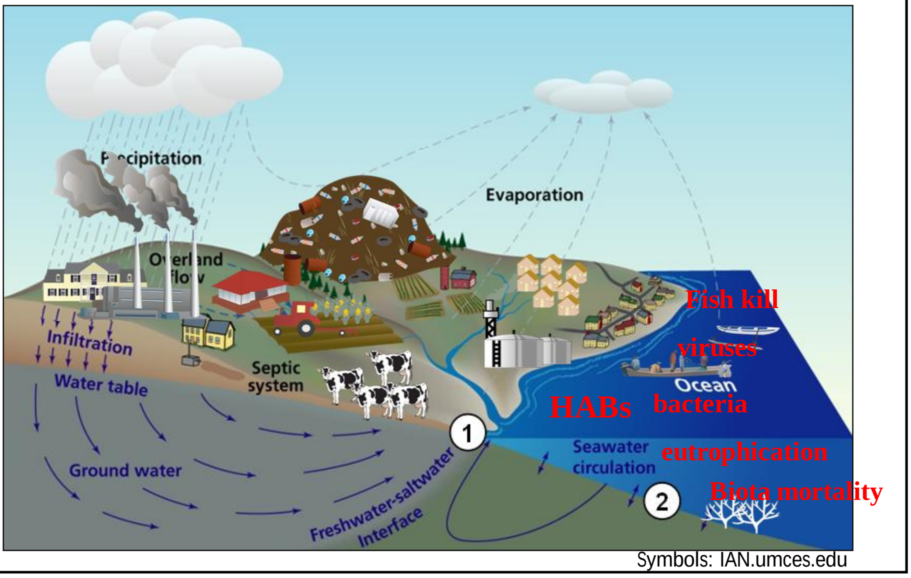
Nutrients are transported from land to sea via SGD pathway



Symbols: IAN.umces.edu

Why study SGD?

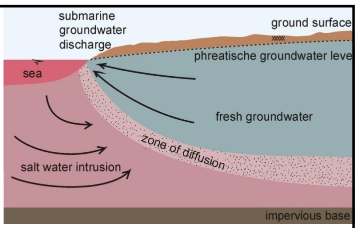
Nutrients are transported from land to sea via SGD pathway

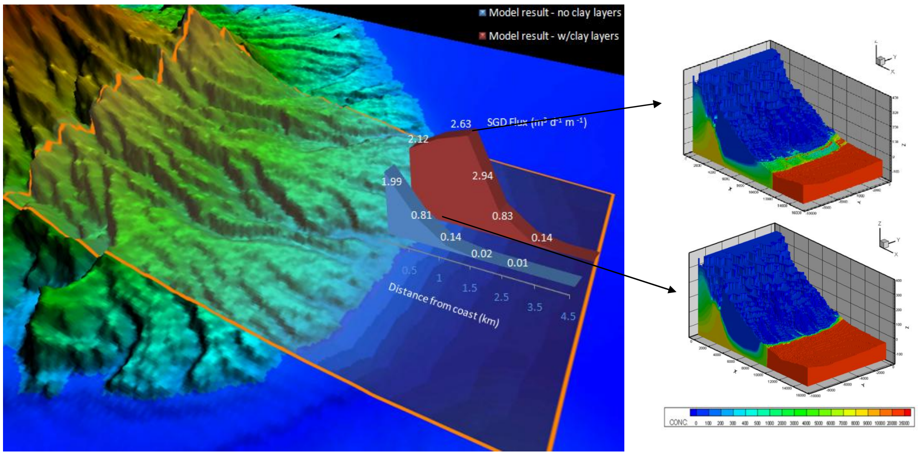


Symbols: IAN.umces.edu

Philippines

Submarine Groundwater Discharge





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

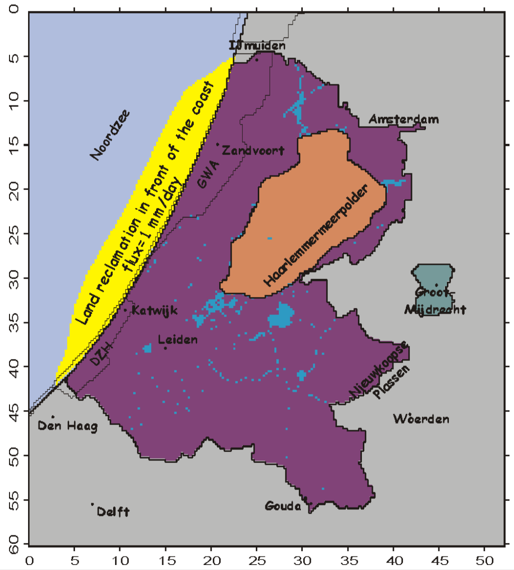
- Improve the 3D density matrix, e.g. by more types of measurements
- Implement effect of climate change and sea level rise on coastal aquifers
- Optimalisation of (ground)water management in coastal aquifers by using 3D variable-density flow models
- Improve calibration of 3D models by using transient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

Solutions

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



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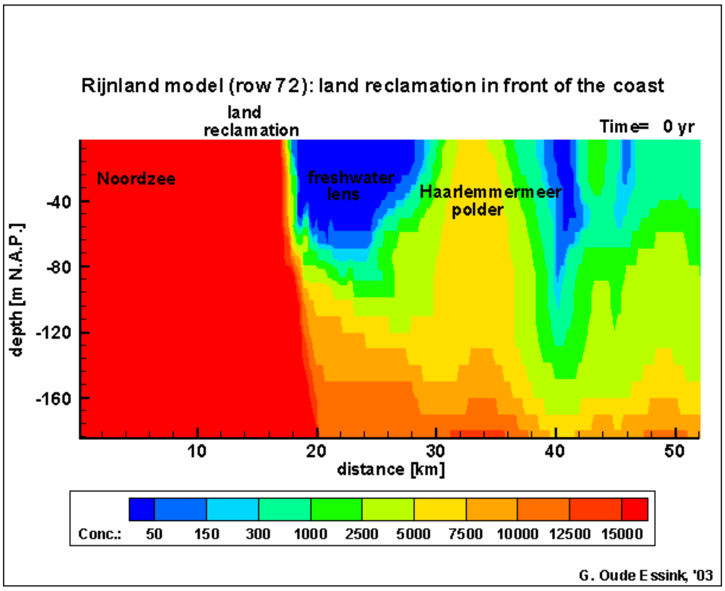
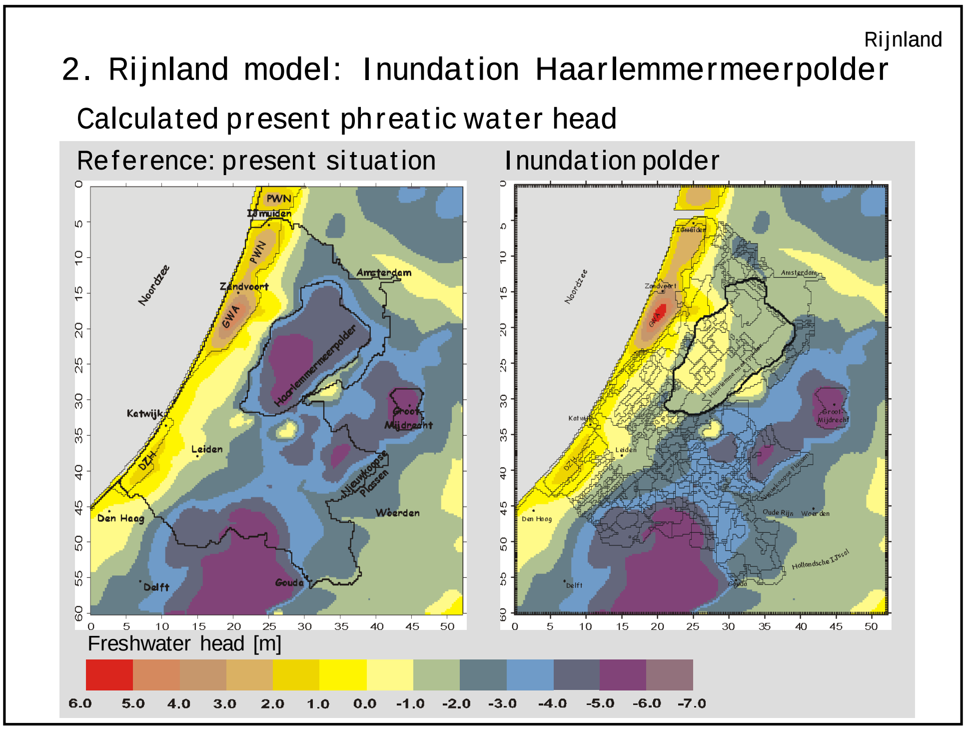
1. Land reclamation in front of the coast


