IHE 2018

Density dependent groundwater flow in the coastal zone

Gualbert Oude Essink, PhD

Lecture set-up:

- PowerPoint sheets
- Lecture Notes
- Practicals numerical modelling

http://freshsalt.deltares.nl

Deltares
Unit Subsurface and Groundwater Systems
gualbert.oudeessink@deltares.nl

13-14-15 June 2018

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

http://freshsalt.deltares.nl

Deltares: gualbert.oudeessink@deltares.nl

Colleagues at Deltares
Groundwater in the Coastal Zone

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


Gualbert Oude Essink


Joost Delsman


Pieter Pauw


Perry de Louw


Esther van Baaren


Jarno Verkaik


Marta Faneca

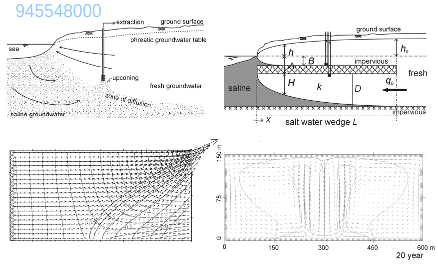
Research on groundwater in the coastal zone

- 18 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

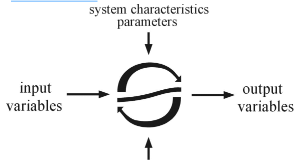
1. Density dependent groundwater flow

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



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

Practicals numeriacl modelling

- PMWIN
- SEAWAT
- Cases:
  - Rotating sharp interface
  - Freshwater lens
  - Henry's case
  - (Elder's case)
- Setup practicals:
  - work in small groups of two persons
  - short report of findings (make screenshots)
  - deliver within one week after finish last lectures

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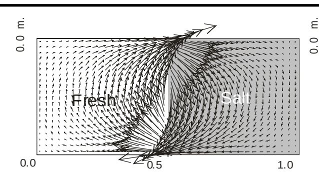
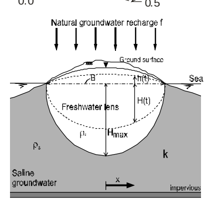
Practicals

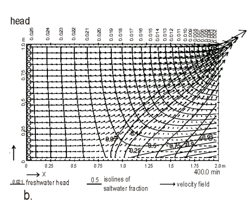
- Rotating sharp interface



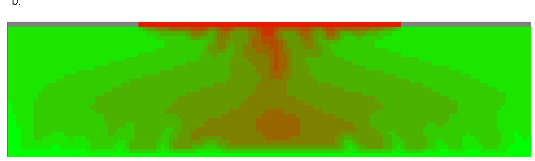
- Freshwater lens



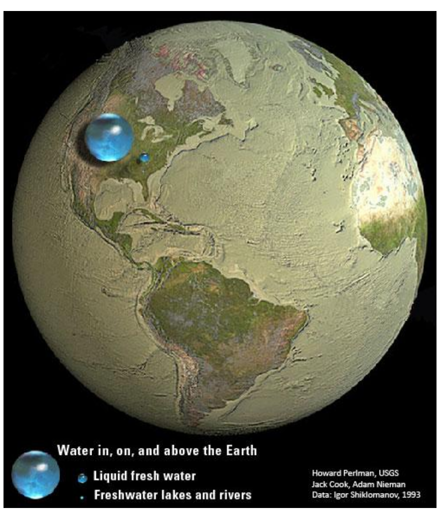
- Henry's case

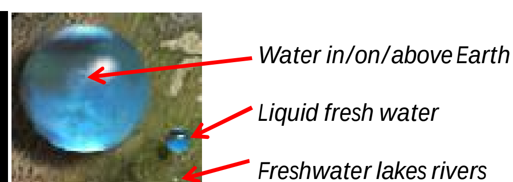


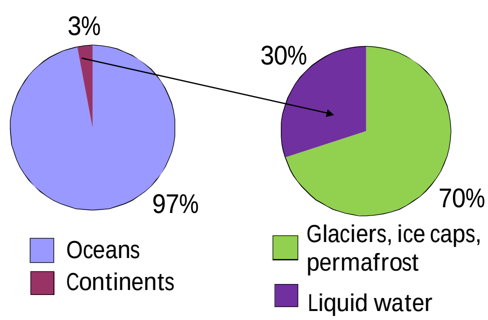
- (Elder's case)



Volumes of water on Earth: a scarce product



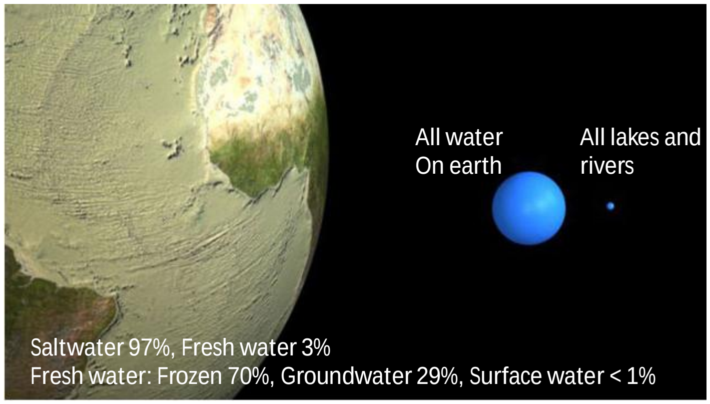




Source: Perlman, USGS; Shiklomanov, 1993

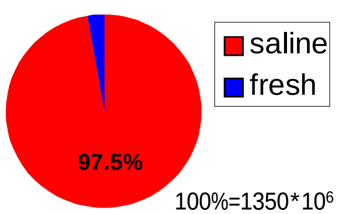
Water Energy Food Nexus
Global water scarcity

Fresh water is a scarce resource…



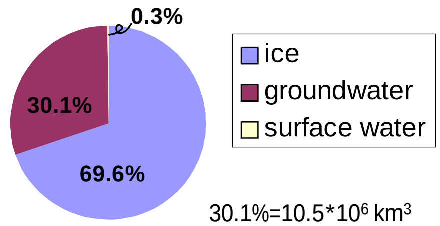
Water on Earth

Total water on Earth



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

Total fresh water on Earth



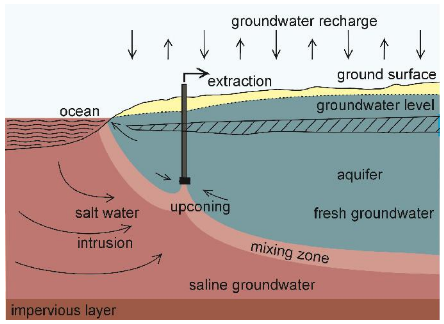
$30.1\% = 10.5 * 10^6\ km^3$

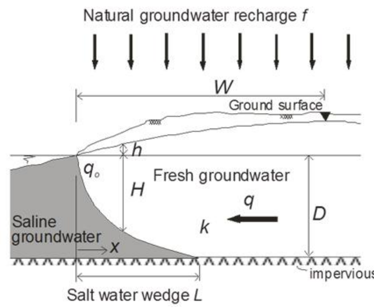
Demand for groundwater (now 30%) increases due to:

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

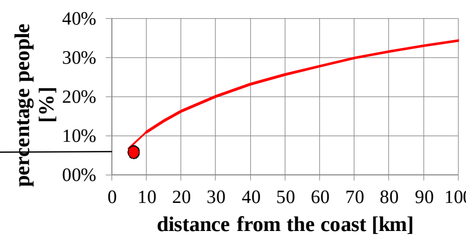
(Source: Cheng, 1998)

Groundwater in the coastal zone





500 million people in the first 5km from the coastline

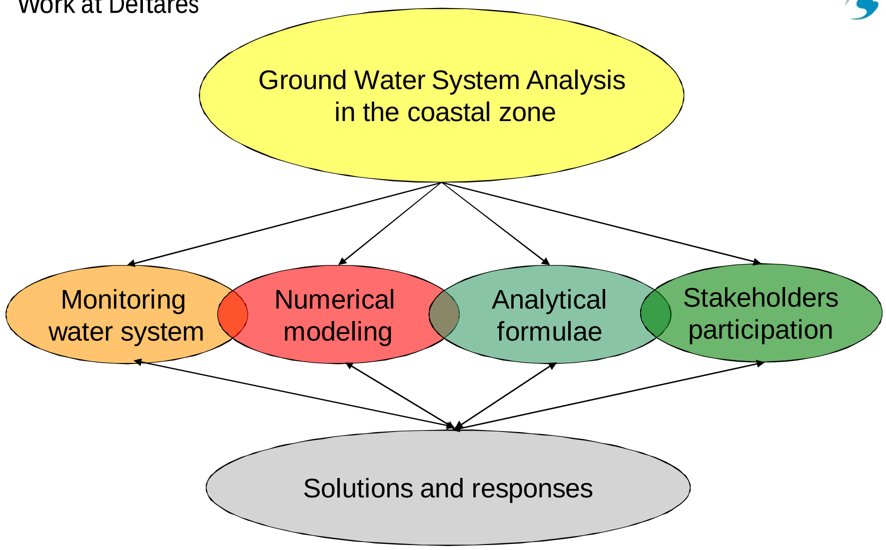


Topics of density driven groundwater flow

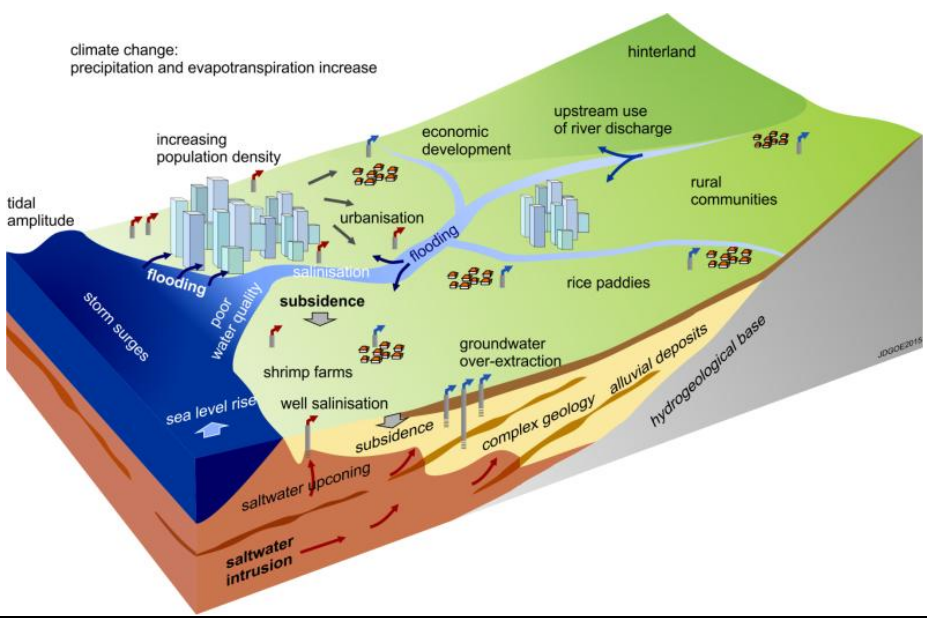
1. Introduction
   - water on earth
   - salt water intrusion
   - freshwater head
2. Interface between fresh and saline groundwater
   - analytical formulae (Badon Ghyben-Herzberg)
   - upconing example
3. Numerical modelling
   - mathematical background
   - Benchmark problems: Henry, Elder, Hydrocoin,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

Deltares
Enabling Delta Life

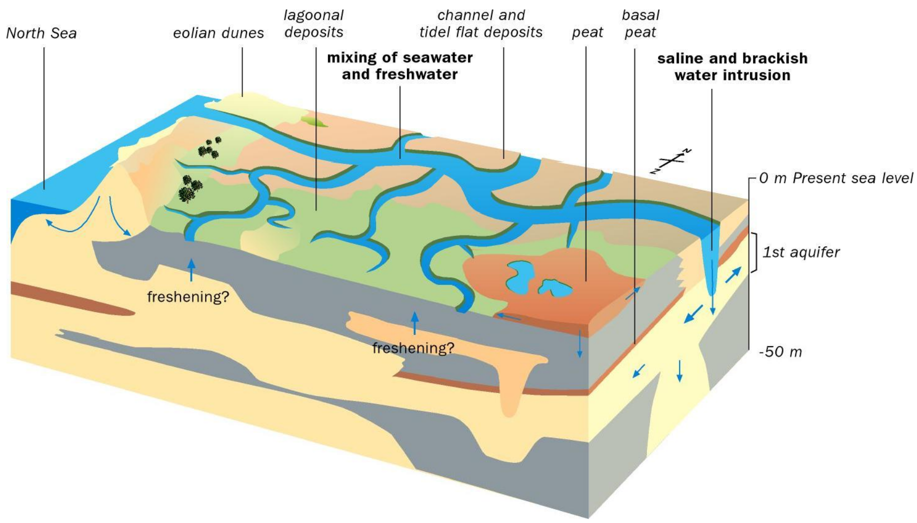
Work at Deltares



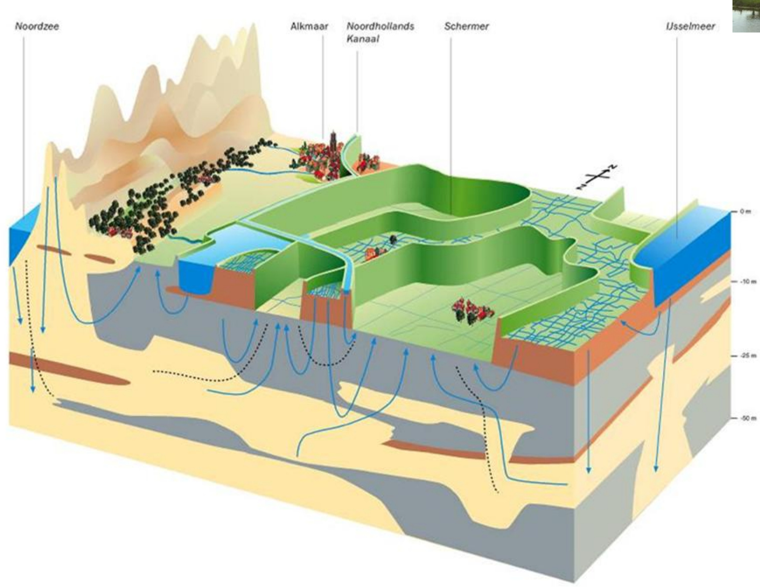
Groundwater issues in the coastal zone/deltaic areas



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)

Home | History | Philosophy | Next meeting | Proceedings | Links

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

www.swim-site.org

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

Salt Water Intrusion Meeting (SWIM)

Home | History | Philosophy | Next meeting | Proceedings | Links

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

www.swim-site.org

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

Salt Water Intrusion Meeting (SWIM)

Home | History | Next meeting | Proceedings | Links | About this site

Back to all proceedings

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

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Preface

A.D. Werner

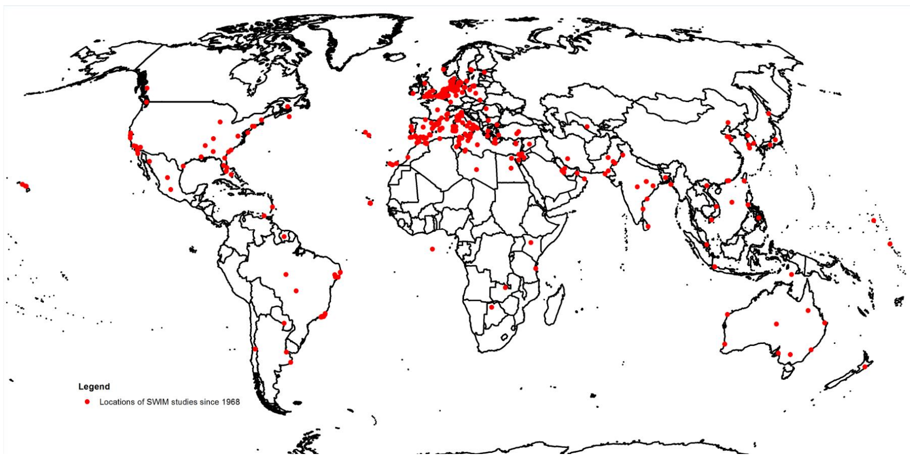
Posters

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

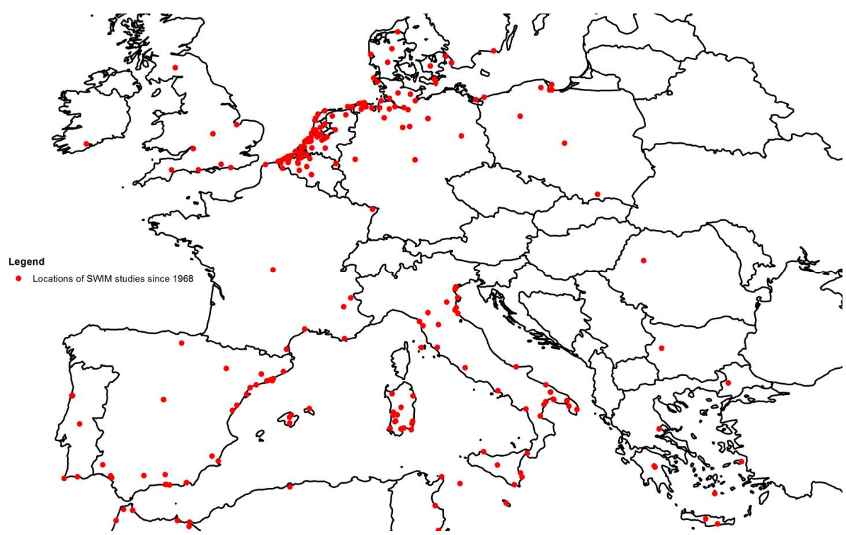
Session 1 - Managing Coastal Groundwater I

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



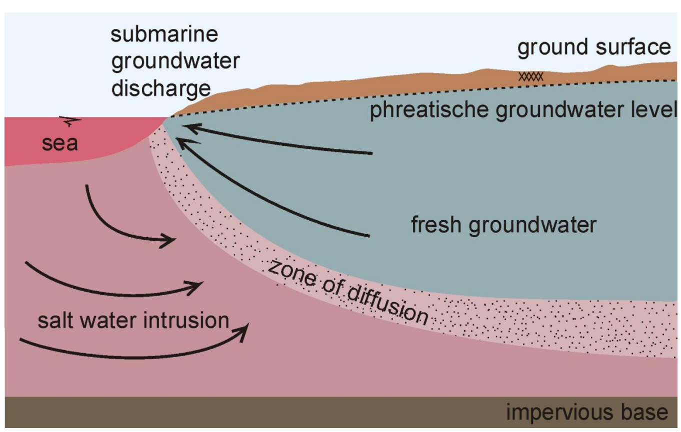
Location of SWIM studies since 1968



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

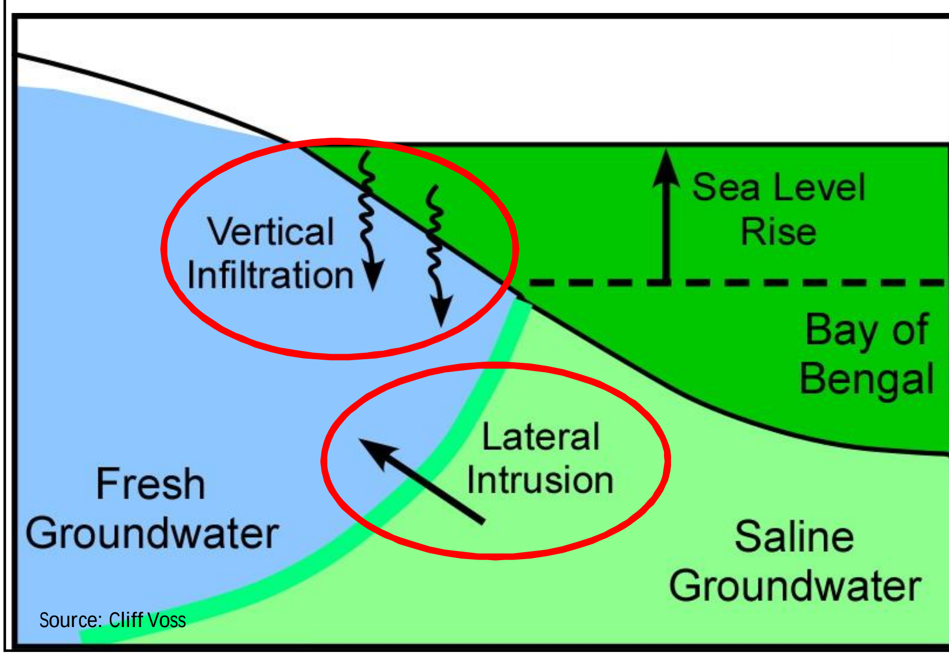
Anthropogenic causes:

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

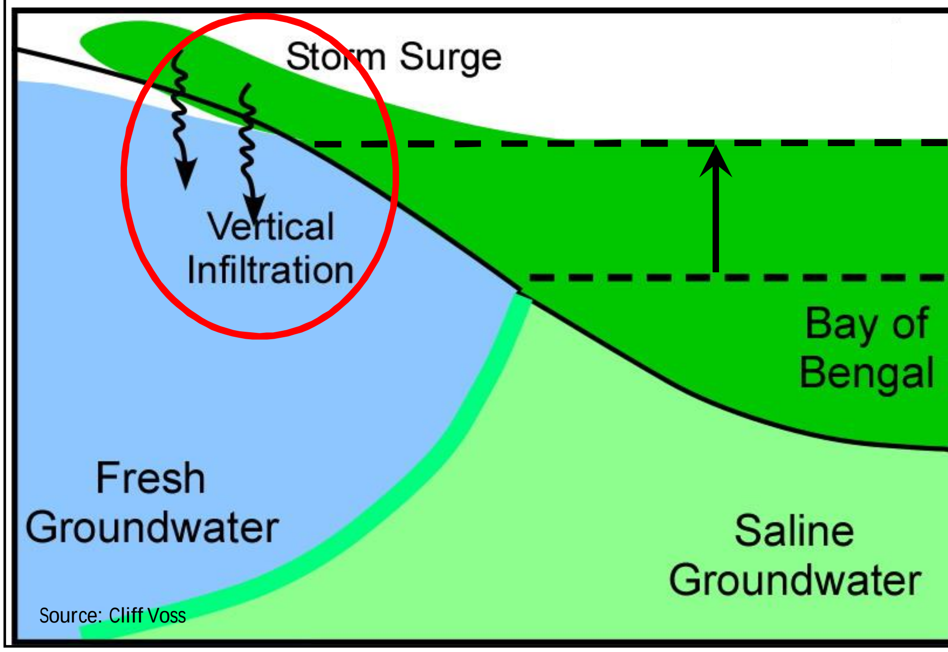
-upconing under extraction wells throughout the world

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

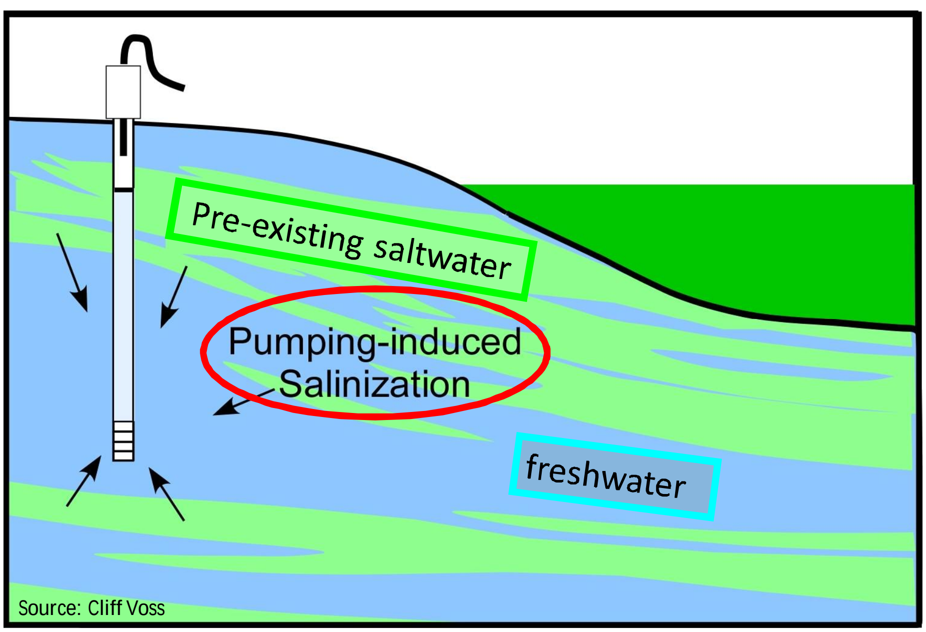
Modes of Salinization due to Sea-Level Rise



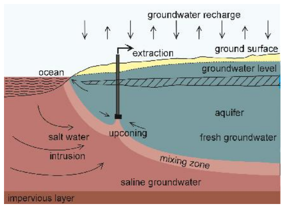
Modes of Salinization due to Sea-Level Rise



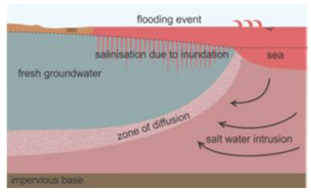
Salinization due to Pumping



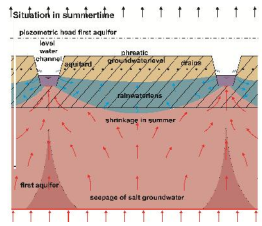
Salinisation processes at local scale



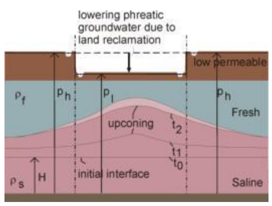
Salt water intrusion groundwater



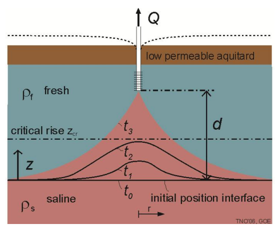
Inundation saline seawater



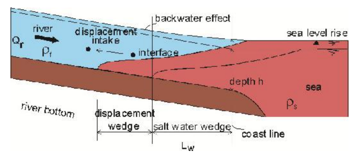
Shallow rainwaterlens



Upconing low-lying area



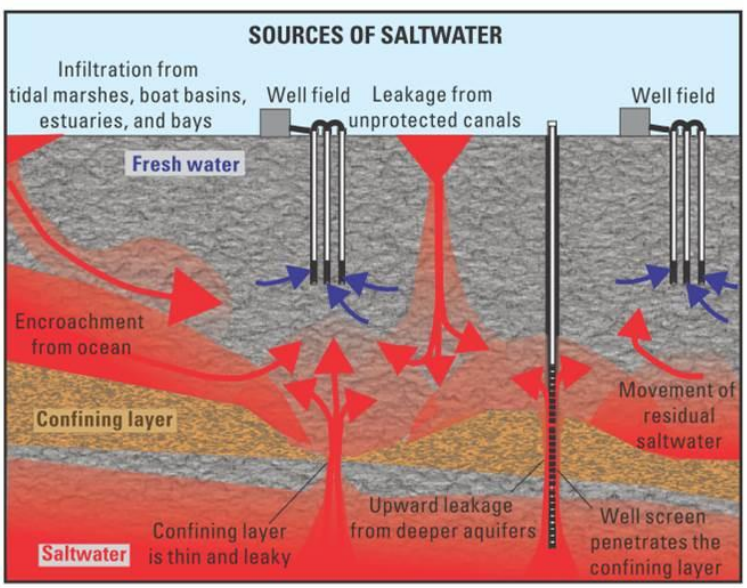
Upconing extraction

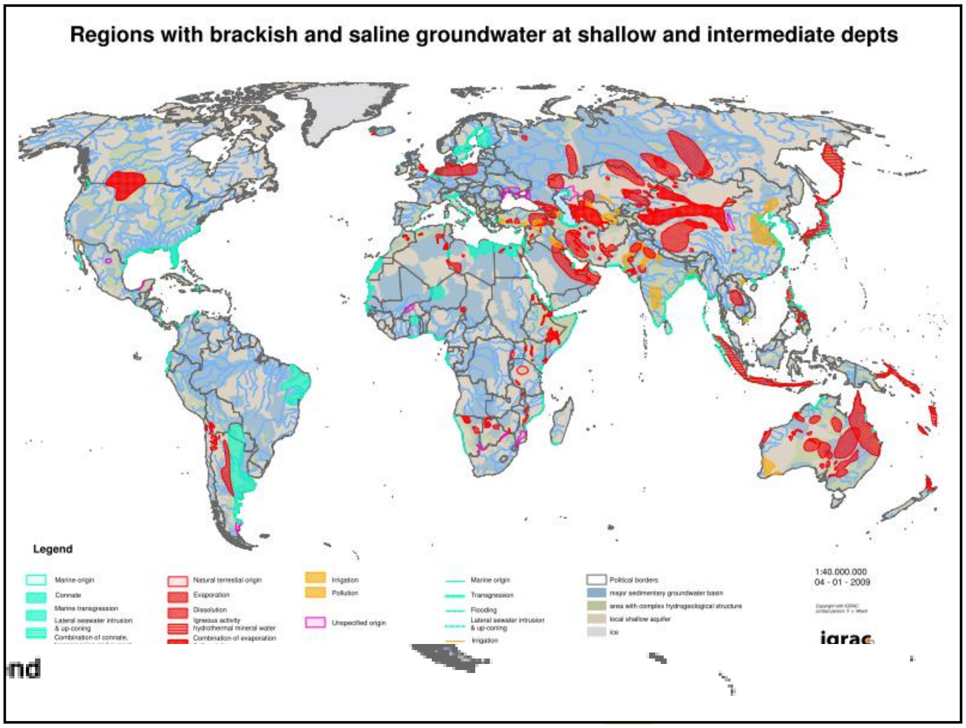


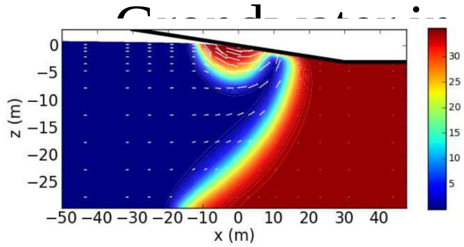
Salt water intrusion surface water

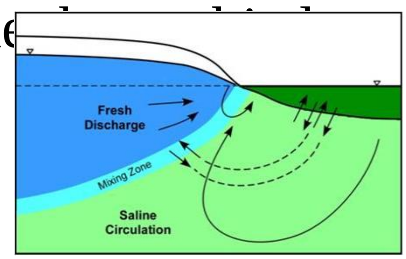
Salinization processes in the coastal zone: combination

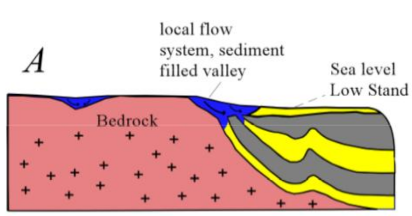
GEUS

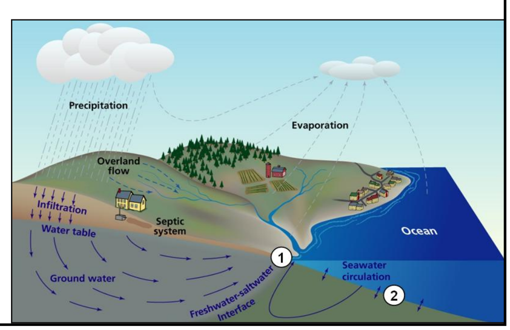






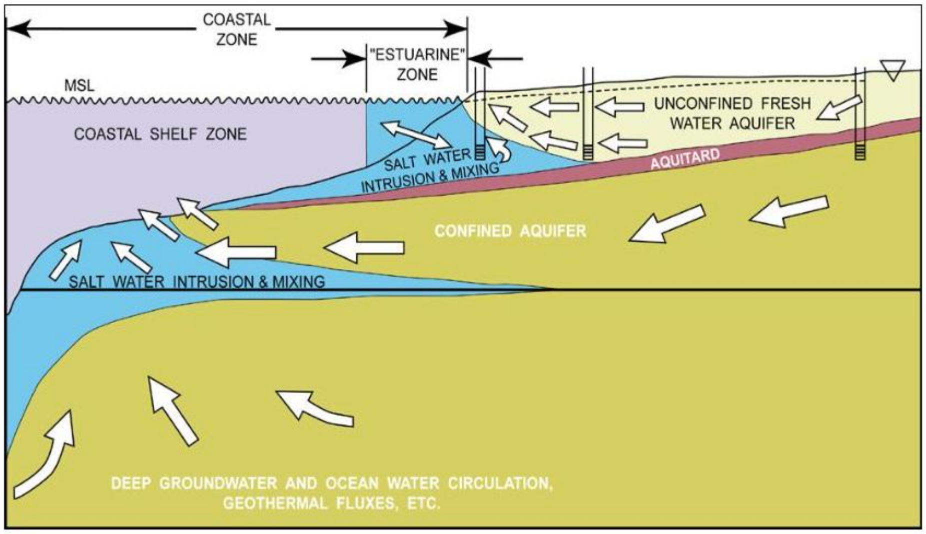




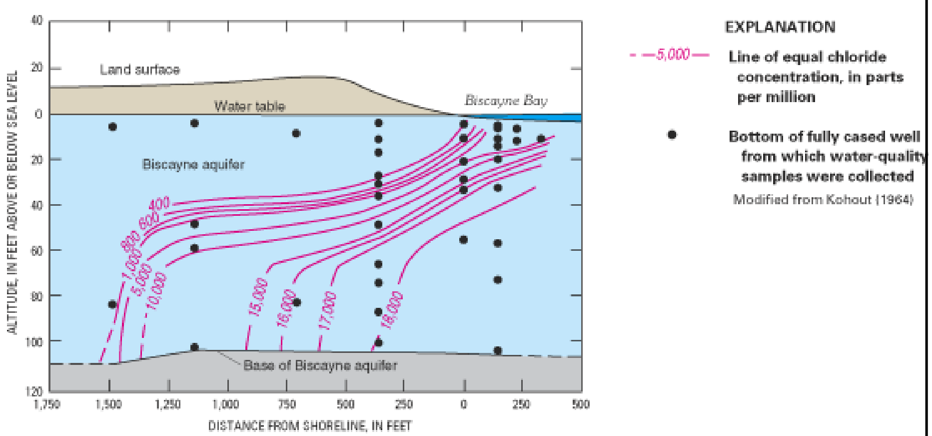


Source: Nature, 2013

Jan van Scorel
20140121

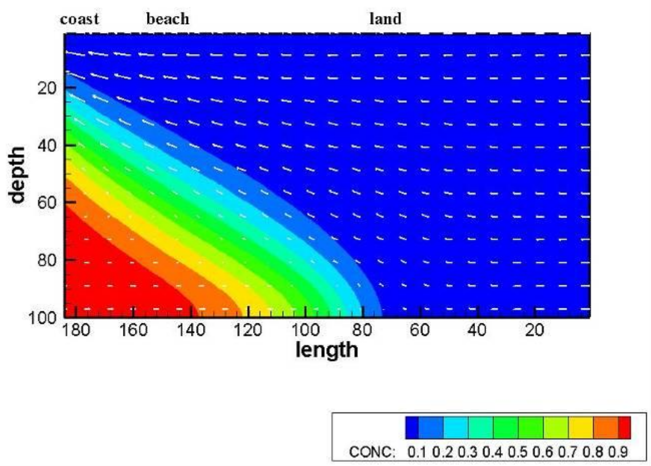


Biscayne aquifer, Florida USA: Henry's case



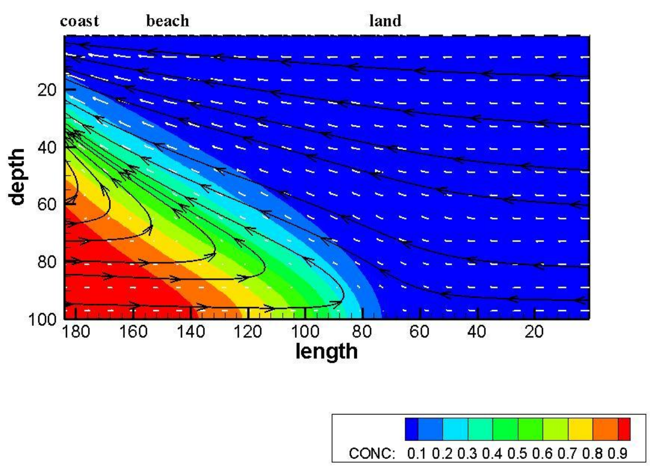
Definition of salt water intrusion

Numerical model: Henry's case

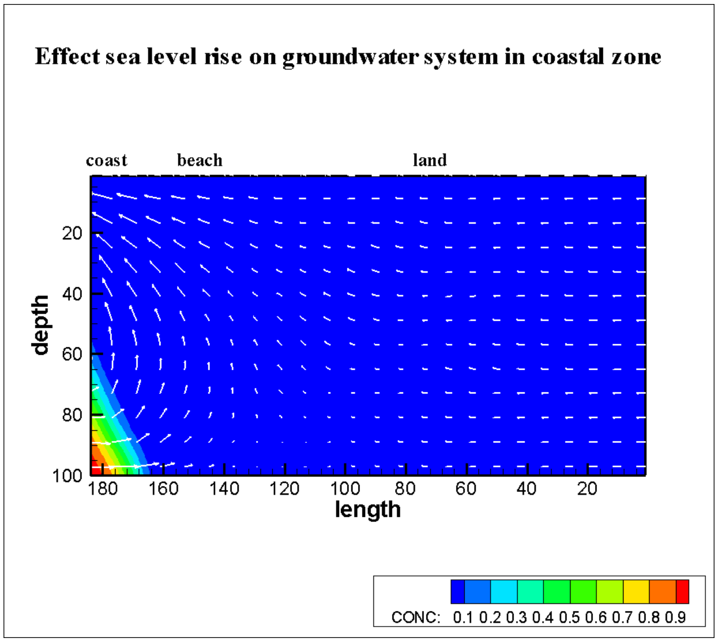


Definition of salt water intrusion

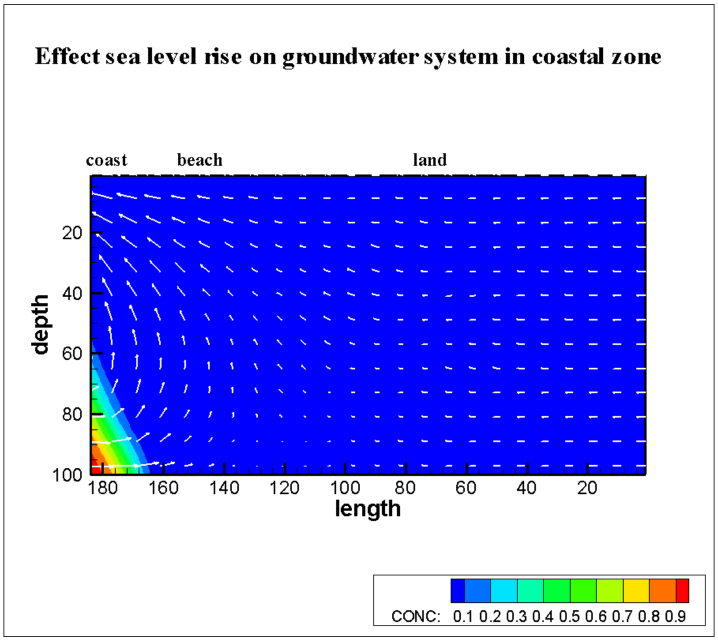
Numerical model: Henry's case



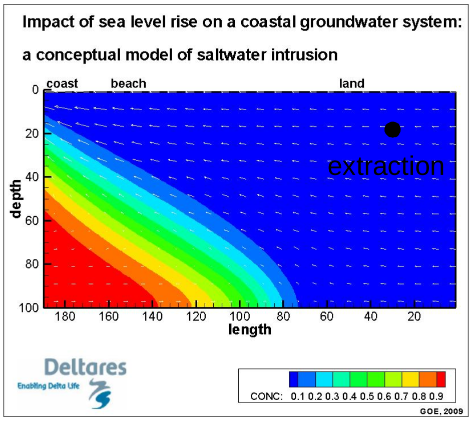
Sea level rise and salt water intrusion

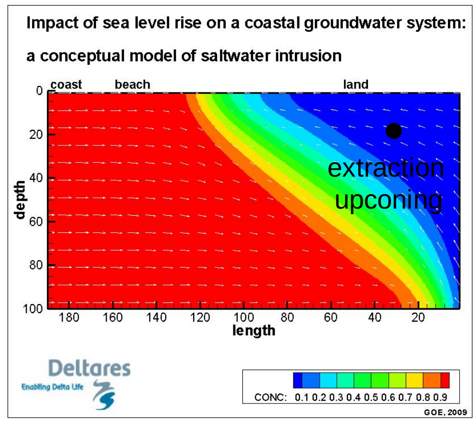


Sea level rise and salt water intrusion

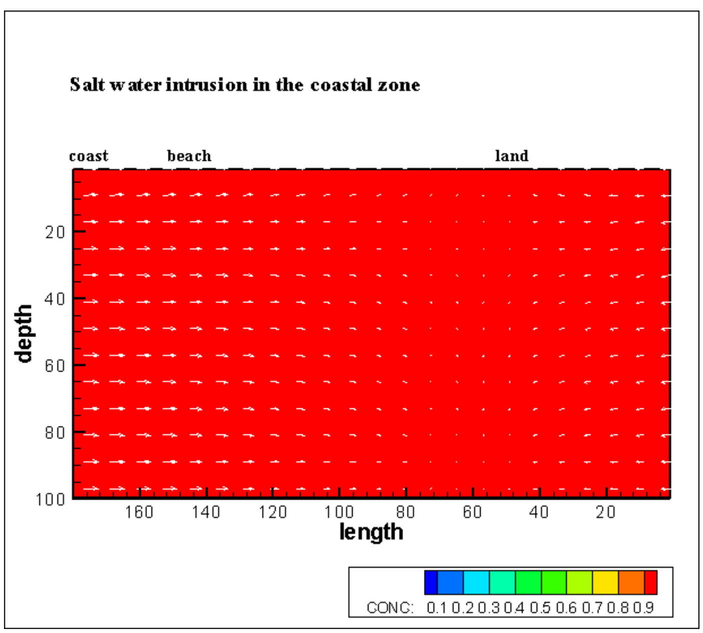


Sea level rise and salt water intrusion





Salt water intrusion



Water on Earth

Some serious developments:

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

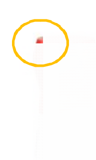
"*in 2025, two third of world population will face shortage of water*"

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)

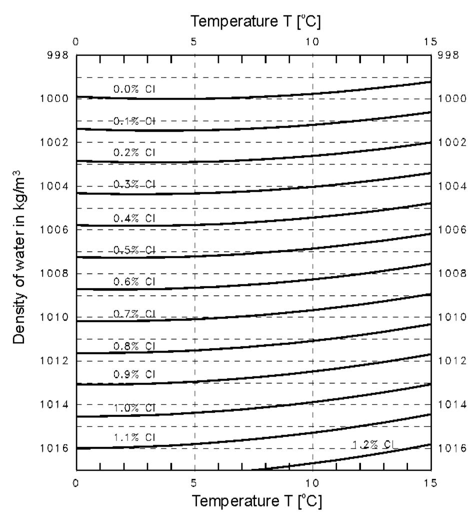
$$\rho_{i,j,k} = \rho_f + \frac{\partial \rho}{\partial C} C_{i,j,k}$$

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

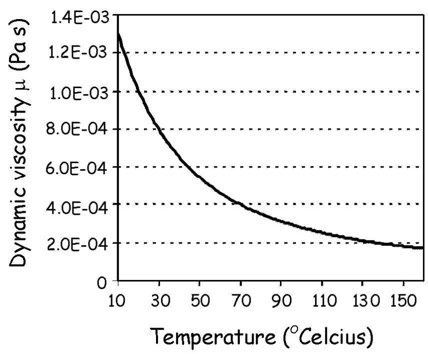


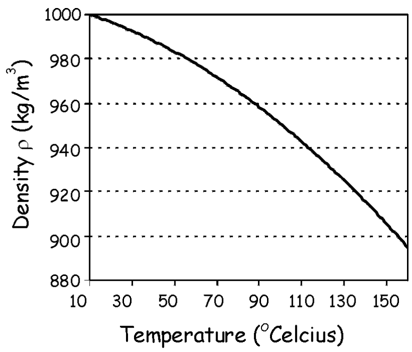
Accurate for T<15 °C and for Cl<1.1 %

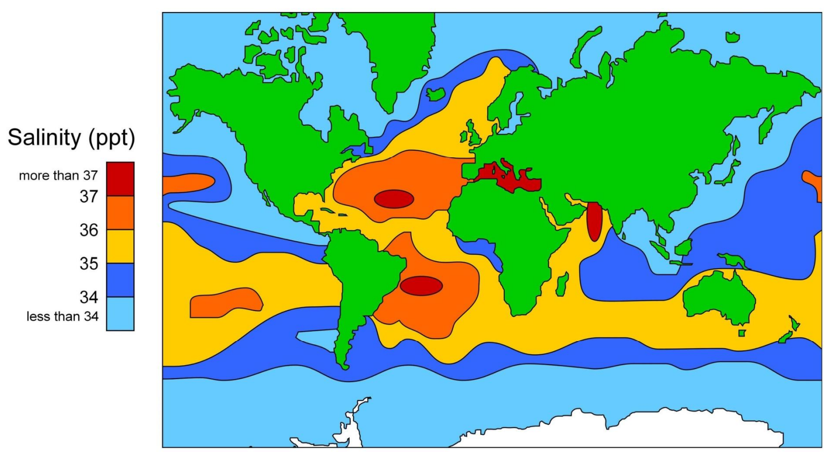
$$\rho_{(S,T)} = 1000 + 0.8054S - 0.0065(T - 4 + 0.2214S)^2$$ Knudsen (1902)

Density and viscosity depend on temperature

(10ºC-160 ºC)







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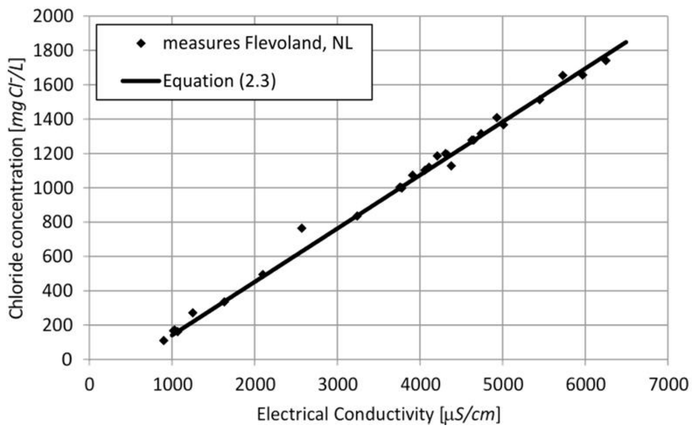
Close relation between
chloride concentration and Electrical Conductivity



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

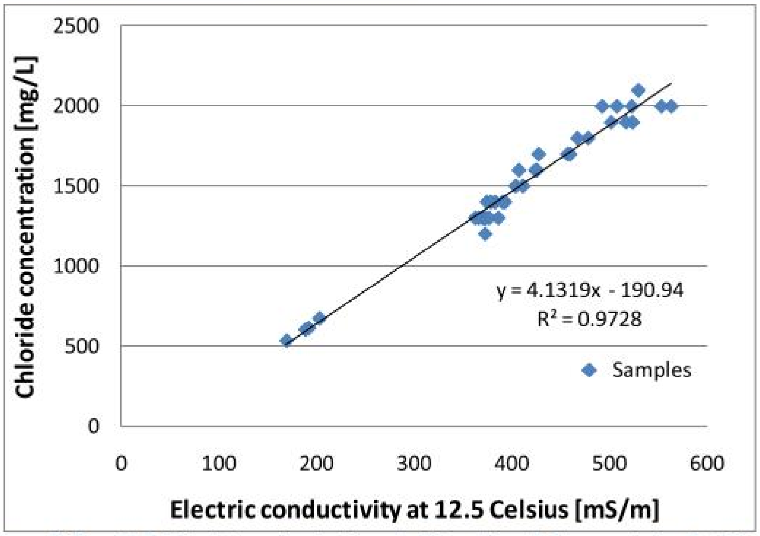
Close relation between
chloride concentration and Electrical Conductivity

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*

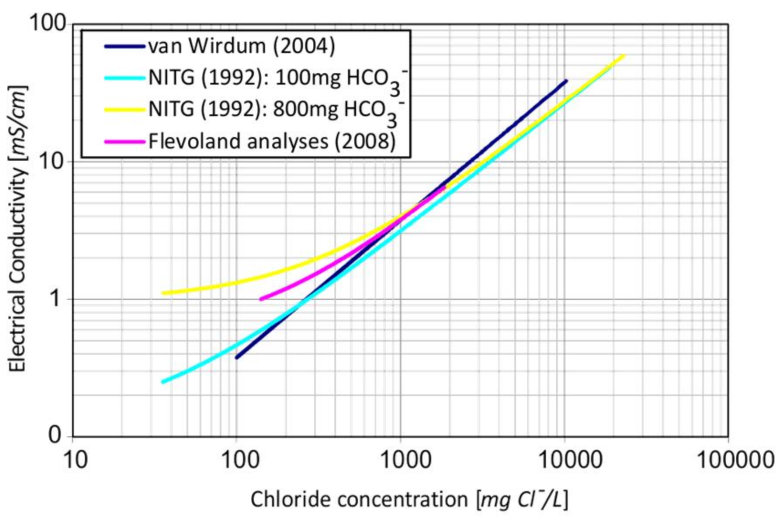
the ratio Cl^- over TDS equal to ~0.554, under stable normal seawater environments

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

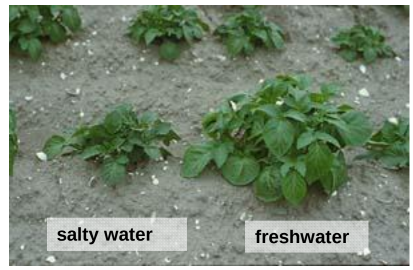


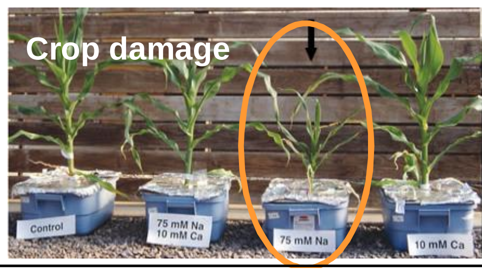
Appendix figure 11: Relation between the electric conductivity and the chloride concentration. For this relation samples from observation well B06D1114 and B06D1087 in between 23-sept-2009 and 9-okt-2010 were plotted.

EC-Chloride



Salt in water is a problem



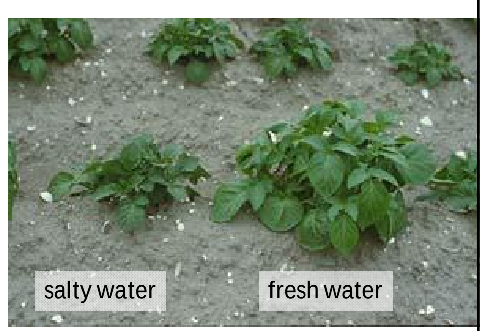


Salt in water is a problem for different water management sectors:

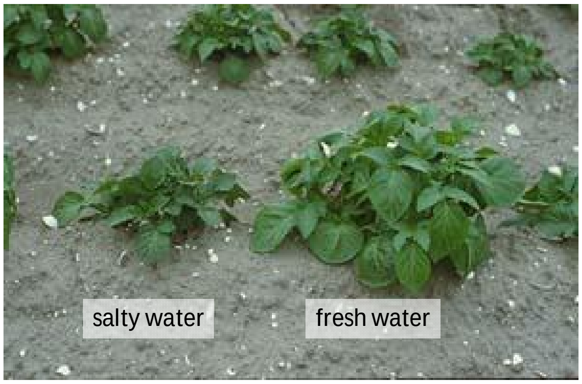
-drinking water:
- taste (100-300 mg Cl^-/l)
- long term health effect
- norm: EC& WHO=150 mg Cl^-/l (live stock=1500 mg Cl^-/l)

-industry:
- corrosion pipes
- preparation food

-irrigation/agriculture:
- production crops
- salt damage

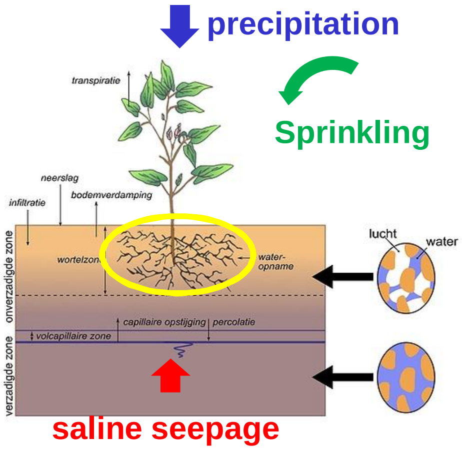


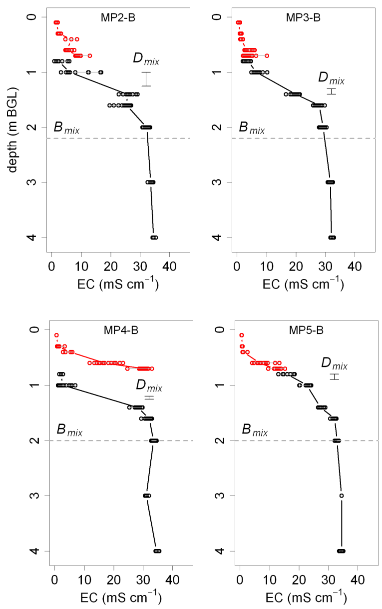
Effects salinisation: salt damage



Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

Salt-resistant crops





Important parameter:

Chloride concentration root zone
Land use
Sensitivity crops

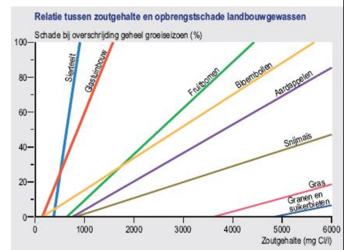
Salt damage to crops

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

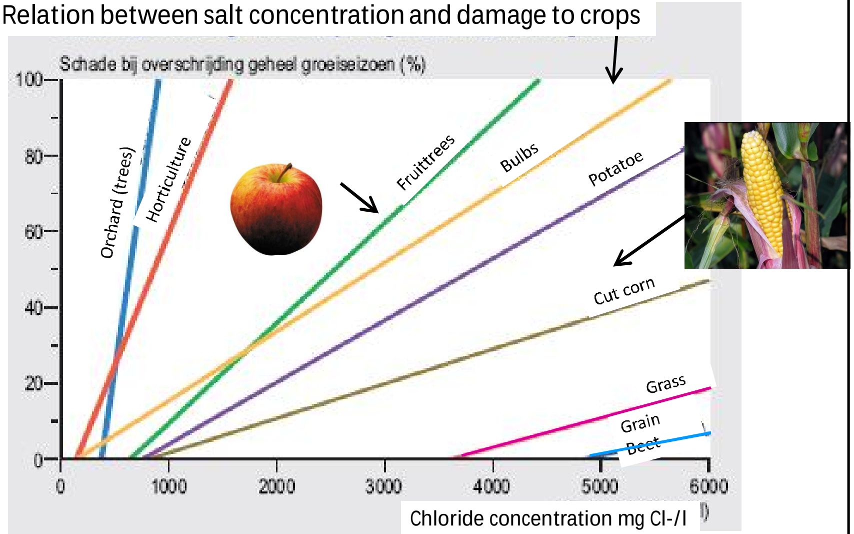
Source: Roest et al., 2003 en Haskoning



Source: MNP, 2005

Salt damage to crops

Relation between salt concentration and damage to crops

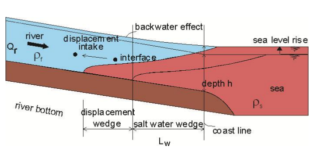


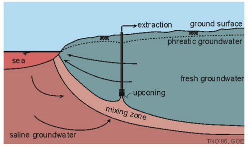
Source: MNP, 2005

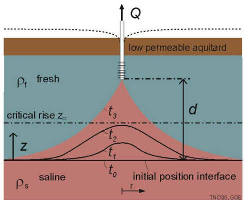
	Soil moisture		Irrigation water	
	Limi	Gradient	Limit	Gradient
Crop	mg/l Cl	%/mg/l Cl	mg/l Cl	%/mg/l Cl
Potatoe	756	0.0163	202	0.0610
Grass	3606	0.0078	962	0.0294
Sugar beat	4831	0.0057	1288	0.0212
Cut Corn	815	0.0091	217	0.0343
Grains	4831	0.0058	1288	0.0218
Fruit trees	642	0.0264	171	0.0991
Orchard (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







Introduction

Processes that accelerate salt water intrusion:

- Sea level rise
- Land subsidence
- Human activities

Threats for:

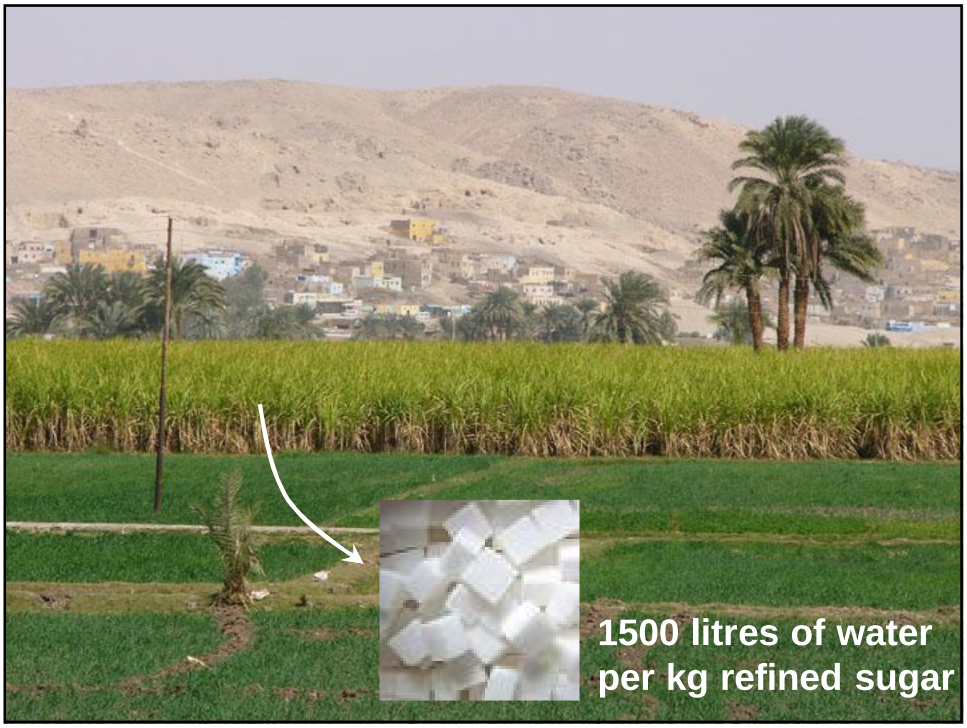
- drinking water supply in dunes:
  - upconing of saline groundwater
  - decrease of fresh groundwater resources
  - recharge areas reduction
- agriculture:
  - salt damage to crops: salt load and seepage
- water management low-lying areas:
  - flushing water channels
- ecology

The water footprint of products

global averages

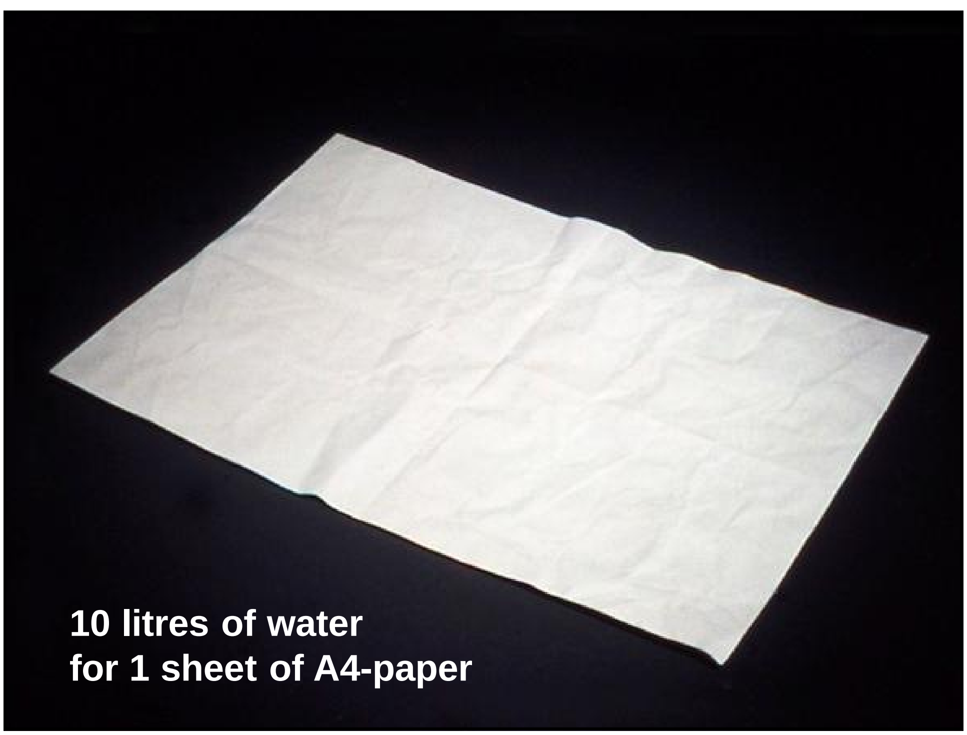
1 kg wheat	**1 m^3 water**
1 kg rice	**3 m^3 water**
1 kg milk	**1 m^3 water**
1 kg cheese	**5 m^3 water**
1 kg pork	**5 m^3 water**
1 kg beef	**15 m^3 water**

[Hoekstra & Chapagain, 2008]


1500 litres of water
per kg refined sugar


2400 litres of water
for 1 hamburger

= 140 litres of water

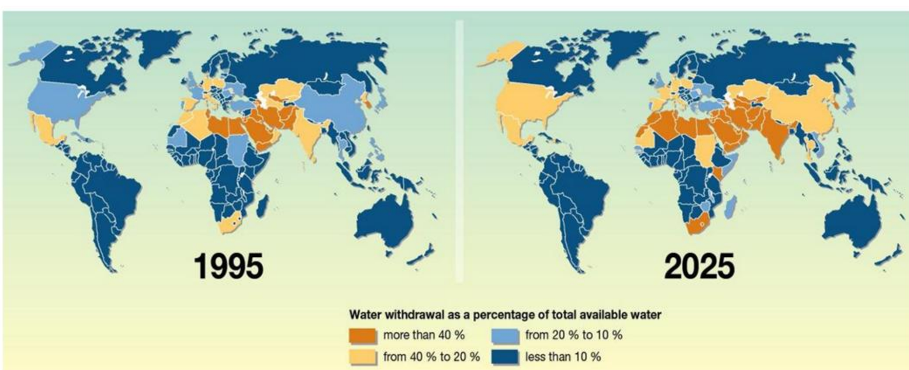


Question:

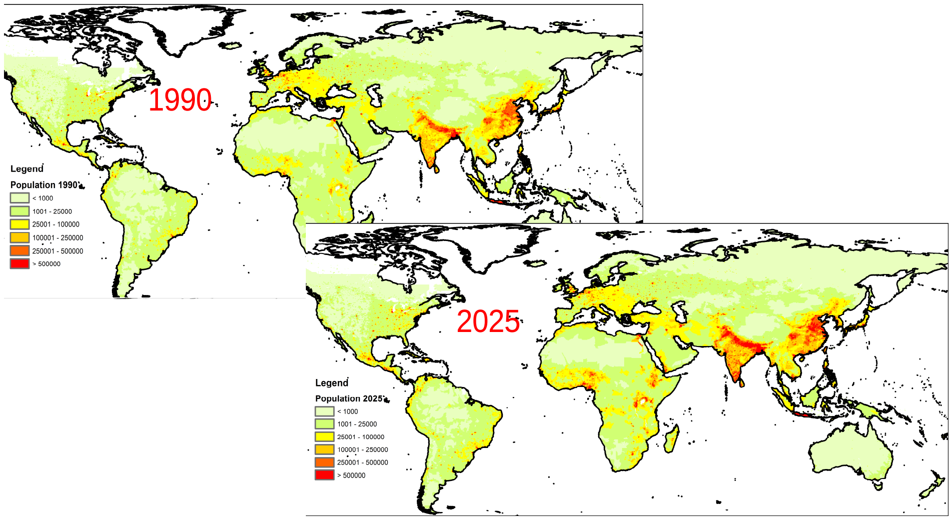
Demand fresh water per capita per day?:

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



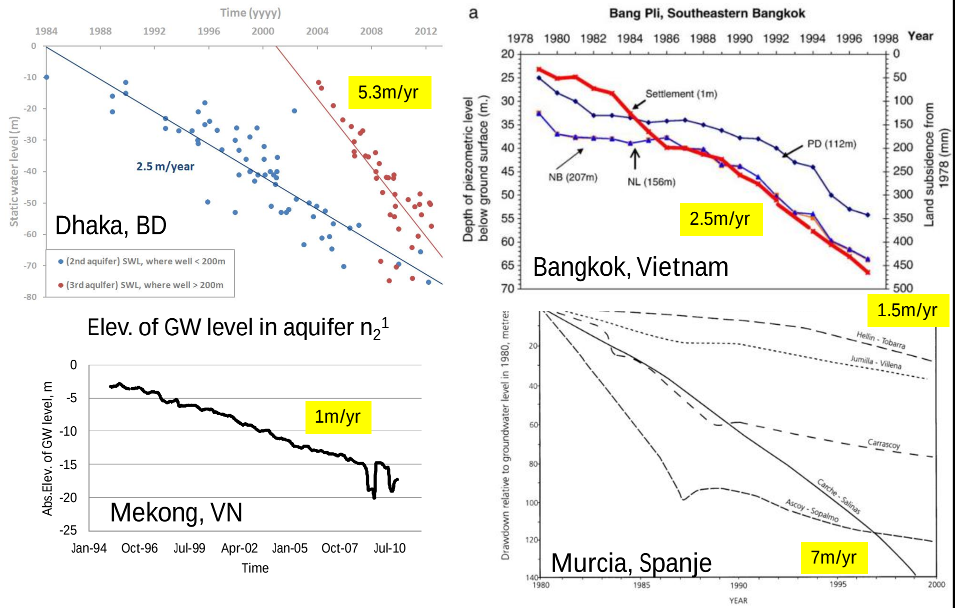
*Global 15 x 15 Minute Grids of the Downscaled Population Based on the SRES B2 Scenario, 1990 and 2025 (~28*28km2 at equator)*

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

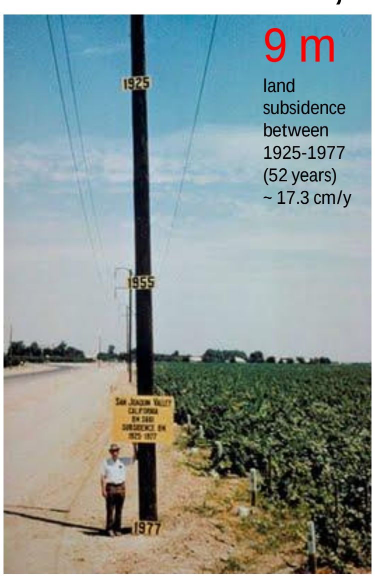


Groundwater overexploitation in Mekong Delta

Land subsidence

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

Land subsidence San Joachim Valley, CA, USA



9 m since 1930s

San Francisco

Los Angeles

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 $\Rightarrow$ oxidation of peat, soil compaction

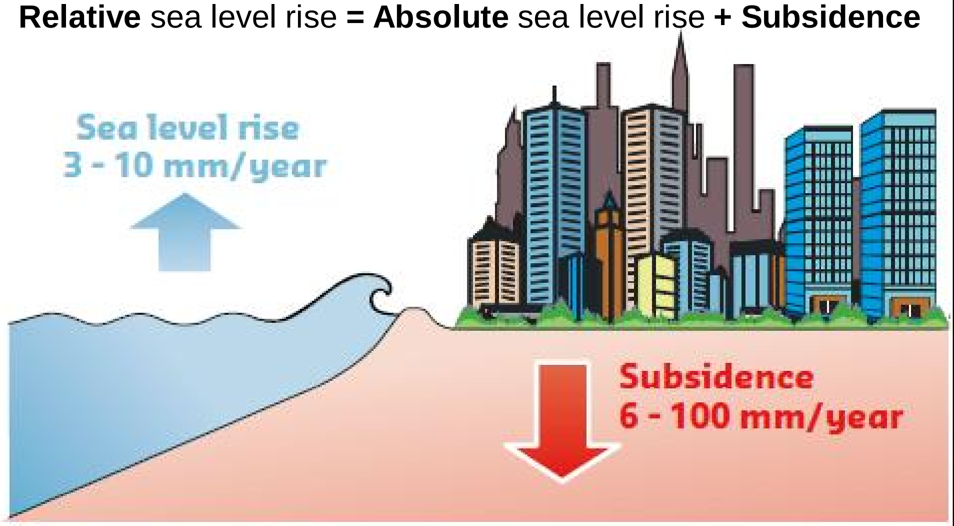
Why discriminating between human-induced and natural processes?

- Magnitude
- Cooping strategy (mitigation versus adaptation)

Impacts

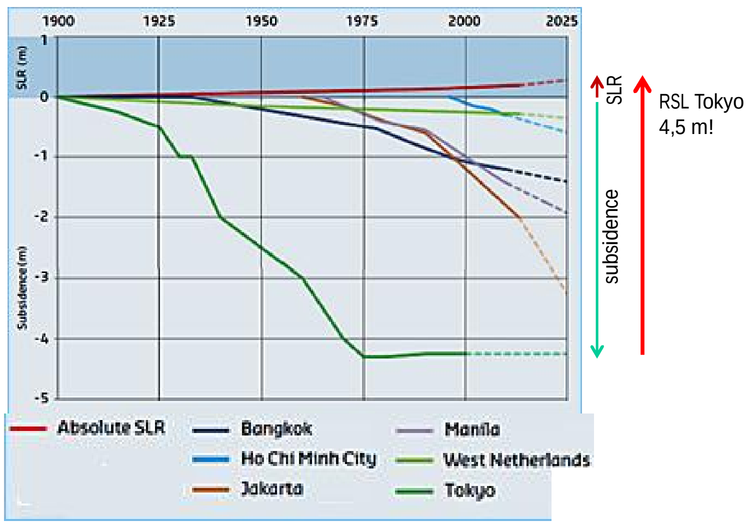
Sinking delta cities

Relative sea level rise **= Absolute** sea level rise **+ Subsidence**

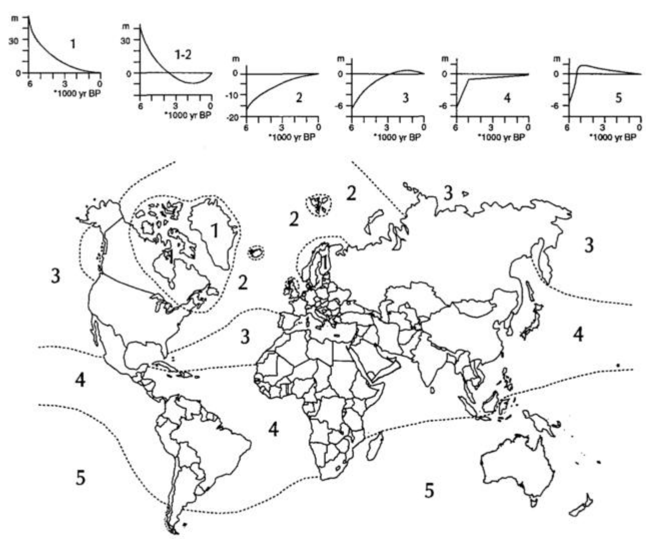


Examples of some major coastal cities

The subsidence issue is underestimated

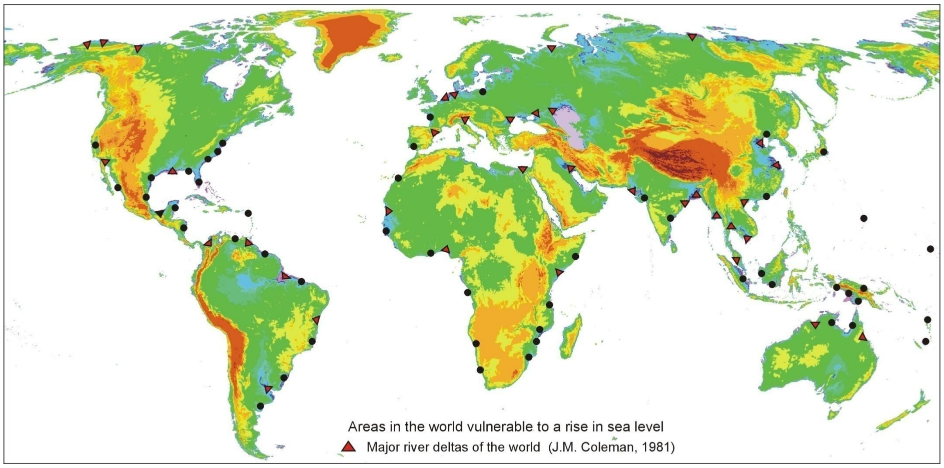


Regional distribution of Holocene Sea-level Changes



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

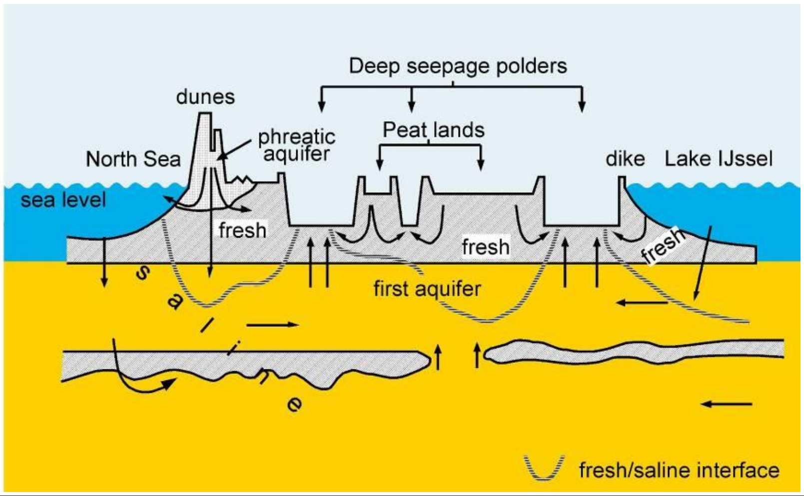
Areas vulnerable to sea level rise



The Netherlands: low-lying lands

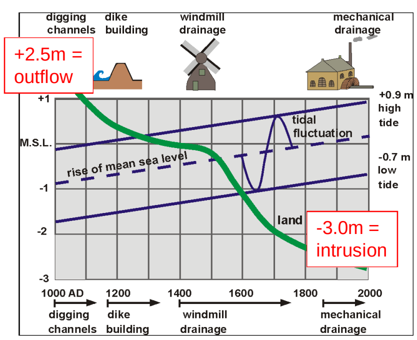
Saline seepage leads to:

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

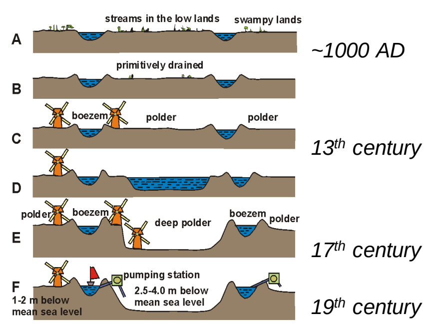


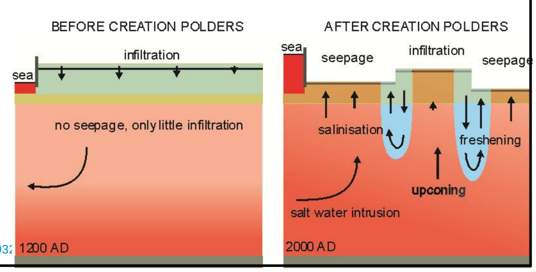
From fresh water outflow to salt water inflow

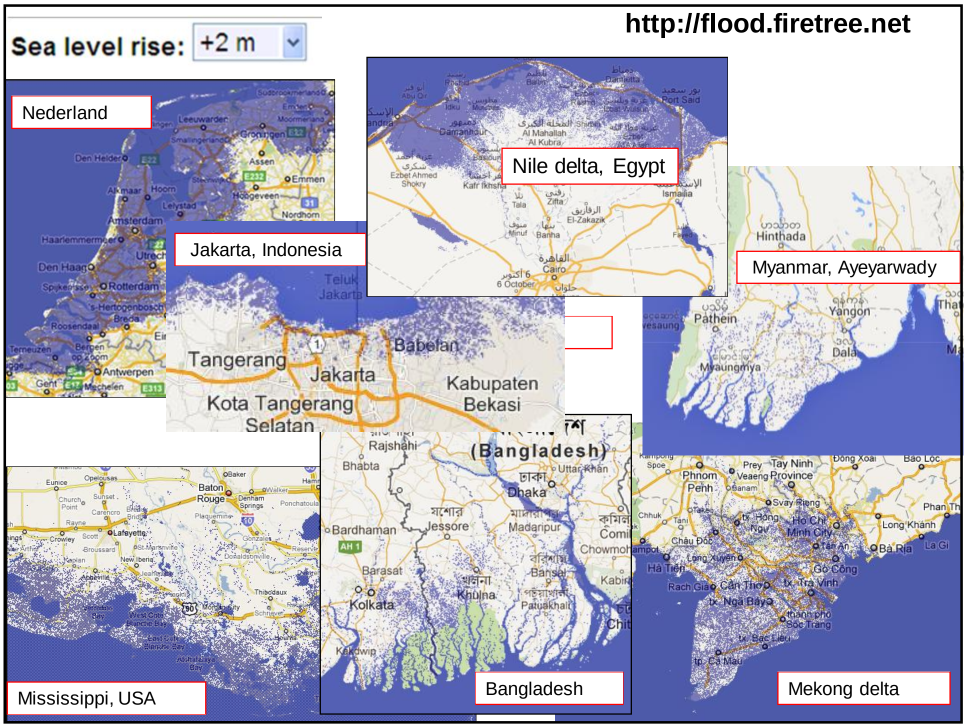
Historical subsidence of the ground surface in Holland

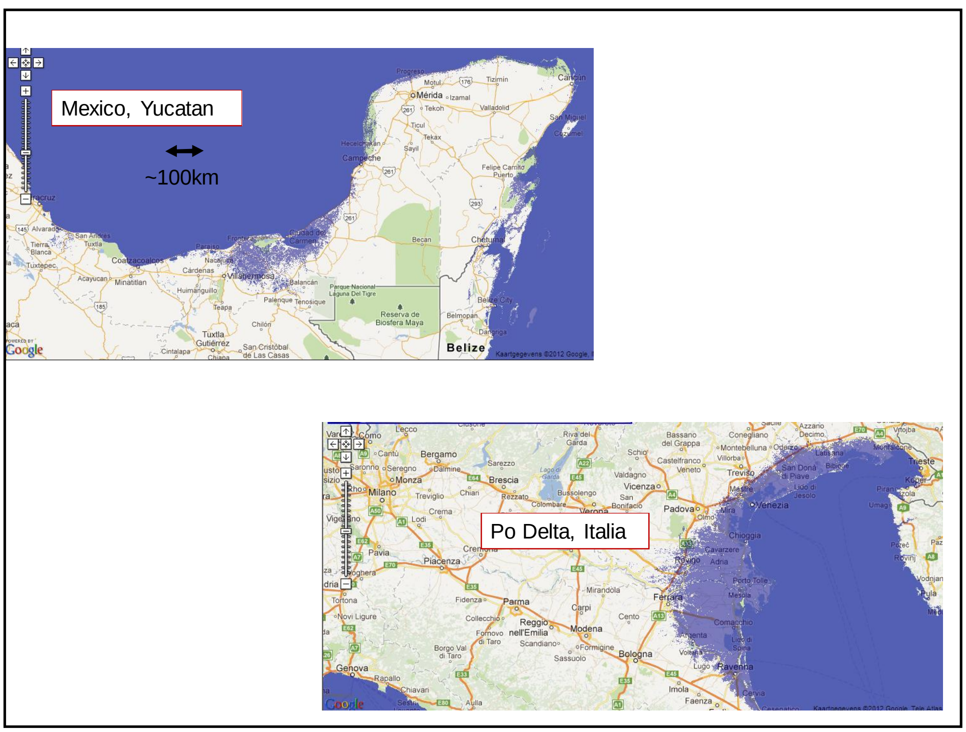


Ground surface

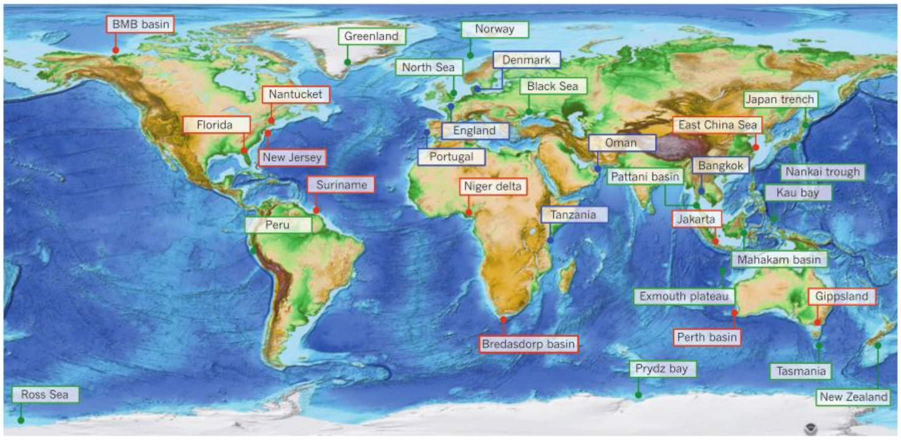





Sea level rise: +2 m
http://flood.firetree.net
Nederland
Nile delta, Egypt
Jakarta, Indonesia
Myanmar, Ayeyarwady
Mississippi, USA
Bangladesh
Mekong delta

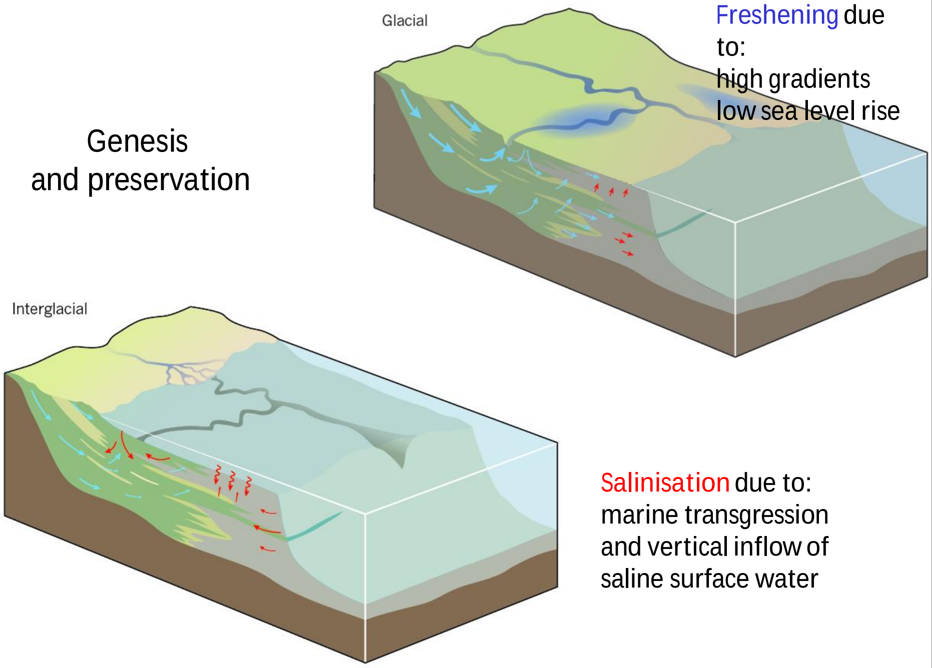

Mexico, Yucatan
~100km
Po Delta, Italia

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



Post et al., Nature, 2013

Genesis
and preservation

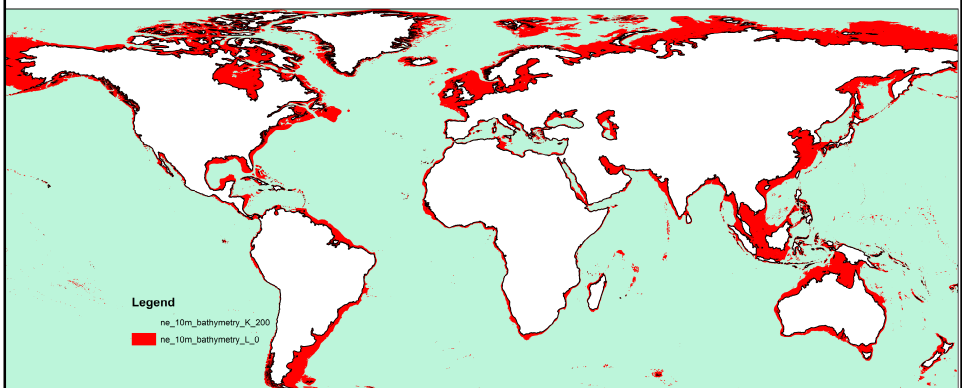


Freshening due to:
high gradients
low sea level rise

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

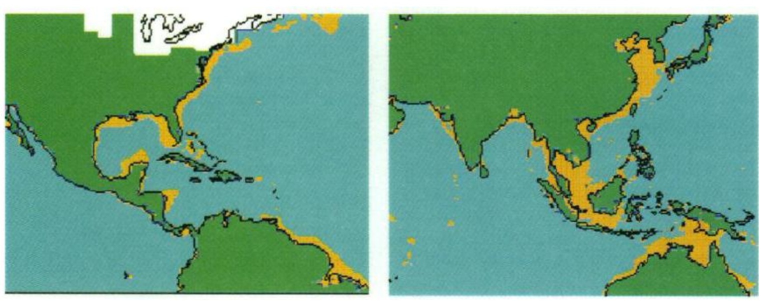
Source: Nature, 2013

Possible locations of offshore (submarine) groundwater



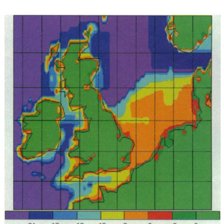
Coastal zone cases around the world

Occurrence related to dynamic sea-levels and coastlines

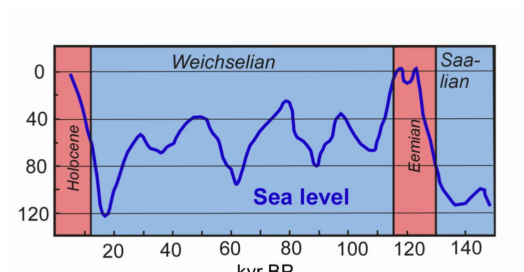


Exposed continental shelves

Peltier, *Science*, 1994

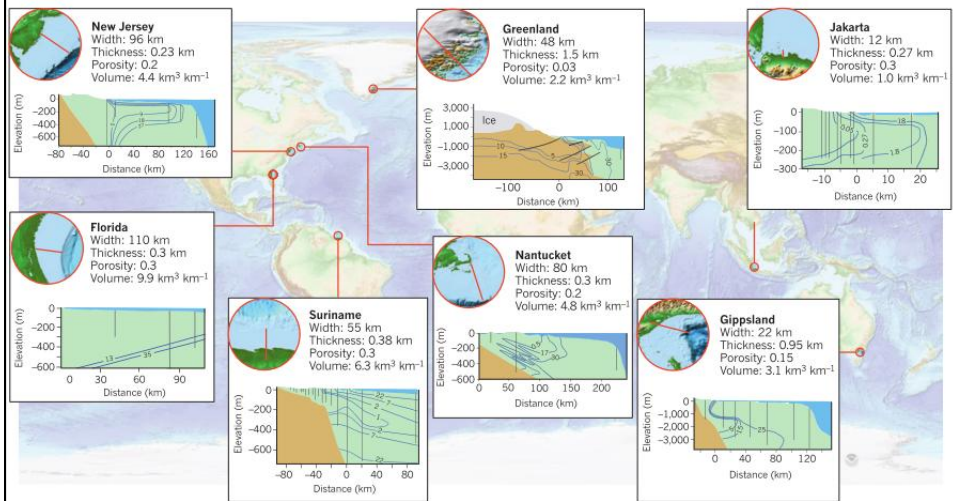


Inundated (kyr BP)



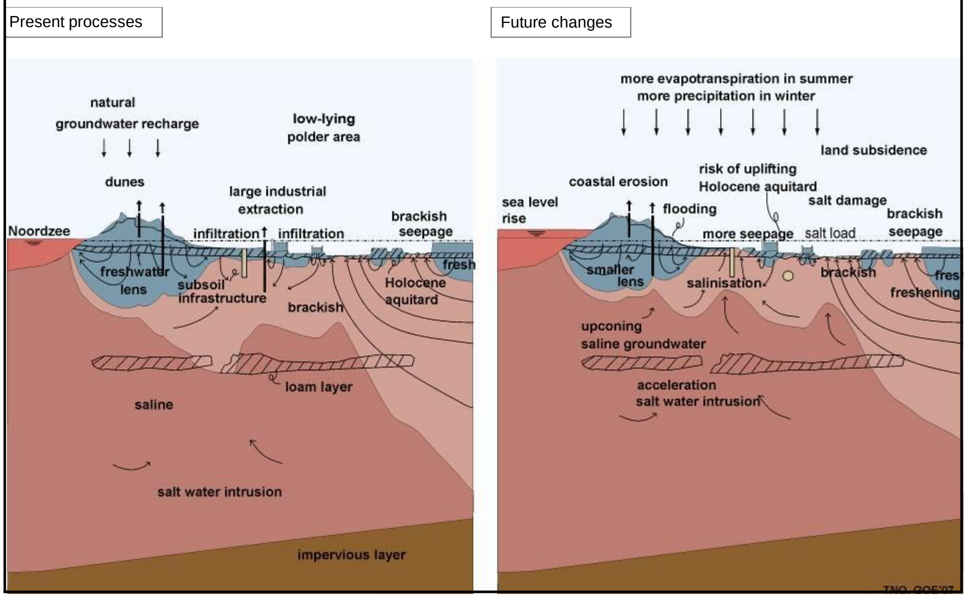
Linsley, Nature, 1996

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

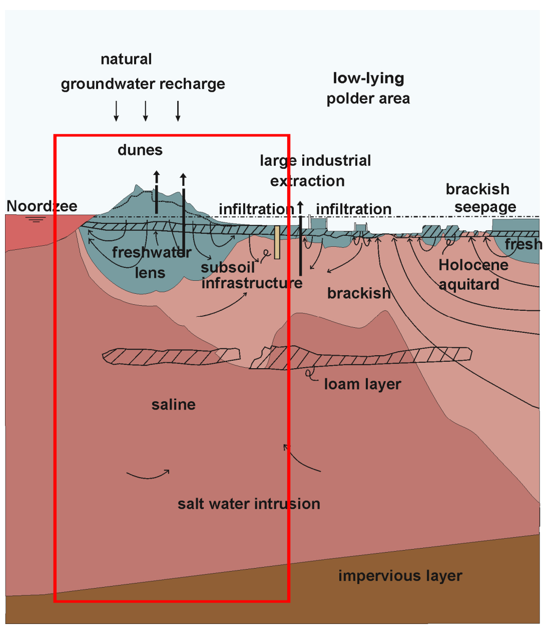


My first density dependent groundwater flow and solute transport model in 1990!