Rijnland model (row 72): land reclamation in front of the coast

G. Oude Essink, '03



Rijnland

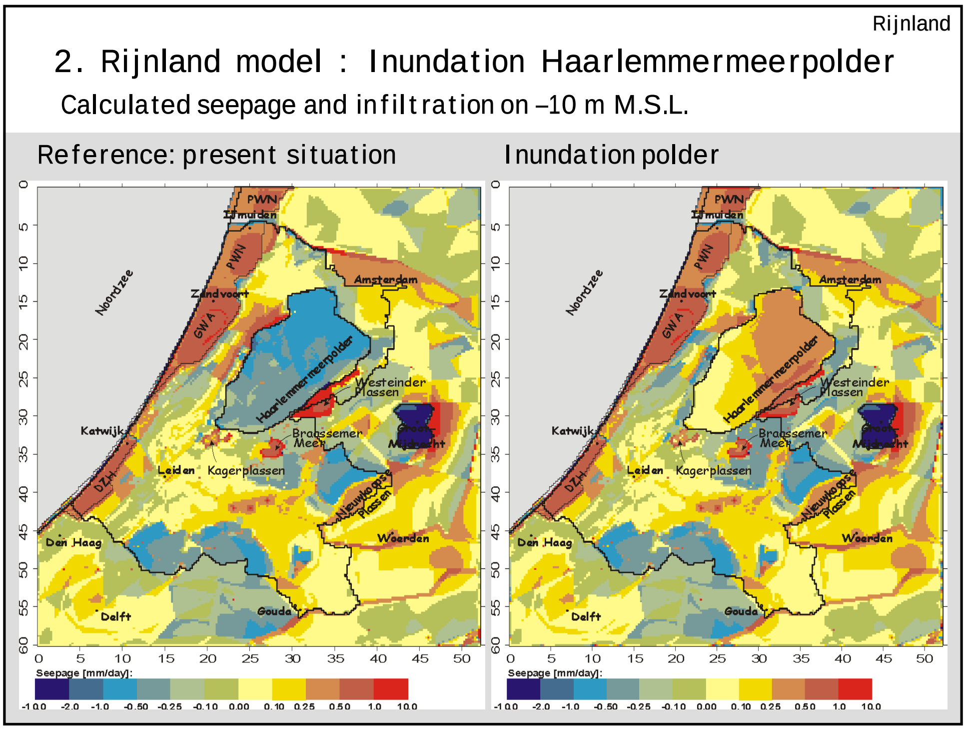
2. Rijnland model: Inundation Haarlemmermeerpolder

Calculated present phreatic water head

Reference: present situation

Inundation polder

Freshwater head [m]



Rijnland

2. Rijnland model : Inundation Haarlemmermeerpolder

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

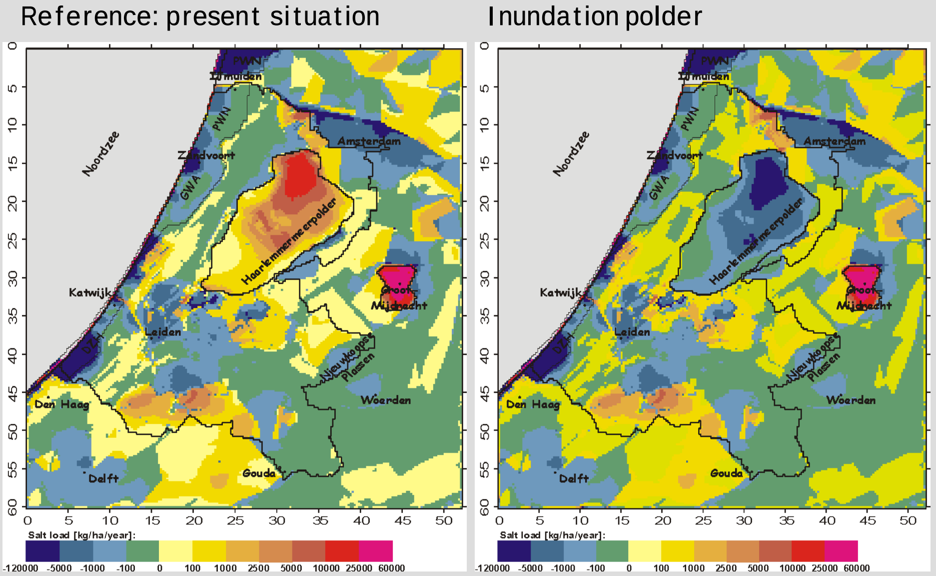
Reference: present situation

Inundation polder

Rijnland

2. Rijnland model: Inundation Haarlemmermeerpolder

Calculated salt load on –10 m M.S.L.