The Dutch groundwater system under stress

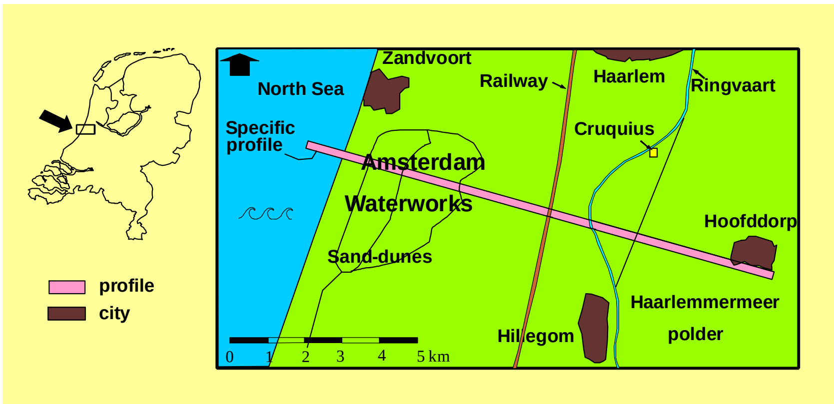


Saltwater intrusion in the Netherlands



Saltwater intrusion in the Dutch coastal zone

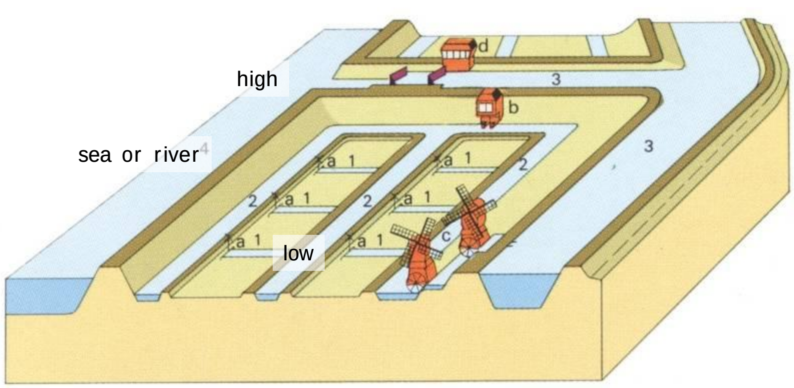
Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



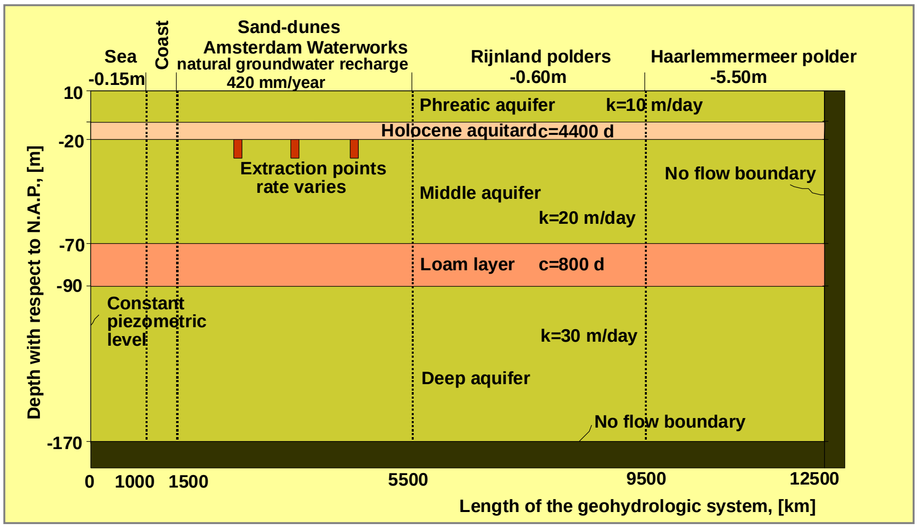
The polder system

A polder is:

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

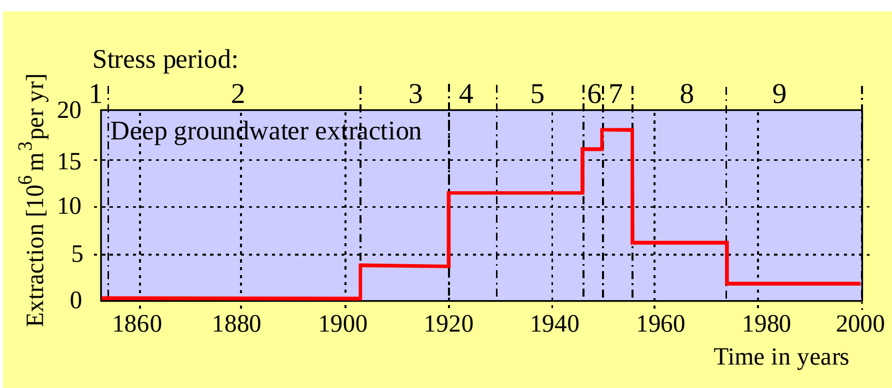


Geometry, subsoil parameters, boundary conditions

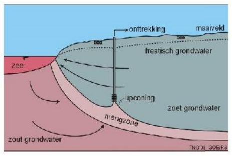


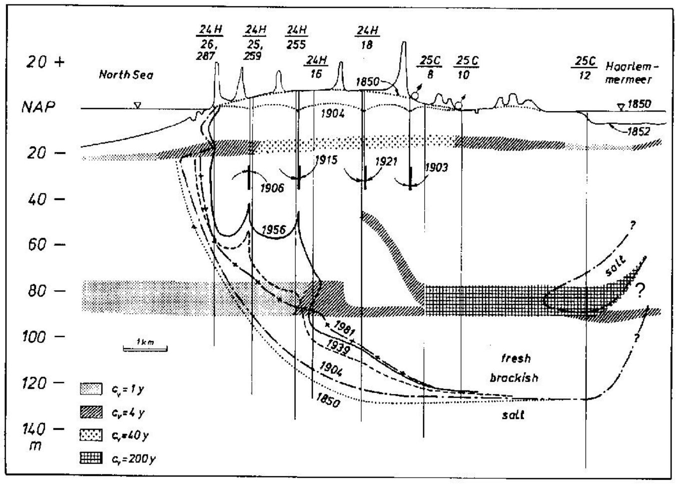
Saltwater intrusion in the Dutch coastal zone

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



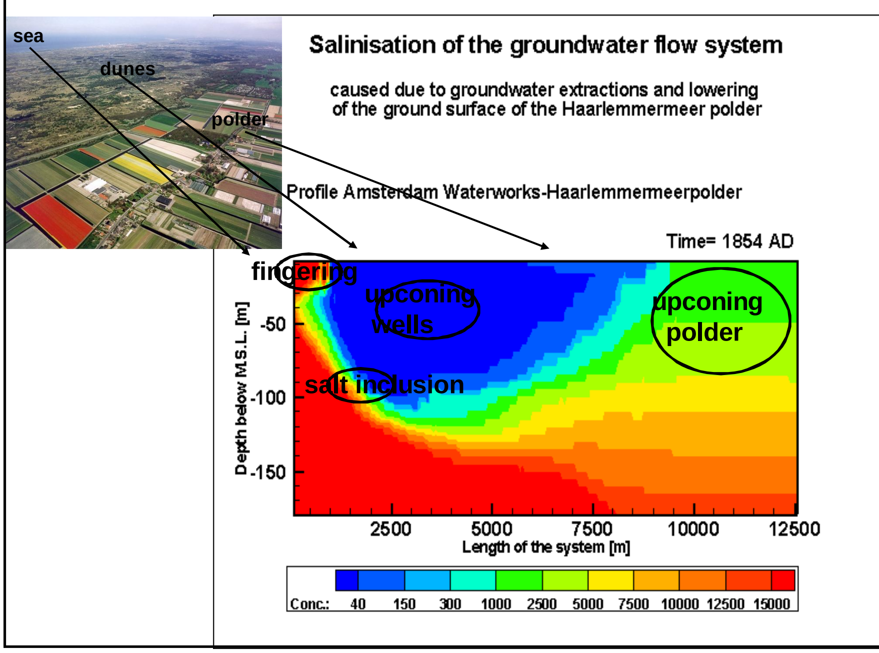
Upconing of brackish-saline groundwater



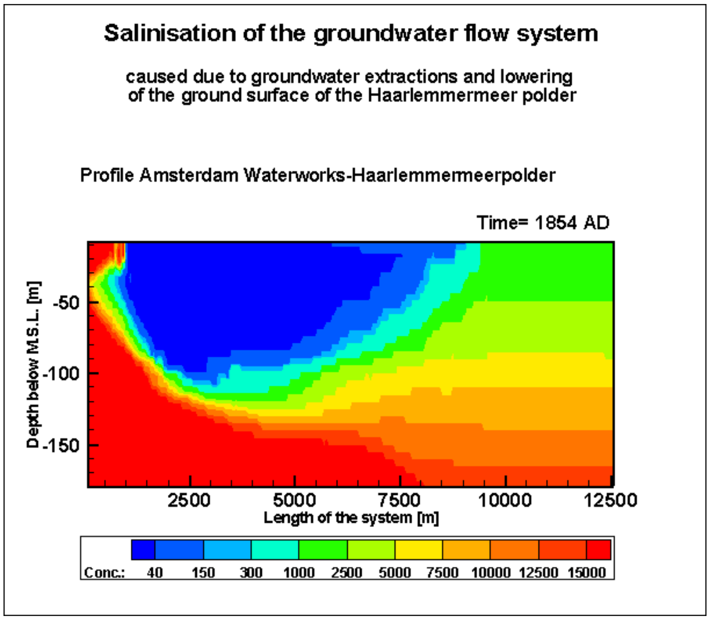


Stuyfzand, 1993

Saltwater intrusion in the Dutch coastal zone



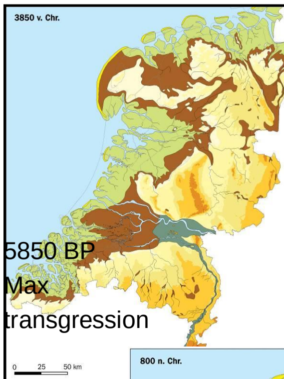
Saltwater intrusion in the Dutch coastal zone



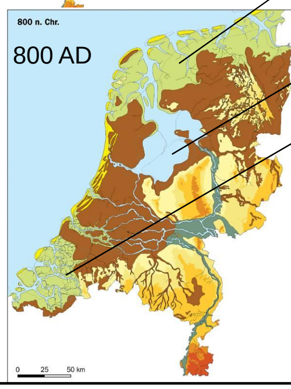
Palaeo hydrogeological modelling

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

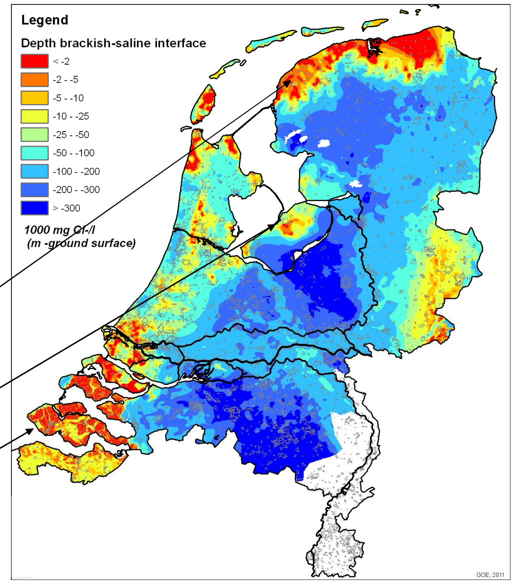
J.R. Delsman, K. Hu-a-ng, P.C. Vos, P.G.B. de Louw, G.H.P. Oude Essink and M.F.P. Bierkens



5850 BP
Max
transgression



800 AD



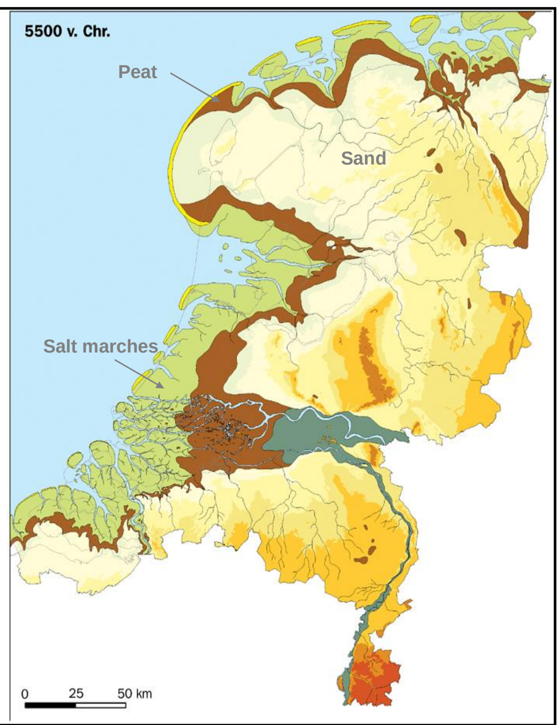
30327

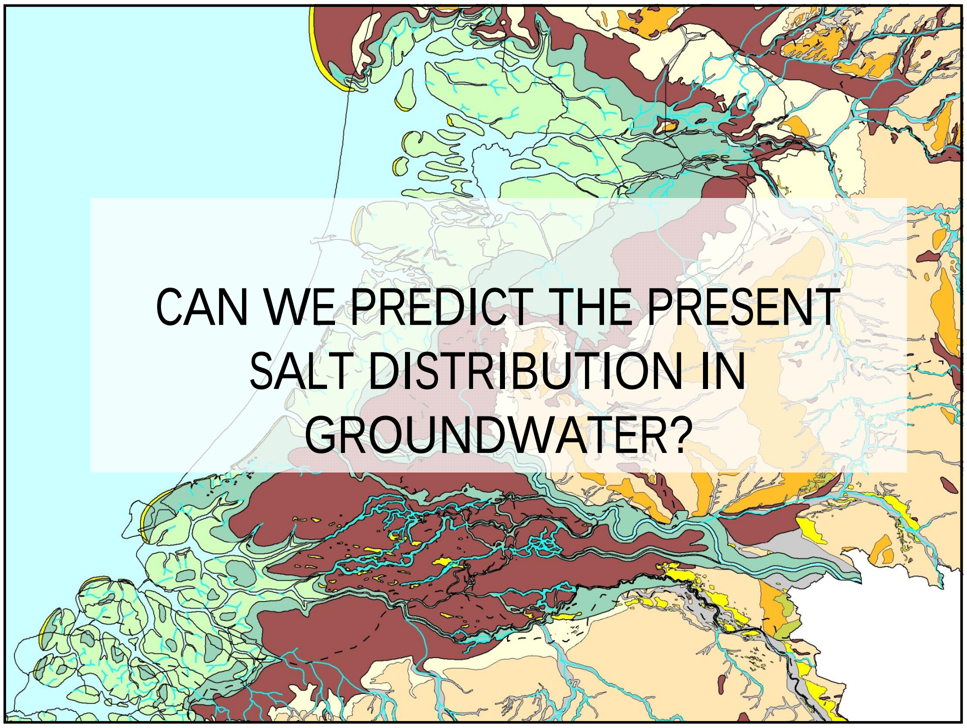
Based on:
- Analyses
- VES
- Borehole measurement

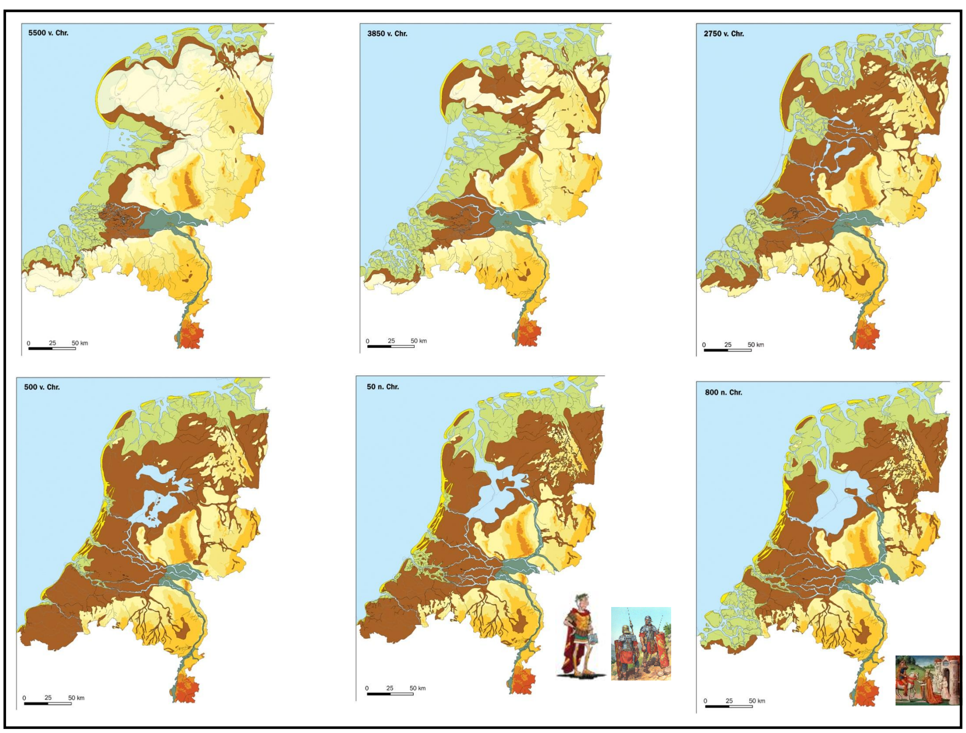
The Holocene transgressions

Major impact on present regional brackish groundwater systems

7500 BP

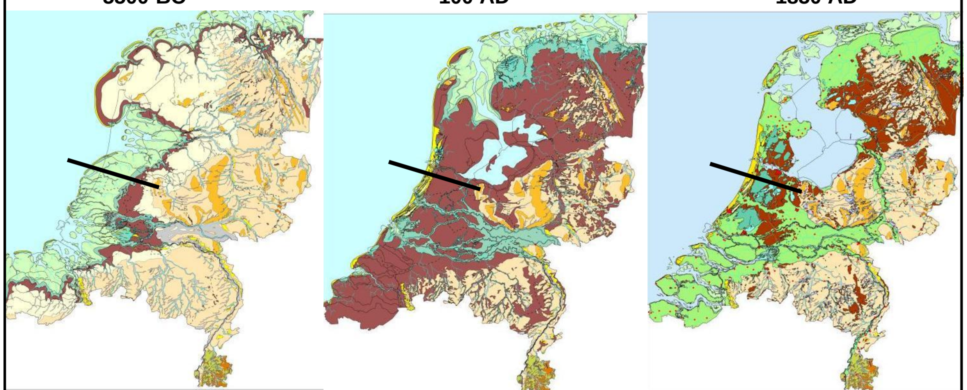



CAN WE PREDICT THE PRESENT SALT DISTRIBUTION IN GROUNDWATER?


5500 v. Chr.
3850 v. Chr.
2750 v. Chr.
500 v. Chr.
50 n. Chr.
800 n. Chr.

Palaeogeographical development

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



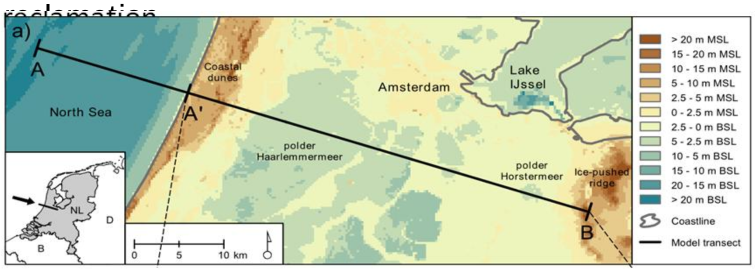
Maximal transgression | **Peat development** | **Reclaimed land, polder**

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

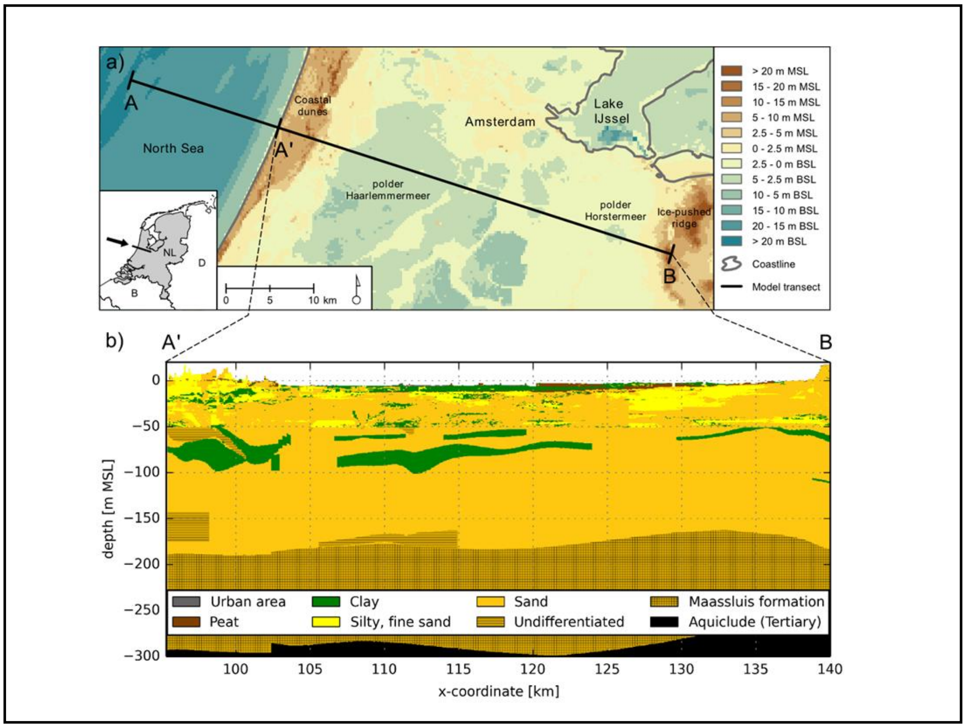
Atlas NL in het Holoceen (Vos et al, 2011)

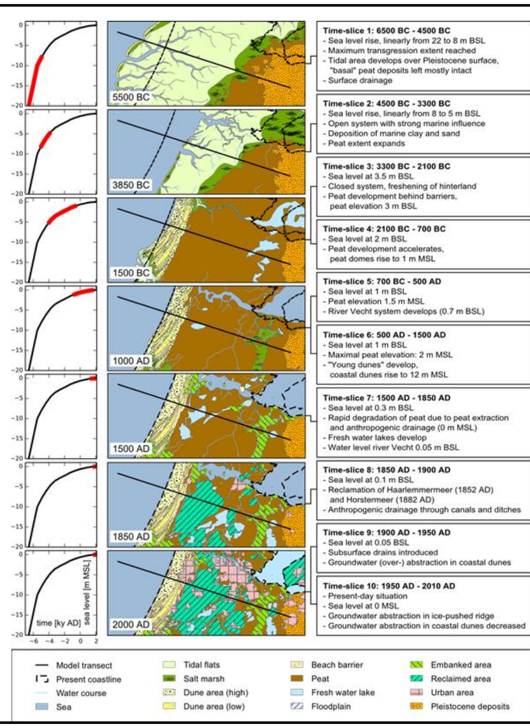
Occurrence of salt under the polder Haarlemmermeer

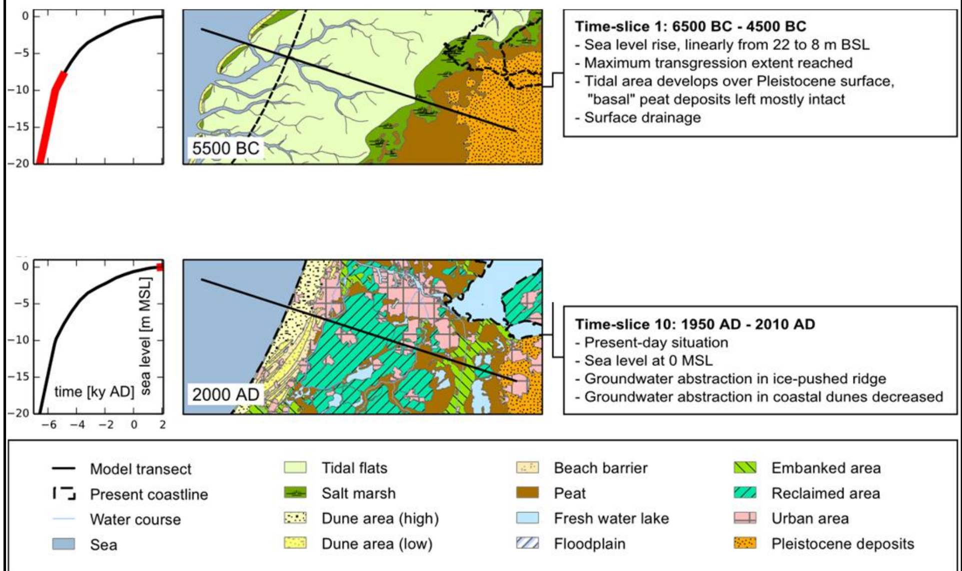
- Model profile Zandvoort - Hoofddorp – Hilversum
- Palaeogeographical development (Vos et al, 2011)
- 6500 BC - 2010 AD
- marine transgression
- Peat development, peat degradation, drainage, reclamation



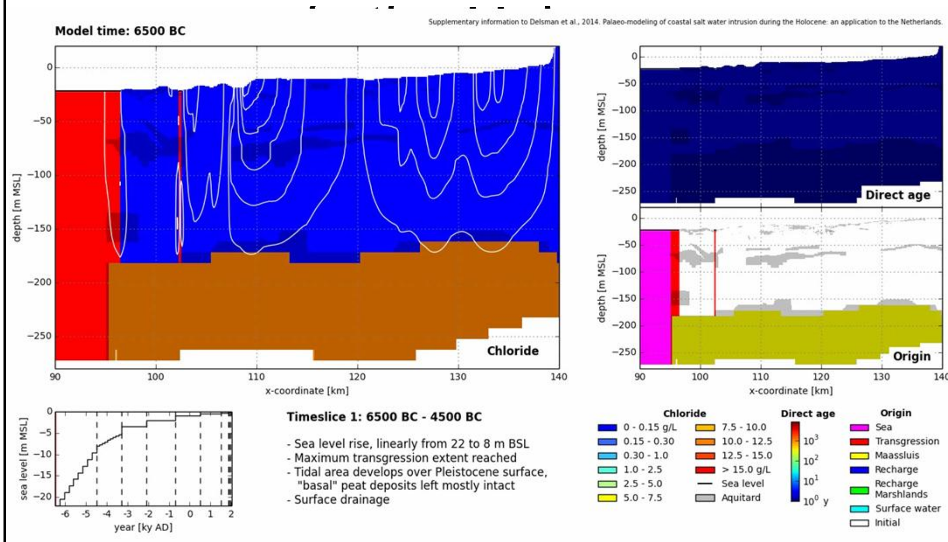
Delsman et al., HESS, 2013


a)
A
A'
B
North Sea
Coastal dunes
Amsterdam
Lake IJssel
polder Haarlemmermeer
polder Horstermeer
Ice-pushed ridge
NL
D
B
0 5 10 km
> 20 m MSL
15 - 20 m MSL
10 - 15 m MSL
5 - 10 m MSL
2.5 - 5 m MSL
0 - 2.5 m MSL
2.5 - 0 m BSL
5 - 2.5 m BSL
10 - 5 m BSL
15 - 10 m BSL
20 - 15 m BSL
> 20 m BSL
Coastline
Model transect
b)
depth [m MSL]
x-coordinate [km]
Urban area
Peat
Clay
Silty, fine sand
Sand
Undifferentiated
Maassluis formation
Aquiclude (Tertiary)


5500 BC
3850 BC
1500 BC
1000 AD
1500 AD
1850 AD
2000 AD
time [ky AD]
sea level [m MSL]
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
Model transect
Present coastline
Water course
Sea
Tidal flats
Salt marsh
Dune area (high)
Dune area (low)
Beach barrier
Peat
Fresh water lake
Floodplain
Embanked area
Reclaimed area
Urban area
Pleistocene deposits

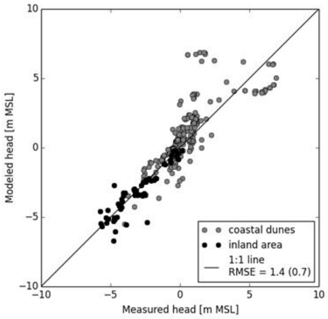


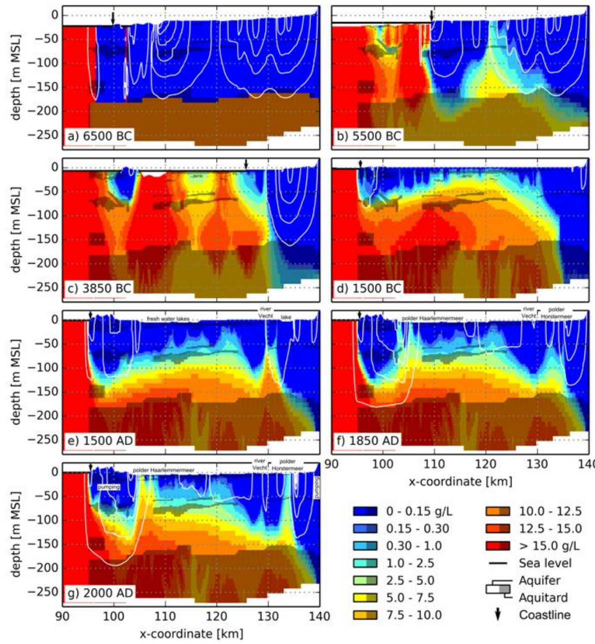
Development saline groundwater



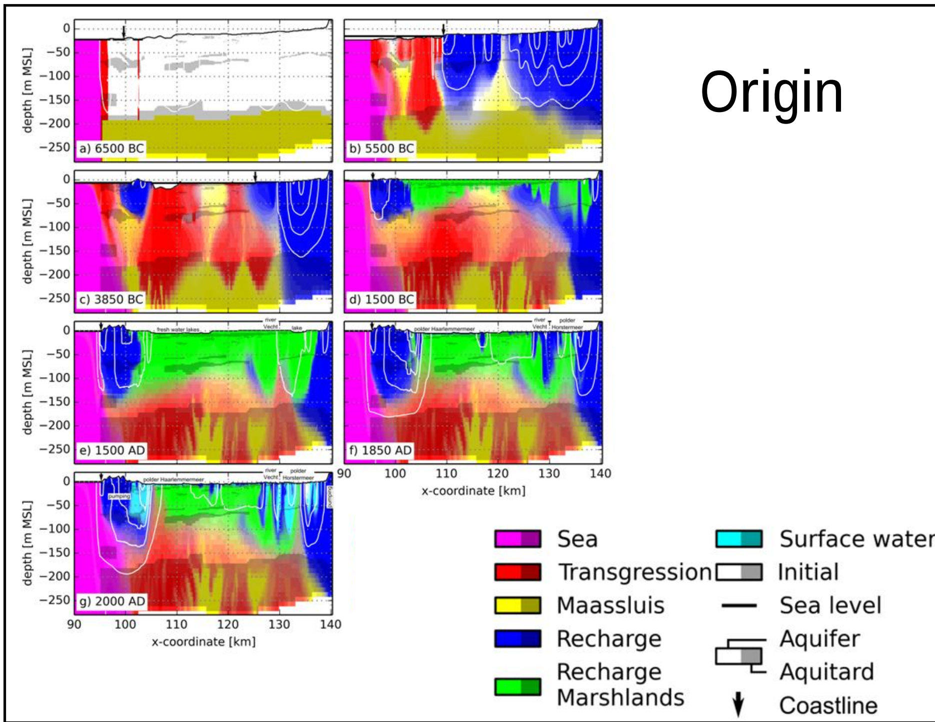
Delsman et al., HESSD, 2013

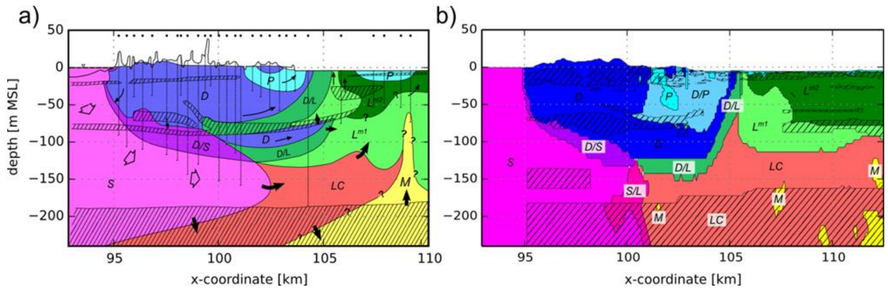
Model versus measurements

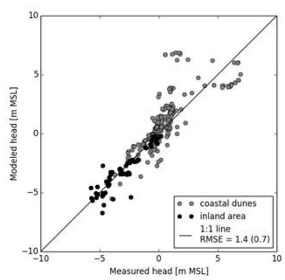




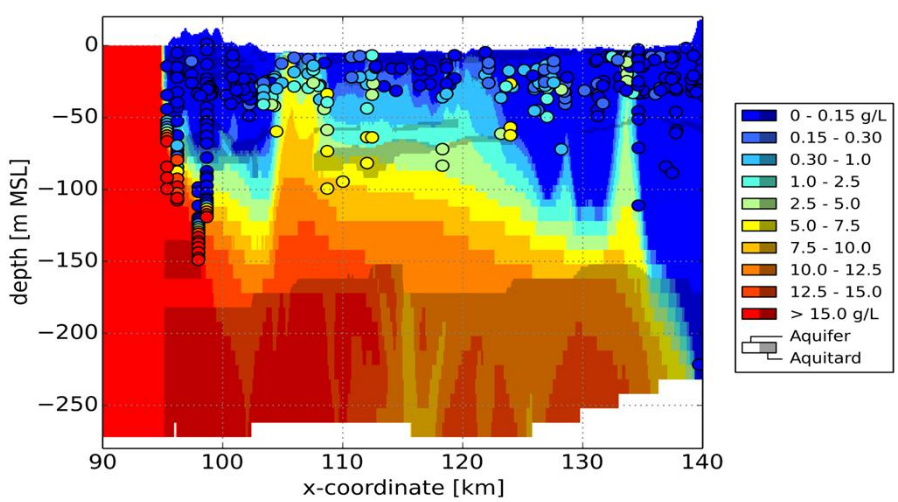
Origin







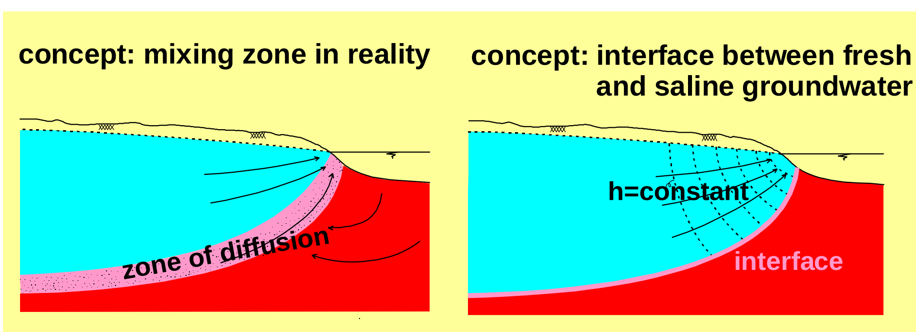
Model versus measurements



Sharp interface between fresh and saline groundwater

Badon Ghyben-Herzberg principle

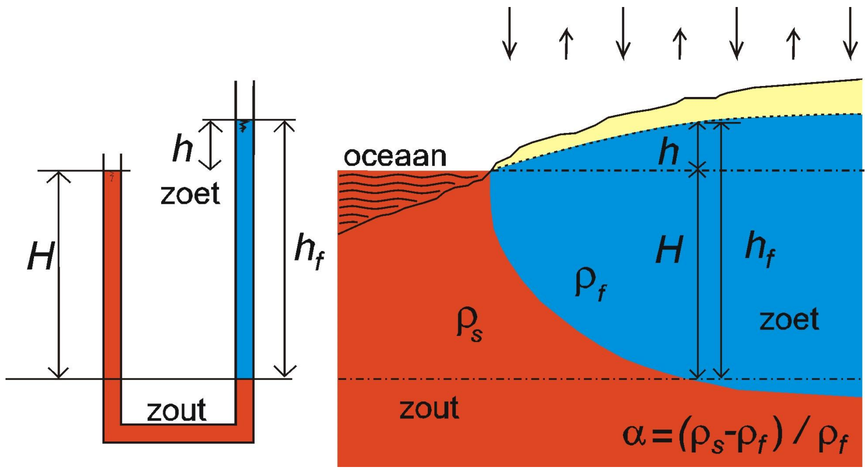
Difference between reality and Badon Ghyben-Herzberg approximation

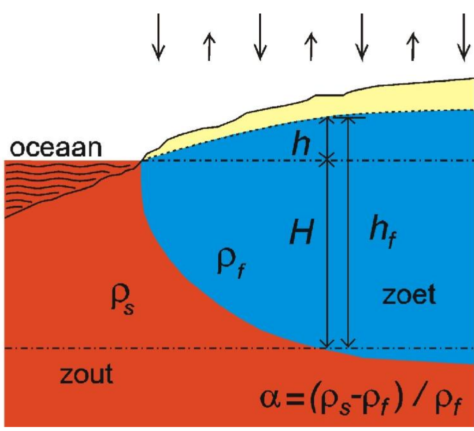


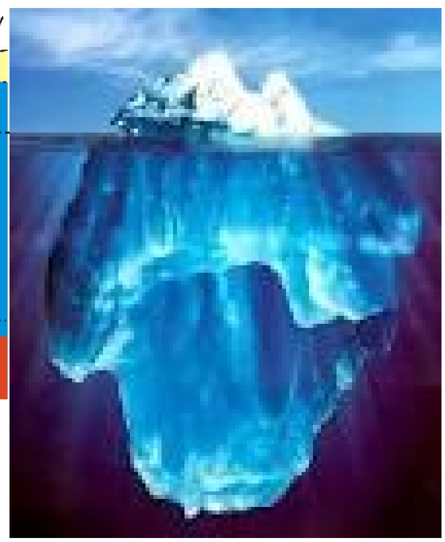
Badon Ghijben-Herzberg principle

The principle suggests an interface between fresh and saline groundwater

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





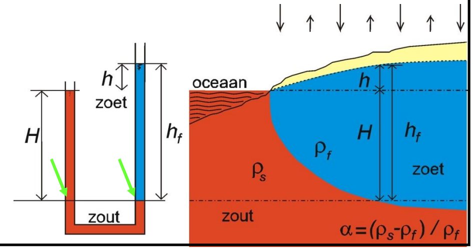


pressure saline groundwater=pressure fresh groundwater

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

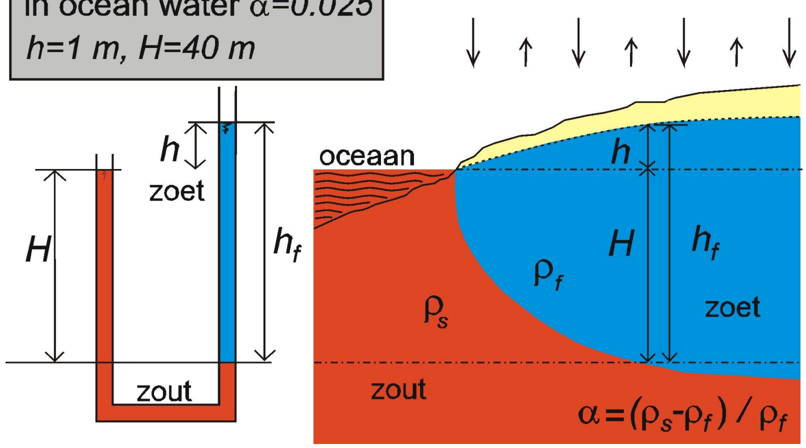
$$h = \frac{\rho_s - \rho_f}{\rho_f} H$$

$$h = \alpha H$$

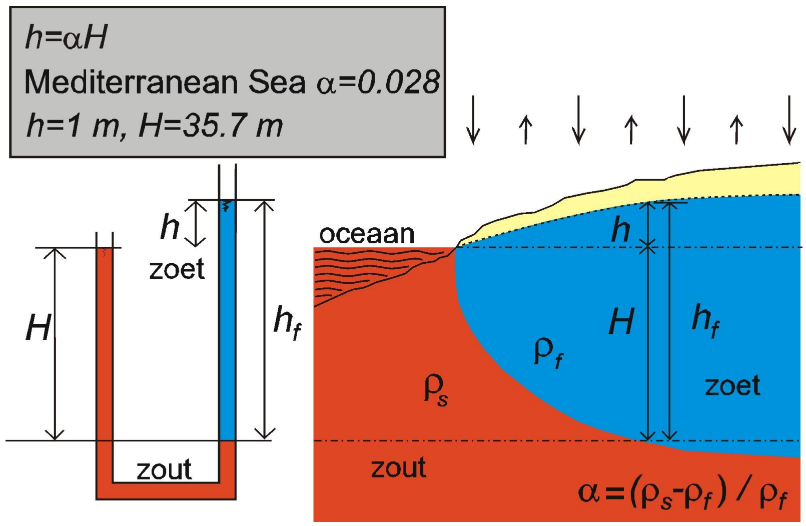


$$h = \alpha H$$

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



$$h = \alpha H$$



Badon Ghyben-Herzberg principle

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

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

Badon Ghyben-Herzberg principle

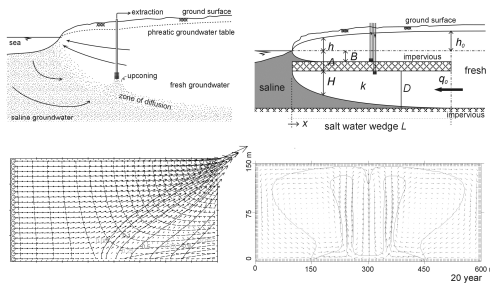
What is the case then $h \neq \alpha H$?

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

Analytical solutions

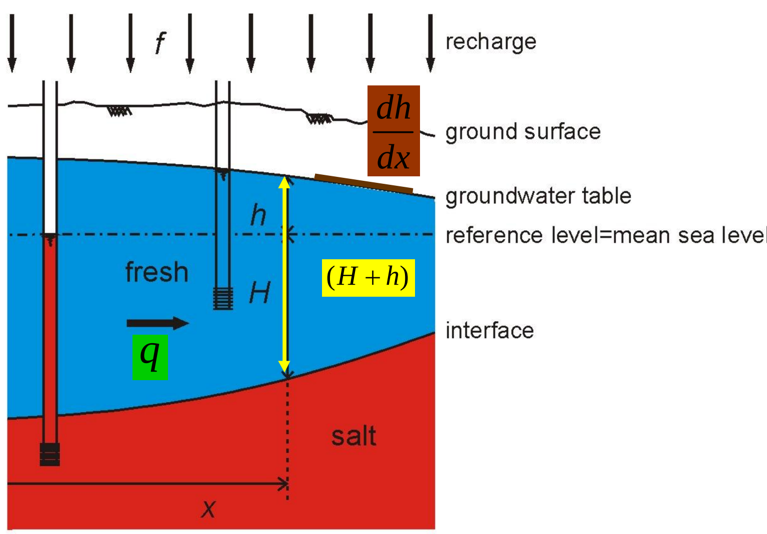
Analytical solutions

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 $q = fx + C1$

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

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

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

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)

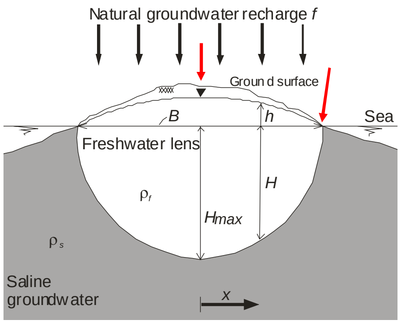
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}}$$

$$h = \alpha H$$

$$q = fx + C1$$

Example 1: Elongated island

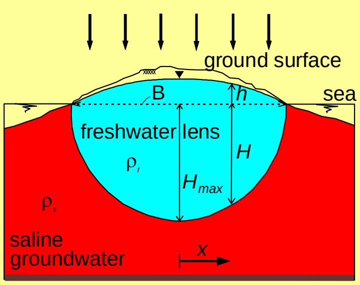
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}} \qquad q = fx + C1$$



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

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

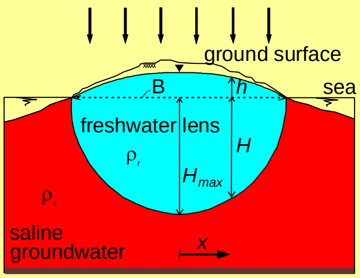
Volume lens

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

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

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)

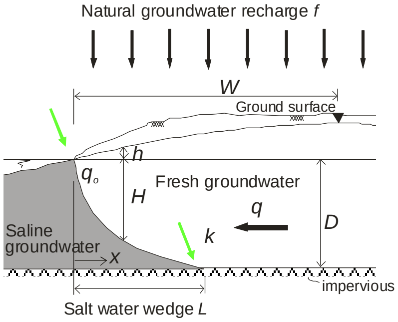
$V = 35203\text{m}^3/\text{m}'$

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

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

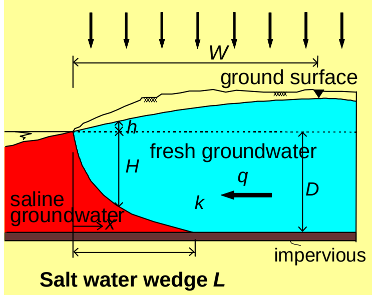
$x = 0 : q = q_0 \rightarrow q_0 = -fW \rightarrow C1 = q_0$

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

Length of salt water wedge

$x = L : H = D$

Example of analytical solutions (II)



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

$$q_0 = -fW$$

$$h = \alpha H$$

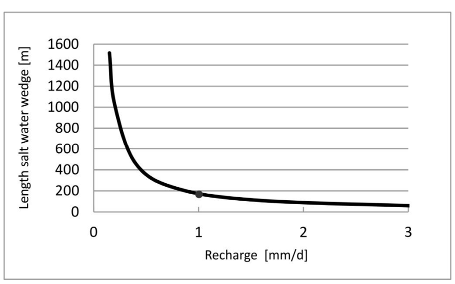
Example:

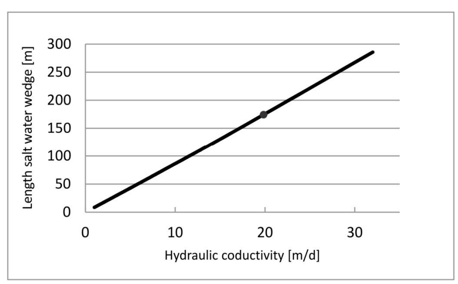
$$W = 3000\text{m},\ f = 0.001\text{m/day}, \alpha = 0.020, k = 20\text{m/day}, D = 50\text{m}$$

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

Lecture notes p. 33

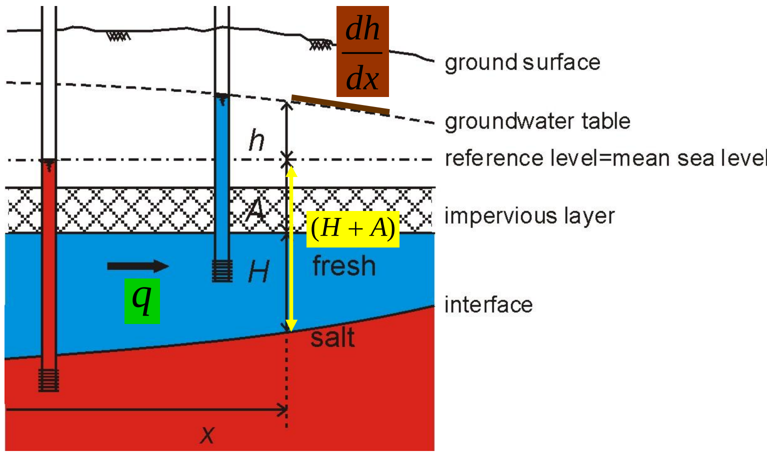
Length of the salt water wedge as a function of a. recharge and b. hydraulic conductivity





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)

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

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

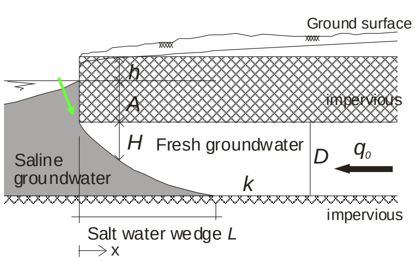
integration gives

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

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

Example 3: salt water wedge confined aquifer

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



Boundary condition

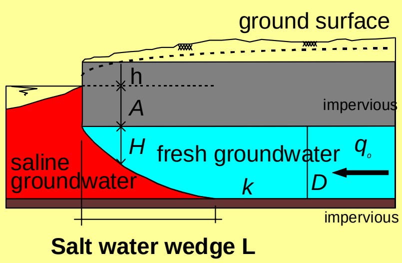
$$x = 0 : H = 0 \rightarrow C = 0$$

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

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

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

Example of analytical solutions (III)



Length of salt water wedge

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

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

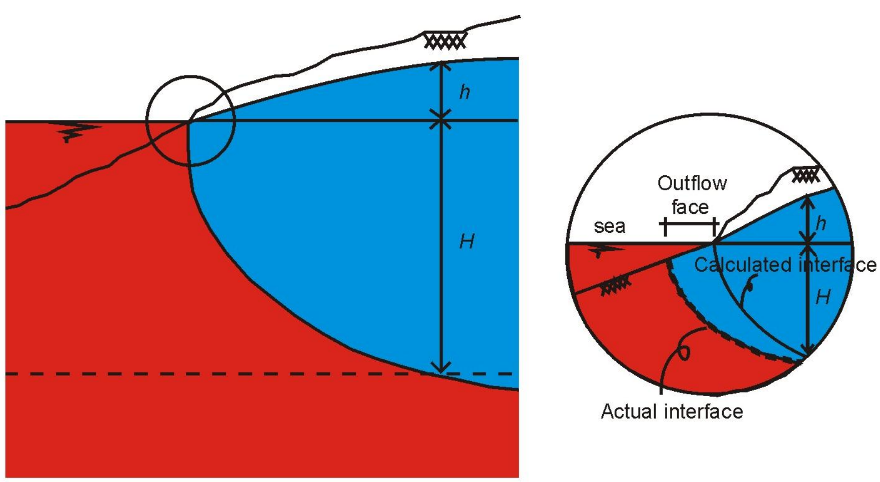
Example:

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

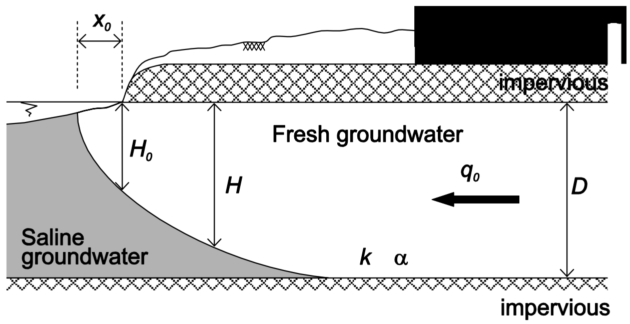
$$L = 250\text{m}$$

Lecture notes p. 35-36

Outflow face (Submarine Groundwater Discharge)



Outflow face (Submarine Groundwater Discharge)

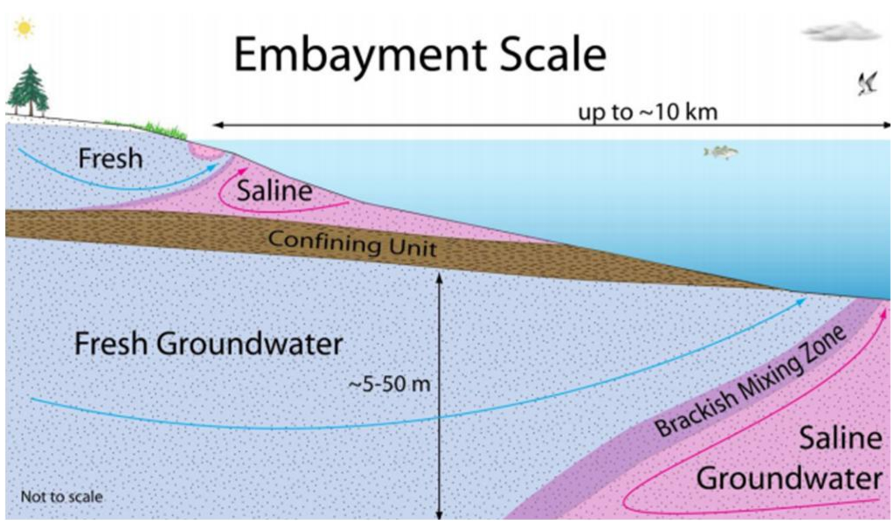


$$x_0 = \frac{q_0}{2k\alpha} \qquad H_0 = \frac{q_0}{k\alpha}$$ Glover (1959)

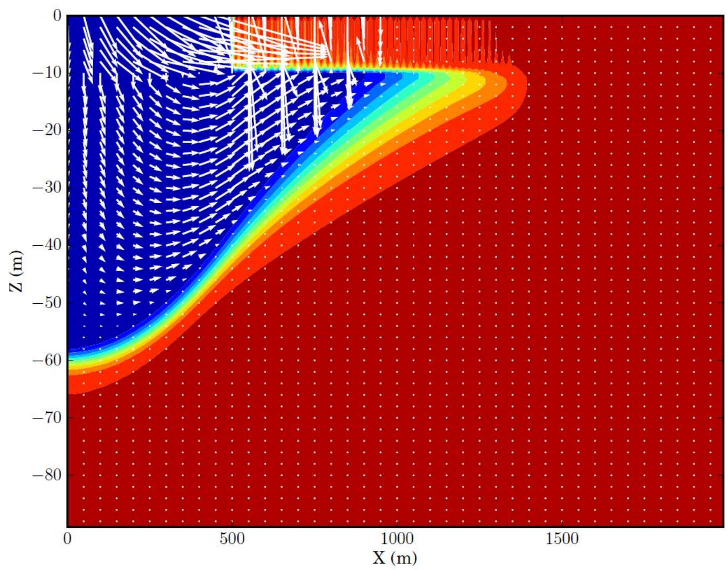
Example:
x_0= f*L/(2ka) = 0.001m/d*20000m/(2*20*0.025) = 20m (only!)

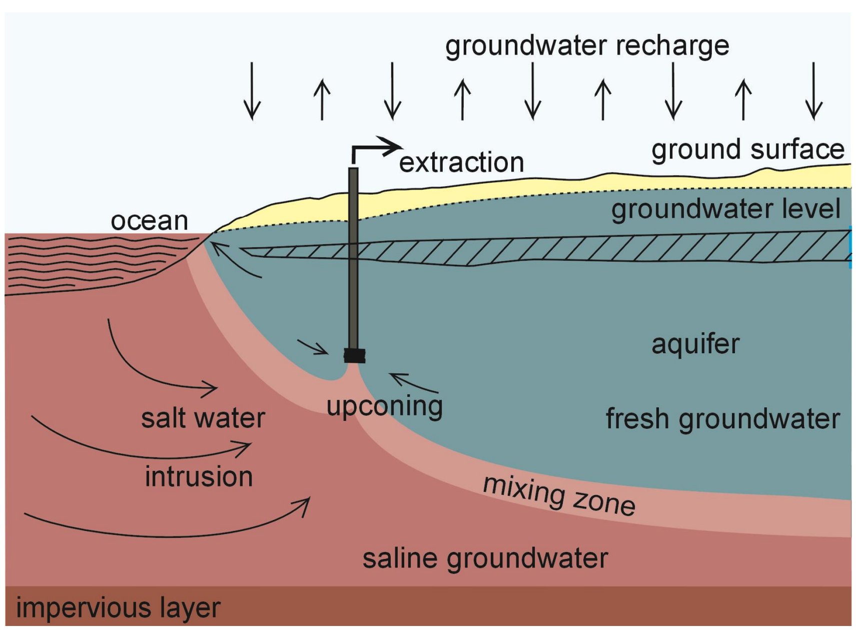
Note: no resistance layer offshore

Outflow face (Submarine Groundwater Discharge)

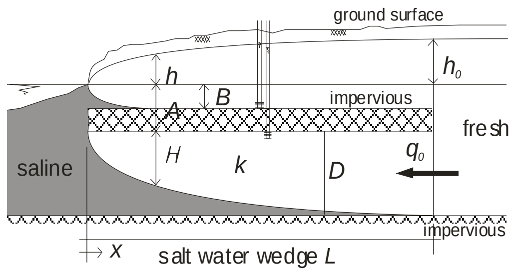


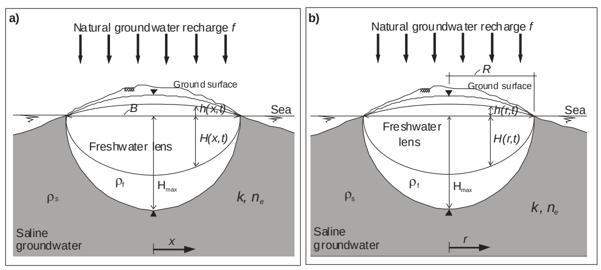
Outflow face (Submarine Groundwater Discharge)





See the lectures for more cases

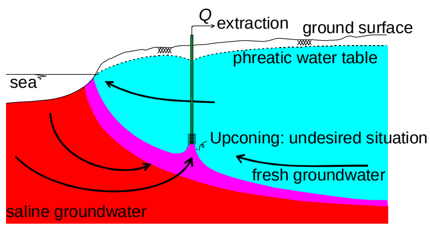




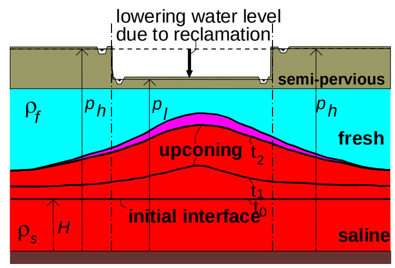
Upconing processes

Upconing of saline groundwater

Under an extraction well



Under a low-lying polder area

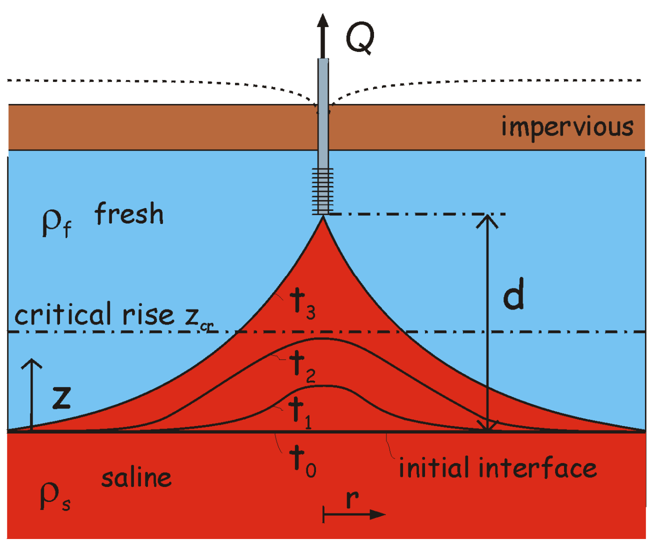


- movement of saline groundwater to extraction wells
- increase in salinity (>150-200 mg Cl-/l)
- lowering of the piezometric head (leads to land subsidence: e.g. Los Angeles: 9 m in the 1930's)

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

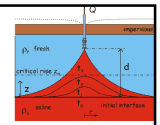
Examples of analytical solutions (IV)

Upconing of saline groundwater under an extraction well



Lecture notes p. 44

Examples of analytical solutions (IV)



Upconing of saline groundwater under an extraction well

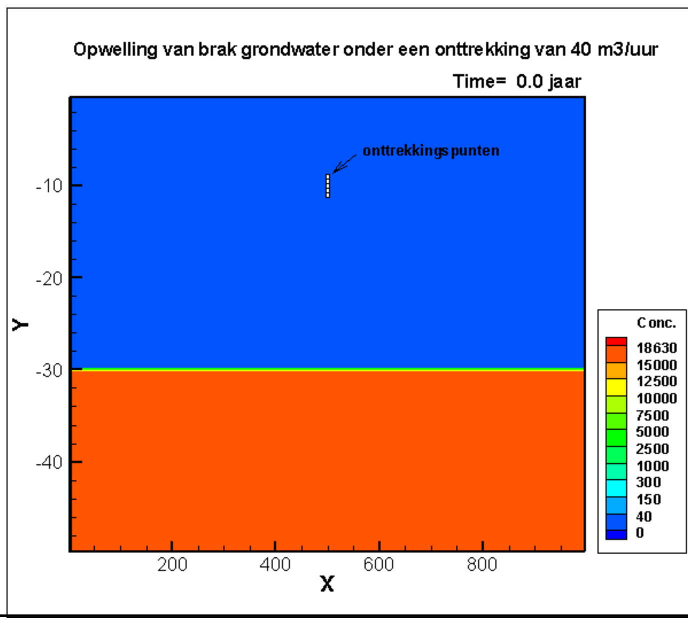
$$z(r,t) = \frac{Q}{2\pi\alpha k_x d}\left[\frac{1}{(1+R'^2)^{1/2}} - \frac{1}{[(1+\gamma')^2 + R'^2]^{1/2}}\right]$$

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

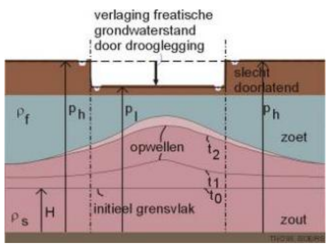
Dagan & Bear, 1968, J. Hydraul. Res 6, 1563-1573

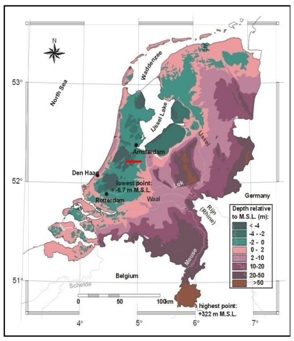
Lecture notes p. 44

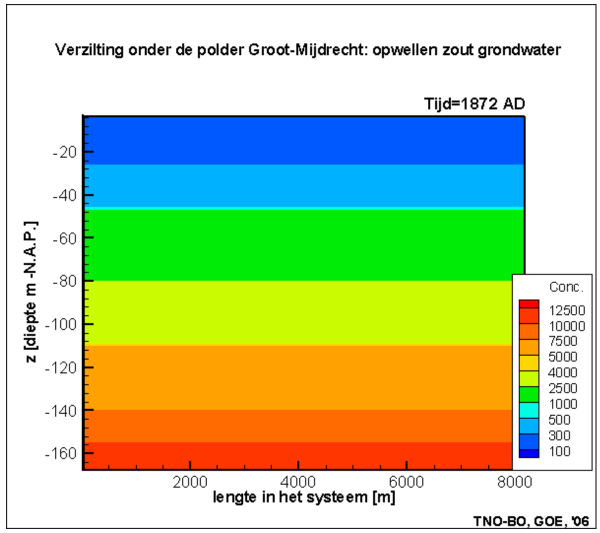
Upconing of salt under an extraction



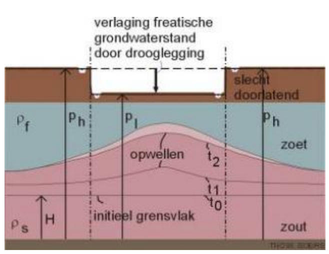
Upconing under a low-lying polder (Groot-Mijdrecht)

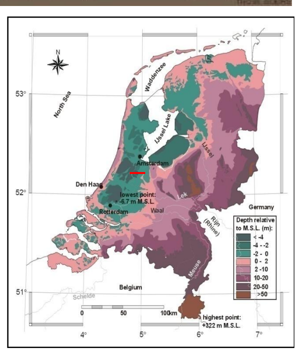


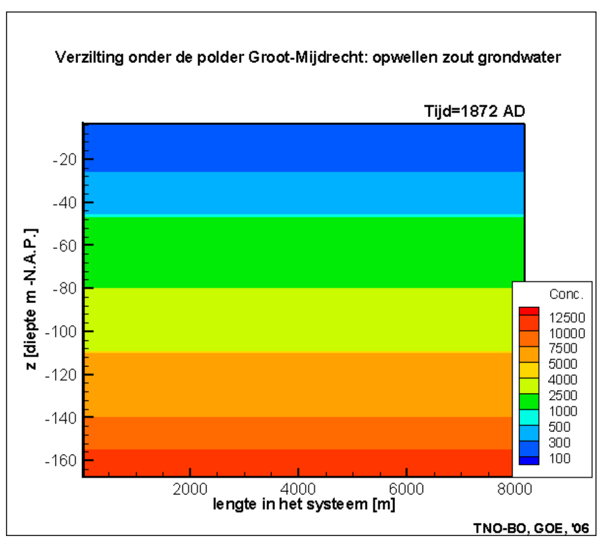




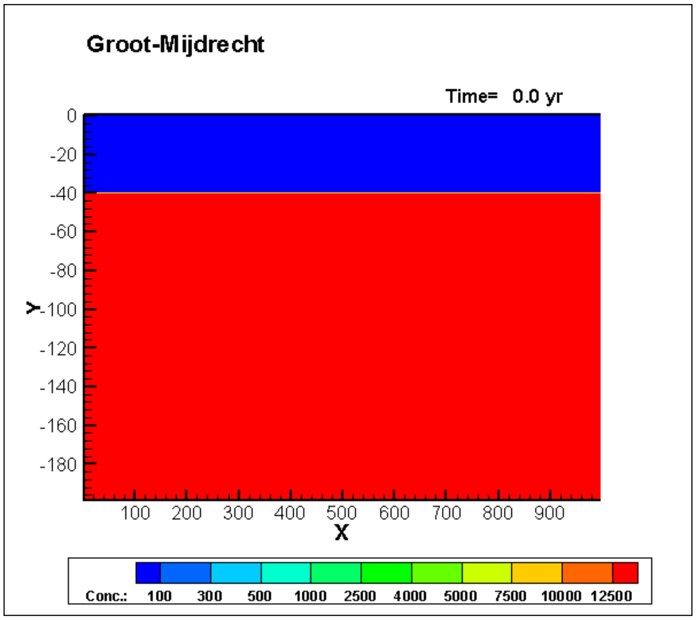
Upconing under a low-lying polder (Groot-Mijdrecht)



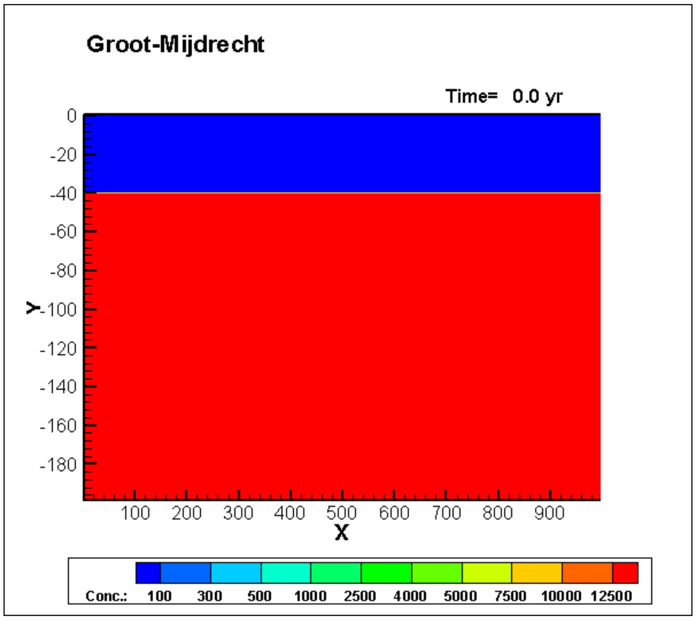




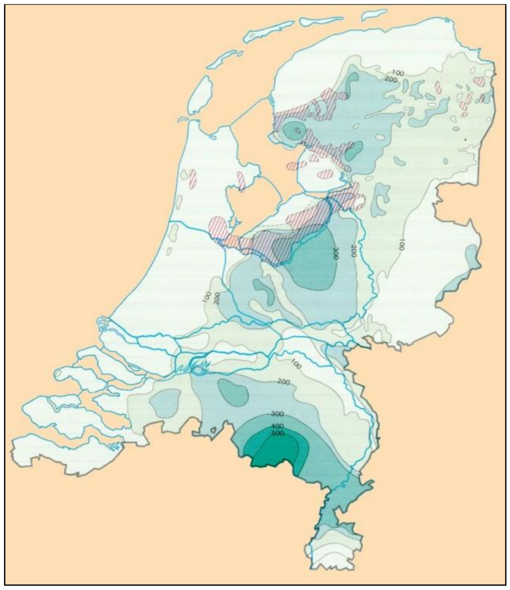
Upconing under a low-lying polder (Groot-Mijdrecht)



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

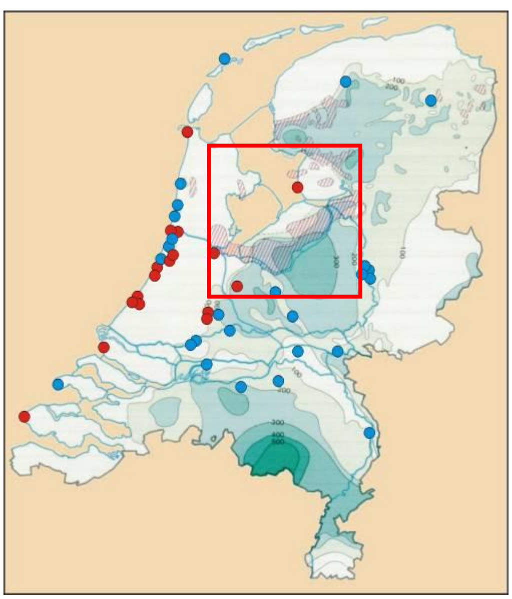


Fresh-salt interface (150 mg Cl^-/l)



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

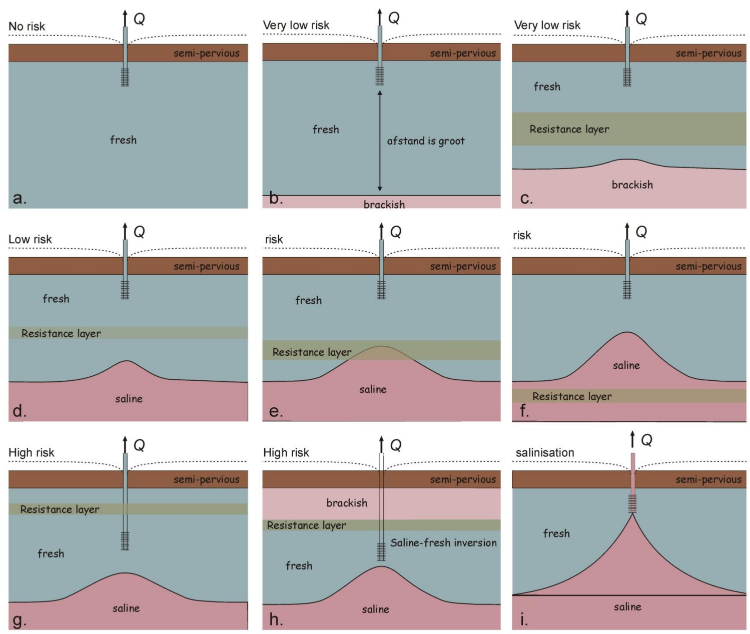
Availability of fresh groundwater



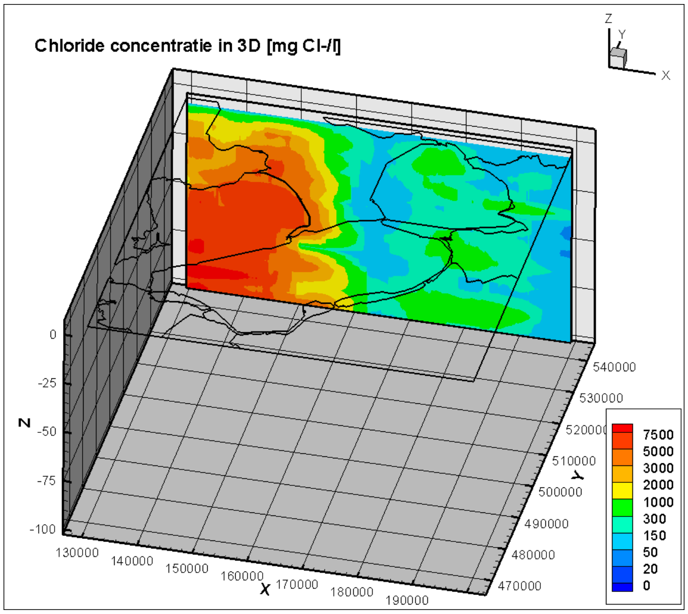
- <100 m
- 100-200 m
- 200-300 m
- 300-400 m
- 400-500 m
- >500 m
- >inversion (salt above fresh)

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

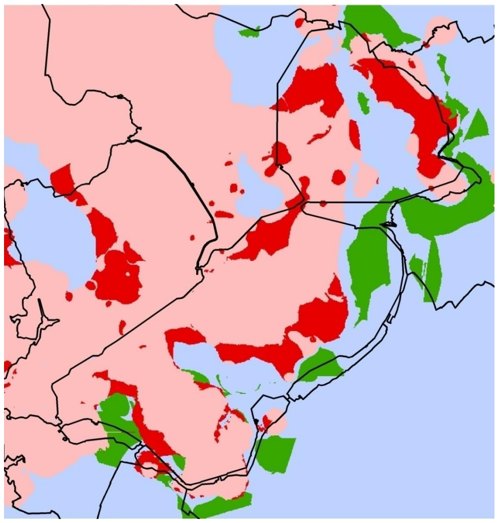
Different risks of upconing saline groundwater



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:

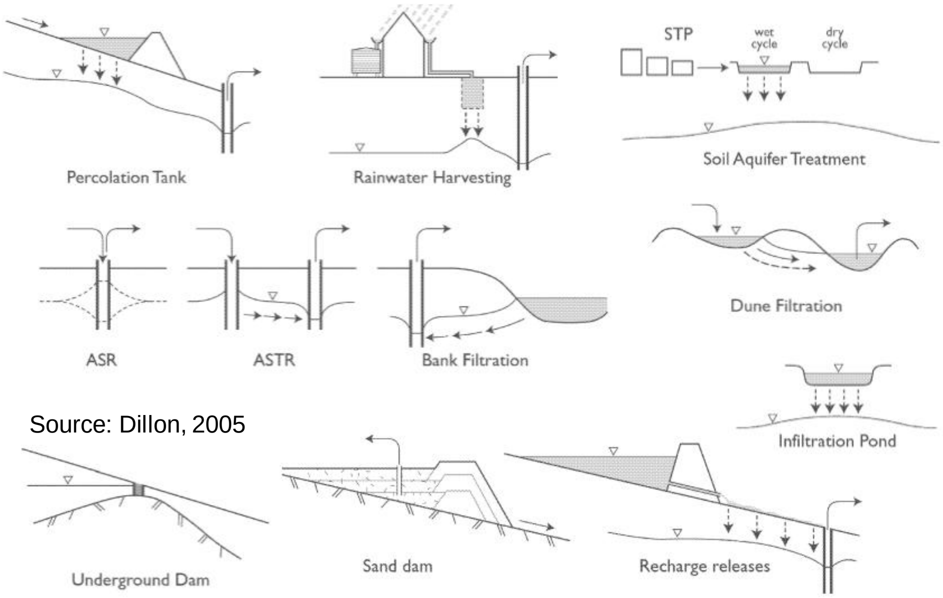
- Monitoring of salinities and piezometric levels
- Numerical modelling of salt water intrusion

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

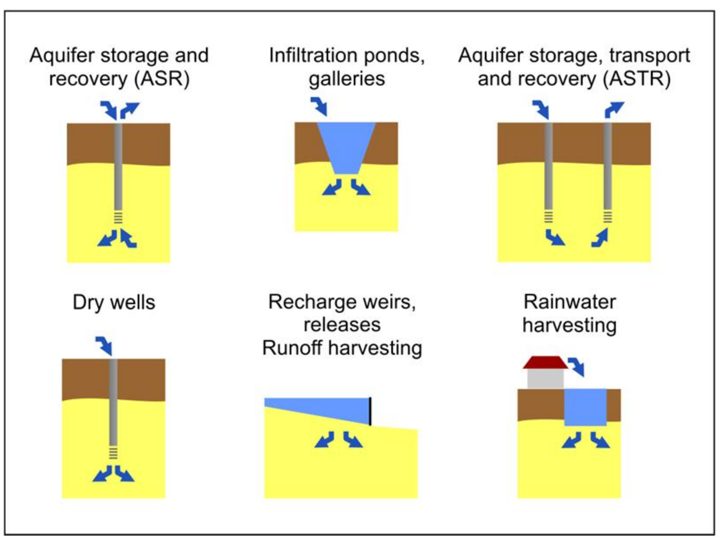
"potential to be a major contribution to UN Millennium Goals for Water Supply"



Source: Dillon, 2005

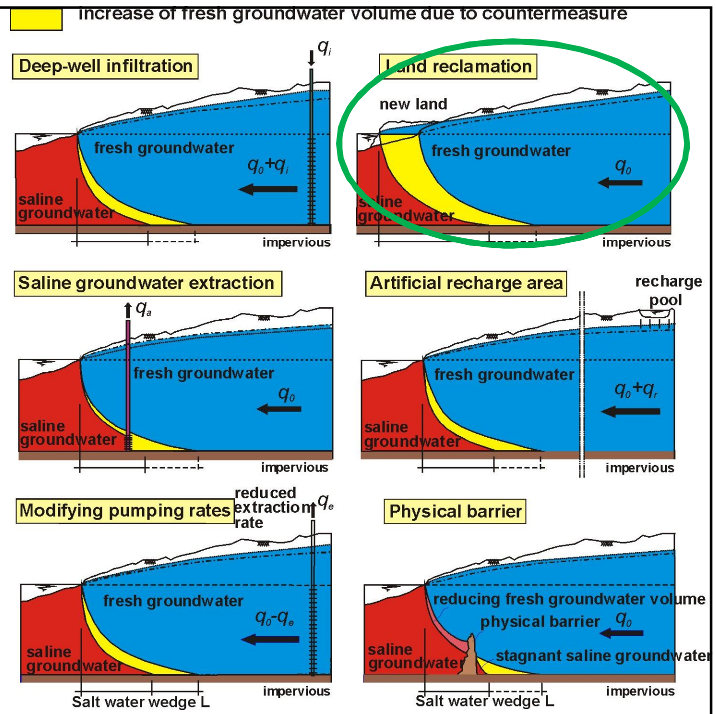
Aquifer Storage and Recovery / Managed Aquifer Recharge

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



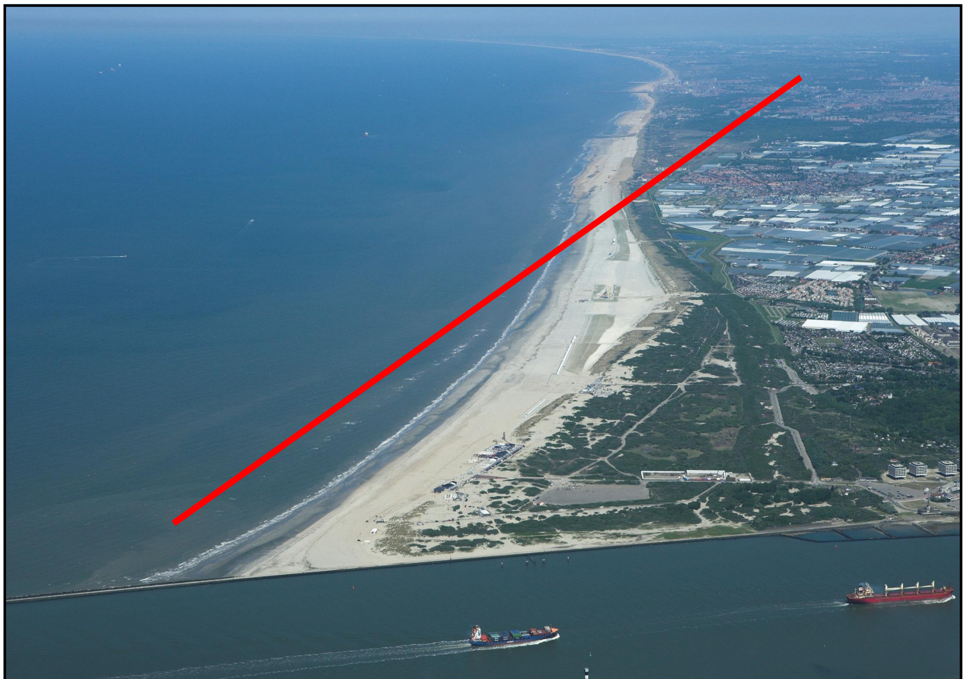
Source: Dillon, 2005

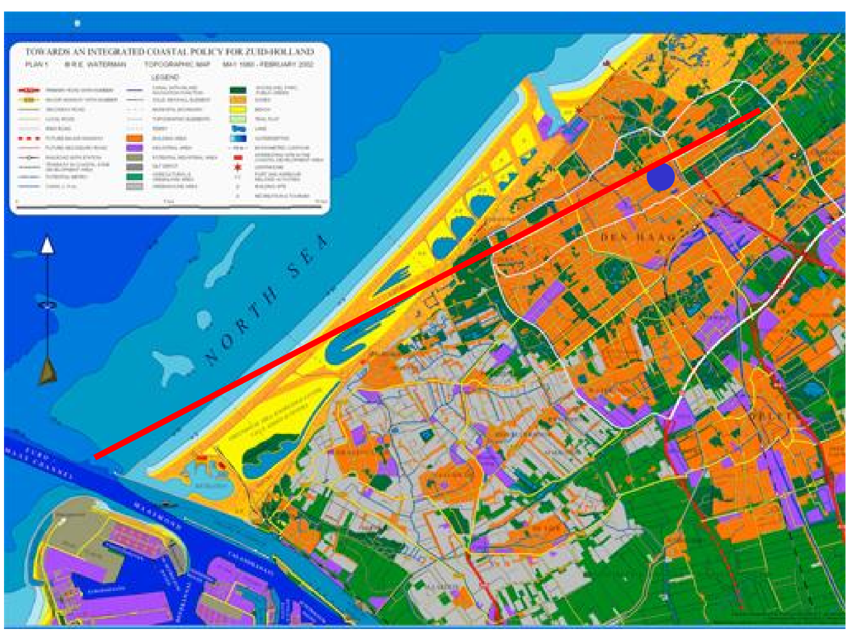
Technical measures to compensate salt water intrusion



Land reclamation

The Zandmotor: effects at the hinterland?



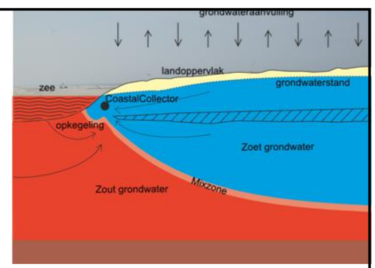


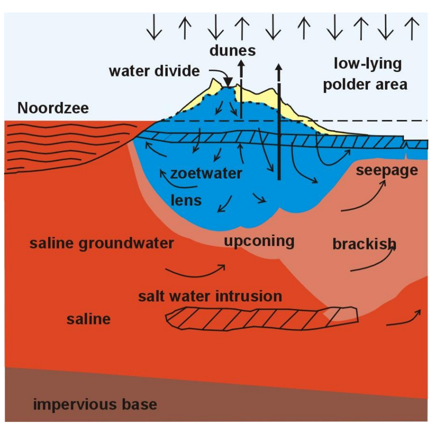
TOWARDS AN INTEGRATED COASTAL POLICY FOR ZUID-HOLLAND
TOPOGRAPHIC MAP
LEGEND
NORTH SEA
DEN HAAG

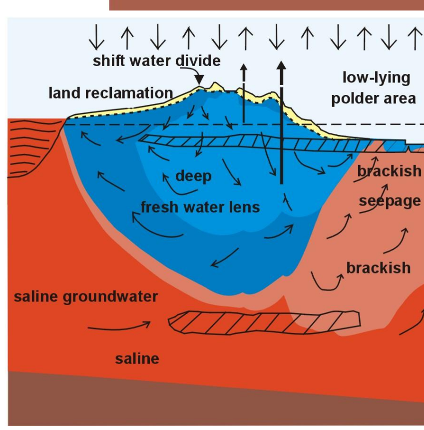
The Zandmotor: effects at the hinterland?

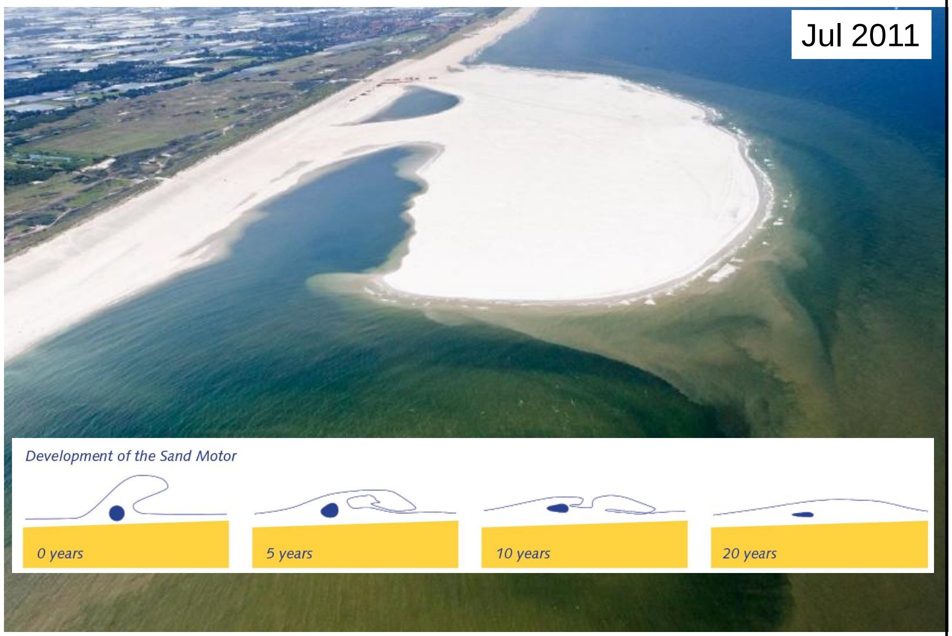
The Zandmotor

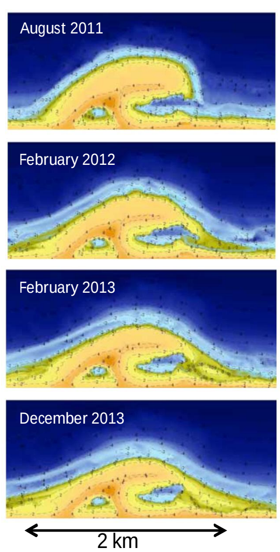
storage extra fresh water?

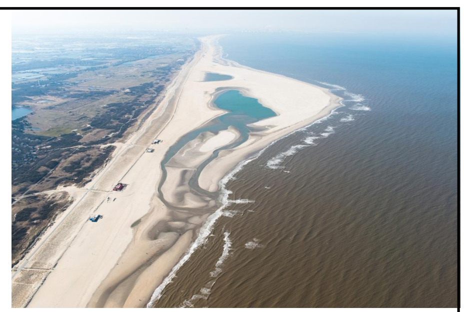




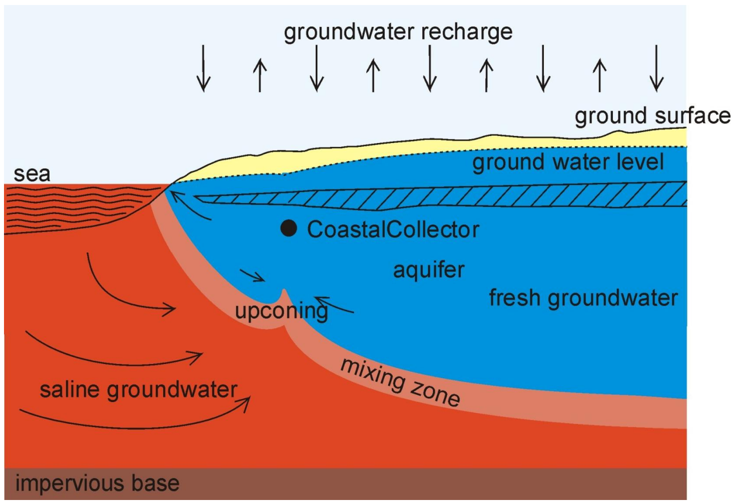



Jul 2011
Development of the Sand Motor
0 years
5 years
10 years
20 years

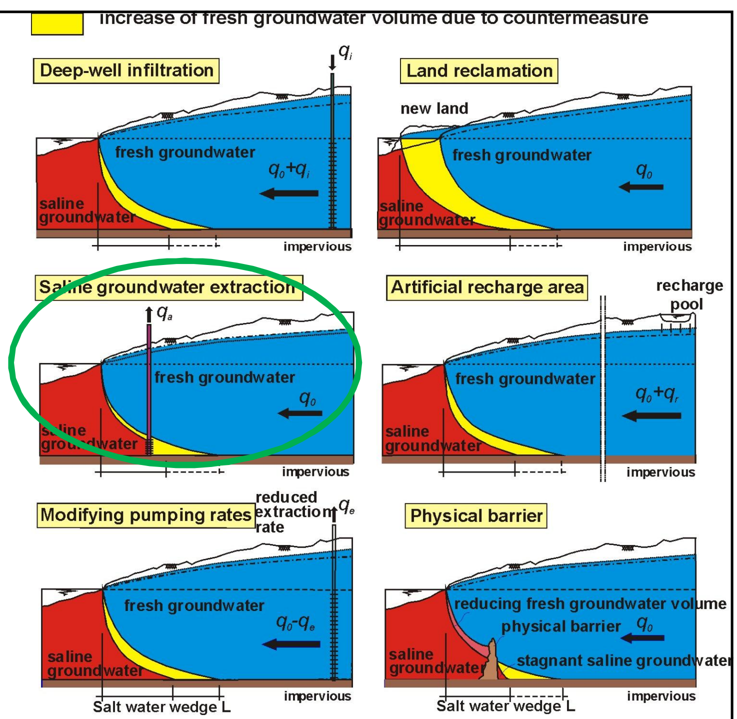

August 2011
February 2012
February 2013
December 2013
2 km



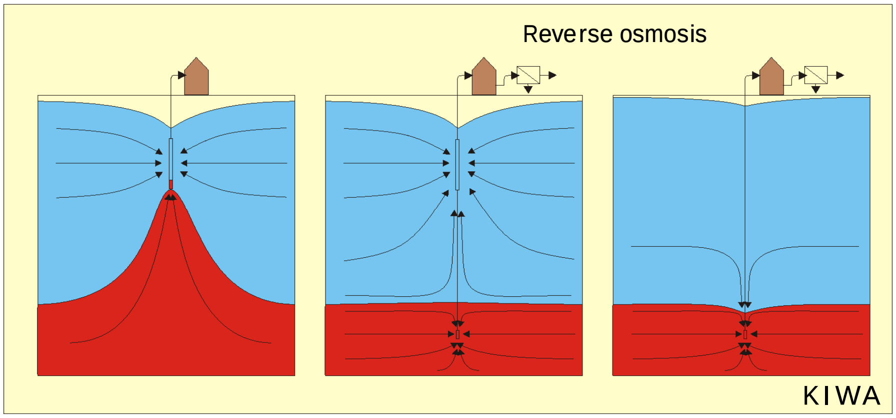
The Coastal Collector



Technical measures to compensate salt water intrusion



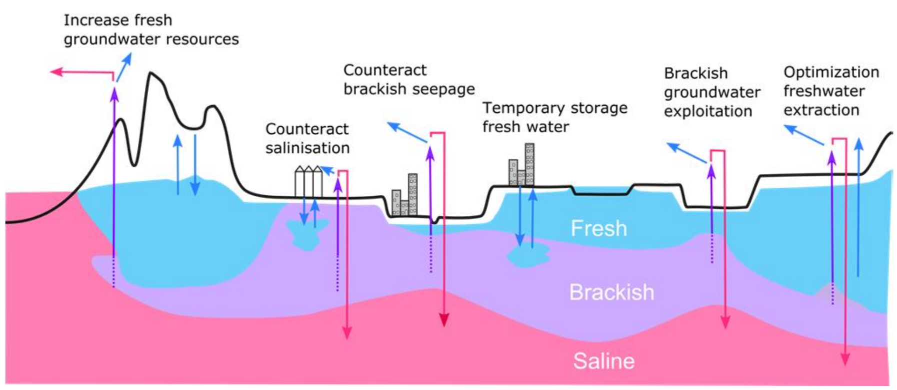
Solution: The Fresh Holder



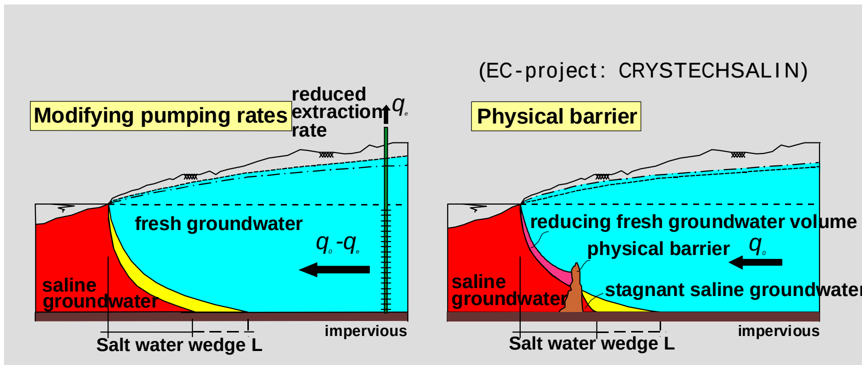
Upconing can be prevented by the extraction of brackish groundwater

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

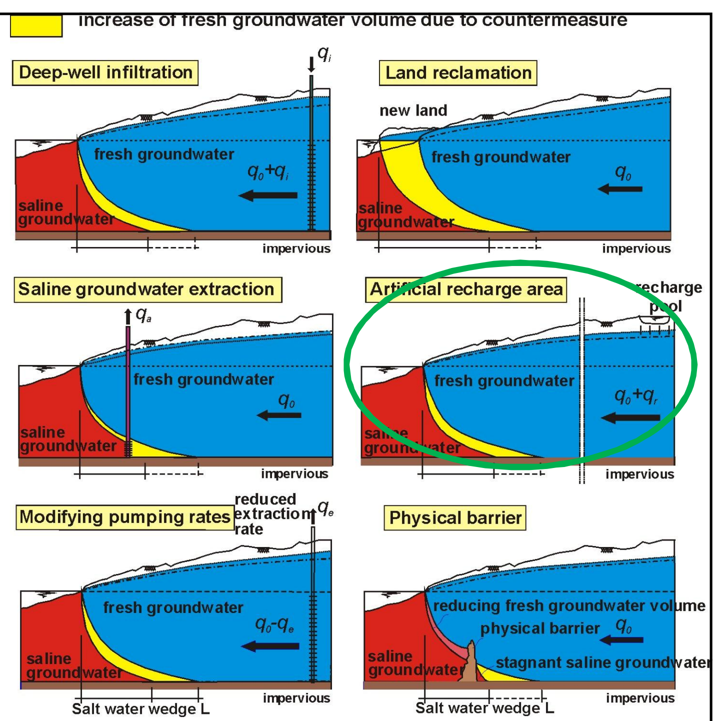
COASTAR: COastal Aquifer STorage And Recovery



Countermeasures of salt water intrusion



Technical measures to compensate salt water intrusion

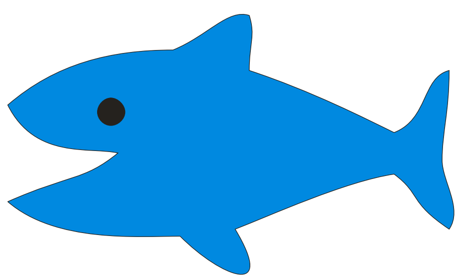


Base idea

Many local solutions for fresh groundwater supply can have regional impact

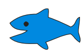
Starring

solution fresh groundwater supply



Starring

Local solution fresh groundwater supply



Starring

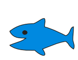
climate and global change

Starring

climate and global change

Solutions and responses

Local solution fresh groundwater supply

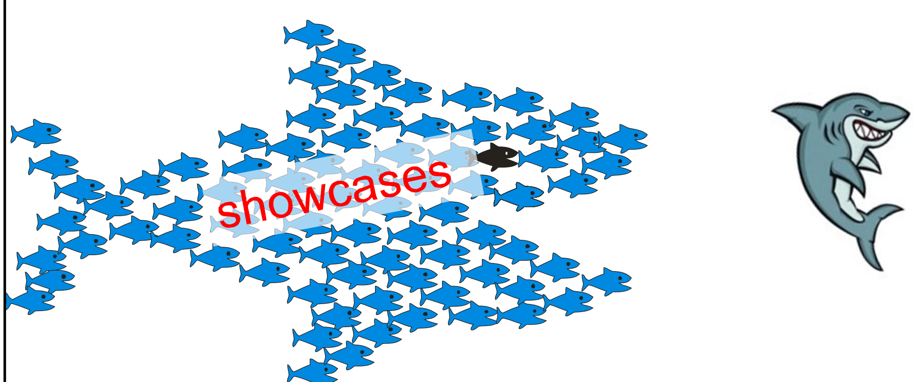


climate and global change

What should be the response?