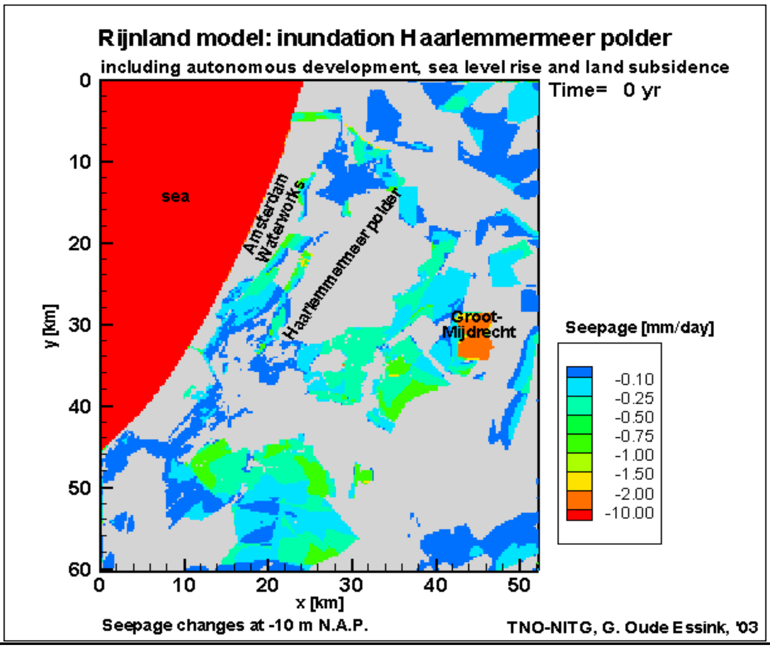


Reference: present situation

Inundation polder

Rijnland

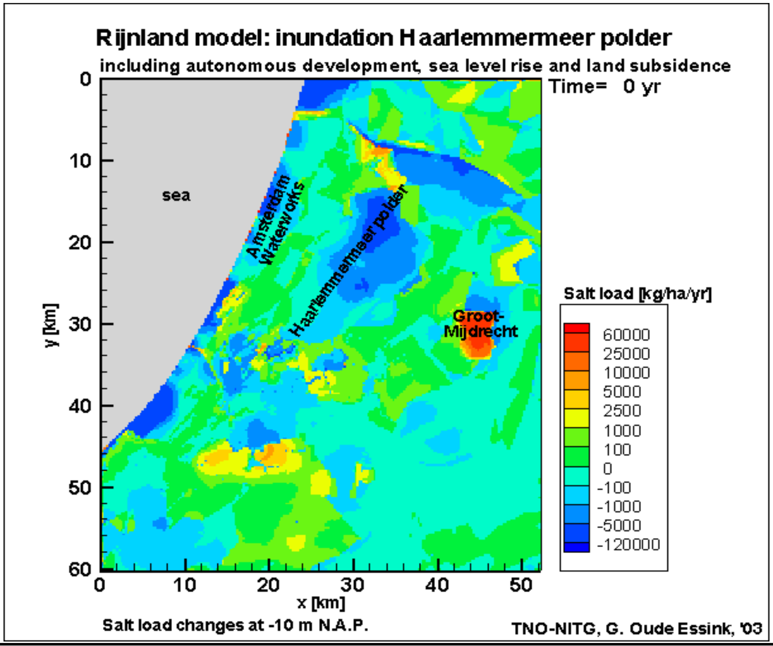
2. Rijnland model: Inundation Haarlemmermeerpolder



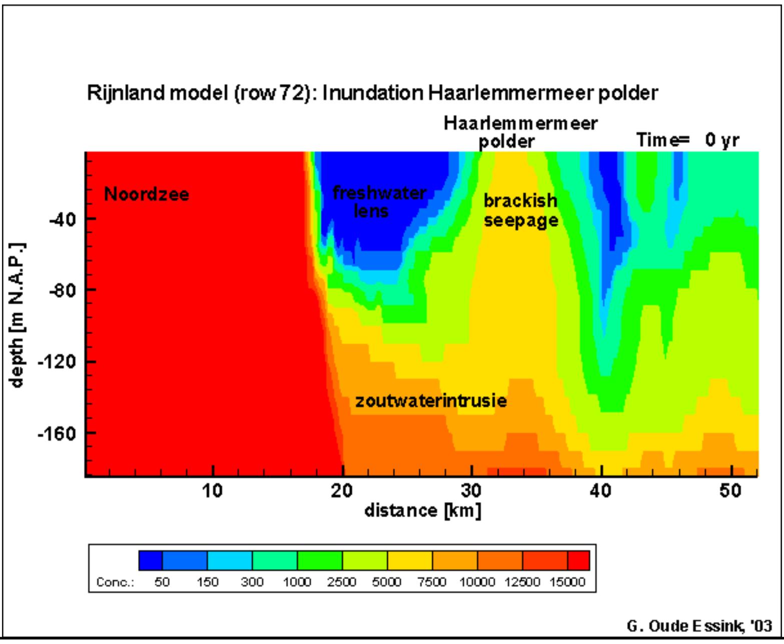
Seepage changes at -10 m N.A.P.

TNO-NITG, G. Oude Essink, '03

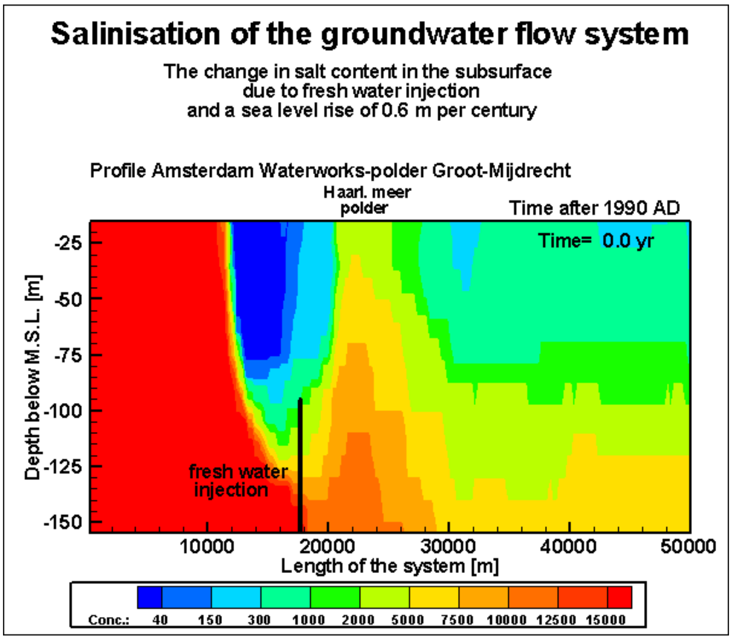
2. Rijnland model: Inundation Haarlemmermeerpolder



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



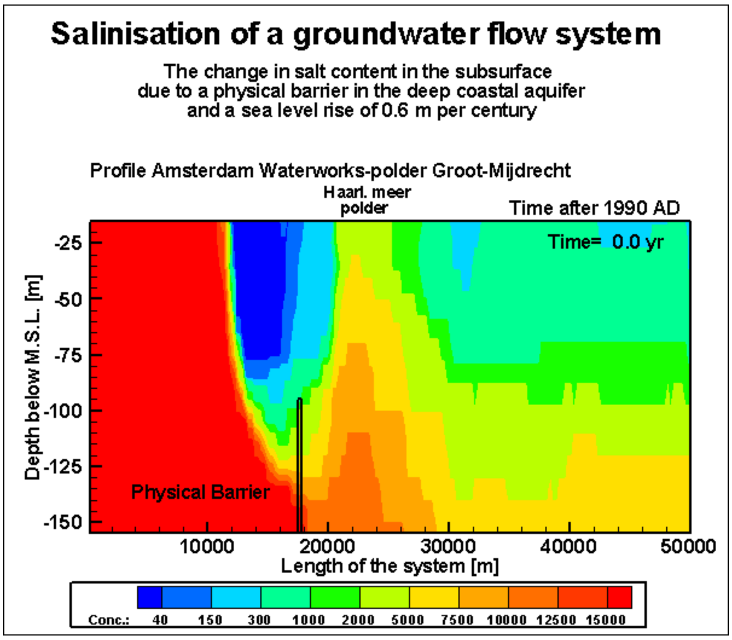
4. Injection of fresh water (conc, 1000 yr)