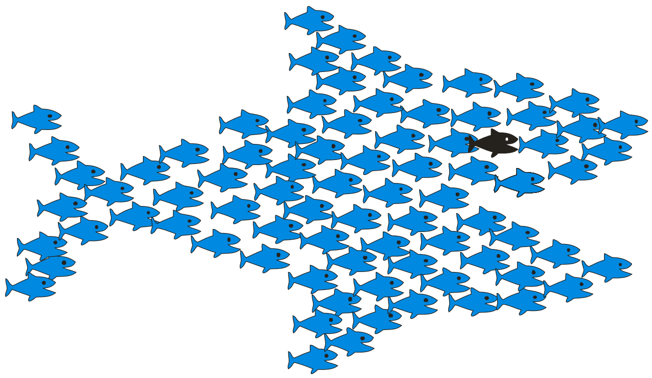
Many local solutions fresh groundwater supply

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



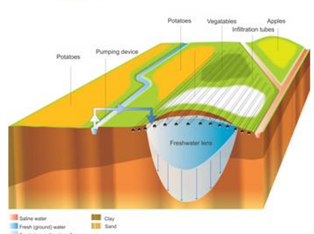
Aquifer Storage and Recovery in the coastal zone

www.go-fresh.info

Goal:
Increase fresh groundwater resources in saline seepage areas in the southwestern part of the Dutch Delta

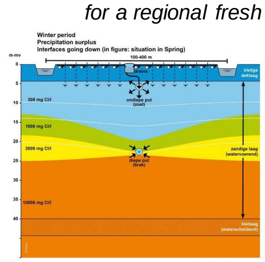
Methods:
3 pilot studies: infiltration of fresh water in times of water excess and extraction in times of droughts

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



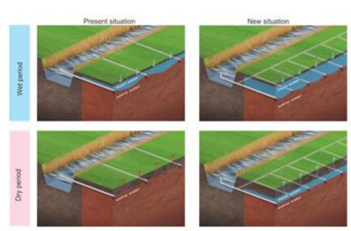
Creekridge Infiltration Test

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



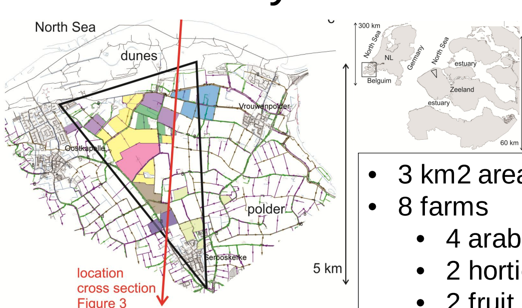
Drains2Buffer

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

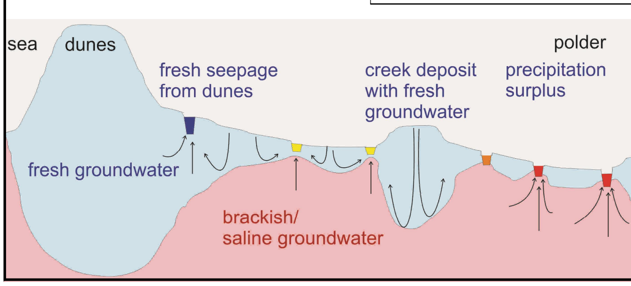
Problem statement

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

Case study: Water Farm

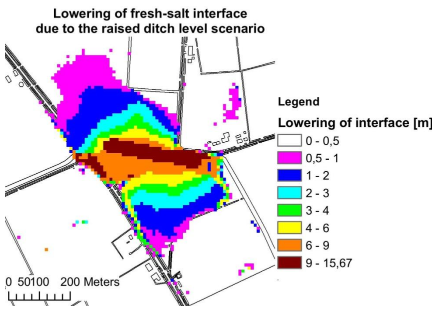


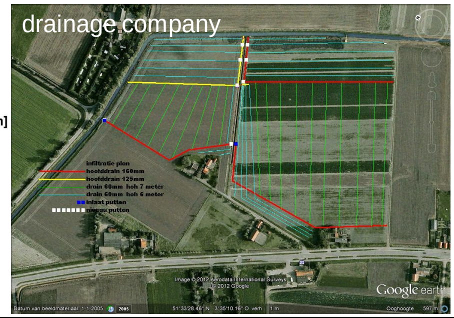
- 3 km2 area
- 8 farms
  - 4 arable farming
  - 2 horticulture
  - 2 fruit
- start case study 2010



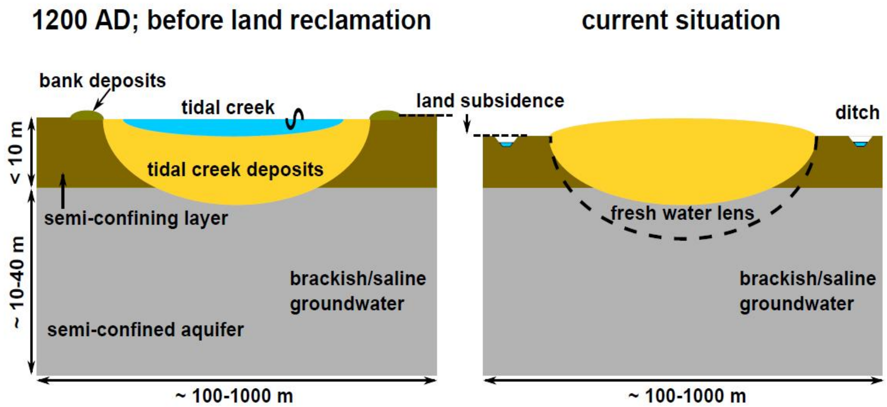
- codesign measures
- communication to outside world

Researchers: scenario analysis



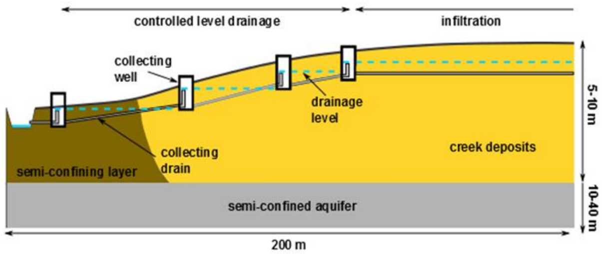


Creek ridges

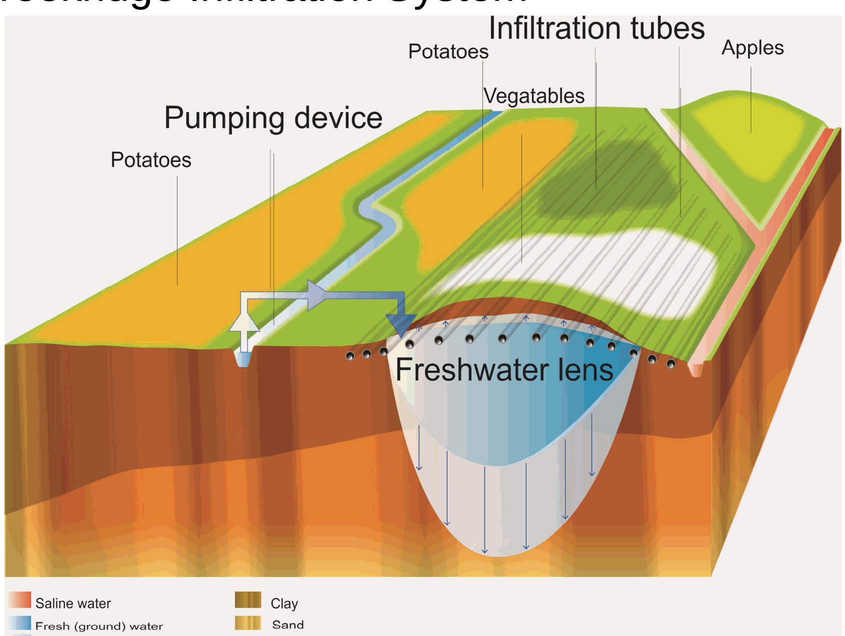


Measure

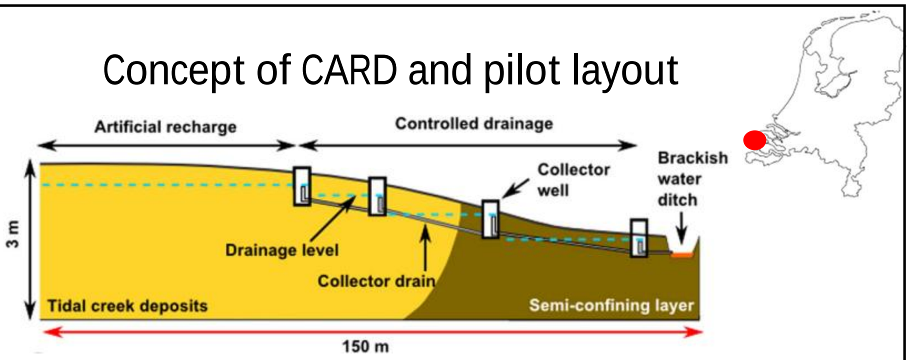
- Controlled level drainage
- Increase groundwater level

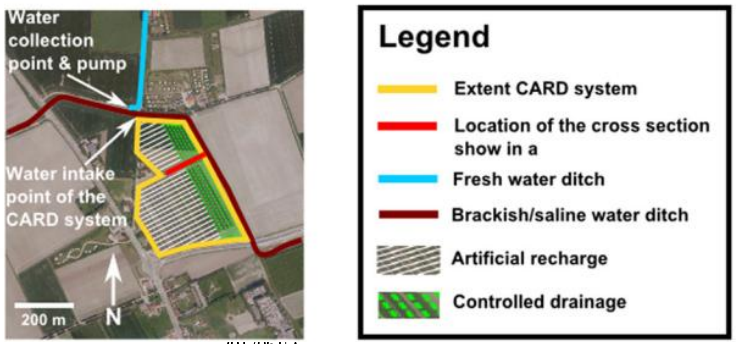


Creekridge Infiltration System

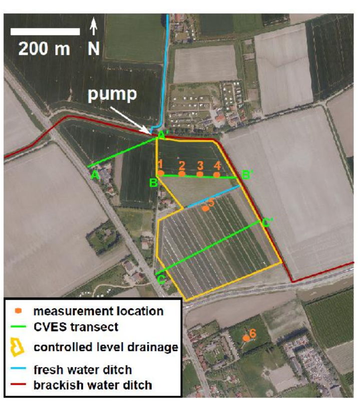


Concept of CARD and pilot layout





Installation of drainage and monitoring network

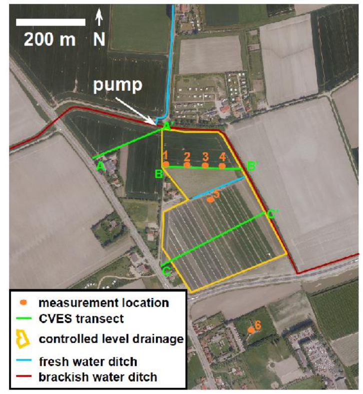


various types of field measurements

Different types of field measurements applied

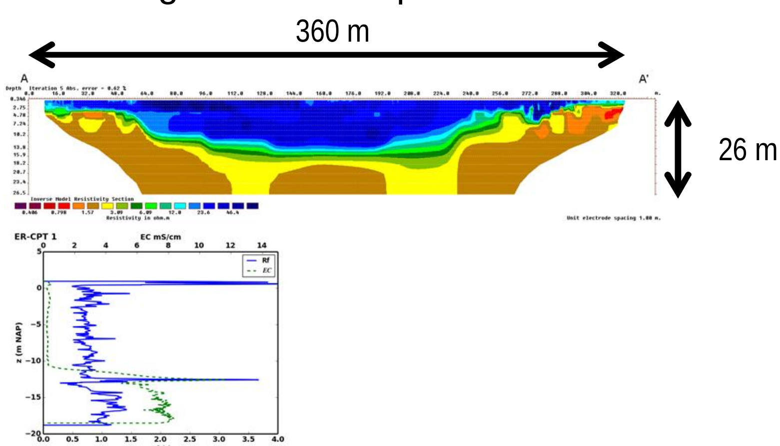
Measurement type	Purpose
Pressure transducers[a]	Groundwater levels
Sampling using piezometer nest	EC_{w20}
SLIMFLEX[b]	EC_{bulk}
CPT[c]	Lithology and EC_{bulk}
CVES[d]	EC_{bulk}
SMD[e]	EC_{bulk}

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



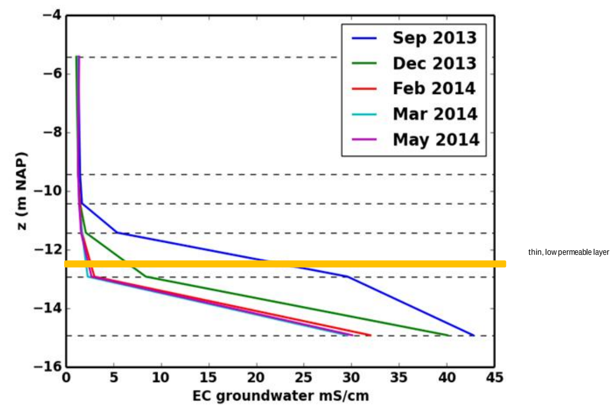
Key field observations (1)

- Fresh groundwater up to -12 m NAP

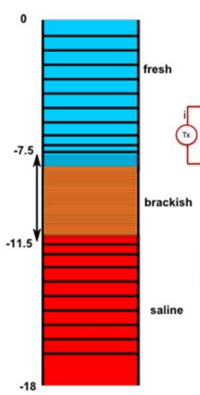


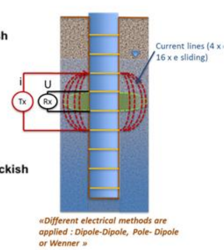
Key field observations (2)

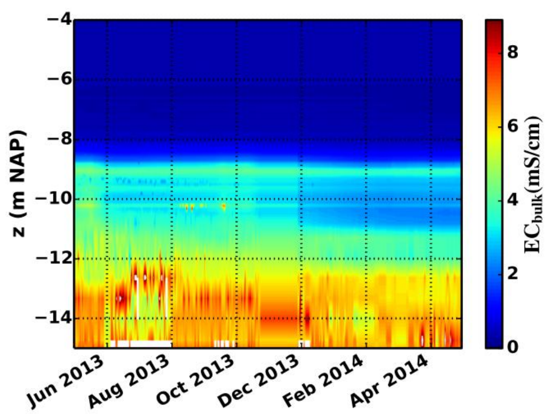
- Freshening up to 2m



Subsurface Monitoring Device (SMD): Monitoring salinities







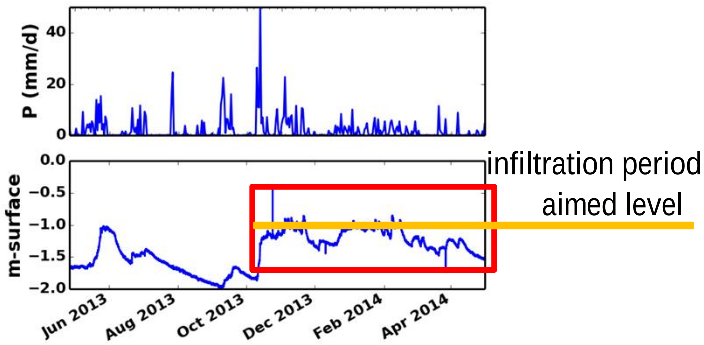
20170615: Proeftuin ZL

imaGeau

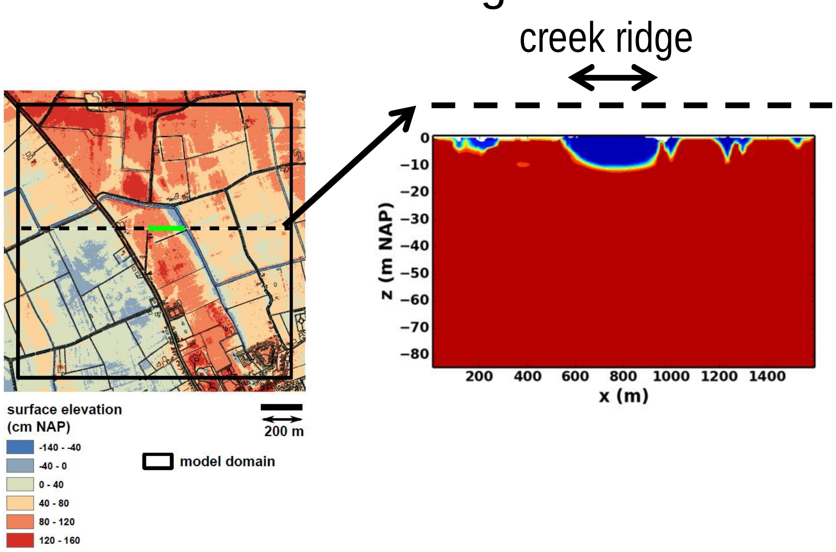
FUGRO

Key field observations (3)

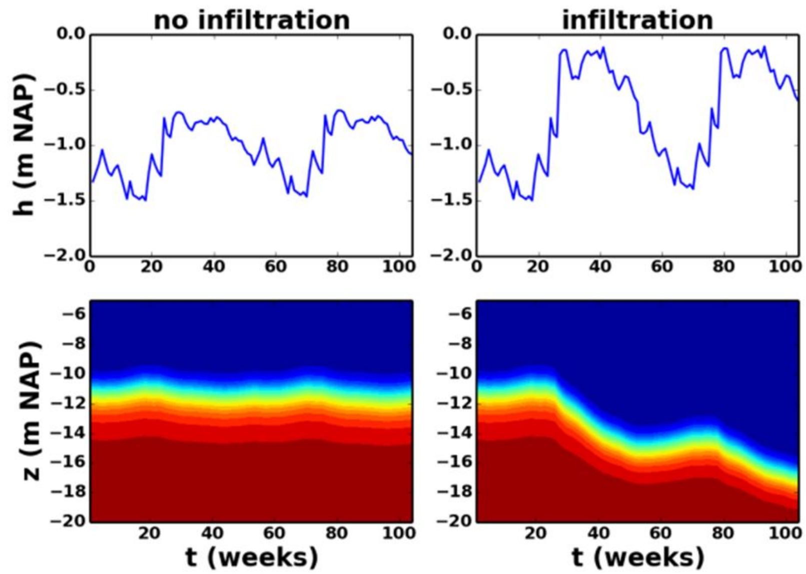
- Groundwater levels and precipitation



Modeling

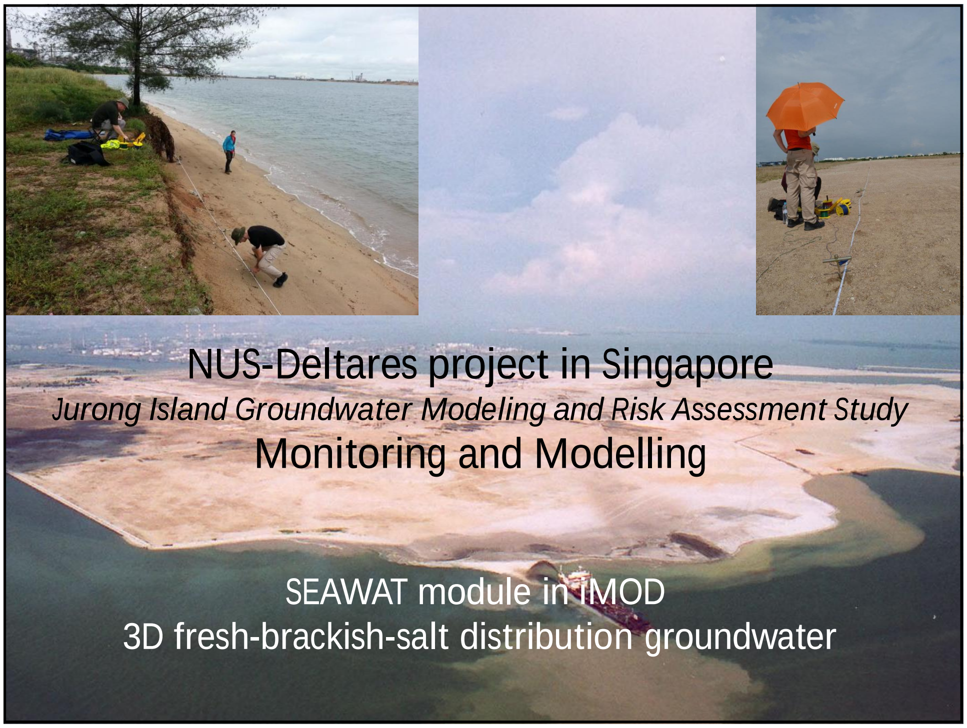


Influence of infiltration

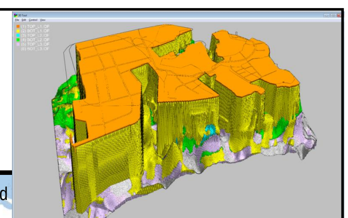


Singapore Jurong Island

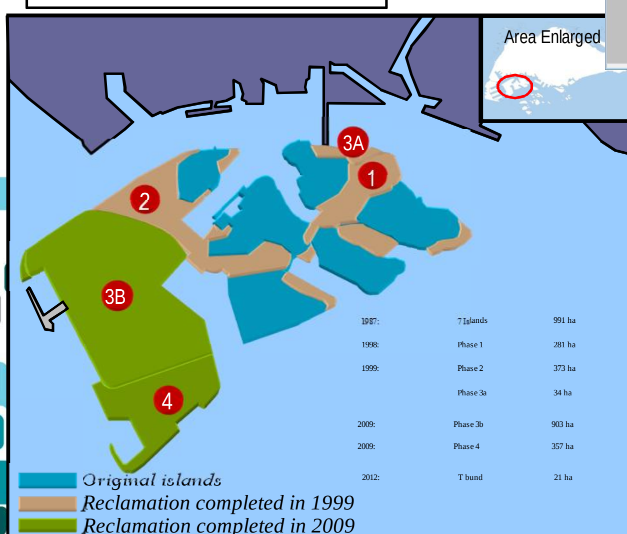
Aquifer Storage and Recovery



Transformation of Jurong Island



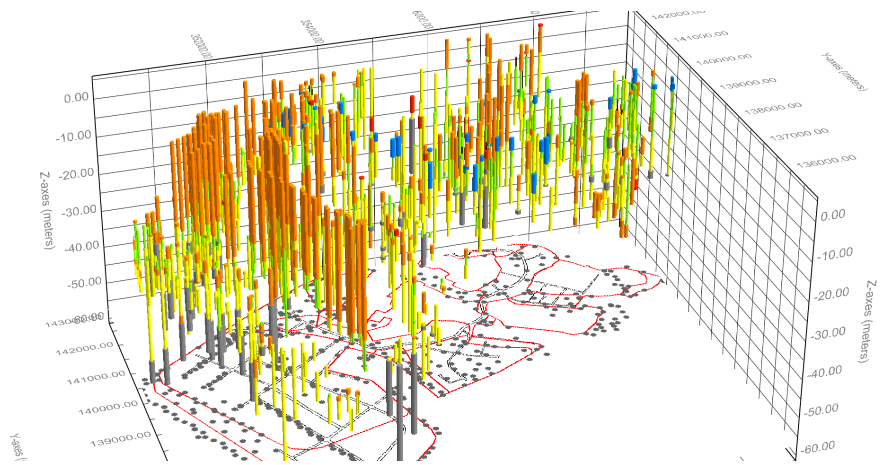
Reclamation Phasing



1987:	7 Islands	991 ha
1998:	Phase 1	281 ha
1999:	Phase 2	373 ha
	Phase 3a	34 ha
2009:	Phase 3b	903 ha
2009:	Phase 4	357 ha
2012:	T bund	21 ha

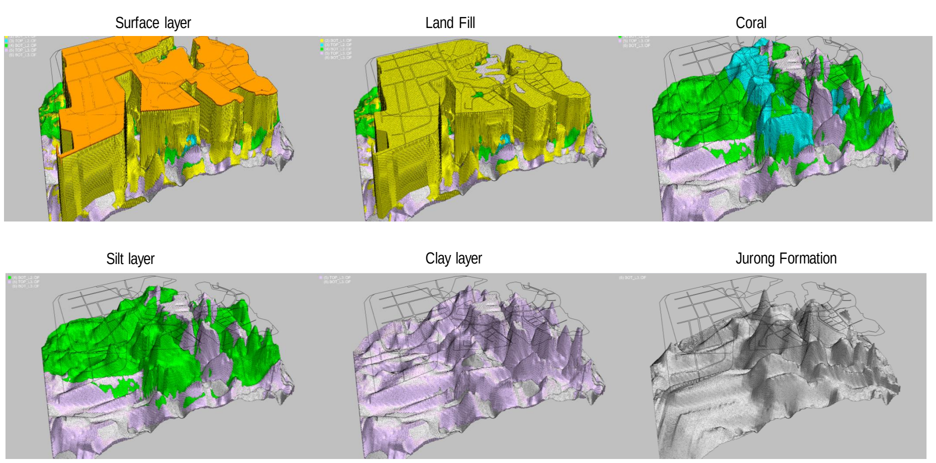
- In 1980s, 7 islands were reclaimed individually to a total land area of 991 ha. *(1960s was 118 ha)*.
- Full-scale reclamation began from **1995** to form Jurong Island.
- Phases 1, 2, 3a completed in 1999; Phases 3b and 4 was completed in 2009.
- Current land area about **2960 ha.**

Boreholes

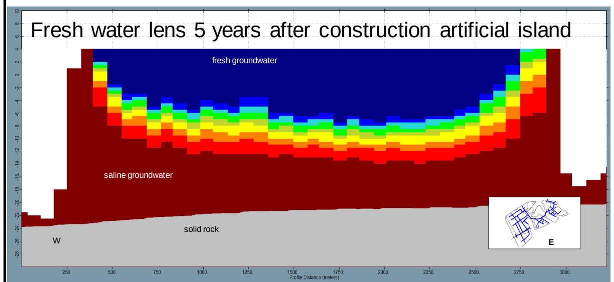


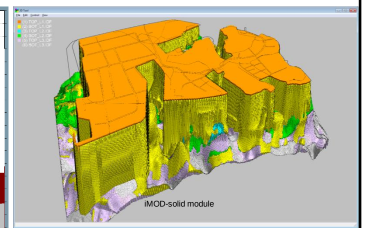
509 boreholes were converted from PDF to IPF, the format that iMOD can read

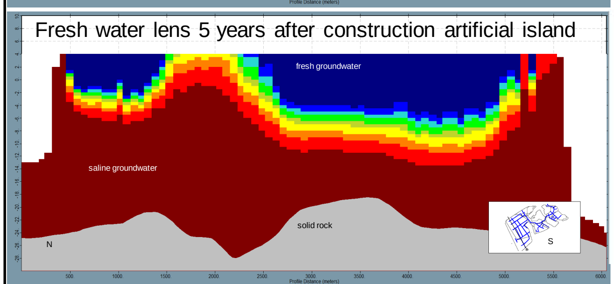
SubSoil Model

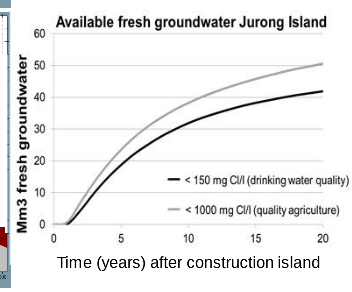


iMOD-SEAWAT Jurong Island Singapore

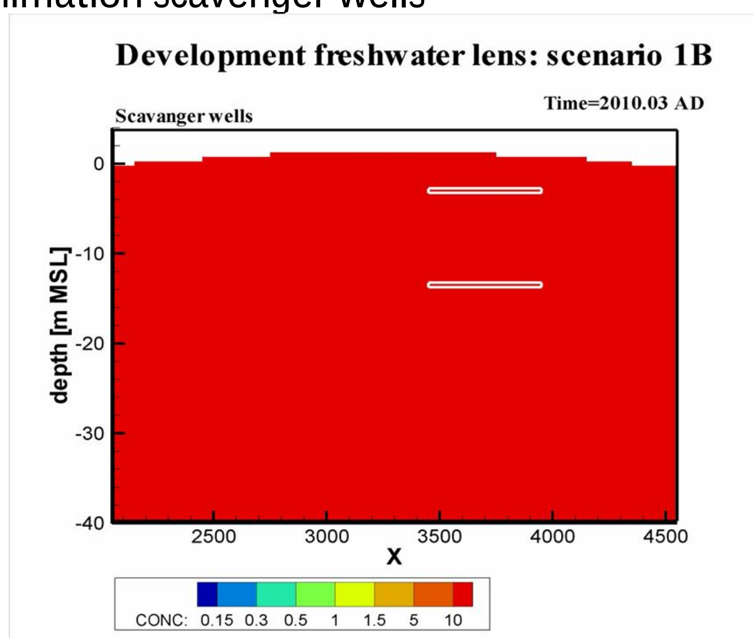


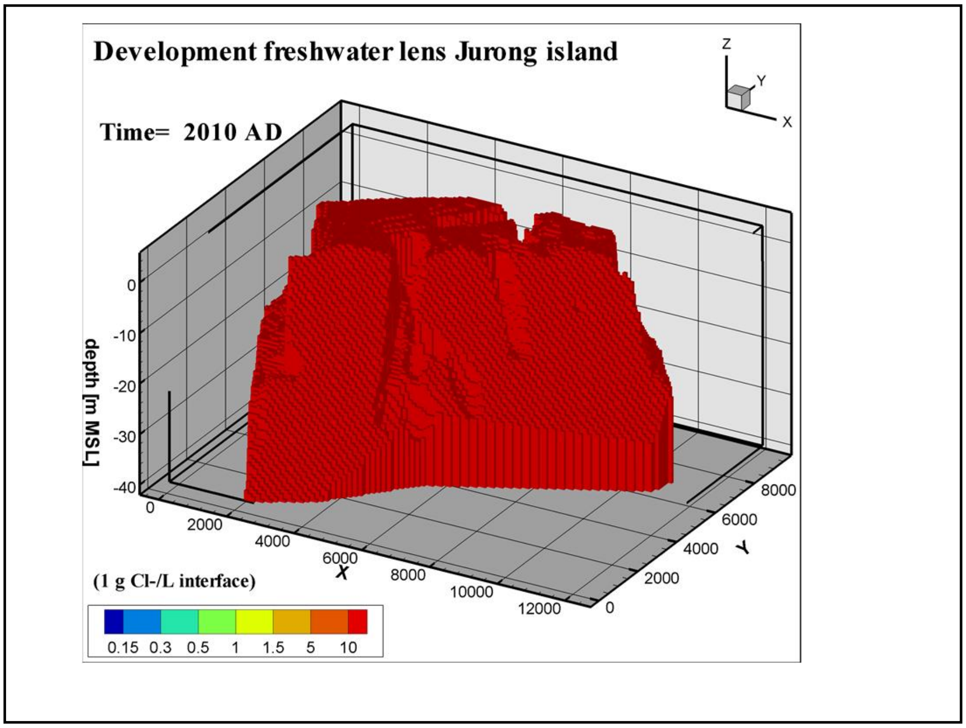




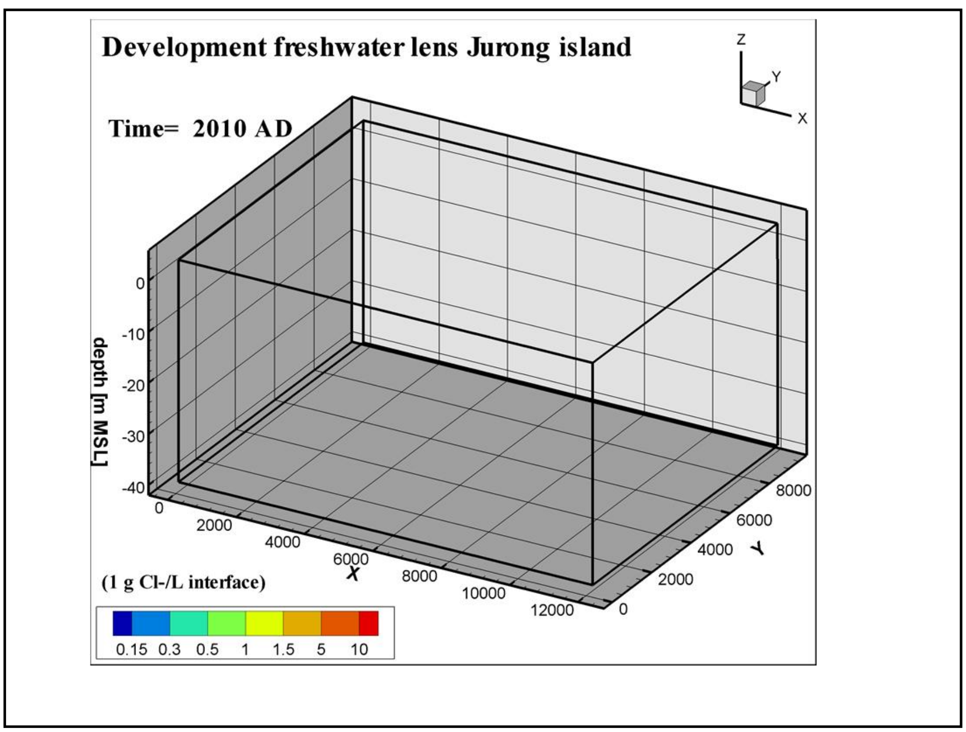


Animation scavenger wells





Development freshwater lens Jurong island
Time= 2010 AD
depth [m MSL]
0
-10
-20
-30
-40
0
2000
4000
6000
X
8000
10000
12000
0
2000
4000
6000
8000
Y
Z
Y
X
(1 g Cl-/L interface)
0.15 0.3 0.5 1 1.5 5 10

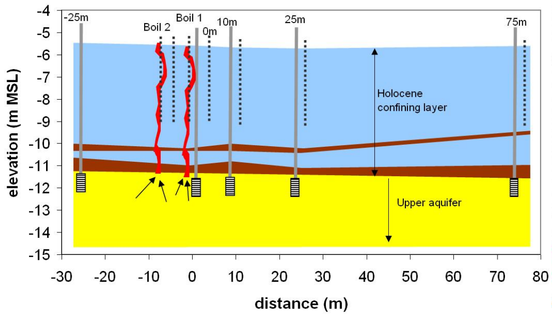


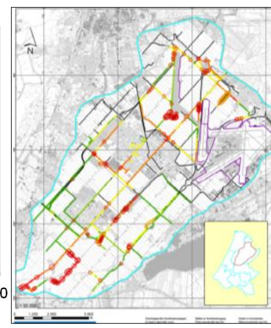
Development freshwater lens Jurong island
Time= 2010 AD
depth [m MSL]
0
-10
-20
-30
-40
0
2000
4000
6000
X
8000
10000
12000
0
2000
4000
6000
8000
Y
Z
Y
X
(1 g Cl-/L interface)
0.15 0.3 0.5 1 1.5 5 10

Example NL:
Salt resistant crops on salty boils

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

Ask Perry de Louw for details





Modelling

salt water intrusion

density dependent groundwater flow

Why mathematical modelling anyway?

A model is only a schematisation of the reality!

Why mathematical modelling anyway?

+:

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

-:

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

Numerical modelling variable density flow

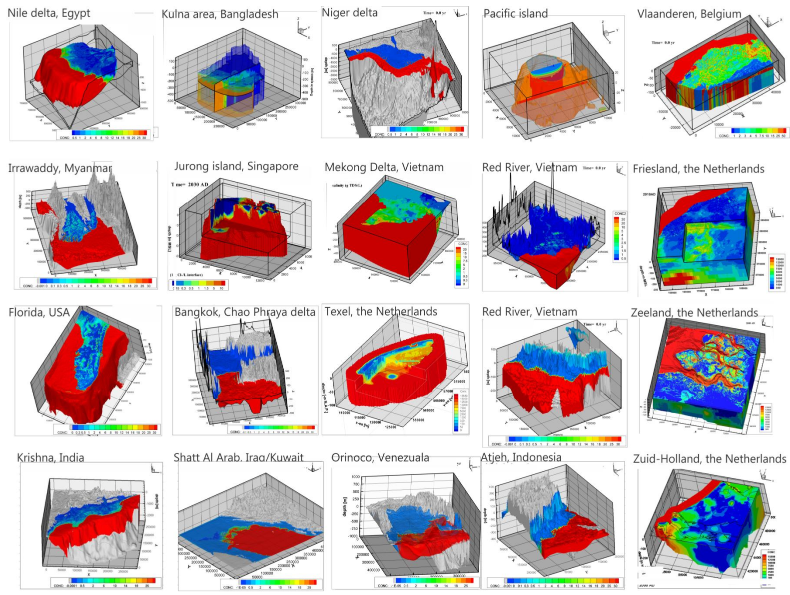
Type:

- sharp interface models
- solute transport models

State of the art:

- three-dimensional
- solute transport
- transient

3D numerical models groundwater coastal zone



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

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

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

Restrictions 3D salt water intrusion modelling

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

Restrictions 3D salt water intrusion modelling now

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

variable density

Stability criteria for solute transport equation (I)

1. Neumann criterion:

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

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

variable density

Stability criteria for solute transport equation (II)

2. Mixing criterion:

$$\Delta t_s \leq \frac{n_e b_{i,j,k}^k}{Q_{i,j,k}^{'}}$$

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

Stability criteria for solute transport equation (III)

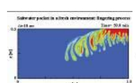
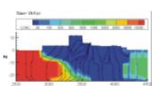
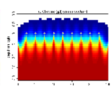
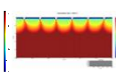
3. Courant criterion:

$0<\xi<=\sim 1$

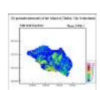
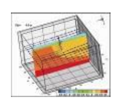
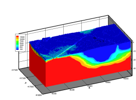
$$\Delta t_s \le \frac{\xi \Delta x}{V_{x,\max}} \qquad \Delta t_s \le \frac{\xi \Delta y}{V_{y,\max}} \qquad \Delta t_s \le \frac{\xi \Delta z}{V_{z,\max}}$$

Modelling fresh-salt groundwater on different scales

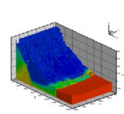
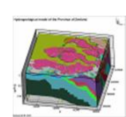
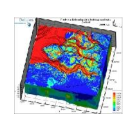
Sub-local: fingering, salty sand boils
Sri Lanka (Tsunami 2004),
Zandmotor
cell size=1cm-1m

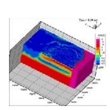
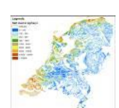
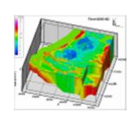
Local: rainwaterlenses, heat-cold
Tholen, Schouwen-Duiveland
cell size=5-25m

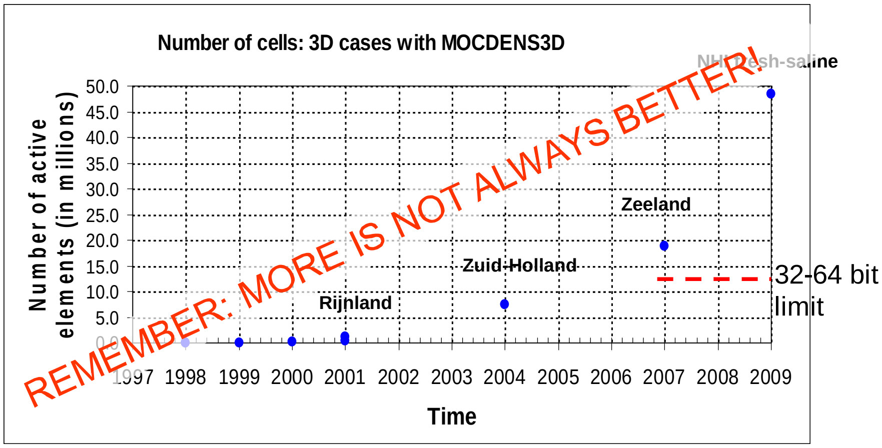
Regional:
Zeeland, Gujarat/India, Philippines
cell size=100m

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

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



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

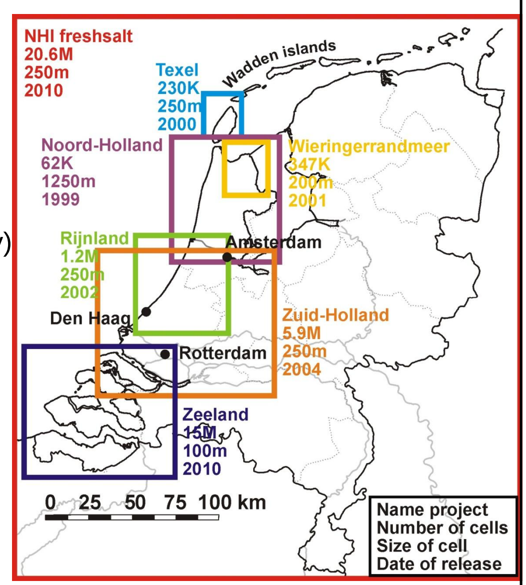
Modelling effect climate change on fresh-salt groundwater

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

Code:

MOCDENS3D (MODFLOW family) similar to SEAWAT

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



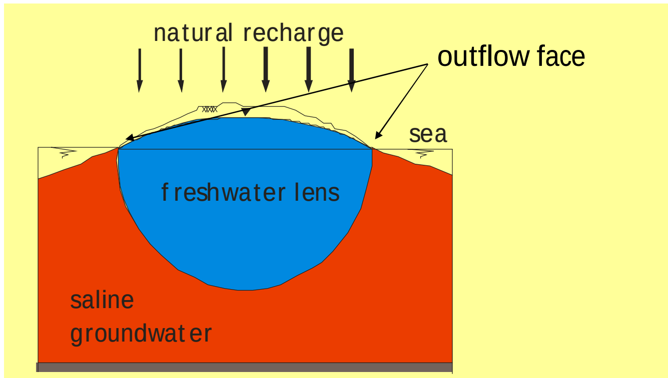
Fields of application of fresh-saline groundwater models

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

Difficulties with variable density groundwater flow

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

Outflow face at the coast is difficult to model



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

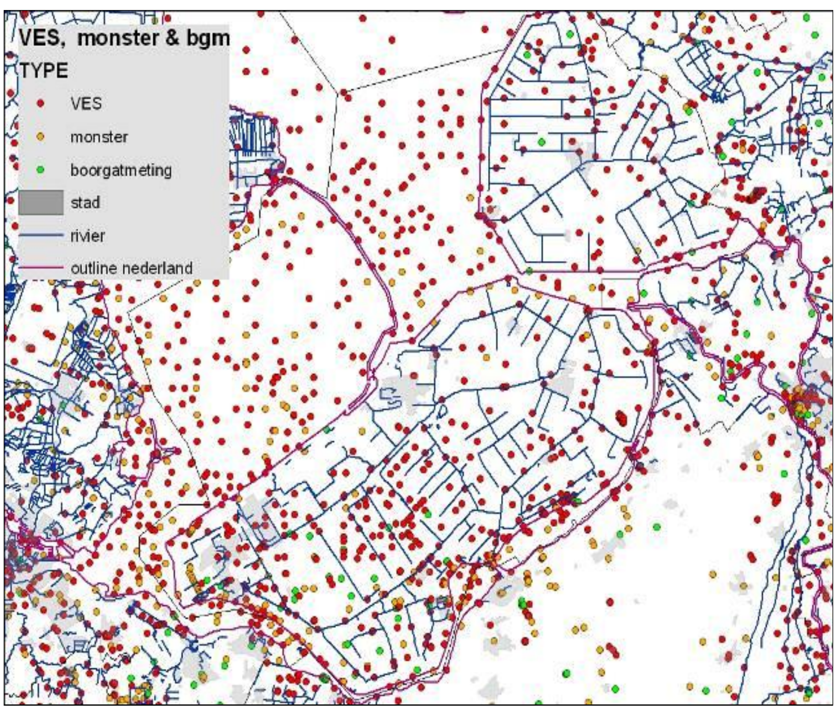
This is numerically difficult to handle

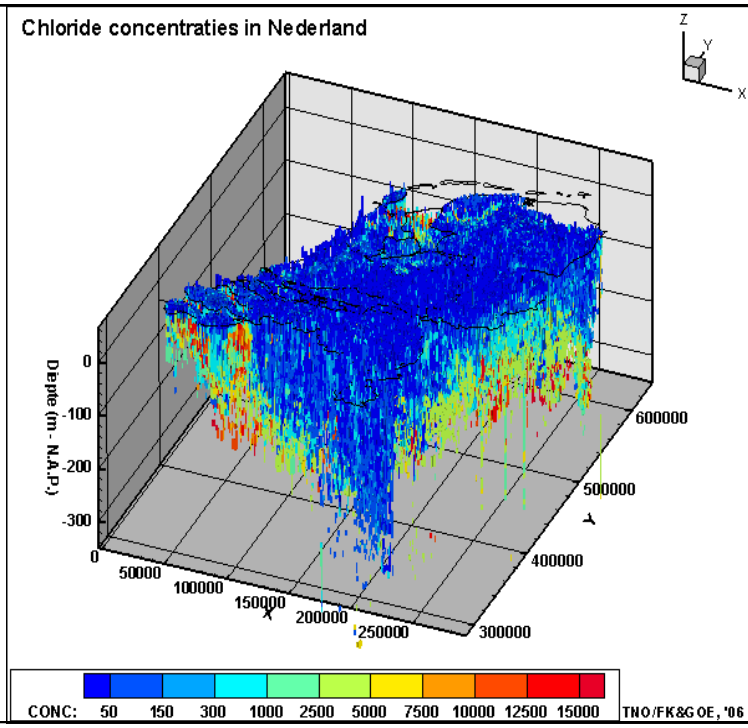
A good initial density distribution is essential

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

‘Procedure’ to improve initial density distribution

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



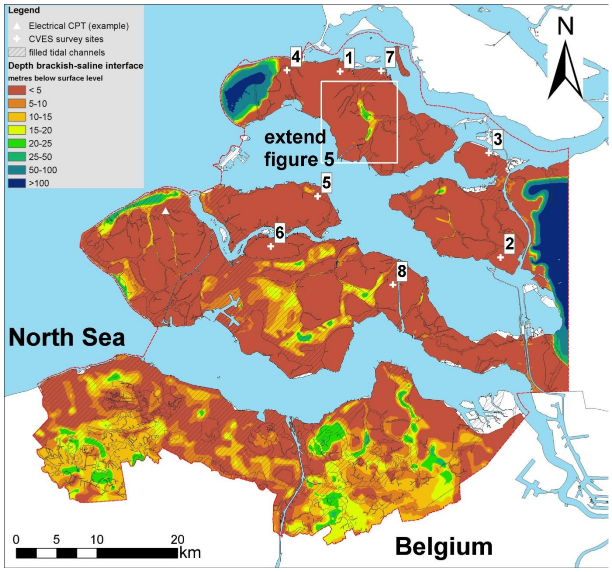


Mapping brackish-saline interface Zeeland

Combining different types of data sources:

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

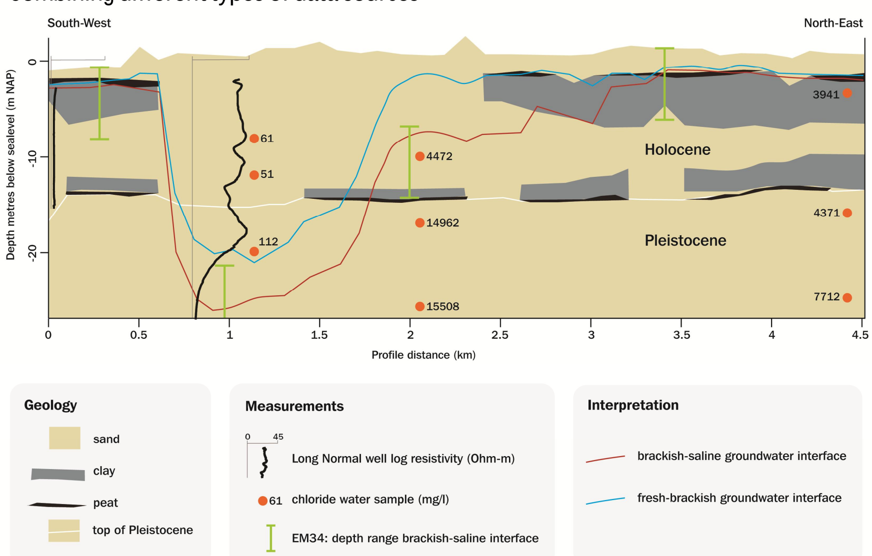
Mapping brackish-saline interface



Goes et al, 2009

Mapping brackish-saline interface

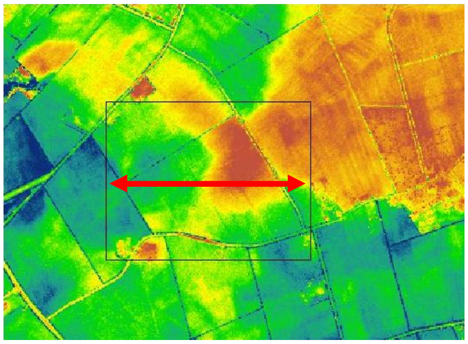
Combining different types of data sources

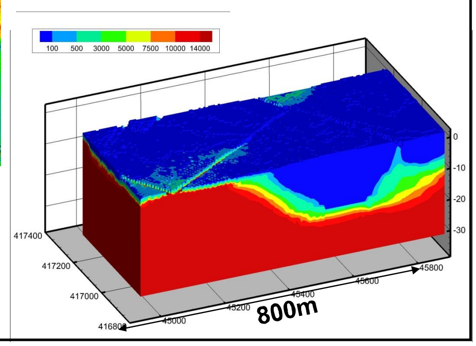


Use variable-density groundwater flow modelling

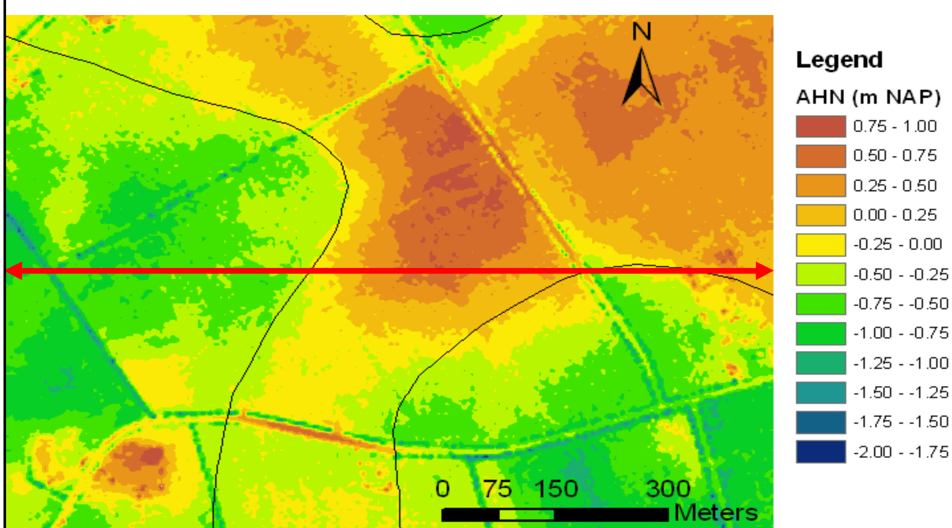
Why a model?