Salinisation of the groundwater flow system

The change in salt content in the subsurface
due to fresh water injection
and a sea level rise of 0.6 m per century

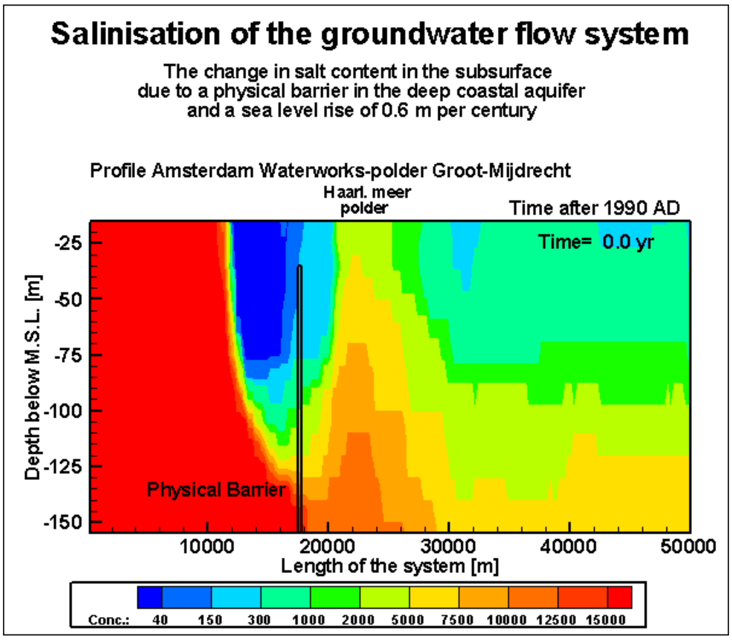
5. Physical barrier (conc, 1000 yr)



Salinisation of a groundwater flow system

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

5. Physical barrier (conc, 1000 yr)



Solute transport models

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

Solute transport equation

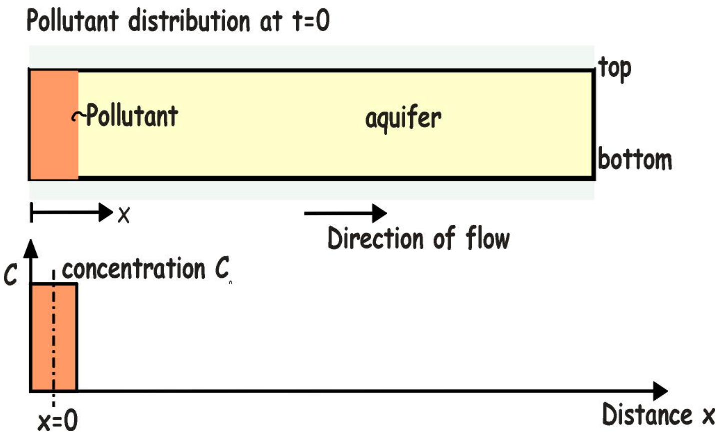
Partial differential equation (PDE):

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

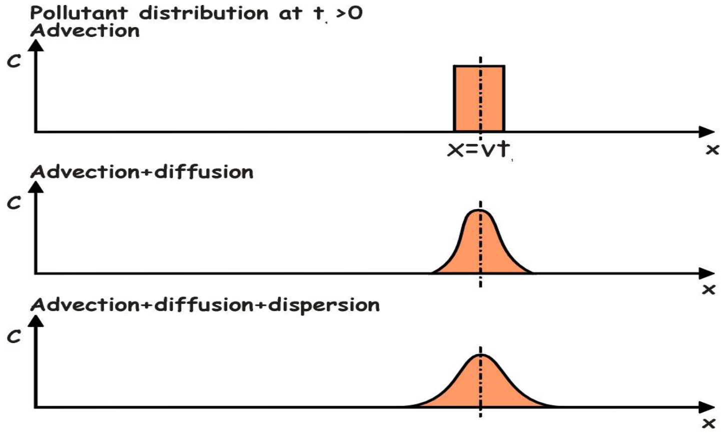
change dispersion advection source/sink decay
in concentration diffusion

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

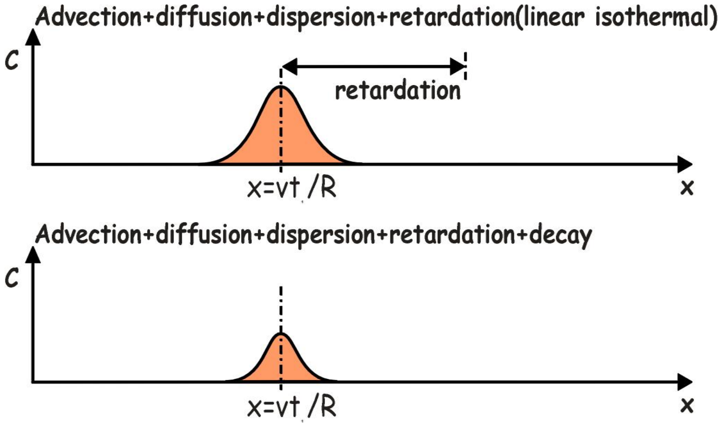
Solute transport equation: column test (I):



Solute transport equation: column test (II):



Solute transport equation: column test (III):



Advection+diffusion+dispersion+retardation(linear isothermal)

Advection+diffusion+dispersion+retardation+decay

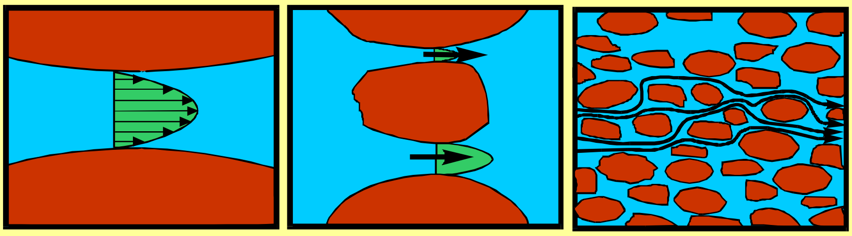
Hydrodynamic dispersion

hydrodynamic dispersion
=
mechanical dispersion+ diffusion

mechanical dispersion:
- tensor
- velocity dependant

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

Mechanical dispersion

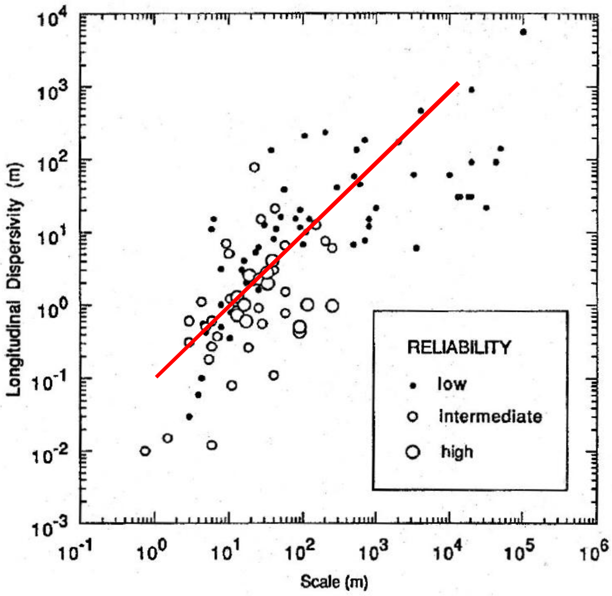


Differences in velocity in the pore

Differences in velocity due to variation in pore-dimension

Differences in velocity due to variation in velocity direction

Scale-dependency longitidinal dispersivity



modelling

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

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

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

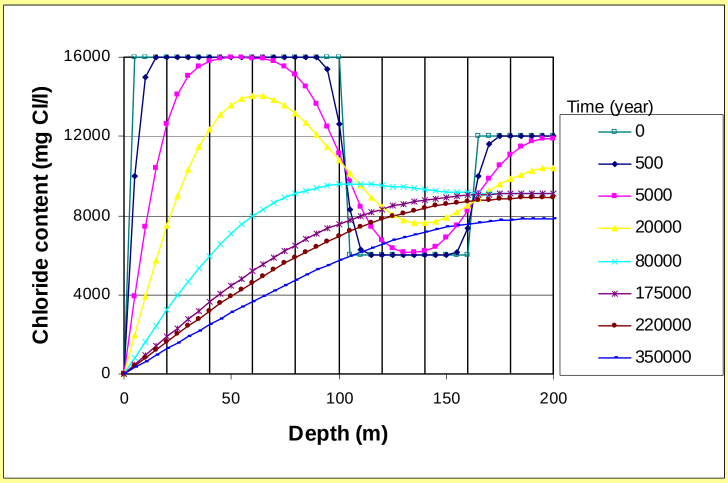
$$C_i^{t+\Delta t} = C_i^t + \frac{D\Delta t}{\Delta z^2}\left(C_{i+1}^t - 2C_i^t + C_{i-1}^t\right) \qquad \frac{D\Delta t}{\Delta z^2} < 0.5$$

---

modelling

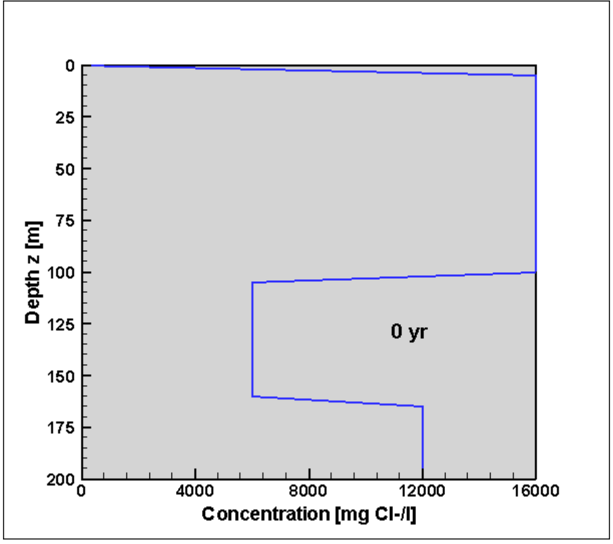
Solute transport equation: diffusion (II)

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

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

buoyancy term

Continuity

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

Freshwater head

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

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

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

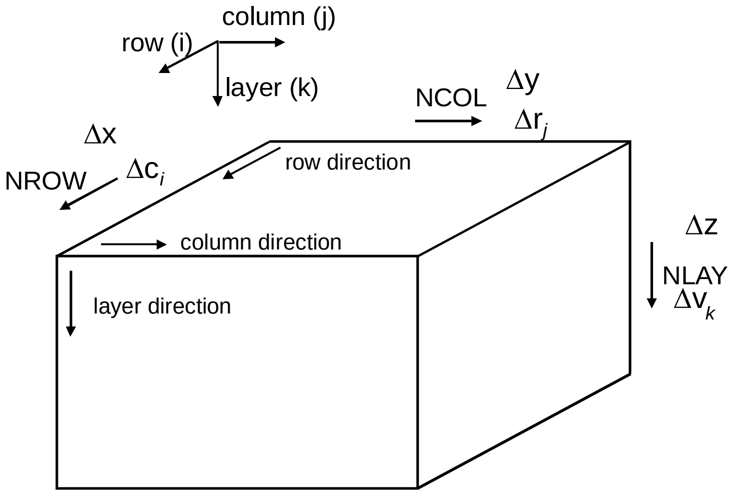
MOCDENS3D is based on MODFLOW

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

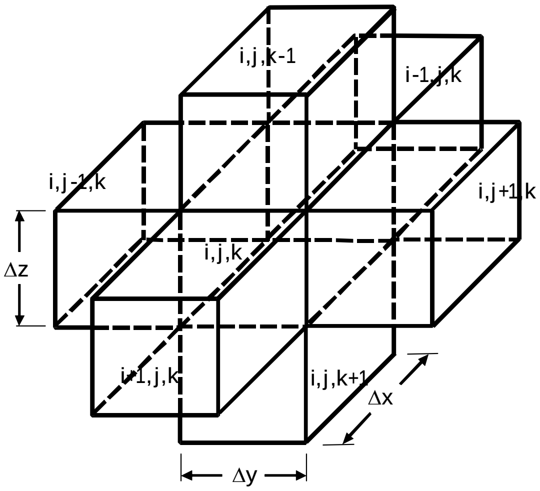
(M.G. McDonald & A.W. Harbaugh, from 1983 on)

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

Nomenclature MODFLOW element [i,j,k]



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



Continuity equation (I)

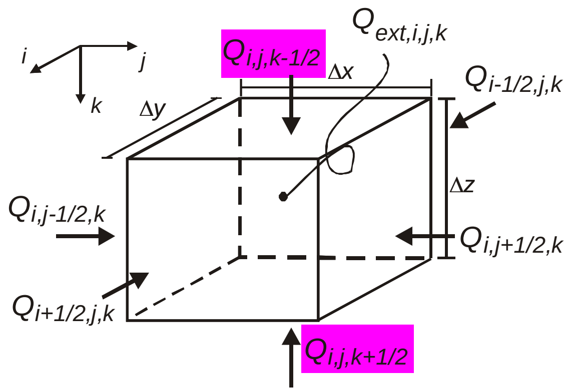
In - Out = Storage

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

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

Continuity equation (II)

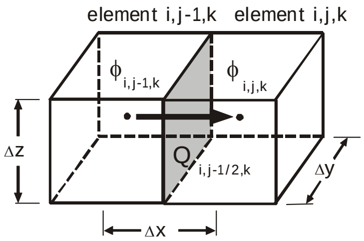
$$\sum Q_i = S_s \frac{\Delta \phi}{\Delta t} \Delta V$$



In = positive

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

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

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

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

$$Q_z = surface * q_z$$

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

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

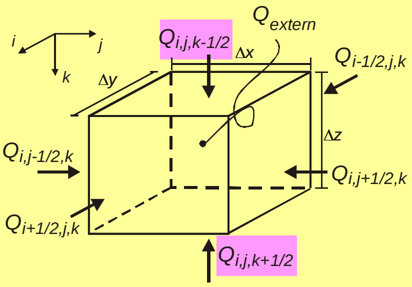
$$Q_{i,j,k-1/2} = CV_{i,j,k-1/2}\left(\phi_{f,i,j,k-1} - \phi_{f,i,j,k} + BUOY_{i,j,k-1/2}\Delta z\right)$$

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:

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

$with:$

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

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

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

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

MOCDENS3D

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

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

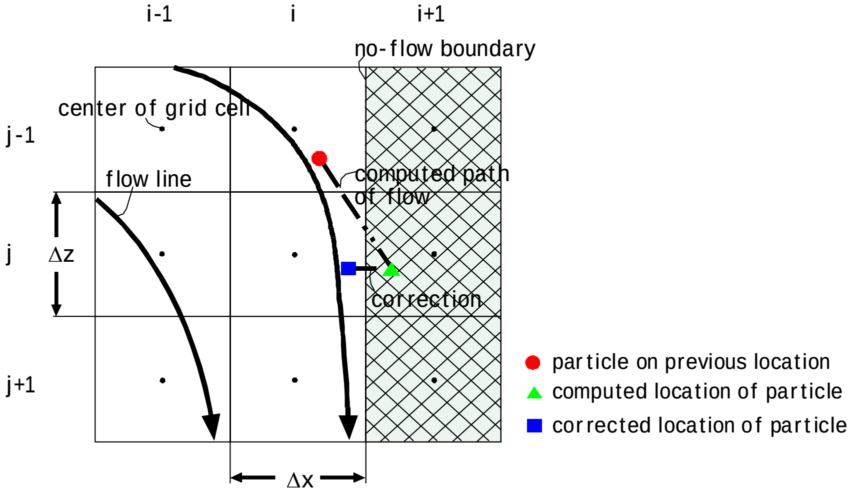
Konikow and Bredehoeft, 1978

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

MOC3D

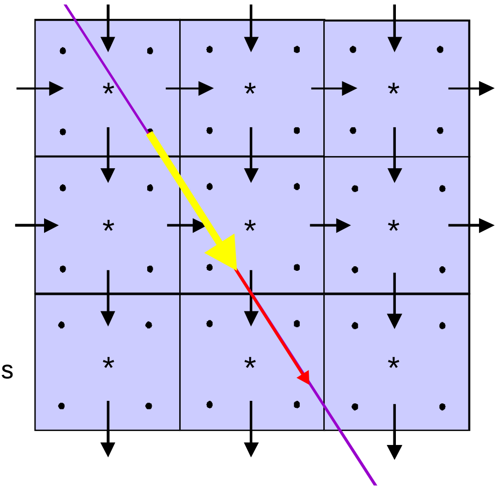
Reflection in boundary



MOC3D

Stability criteria (I I I)

3. Courant criterium



- * Node element
- • Particle

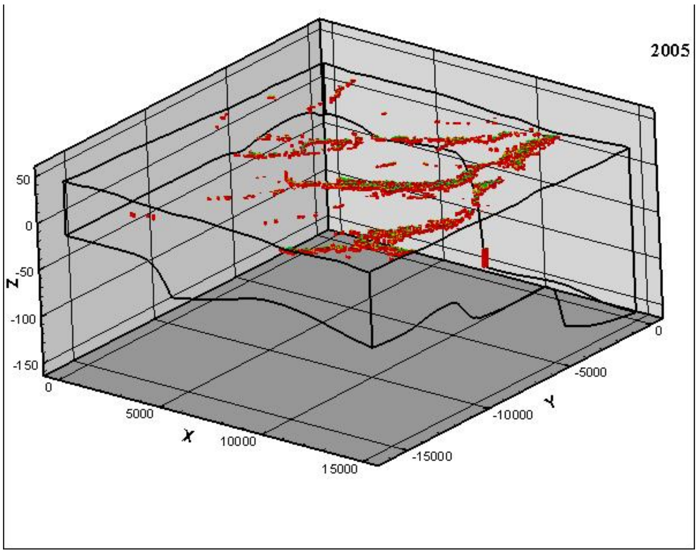
╲ Velocity direction

↘ Movement particles

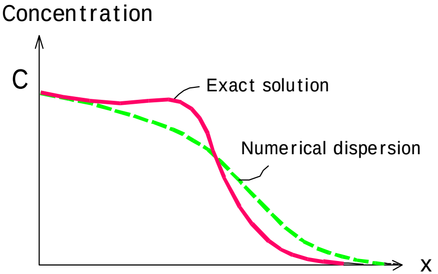
$0<\xi<=\sim1$

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

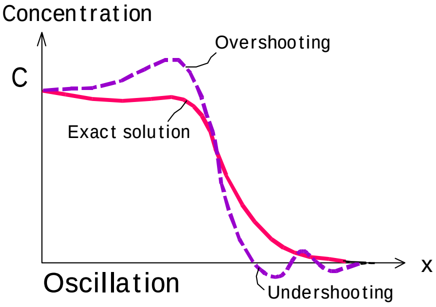
Courant criterion: places where timestep is smaller than 40 days



Numerical dispersion and oscillation



Numerical dispersion



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!!

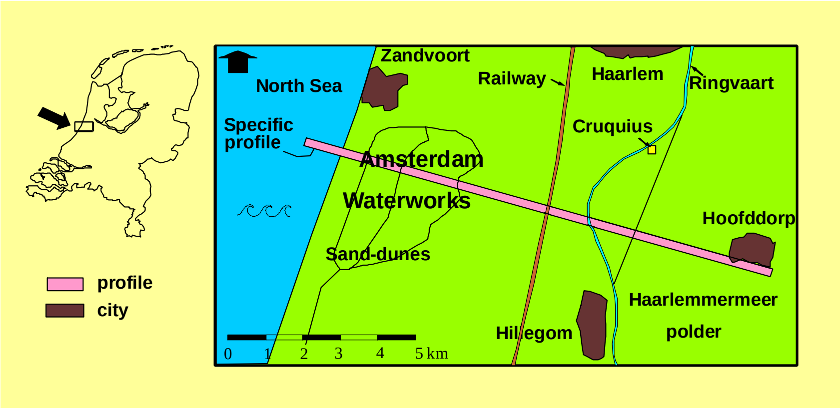
Numerical dispersion problem (III)

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

---

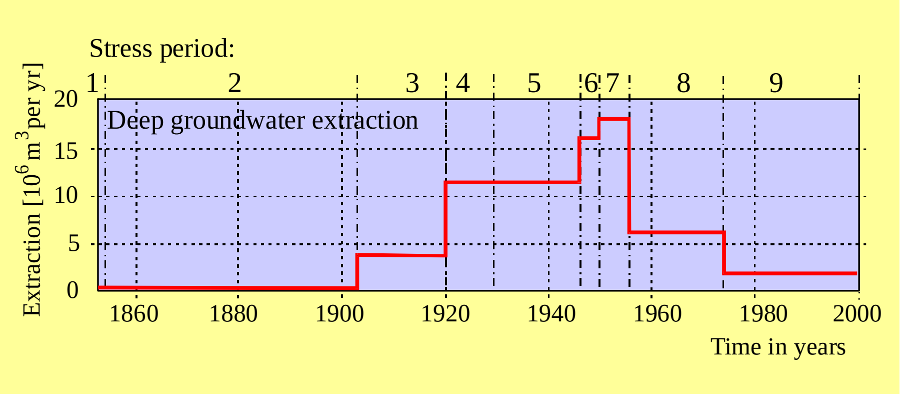
Effect of α_L on the salinisation of the aquifer (I)

Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



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

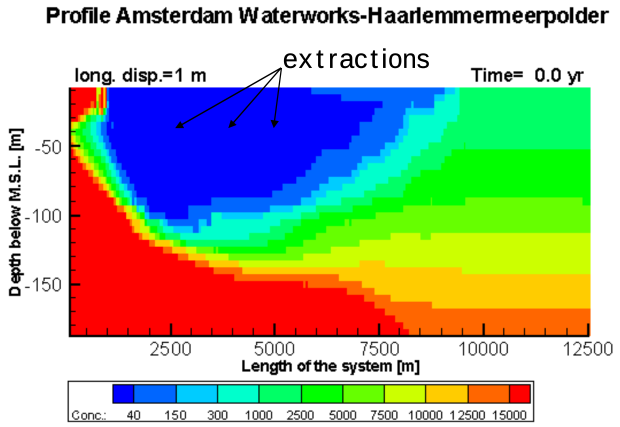
Grondwater extractions out of the middle aquifer in the sand-dune area of Amsterdam Waterworks



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

α_L=1 m

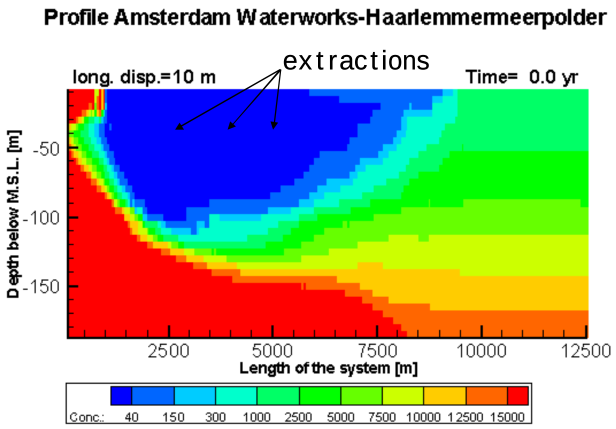
Initial situation: 154 years ago



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

α_L=10 m

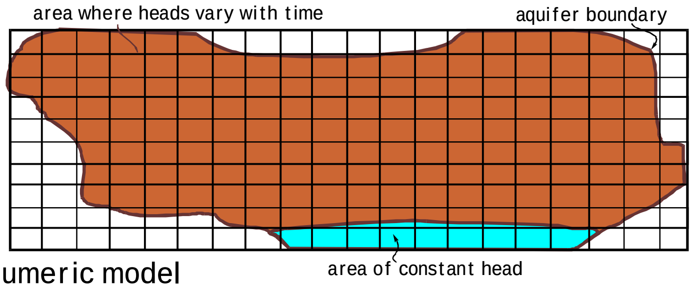
Initial situation: 154 years ago



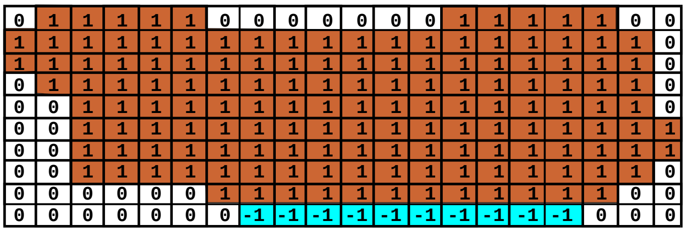
MODFLOW

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

---

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:

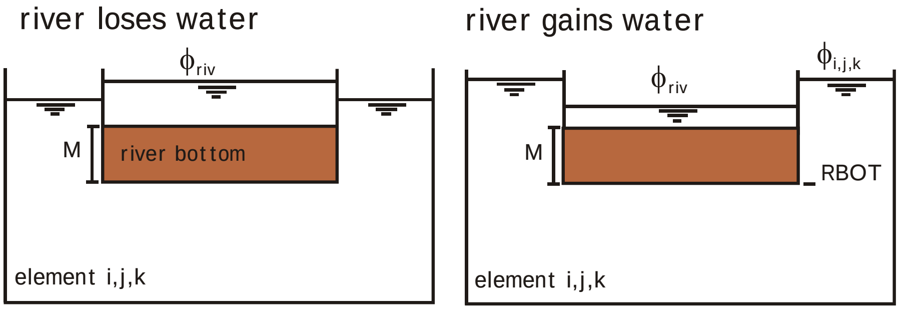
$$Q_{ext,i,j,k} = P_{i,j,k}\phi^{t+\Delta t}_{i,j,k} + Q'_{i,j,k}$$

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

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

MODFLOW

2. River package (I)


river loses water

river gains water

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

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

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:

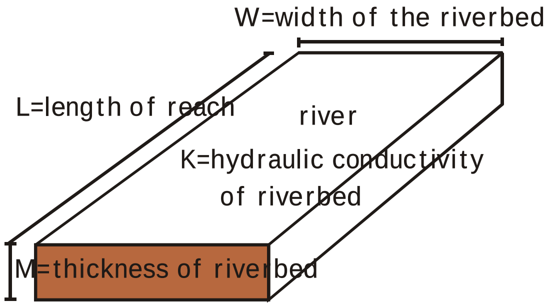
$$Q_{ext,i,j,k} = P_{i,j,k}\phi_{i,j,k}^{t+\Delta t} + Q'_{i,j,k}$$

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

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

2. River package (III)

Determine the conductance of the river in one element:

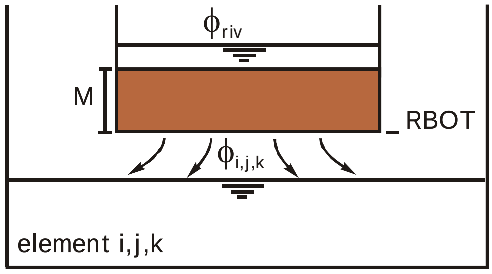


where $C_{riv} = \dfrac{KLW}{M}$ is the conductance [L^2/T] of the river

---

2. River package (IV)

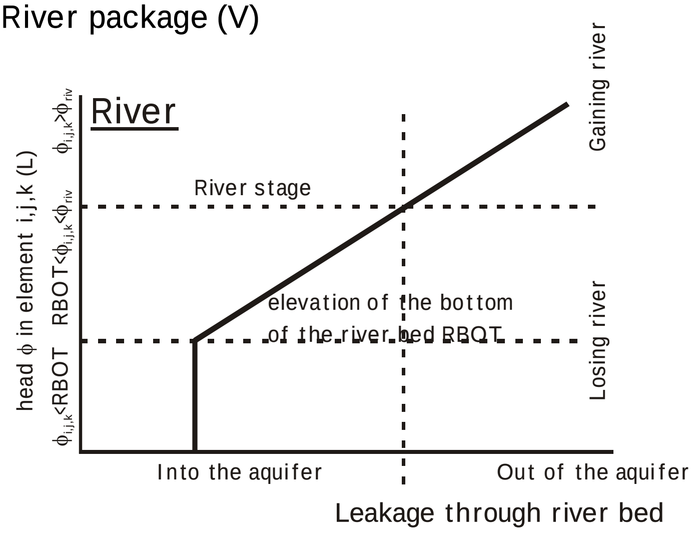
Leakage to the groundwater system



Special case:

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

2. River package (V)



---

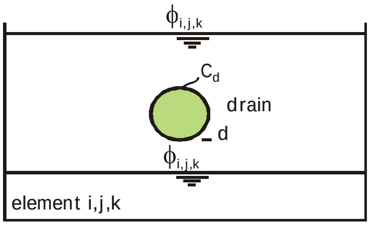
3. Recharge package

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

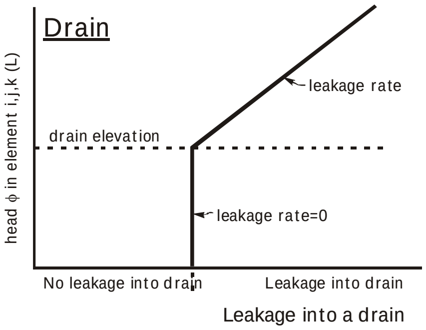
4. Drain package

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

Special case:



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



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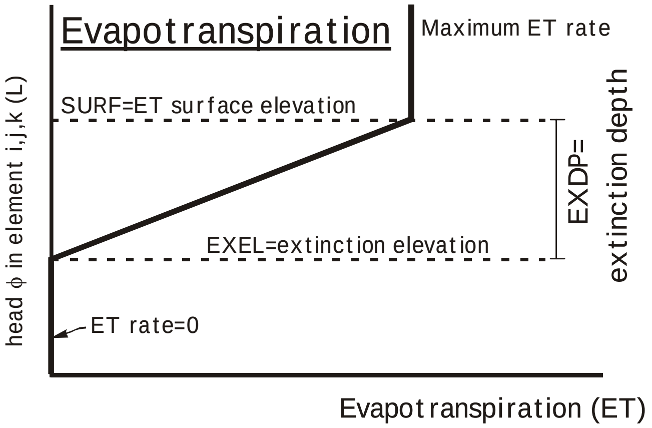
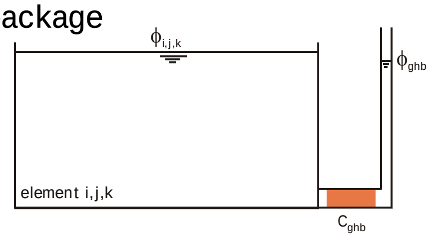
5. Evapotranspiration package

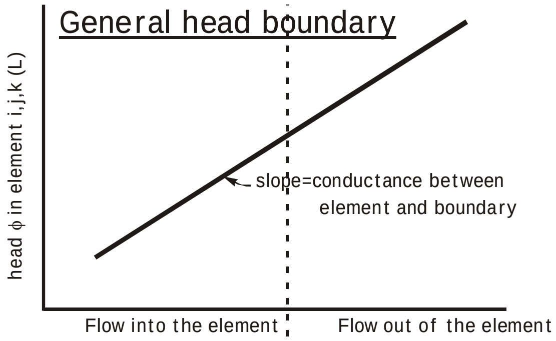


MODFLOW

6. General head boundary package

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





Flow to a general head boundary

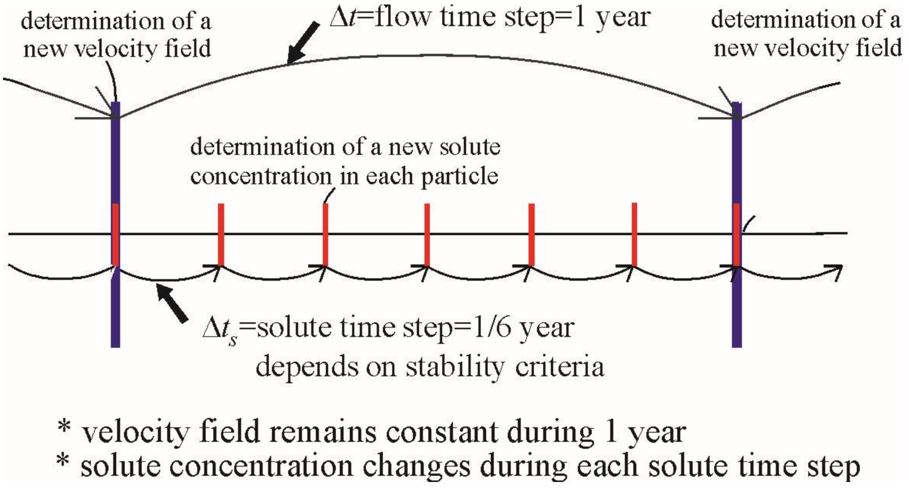
---

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

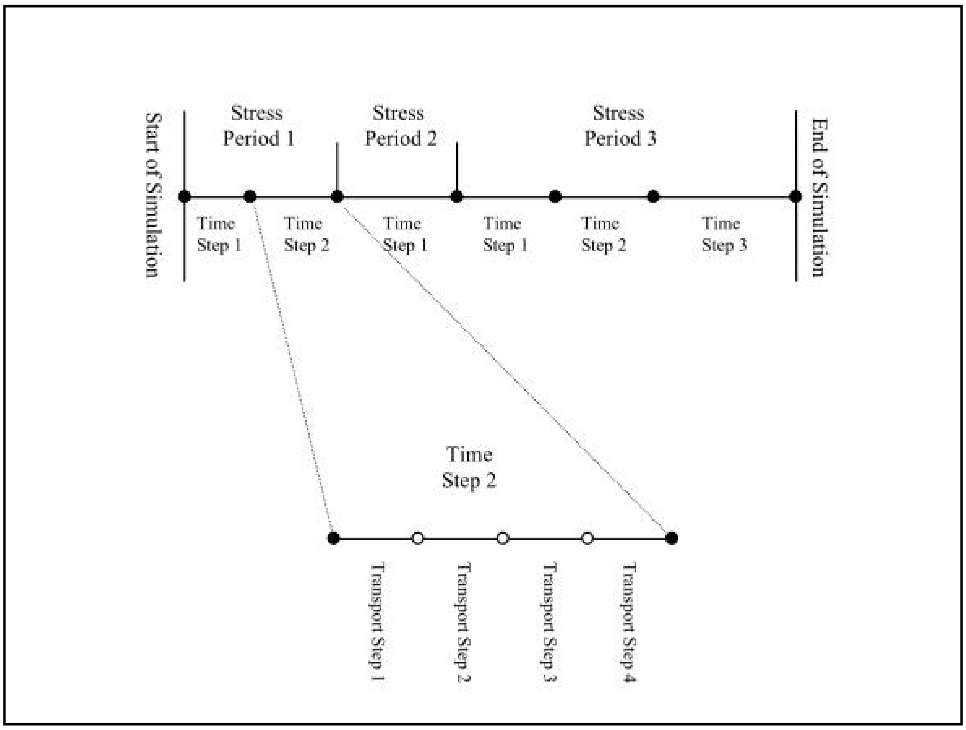
Time indication MODFLOW

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

Flow time step and solute time step



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


Start of Simulation
Stress Period 1
Stress Period 2
Stress Period 3
End of Simulation
Time Step 1
Time Step 2
Time Step 1
Time Step 1
Time Step 2
Time Step 3
Time Step 2
Transport Step 1
Transport Step 2
Transport Step 3
Transport Step 4