- variation in ground surface directly affects fresh-saline disribution



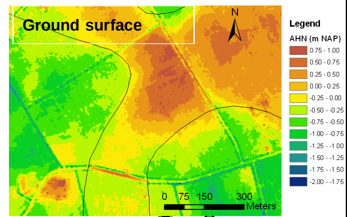


Use variable-density groundwater flow modelling

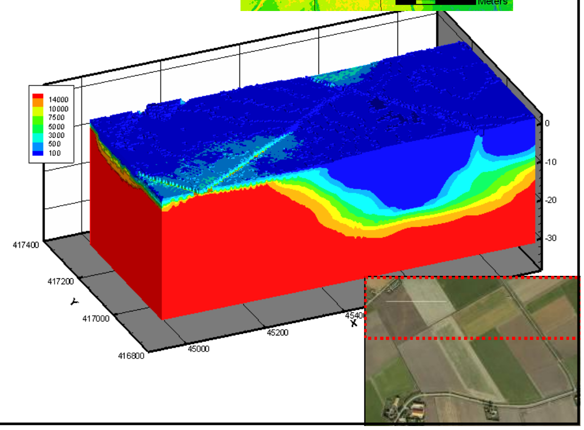


Local 3D model of the agricultural plot

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

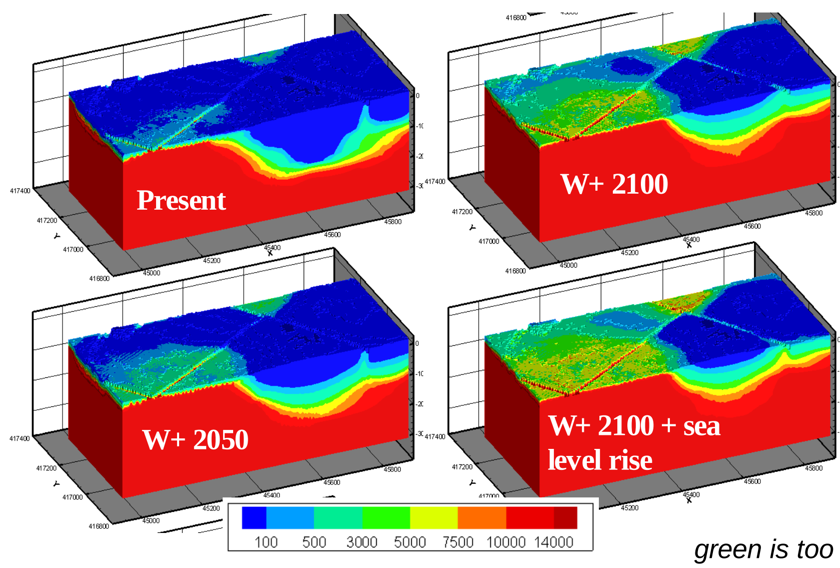


Code:
MOCDENS3D



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

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

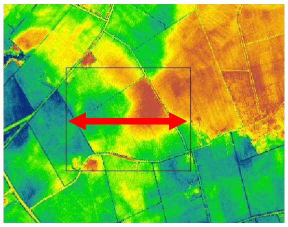


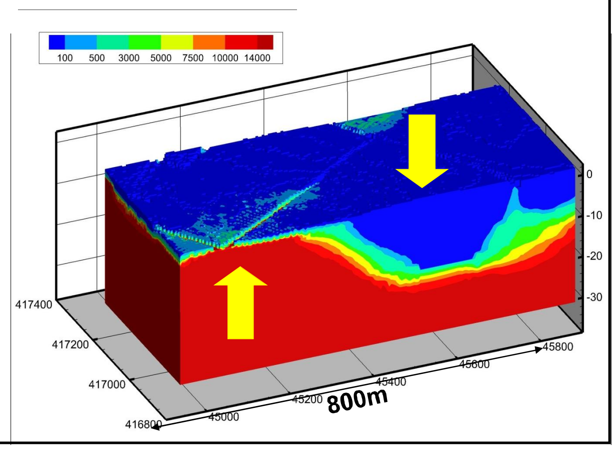
green is too salty to grow fresh crops

Use variable-density groundwater flow modelling

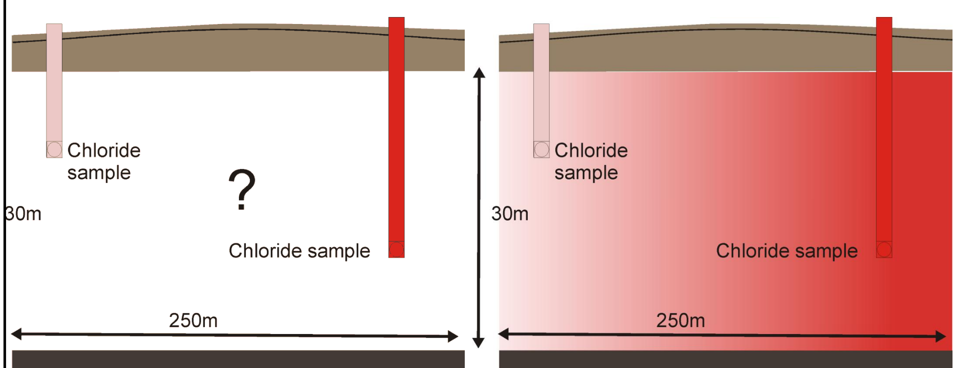
Why a model?

- variation in ground surface directly affects fresh-saline disribution

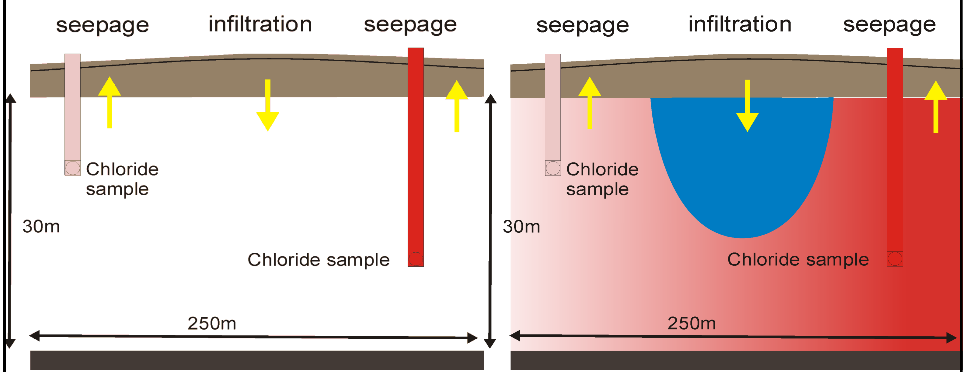




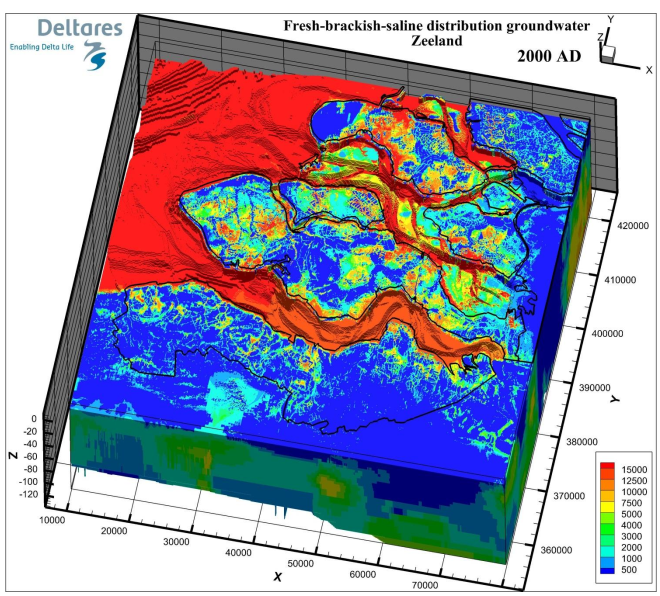
Interpolation chloride



Using flow model for better interpolate chloride



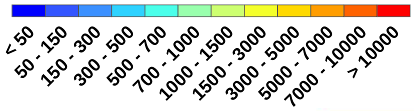
3D fresh-saline groundwater distribution



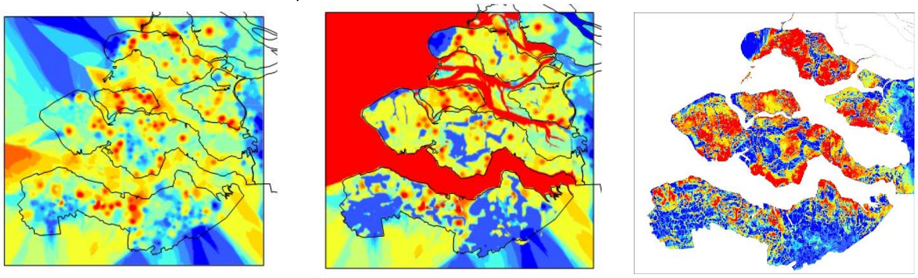
Regional groundwater model:

From chloride measurements to a 3D distribution

mg Cl/l



results at - 6.5 m msl



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*

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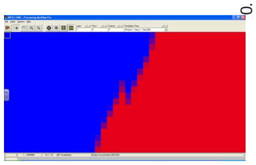
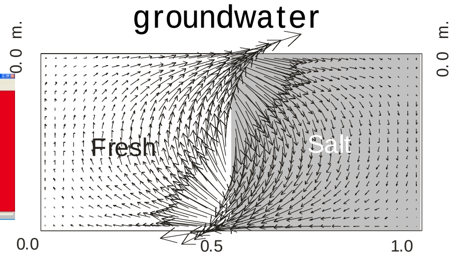
Examples of variable-density groundwater flow

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

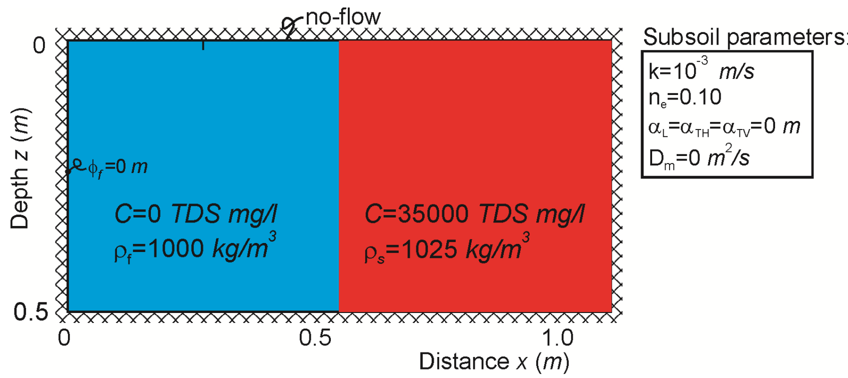
Case 1: Vertical interface between fresh and saline groundwater



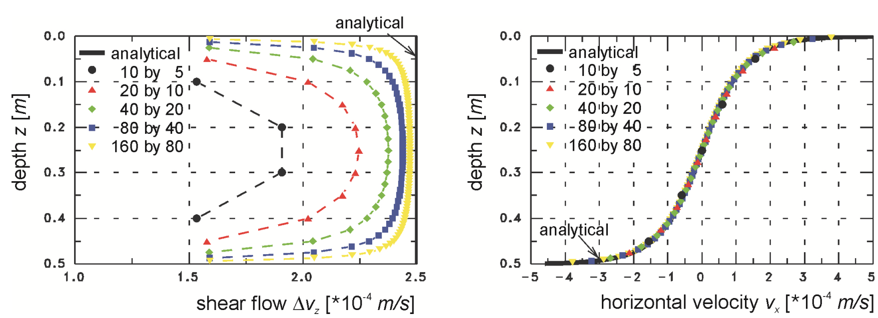


Parameters			
Layers	20	K_{hor}	1 10^{-3} m/s
Rows	1	T	2.5 10^{-5} m/s
Columns	40	Anisotropy K_{hor}/K_{ver}	1
Δx	0.025 m	n_e	0.1
Δy	1 m	α_L	0 m
Δz	0.025 m	α_T	0 m
Stress periods	15		
Initial concentration	0 and 35000 mg/l		
bouyancy	0.025		

Vertical interface

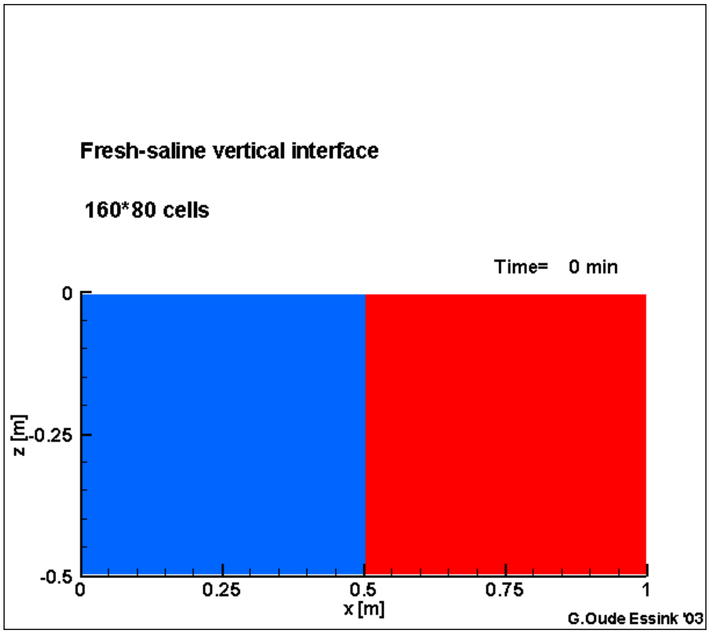


Effect of the number of cells on the shear flow at the interface at t=0

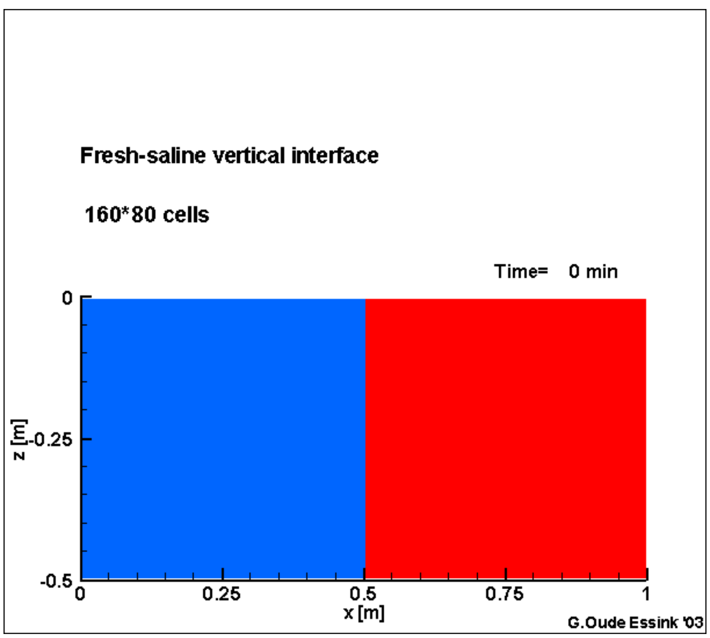


$$\Delta v_z = \frac{k}{n_e}\left(\frac{\rho_s - \rho_f}{\rho_f}\right) \qquad v_x = \frac{k}{n_e}\left(\frac{\rho_s - \rho_f}{\rho_f}\right)\frac{1}{\pi}\ln\tan\left(\frac{\pi z}{2D}\right)$$

Vertical interface



Vertical interface



The effect of numerical solvers on the salt transport

Examples

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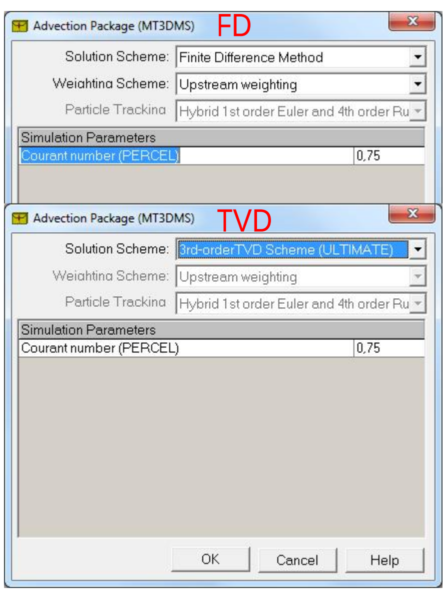
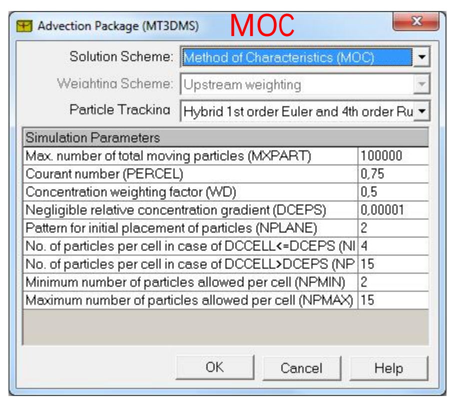
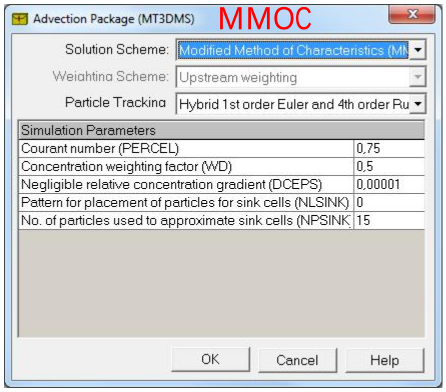
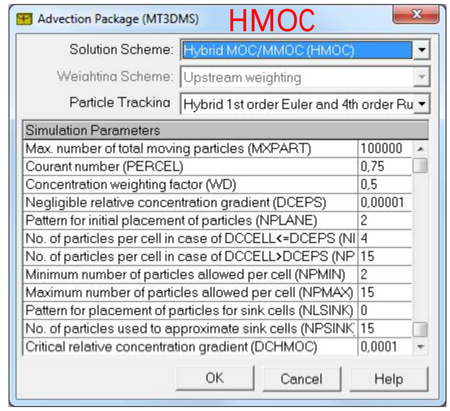
Default parameters solvers





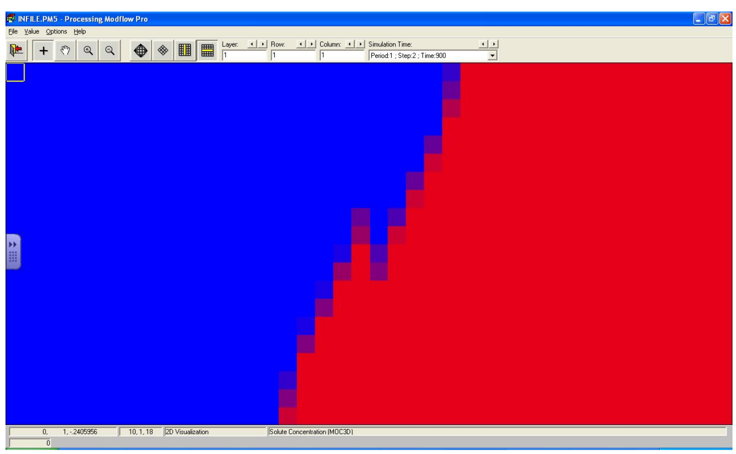
Default parameters solvers



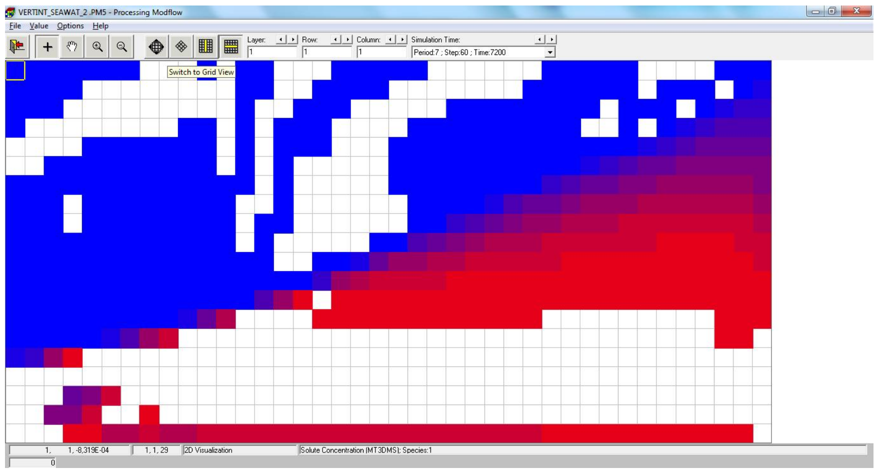


More information:
Zheng, C., & Wang, P. (1999). MT3DMS: A modular three-dimensional multispecees transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems. Technical report, Waterways Experiment Station, US Army Corps of Engineers.

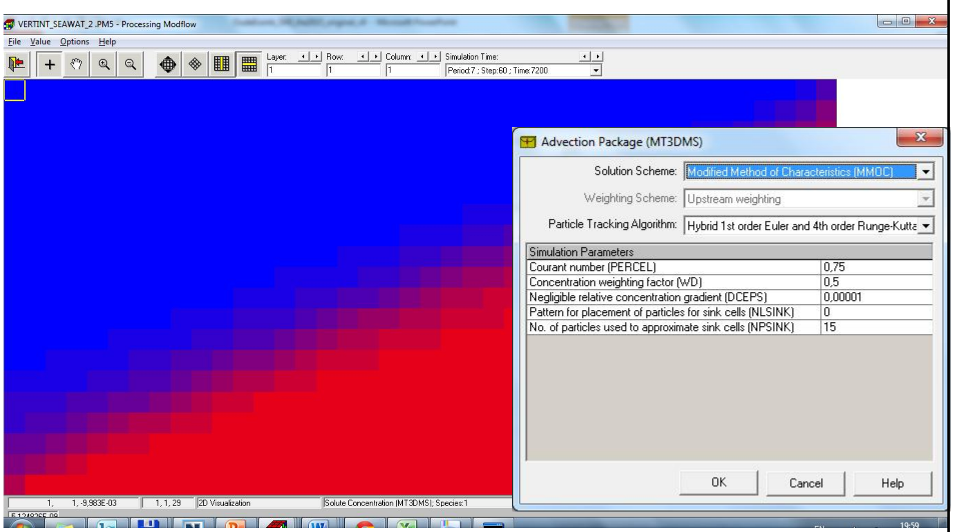
1 particle per cell



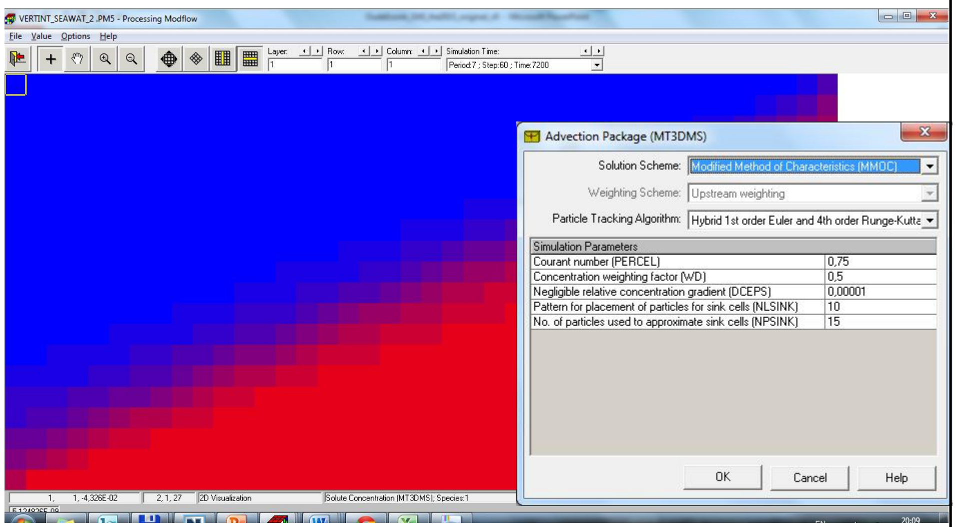
ULTIMATE



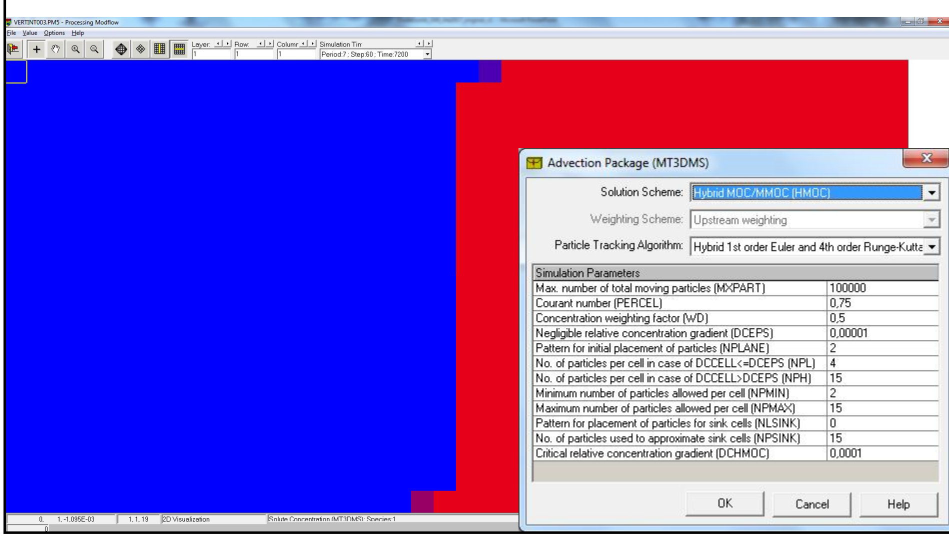
MMOC, NPLANE=0



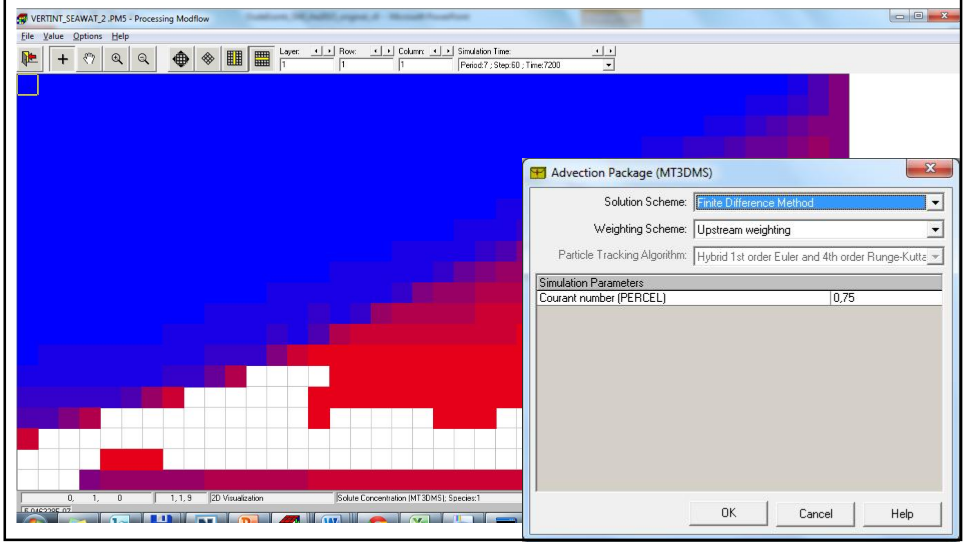
MMOC, NPLANE=10



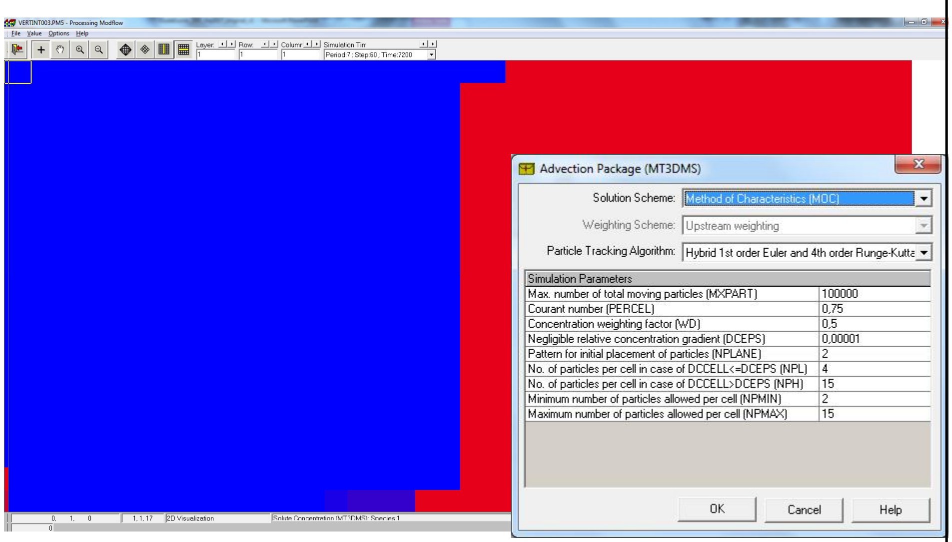
HMOC



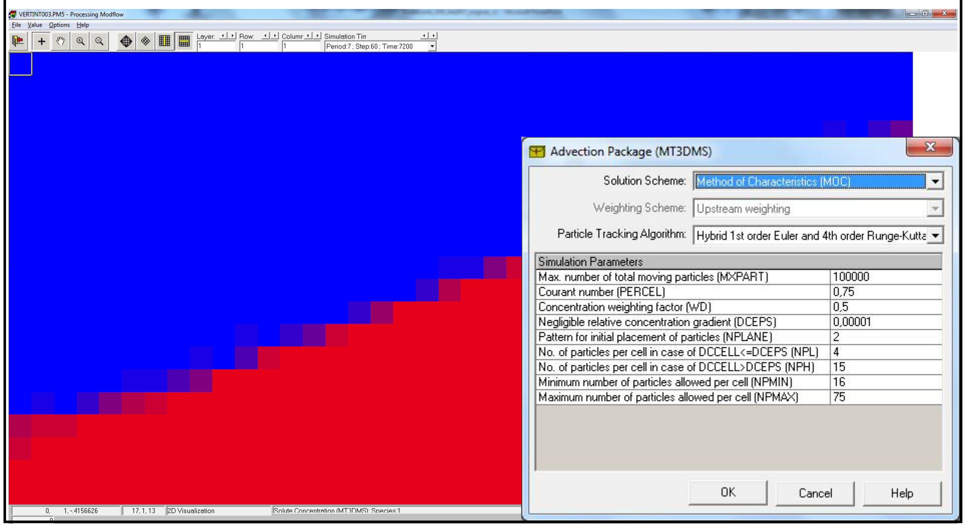
Finite Difference Method



MOC

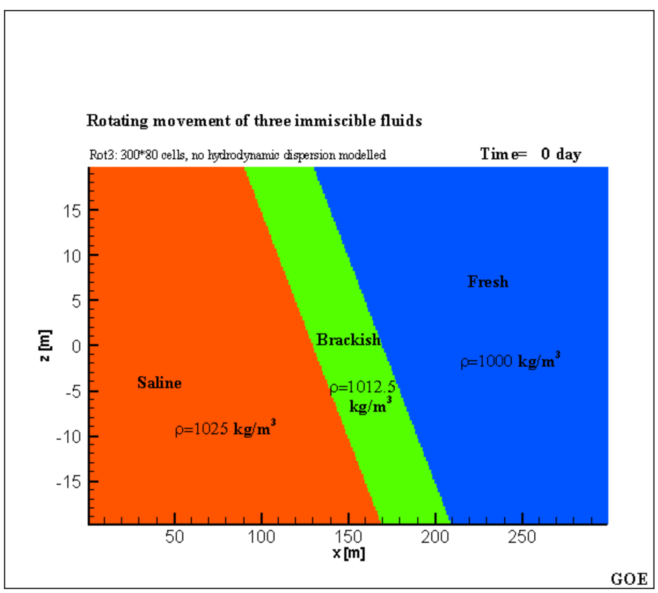


MOC

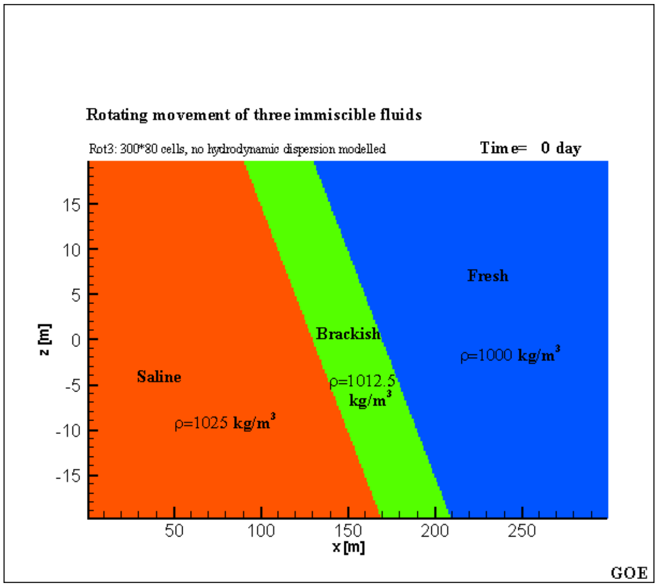


cases

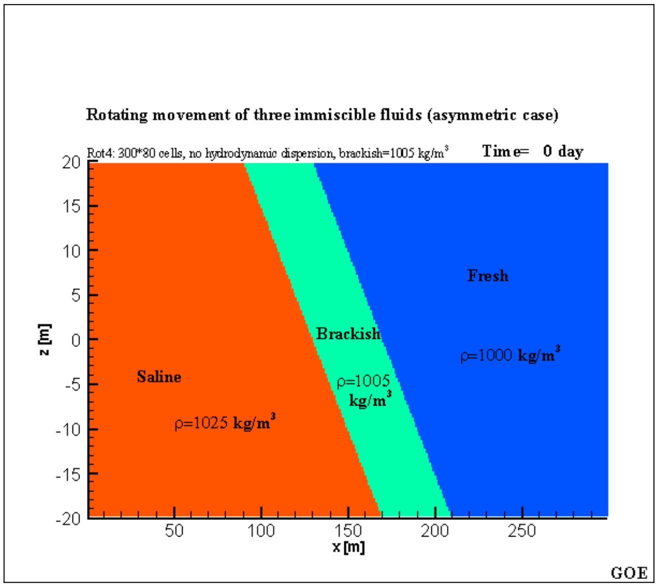
Rotating immiscible interfaces



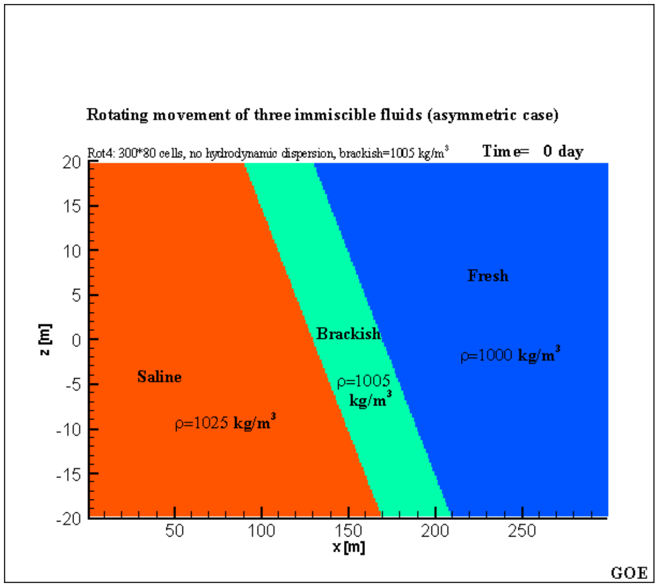
Rotating immiscible interfaces



Rotating immiscible interfaces (asymmetric)

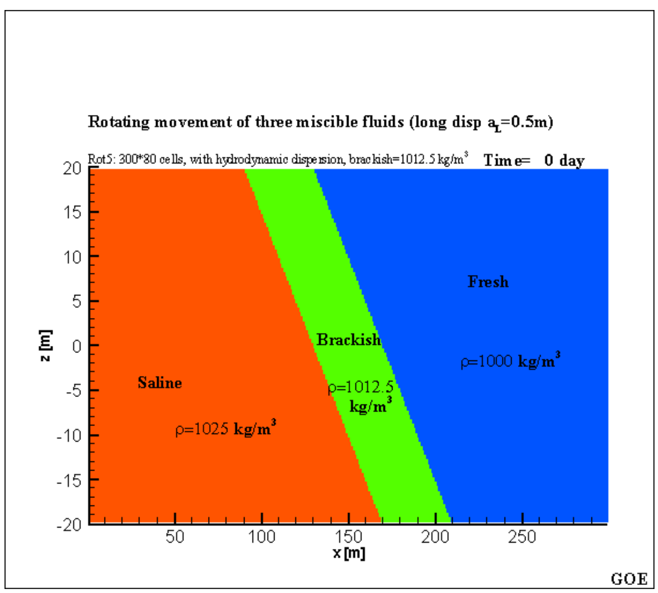


Rotating immiscible interfaces (asymmetric)



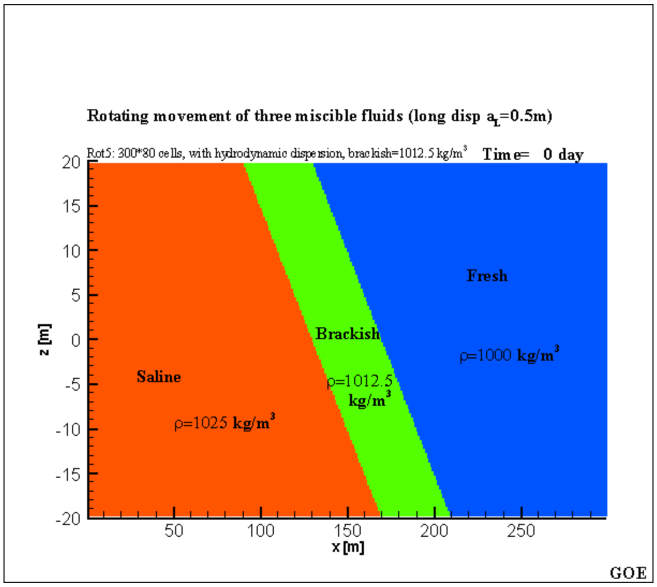
Bakker, M., Oude Essink, G.H.P. & Langevin, C. 2004. The rotating movement of three immiscible fluids, J. of Hydrology 287, 270-278

Rotating interfaces with dispersion α_L=0.5m



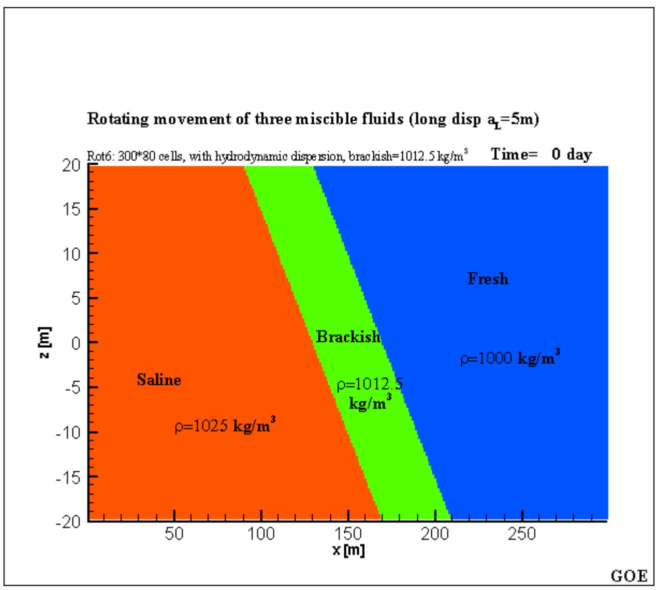
cases

Rotating interfaces with dispersion α_L=0.5m

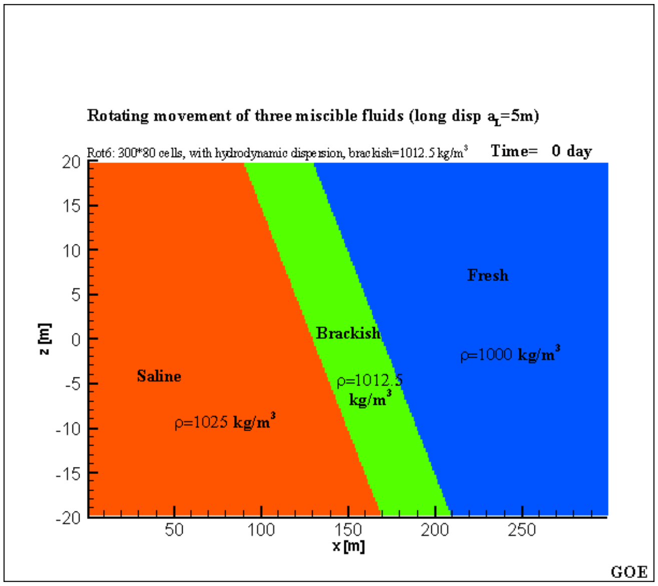


cases

Rotating interfaces with dispersion α_L=5m



Rotating interfaces with dispersion α_L=5m



Rotating immiscible interfaces

Conclusion:

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

Salt water pocket in a fresh environment

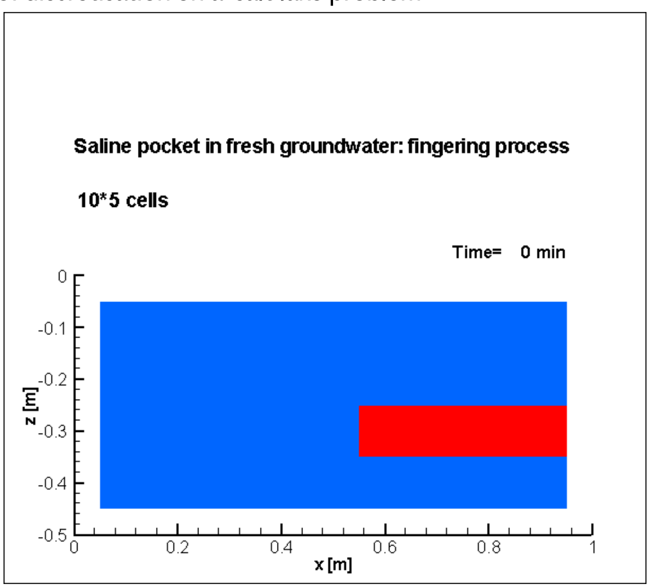
Grid convergence

Time step

cases

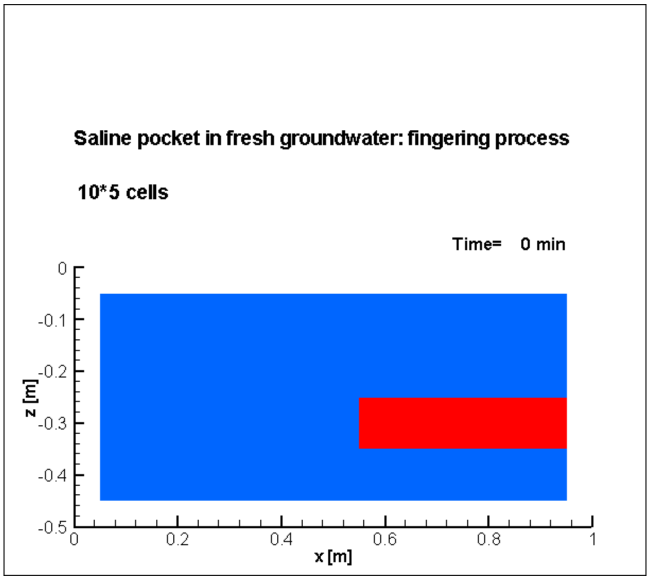
Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



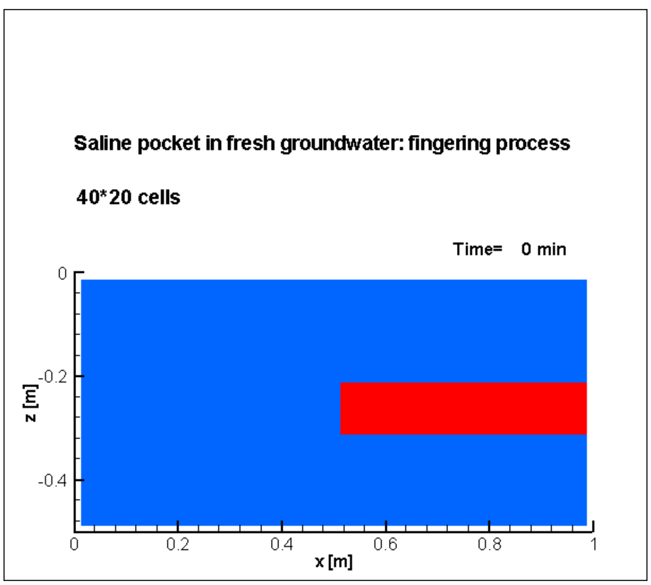
Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



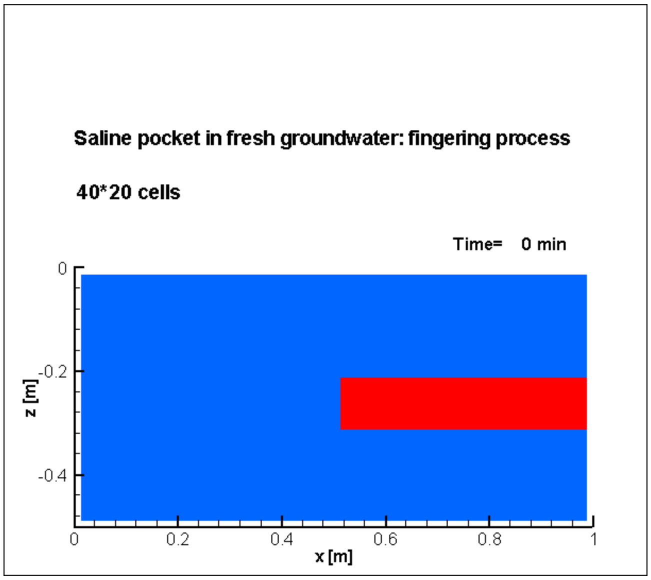
Salt water pocket in a fresh environment (II)

Effect of discretisation



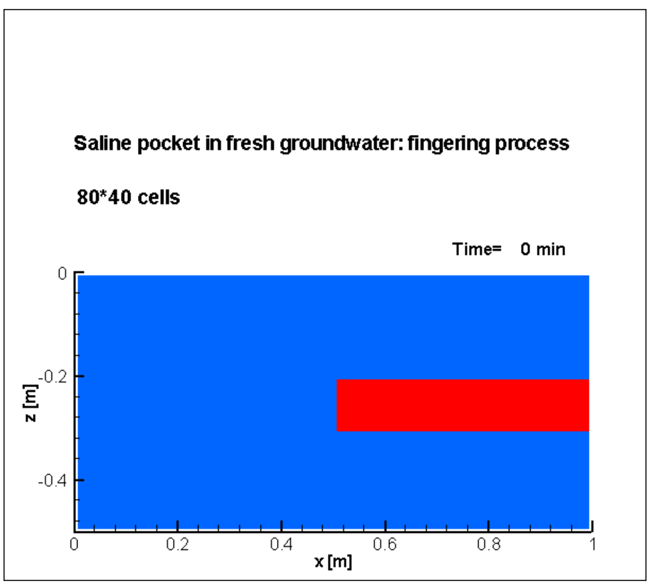
Salt water pocket in a fresh environment (II)

Effect of discretisation



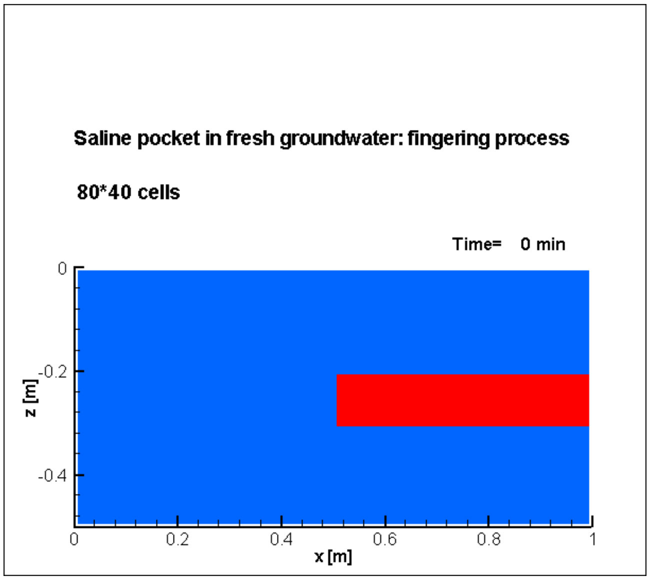
Salt water pocket in a fresh environment (III)

Effect of discretisation



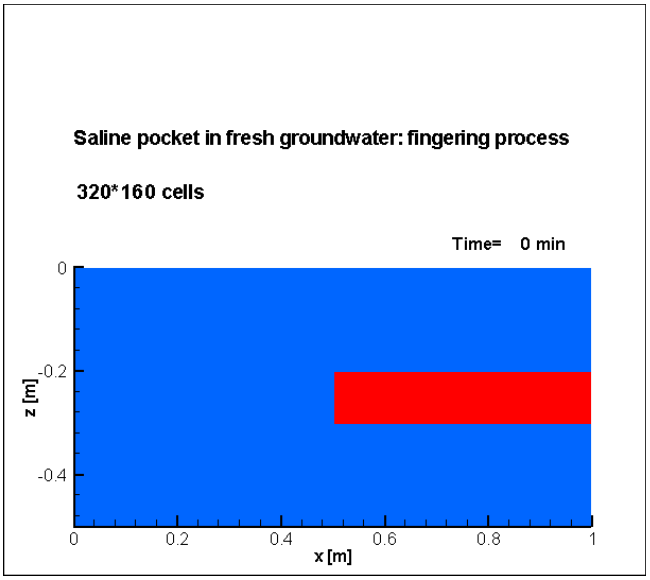
Salt water pocket in a fresh environment (III)

Effect of discretisation



Salt water pocket in a fresh environment (IV)

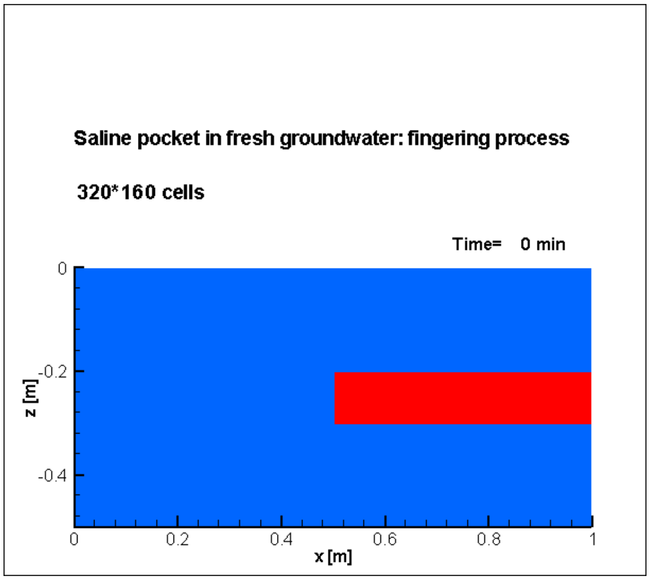
Effect of discretisation



cases

Salt water pocket in a fresh environment (IV)

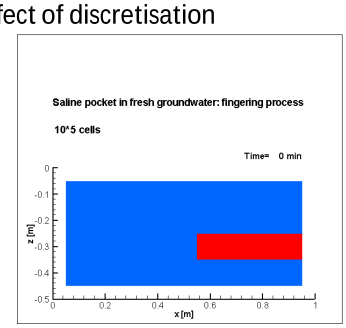
Effect of discretisation

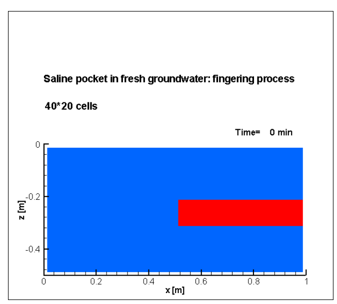


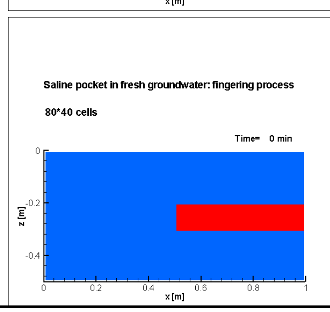
cases

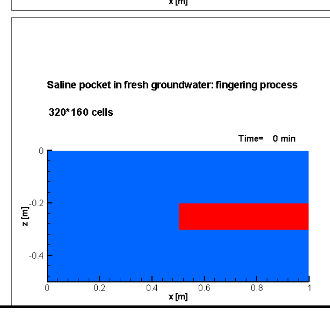
Salt water pocket in a fresh environment (V)

Effect of discretisation

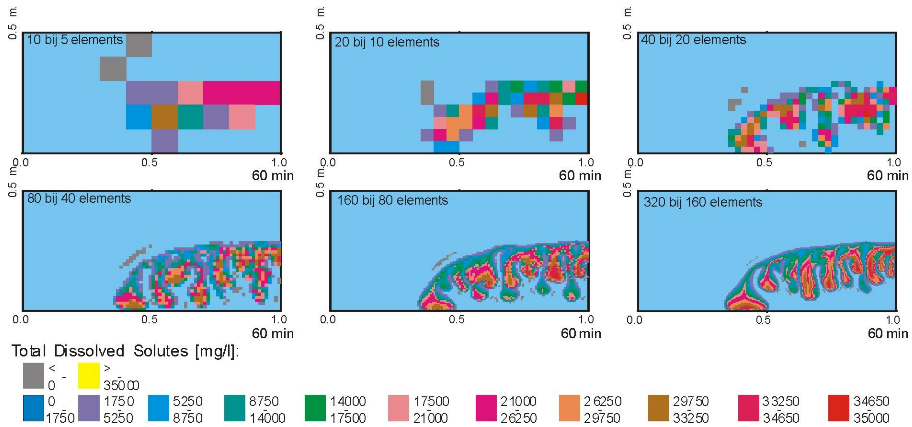






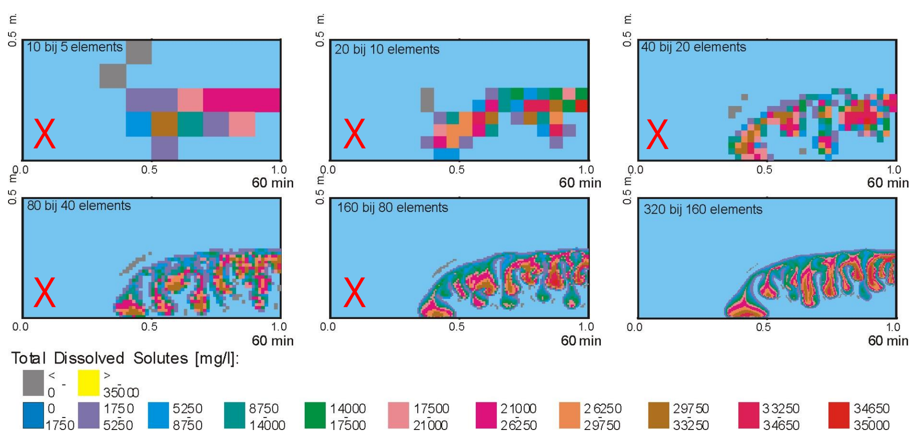


Effect of size model cell on physical process



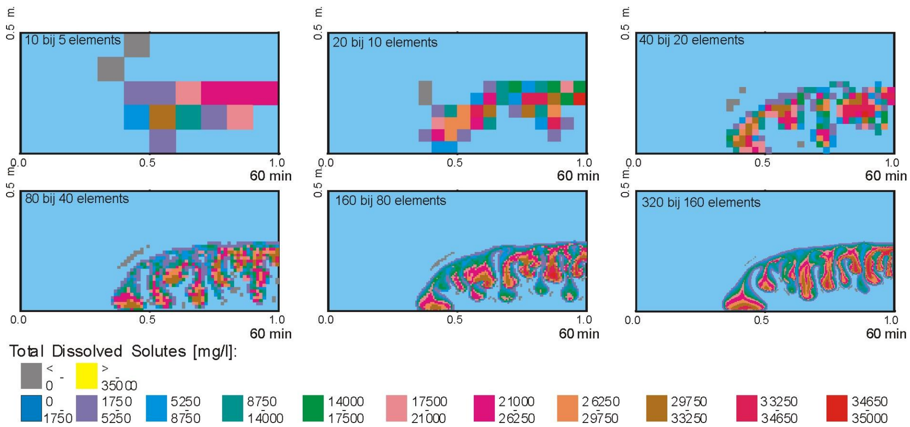
Size of cell has a large effect on modelling result!

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



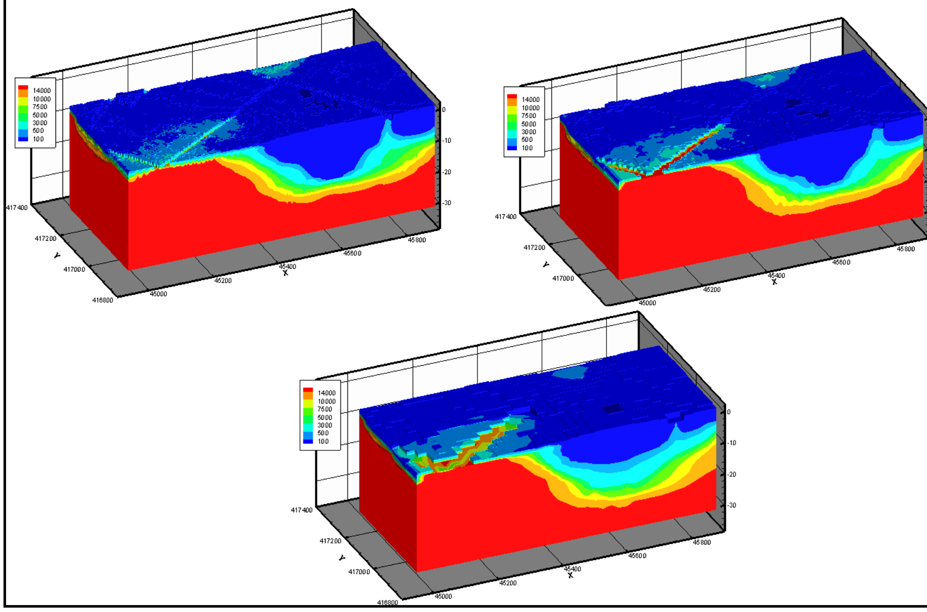
BUT: all models are GOOD for predicting the moment of touching the base!

Salt water pocket in a fresh environment (VI)

Conclusion:

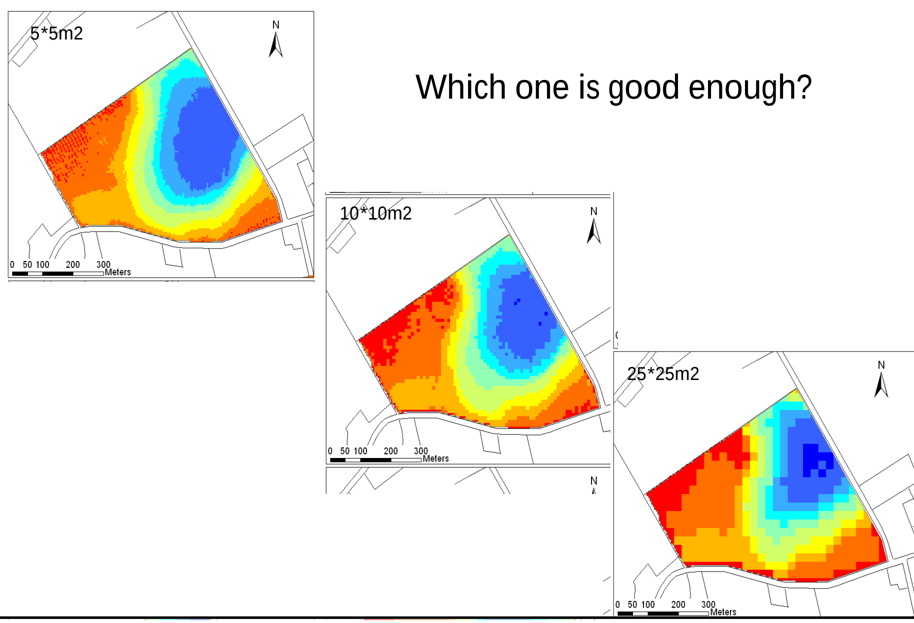
- For some physical processes, a large number of cells is necessary
- Check always grid convergence!

Different model scales: 5, 10, 25m2

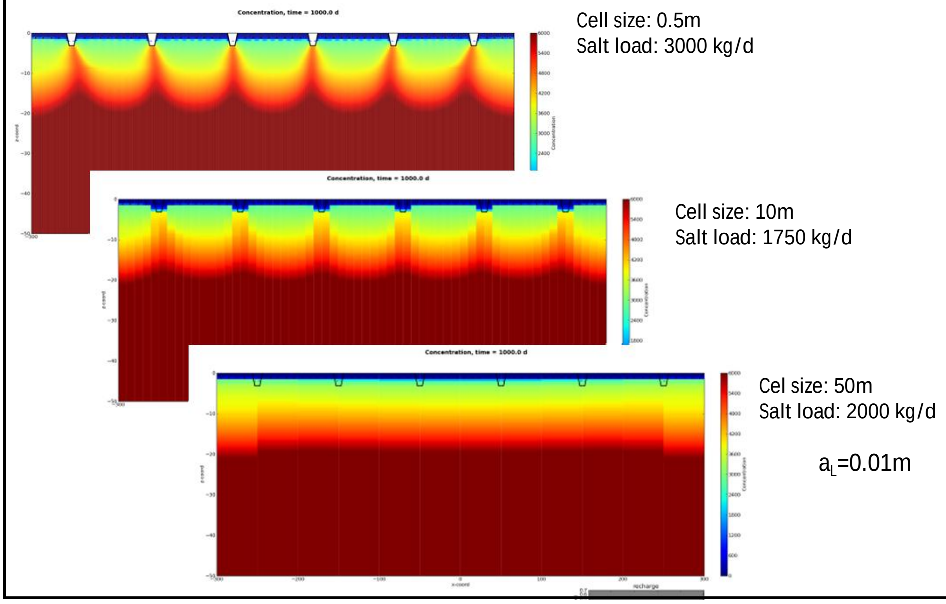


Different model scales

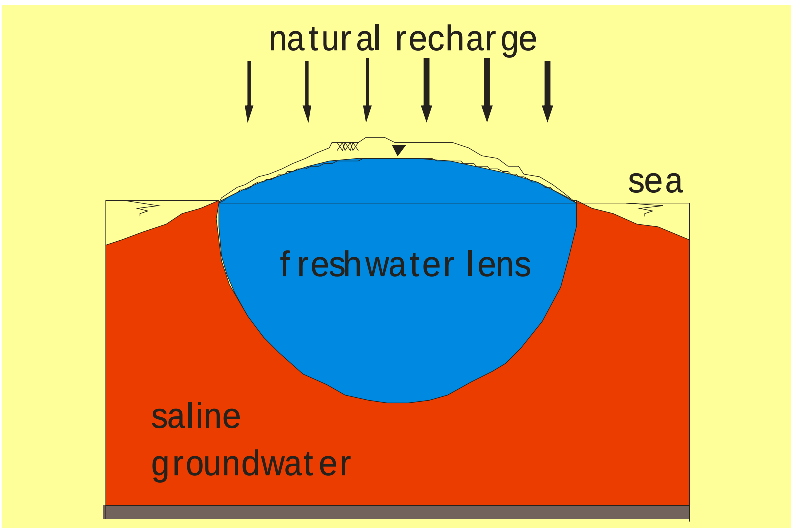
Which one is good enough?



Upscaling issues: upconing under ditch



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

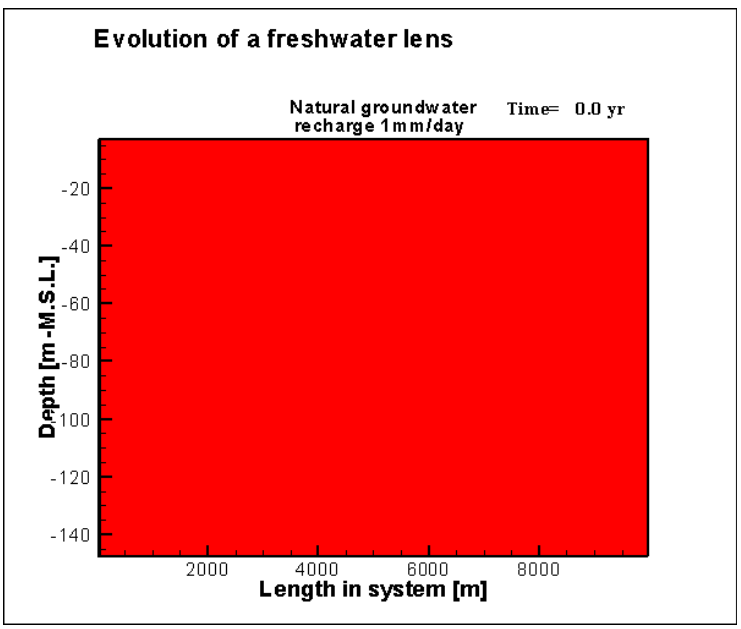
T = specific time scale

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

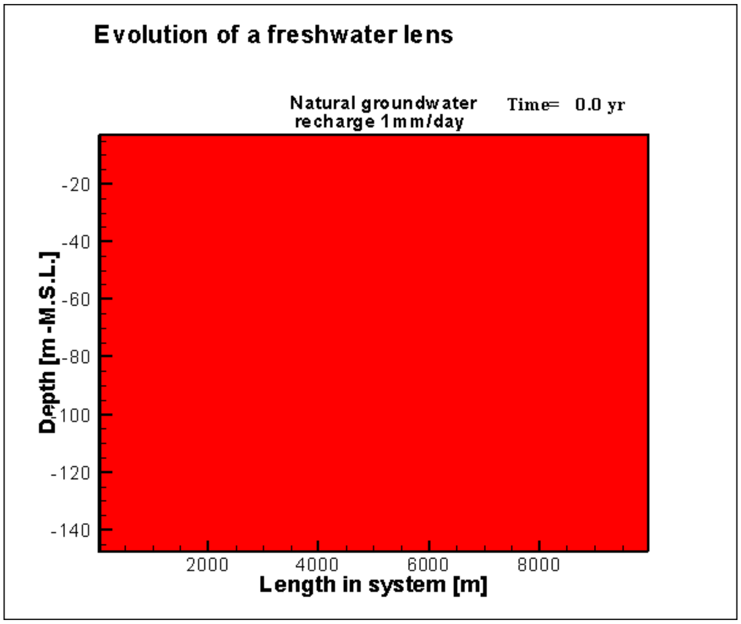
In the Netherlands: T = 75-200 jaar,

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

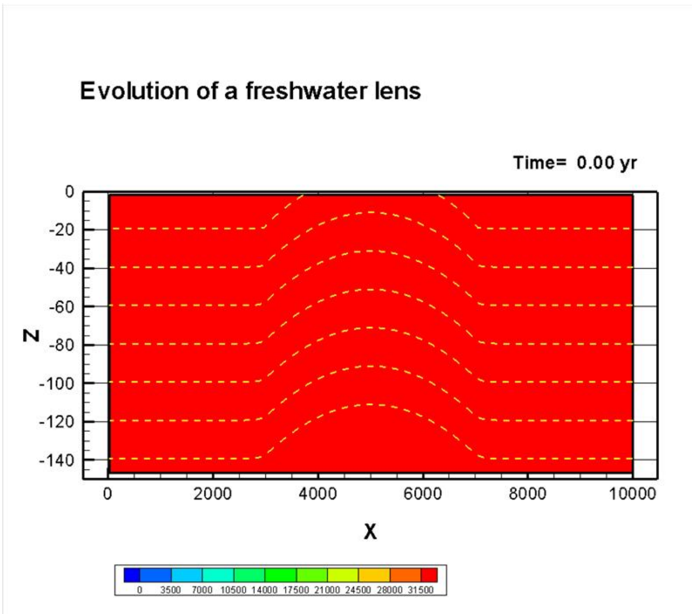
Concept: evolution freshwater lens (not Griend!)



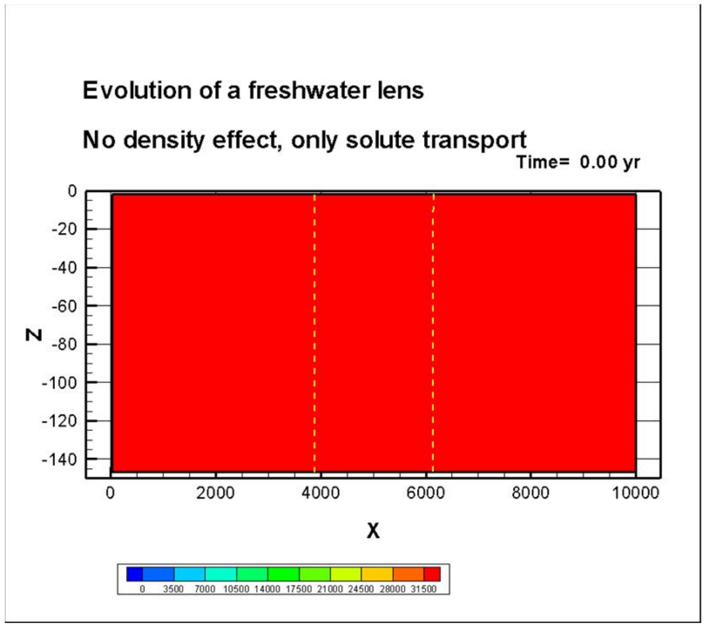
Concept: evolution freshwater lens (not Griend!)



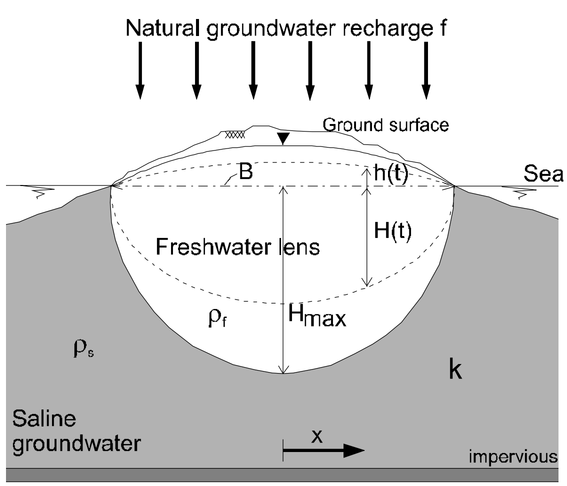
Evolution freshwater lens



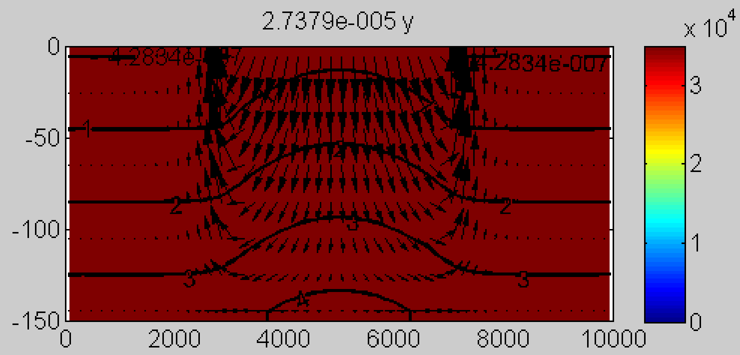
Evolution freshwater lens: no density effects



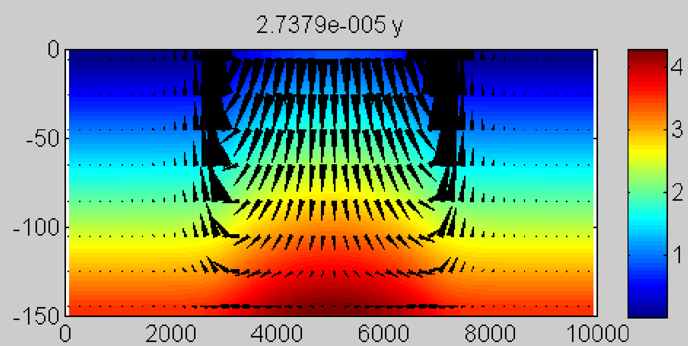
Case 2: Development of a freshwater lens



Evolution lens



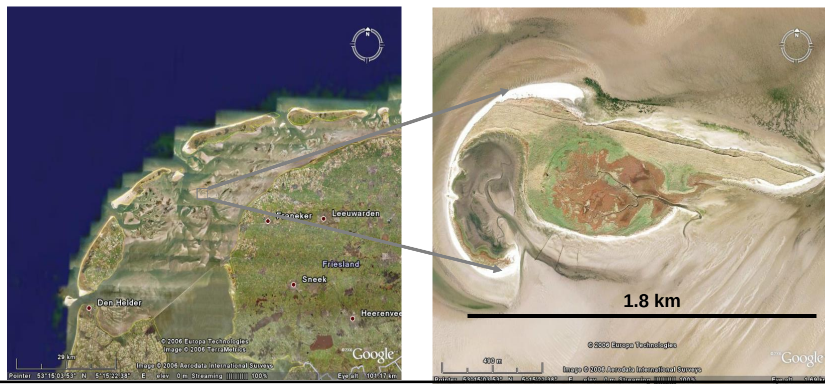
Evolution freshwater head



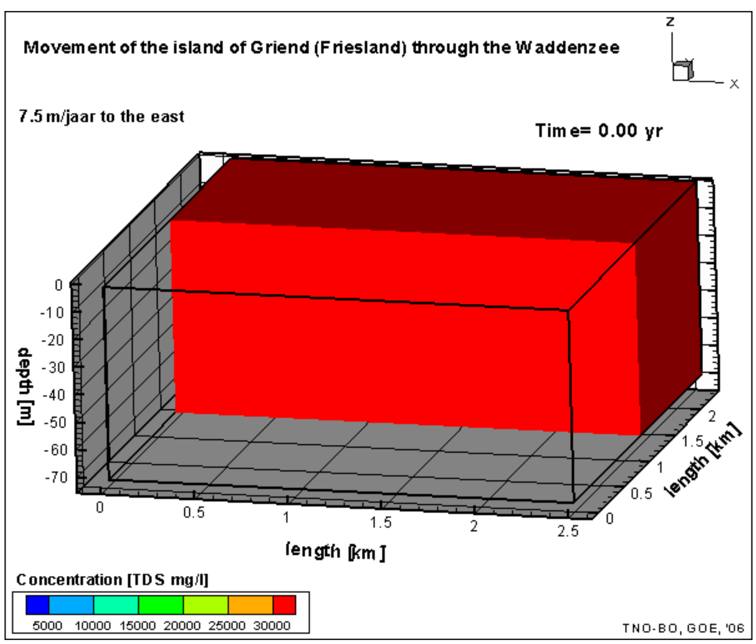
The island of Griend

Issues:

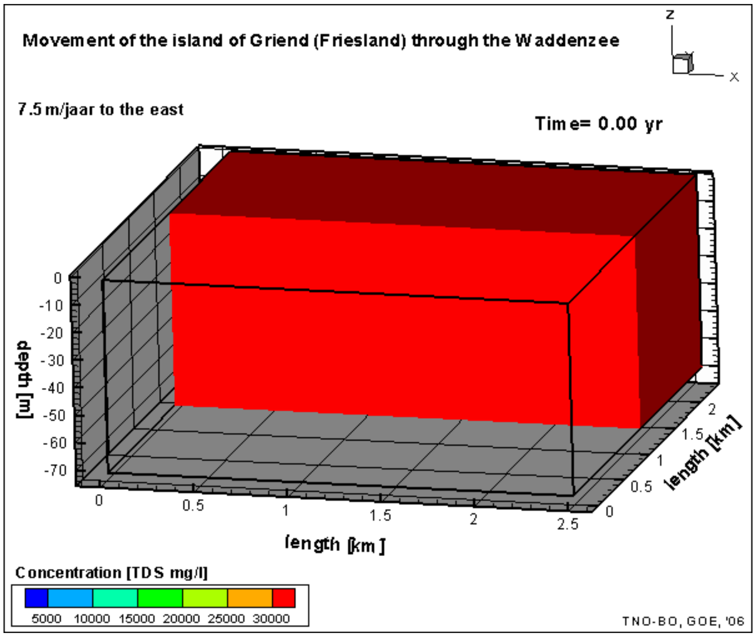
1. Small island moves ~7.5m per year to the east
2. Effect on the volume of the freshwater lens:
   - Can a lens be developed?
   - What is the thickness of the lens?



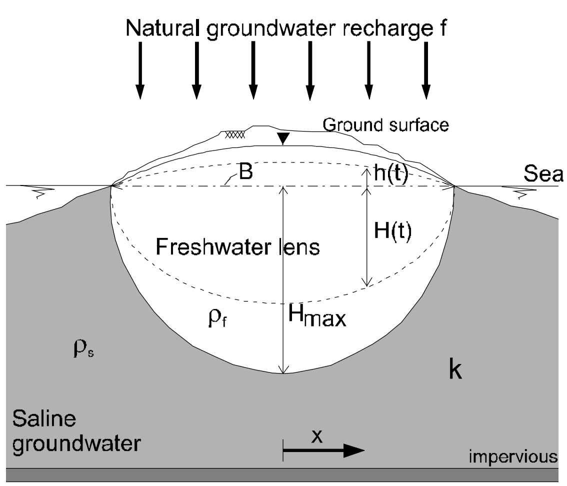
Movement of De Griend and creation of the lens



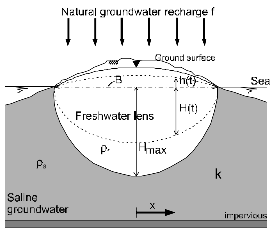
Movement of De Griend and creation of the lens



Case 2: Development of a freshwater lens

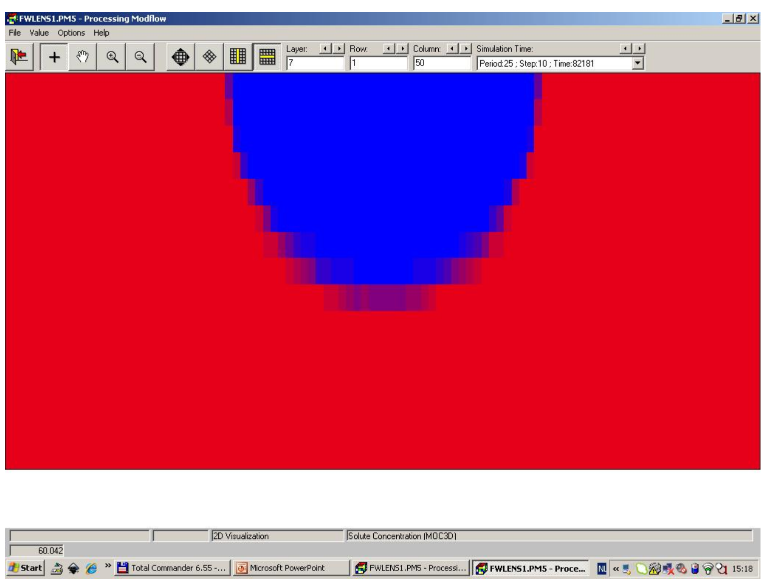


Case 2: Development of a freshwater lens

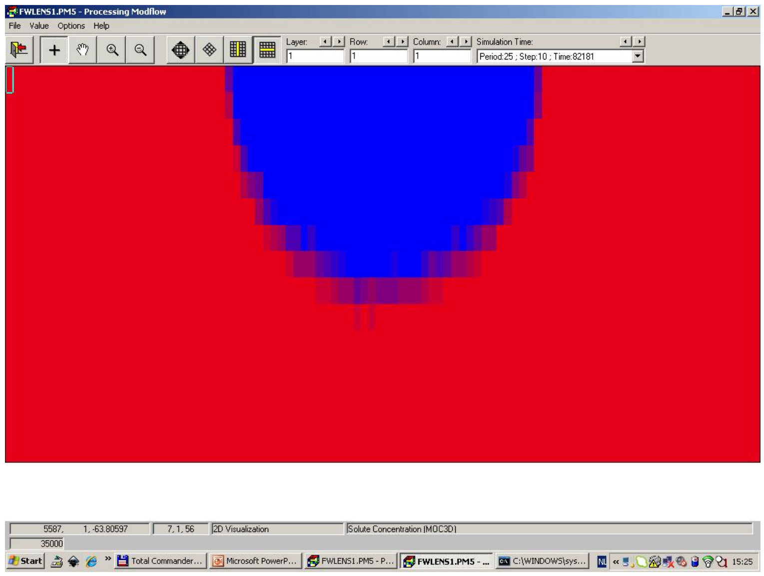


Parameters			
Layers	15	K_{hor}	20 m/d
Rows	1	T	200 m/d
Columns	100	Anisotropy K_{hor}/K_{ver}	10
Δx	100 m	ne	0.35
Δy	10 m	αL	0 m
Δz	10 m	αT	0 m
Stress periods	10	recharge	360 mm/y
Initial concentration	35000 mg/l	Recharge concentration	0 mg/l
bouyancy	0.025		

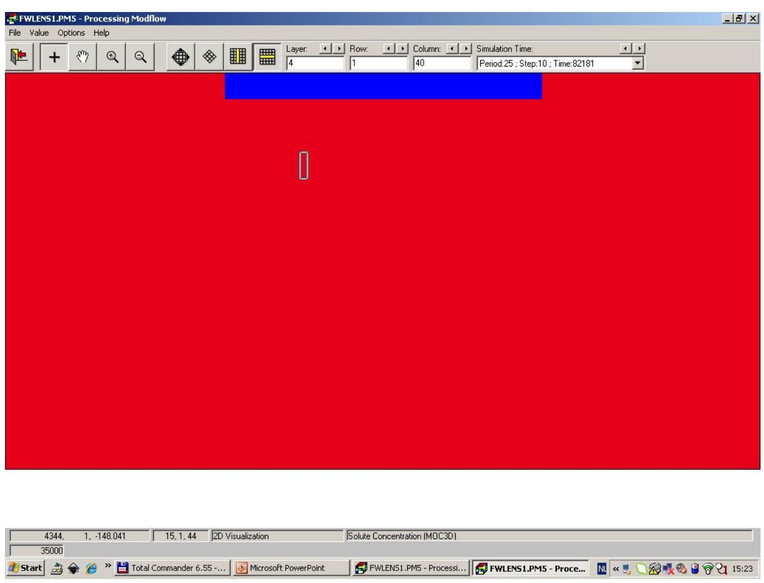
MOCDENS3D, no disp, 16part



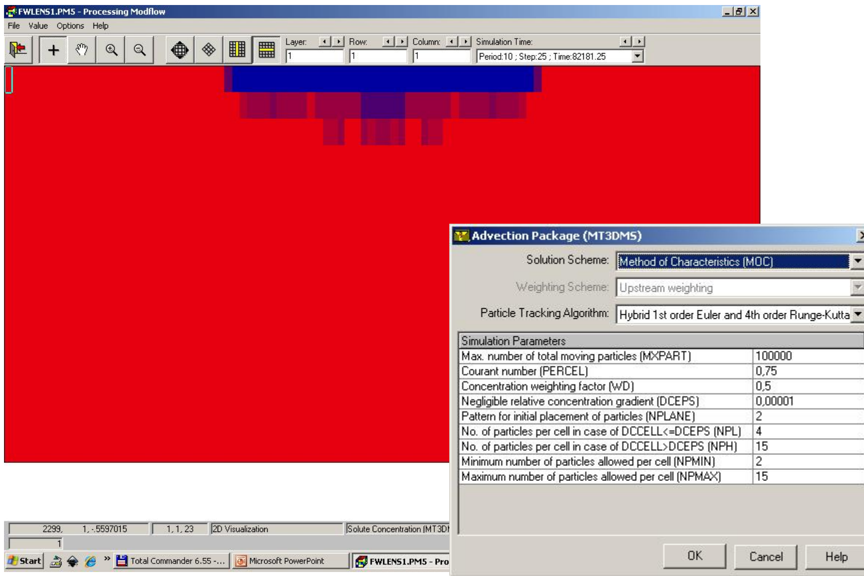
MOCDENS3D, no disp, 4part



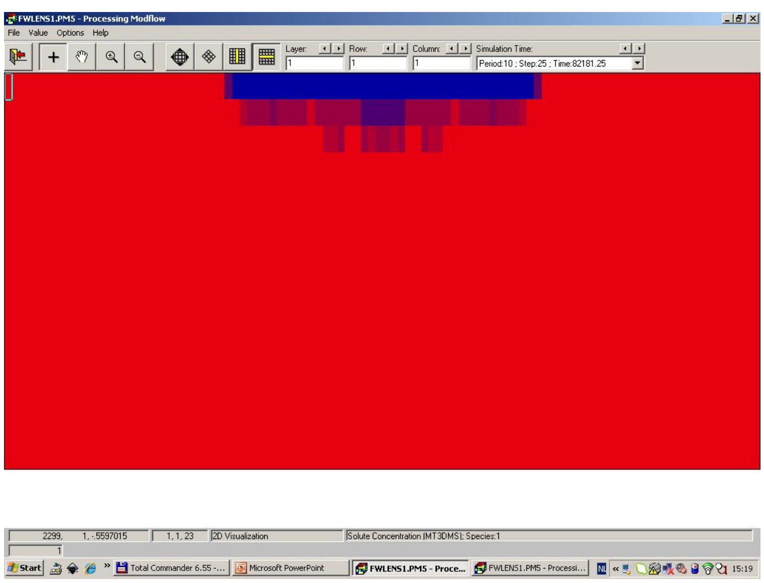
MOCDENS3D, no disp, 1part



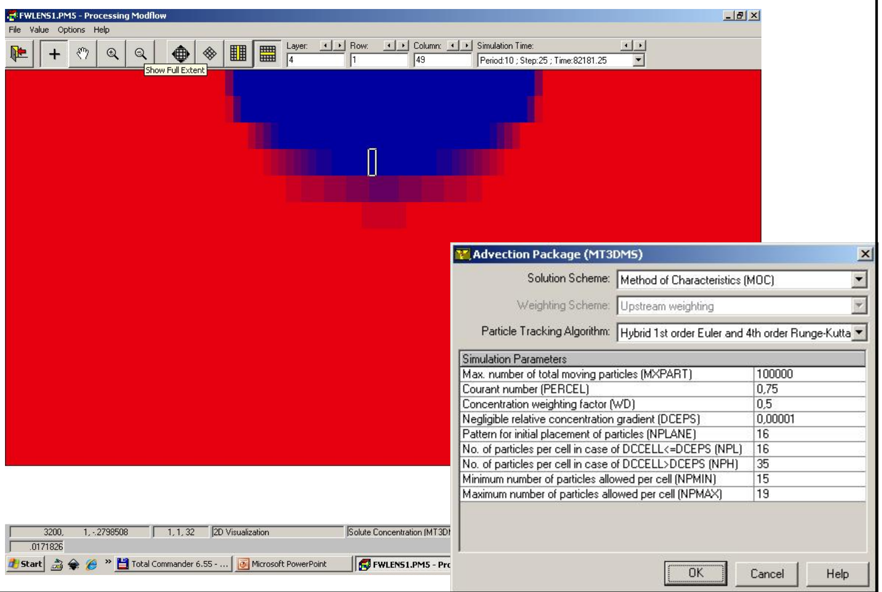
SEAWAT, MOC, NPLANE=2



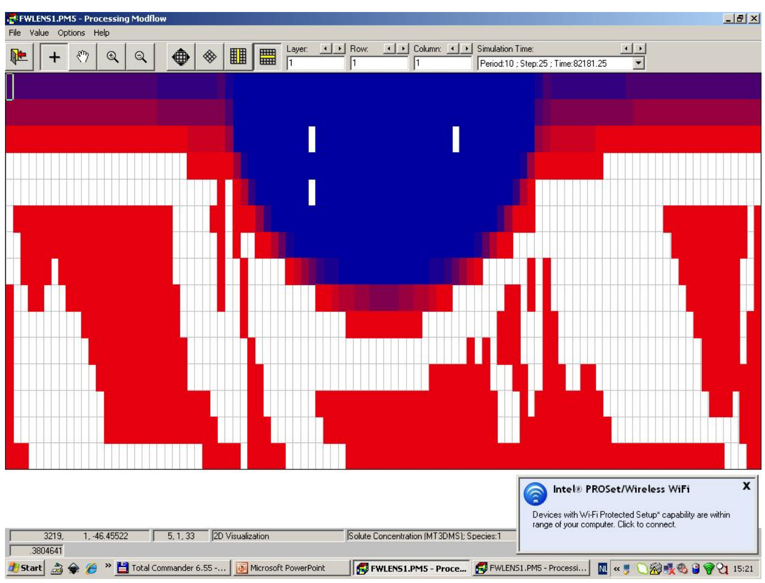
SEAWAT, MOC, 4.NPLANE=16



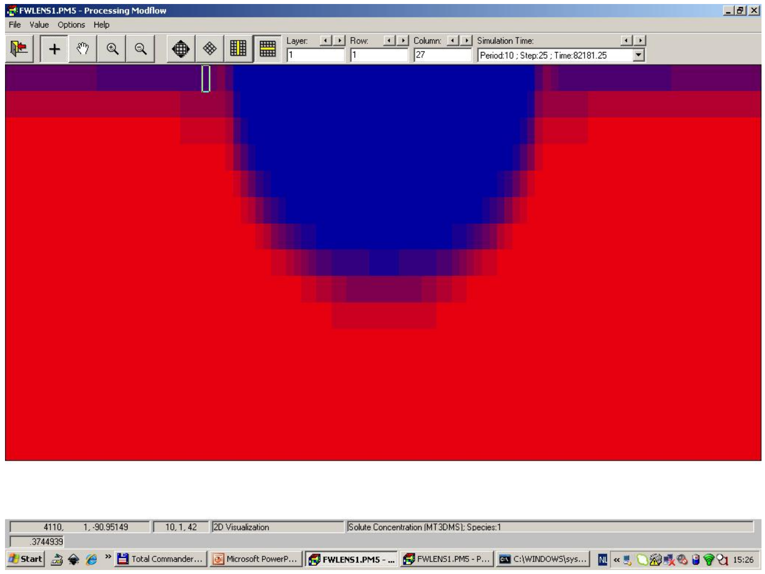
SEAWAT, MOC, 20sec, NPLANE=16, etc.



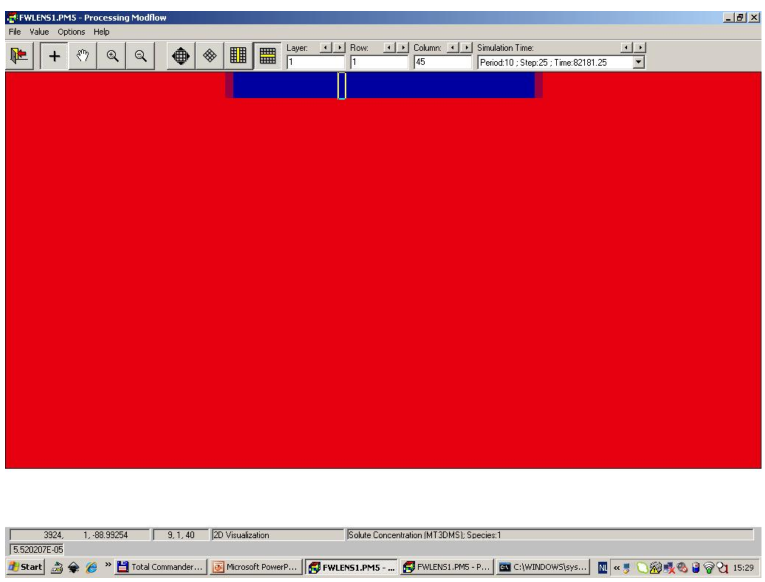
SEAWAT, ULTIMATE, 16.56sec



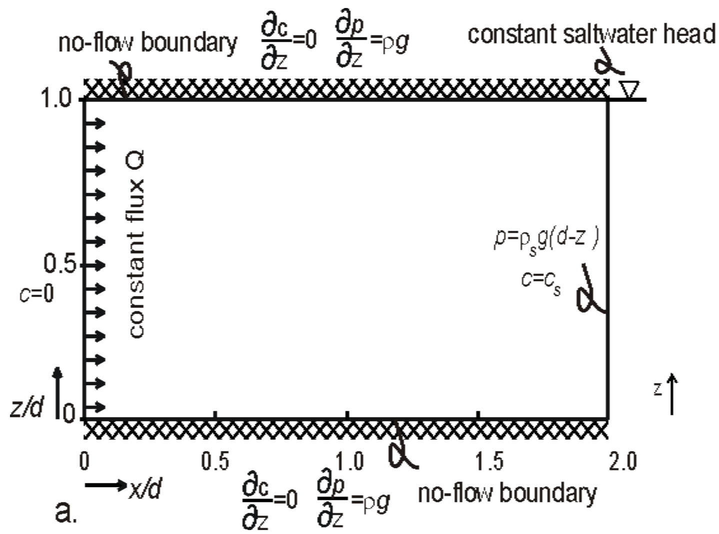
SEAWAT, MMOC, 8.5sec



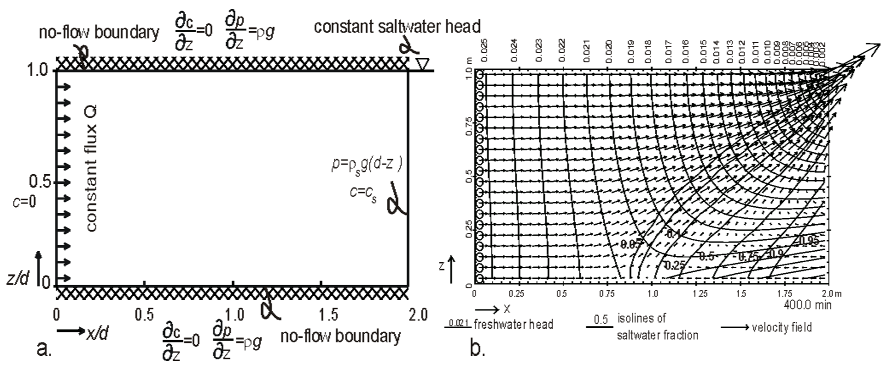
SEAWAT, HMOC, 6.8sec



Henry’s problem (1964)

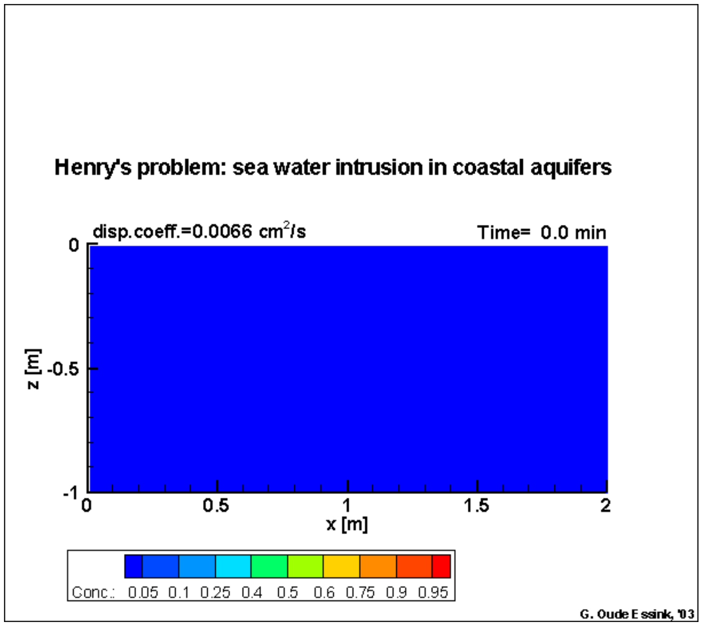


Henry’s problem



cases

Henry's problem



cases

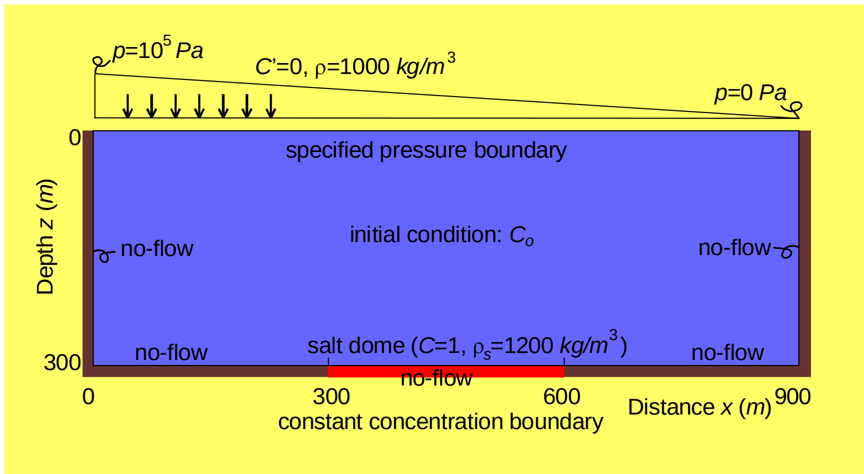
Henry's problem

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!

cases

Hydrocoin:

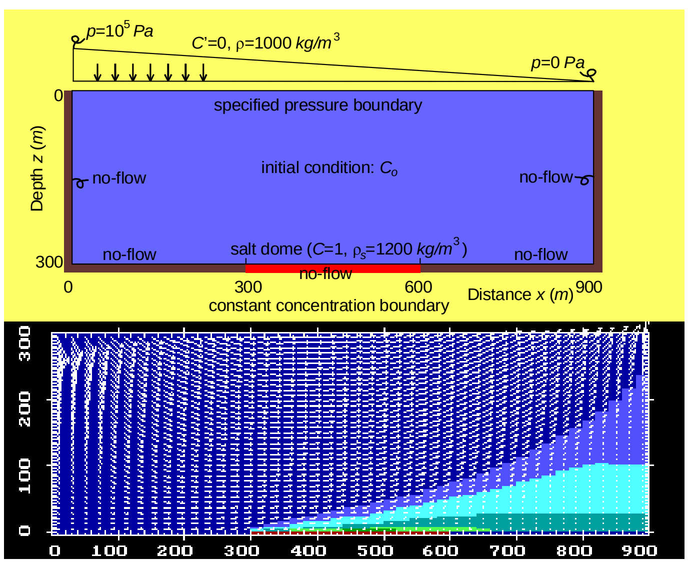
disposal of high-level nuclear waste
groundwater movement near salt domes
Gorleben salt dome, Germany



cases

Hydrocoin:

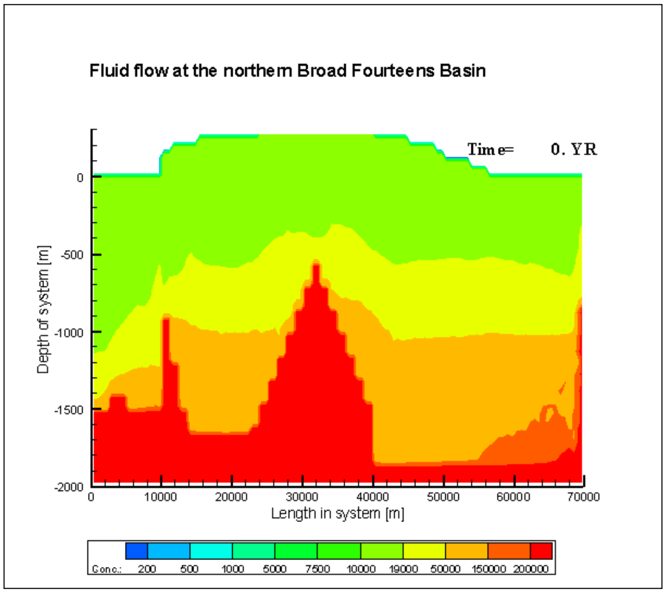
groundwater movement near salt domes



Salt fraction:

Broad 14 Basin, North Sea

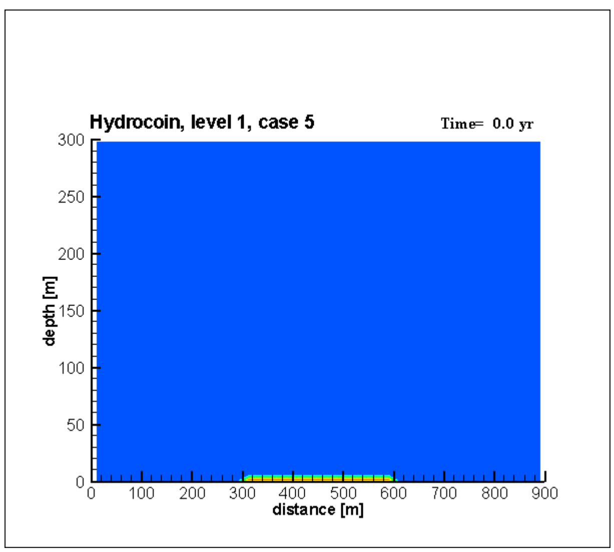
Geofluids'03, with L. Bouw



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

Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

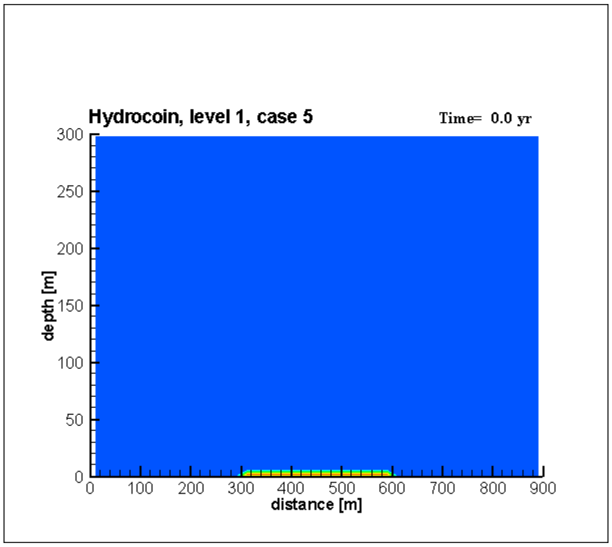


recirculation type

cases

Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

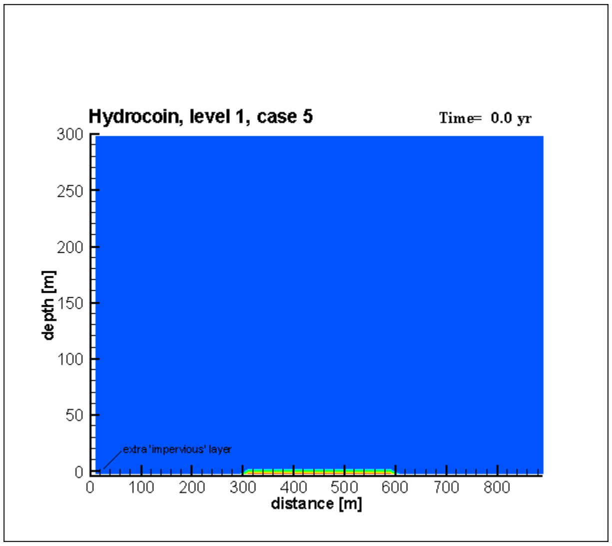


recirculation type

cases

Hydrocoin: effect of boundary condition (II)

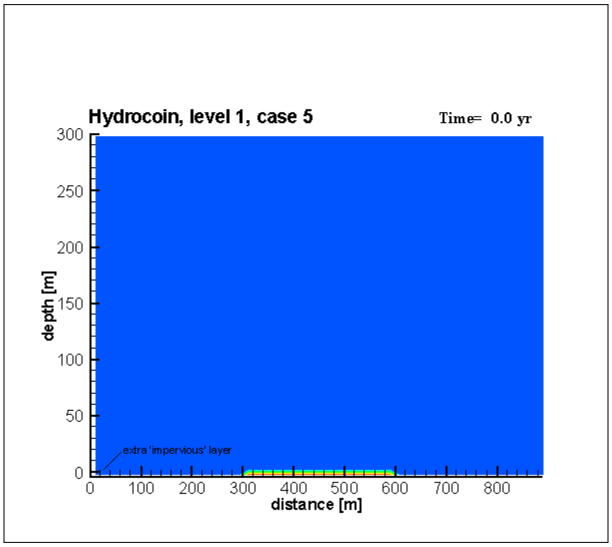
supply of brine through only hydrodynamic dispersion



swept-forward type

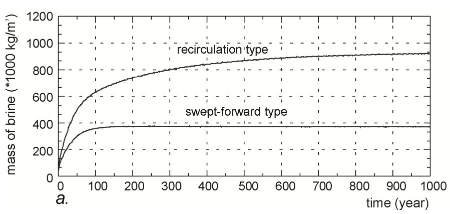
Hydrocoin: effect of boundary condition (II)

supply of brine through only hydrodynamic dispersion

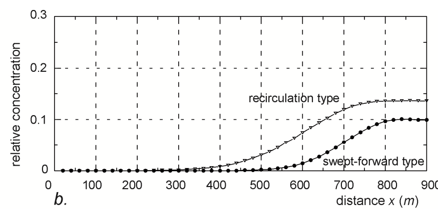


swept-forward type

Hydrocoin: difference recirculation vs swept forward



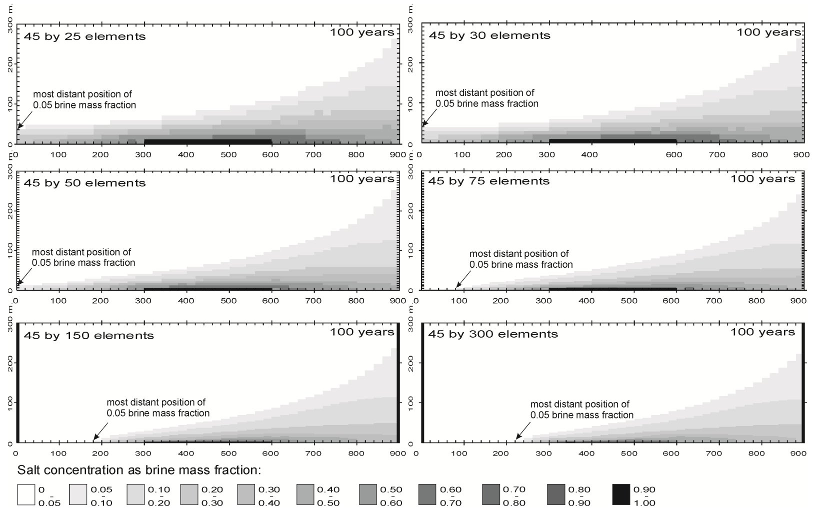
total mass of brine



brine conc at depth=200m

Lecture notes, p. 86-91

Hydrocoin: effect of vertical grid size

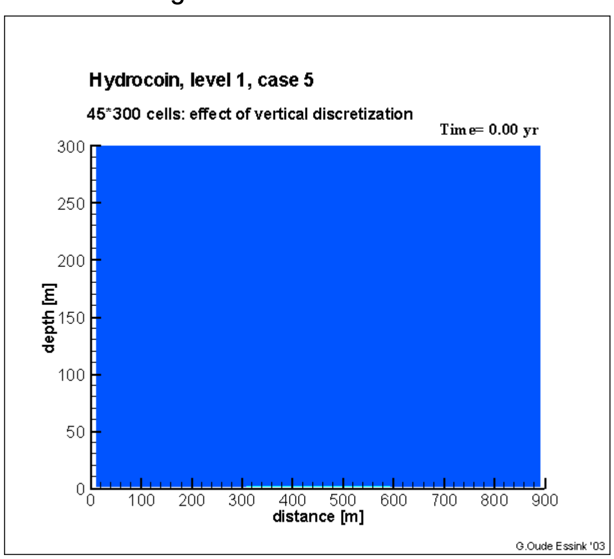


Recirculation type

cases

Hydrocoin: effect of vertical discretization (III)

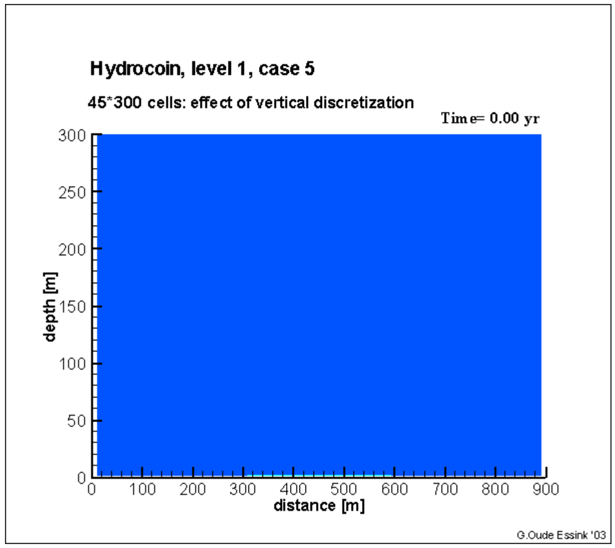
more vertical cells give better solution



like the swept-forward type

Hydrocoin: effect of vertical discretization (III)

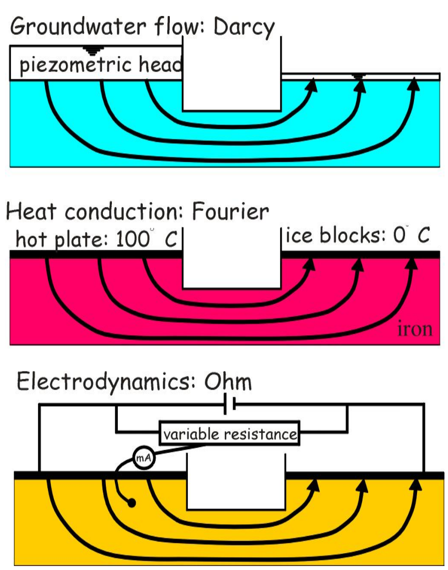
more vertical cells give better solution



like the swept-forward type

Analogy physical processes

Heat transport (analogy with solute transport)



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

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

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

Heat transport

Conduction and convection of heat

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

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

thermal conductivity [Joule/(ms ^{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)]

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

cases

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

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

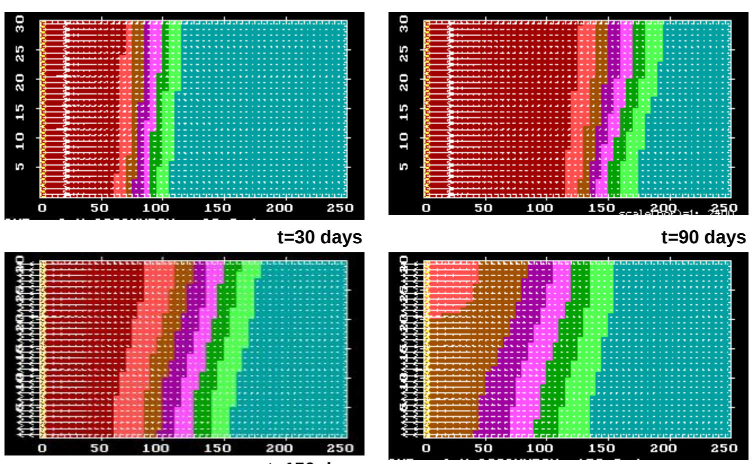
Equation of state: relation density & temperature

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

Analogy between solute and heat transport

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

Energy storage in geothermal reservoirs



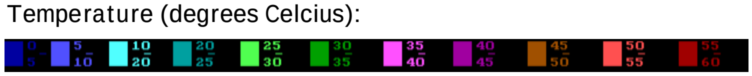
t=30 days

t=90 days

t=150 days

t=210 days

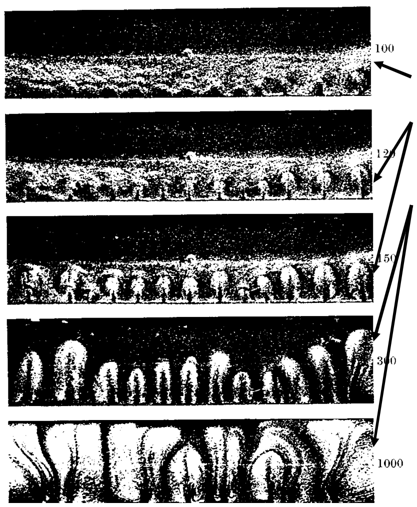
Temperature (degrees Celcius):



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

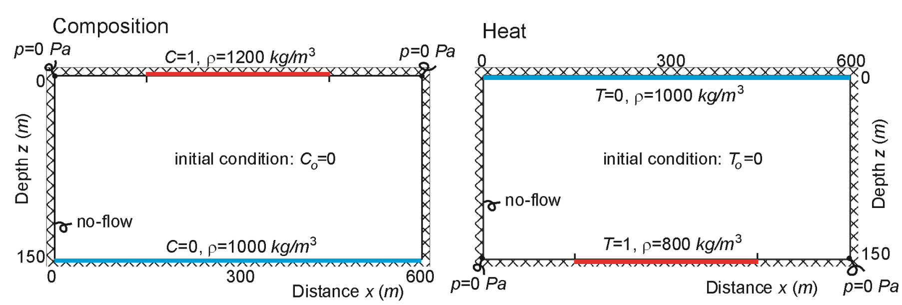
Convection of heat occurs when:

Rayleigh number > $4\pi^2$

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

Elder problem (II)

Anology composition and heat

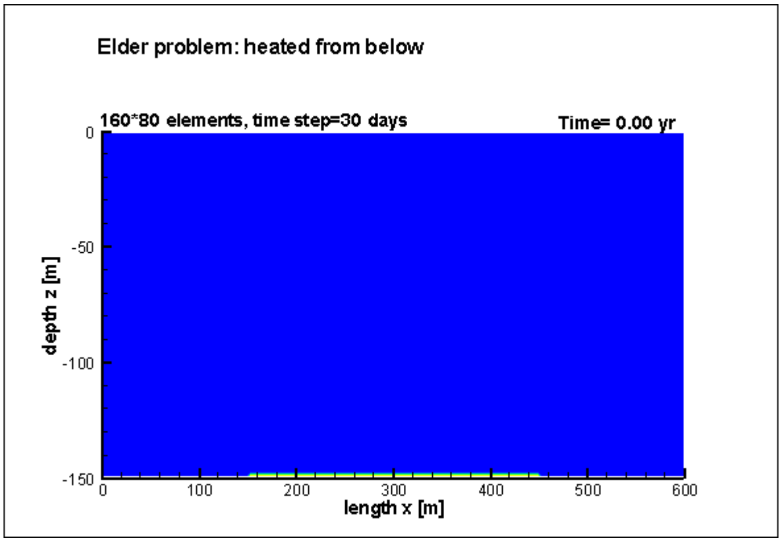


Lecture notes, p. 91-96

cases

Elder problem (III)

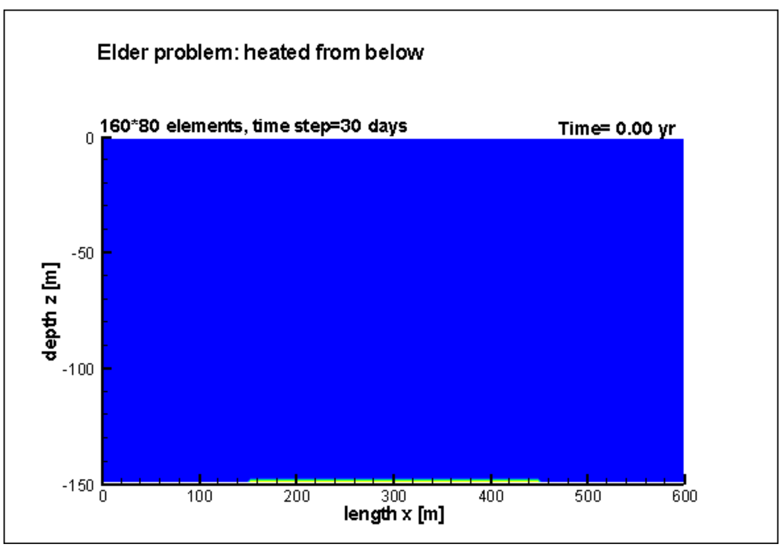
Development of convection cells (Rayleigh number=400)



cases

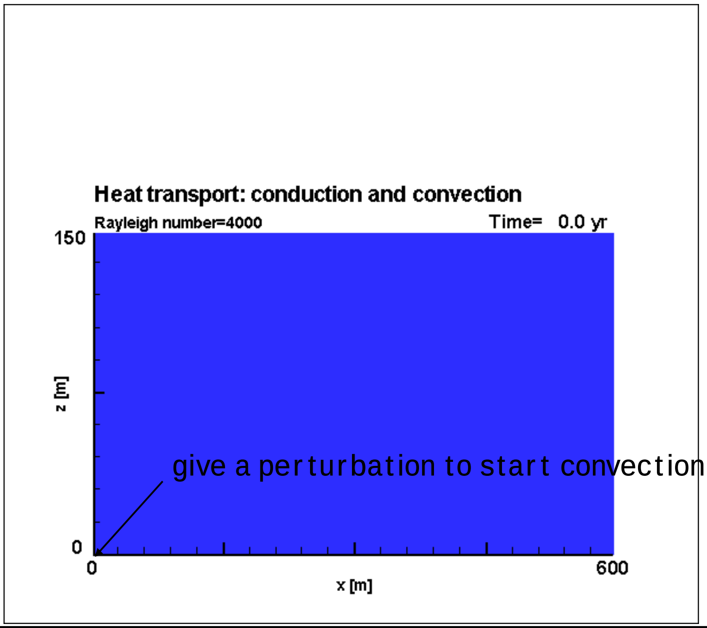
Elder problem (III)

Development of convection cells (Rayleigh number=400)



cases

Heat transport (Rayleigh number=4000)



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

Sri Lanka
Some days after December 26th, 2004

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

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

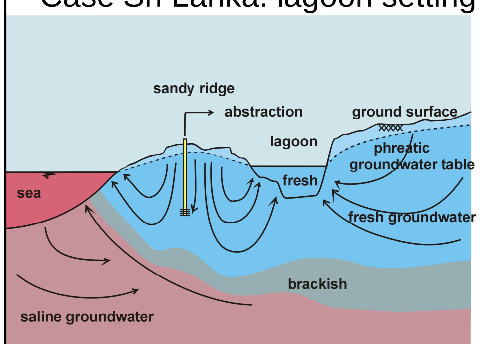
1. Fingering processes in the subsoil
2. Evolution of a freshwater lens after flooding by sea water
3. Freshwater lens in a coastal aquifer with a brackish lagoon

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

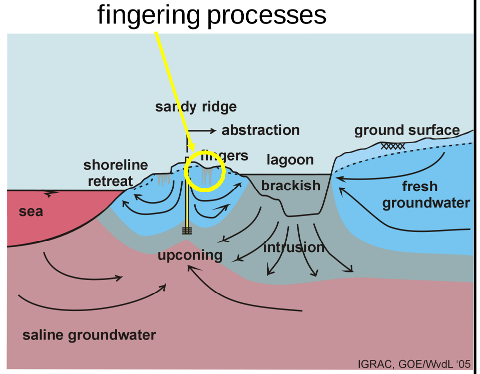
Concept 1: Fingering processes in the subsoil

Case Sri Lanka: lagoon setting

fingering processes

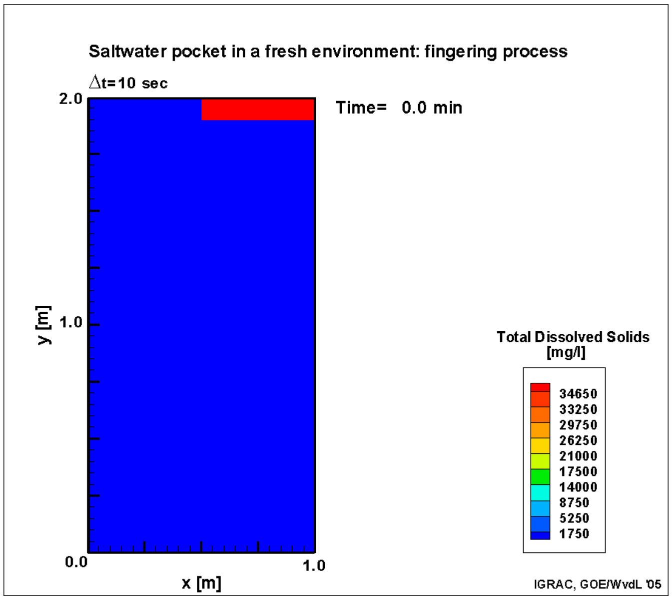


Before the Tsunami

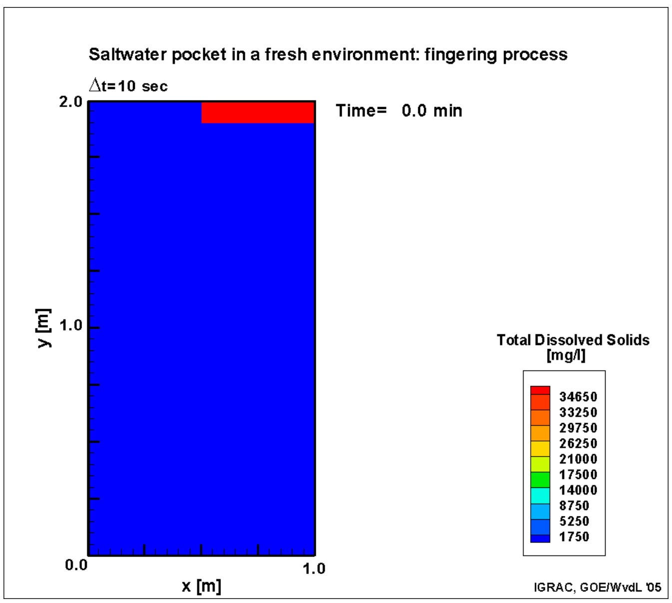


After the Tsunami

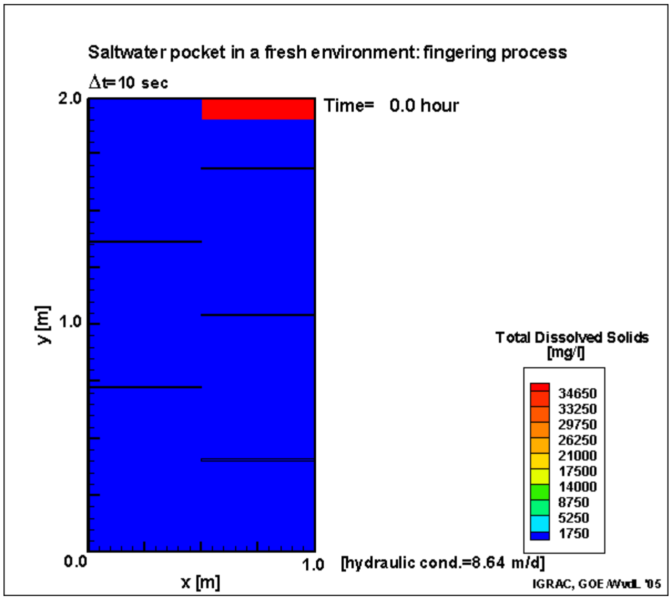
Concept 1: Fingering processes in the subsoil



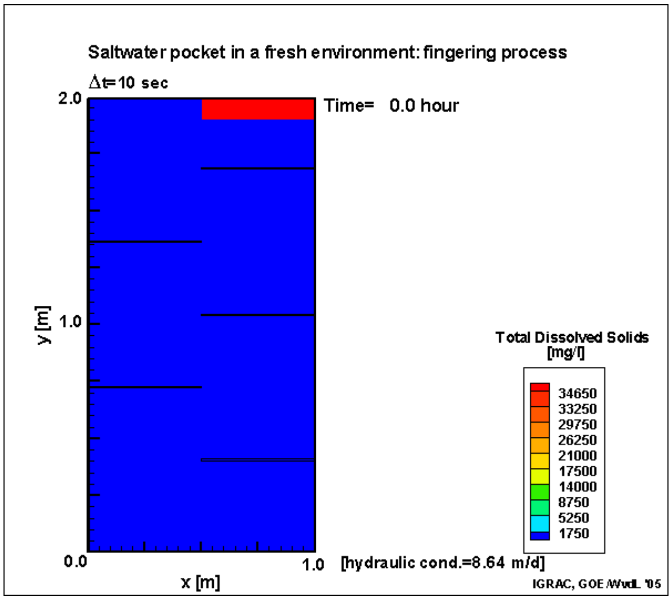
Concept 1: Fingering processes in the subsoil



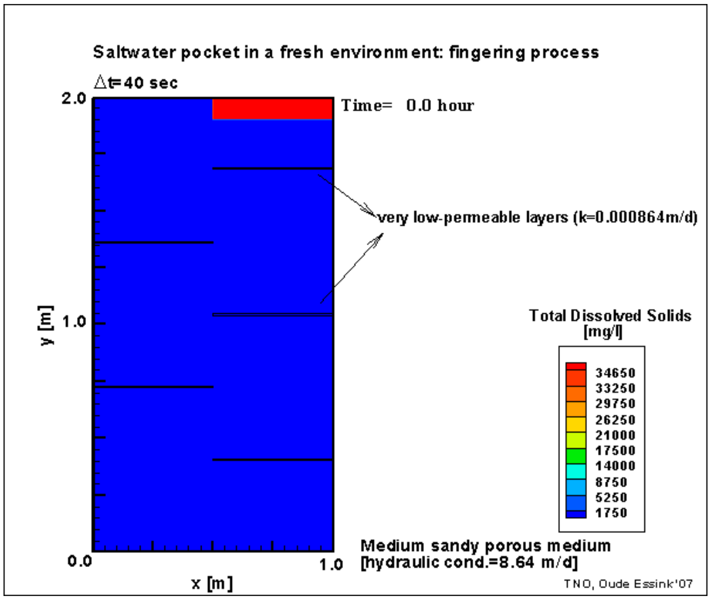
Concept 1: Fingering processes in the subsoil



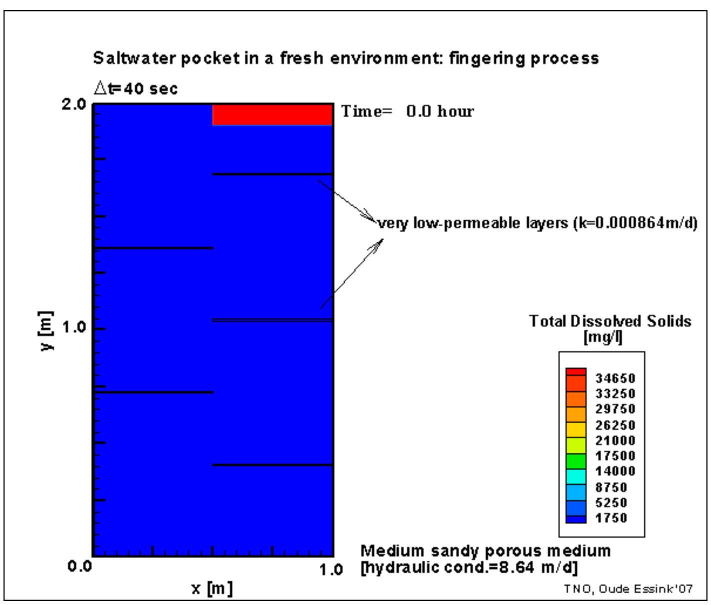
Concept 1: Fingering processes in the subsoil



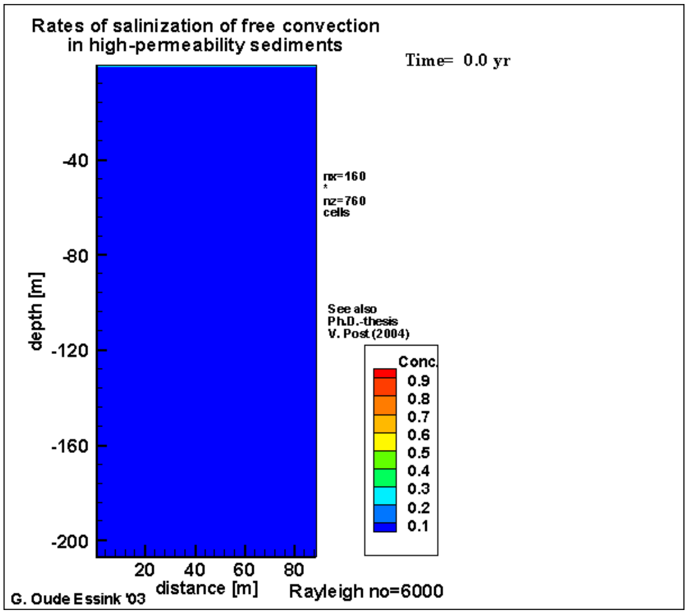
Concept 1: Fingering processes in the subsoil



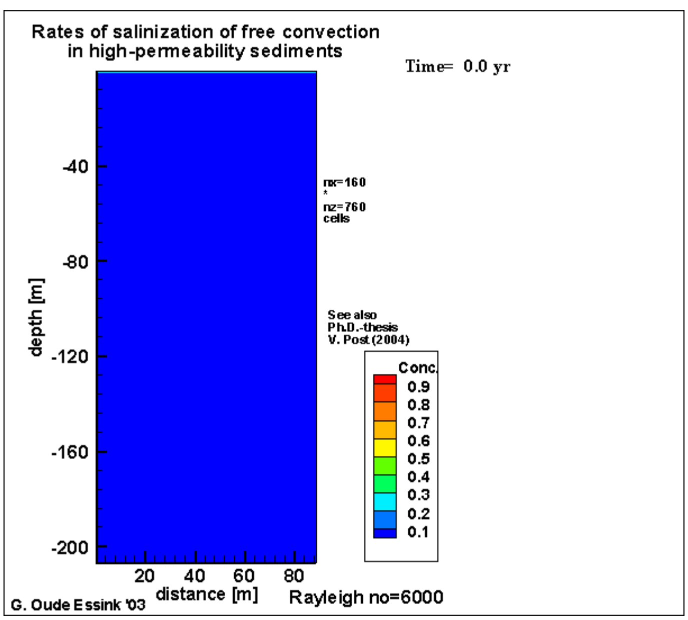
Concept 1: Fingering processes in the subsoil



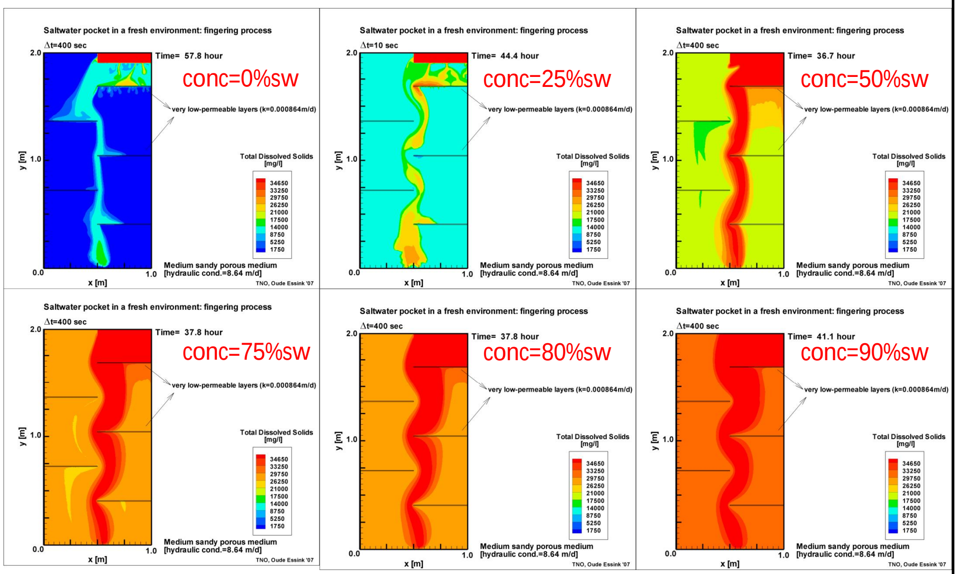
Concept 1: Fingering processes in the subsoil



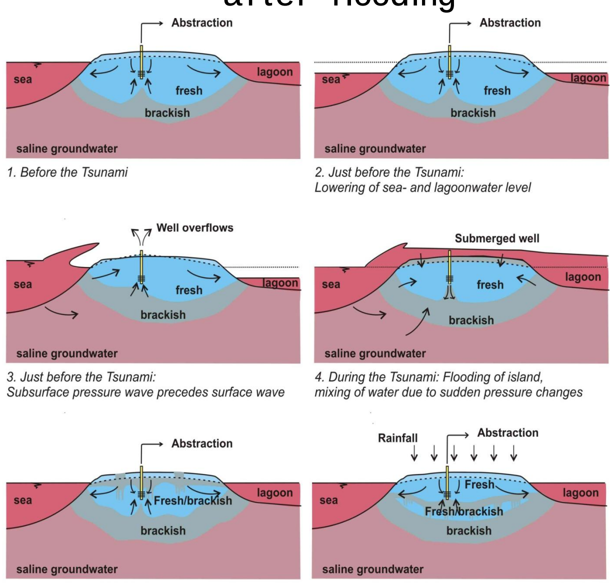
Concept 1: Fingering processes in the subsoil



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

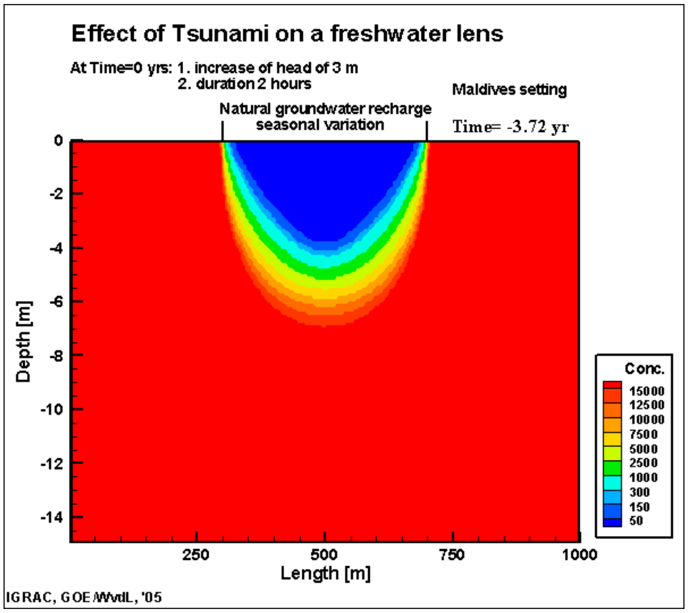
3. Just before the Tsunami: Subsurface pressure wave precedes surface wave

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

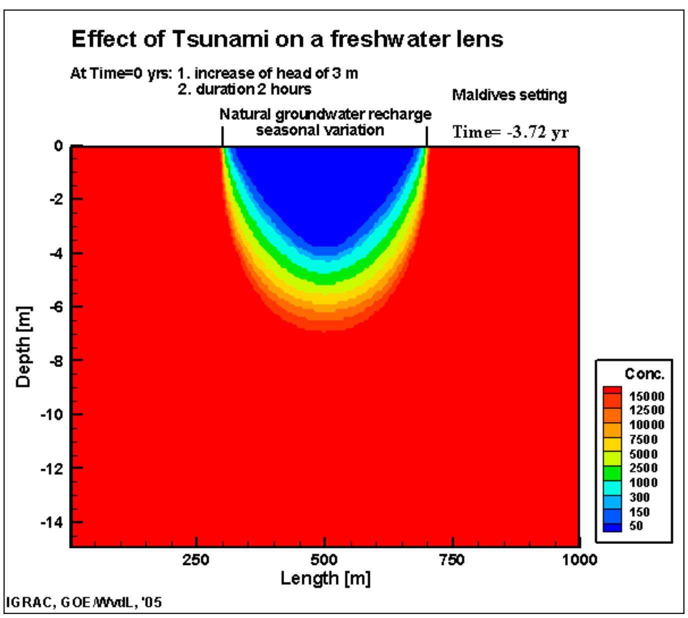
5. After the Tsunami Freshwater mixed with brackish water

6. After the Tsunami Recharge by rainfall replaces brackish water

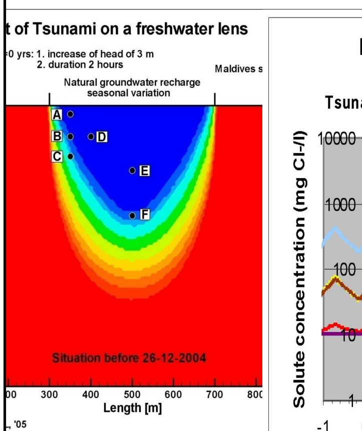
Concept 2: Evolution of a freshwater lens after flooding

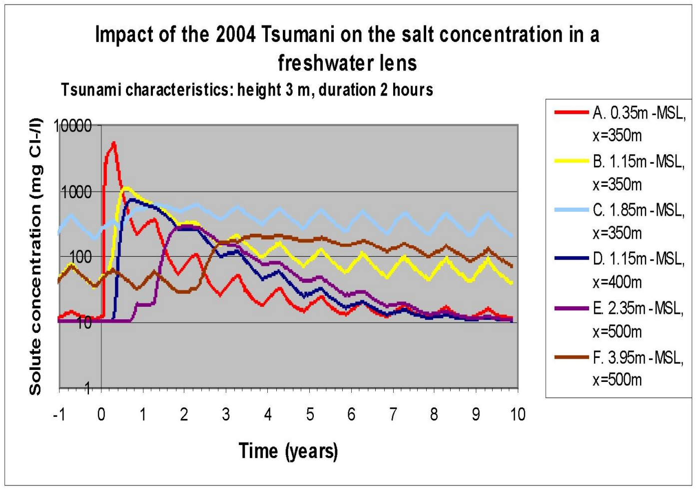


Concept 2: Evolution of a freshwater lens after flooding



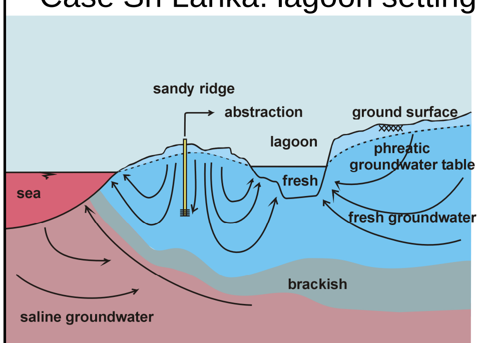
Concept 2: Evolution of a freshwater lens after flooding



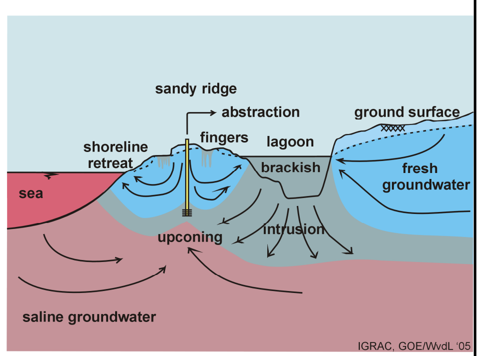


Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

Case Sri Lanka: lagoon setting

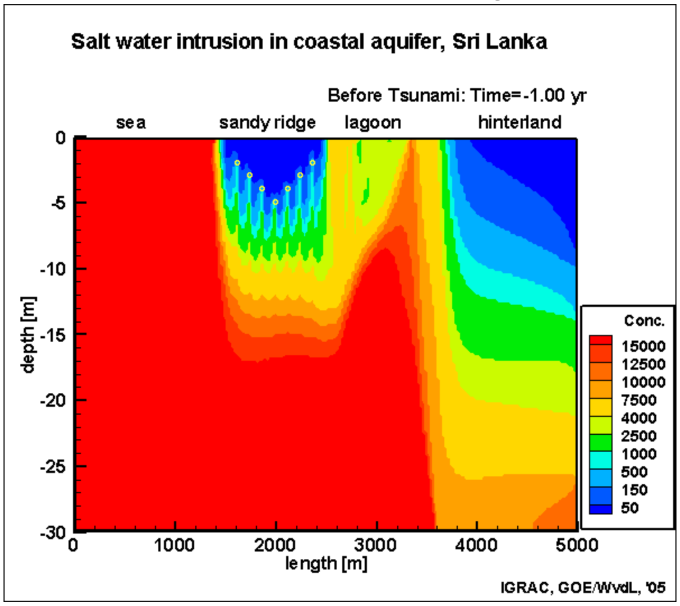


Before the Tsunami



After the Tsunami

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



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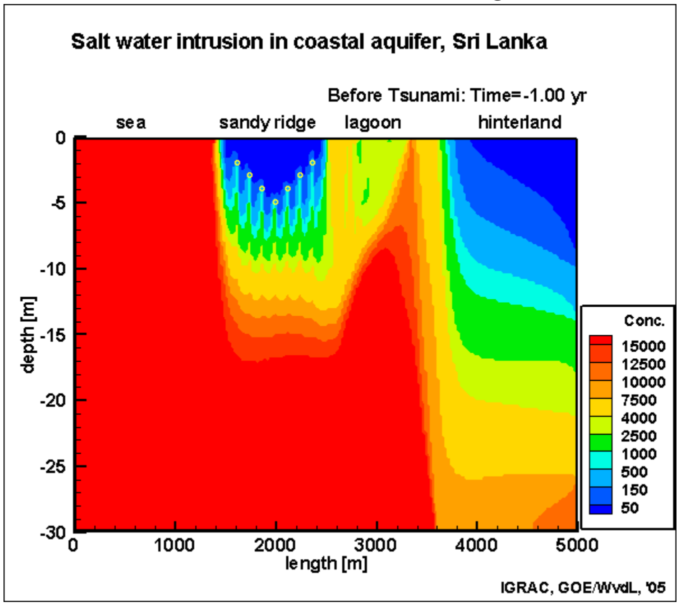

Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon