IHE 2016

Density dependent groundwater flow

salt water intrusion (and heat transport)

Gualbert Oude Essink

Lecture set-up:

- PowerPoint sheets
- Practicals

http://freshsalt.deltares.nl

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16-17-20-21 June 2016

Groundwater in the Coastal Zone

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

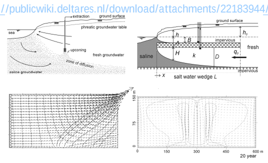
Joost Delsman   Pieter Pauw   Sebastian Huizer

Perry de Louw   Esther van Baaren   Jarno Verkaik   Marta Faneca   Gualbert Oude Essink

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

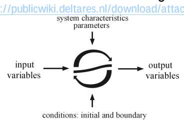
1. Density dependent groundwater flow

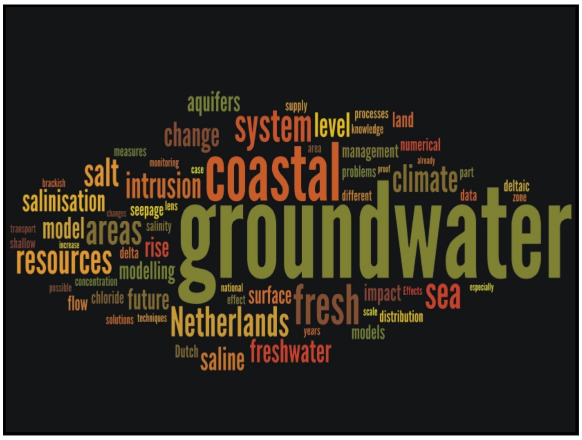
http://publicwiki.deltares.nl/download/attachments/22183944/gwm2.pdf?version=1&modificationDate=126894



2. Groundwater modelling

http://publicwiki.deltares.nl/download/attachments/22183944/gwm1.pdf?version=1&modificationDate=126875





Introduction

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 - Geological Survey of the Netherlands
- Utrecht University: 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
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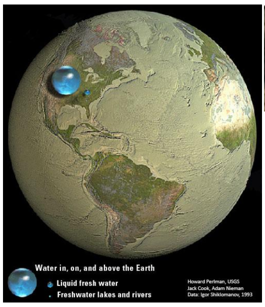
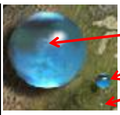
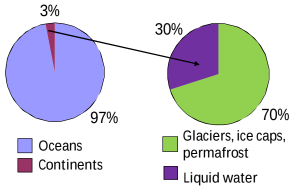
Research on groundwater in the coastal zone

- 18 years experience in 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)

Volumes of water on Earth: a scarce product







Source: Perlman, USGS; Shiklomanov, 1993

Salt Water Intrusion Meeting, since 1968

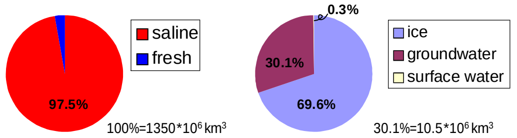
http://www.swim-site.org/

Themes

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

Water on Earth

Total water on Earth — Total fresh water on Earth



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)

www.swim-site.org

Salt Water Intrusion Meeting (SWIM)

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Welcome to the homepage of the Salt Water Intrusion Meeting

The Salt Water Intrusion Meeting (SWIM) has been held in different European countries on a biennial basis since 1968 with an increasing number and diversity of participants. In spite of its name, SWIM is not solely restricted to seawater intrusion problems. The meetings are very successful in bringing together people who are interested in saline groundwater issues: well-known specialists, water managers and students.

The growing interest among scientists and water managers reflects the increasing relevance of managing saline groundwaters all around the world, especially in densely populated coastal areas. Problems include:

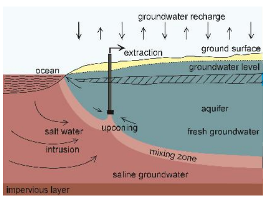
- over-exploitation of water resources, especially in arid and semi-arid areas
- increased demand due to economic development and population growth
- quality deterioration of the available surface water resources
- insufficient knowledge of the aquifer architecture and processes to design sound management programmes
- climate change and sea level rise

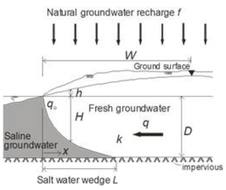
Philosophy of SWIM

The SWIM aims to bring together specialists, exchange ideas and discuss results on saline groundwater problems in a friendly and relaxed atmosphere. The meetings have always maintained their informal character with contributions from well-known scientists mixed with young people giving their first presentation. The ambiance during the meetings of the last 34 years can be characterized as based on personal contacts and good discussions. There is no SWIM association or so, with memberships and fees; SWIM is carried by persons and institutions in various countries, which have confidence in it and see the usefulness of these meetings.

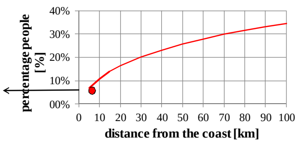
www.swim-site.org

Groundwater in the coastal zone





500 million people in the first 5km from the coastline



Salt Water Intrusion Meeting (SWIM)

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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 13th, 15th, 16th, 17th, 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.

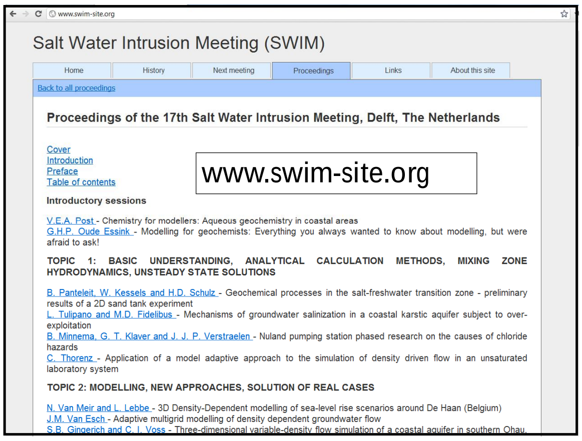
www.swim-site.org

Available for download:

- Proceedings of the 21th Salt Water Intrusion Meeting, S. Miguel, Azores, Portugal
- Abstracts of the 20th Salt Water Intrusion Meeting, Naples, Florida, USA
- Proceedings of the 19th Salt Water Intrusion Meeting, Cagliari, Italy
- Abstracts of the 18th Salt Water Intrusion Meeting, Cartagena, Spain
- Proceedings of the 17th Salt Water Intrusion Meeting, Delft, The Netherlands
- Proceedings of the 16th Salt Water Intrusion Meeting, Wolin Island, Poland
- Proceedings of the 15th Salt Water Intrusion Meeting, Ghent, Belgium
- Proceedings of the 13th Salt Water Intrusion Meeting, Cagliari, Italy

For sale (external links)

- Proceedings of the 18th Salt Water Intrusion Meeting, Cartagena, Spain
- Proceedings of the 12th Salt Water Intrusion Meeting, Barcelona, Spain
- Proceedings of the 6th Salt Water Intrusion Meeting, Hannover, Germany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Salt Water Intrusion Meeting (SWIM)

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Back to all proceedings

Proceedings of the 17th Salt Water Intrusion Meeting, Delft, The Netherlands

Cover
Introduction
Preface
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www.swim-site.org

Introductory sessions

V.E.A. Post - Chemistry for modellers: Aqueous geochemistry in coastal areas
G.H.P. Oude Essink - Modelling for geochemists: Everything you always wanted to know about modelling, but were afraid to ask!

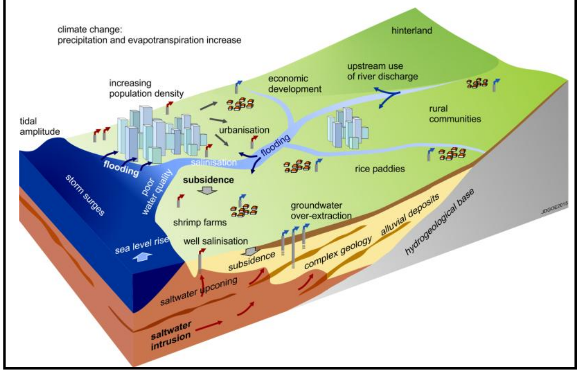
TOPIC 1: BASIC UNDERSTANDING, ANALYTICAL CALCULATION METHODS, MIXING ZONE HYDRODYNAMICS, UNSTEADY STATE SOLUTIONS

B. Panteleit, W. Kessels and H.D. Schulz - Geochemical processes in the salt-freshwater transition zone - preliminary results of a 2D sand tank experiment
L. Tulipano and M.D. Fidelibus - Mechanisms of groundwater salinization in a coastal karstic aquifer subject to over-exploitation
B. Minnema, G. T. Klaver and J. J. P. Verstraelen - Nuland pumping station phased research on the causes of chloride hazards
C. Thorenz - Application of a model adaptive approach to the simulation of density driven flow in an unsaturated laboratory system

TOPIC 2: MODELLING, NEW APPROACHES, SOLUTION OF REAL CASES

N. Van Meir and L. Lebbe - 3D Density-Dependent modelling of sea-level rise scenarios around De Haan (Belgium)
J.M. Van Esch - Adaptive multigrid modelling of density dependent groundwater flow
S.B. Gingerich and C. I. Voss - Three-dimensional variable-density flow simulation of a coastal aquifer in southern Ohau,

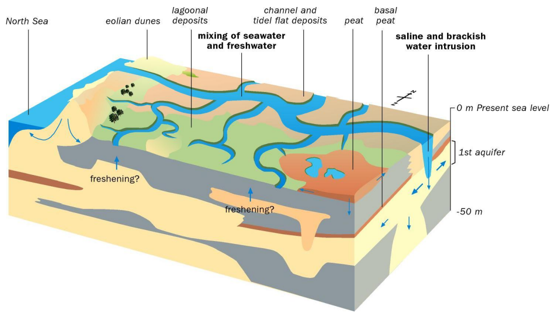
Groundwater issues in the coastal zone/deltaic areas

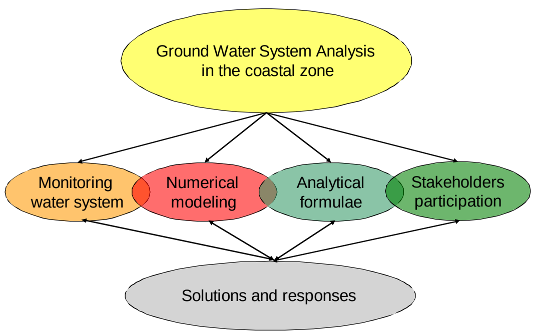


Topics of density driven groundwater flow

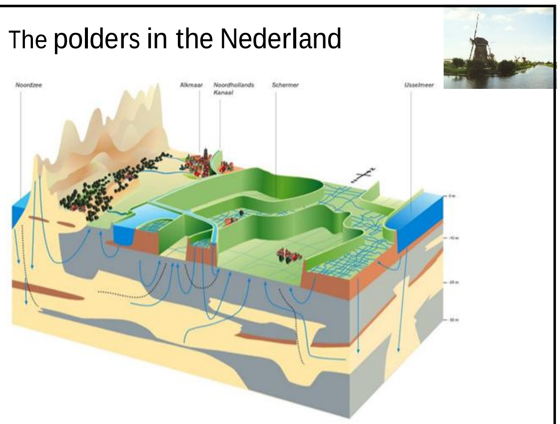
1. Introduction
   - water on earth
   - salt water intrusion
   - freshwater head
2. Interface between fresh and saline groundwater
   - analytical formulae (Badon Ghyben-Herzberg)
   - upconing example
3. Numerical modelling
   - mathematical background
   - Benchmark problems: Henry, Elder, Hydrocoin,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

Past, before man





The polders in the Nederland



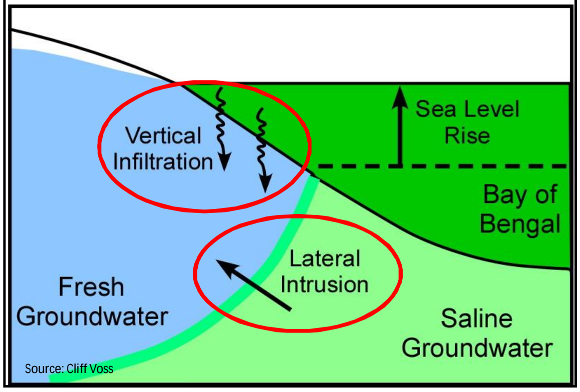
Groundwater in the future

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

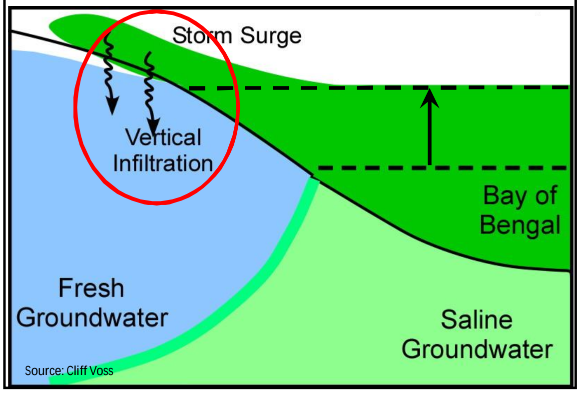
Direct anthopogenic influence on groundwater is more important than climate effect

Modes of Salinization due to Sea-Level Rise



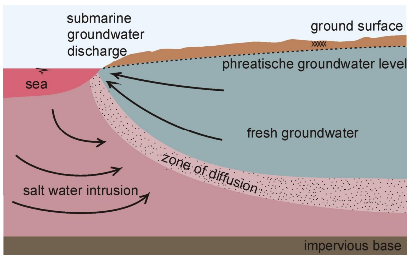
Introduction SWI

Modes of Salinization due to Sea-Level Rise

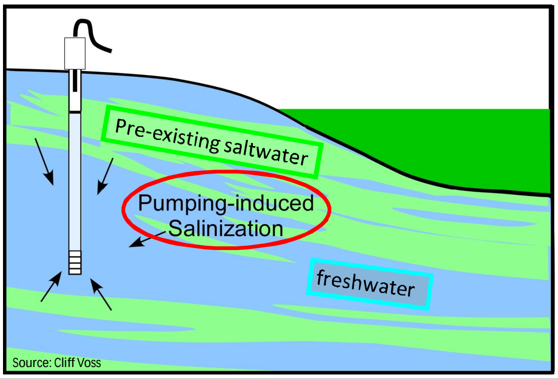


Definition of salt water intrusion

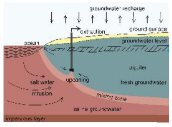
Inflow of saline water into an aquifer which contains fresh water



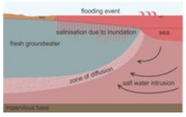
Salinization due to Pumping



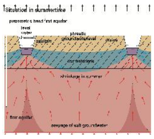
Salinisation processes at local scale



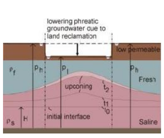
Salt water intrusion groundwater



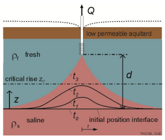
Inundation saline seawater



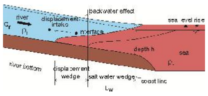
Shallow rainwaterlens



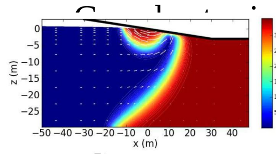
Upconing low-lying area

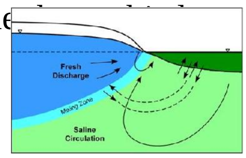


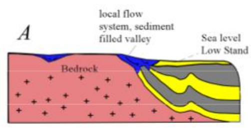
Upconing extraction

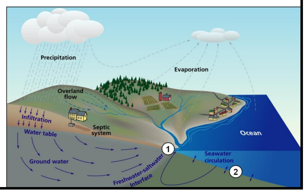


Salt water intrusion surface water





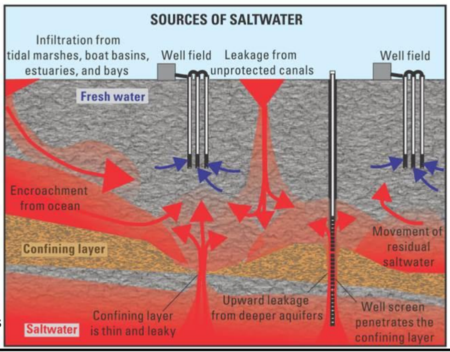




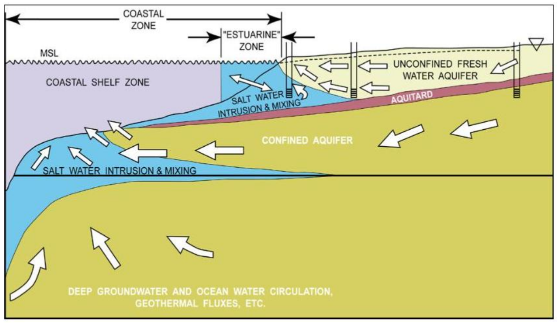
Source: Nature, 2013

Jan van Scorel
20140121

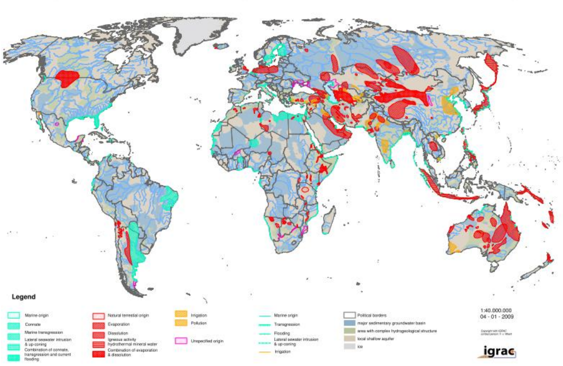
Salinization processes in the coastal zone: combination



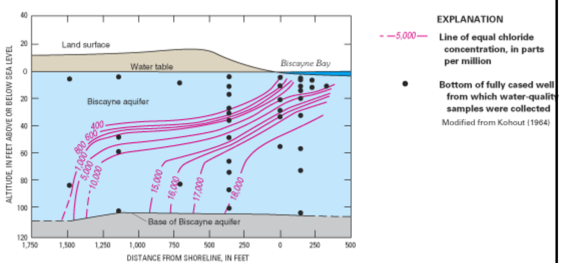
GEUS



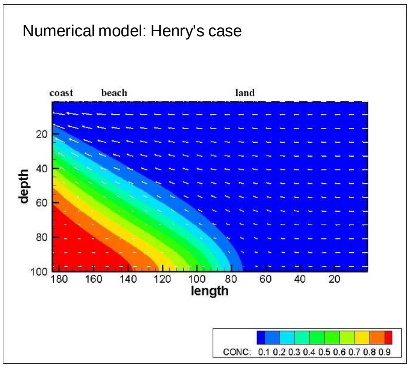
Regions with brackish and saline groundwater at shallow and intermediate depts



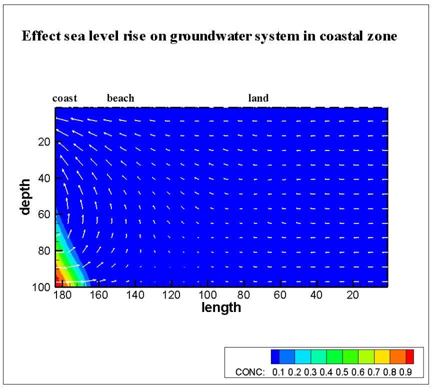
Biscayne aquifer, Florida USA: Henry's case



Definition of salt water intrusion



Sea level rise and salt water intrusion



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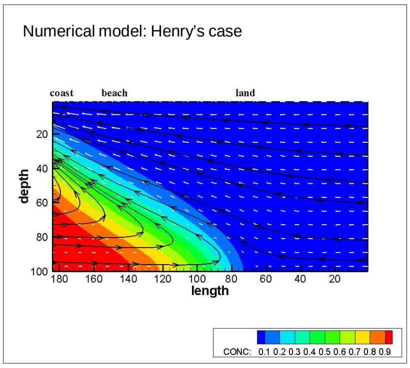
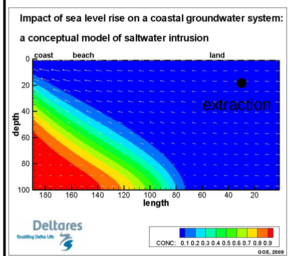
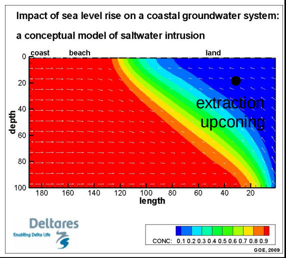
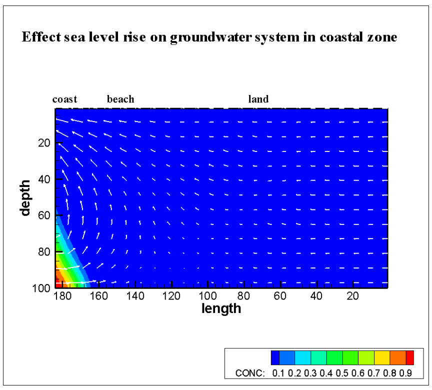


Sea level rise and salt water intrusion

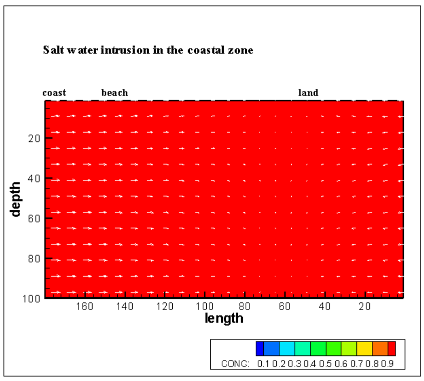




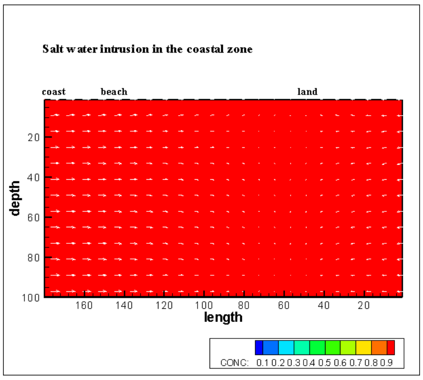
Sea level rise and salt water intrusion



Salt water intrusion



Salt water intrusion



In 1 liter ocean: about 35 gr salt

In 1 liter ocean: about 35 gr salt

Water on Earth

Some serious developments:

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

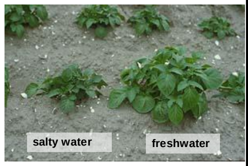
"*in 2025, two third of world population will face shortage of water*"

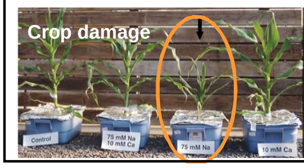
In 1 liter Dead Sea water (Jordan/Israel) : about 280 gr salt

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

Jan van Scorel
20140121

Salt in water is a problem





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

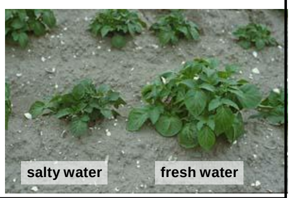
Jan van Scorel
20140121

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



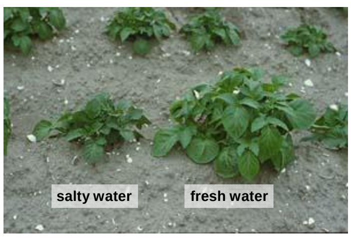
Definition fresh-brackish-saline

Klasse	Chloride concentratie (mg Cl-/l)
Zoet	< 1000
Brak	1000 – 3000
Zout	> 3000

Zeeland
Tabel 1: De gebruikte definities voor zoet, brak en zout grondwater in de Zeeuwse Delta. De chloride concentratie, een conservatieve stof die relatief veel bemeten is t.o.v. andere stoffen, is de dominante representant voor het zoutgehalte.

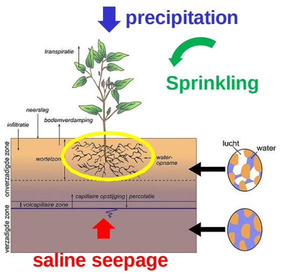
Type	mS/cm	mg TDS/l	Drinking- or irrigation water
Non-saline or fresh water	<0.8	<600 *	Drinking and irrigation water
Slightly saline	0.8 - 2	600-1.500	Irrigation water
Moderately saline	2-10	1.500-7.000	Primary drainage water and groundwater
Highly saline	10-25	7.000-15.000	Secondary drainage water and groundwater
Very highly saline	25 - 45	15.000-35.000	Seawater is 35000 TDS mg/l
Brine	>45	>45.000	

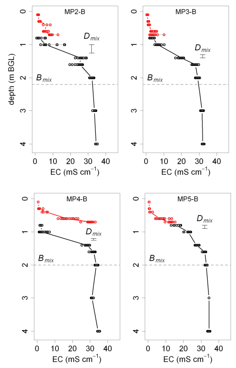
Effects salinisation: salt damage



Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

Salt-resistant crops





Important parameter:
Chloride concentration root zone
Land use
Sensitivity crops

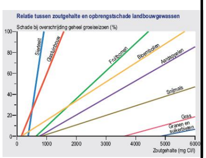
	Soil moisture		Irrigation water	
	Limi	Gradient	Limit	Gradient
Crop	**mg/l Cl**	**%/mg/l Cl**	**mg/l Cl**	**%/mg/l Cl**
Potatoe	756	0.0163	202	0.0610
Grass	3606	0.0078	962	0.0294
Sugar beat	4831	0.0057	1288	0.0212
Cut Corn	815	0.0091	217	0.0343
Grains	4831	0.0058	1288	0.0218
Fruit trees	642	0.0264	171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

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

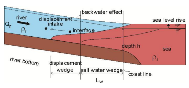
Source: Roest et al., 2003 en Haskoning

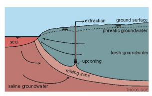


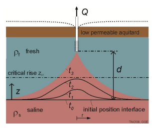
Source: MNP, 2005

Why is salinisation a pressing problem?

- 30% of world population lives <70 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

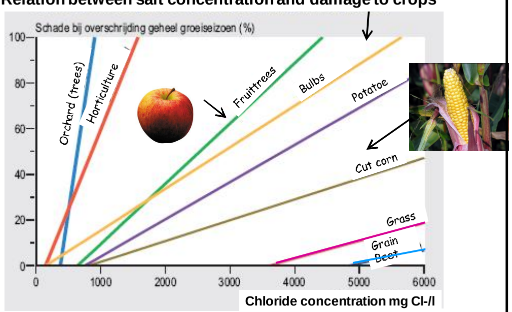






Salt damage to crops

Relation between salt concentration and damage to crops



Source: MNP, 2005

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)

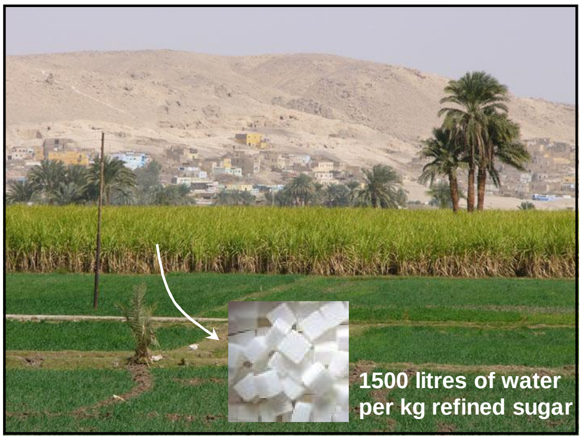
Introduction

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

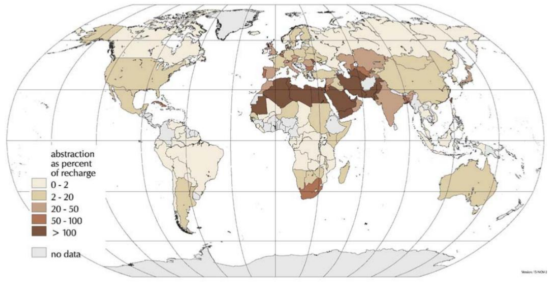
global averages

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

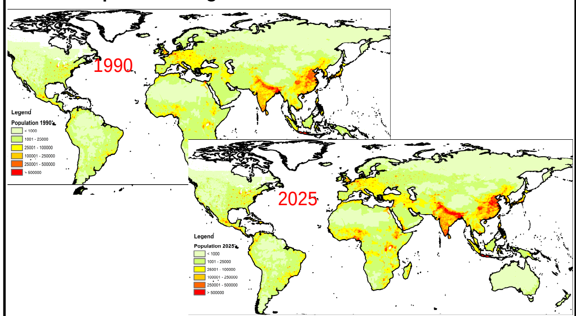
[Hoekstra & Chapagain, 2008]

= 140 litres of water

Water withdrawal: abstraction as % of recharge



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)*

Question:

Demand fresh water per capita per day in the Netherlands?:

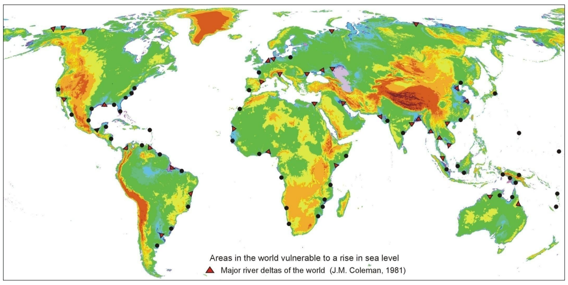
a. 10 litre/day
b. 25 litre/day
c. 100 litre/day
d. 200 litre/day

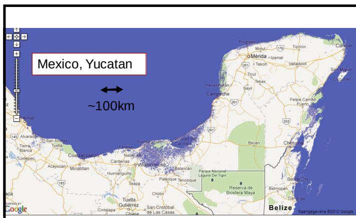
Reasons and drawbacks of using groundwater

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 !

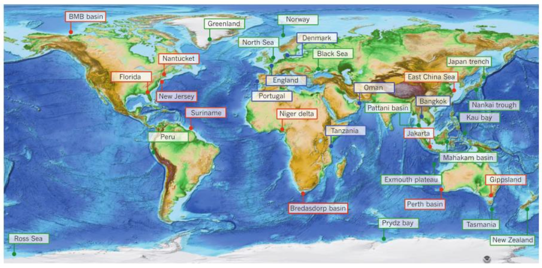
Areas vulnerable to sea level rise



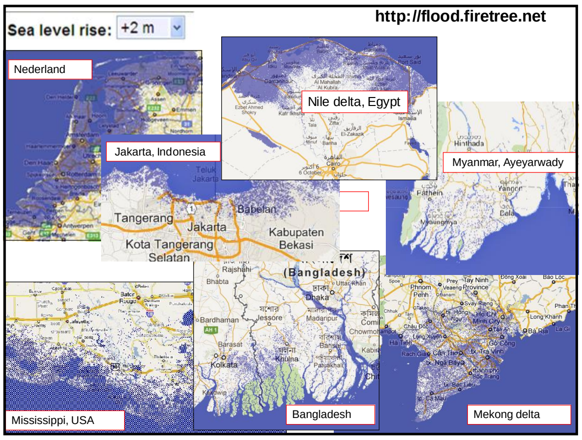


The Netherlands: low-lying lands

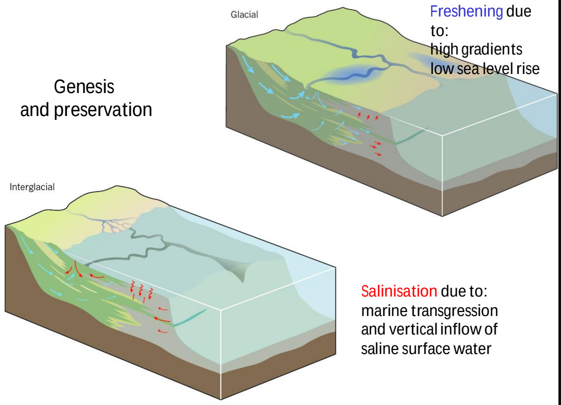
World map of topography and bathymetry showing known occurrences of fresh and brackish offshore groundwater



Post et al., Nature, 2013

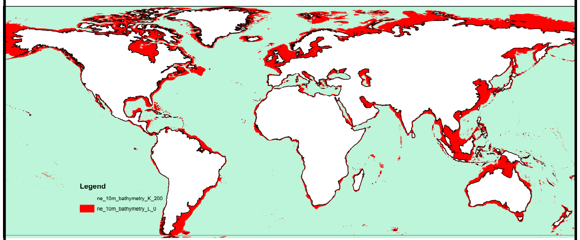


Genesis
and preservation

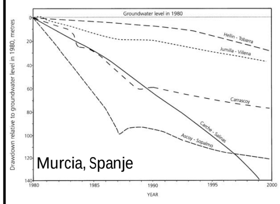


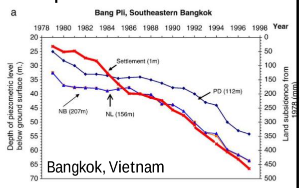
Source: Nature, 2013

Possible locations of offshore (submarine) groundwater



Serious overexploitation aquifers worldwide





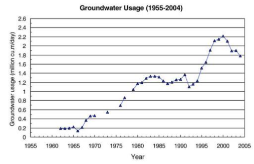
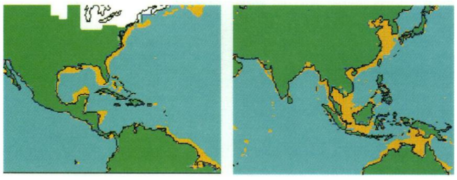


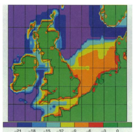
Fig. 3. Groundwater pumping rate in the Bangkok Plain versus time.

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

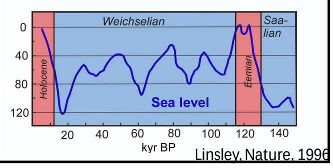


Exposed continental shelves

Peltier, *Science*, 1994



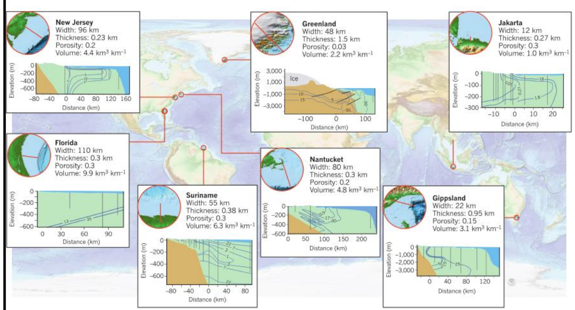
Inundated (kyr BP)



Linsley, Nature, 1996

Groundwater overexploitation in Mekong Delta

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

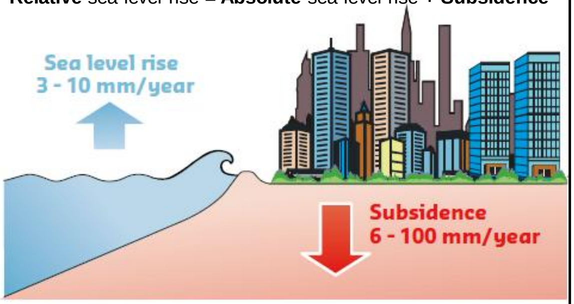


Land subsidence

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

Sinking delta cities

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



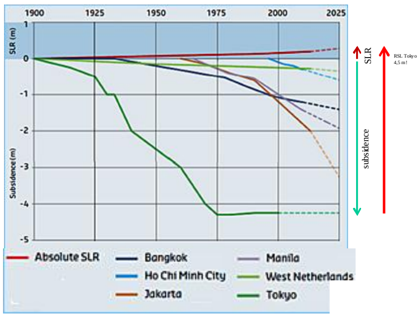

Learn from other areas

Want to get an idea about the effects of climate change in your delta?

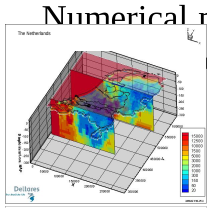
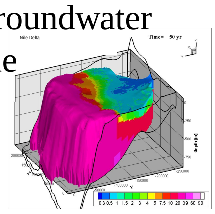
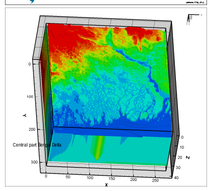
Evaluate past water management in the Dutch delta

Examples of some major coastal cities

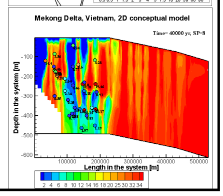
The subsidence issue is underestimated



Numerical models groundwater coastal zone

Mekong,
Just started research
UDW project

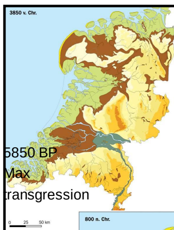


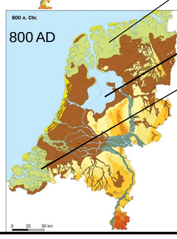
Land subsidence San Joachim Valley, CA, USA

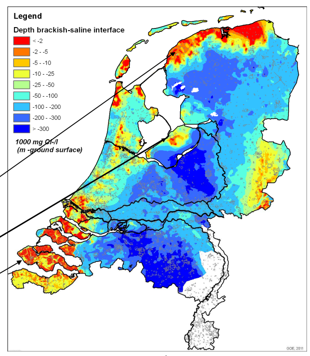
9 m since 1930s

San Francisco

Los Angeles



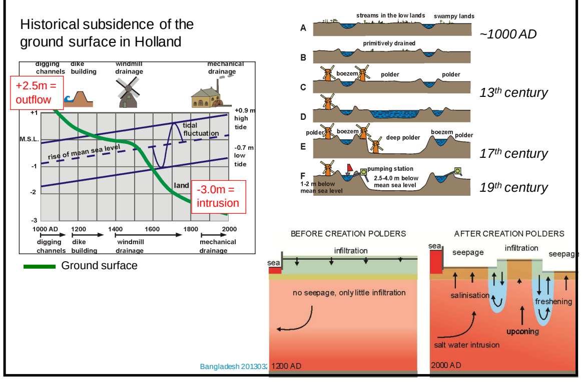




Based on:
- Analyses
- VES
- Borehole measurement

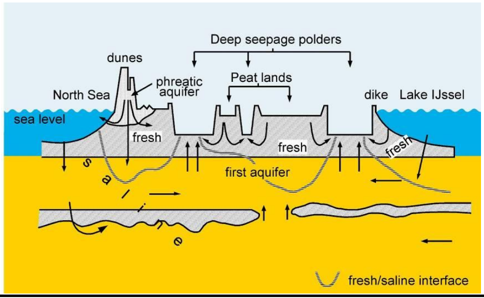
From fresh water outflow to salt water inflow

Historical subsidence of the ground surface in Holland

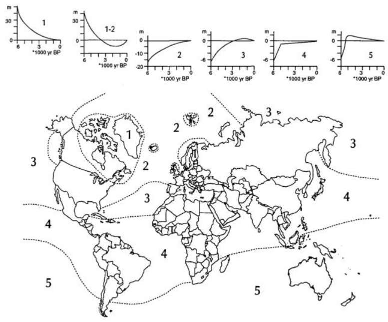


Saline seepage leads to:

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



Regional distribution of Holocene Sea-level Changes

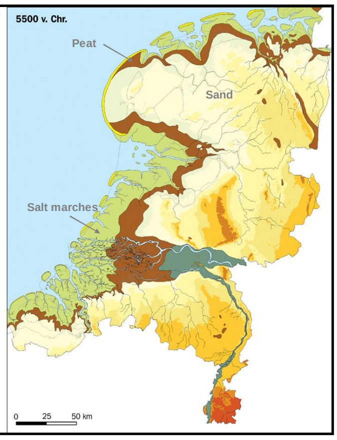


Source: Pirazzoli, P.A. & Pluet, J., 1991. World Atlas of Holocene Sea-level Changes. Elsevier Oceanography Series, Vol. 58

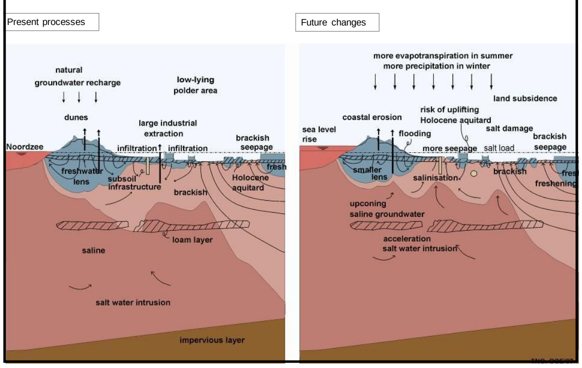
The Holocene transgressions

Major impact on present regional brackish groundwater systems

7500 BP

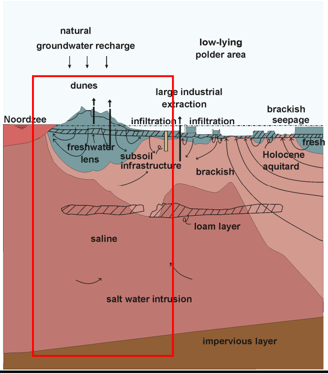


The Dutch groundwater system under stress

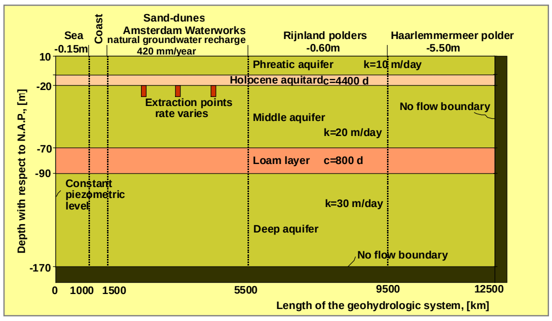


My first density dependent groundwater flow and solute transport model in 1990!

Saltwater intrusion in the Netherlands

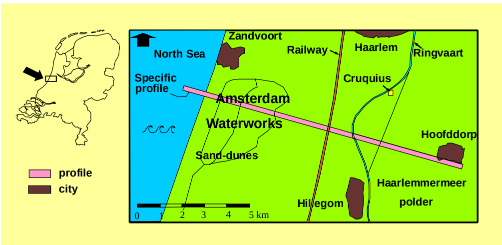


Geometry, subsoil parameters, boundary conditions



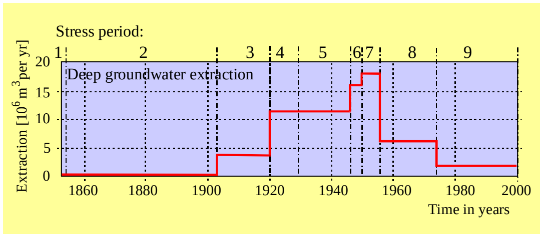
Saltwater intrusion in the Dutch coastal zone

Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



Saltwater intrusion in the Dutch coastal zone

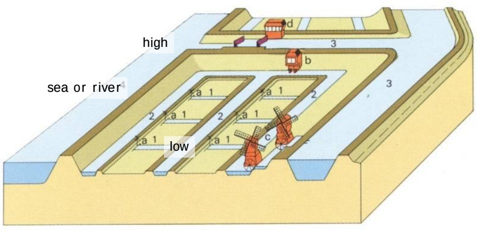
Grondwater extractions out of the middle aquifer in the sand-dune area of Amsterdam Waterworks



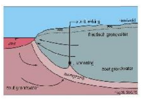
The polder system

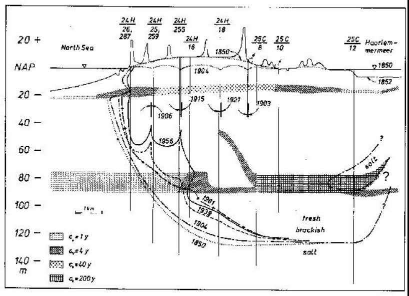
A polder is:

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



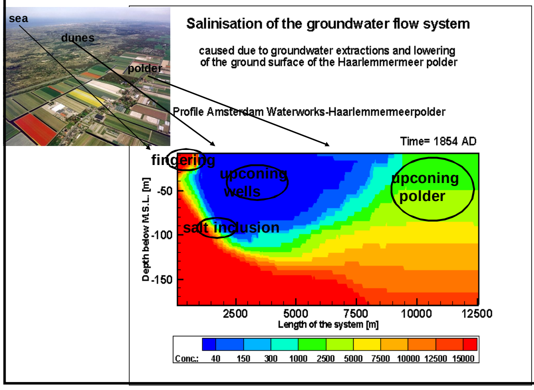
Upconing of brackish-saline groundwater

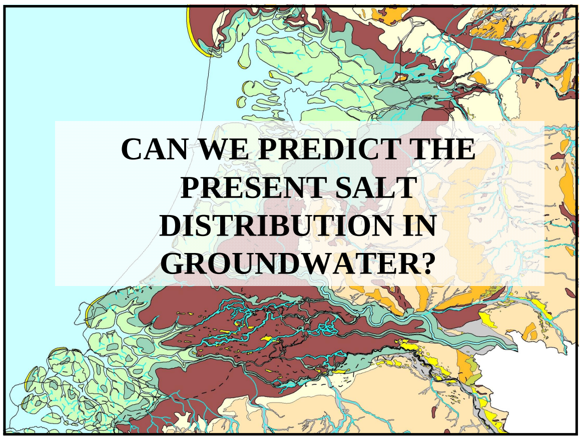




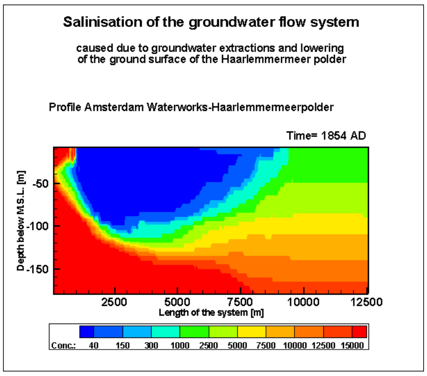
Stuyfzand, 1993

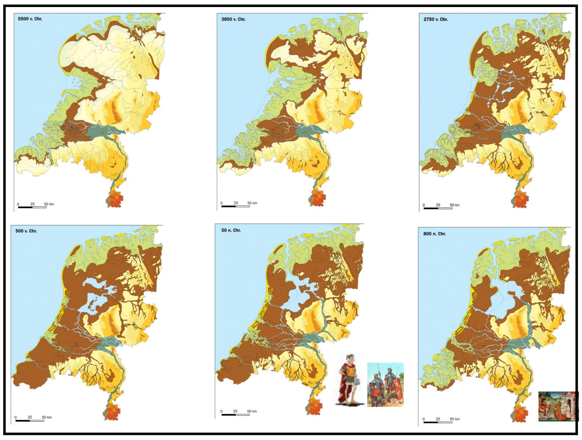
Saltwater intrusion in the Dutch coastal zone





Saltwater intrusion in the Dutch coastal zone



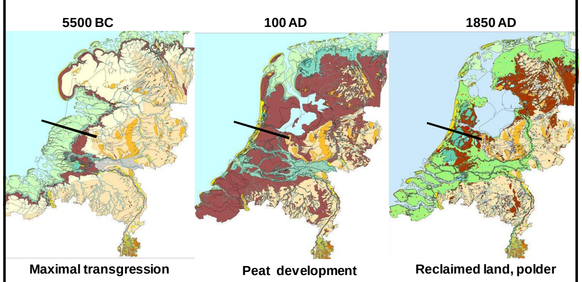


Palaeo hydrogeological modelling

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

Palaeogeografical development



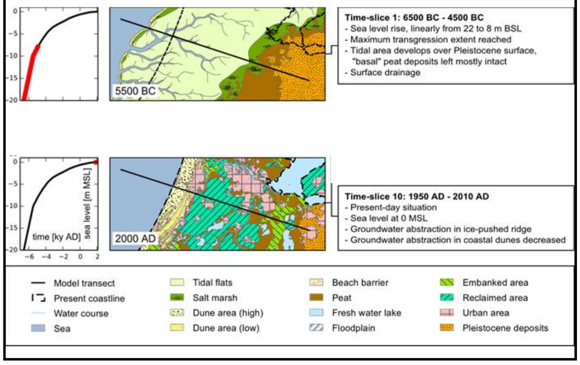
Delsman, J.R., Hu-a-ng, K.R.M., Vos, P.C., De Louw, P.G.B., Oude Essink, G.H.P., Stuyfzand, P.J. and Bierkens, M.F.P. 2013, Palaeo-modeling of coastal salt water intrusion during the Holocene: an application to the Netherlands, Hydrol. Earth Syst. Sci. Discuss., 10, 13707–13742

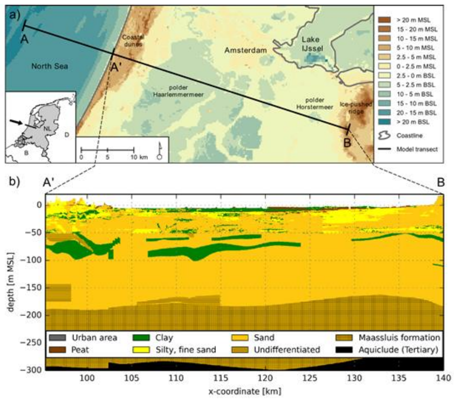
Atlas NL in het Holoceen (Vos et al, 2011)

Occurrence of salt under the polder Haarlemmermeer

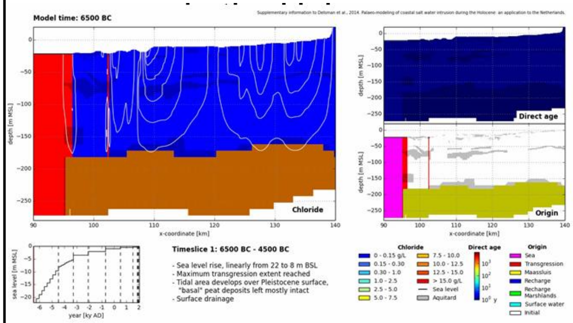
- Model profile Zandvoort - Hoofddorp – Hilversum
- Palaeogeographical development (Vos et al, 2011)
- 6500 BC - 2010 AD
- marine transgression
- Peat development, peat degradation, drainage, reclamation

Delsman et al., HESS, 2013

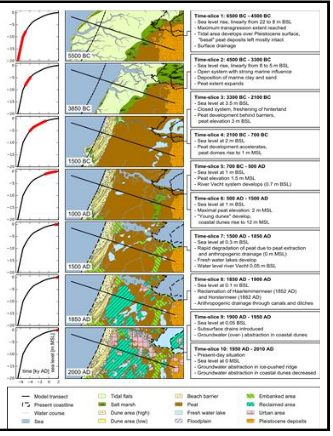




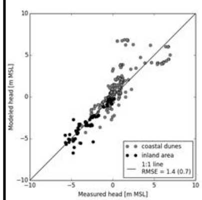
Development saline groundwater

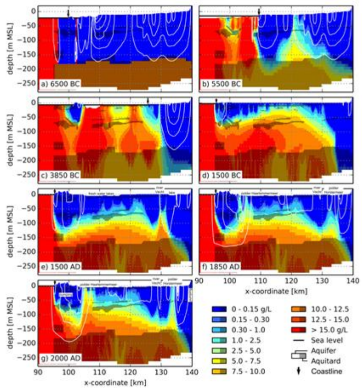


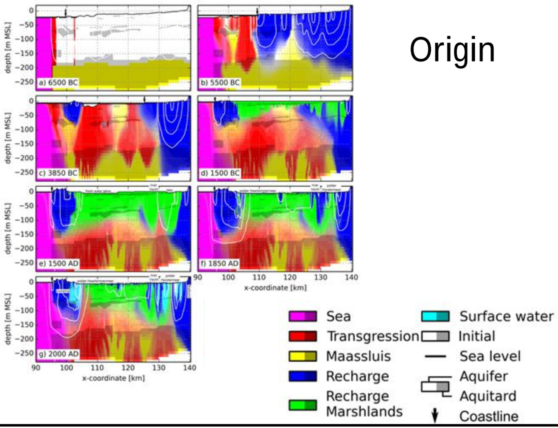
Delsman et al., HESSD, 2013



Model versus measurements



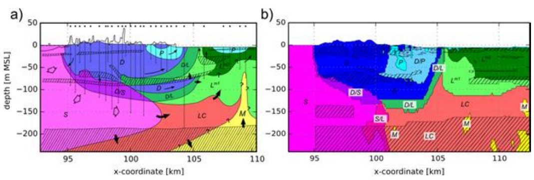


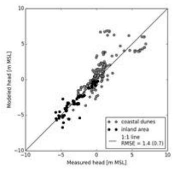


Origin

Base idea

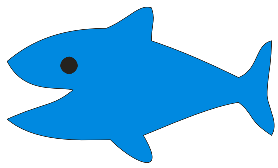
Many local solutions for fresh groundwater supply can have regional impact



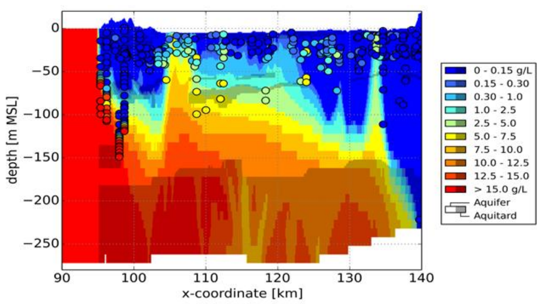


Starring

solution fresh groundwater supply

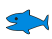


Model versus measurements



Starring

Local solution fresh groundwater supply



Starring

climate and global change

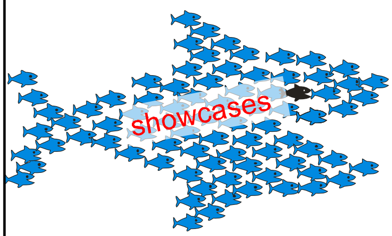
What should be the response?

Starring

climate and global change

Many local solutions fresh groundwater supply

climate and global change



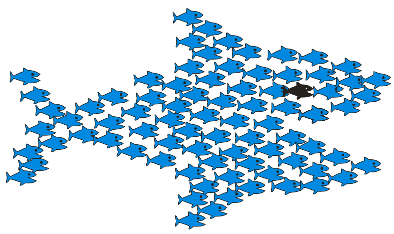
Many local solutions for fresh groundwater supply can have regional impact!

Solutions and responses

Local solution fresh groundwater supply

climate and global change

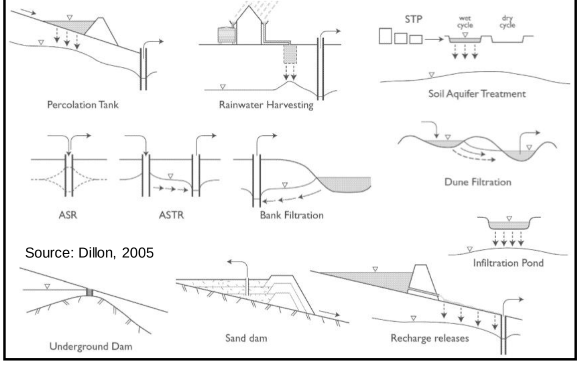
-upscaling local cases to regional strategy
-assess economical feasibility
-increase impact: communicate our showcases
-working together



Compensating measures

Aquifer Storage and Recovery

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



Source: Dillon, 2005

Possible solutions to stop salt water intrusion:

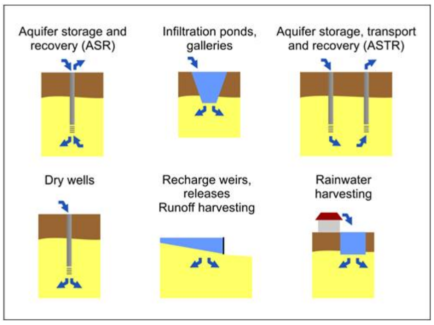
- Restriction of groundwater extractions through permits
- Co-operation between authorities and water users
- Desalinisation of saline water
- Technical countermeasures of salt water intrusion
  - six examples

Tools to understand salt water intrusion:

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

Aquifer Storage and Recovery / Managed Aquifer Recharge

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

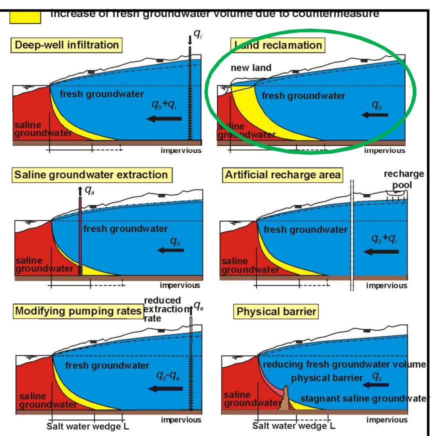


Source: Dillon, 2005

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)

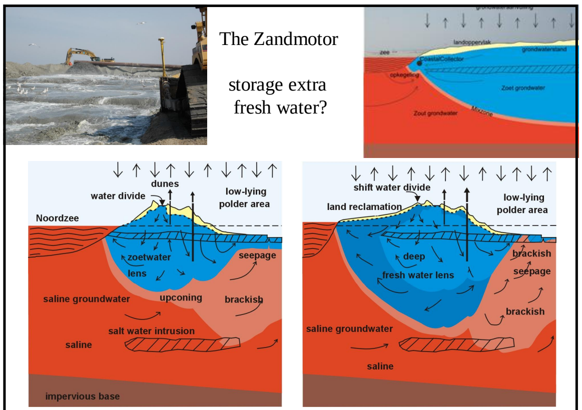
Technical measures to compensate salt water intrusion

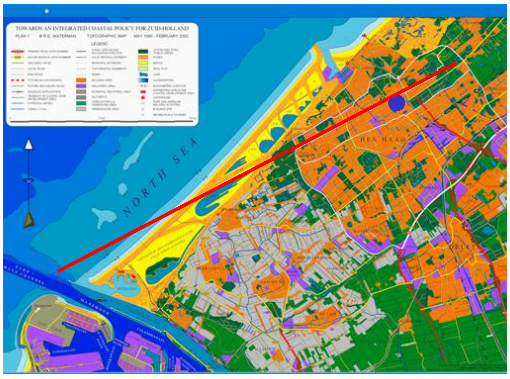


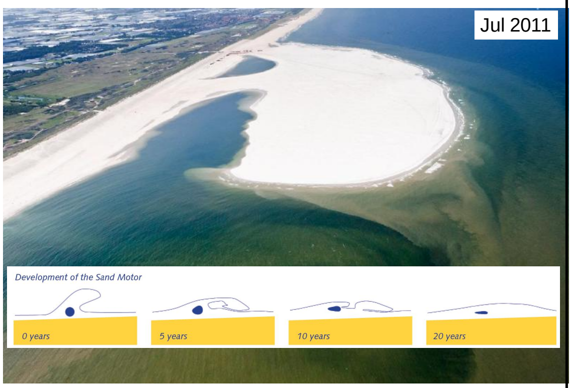
Land reclamation

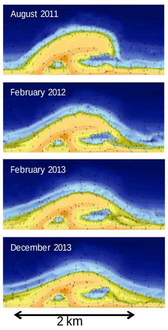
The Zandmotor: effects at the hinterland?

The Zandmotor: effects at the hinterland?

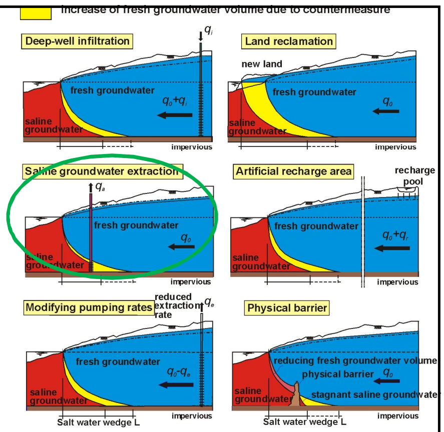






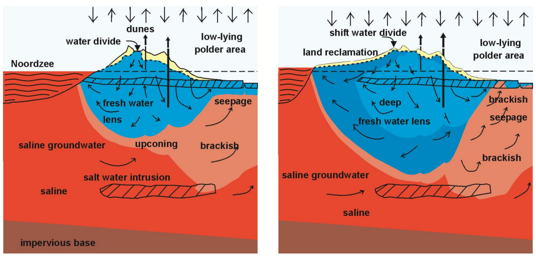


Technical measures to compensate salt water intrusion

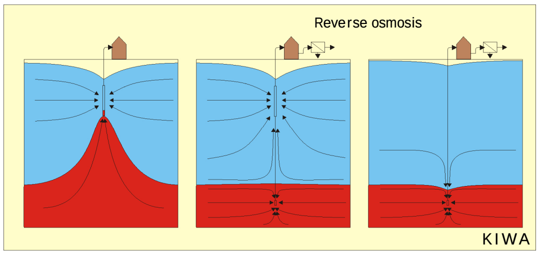


Land reclamation in front of the coast

Increase fresh water resources



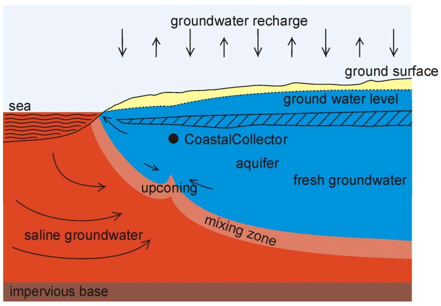
Solution: The Fresh Holder



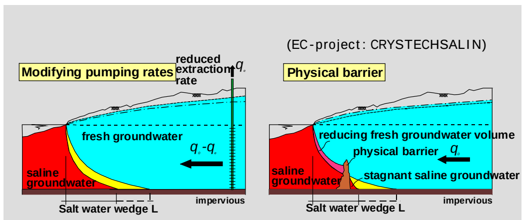
Upconing can be prevented by the extraction of brackish groundwater

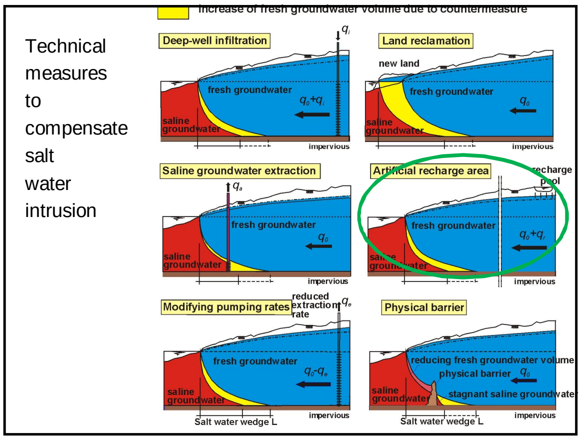
This brackish groundwater can be transformed to water of agricultural water quality by using the membrane filtration technique

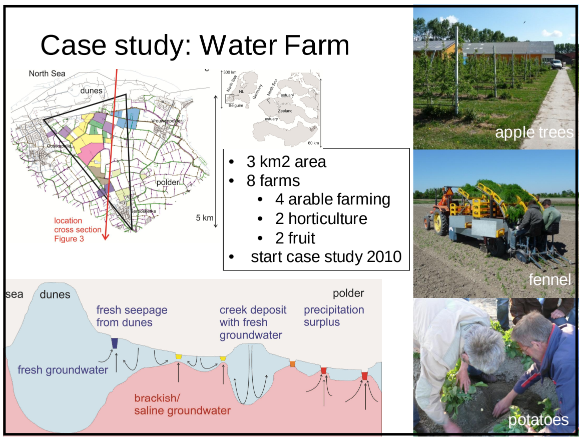
The Coastal Collector

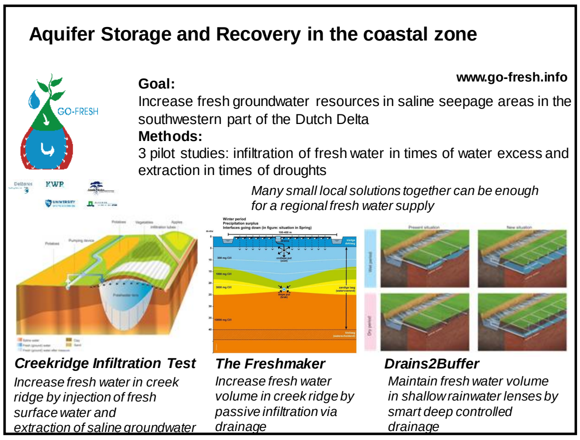


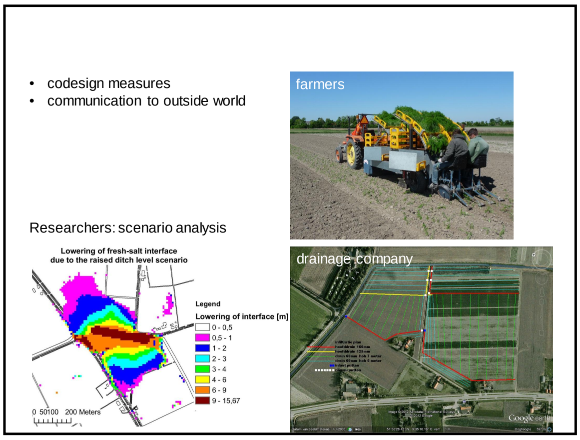
Countermeasures of salt water intrusion

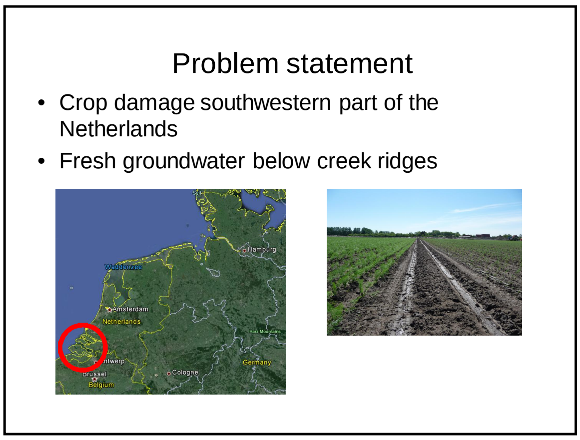


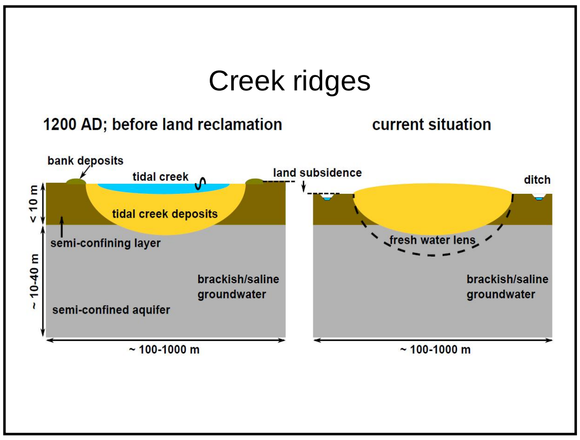

Increase of fresh groundwater volume due to countermeasure
Technical measures to compensate salt water intrusion
Deep-well infiltration
Land reclamation
new land
fresh groundwater
saline groundwater
impervious
Saline groundwater extraction
Artificial recharge area
recharge pool
Modifying pumping rates
reduced extraction rate
Physical barrier
reducing fresh groundwater volume
physical barrier
stagnant saline groundwater
Salt water wedge L


Case study: Water Farm
North Sea
dunes
polder
5 km
location cross section Figure 3
3 km2 area
8 farms
4 arable farming
2 horticulture
2 fruit
start case study 2010
sea
dunes
fresh seepage from dunes
creek deposit with fresh groundwater
precipitation surplus
polder
fresh groundwater
brackish/ saline groundwater
apple trees
fennel
potatoes


Aquifer Storage and Recovery in the coastal zone
GO-FRESH
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

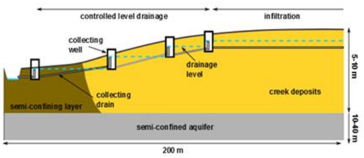

codesign measures
communication to outside world
farmers
Researchers: scenario analysis
Lowering of fresh-salt interface due to the raised ditch level scenario
Legend
Lowering of interface [m]
0 - 0,5
0,5 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 9
9 - 15,67
0 50100 200 Meters
drainage company


Problem statement
Crop damage southwestern part of the Netherlands
Fresh groundwater below creek ridges
Hamburg
Amsterdam
Netherlands
Antwerp
Brussel
Belgium
Cologne
Germany


Creek ridges
1200 AD; before land reclamation
current situation
bank deposits
tidal creek
land subsidence
ditch
tidal creek deposits
< 10 m
semi-confining layer
fresh water lens
~ 10-40 m
brackish/saline groundwater
semi-confined aquifer
~ 100-1000 m

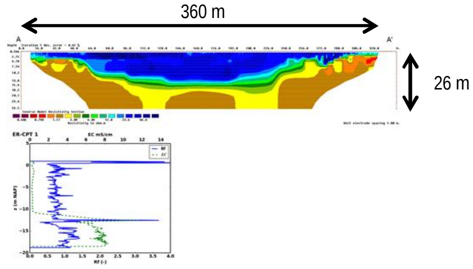
Measure

- Controlled level drainage
- Increase groundwater level

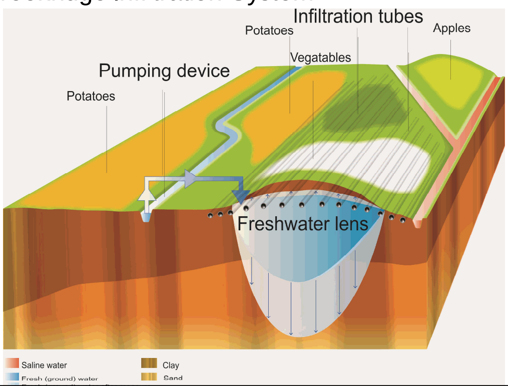


Key field observations (1)

- Fresh groundwater up to -12 m NAP

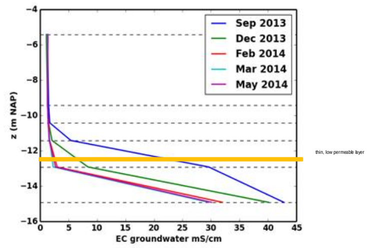


Creekridge Infiltration System

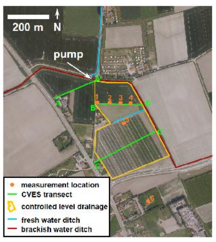


Key field observations (2)

- Freshening up to 2m



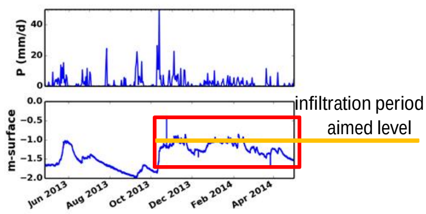
Installation of drainage and monitoring network



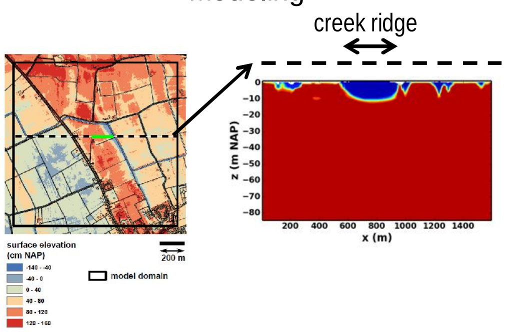
- **various types of field measurements**

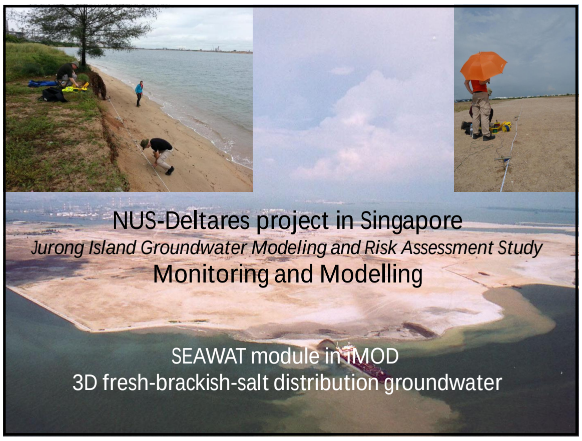
Key field observations (3)

- Groundwater levels and precipitation

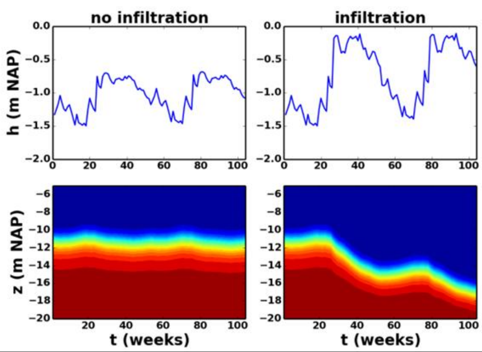


Modeling

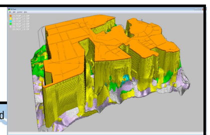




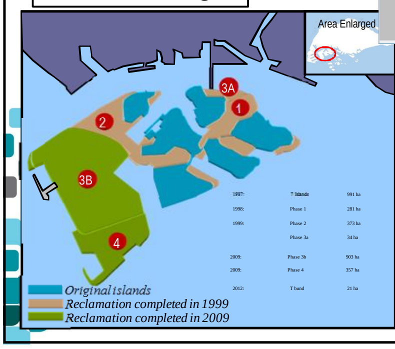
Influence of infiltration



Transformation of Jurong Island



Reclamation Phasing

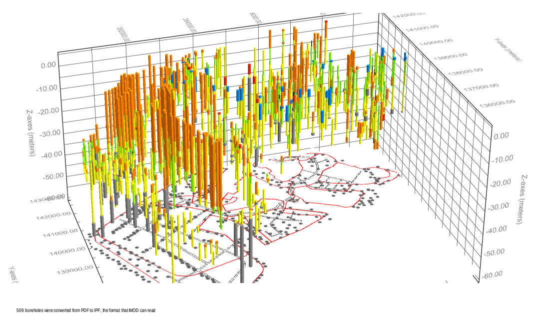


- In 1980s, 7 islands were reclaimed individually to a total land area of 991 ha. *(1960s was 118 ha).*
- Full-scale reclamation began from **1995** to form Jurong Island.
- Phases 1, 2, 3a completed in 1999; Phases 3b and 4 was completed in 2009.
- Current land area about **2960 ha.**

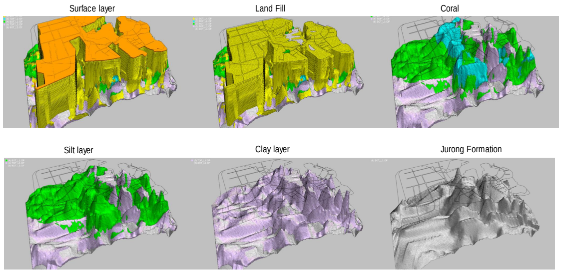
Singapore Jurong Island

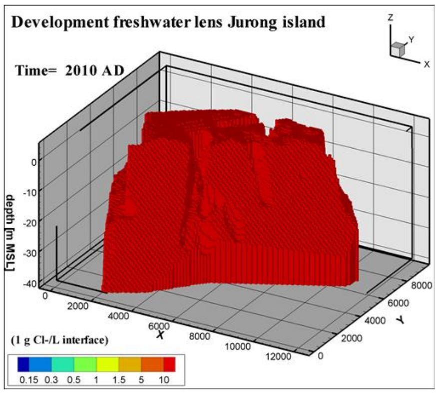
Aquifer Storage and Recovery

Boreholes

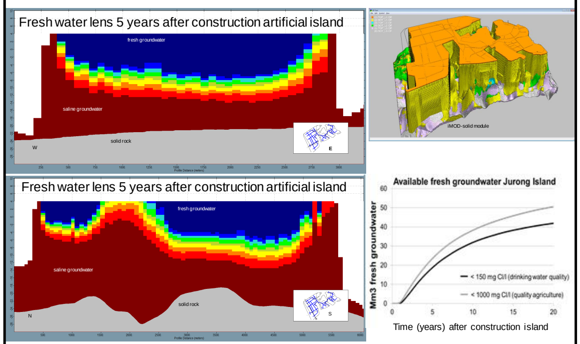


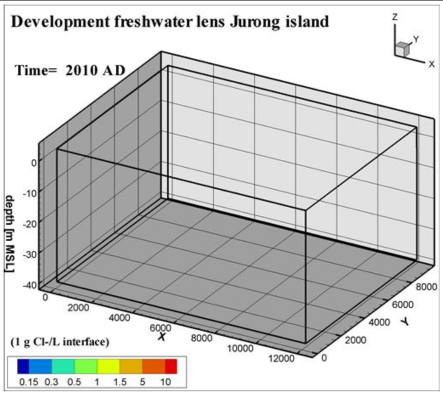
SubSoil Model



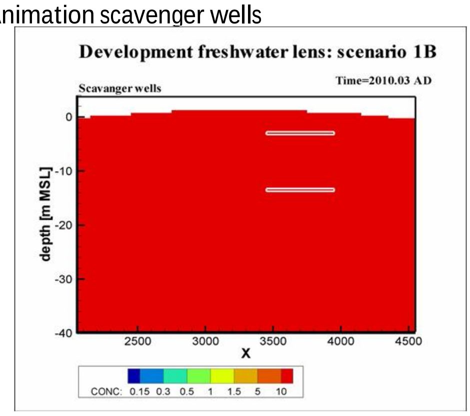


iMOD-SEAWAT Jurong Island Singapore

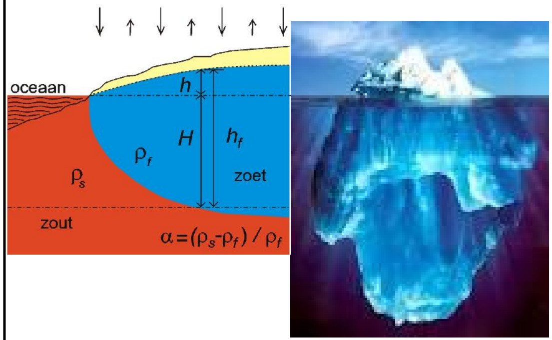




Animation scavenger wells

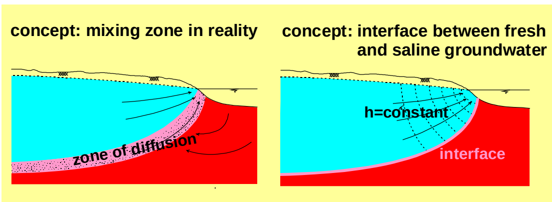


Sharp interface between fresh and saline groudwater



Badon Ghyben-Herzberg principle

Difference between reality and Badon Ghyben-Herzberg approximation

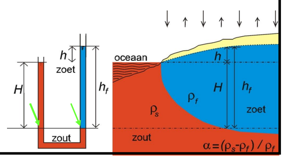


pressure saline groundwater=pressure fresh groundwater

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

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

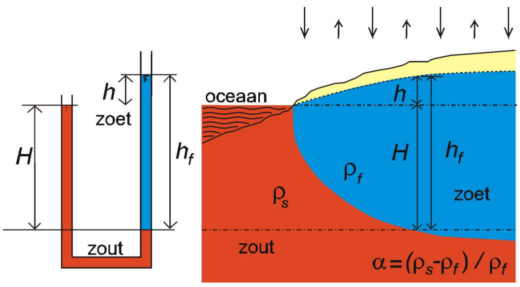
$$h = \alpha H$$



Badon Ghijben-Herzberg principle

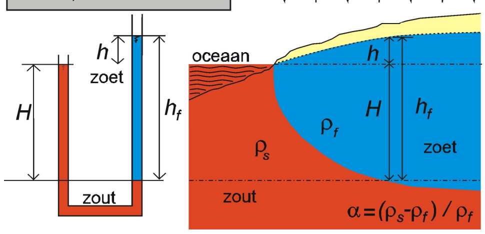
The principle suggests an interface between fresh and saline groundwater

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

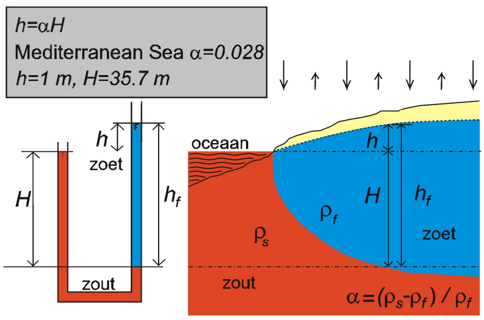


$$h = \alpha H$$

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



$$h = \alpha H$$



Analytical solutions

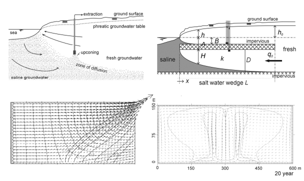
Badon Ghyben-Herzberg principle

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

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

Analytical solutions

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



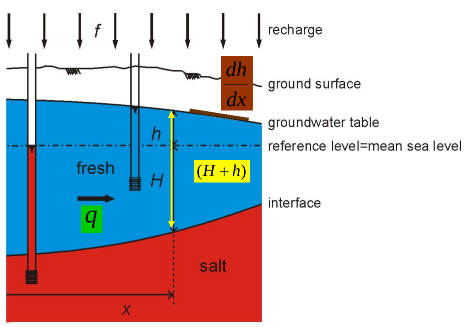
http://public.deltares.nl/display/FRESHSALT/Download

Badon Ghyben-Herzberg principle

What is the case then h≠αH?

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

Unconfined aquifer (1D situation)



Unconfined aquifer (1D situation)

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

(II) Continuity $dq = f dx$

(III) BGH $h = \alpha H$

Unconfined aquifer (1D situation)

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

$$h = \alpha H$$

$$q = fx + C1$$

Unconfined aquifer (1D situation)

$dq = f dx$ integration gives $q = fx + C1$

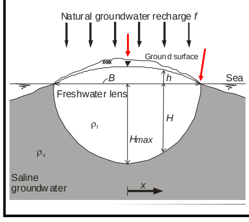
$$-k(H+h)\frac{dh}{dx} = fx + C1$$

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

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

Example 1: Elongated island

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



Boundary conditions

$x = 0 : q = 0 \rightarrow C1 = 0$

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

Unconfined aquifer (1D situation)

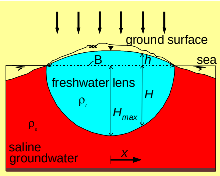
$$HdH = -\frac{fx + C1}{k\alpha(1+\alpha)}dx$$

integration gives

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

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

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

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

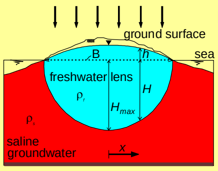
Volume lens

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

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

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

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

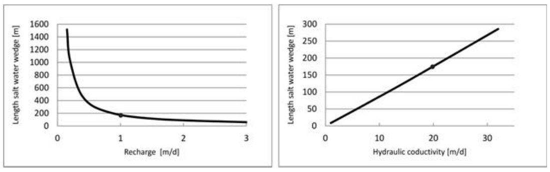
Volume lens (wrong in lectures notes)

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

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

Lecture notes p. 32

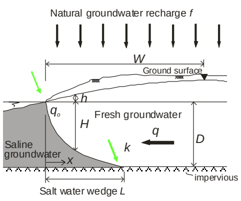
Length of the salt water wedge as a function of a. recharge and b. hydraulic conductivity



the dots resample with the example mentioned above

Example 2: salt water wedge

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



Boundary conditions

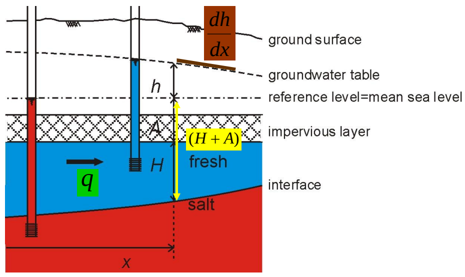
$x = 0 : q = q_0 \rightarrow q_0 = -fW \rightarrow C1 = q_0$

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

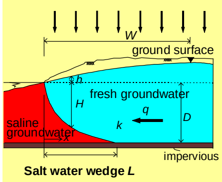
Length of salt water wedge

$x = L : H = D$

Confined aquifer (1D situation)



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

Confined aquifer (1D situation)

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

(II) Continuity $\quad q = q_0$

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

Confined aquifer (1D situation)

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

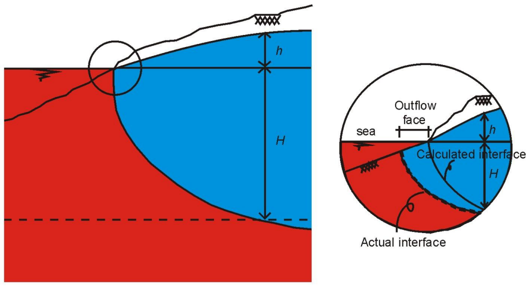
$$HdH=-\frac{q_0}{k\alpha}dx$$

integration gives

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

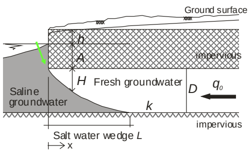
$$H=\sqrt{-\frac{2q_0x}{k\alpha}+2C}$$

Outflow face (Submarine Groundwater Discharge)



Example 3: salt water wedge confined aquifer

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



Boundary condition

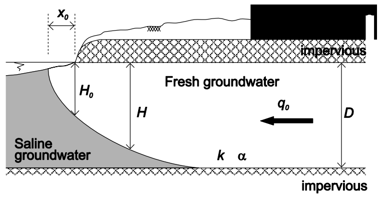
$$x=0: H=0\rightarrow C=0$$

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

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

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

Outflow face (Submarine Groundwater Discharge)

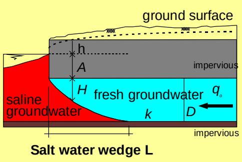


$$x_0=\frac{q_0}{2k\alpha}\qquad H_0=\frac{q_0}{k\alpha}$$ Glover (1959)

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

Note: no resistance layer offshore

Example of analytical solutions (III)



Length of salt water wedge

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

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

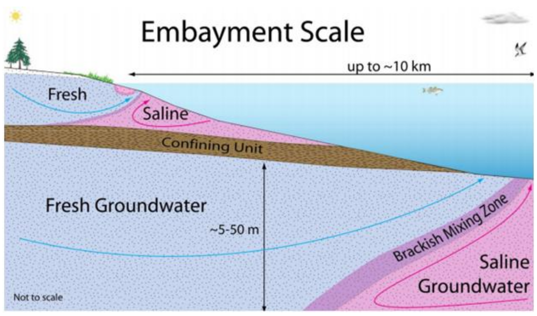
Example:

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

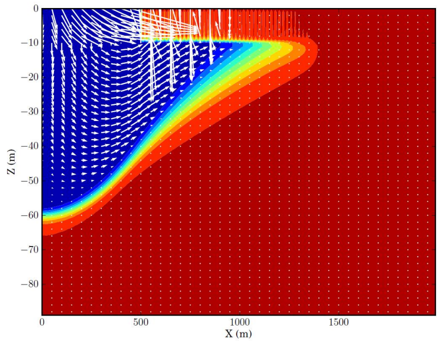
$$L=250\text{m}$$

Lecture notes p. 35-36

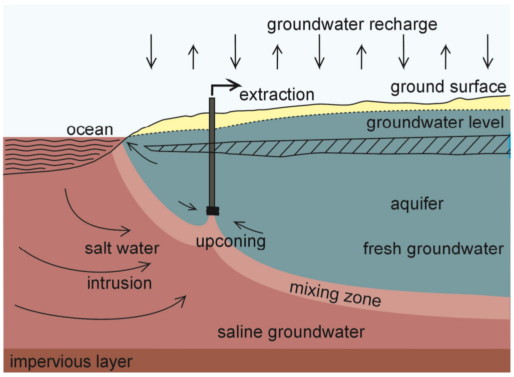
Outflow face (Submarine Groundwater Discharge)



Outflow face (Submarine Groundwater Discharge)

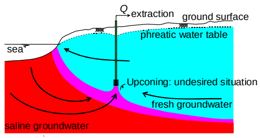


Upconing processes

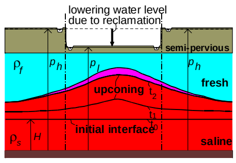


Upconing of saline groundwater

Under an extraction well



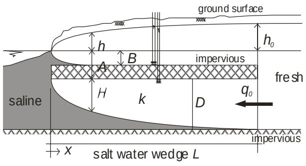
Under a low-lying polder area

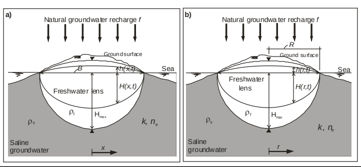


- movement of saline groundwater to extraction wells
- increase in salinity (>150-200 mg Cl-/l)
- lowering of the piezometric head (leads to land subsidence: e.g. Los Angeles: 9 m in the 1930's)

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

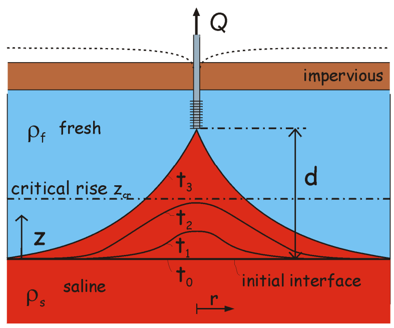
See the lectures for more cases





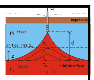
Examples of analytical solutions (IV)

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

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

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

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

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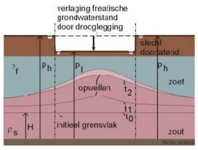
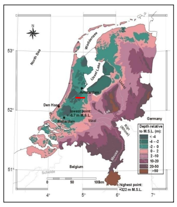
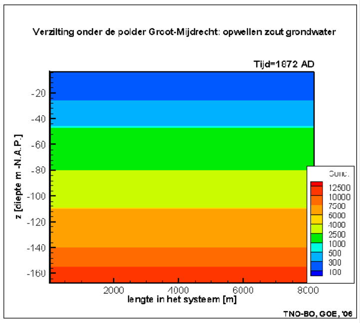
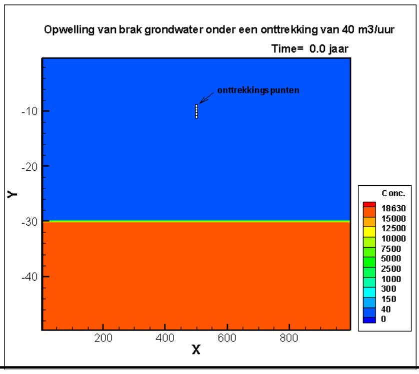
Upconing under a low-lying polder (Groot-Mijdrecht)



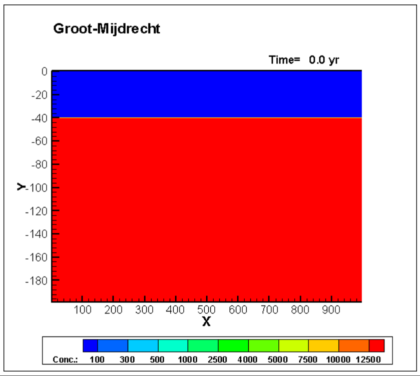




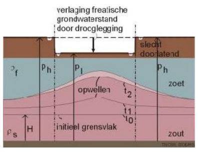
Upconing of salt under an extraction

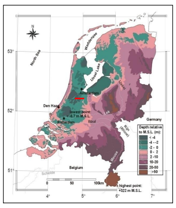


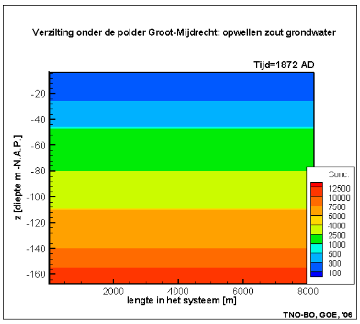
Upconing under a low-lying polder (Groot-Mijdrecht)



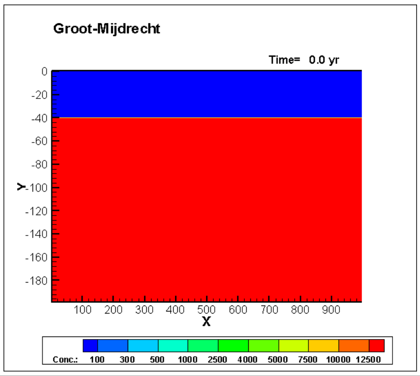
Upconing under a low-lying polder (Groot-Mijdrecht)



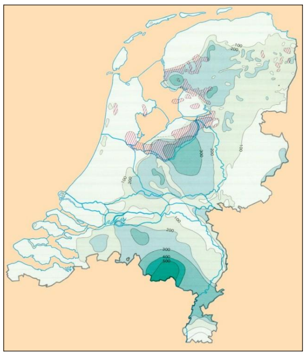




Upconing under a low-lying polder (Groot-Mijdrecht)

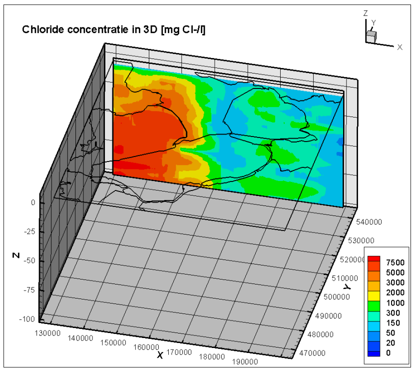


Fresh-salt interface (150 mg Cl⁻/l)

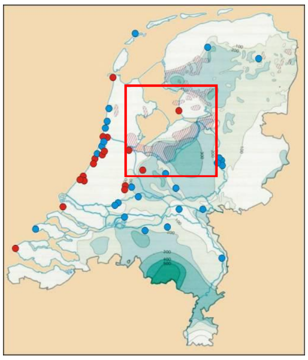


- <100 m
- 100-200 m
- 200-300 m
- 300-400 m
- 400-500 m
- >500 m
- >inversion (fresh under salt)

Animation 3D Chloride concentration



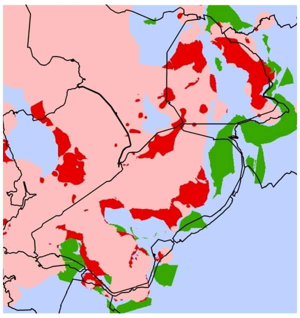
Availability of fresh groundwater



- <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)

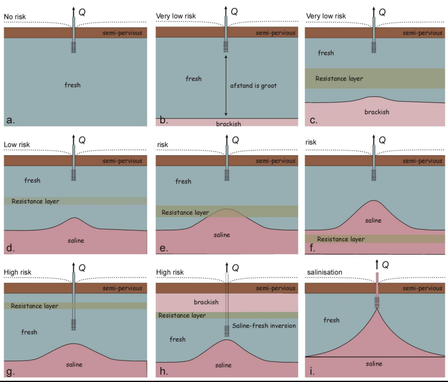
Upconing in Flevoland



Risk depends on:
- Initial position interface
- Resistance layers
- Existance inversion
- Extraction rate and scheme

- High risk
- Low risk
- Very low risk

Different risks of upconing saline groundwater



Modelling

salt water intrusion

density dependent groundwater flow

Why mathematical modelling anyway?

A model is only a schematisation of the reality!

Solute transport models

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

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

Solute transport equation

Partial differential equation (PDE):

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

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

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

Numerical modelling variable density flow

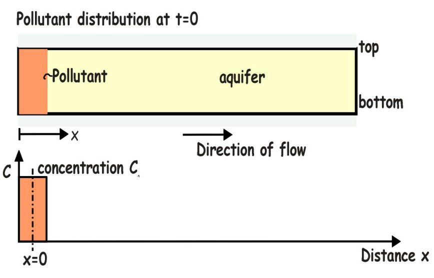
Type:

- sharp interface models
- solute transport models

State of the art:

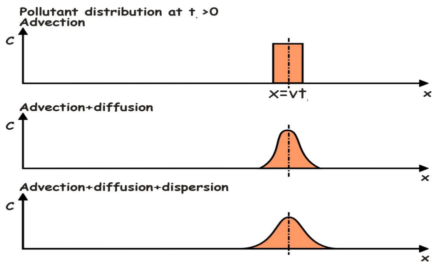
- three-dimensional
- solute transport
- transient

Solute transport equation: column test (I):



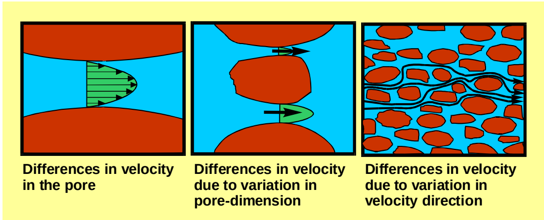
modelling

Solute transport equation: column test (II):



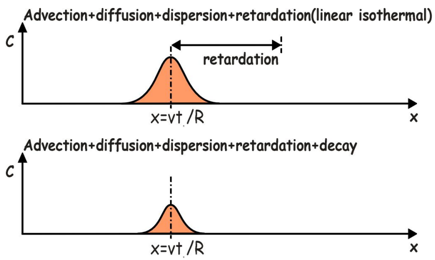
modelling

Mechanical dispersion



modelling

Solute transport equation: column test (III):



modelling

Solute transport equation: diffusion (I)

diffusion is a slow process: diffusion equation

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

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

similarity with non-steady state groundwater flow equation

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

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

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

modelling

Hydrodynamic dispersion

hydrodynamic dispersion
=
mechanical dispersion+ diffusion

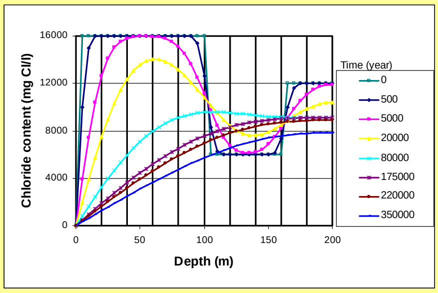
mechanical dispersion:
- tensor
- velocity dependant

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

modelling

Solute transport equation: diffusion (II)

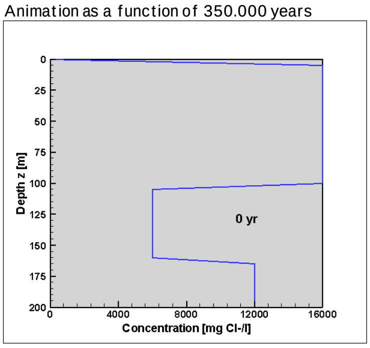
diffusion is a slow process: diffusion equation $\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2}$



modelling

Solute transport equation: diffusion (III)

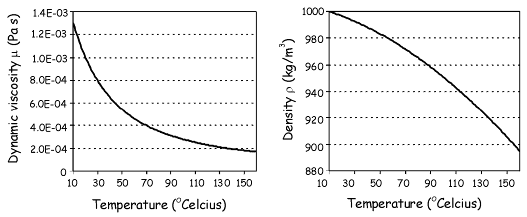
Animation as a function of 350.000 years



EOS

Density and viscosity depend on temperature

(10°C-160°C)



MOCDENS3D

Groundwater flow equation (MODFLOW, 1988)

Darcy

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

Continuity

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

buoyancy term

Freshwater head

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

Advection-dispersion equation (MOC3D, 1996)

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

Equation of state: relation density & concentration

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

EOS

Examples of equations of state

Knudsen (1902)

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

T<15 °C, S<20 ppt

Linear (concentration)

$$\rho_{(C)} = \rho_f[1 + \alpha\frac{C_i}{C_s}]$$ where a=relative density difference

Linear (temperature)

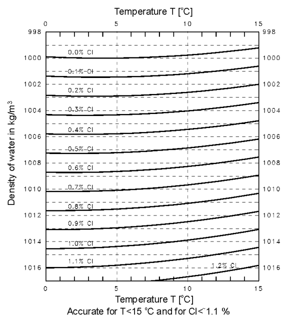
$$\rho_{(T)} = \rho_f[1 - \beta(T - T')]$$

Exponential (temperature, pressure, salt)

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

EOS

Density depends on salinity and temperature



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

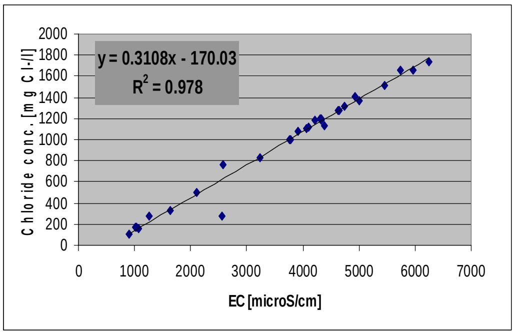
Equation of state (SEAWAT)

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

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)

Close relation between chloride concentration and Electrical Conductivity

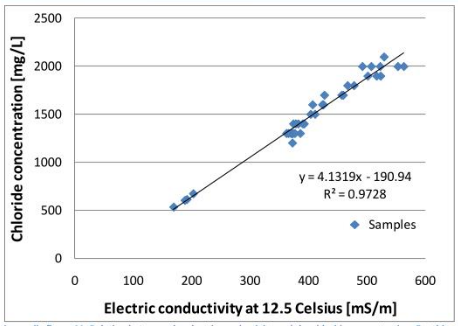


Some existing 3D codes which simulate variable density groundwater flow in porous media:

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

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)

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

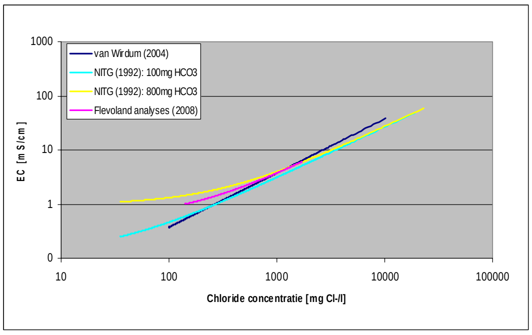


Appendix figure 11: Relation between the electric conductivity and the chloride concentration. For this relation samples from observation well B06D1114 and B06D1087 in between 23-sept-2009 and 9-okt-2010 were plotted.

Restrictions 3D salt water intrusion modelling in 2015

- 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

EC-Chloride



Restrictions 3D salt water intrusion modelling in 2015

- 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 software*

MOCDENS3D is based on MODFLOW

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

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

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

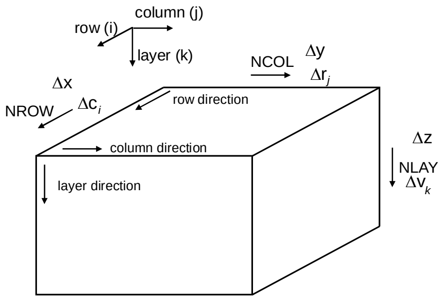
Continuity equation (I)

In - Out = Storage

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

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

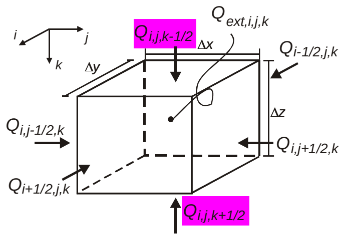
Nomenclature MODFLOW element [i,j,k]



Continuity equation (II)

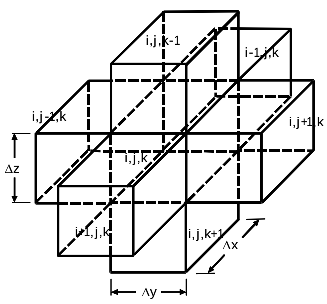
$$\sum Q_i = S_s \frac{\Delta \phi}{\Delta t}\Delta V$$

In = positive

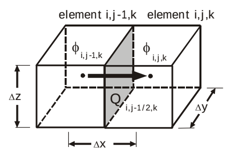


$$Q_{i,j-1/2,k}+Q_{i,j+1/2,k}+Q_{i-1/2,j,k}+Q_{i+1/2,j,k}+Q_{i,j,k-1/2}+Q_{i,j,k+1/2}+Q_{ext,i,j,k}$$
$$=SS_{i,j,k}\frac{\phi^{t}_{i,j,k}-\phi^{t+\Delta t}_{i,j,k}}{\Delta t}\Delta V$$

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



Flow equation (Darcy's Law)



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

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

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

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

Density dependent vertical flow equation

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

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

$$Q_z = surface * q_z$$

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

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

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

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

where $CV_{i,j,k-1/2} = \frac{k_{i,j,k-1/2}\,\Delta x\,\Delta y}{\Delta z}$ =conductance [L²/T]

Thé variable density groundwater flow equation

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

and:

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

gives:

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

$with:$

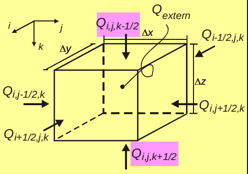
$$HCOF_{i,j,k} = P_{i,j,k} - SC1_{i,j,k}/(\Delta t)$$

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

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

Density dependent groundwater flow equation

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



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

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

Equation of state

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

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

or

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

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

Takes into account all external sources

Rewriting the term:

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

Method of Characteristics (MOC)

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

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

Lagrangian approach:

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

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

Length flow time step

NOT EQUAL TO SOLUTE TIME STEP !

Stability criteria for solute transport equation (I)

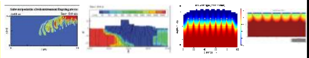
1. Neumann criterion:

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

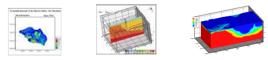
$$\Delta t_s \leq \frac{0.5}{\frac{D_{xx}}{\Delta x^2}+\frac{D_{yy}}{\Delta y^2}+\frac{D_{zz}}{\Delta z^2}}$$

Modelling fresh-salt groundwater on different scales

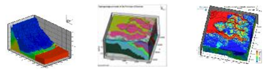
Sub-local: fingering, salty sand boils
Sri Lanka (Tsunami 2004),
Zandmotor
cell size=1cm-1m



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

variable density

Stability criteria for solute transport equation (II)

2. Mixing criterion:

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

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

variable density

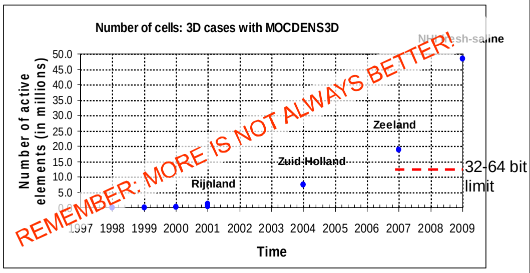
Stability criteria for solute transport equation (III)

3. Courant criterion:

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

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

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



Difficulties with variable density groundwater flow

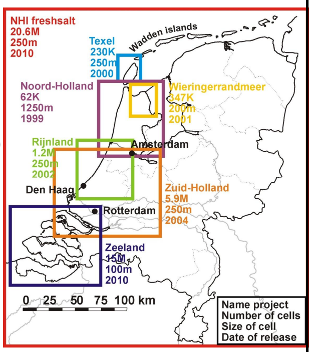
- Initial density distribution (effects on velocity field) !
- Velocities freshwater lens at the outflow face near the sea
- Boundary conditions (especially concentration boundaries)
- Choice of element size
- Length of flow time step to recalculate groundwater flow

Modelling effect climate change on fresh-salt groundwater

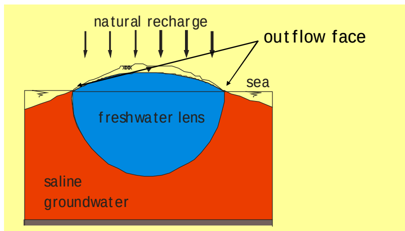
Modelling:
- variable-density
- 3D, non-steady
- groundwater flow
- coupled solute transport

Code:
MOCDENS3D (MODFLOW family)
similar to SEAWAT

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



Outflow face at the coast is difficult to model

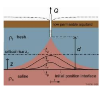


Flow converges and thus velocities are very high at the outflow face

This is numerically difficult to handle

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)

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

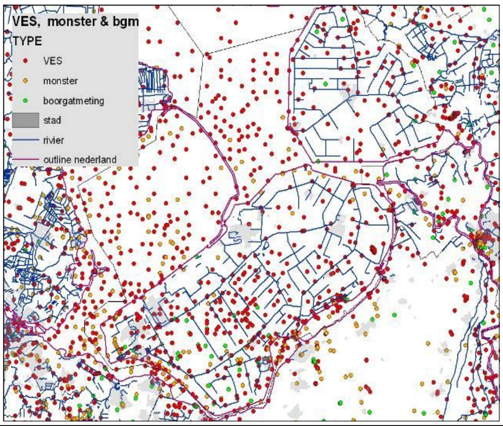
- Implement all chloride data
  - Analyses, Borehole, VES, Airborne techniques (HEM, SkyTem)
  - Better old then nothing
  - Better VES then nothing
- Interpolate and extrapolate
  - Sea = easy (salt)
  - Inland = fresh?
- Start with simulation (10/20/30 years) with mol.diffusion*1000 to smooth out artificial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

Mapping brackish-saline interface Zeeland

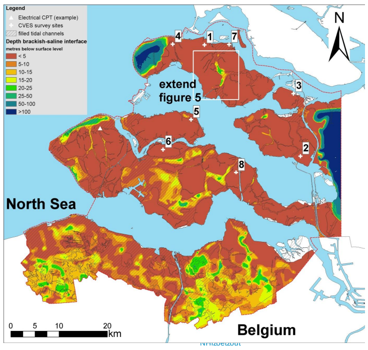
•Combining different types of data sources:

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**		

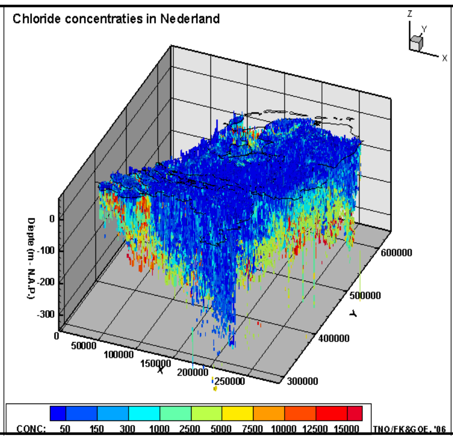
20150322 DGG



Mapping brackish-saline interface

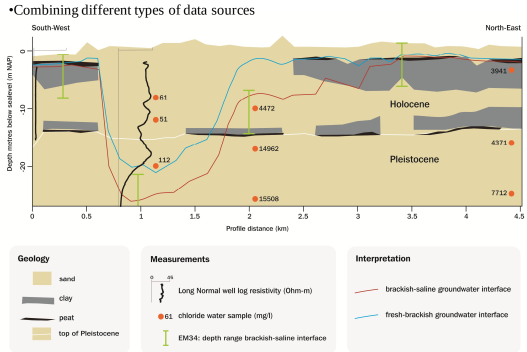


Goes et al, 2009



Mapping brackish-saline interface

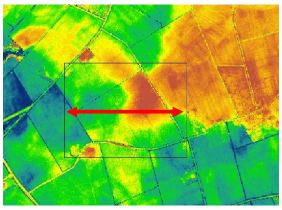
•Combining different types of data sources

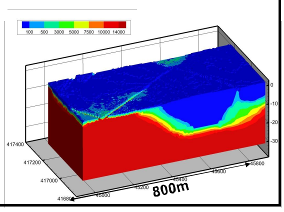


Use variable-density groundwater flow modelling

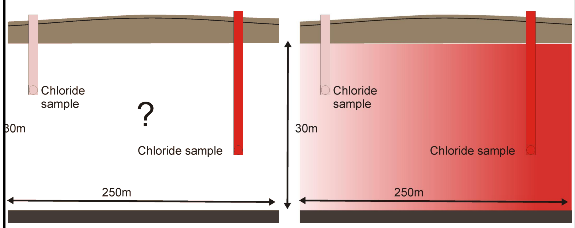
Why a model?

• variation in ground surface directly affects fresh-saline disribution

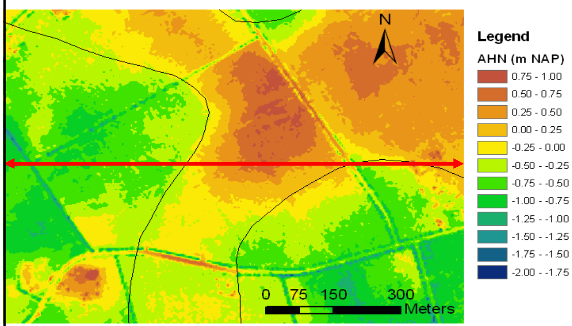




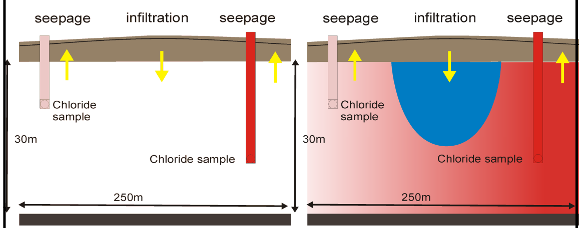
Interpolation chloride



Use variable-density groundwater flow modelling



Using flow model for better interpolate chloride



Use variable-density groundwater flow modelling

Why a model?

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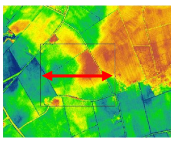
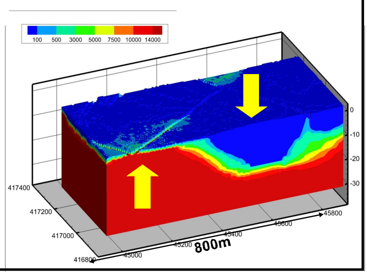
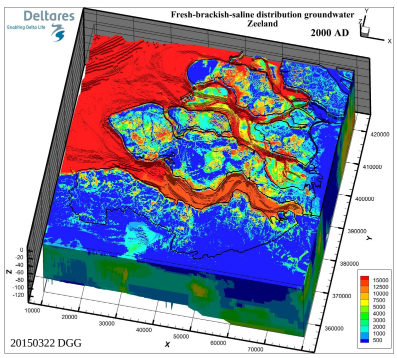


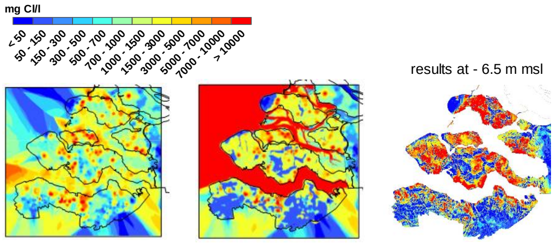


3D fresh-saline groundwater distribution



Regional groundwater model:

From chloride measurements to a 3D distribution



Step 1:
interpolating data:
- *Groundwater samples*
- *Geo-electrical borehole logs*
- *(C)VES, EM, electrical CPT*

Step 2:
including interfaces
- *Mapped fresh-brackish*
- *Mapped brackish-salt*

Step 3:
model result 2010:
- *Model as interpolator*

EWRMP 201511

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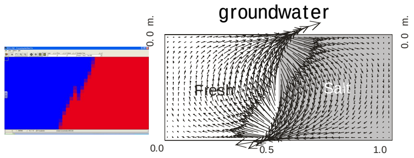
modelling

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		

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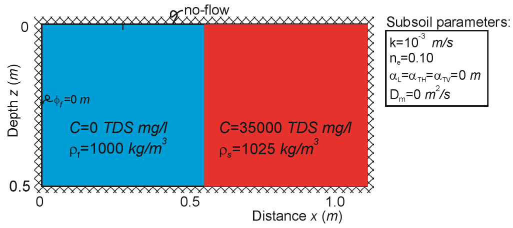
cases

Rotating immiscible interfaces

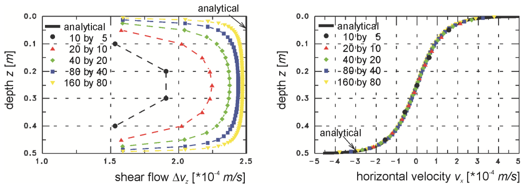
Conclusion:

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

Vertical interface



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



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

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

The effect of numerical solvers on the salt transport

Examples

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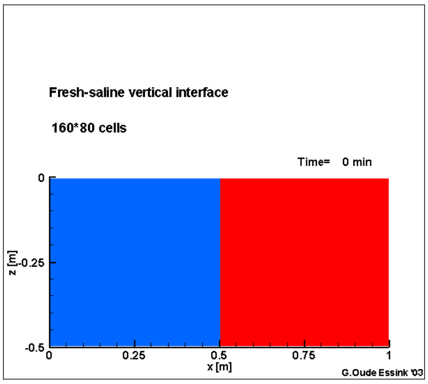
Vertical interface



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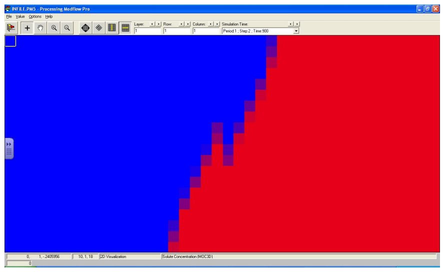
1 particle per cell



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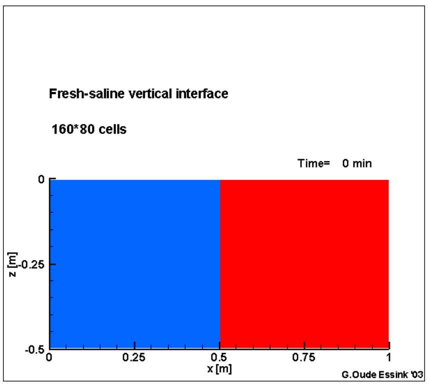
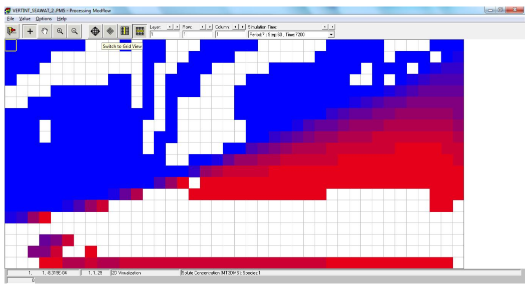
Vertical interface



ULTIMATE



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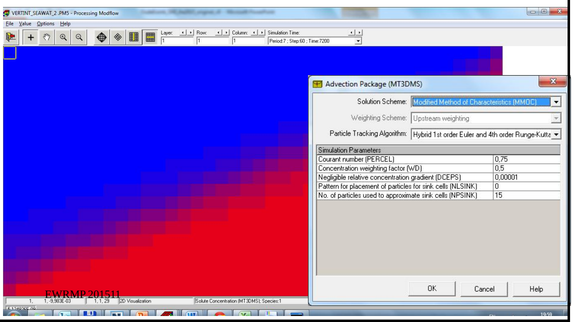
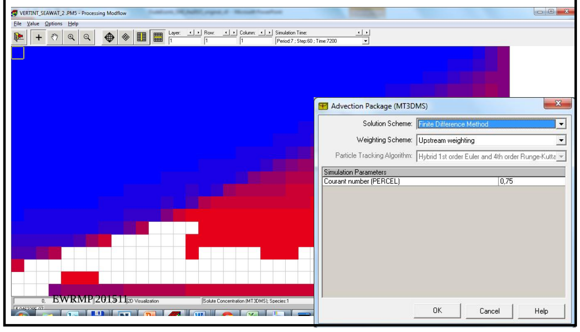
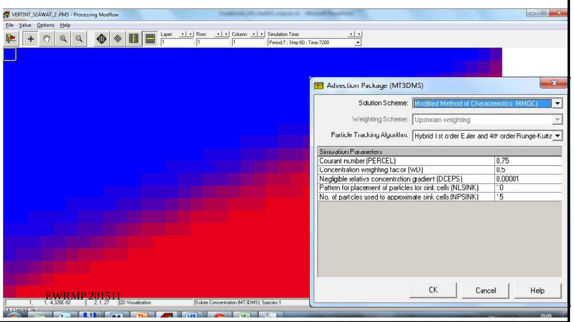
MMOC, NPLANE=0



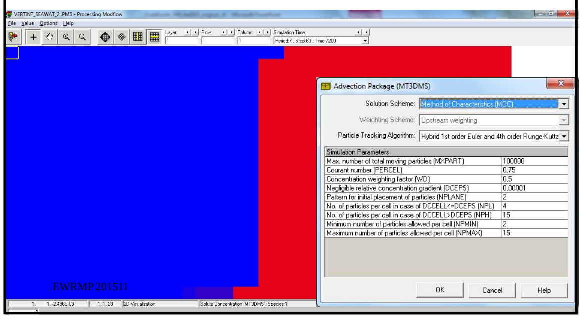
Finite Difference Method



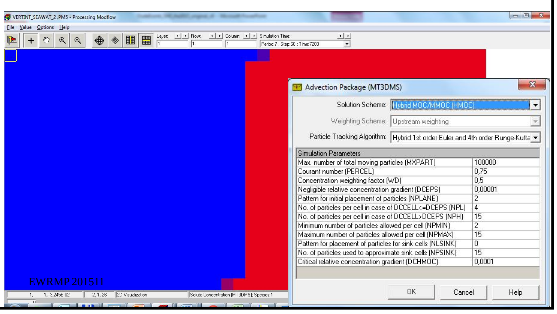
MMOC, NPLAN=10



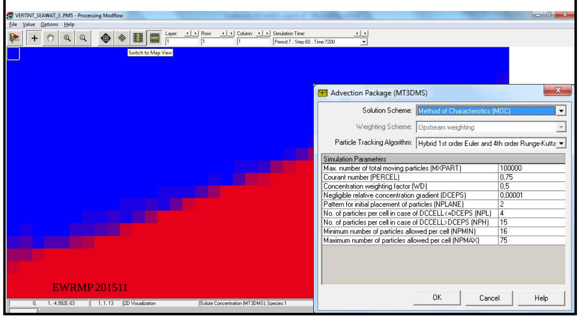
MOC



HMOC

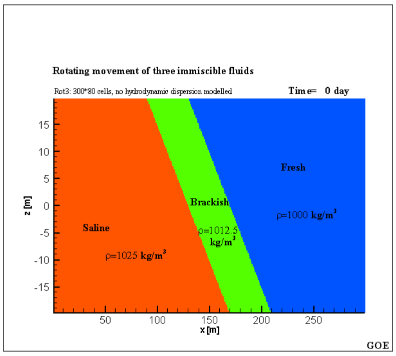


MOC



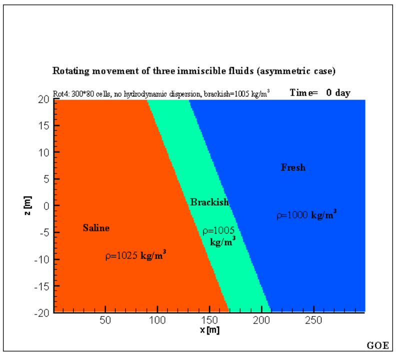
cases

Rotating immiscible interfaces



cases

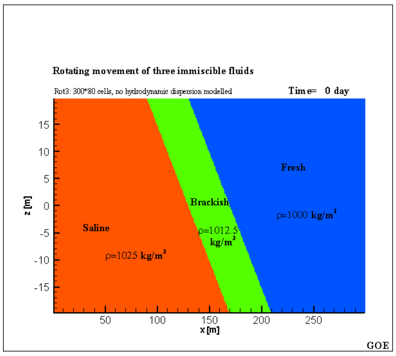
Rotating immiscible interfaces (asymmetric)



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

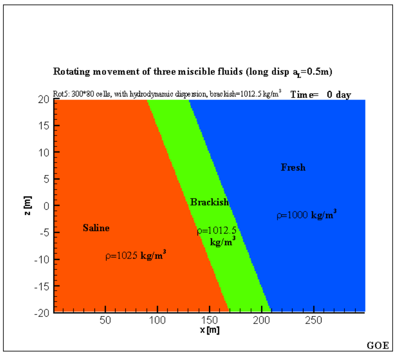
cases

Rotating immiscible interfaces



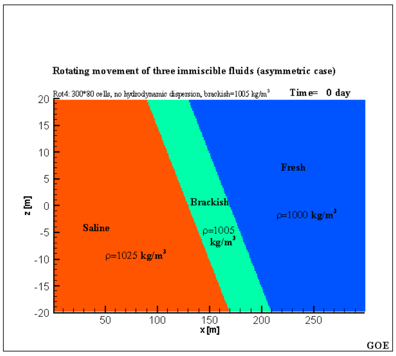
cases

Rotating interfaces with dispersion α_L=0.5m



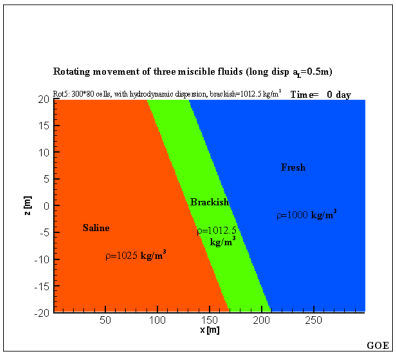
cases

Rotating immiscible interfaces (asymmetric)



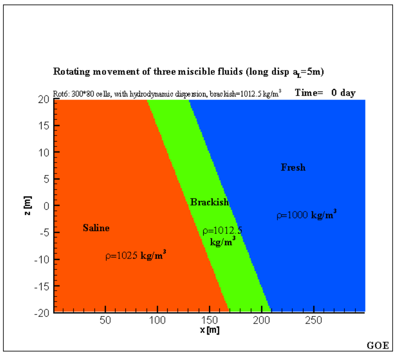
cases

Rotating interfaces with dispersion α_L=0.5m



cases

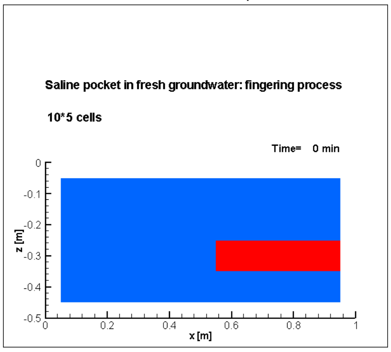
Rotating interfaces with dispersion α_L=5m



cases

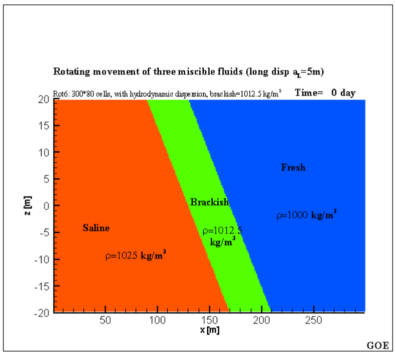
Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



cases

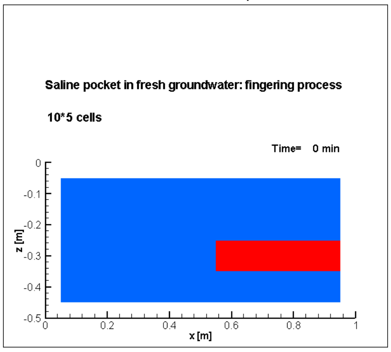
Rotating interfaces with dispersion α_L=5m



cases

Salt water pocket in a fresh environment (I)

Effect of discretisation on a 'salt lake problem'



Salt water pocket in a fresh environment

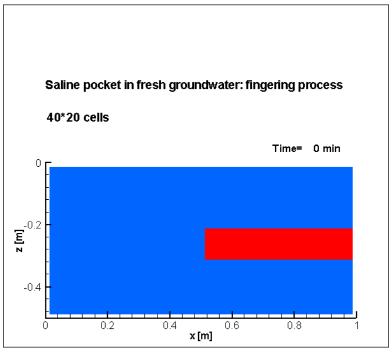
Grid convergence

Time step

cases

Salt water pocket in a fresh environment (II)

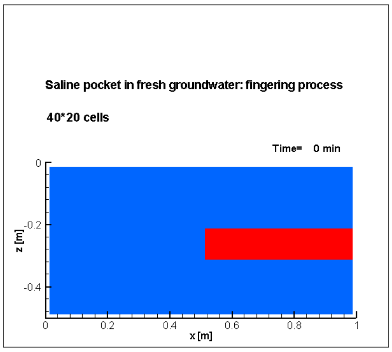
Effect of discretisation



cases

Salt water pocket in a fresh environment (II)

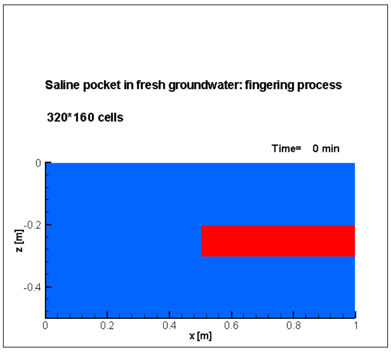
Effect of discretisation



cases

Salt water pocket in a fresh environment (IV)

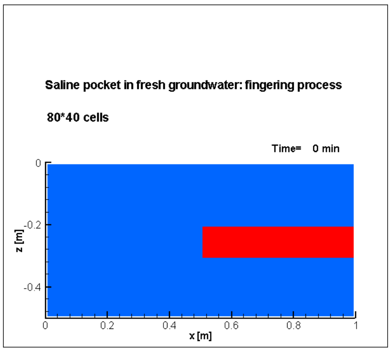
Effect of discretisation



cases

Salt water pocket in a fresh environment (III)

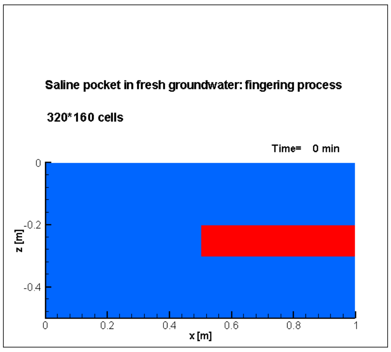
Effect of discretisation



cases

Salt water pocket in a fresh environment (IV)

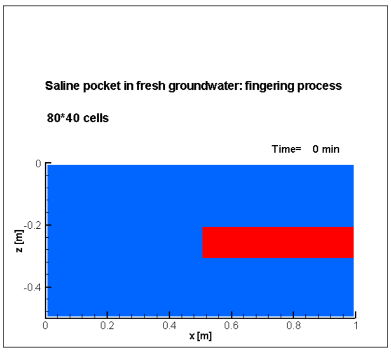
Effect of discretisation



cases

Salt water pocket in a fresh environment (III)

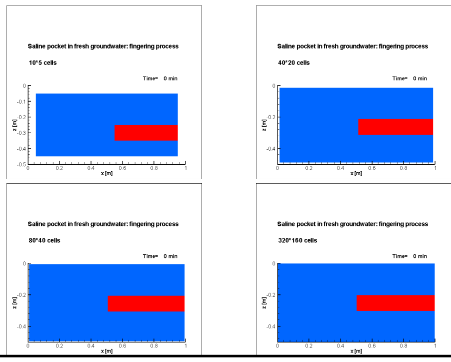
Effect of discretisation



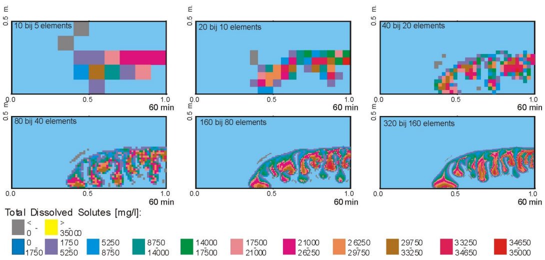
cases

Salt water pocket in a fresh environment (V)

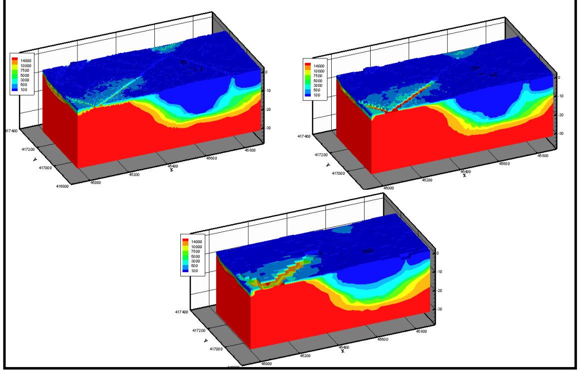
Effect of discretisation



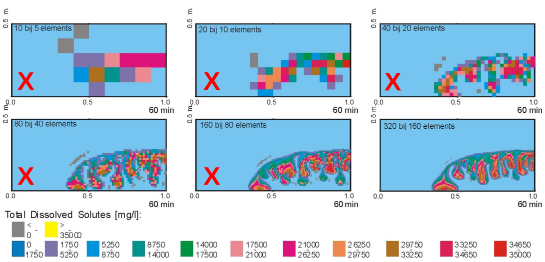
Effect of size model cell on physical process



Different model scales: 5, 10, 25m2



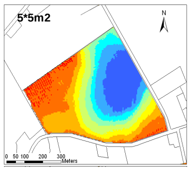
Effect of size model cell on physical process

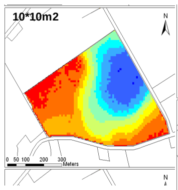


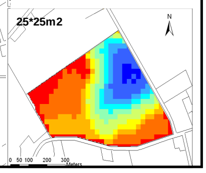
X= LOUSY models for predicting exact number of salt water fingers

Different model scales

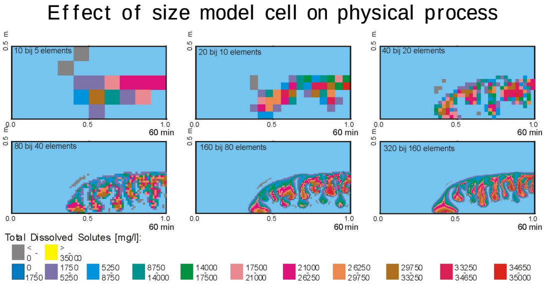
Which one is good enough?





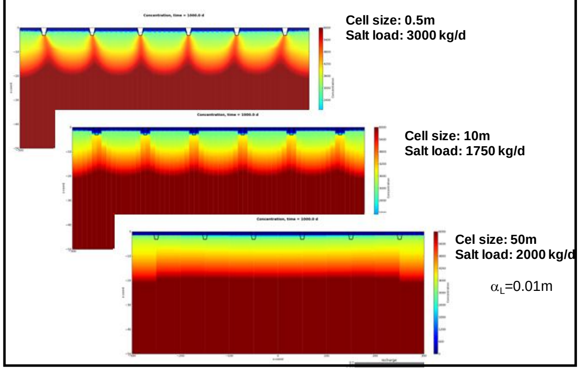


Effect of size model cell on physical process



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

Upscaling issues: upconing under ditch

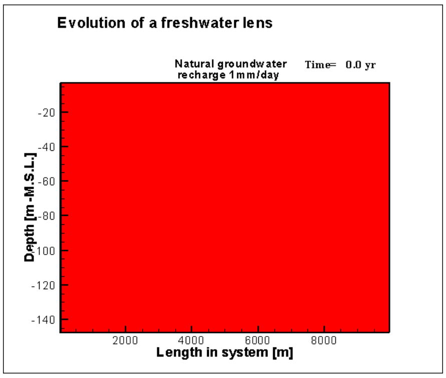


Salt water pocket in a fresh environment (VI)

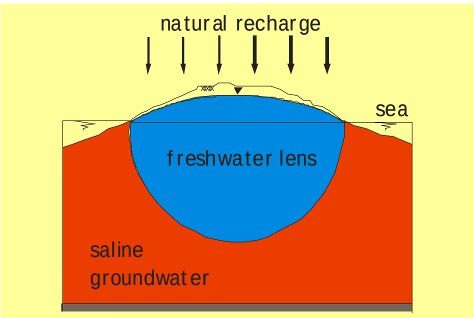
Conclusion:

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

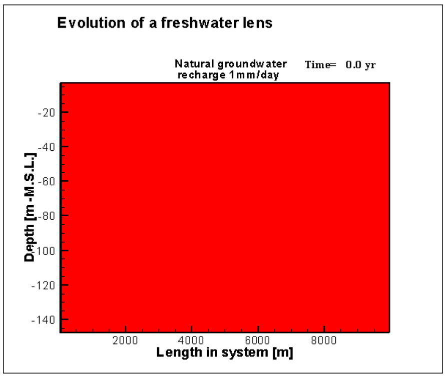
Concept: evolution freshwater lens (not Griend!)



Evolution of a freshwater lens



Concept: evolution freshwater lens (not Griend!)



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

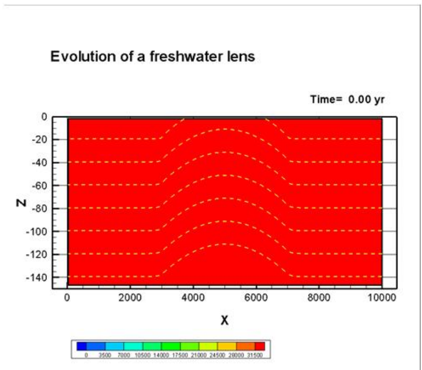
T = specific time scale

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

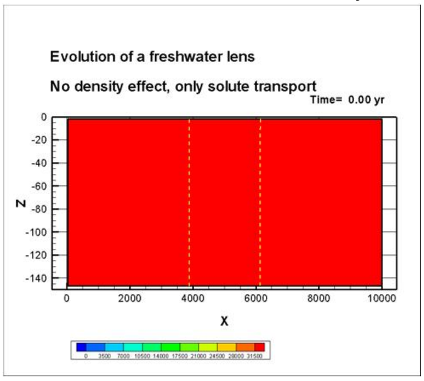
In the Netherlands: T = 75-200 jaar,

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

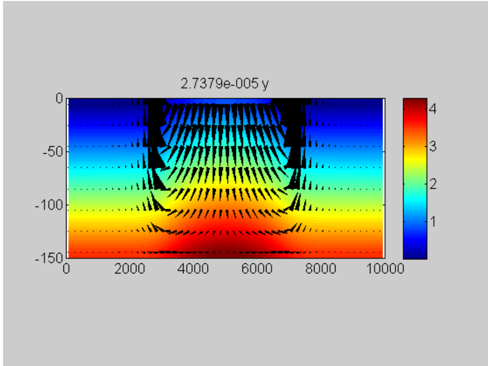
Evolution freshwater lens



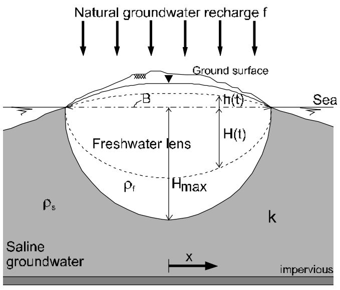
Evolution freshwater lens: no density effects



Evolution freshwater head

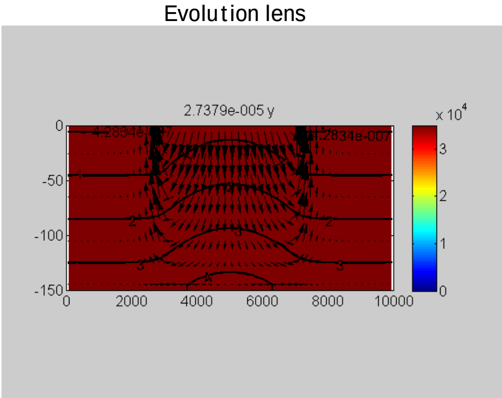


Case 2: Development of a freshwater lens



Evolution freshwater head

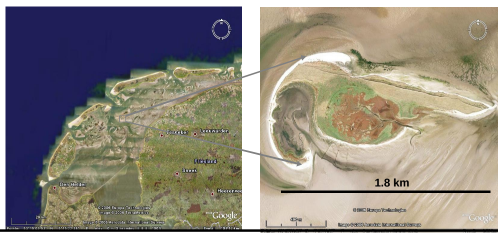
Evolution lens



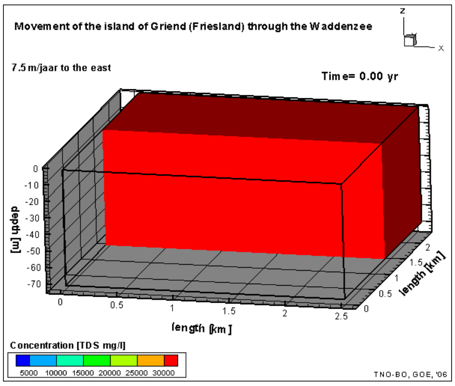
The island of Griend

Issues:

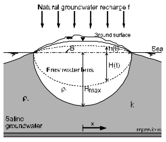
1. Small island moves ~7.5m per year to the east
2. Effect on the volume of the freshwater lens:
   - Can a lens be developed?
   - What is the thickness of the lens?



Movement of De Griend and creation of the lens

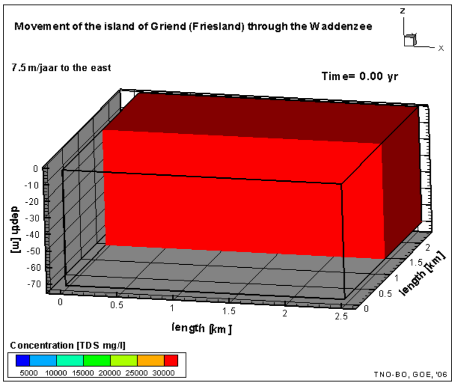


Case 2: Development of a freshwater lens

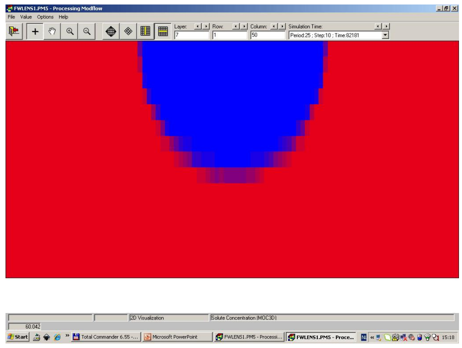


Parameters			
Layers	15	K_{hor}	20 m/d
Rows	1	T	200 m/d
Columns	100	Anisotropy K_{hor}/K_{ver}	10
Δx	100 m	ne	0.35
Δy	10 m	αL	0 m
Δz	10 m	αT	0 m
Stress periods	10	recharge	360 mm/y
Initial concentration	35000 mg/l	Recharge concentration	0 mg/l
bouyancy	0.025		

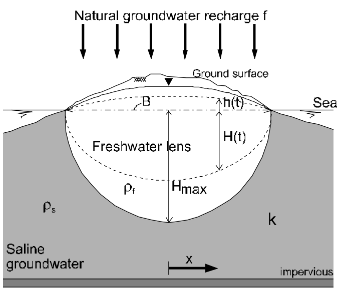
Movement of De Griend and creation of the lens



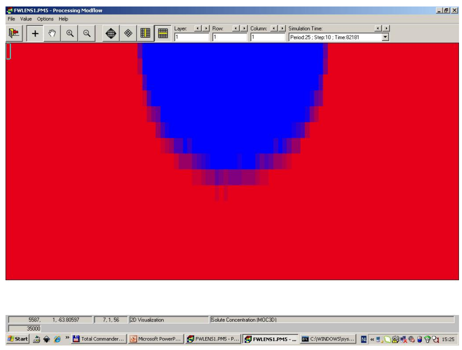
MOCDENS3D, no disp, 16part



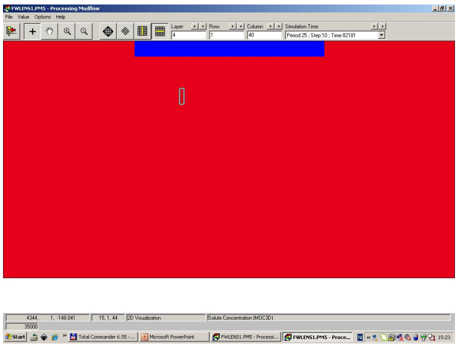
Case 2: Development of a freshwater lens



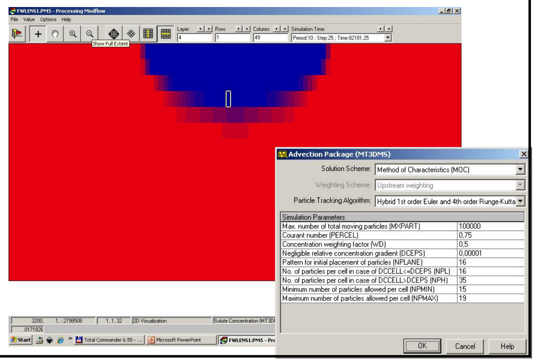
MOCDENS3D, no disp, 4part



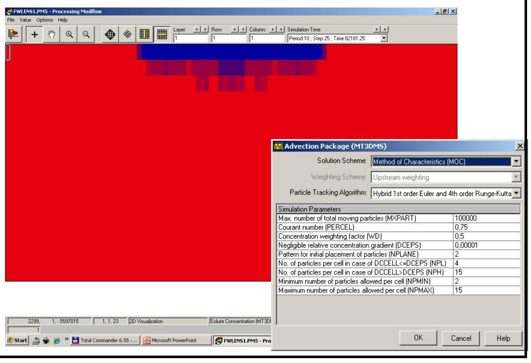
MOCDENS3D, no disp, 1part



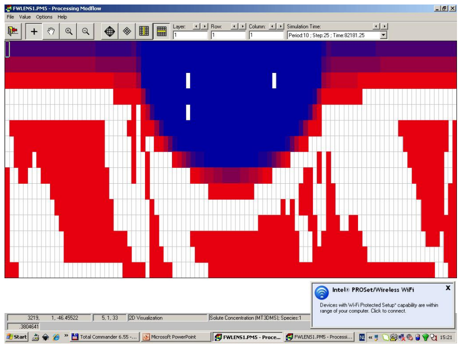
SEAWAT, MOC, 20sec, NPLANE=16, etc.



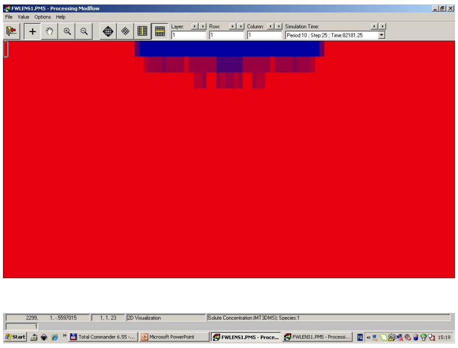
SEAWAT, MOC, NPLANE=2



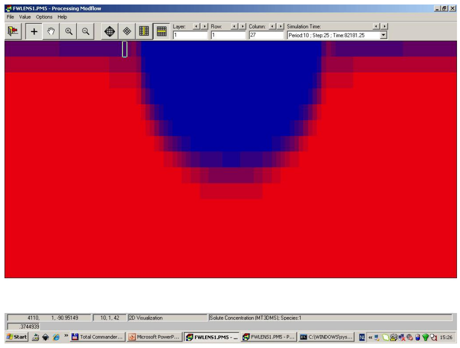
SEAWAT, ULTIMATE, 16.56sec



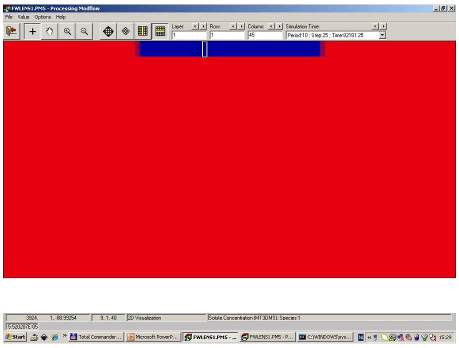
SEAWAT, MOC, 4.NPLANE=16



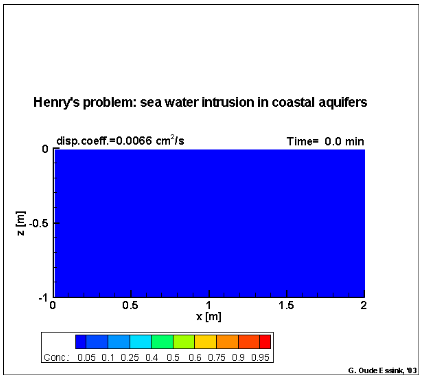
SEAWAT, MMOC, 8.5sec



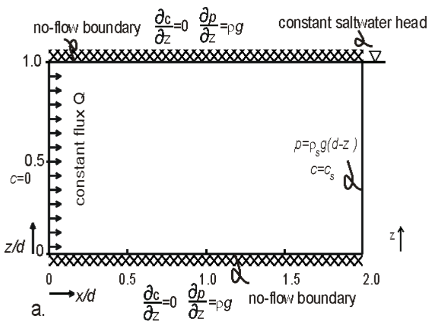
SEAWAT, HMOC, 6.8sec



Henry's problem



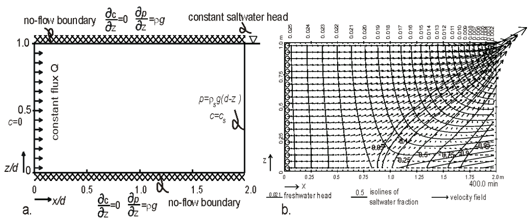
Henry's problem (1964)



Henry's problem

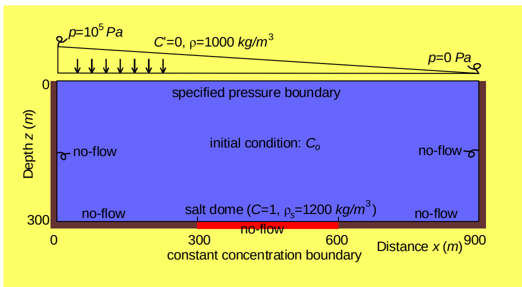
Don't use the Henry problem as a variable-density benchmark, because even with a constant density model, the results are more or less the same!

Henry's problem



Hydrocoin:

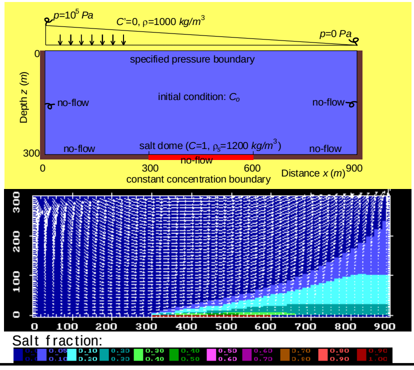
disposal of high-level nuclear waste
groundwater movement near salt domes
Gorleben salt dome, Germany



cases

Hydrocoin:

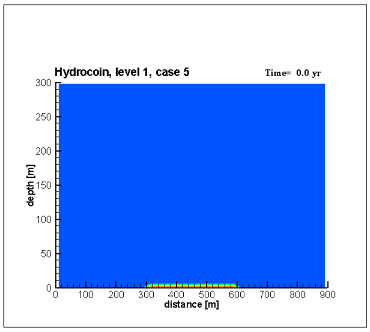
groundwater movement near salt domes



cases

Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

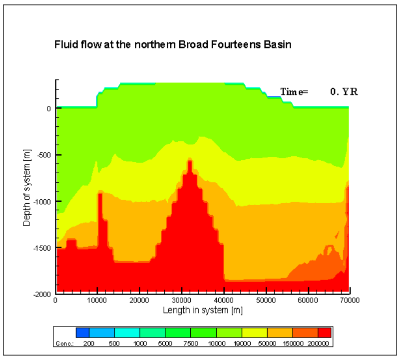


recirculation type

cases

Broad 14 Basin, North Sea

Geofluids'03, with L. Bouw

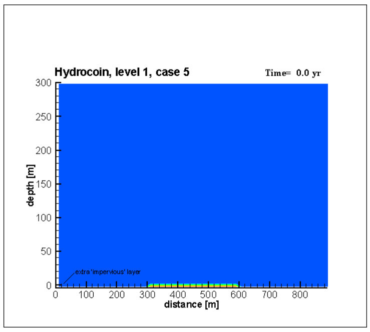


Bouw, L. & Oude Essink, G.H.P. 2003. Development of a freshwater lens in the inverted Broad Fourteens Basin, Netherlands offshore, J. of Geochemical Exploration (78-79), 321-325.

cases

Hydrocoin: effect of boundary condition (II)

supply of brine through only hydrodynamic dispersion

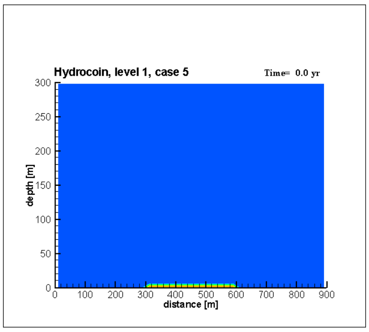


swept-forward type

cases

Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

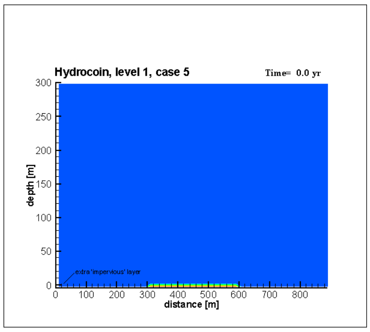


recirculation type

cases

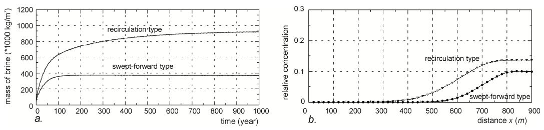
Hydrocoin: effect of boundary condition (II)

supply of brine through only hydrodynamic dispersion



swept-forward type

Hydrocoin: difference recirculation vs swept forward



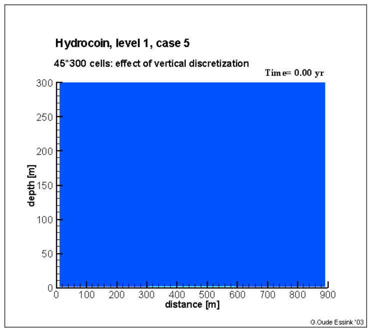
total mass of brine

brine conc at depth=200m

Lecture notes, p. 86-91

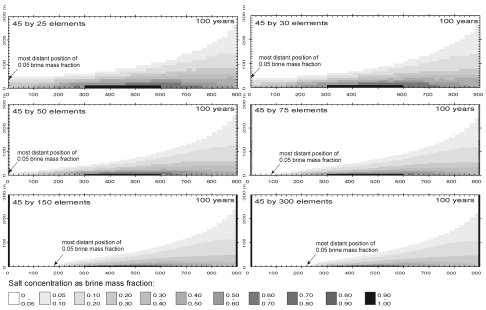
Hydrocoin: effect of vertical discretization (III)

more vertical cells give better solution



like the swept-forward type

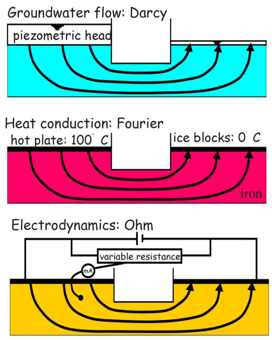
Hydrocoin: effect of vertical grid size



Recirculation type

Analogy physical processes

Heat transport (analogy with solute transport)



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

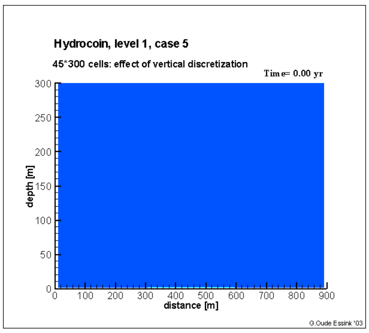
$$h = -\lambda \frac{\partial T}{\partial x}$$

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

cases

Hydrocoin: effect of vertical discretization (III)

more vertical cells give better solution



like the swept-forward type

Conduction and convection of heat

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

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

thermal conductivity [Joule/(ms °C)]

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

continuity equation

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

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

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

Analogy solute and heat transport

Solute: advection-dispersion equation

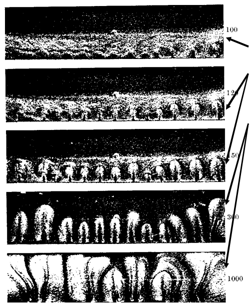
$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(CV_i)+\frac{(C-C)'W}{n_e}$$

Heat: convection-conduction equation

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

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

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

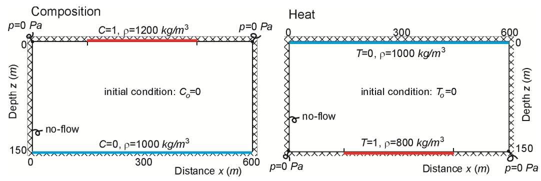
$$\rho_{i,j,k}=\rho_f(1-\alpha_f T_{i,j,k})$$

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

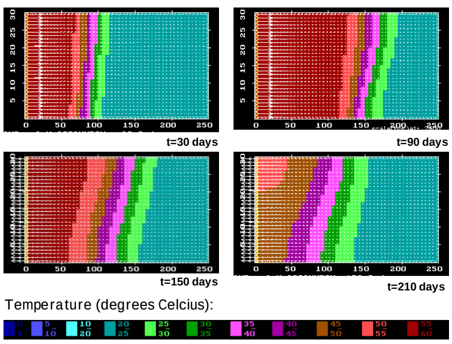
Elder problem (II)

Anology composition and heat



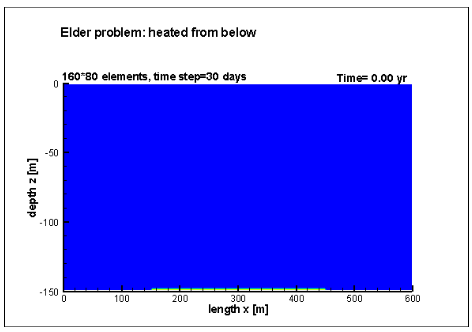
Lecture notes, p. 91-96

Energy storage in geothermal reservoirs



Elder problem (III)

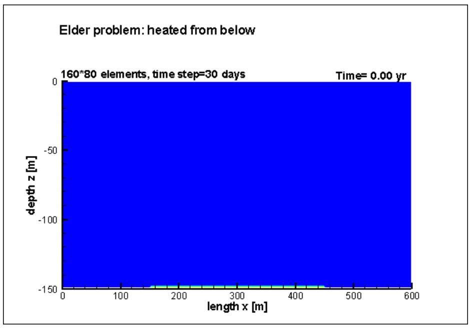
Development of convection cells (Rayleigh number=400)



cases

Elder problem (III)

Development of convection cells (Rayleigh number=400)



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

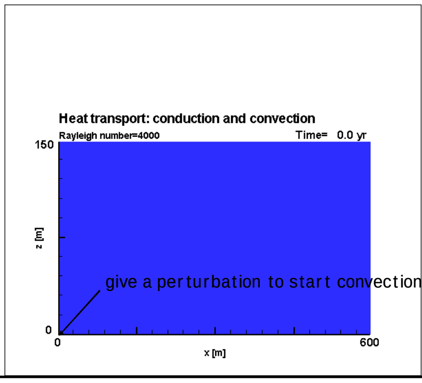
Impression of relevant salinisation processes by conceptual models of salt water intrusion in coastal aquifers:

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

cases

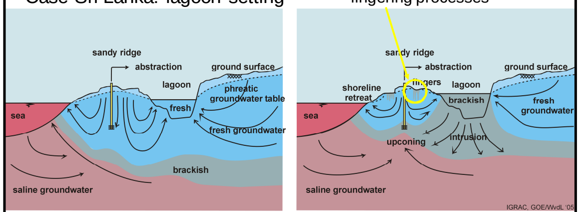
Heat transport (Rayleigh number=4000)



Concept 1: Fingering processes in the subsoil

Case Sri Lanka: lagoon setting

fingering processes



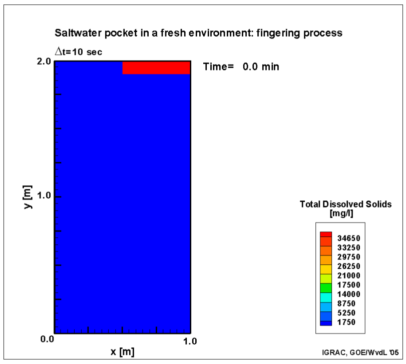
Before the Tsunami

After the Tsunami

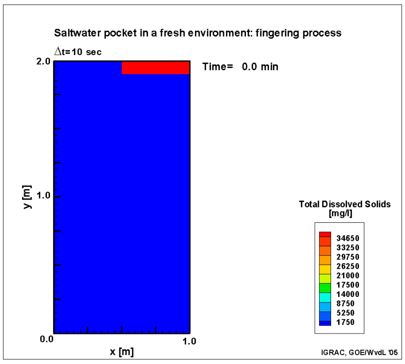
Impact of the 26-12-04 Tsunami on groundwater systems

Sri Lanka
Some days after December 26th, 2004

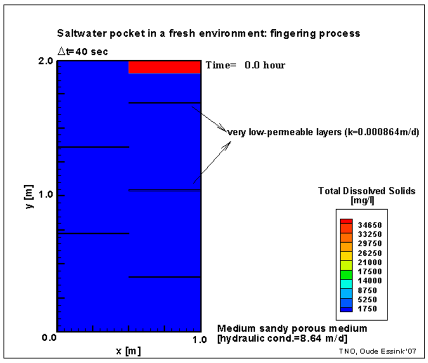
Concept 1: Fingering processes in the subsoil



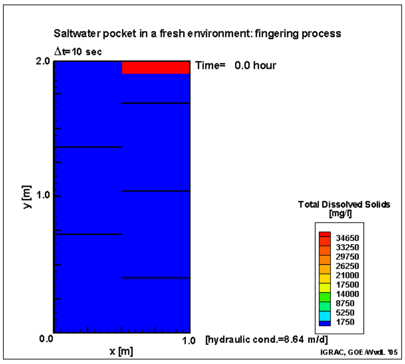
Concept 1: Fingering processes in the subsoil



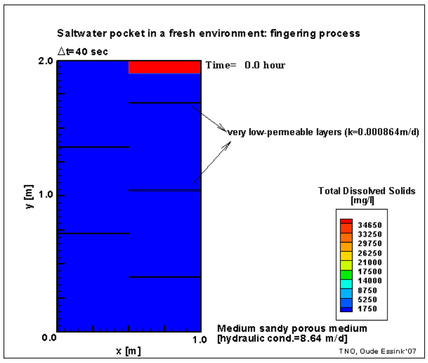
Concept 1: Fingering processes in the subsoil



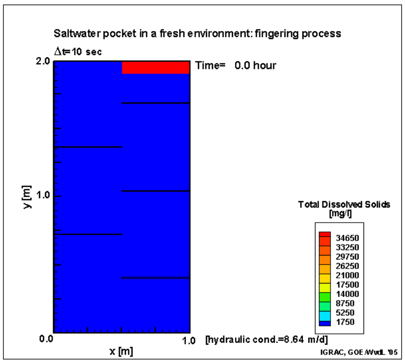
Concept 1: Fingering processes in the subsoil



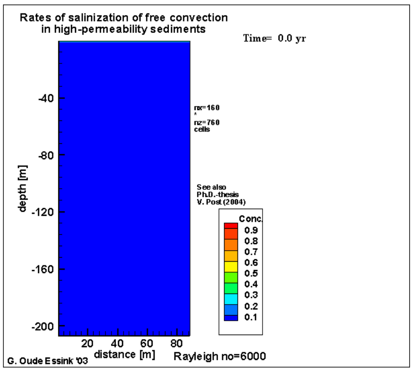
Concept 1: Fingering processes in the subsoil



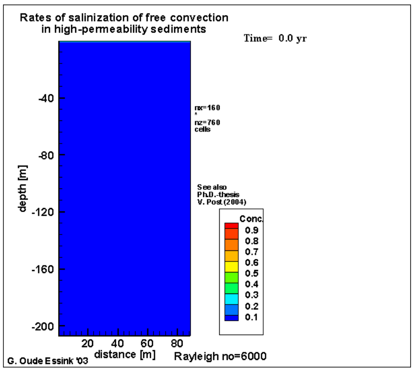
Concept 1: Fingering processes in the subsoil



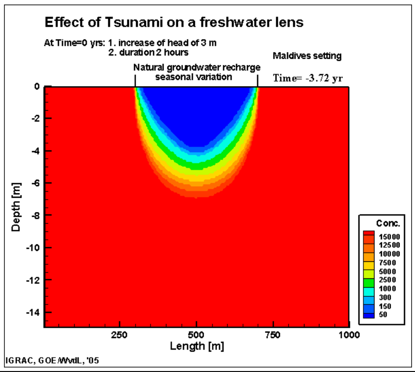
Concept 1: Fingering processes in the subsoil



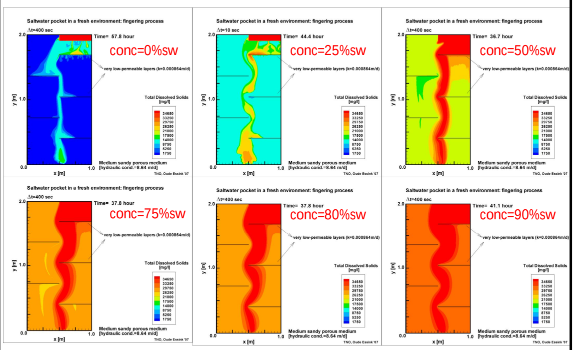
Concept 1: Fingering processes in the subsoil



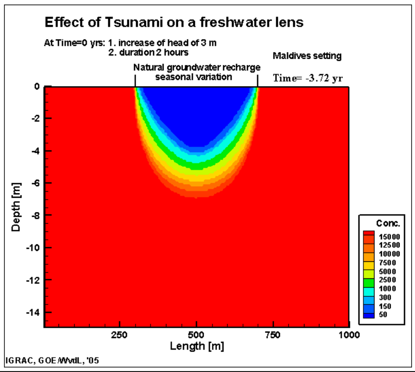
Concept 2: Evolution of a freshwater lens after flooding



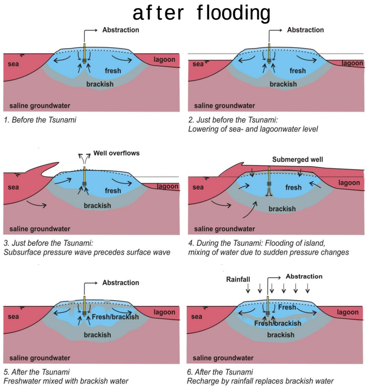
Fingering processes in the subsoil



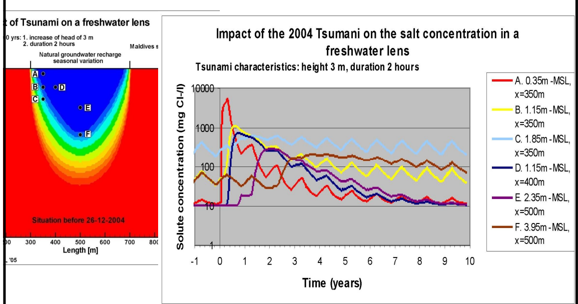
Concept 2: Evolution of a freshwater lens after flooding



Concept 2: Evolution of a freshwater lens after flooding

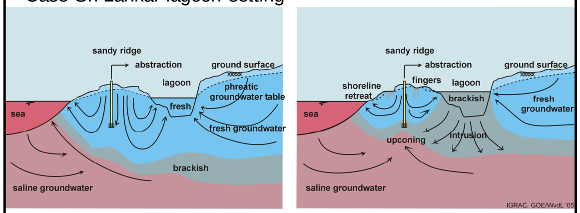


Concept 2: Evolution of a freshwater lens after flooding



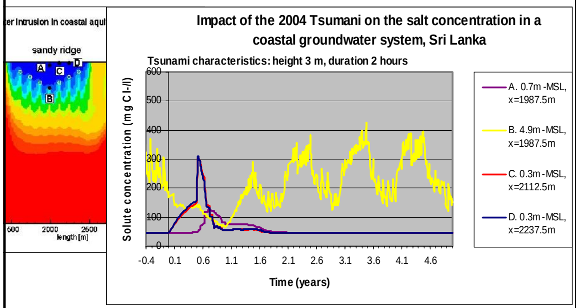
Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

Case Sri Lanka: lagoon setting

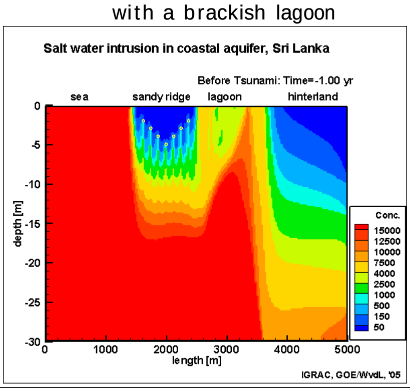


Before the Tsunami After the Tsunami

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

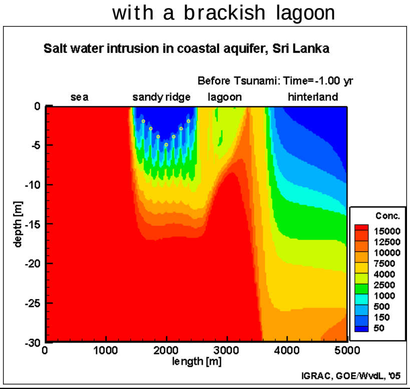


Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon



Effect sea level rise

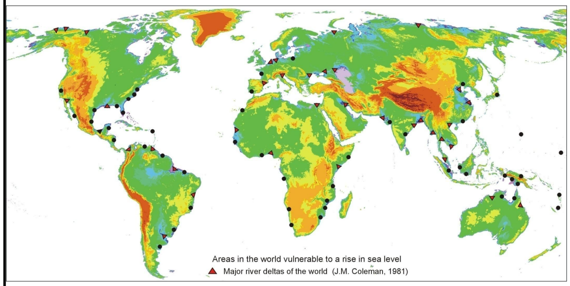
Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon



Effects of sea level rise on groundwater resources in deltaic areas

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

Effects of sea level rise on groundwater resources in deltaic areas

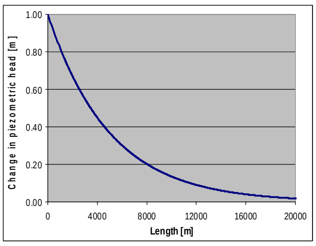


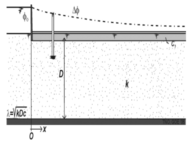
Digital Elevation Model (DEM)

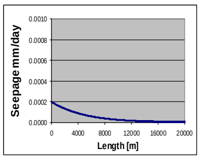
Effect of sea level rise:

Case 2 with Dutch subsoil parameters

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

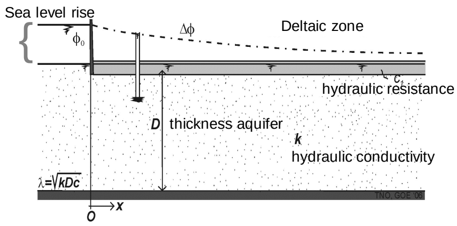






Effect of sea level rise:

Analytical approach for zone of influence in deltaic areas



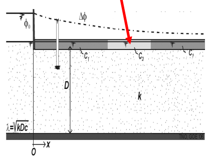
$$\Delta\phi(x) = \phi_0 e^{-x/\lambda}$$

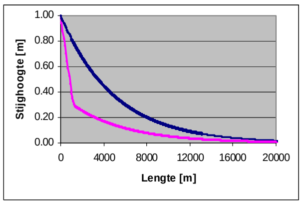
$$\lambda = \sqrt{kDc}$$

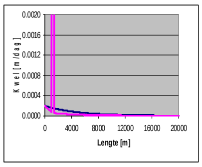
- Zone of influence is equal to sqrt(kDc)
- At x=3λ, only 5% of sea level rise is detactable

Case 3 with Dutch subsoil parameters

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



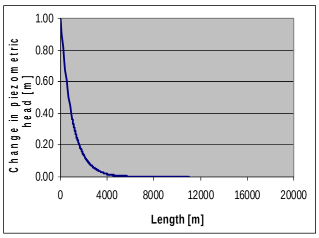


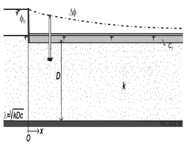


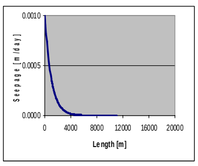
Effect of sea level rise:

Case 1 with Dutch subsoil parameters

kD = 1000 m²/day
c = 1000 day
λ = 1000 m

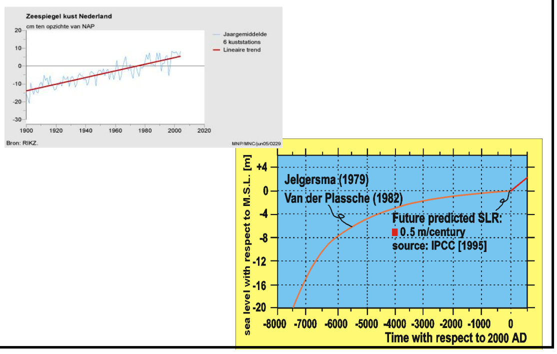






Climate change is HOT!

Past and future sea level rise in the Netherlands

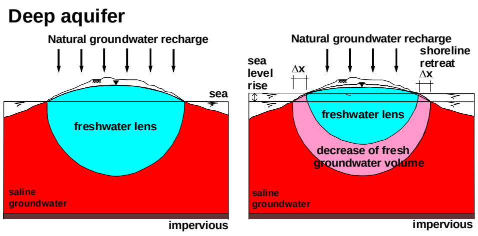


Implementing new KNMI06 climate scenarios

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

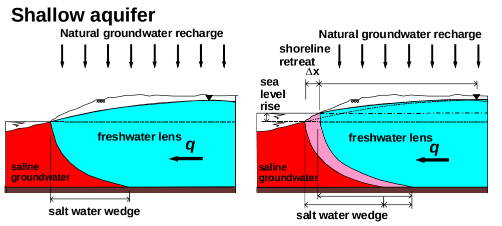
Effect of a relative sea level rise (1):

Deep aquifer



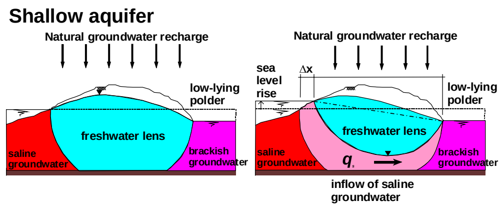
Effect of a relative sea level rise (2):

Shallow aquifer

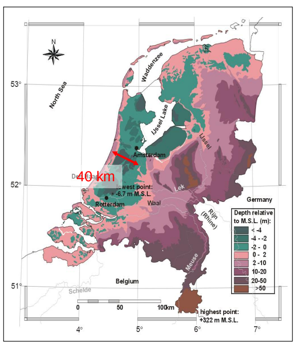


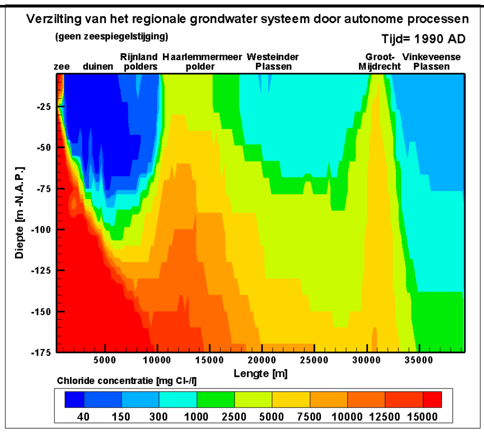
Effect of a relative sea level rise (3):

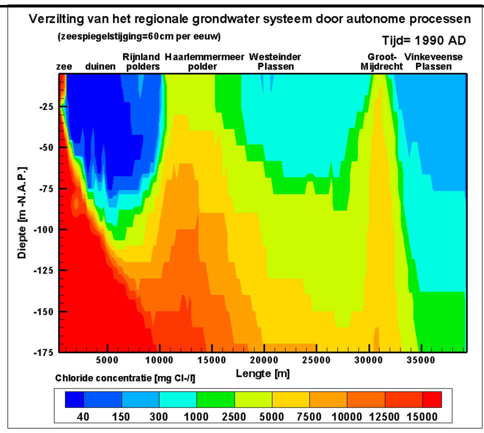
Shallow aquifer

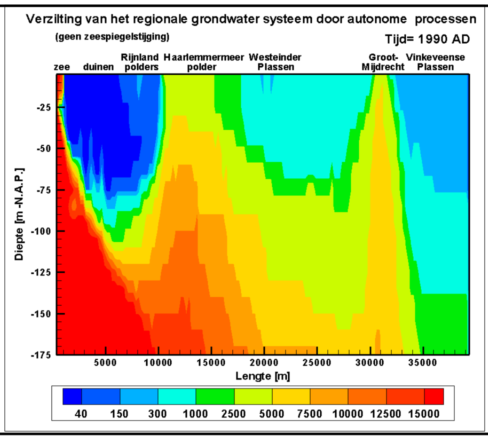


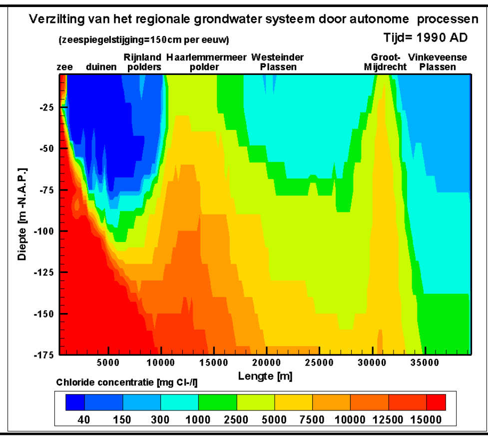
2D Profile and effect sea level rise

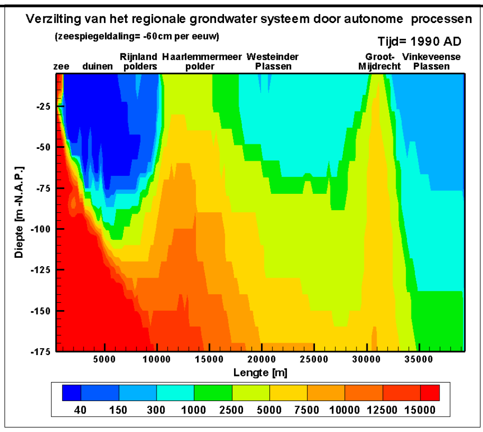






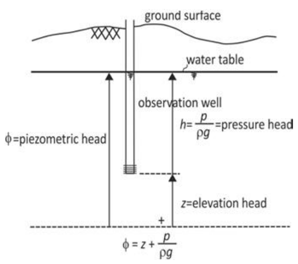






Point water head
and
Freshwater head ϕ_f

Piezometric head ϕ



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

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

Special case: hydrostatic pressure: $q_z=0$

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

no vertical flow

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

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

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

+

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

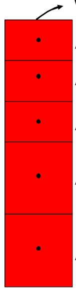
Freshwater head ϕ_f

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

1. Groundwater with different densities can be compared
2. Fictive parameter
3. Hydrologists like to use heads instead of pressures
4. Pressure sometimes better
5. Confusing (heads not perpendicular to streamlines)

Hydrostatic boundary condition at the sea

Water level=+0m MSL



- Δz=5m: $\rho = 1025$ kg/m3 ⟶ $\phi_{f1} = 0\text{m} + 0.025 * 2.5\text{m} = 0.0625\text{m}$
- Δz=5m: $\rho = 1025$ kg/m3 ⟶ $\phi_{f2} = 0.0625 + 0.025 * 5\text{m} = 0.1875\text{m}$
- Δz=5m: $\rho = 1025$ kg/m3 ⟶ $\phi_{f3} = 0.1875 + 0.025 * 5\text{m} = 0.3125\text{m}$
- Δz=10m: $\rho = 1025$ kg/m3 ⟶ $\phi_{f4} = 0.3125 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.50\text{m}$
- Δz=10m: $\rho = 1025$ kg/m3 ⟶ $\phi_{f5} = 0.50 + 0.025 * (5\text{m} + 5\text{m}) = 0.75\text{m}$

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

Freshwater head ϕ_f

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

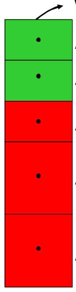
$$\phi_f = h_f + z$$

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

e.g.:
ρ_s=1025kg/m3
h=10m
ϕ_f=10.25m

Hydrostatic boundary condition at the sea

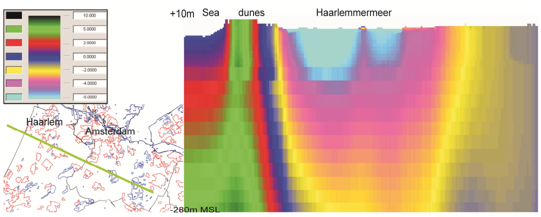
Water level=+0m MSL



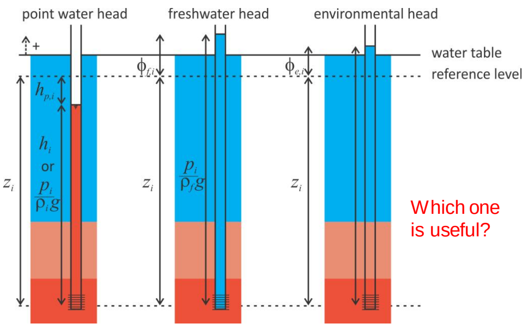
- Δz=5m: $\rho = 1010$ kg/m3 ⟶ $\phi_{f1} = 0\text{m} + 0.010 * 2.5\text{m} = 0.025\text{m}$
- Δz=5m: $\rho = 1010$ kg/m3 ⟶ $\phi_{f2} = 0.025 + 0.010 * 5\text{m} = 0.075\text{m}$
- Δz=5m: $\rho = 1025$ kg/m3 ⟶ $\phi_{f3} = 0.075 + 0.010 * 2.5\text{m} + 0.025 * 2.5\text{m} = 0.1625\text{m}$
- Δz=10m: $\rho = 1025$ kg/m3 ⟶ $\phi_{f4} = 0.1625 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.35\text{m}$
- Δz=10m: $\rho = 1025$ kg/m3 ⟶ $\phi_{f5} = 0.35 + 0.025 * (5\text{m} + 5\text{m}) = 0.60\text{m}$

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

Example 2D profile NHI model freshwater head ϕ_f



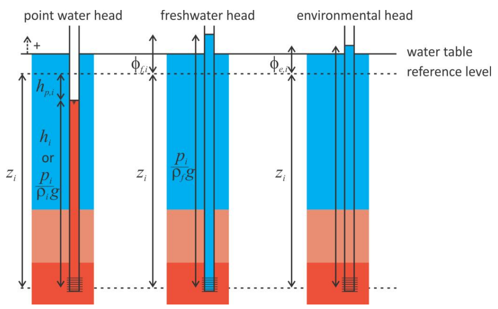
$$h_{f,i} = \frac{\rho_i}{\rho_f} h_i - \frac{\rho_i - \rho_f}{\rho_f} z_i \qquad h_{f,i} = z_i + \frac{P_i}{\rho_f g}$$



Which one is useful?

Post, Kooi and Simmons, 2007, Ground Water

Which one is useful?



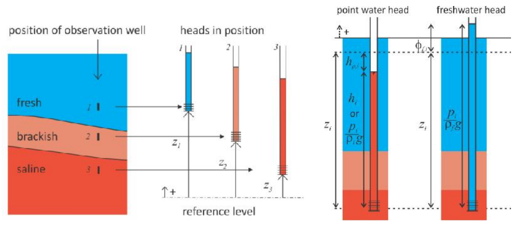
Post, Kooi and Simmons, 2007, Ground Water

Point water head | Freshwater head

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

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

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



Point water head

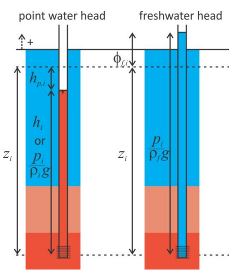
$$h_{p,i} = z_i + h_i \longleftrightarrow h_i = h_{p,i} - z_i$$

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

Freshwater head

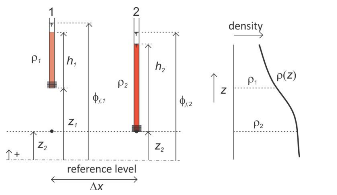
$$\phi_{f,i} = z_i + \frac{p_i}{\rho_f g} \longleftrightarrow \phi_{f,i} = z_i + \frac{h_i \rho_i}{\rho_f}$$

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



Post, Kooi and Simmons, 2007, Ground Water

Freshwater head ϕ_f: horizontal flow?

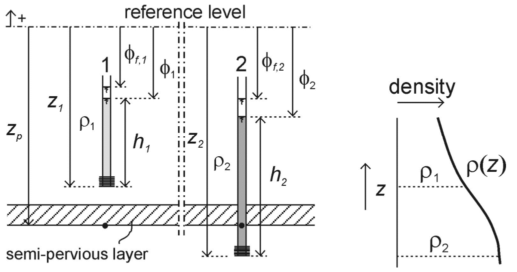


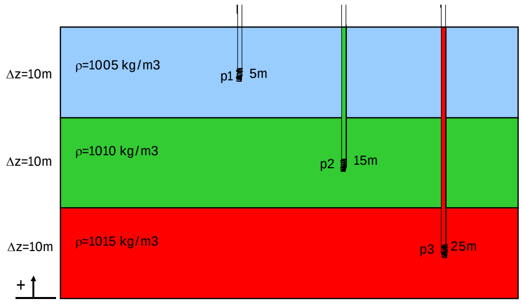
$$p_1^{at\ z=z_2} = \rho_1 g h_1 + \int_{z_2}^{z_1} \rho(z) g dz \qquad \phi_{f,1}^{at\ z=z_2} = z_2 + \frac{\rho_1}{\rho_f} h_1 + \frac{1}{\rho_f g}\int_{z_2}^{z_1} \rho(z) g dz$$

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

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

Freshwater head ϕ_f : vertical flow?

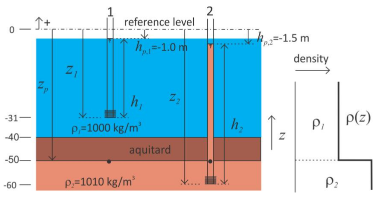




Flow or no flow? (if p≠hydrostatic than flow)

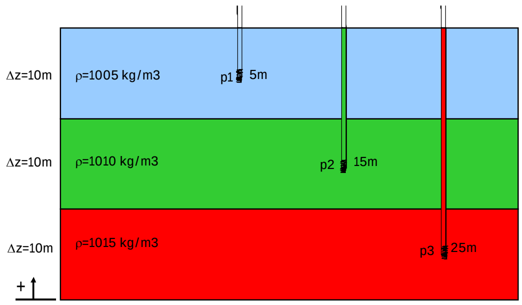
Calculate to freshwater head!

Freshwater head ϕ_f

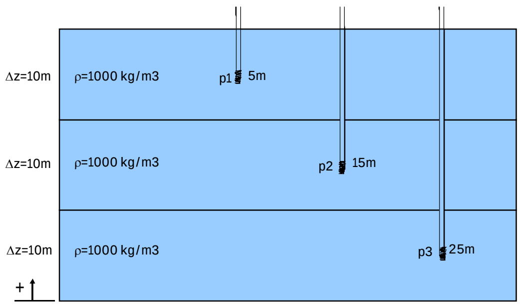


$$\phi_{f,1}^{z=-50} = -50 + \frac{1000}{1000}30 + \frac{1}{1000g}\int_{-50}^{-31}1000gdz = -50 + 30 + 19 = -1.0$$

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

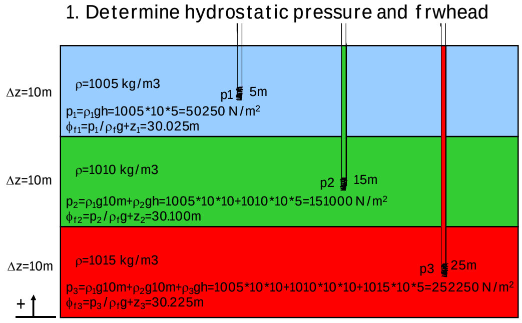


1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)



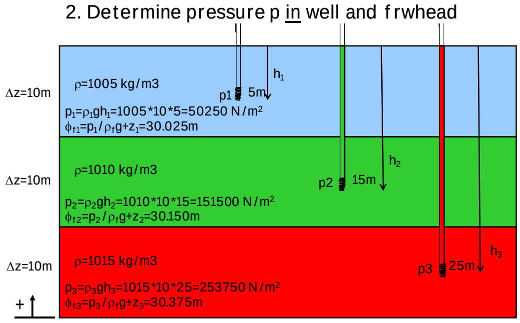
No flow

1. Determine hydrostatic pressure and frwhead

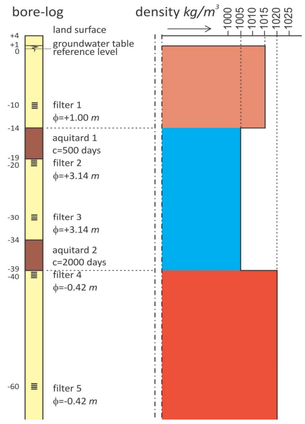


1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)

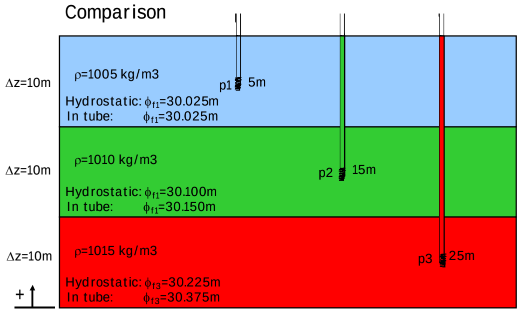
2. Determine pressure p in well and frwhead



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



Comparison

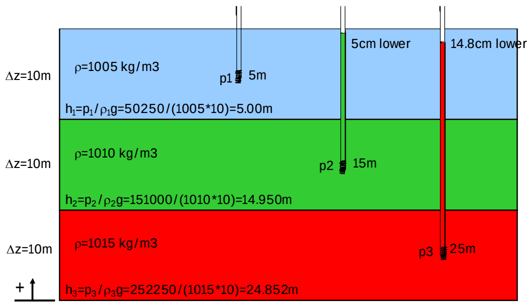


Conclusion: freshwater head not equal, so vertical upward flow!

Take home message

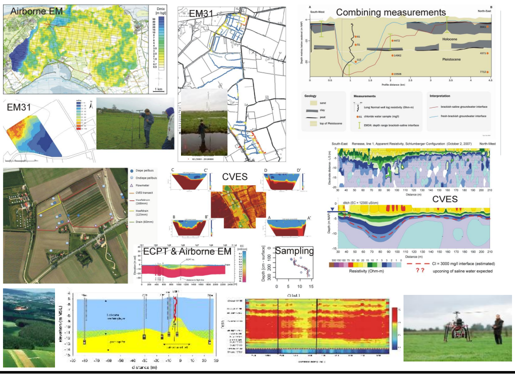
1. In coastal area (with fresh-brackish-saline groundwater), always measure head and Electrical Conductivity (EC)
2. Convert EC to density
3. Determine freshwater head with lecture notes and ppt
4. Determine flow

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

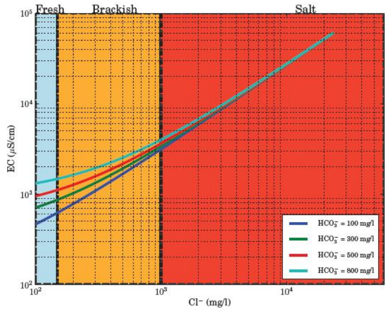


Monitoring

Monitoring



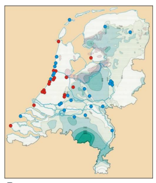
EC and Chloride



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

Monitoring salt in groundwater

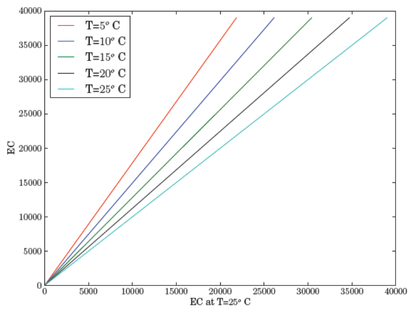
- Why monitoring?
  - Mapping salt concentrations in the groundwater
  - Detection of trends (upconing near pumping stations)
  - System and process knowledge
  - Input for a groundwater model



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

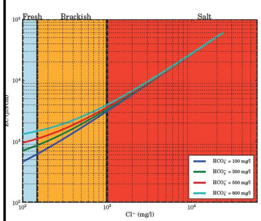
Source: V. Post, 2007

EC and Chloride

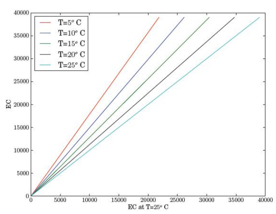


2((b) EC and temperature standardized EC.

EC and Chloride



EC-Cl at different HCO_3^- concentrations.



(b) EC and temperature standardized EC.

P. Pauw, 2009

20120622 SWIM22

Airborne measurements

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

Source: Koos Groen

Surface measurements

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

Source: Koos Groen

Monitoring salt in groundwater: Indirect methods

Indirect methods measure the **conductance** of:

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

AND

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

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

Source: V. Post, 2007

Cone Penetration Tests

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

Source: Koos Groen

Monitoring salt in groundwater: Indirect methods

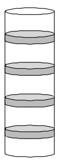
Method	Advantages	Disadvantages
1. Electrical conductance measurements	•High resolution (3D) •Depth ~200 m	•Time consuming
2. Electromagnetic measurements	•Fast	•Limited vertical resolution •Sensitive for underground conductors (pipes)
3. Satellites	•Suitable for large areas	•Small vertical resolution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

Source: V. Post, 2007

Monitoring salt in groundwater: Direct methods

Method	Advantage	Disadvantage
1. Observation well	•High accuracy •Detection trends	•Costly •Point measurement
2. Well screens in observation well	•High accuracy •Detection trends •High vertical resolution	•Costly
3. Sediment sample (extraction milliliters of water)	•High accuracy •High vertical resolution	•Very costly and time consuming

Direct methods 1 and 2

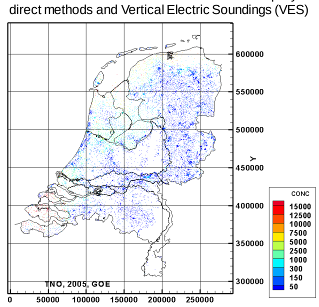


Source: V. Post, 2007

Method used at Deltares

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

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



Source: Oude Essink et al (2005)

Electrical conductance measurements

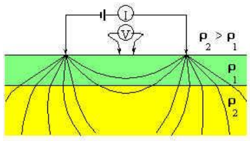
1. Measuring:
   - **Inside a borehole**
   - From surface level
   - From the air

Source: TNO

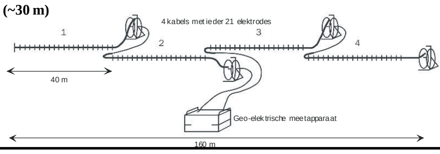
Source: V. Post, 2007

Types geo-electrical measurements

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



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



20120622 SW

Electrical conductance measurements

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

Source: Vitens

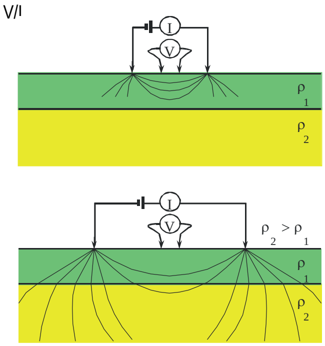
Source: V. Post, 2007

VES measurement end 1950s/begin 1960s

Principle geo-elektrical measurement

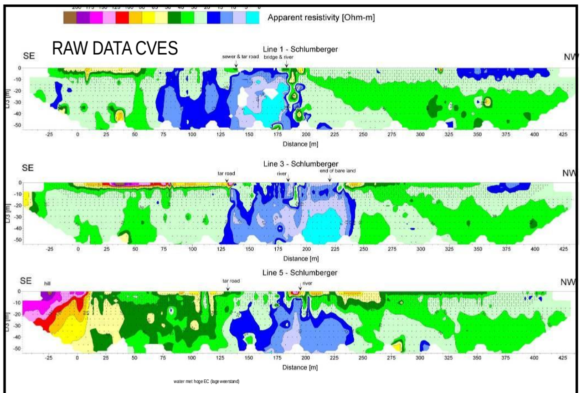
I: currentelektrode, V: potentialelektrodes, Ra: appearant elektrical resistiuvity

Ra = constant * V/I

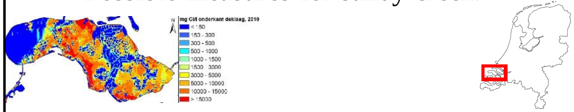


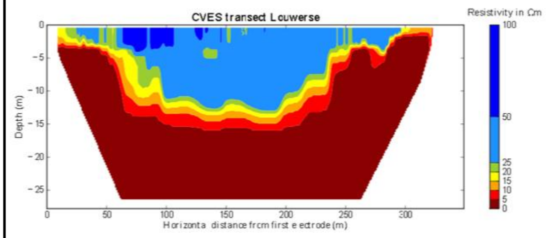
20120622 SWIM22

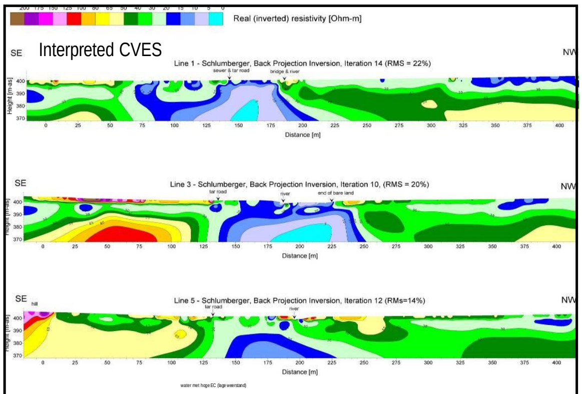
CVES measurements 2010s



Possible measures for sandy creeks

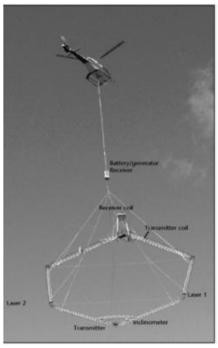




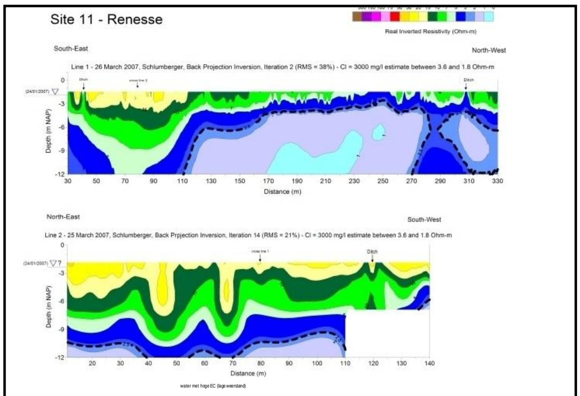


Electrical conductance measurements

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



Source: V. Post, 2007



Monitoring salt in groundwater: Indirect methods

- Electrical conductance measurements

$\rho_s = F^* \rho_w$

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

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

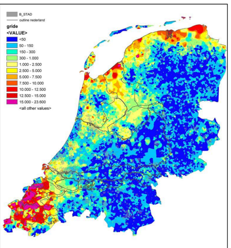
F varies with the resistance of the groundwater (Clay, peat)

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

VES measurements are used in combination with borehole logging

Source: Oude Essink, 2005

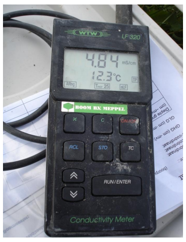
Result: chloride concentration bottom Holocene toplayer


Source: Oude Essink, 2005

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

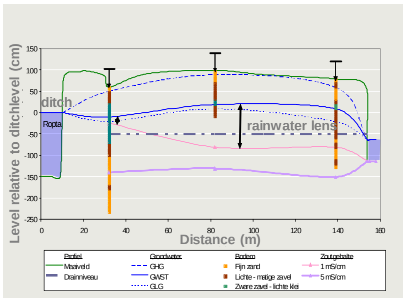



T-EC probe

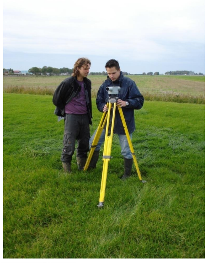
Use field measurements to understand the process



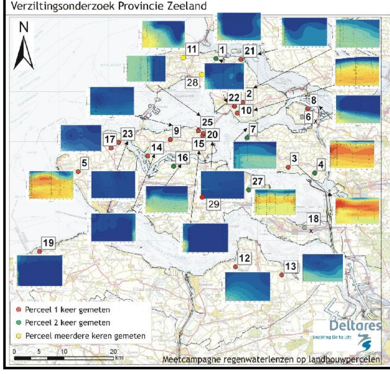


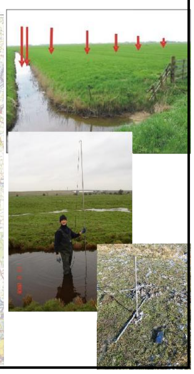
T EC fieldwork

Altitude measurements

TEC-probe Monitoring campaign 2005-2009





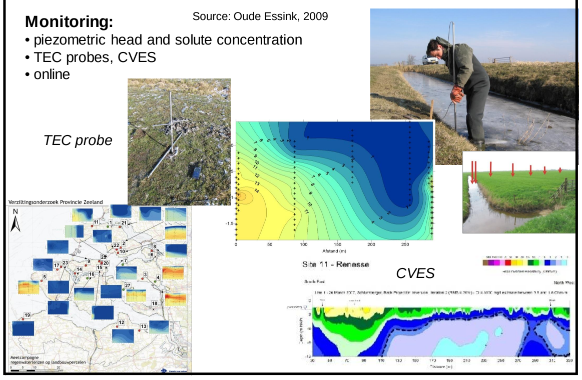
CliWat www.cliwat.eu

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

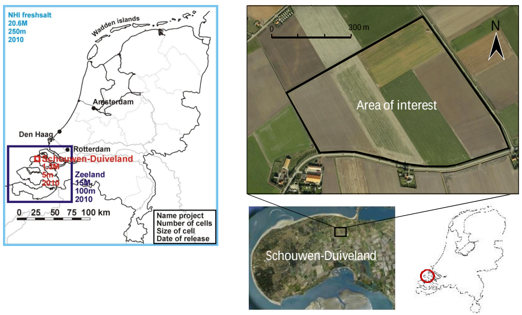
Example: Assessing effect of climate change on salt water intrusion

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

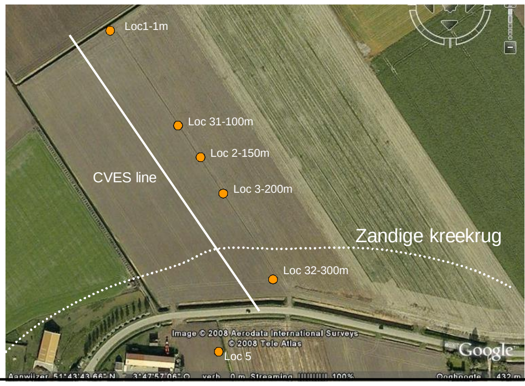
Source: Oude Essink, 2009



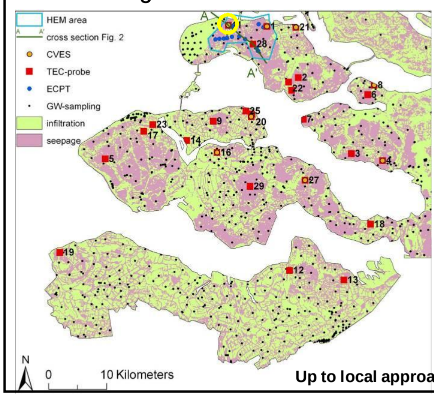
Description local area



Site 11: from infiltration to seepage



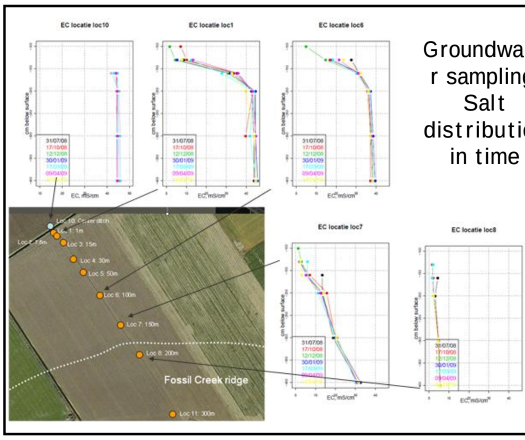
Monitoring network in our Pilot Area Zeeland



Up to local approach

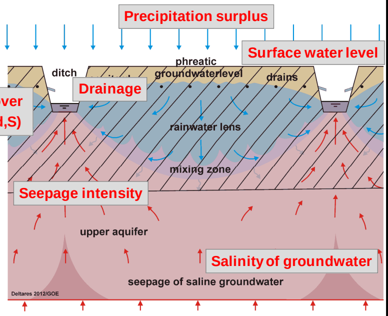
CLIWAT CLIMATE & WATER

BGR GEOZENTRUM HANNOVER



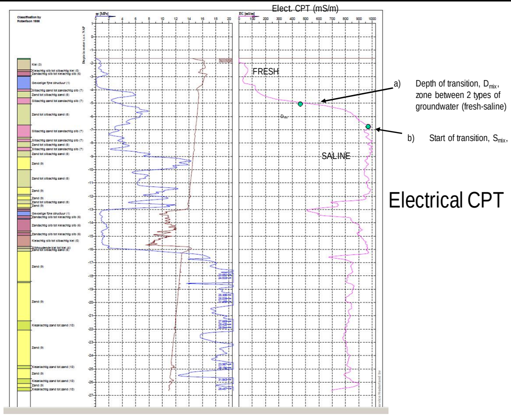
Groundwater sampling: Salt distribution in time

Factors controlling fresh-salt interface

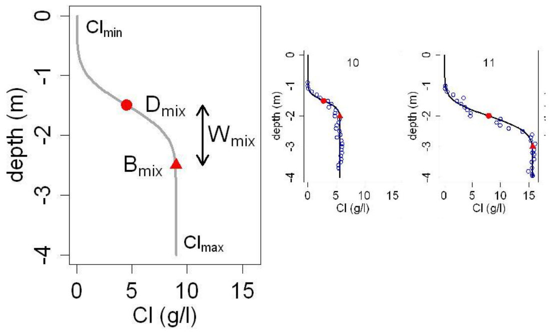


Important factors:

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

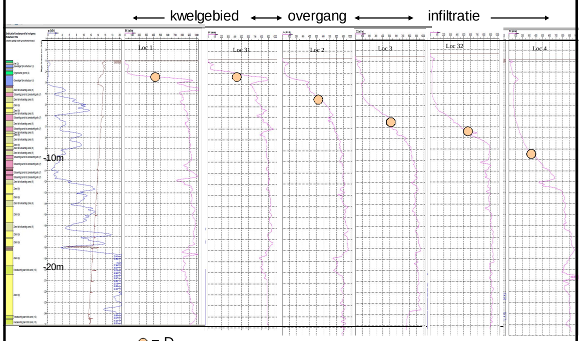


Lens characteristics



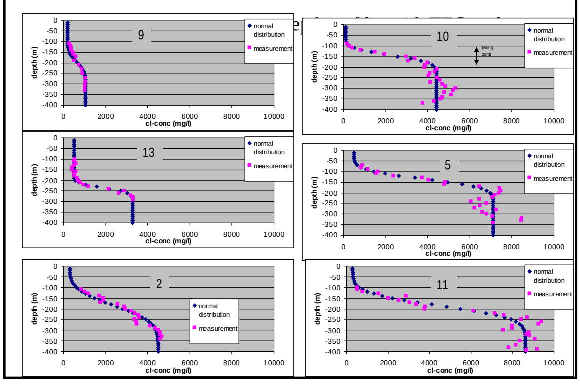
Louw, P.G.B., de, Eeman, S., Siemon, B., Voortman, B.R., Gunnink, J., Baaren, E.S., van and G.H.P. Oude Essink, Shallow rainwater lenses in deltaic areas with saline seepage, *Hydrol. Earth Syst. Sci. Discuss.*, 8, 7657-7707, 2011.

Results from ECPT's (soundings)



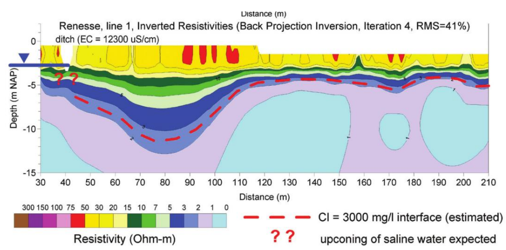
○ = D_{mix}

ECPT = electrical cone penetration test

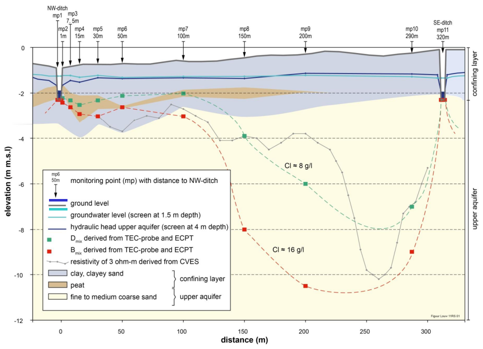


CVES

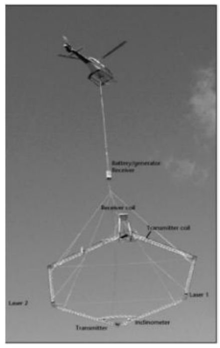
CVES: continuous vertical eletrical sounding



Seepage / infiltration determines thickness rainwaterlens

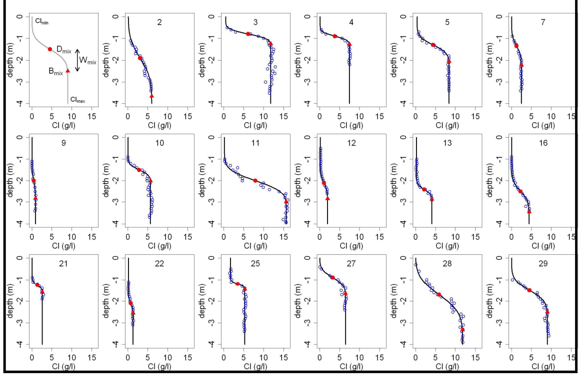


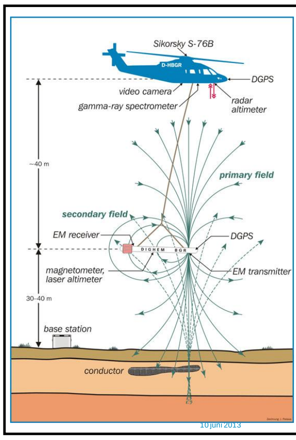
Electrical conductance measurements



10 juni 2013

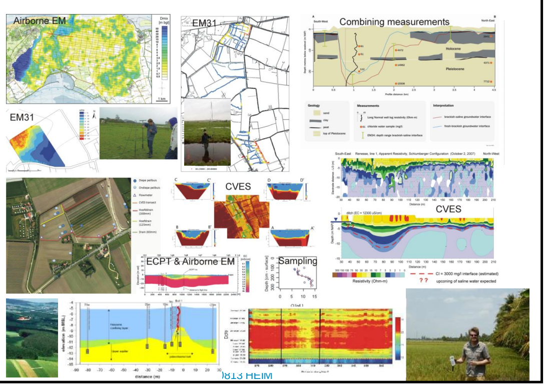
TEC-probe results



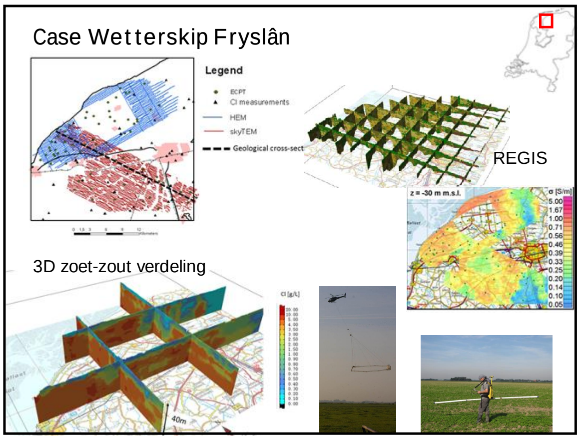


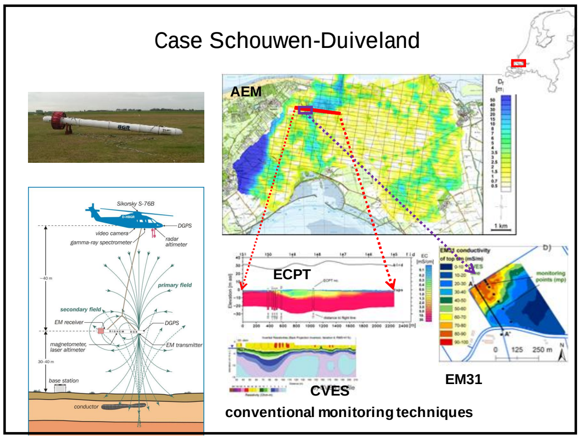
10 juni 2013

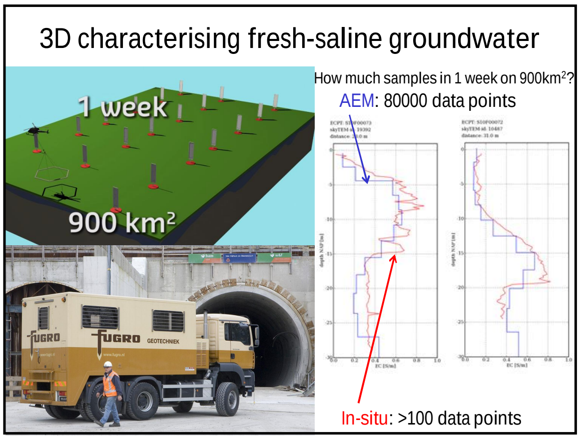
Combining different (fresh-salt) monitoring techniques

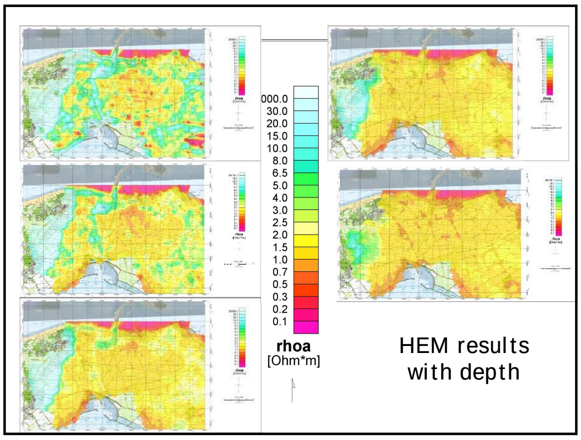


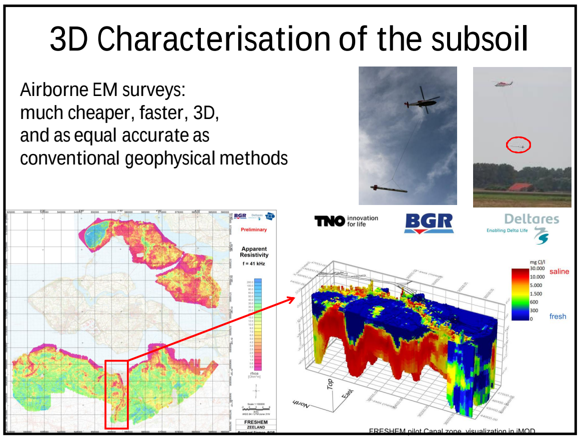
Case Wetterskip Fryslân

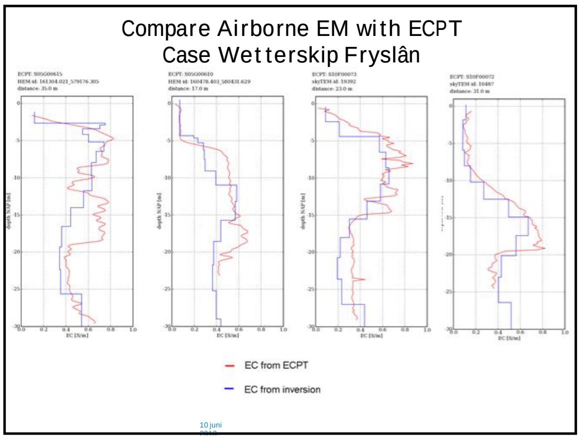


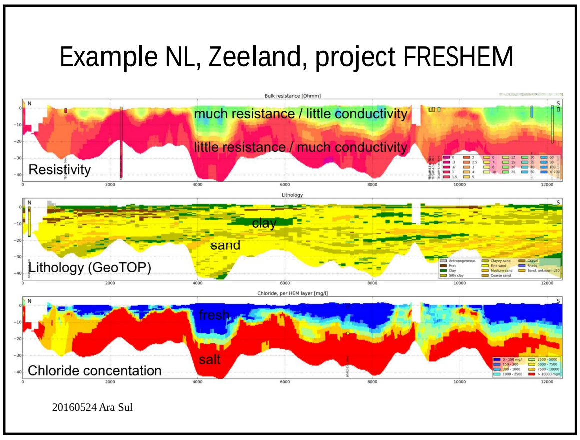

Case Schouwen-Duiveland
AEM
ECPT
CVES
EM31
conventional monitoring techniques


3D characterising fresh-saline groundwater
1 week
900 km²
How much samples in 1 week on 900km²?
AEM: 80000 data points
In-situ: >100 data points

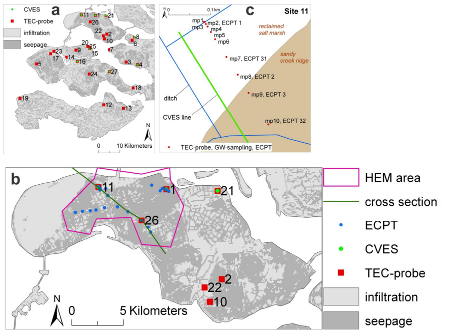

rhoa
[Ohm*m]
HEM results
with depth


3D Characterisation of the subsoil
Airborne EM surveys:
much cheaper, faster, 3D,
and as equal accurate as
conventional geophysical methods
TNO innovation for life
BGR
Deltares
saline
fresh


Compare Airborne EM with ECPT
Case Wetterskip Fryslân
EC from ECPT
EC from inversion

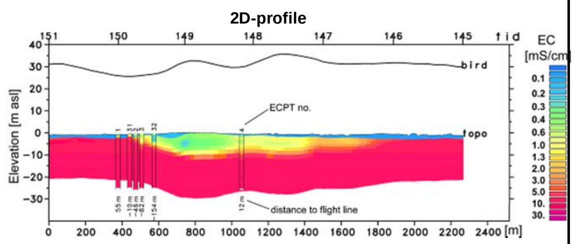

Example NL, Zeeland, project FRESHEM
much resistance / little conductivity
little resistance / much conductivity
Resistivity
clay
sand
Lithology (GeoTOP)
fresh
salt
Chloride concentation
20160524 Ara Sul

Combining monitoring techniques

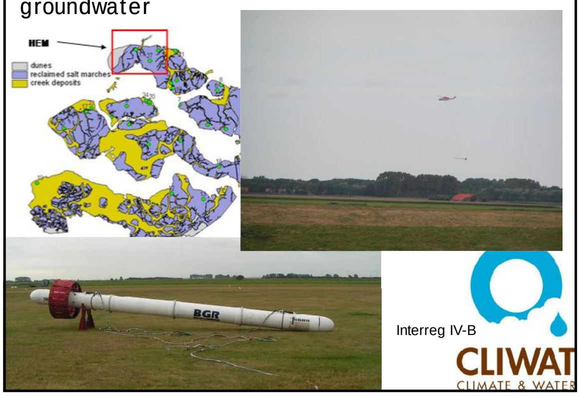


10 juni 2013

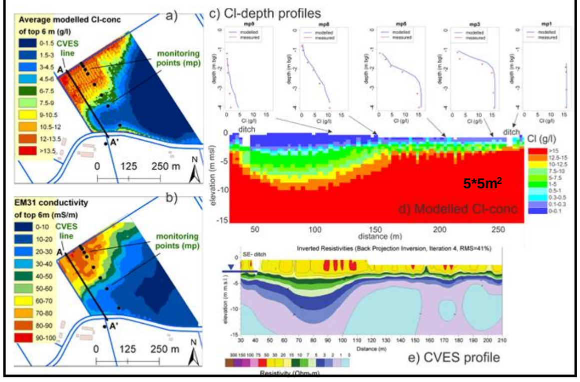
Thickness rainwater lens (D_{mix}) by HEM



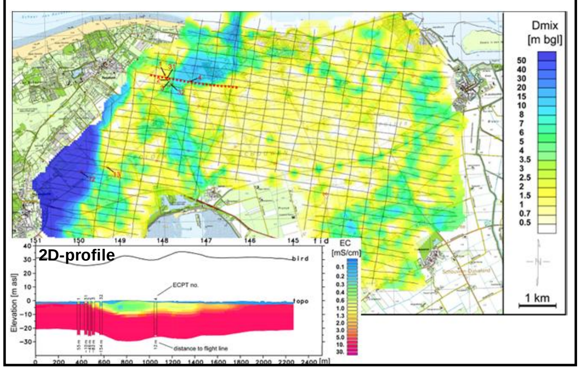
Helicopter-EM data for mapping fresh-saline groundwater



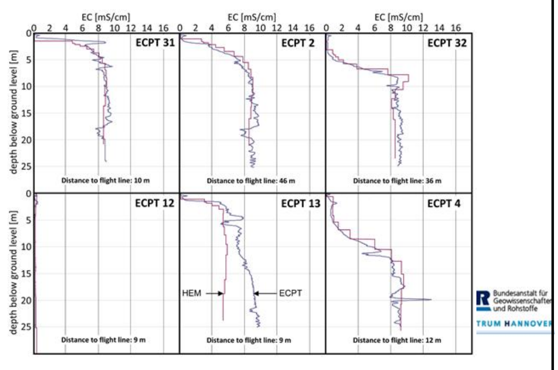
Comparison monitoring data with model results



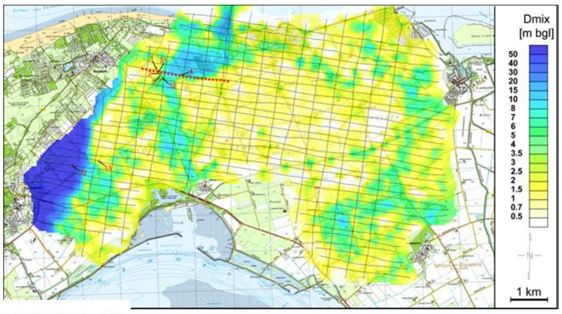
Thickness rainwater lens (D_{mix}) by HEM



Comparison HEM – ECPT

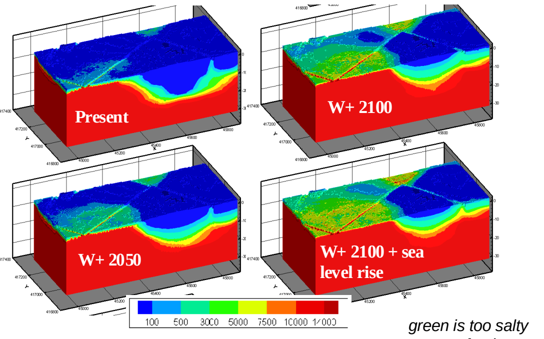


Rainwater lens thickness (D_{mix}= average position mixing zone) mapped with HEM



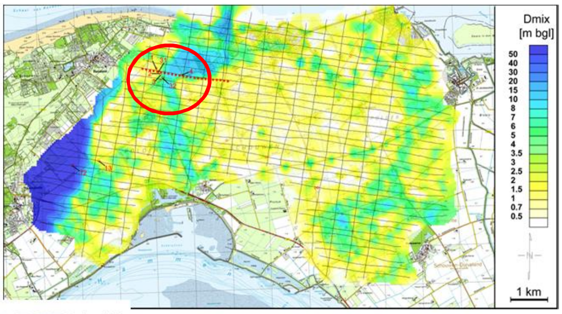
BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER

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



green is too salty to grow fresh crops

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



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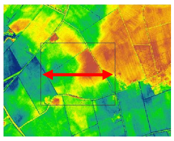
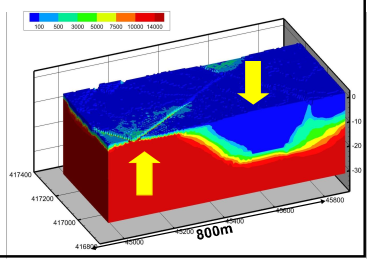
Use variable-density groundwater flow modelling

Why a model?

- variation in ground surface directly affects fresh-saline disribution

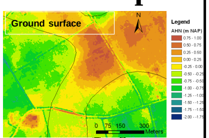




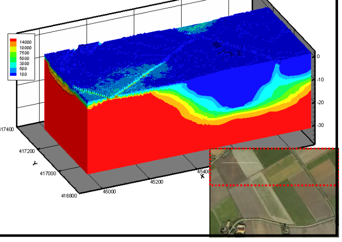
Local 3D model of the agricultural plot

Modelling:

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



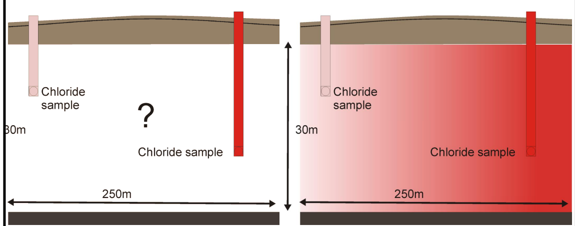
Code:
MOCDENS3D



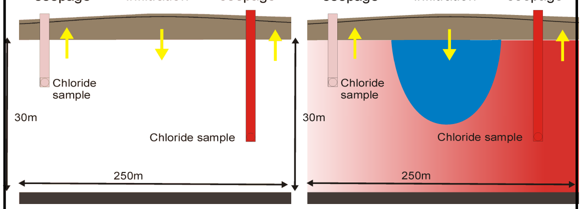
Assessing effects:

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

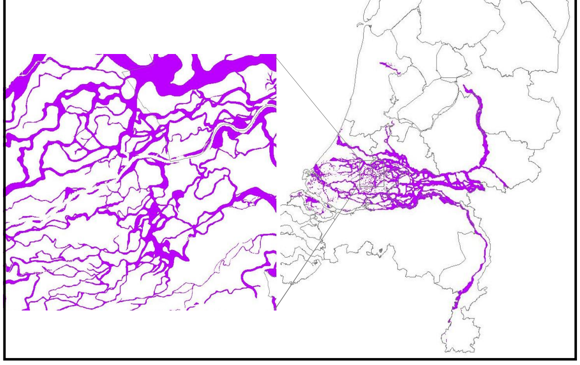
Interpolation chloride



Using flow model for better interpolate chloride



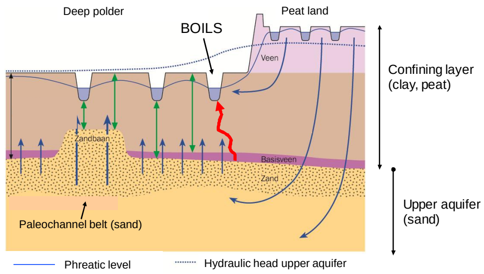
(Burried) Paleochannel belts



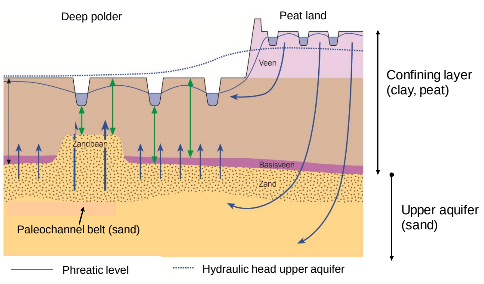
Salty boils

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

Preferential seepage via boils

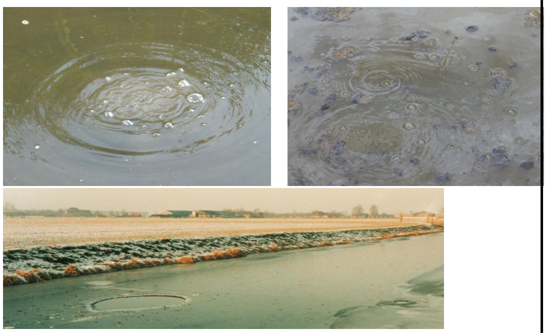


Upward groundwater seepage in a deep polder and paleochannel belts as preferential flow paths

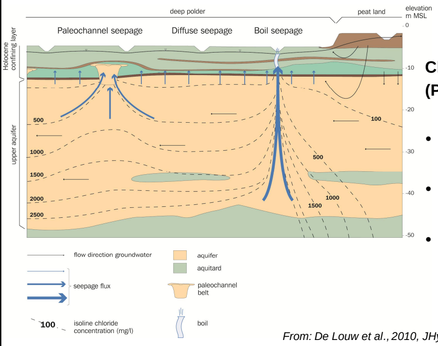


Preferential saline seepage via boils

Preferential saline seepage via boils



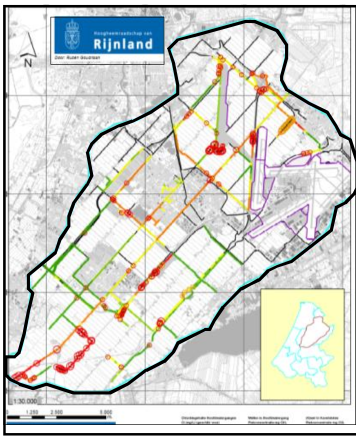
Three types of upward groundwater seepage



Cl-conc seepage: (Polder Noordplas)

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

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

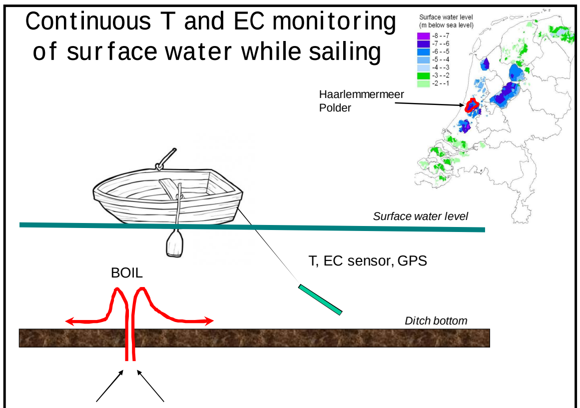


Mapped boils and Cl-conc. surface water

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

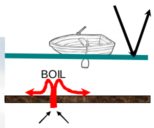
Cl-conc surface water
0-300 mg/l
300-600 mg/l
600-1000 mg/l
> 1000 mg/l

Continuous T and EC monitoring of surface water while sailing

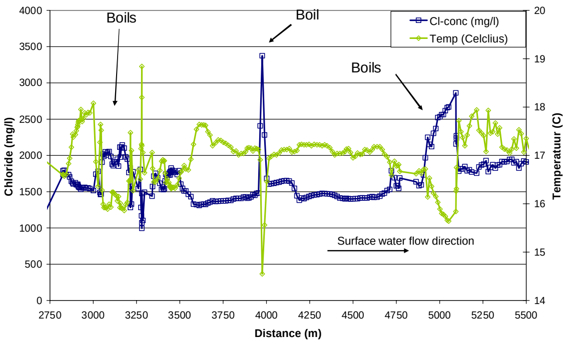


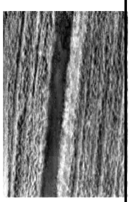
LARS technology (TNO Industry): Thermal Infra-red

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

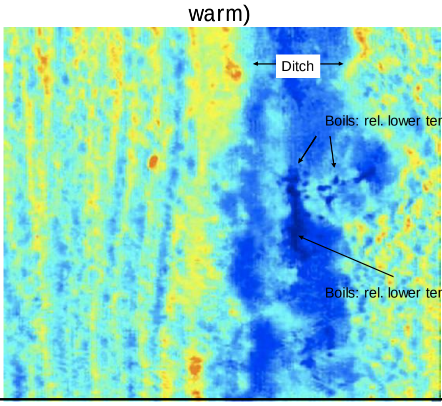


T and EC measurements in surface water (canal)

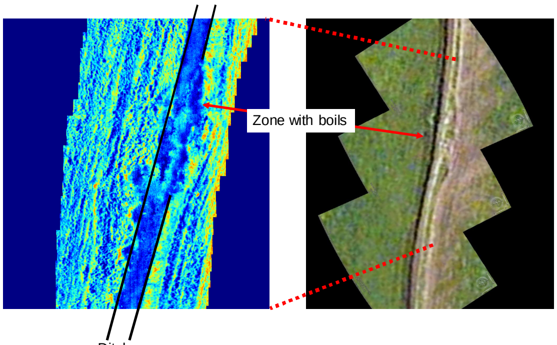


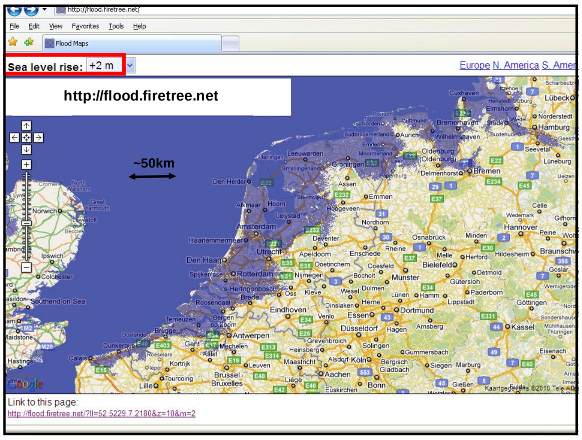


Thermal infra-red results (blue is cold, red is warm)



Salt water intrusion in the Netherlands

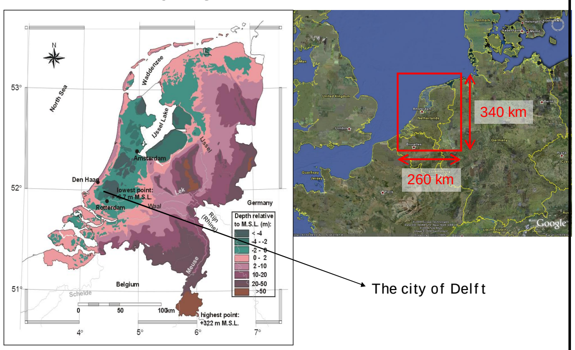




To get an idea about the possible future effects of sea level rise and climate change in your delta …

evaluate of the past water management in the Dutch delta

The 'low-lying' lands: Netherlands



Case study: The Netherlands

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

Intensive water management system

Coping with salt water intrusion problems since 1950's

Infrastructure to protect our low-lying land from flooding

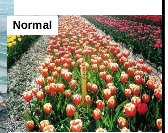
The 'low-lying' lands: Netherlands

The facts:

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

River flooding in 1995

Combination of heavy rains upstream the catchment & short retention time



The Great Flooding in february 1953

Combination of high tide and heavy storm:

-1853 casualties
-2000 km^2 flooded

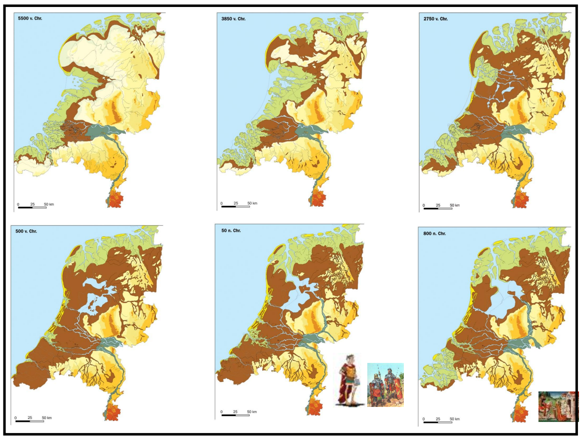
Dike collapse 2003

Combination of peat dike instability and very dry summer

Estimated water management costs 'to keep our feet dry'

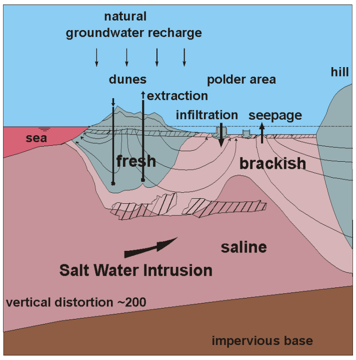
Costs up till 2050 in billion euros:

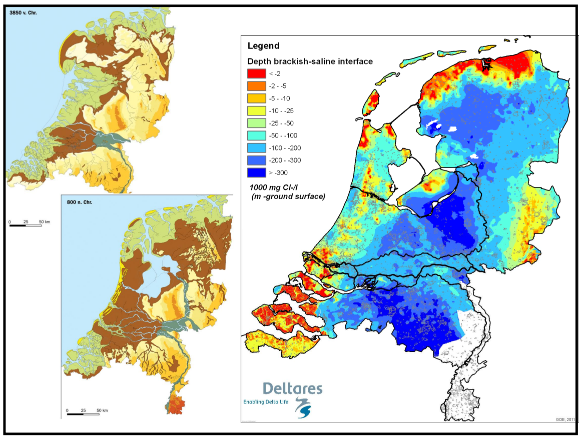
rivers: upper part	5.7
rivers: lower part	5.6
low-lands	1.7
coastal zone	8.0
infrastructure	3.5
purchase of ground	2.0
	-----+
	26.5 billion euros



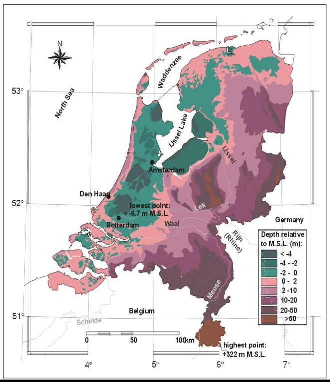
Dutch setting

Salt water intrusion in the Netherlands

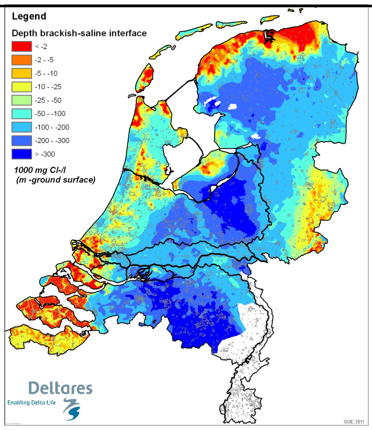




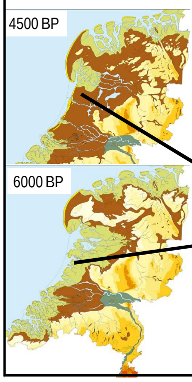
Present ground surface in the Netherlands

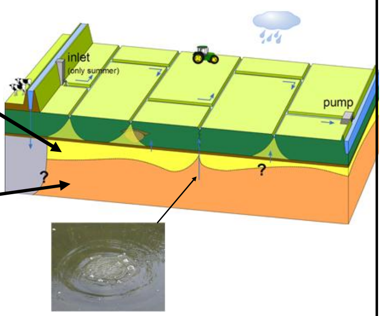


Fresh-Salt interface

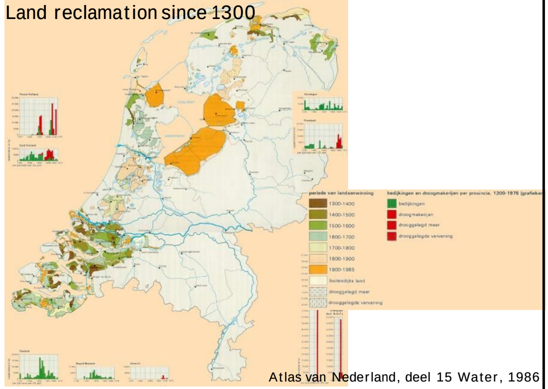


Hydrogeology





Land reclamation since 1300



Atlas van Nederland, deel 15 Water, 1986

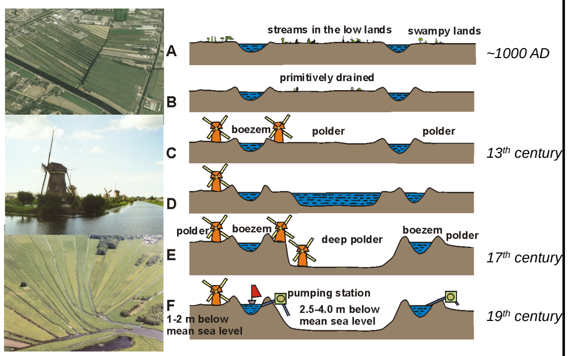
Salinisation of the Dutch subsurface

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

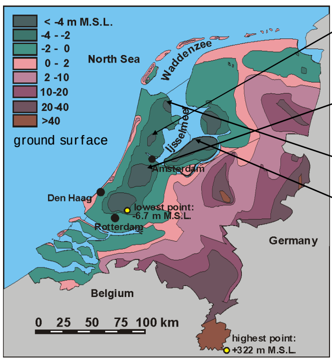
Anthropogenic causes:
- land subsidence
- polder level lowering
- groundwater extractions

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

Development of the Dutch 'Polder' Landscape



Abrupt land subsidence



position polders:

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

Haarlemmermeer polder 1850-1852

Wieringermeer polder ~1930

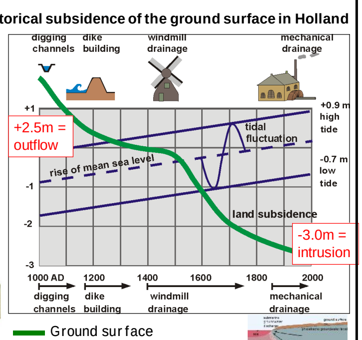
Flevo polders 1950-60s

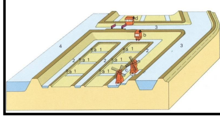
From fresh water outflow to salt water inflow

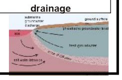
Causes:

- Autonomous processes
- Land subsidence
- Abrupt land reclamation

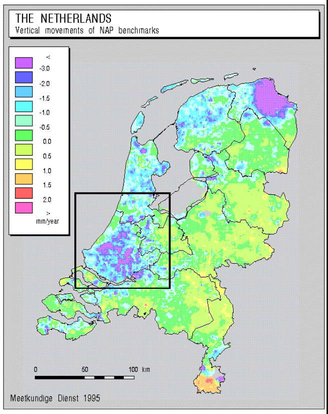
- Climate change
- Sea level rise
- Change in net recharge







Land subsidence
related to M.S.L.



The polder system

Many agricultural plots with different water levels throughout the season

Land subsidence

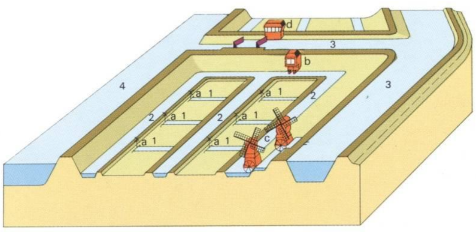
up to 1 m per century

The polder system

The polder system

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

a sophisticated drainage system



The polder system

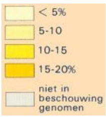
Bulb farms at the landside of the sand dunes

'Wetting' damage

Normal situation

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

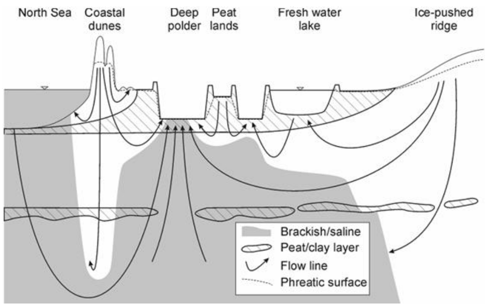
Salt damage in 1976 (very dry year)



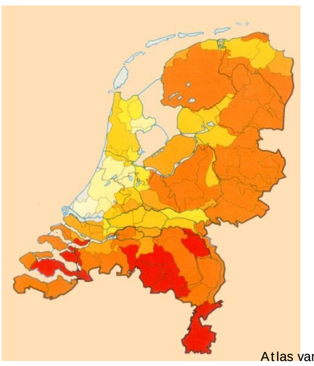
Salt damage [percentage] in potential crop-production

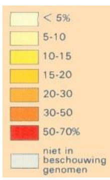
Atlas van Nederland, deel 15 Water, 1986

Now focus on groundwater…



Drought damage in 1976 (very dry year)





Drought damage [percentage] in potential crop-production

Atlas van Nederland, deel 15 Water, 1986

Threats to water management due to climate change:

Short term threats:

- -flooding
- -dike collapse
- -drought

asks for operational water management

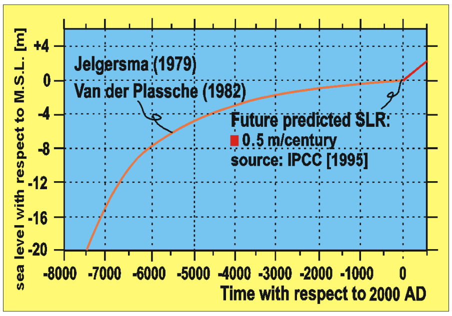
Long term threats:

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

asks for strategic water management

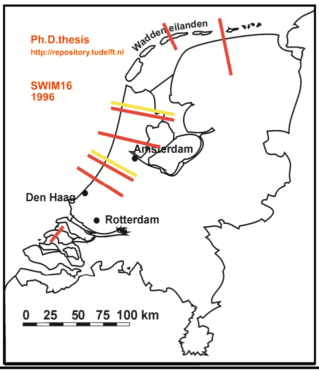
Dutch setting

Past and future sea level rise in the Netherlands



Modelling effect sea level rise on salt water intrusion

2D models

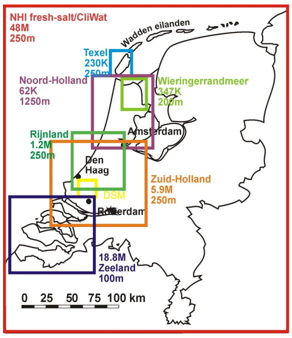


Numerical variable density models at Deltares

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

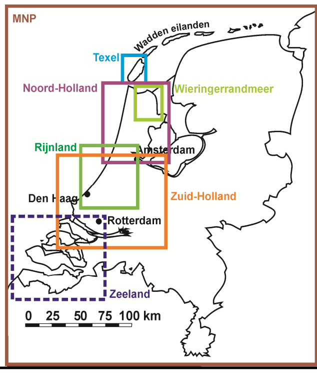
Code (MODFLOW family):
MOCDENS3D
SEAWAT

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

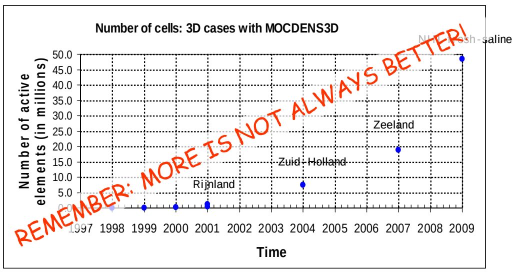


Modelling effect sea level rise on salt water intrusion

3D models

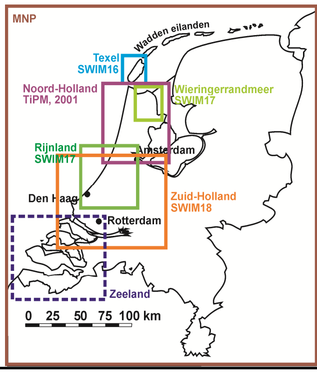


'DO NOT DO THIS AT HOME!' (DATA PROBLEM)

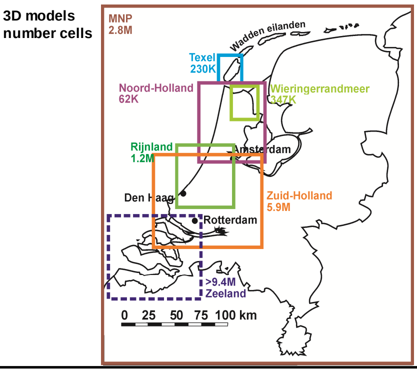


Modelling effect sea level rise on salt water intrusion

3D models
SWIM

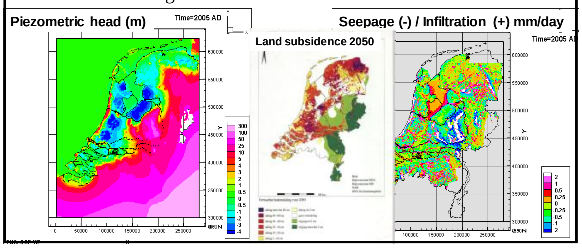


Modelling effect sea level rise on salt water intrusion



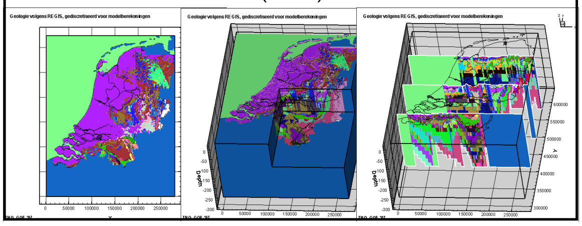
Recent model study for the whole Netherlands on the effect of sea level rise of water management (3)

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

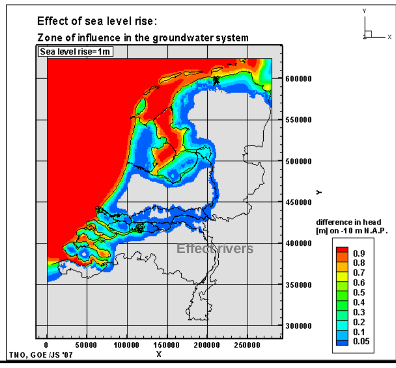


Recent model study for the whole Netherlands on the effect of sea level rise of water management (1)

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

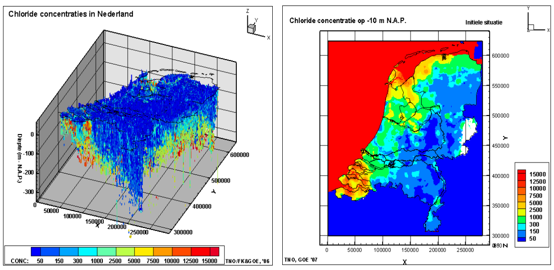


Results: zone of influence 1m sea level rise

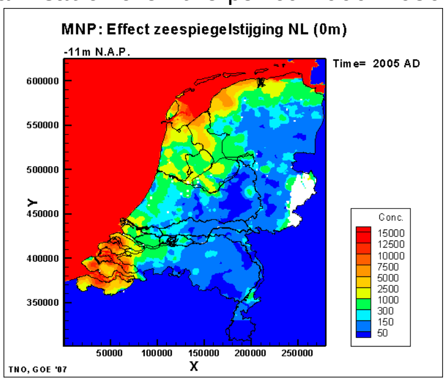


Recent model study for the whole Netherlands on the effect of sea level rise of water management (2)

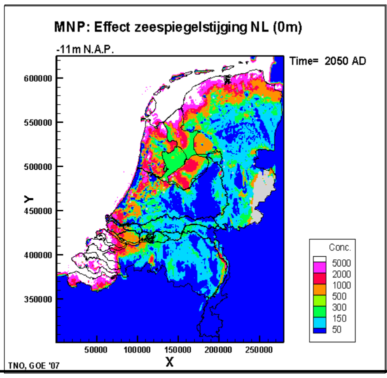
Using the national 3D salt concentration in groundwater
Zoet-Zout REGIS: ~65000 measuring points (analyses, VES, Borehole)



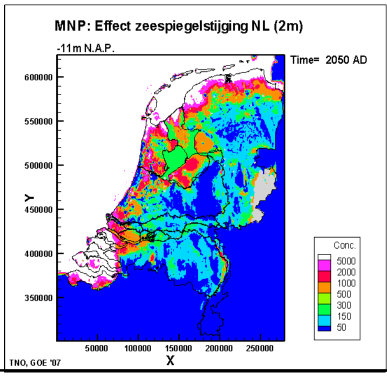
Salinisation over the period 2000-2050



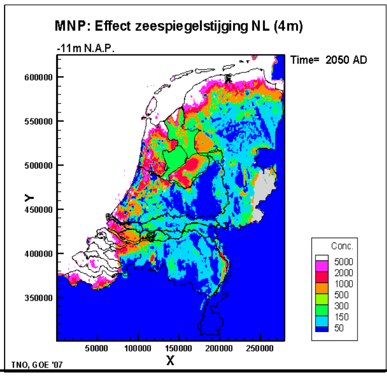
Salinisation subsoil at 0m sea level rise in 2050



Salinisation subsoil at 2m sea level rise in 2050

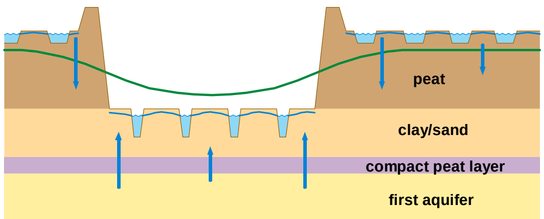


Salinisation subsoil at 4m sea level rise in 2050

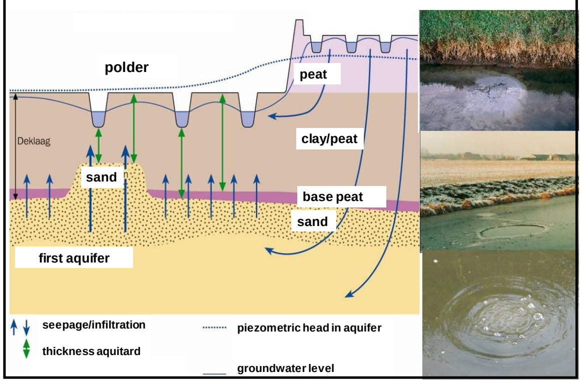


Salty wells

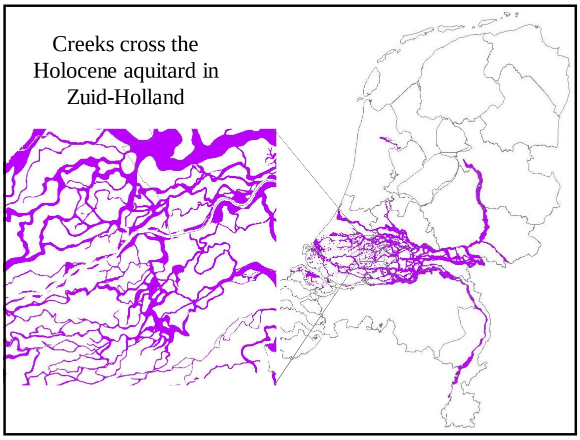
Seepage and infiltration situation around deep polders



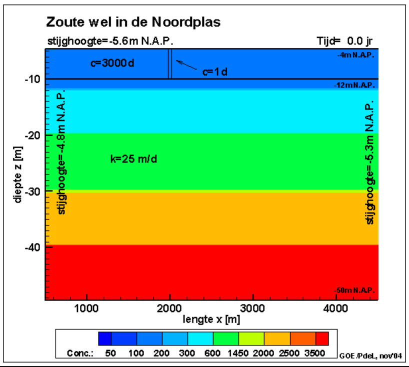
Risk of instable Holocene aquitards (1)

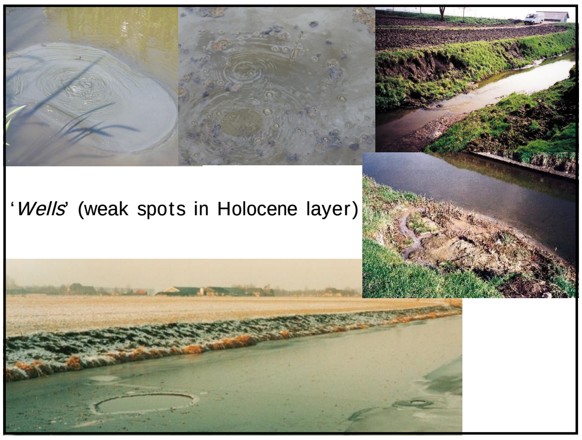


Creeks cross the Holocene aquitard in Zuid-Holland



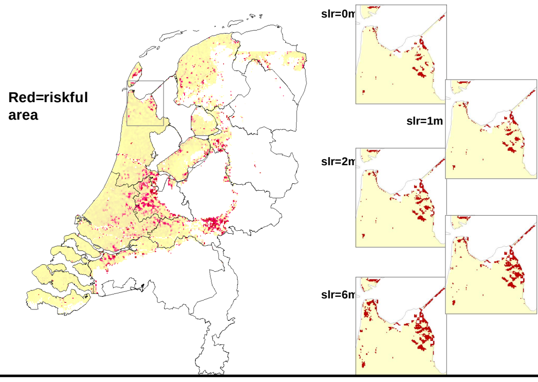
Simulation of salt groundwater towards *wells*



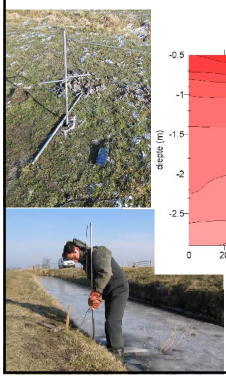


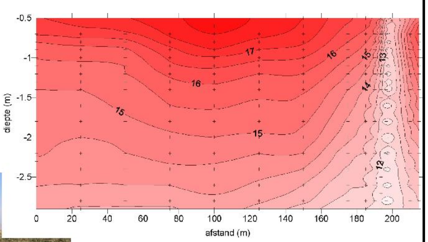
'*Wells*' (weak spots in Holocene layer)

Risk of instable Holocene aquitards (2)

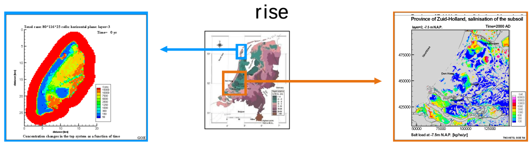


Temperature measurements





Quantification hydrogeological impacts of sea level rise



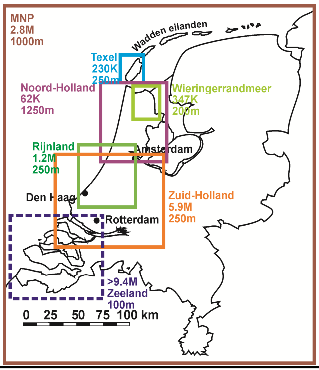
Situation at 2100 AD with sea level rise of 0.5m/century,

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

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

Modelling effect sea level rise on salt water intrusion

3D models
number cells
grid size



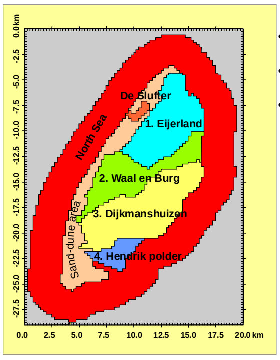
Model of the island of Texel

Characteristics 3D Cases (I): geometry & subsoil

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

* calibration with seepage & salt load in polders
**molecular diffusion=10^{-9} m^2/s; trans. disp.=1/10 long. disp.

Characteristics of the island of Texel (I)



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

Sand-dune area at western side

'De Slufter' is a tidal salt-marsh

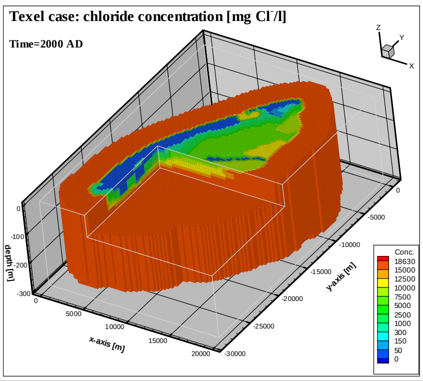
North Sea surrounds the island

Characteristics 3D Cases (II): model parameters

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

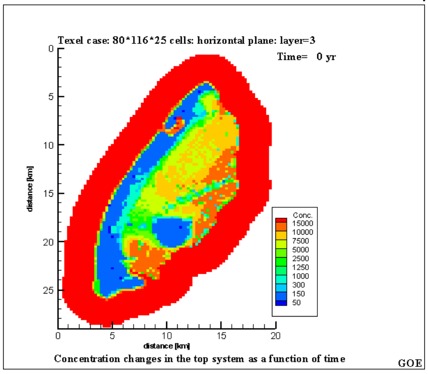
convergence head criterion= 10^{-5}/10^{-4} m
flow time step Δt=1 year

Texel: present 3D chloride distribution



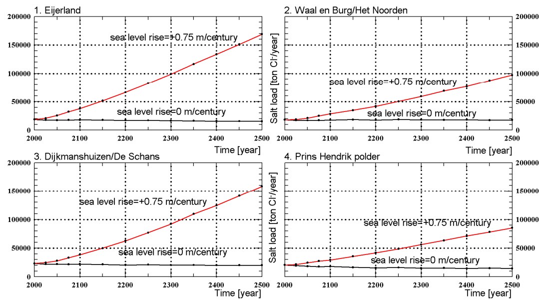
Texel

Texel: reference case=autonomous development



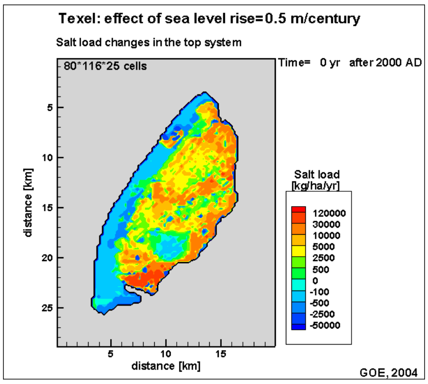
Texel

Texel: change in salt load of the four polders



Texel

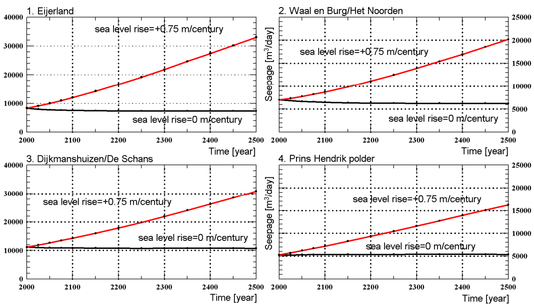
Texel: effect of sea level rise on salt load



Model of the Province of Zuid-Holland

Texel

Texel: change in seepage of the four polders



Case study: Province of Zuid-Holland

European water framework directive

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

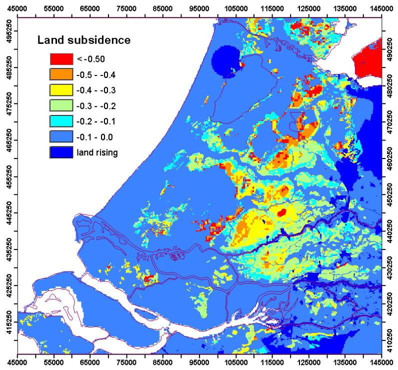
Identification of all fresh groundwater bodies in the province

How fast is the salinisation process?

More seepage, more salt load?

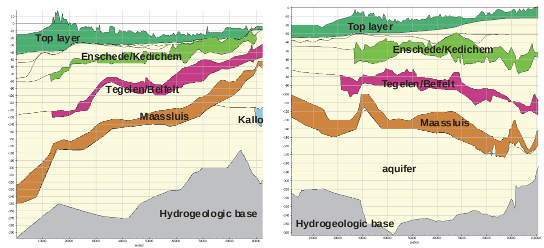
Land subsidence

2050

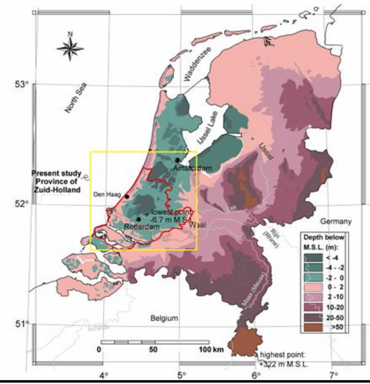


Source: RIZA

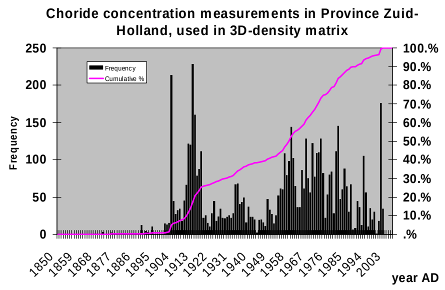
Position and name of aquitards



Location of the Province of Zuid-Holland



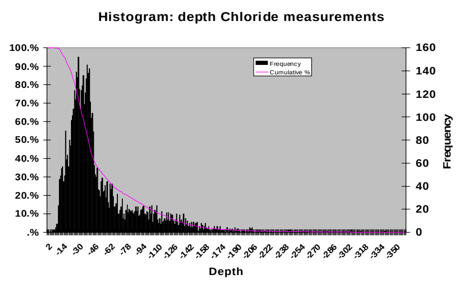
3D interpolation of chloride-concentration



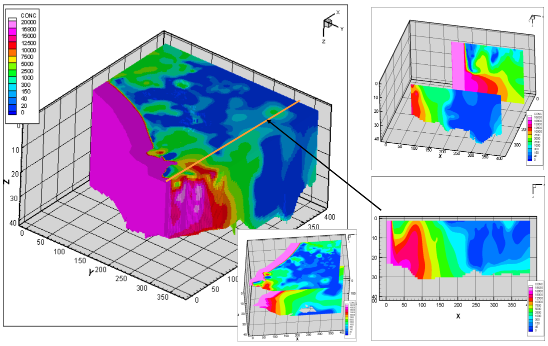
Numerical model description

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

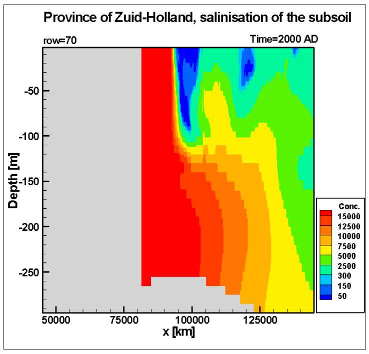
3D interpolation of chloride-concentration



Initial chloride distribution



Results: Chloride conc. in 200 yrs

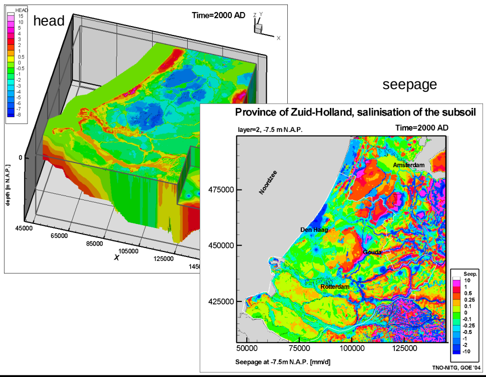


Present freshwater volume

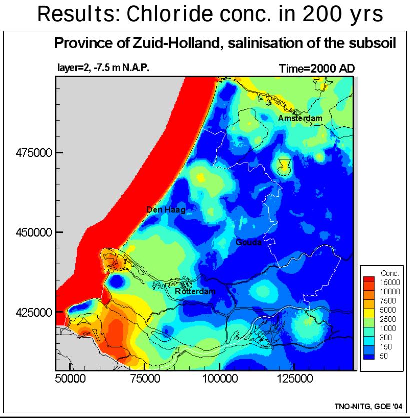
27 billion m^3

36% fresh, 14% brackish, 50% saline

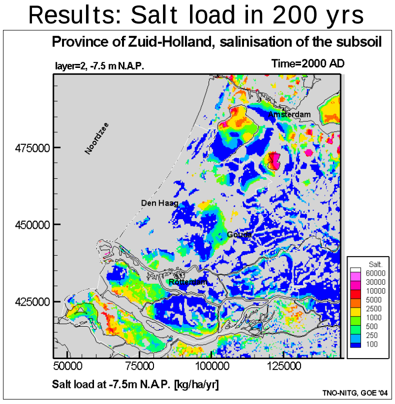
Results: freshwater head and seepage at 2000 AD



Results: Chloride conc. in 200 yrs



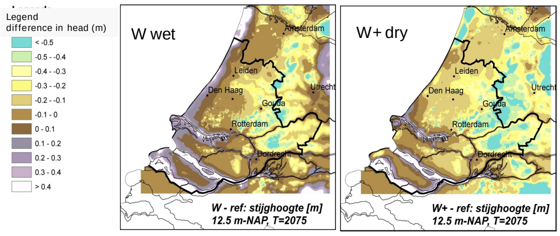
Results: Salt load in 200 yrs



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

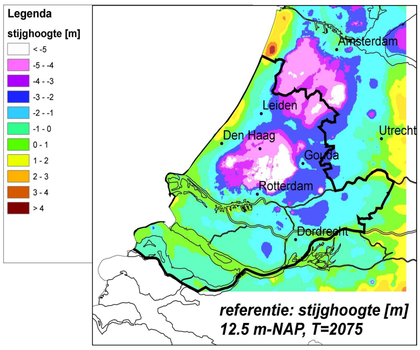
Some regional modelling results

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

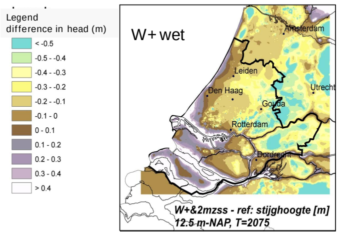


Sea level rise is 85 cm

Freshwater head at -12.5 M.S.L.

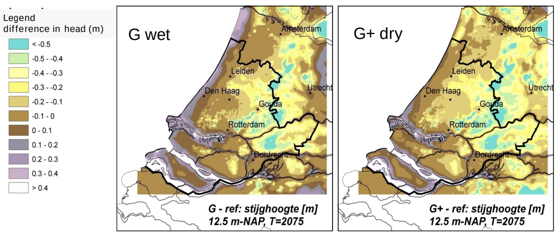


Difference in freshwater headon op -12.5 N.A.P.: W scenarios



Sea level rise is 200 cm

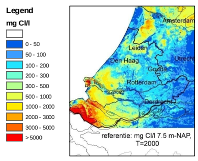
Difference in freshwater head on op -12.5 N.A.P.: G scenarios



Sea level rise is 60 cm

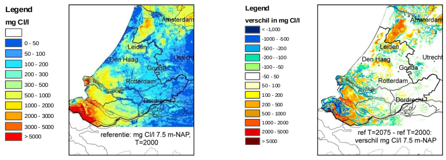
Including change in natural groundwater recharge

Salinisation/freshening Netherlands?: Present situation



modelstudy

Salinisation/freshening Netherlands?: Autonomous processes



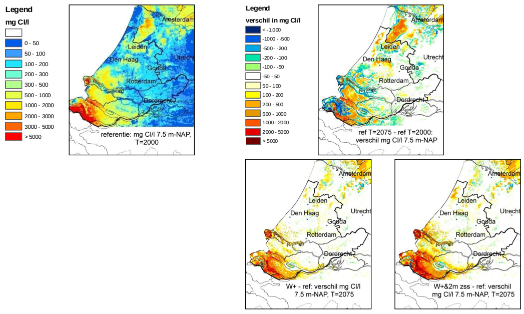
modelstudy

Rainwater lenses in an agricultural setting

Shallow dynamic freshwater bodies flowing upon brackish-saline groundwater

- density dependent
- dynamics: seasonal & long-year

Salinisation/freshening Netherlands?: climate change

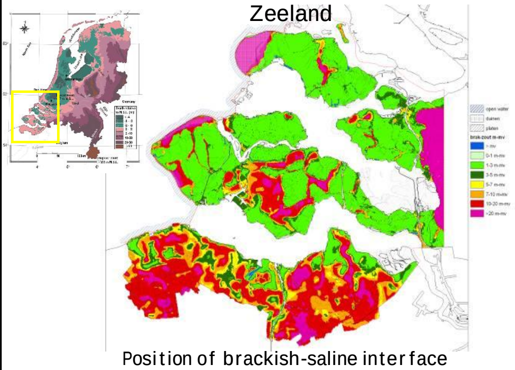


85 cm sea level rise

200 cm sea level rise

modelstudy

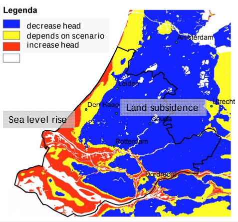
Salinisation of the phreatic groundwater in Zeeland



Position of brackish-saline interface

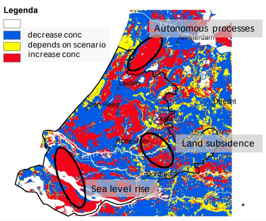
Effect climate scenarios in 2075 on

freshwater head



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

salinisation

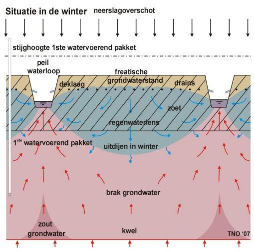


Increase or decrease concentration for all climate scenarios G, G+, W, W+

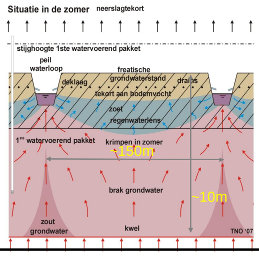
Modelstudie PZH

Salinisation of the phreatic groundwater in Zeeland

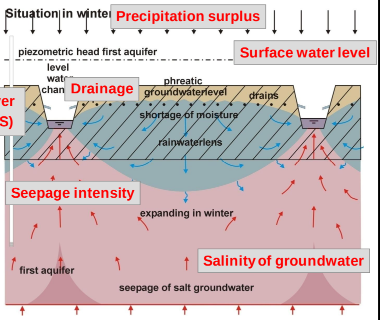
Dynamic rainwater lenses floating on saline groundwater



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



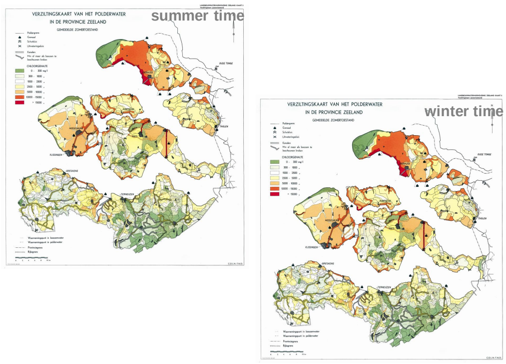
Factors controlling fresh-salt interface



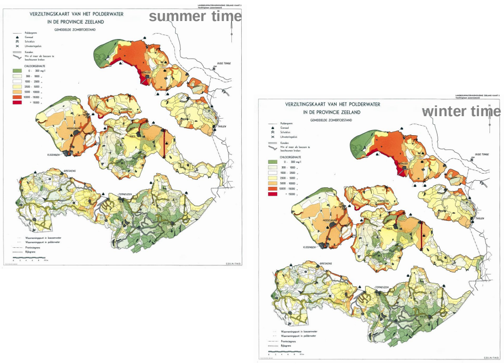
Important factors:

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

Salinisation surface water



Salinisation surface water



Problem definition dynamic freshwater lenses

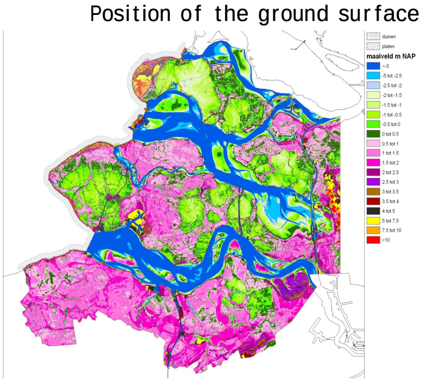
Salt in the agricultural plots originates from:

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

The salinisation will increase due to:

- sea level rise
- climate change
- water level management

Position of the ground surface



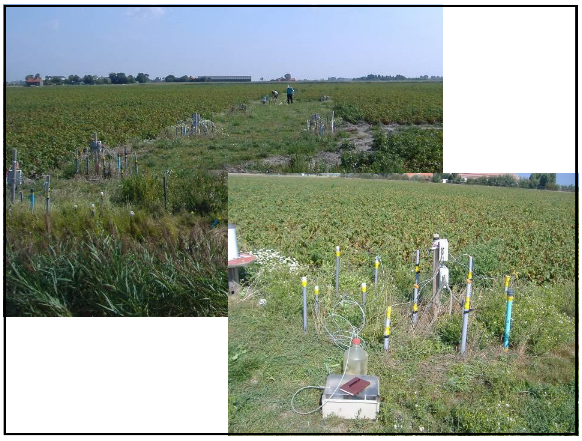
How to tackle the problem?

Field measurements at parcels

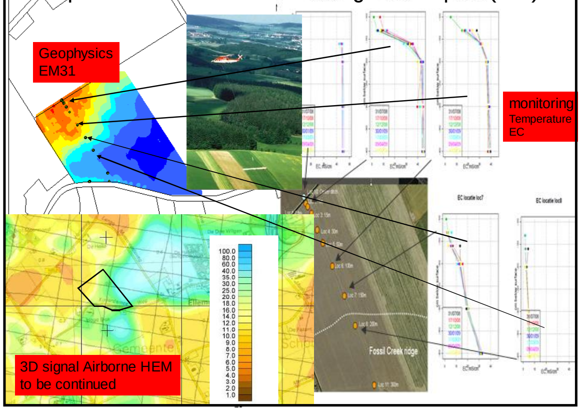
- fresh-brackish-salt interface at local scale using T-EC-probe and later CVES and ERT
- groundwater level and quality
- surface water level and quality

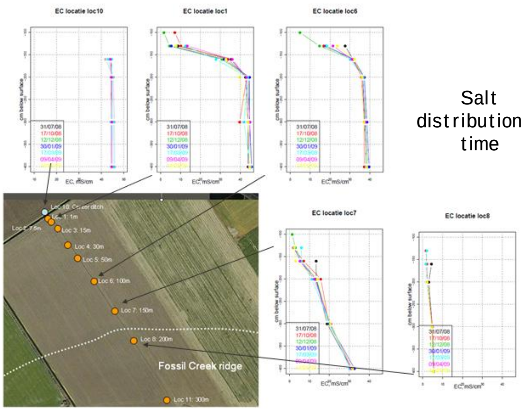
Modelling

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



Comparison different monitoring techniques (1/5)





Salt distribution in time

Local 3D model of the agricultural plot

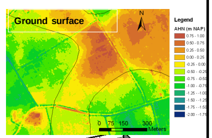
Modelling:

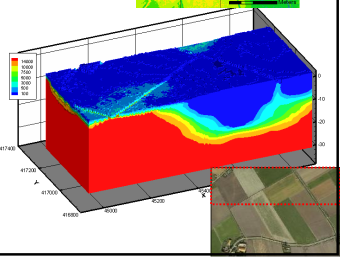
- variable-density
- 3D, non-steady
- groundwater flow & coupled solute transport
- model cell size: 5*5m²

Code:
MOCDENS3D

Assessing effects:

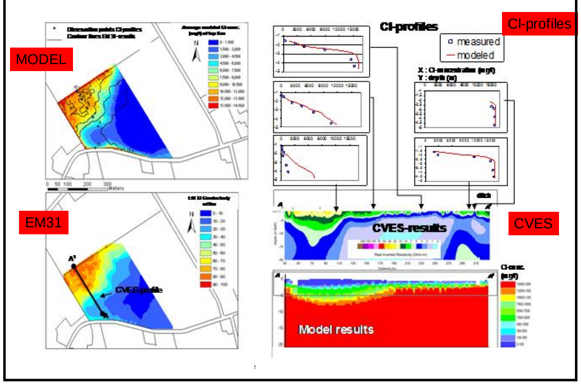
- autonomous salinisation
- sea level rise
- changing recharge pattern
- (adaption measures)



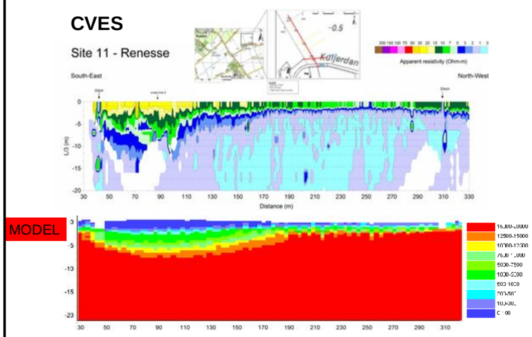


- TEC
- sampling
- EM31
- CVES
- HEM
- ECPT
- Numerical models (2D and 3D)

Comparison model with EM31, CVES, profiles



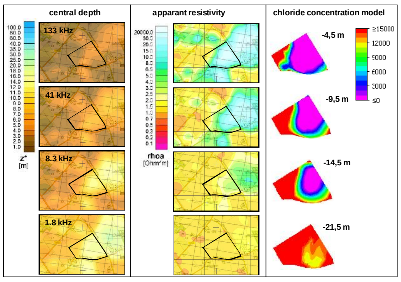
Comparison 3D model and CVES



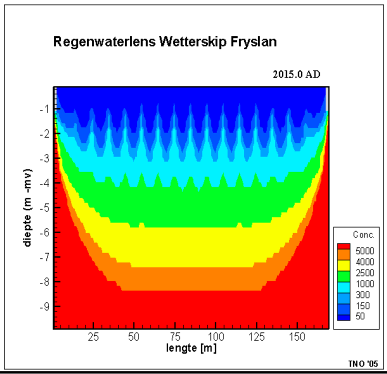
To be continued…

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

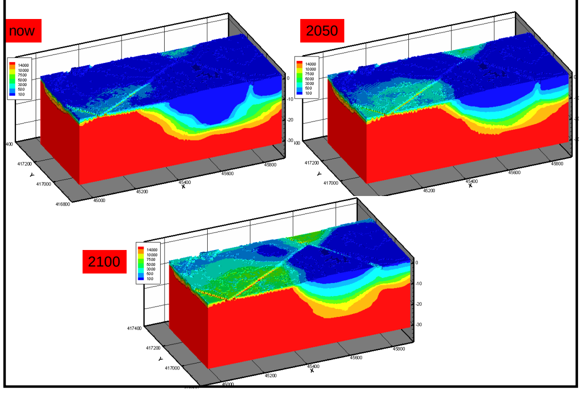
HEM data



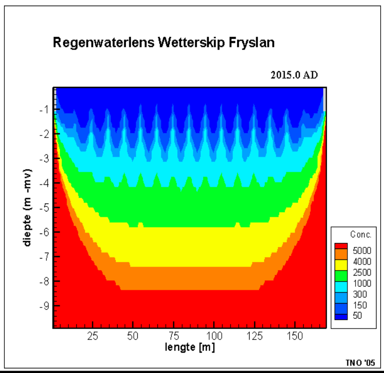
Model the dynamics of fresh-brackish-salt interface



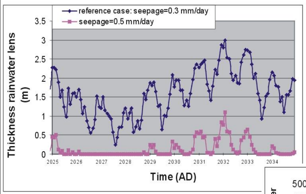
Climate change scenario (dry): model result



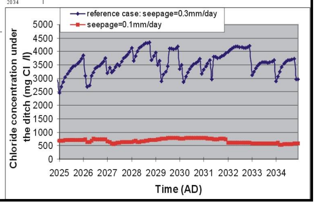
Model the dynamics of fresh-brackish-salt interface



Thickness of the lens and salt load to surface water varies



depends on seepage



International

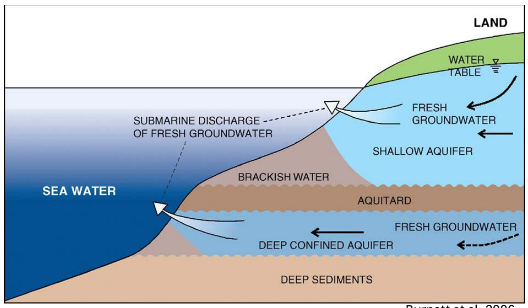
- Philippines (submarie groundwater discharge)
- Gujarat, India (evaluation anti-swi measures)
- Maldives (effect dec 2004 Tsunami)

Conclusions (salinisation Dutch aquifers):

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

What is Submarine Groundwater Discharge (SGD)?

any flow of water out across the sea floor



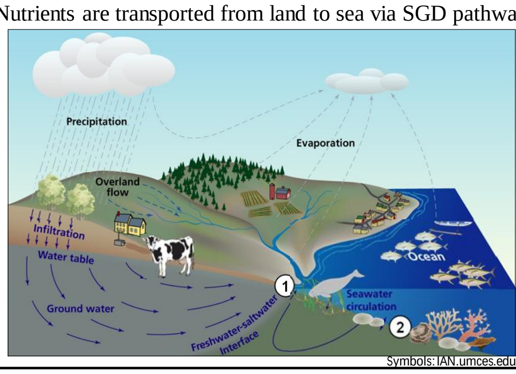
Burnett et al, 2006

Recommendations (salinisation Dutch aquifers):

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

Why study SGD?

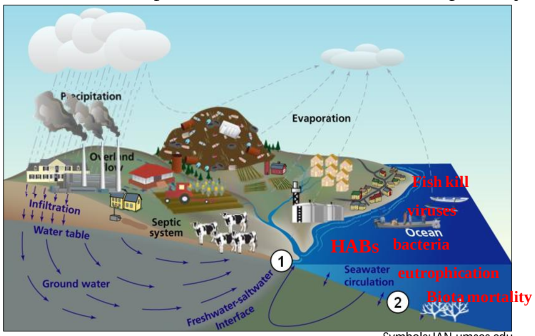
Nutrients are transported from land to sea via SGD pathway



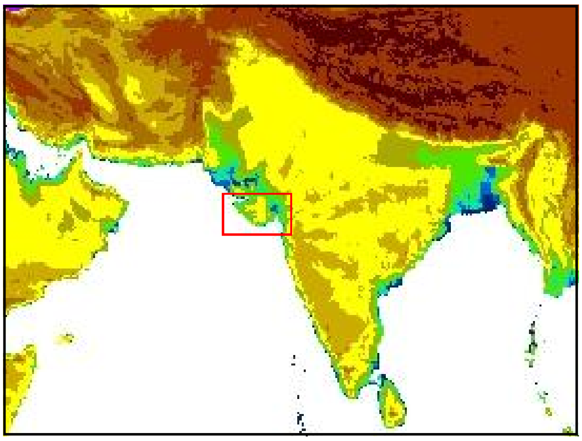
Symbols: IAN.umces.edu

Why study SGD?

Nutrients are transported from land to sea via SGD pathway

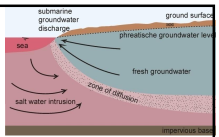


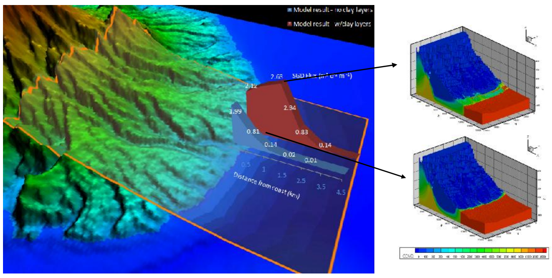
Symbols: IAN.umces.edu



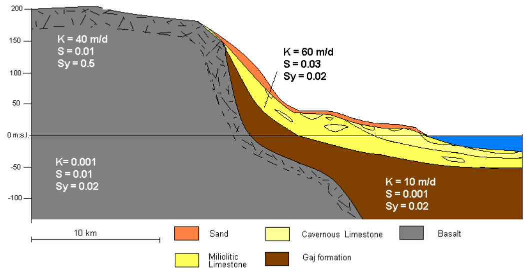
Philippines

Submarine Groundwater Discharge





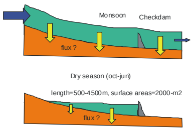
Hydrogeology, 2D profile



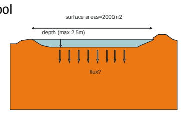
Gujarat, India

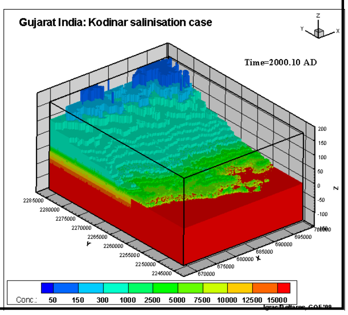
Learning from the Salinity Ingress Prevention Measures in the Coastal Area of Gujarat

Checkdam

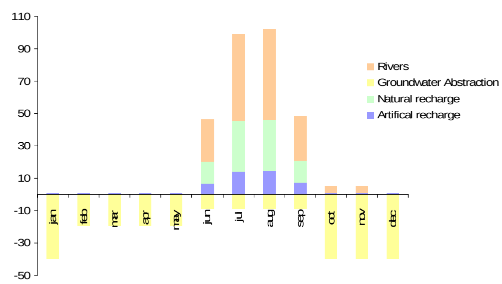


Pool

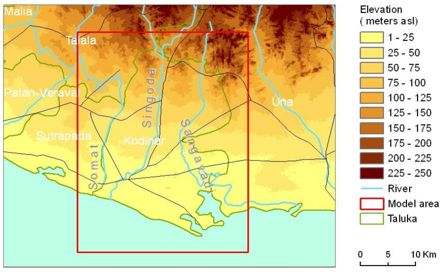




Waterbalance

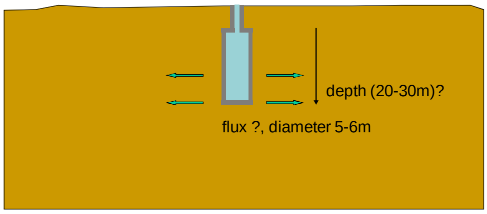


Topography, elevation

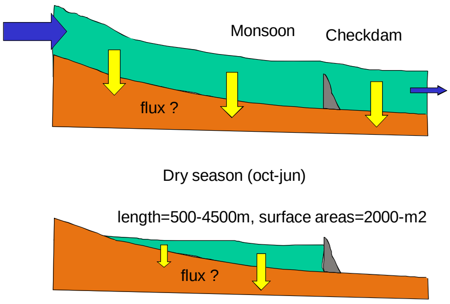


Concept Percolation tank

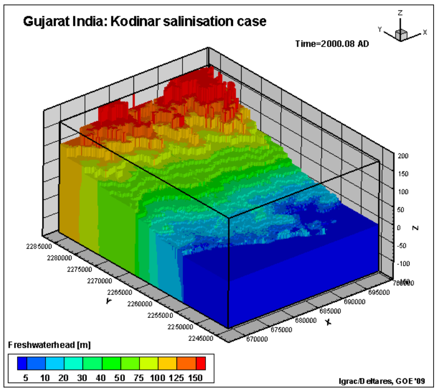
number of wells per village: ?



Concept Checkdam

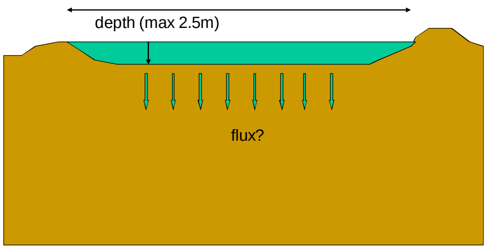


Freshwater head

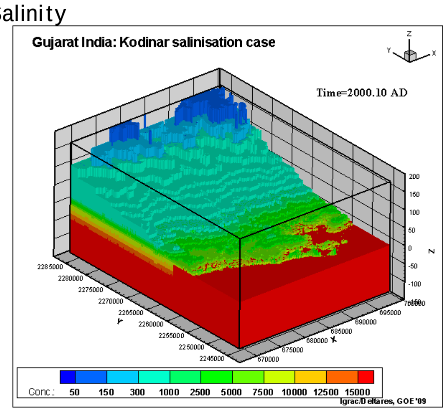


Concept Pond

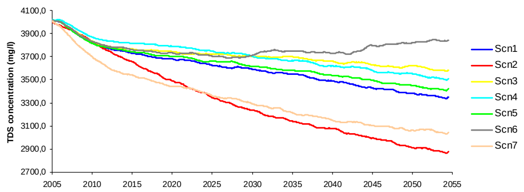
surface areas=2000m2



Salinity



Average TDS concentration



Scn1. Reference case
Scn2. Reference case without artificial recharge
Scn3. Business as usual – increase in population, increase in abstraction
Scn4. Business to the max (agricultural production and increase abstraction in summer)
Scn5. Reference case plus industrial zone development (increase of industr. abstraction)
Scn6. Drought scenario – climate change, sea level rise
Scn7. Reference case plus water saving measures

Model of the Kop van Noord-Holland,

The Netherlands

Oude Essink, G. H. P. 2001. Saltwater intrusion in 3D large-scale aquifers: a Dutch case. Phys. & Chem. of the Earth 26(4): 337-344.

Conclusions (modelling of variable-density flow)

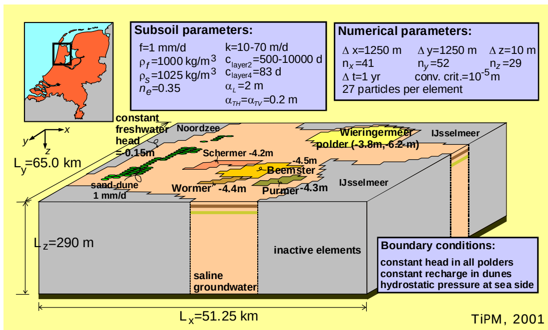
- Don't use the Henry problem to test your variable-density code
- Use enough cells to model the Hydrocoin and Elder problem

For modelling 3D systems:

- Remember the Peclet discretisation limitation for cell sizes (unless you're using the method of characteristics!)
- Longitudinal dispersivity should not be too large (e.g. <10m)
- It's important to derive a very accurate density distribution (as that significantly effects the velocity field!)
- Watch out for numerical problems at the outflow face to the sea

Noord-Holland

Characteristics of the Kop van Noord-Holland (I)



Challenges for the future

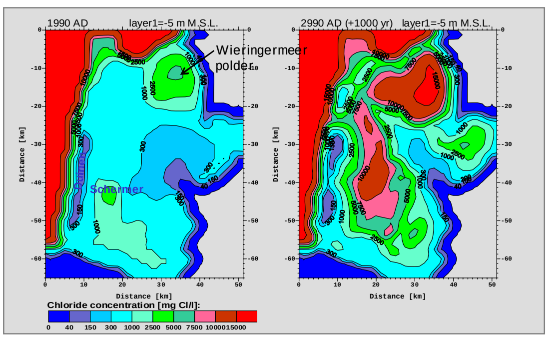
- Improve the 3D density matrix, e.g. by more types of measurements
- Implement effect of climate change and sea level rise on coastal aquifers
- Optimalisation of (ground)water management in coastal aquifers by using 3D variable-density flow models
- Improve calibration of 3D models by using transient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

Noord-Holland

Kop van Noord-Holland (II)

Reference case=autonomous development

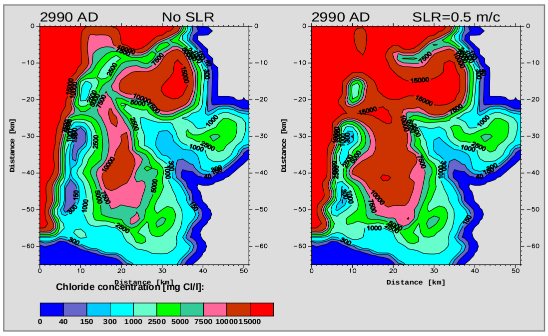
Change in concentration in the top system during 1000 years



Kop van Noord-Holland (III)

Sea level rise case=0.50 m/century

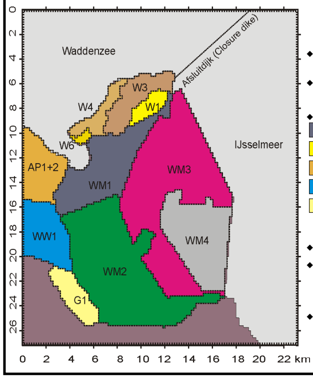
Change in concentration in the top system during 1000 years



Model of the Wieringermeer polder

Model of the Wetterskip of Fryslan

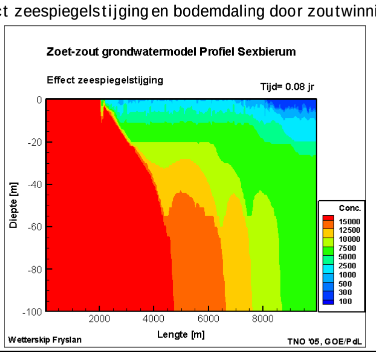
Characteristics of the Wieringermeer polder



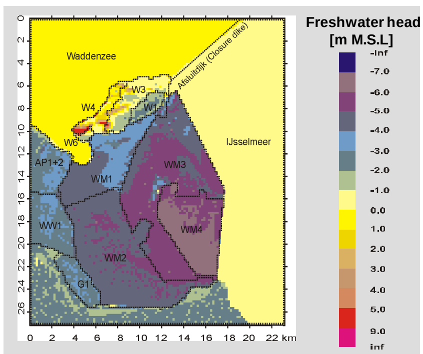
- Land surface polder: ~200 km^2
- Reclaimed from the sea in the 1930's
- Geometrical units:
  - WM1-WM4 Wieringermeer polder
  - W1-W6 Wieringen
  - AP1+2 Anna Palowna polder
  - WW1 Wieringerwaard
  - G1 Groet polder
- Waddenzee: tidal salt marsh/innersea
- IJsselmeer freshwater lake (before 1932 innersea)
- 11 polder units in studied area

Wetterskip Fryslan

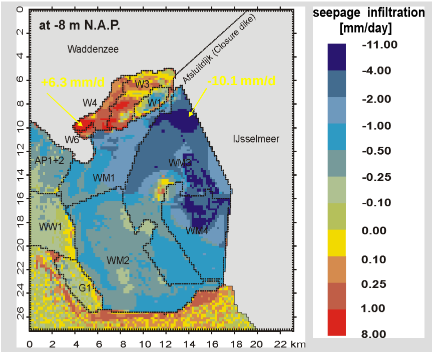
- Zoutverdeling – Huidige en toekomstige situatie (+30jaar)
- Effect zeespiegelstijging en bodemdaling door zoutwinning



Present phreatic water level



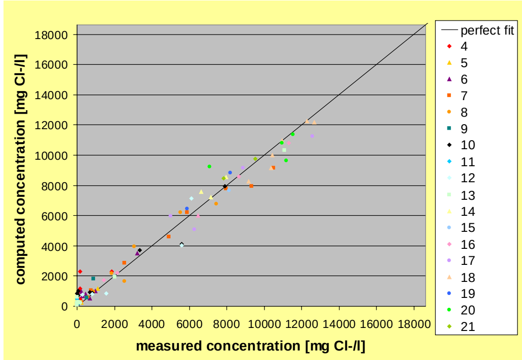
Calculated present seepage and infiltration



seepage
=
upward
flow

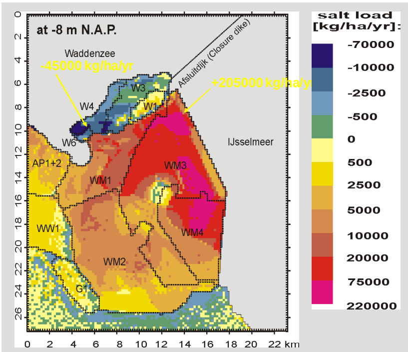
Wieringermeer

Calibration characteristics (II): concentration



Wieringermeer

Calculated present salt load



salt load
=
seepage
*
Cl-conc

Wieringermeer

Two future scenarios (during 50 years):

I Reference case
- present mean sea level
- autonomous development

II Sea level rise case
- relative sea level rise of 0.75 m/century

Interest is focused on:

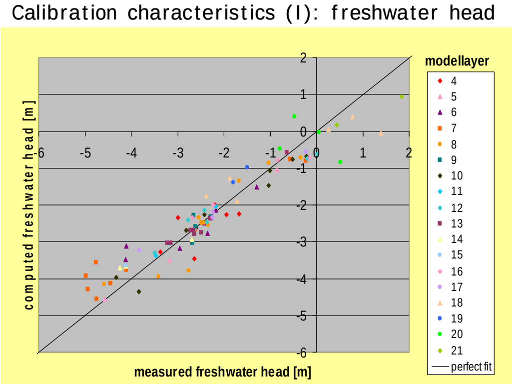
A. Change in concentration in top layer

B. Change in seepage in the polder

C. Change in salt load in the polder

Wieringermeer

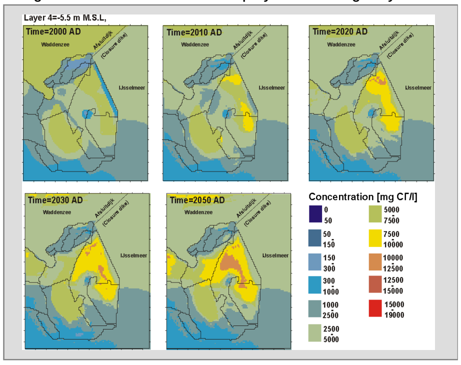
Calibration characteristics (I): freshwater head



Wieringermeer

Wieringermeer: reference case

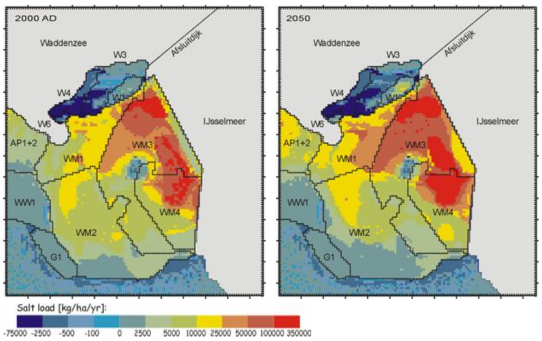
Change in concentration in the top system during 50 years



Wieringermeer

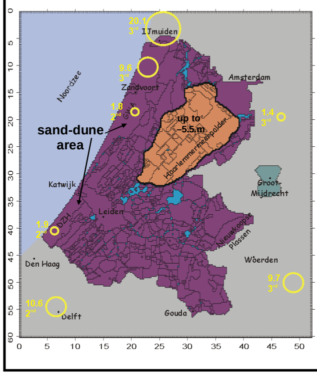
Wieringermeer: reference case

Change in salt load in the top system during 50 years



Rijnland

Characteristics of the Waterboard Rijnland



- Land surface: ~1100 km^2
- Geometrical units:
  1. Waterboard of Rijnland
  2. Haarlemmermeerpolder
  3. Open Water
  4. Sea
  5. Remaining land
  6. Polder Groot-Mijdrecht
- 550 polder units in Water Board

○ =position of extraction

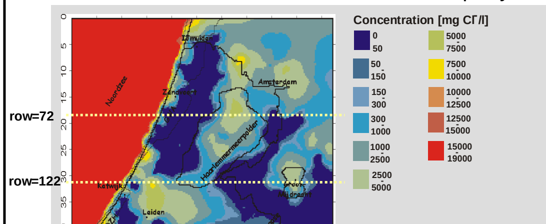
9.6 =rate of extraction [10^6 m^3/yr]

3^{rd} =aquifer from which water is extracted

Model of the Waterboard Rijnland

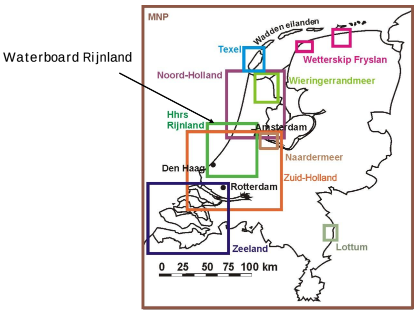
Rijnland

Present chloride concentration in the top layer



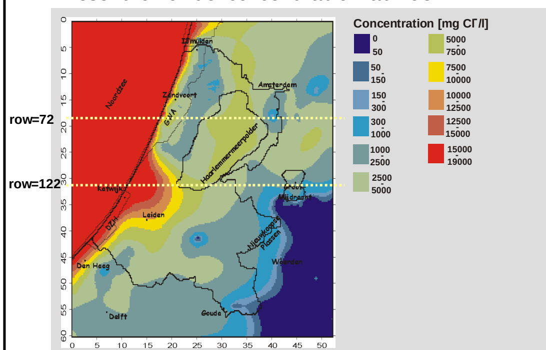
Based on 6921 density points in the system, deduced from the National Groundwater Model NAGROM

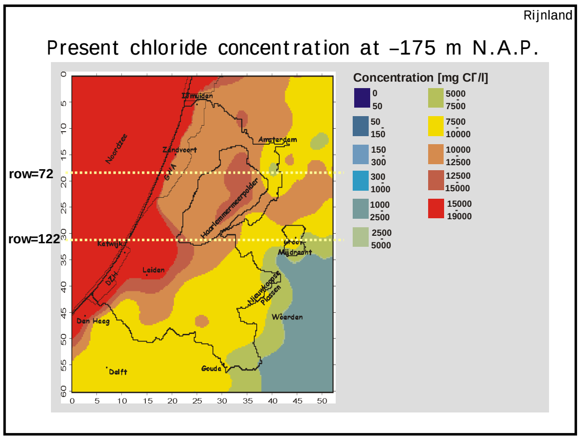
3D Case: effect measurements Waterboard Rijnland

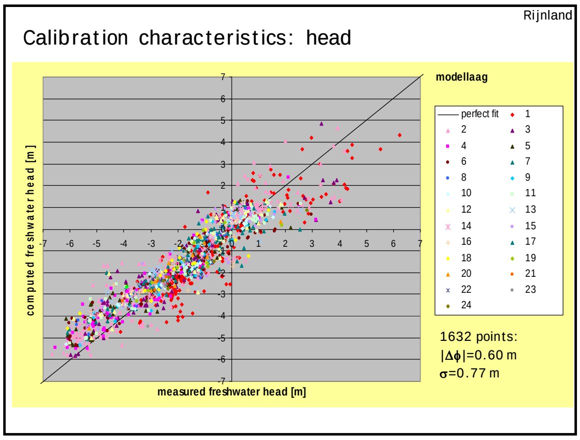


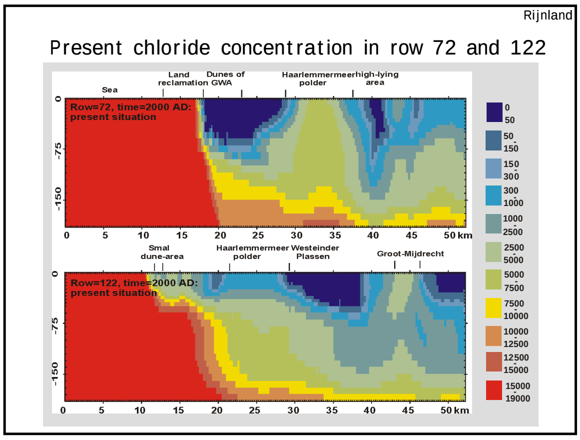
Rijnland

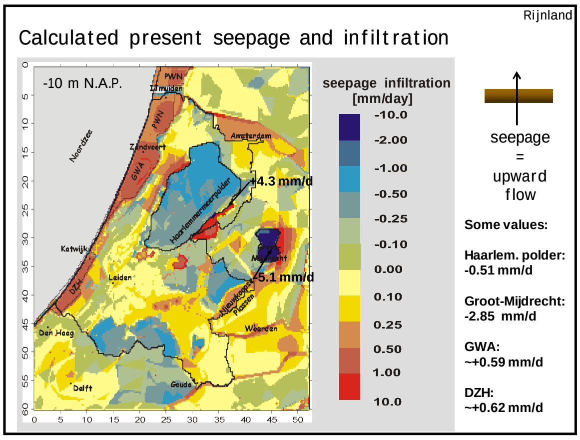
Present chloride concentration at –95 m N.A.P.

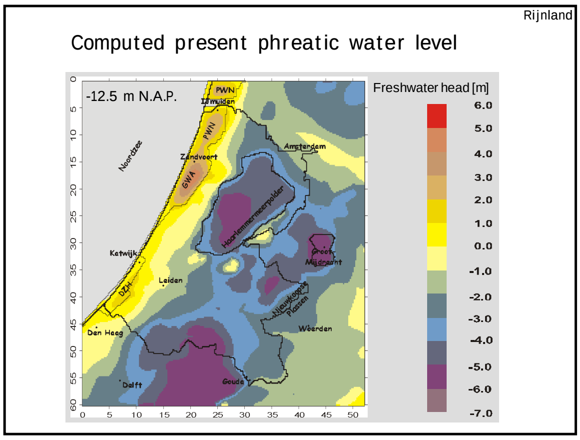


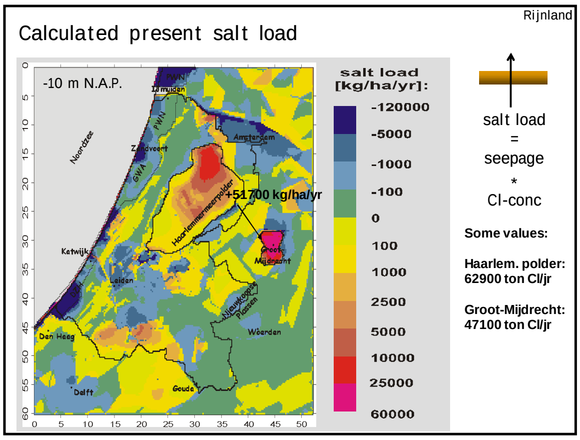

Rijnland
Present chloride concentration at –175 m N.A.P.
Concentration [mg Cl⁻/l]
0 50
50 150
150 300
300 1000
1000 2500
2500 5000
5000 7500
7500 10000
10000 12500
12500 15000
15000 19000
row=72
row=122
IJmuiden
Amsterdam
Zandvoort
Noordzee
GWA
Haarlemmermeerpolder
Katwijk
Mijdrecht
Leiden
DZH
Nieuwkoopse Plassen
Woerden
Den Haag
Delft
Gouda


Rijnland
Calibration characteristics: head
modellaag
perfect fit
computed freshwater head [m]
measured freshwater head [m]
1632 points:
|Δϕ|=0.60 m
σ=0.77 m


Rijnland
Present chloride concentration in row 72 and 122
Sea
Land reclamation
Dunes of GWA
Haarlemmermeer polder
high-lying area
Row=72, time=2000 AD: present situation
Smal dune-area
Haarlemmermeer polder
Westeinder Plassen
Groot-Mijdrecht
Row=122, time=2000 AD: present situation
50 km
0 50
50 150
150 300
300 1000
1000 2500
2500 5000
5000 7500
7500 10000
10000 12500
12500 15000
15000 19000


Rijnland
Calculated present seepage and infiltration
-10 m N.A.P.
seepage infiltration [mm/day]
-10.0
-2.00
-1.00
-0.50
-0.25
-0.10
0.00
0.10
0.25
0.50
1.00
10.0
+4.3 mm/d
+5.1 mm/d
seepage = upward flow
Some values:
Haarlem. polder: -0.51 mm/d
Groot-Mijdrecht: -2.85 mm/d
GWA: ~+0.59 mm/d
DZH: ~+0.62 mm/d


Rijnland
Computed present phreatic water level
-12.5 m N.A.P.
Freshwater head [m]
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0


Rijnland
Calculated present salt load
-10 m N.A.P.
salt load [kg/ha/yr]:
-120000
-5000
-1000
-100
0
100
1000
2500
5000
10000
25000
60000
+51700 kg/ha/yr
salt load = seepage * Cl-conc
Some values:
Haarlem. polder: 62900 ton Cl/jr
Groot-Mijdrecht: 47100 ton Cl/jr

Rijnland

Four future scenarios (during 500 years):

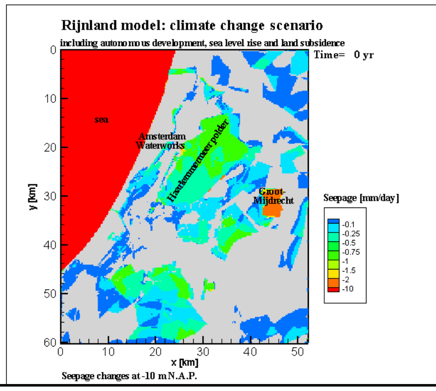
I. Reference case
-to determine autonomous salt water intrusion

II. Climate change case:
-sea level rise of 0.9 m/century
-increase of natural recharge in dunes with 6%
-decrease of groundwater extraction in some sand-dunes
-land subsidence in polder area: 0.3 and 1.0 m/century

III. Compensating measures

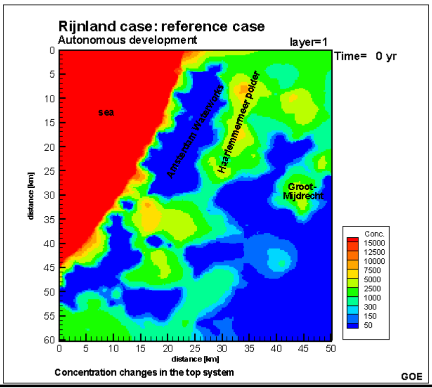
Rijnland

Rijnland model : II. climate change case (seepage, 500 yr)



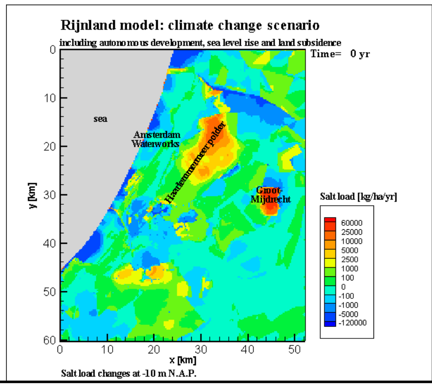
Rijnland

Rijnland model: I. reference case (conc., 500 yr)



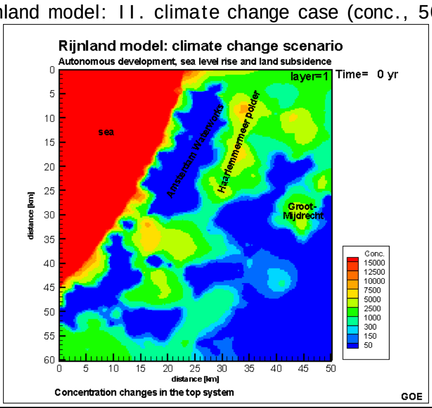
Rijnland

Rijnland model: II. climate change case (salt load, 500 yr)



Rijnland

Rijnland model: II. climate change case (conc., 500 yr)



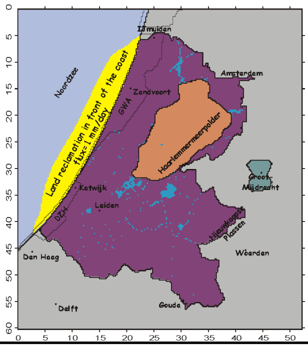
Solutions

Possible measures to compensate salt water intrusion

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

Rijnland

1. Rijnland model: land reclamation case

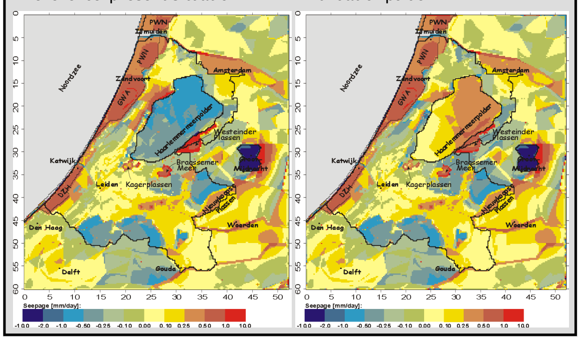


Rijnland

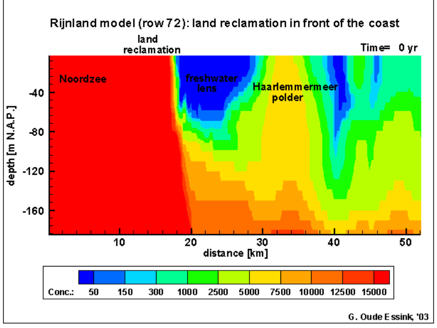
2. Rijnland model : Inundation Haarlemmermeerpolder

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

Reference: present situation | Inundation polder



1. Land reclamation in front of the coast

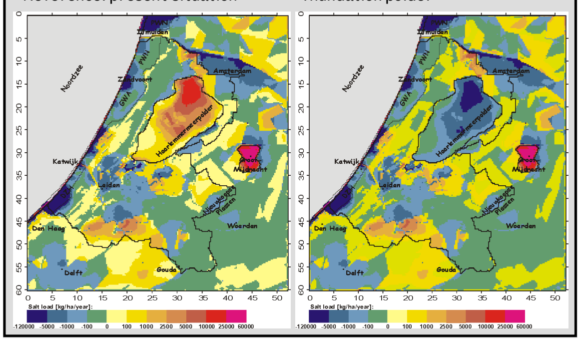


Rijnland

2. Rijnland model: Inundation Haarlemmermeerpolder

Calculated salt load on –10 m M.S.L.

Reference: present situation | Inundation polder

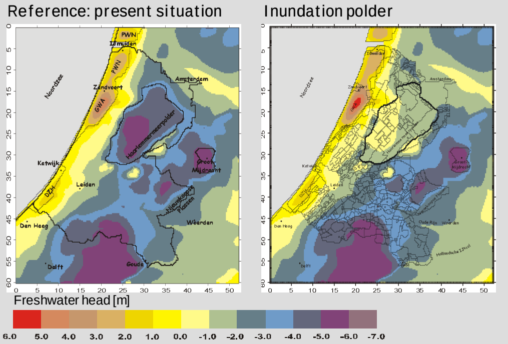


Rijnland

2. Rijnland model: Inundation Haarlemmermeerpolder

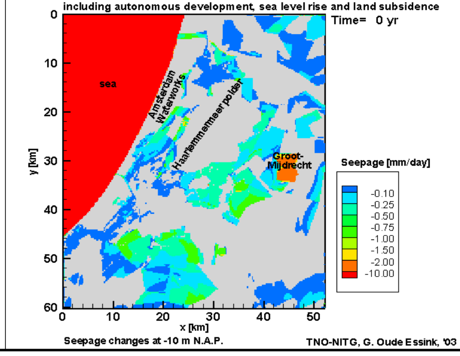
Calculated present phreatic water head

Reference: present situation | Inundation polder



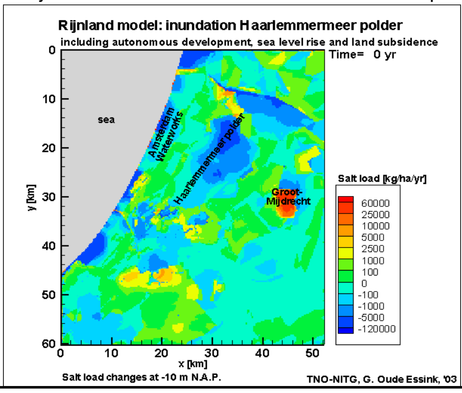
Rijnland

2. Rijnland model: Inundation Haarlemmermeerpolder

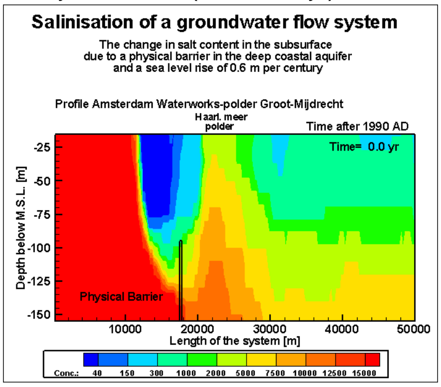


Rijnland

2. Rijnland model: Inundation Haarlemmermeerpolder

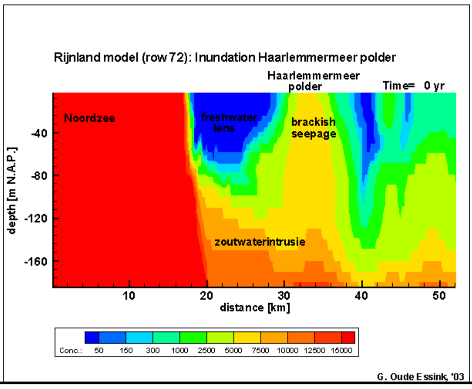


5. Physical barrier (conc, 1000 yr)

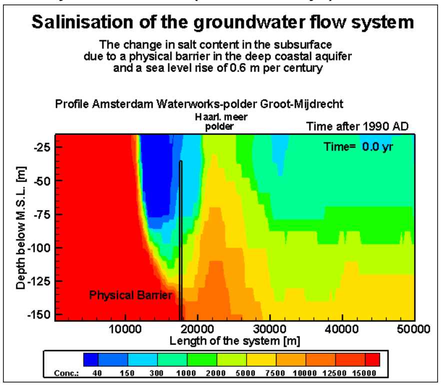


Rijnland

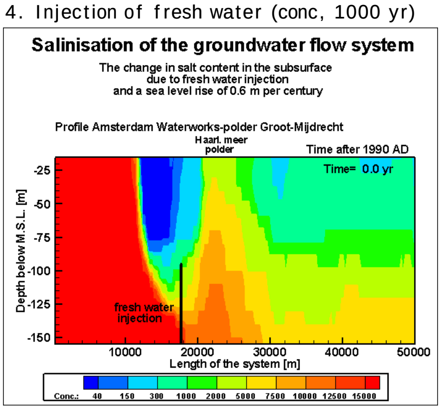
2. Rijnland model: Inundation Haarl.polder (conc, 500 jr)



5. Physical barrier (conc, 1000 yr)



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



MOCDENS3D

MOCDENS3D is similar to SEAWAT

modelling

MOCDENS3D
non-steady 3D variable-density groundwater flow

• Genesis present salt-fresh distribution

• Upconing of saline groundwater under extraction wells

• Effects of land subsidence and climate change on groundwater systems

MOCDENS3D

Characteristics MOCDENS3D:

- integration of MODFLOW and MOC3D
- finite difference method for groundwater flow
- method of characteristics (particle tracking) for solute transport
- transient flow of groundwater

Advantage MOCDENS3D:

- no numerical problems if grid Peclet numbers are high
- large-scale geometries with limited number of elements are no problem

MOCDENS3D

MOCDENS3D

MOCDENS3D = MOC3D (*Konikow et al.*, 1996)
but adapted for density differences

• density dependent groundwater flow
  - motion: Darcy
  - continuity: mass balance
• solute transport
  - advection
  - hydrodynamic dispersion: mixing of solutes
• fresh, brackish and saline groundwater
• relation between density & concentration

Solving the solute transport equetion

MOC particle tracking

MOC3D

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

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

The Peclet number stands for the ratio between advection and dispersion

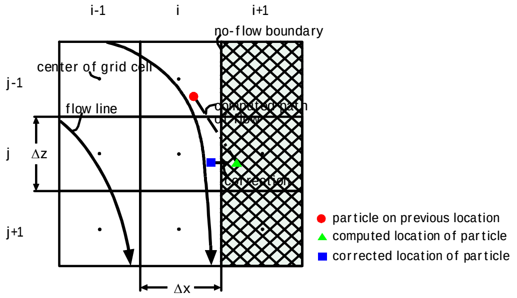
MOC3D

Procedure of MOC: advective transport by particle tracking

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

MOC3D

Reflection in boundary



MOC3D

Steps in MOC-procedure

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

Konikow and Bredehoeft, 1978

MOC3D

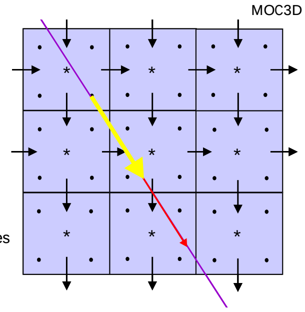
Stability criteria (III)

3. Courant criterium

* Node element
• Particle

Velocity direction

Movement particles



$0<\xi<=\sim 1$

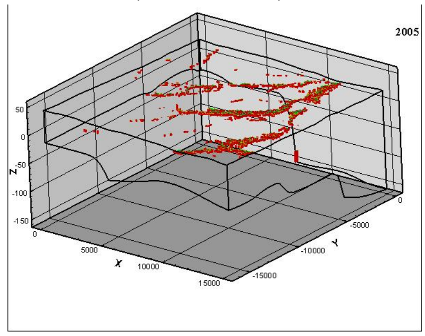
$$\Delta t_s \le \frac{\xi \Delta x}{V_{x,\max}} \qquad \Delta t_s \le \frac{\xi \Delta y}{V_{y,\max}} \qquad \Delta t_s \le \frac{\xi \Delta z}{V_{z,\max}}$$

MOC3D

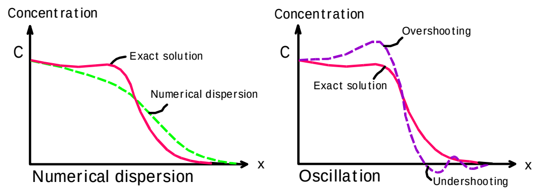
Causes of errors in MOC-procedure

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

Courant criterion: places where timestep is smaller than 40 days



Numerical dispersion and oscillation



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

Numerical dispersion problem (I)

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

Peclet number $Pe \leq 2$ to 4

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

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

Numerical dispersion problem (II)

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

$\Delta x \leq 2\alpha_L$ to $4\alpha_L$

where α_L = longitudinal dispersivity [L]

What does that mean?

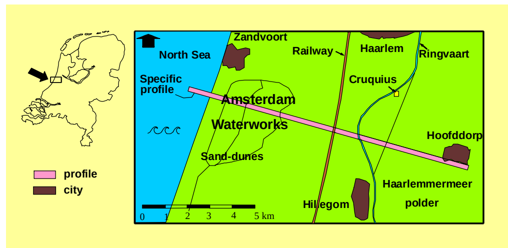
If α_L is small, then Δx should be small too!!

Numerical dispersion problem (III)

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

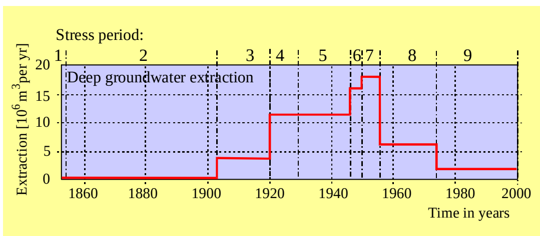
Effect of α_L on the salinisation of the aquifer (I)

Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



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

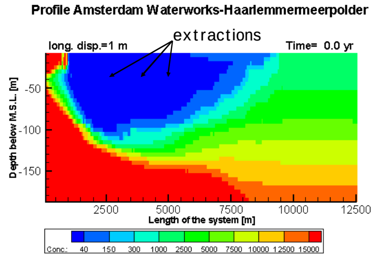
Grondwater extractions out of the middle aquifer in the sand-dune area of Amsterdam Waterworks



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

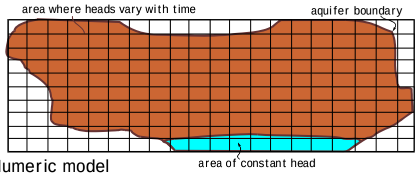
α_L=1 m

Initial situation: 154 years ago



Boundary conditions in MODFLOW (I)

Example of a system with three types of boundary conditions



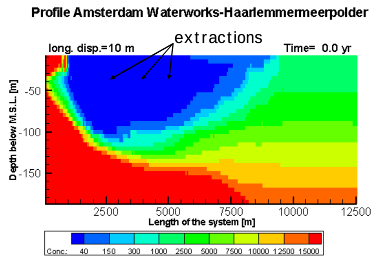
Numeric model

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

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

α_L=10 m

Initial situation: 154 years ago



Boundary conditions in MODFLOW (II)

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

MODFLOW

Packages in MODFLOW

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

1. Well package

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

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

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

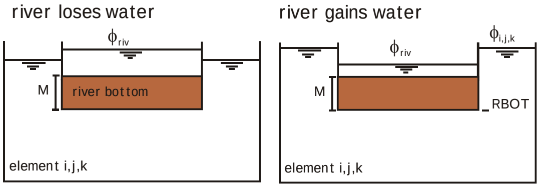
$$Q_{ext,i,j,k} = -10 \quad \text{(in = positive)}$$

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

2. River package (I)

river loses water

river gains water



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

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

2. River package (II)

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

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

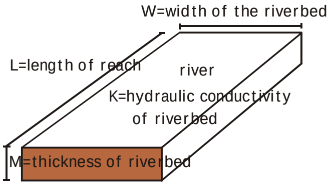
$$Q_{ext,i,j,k} = P_{i,j,k}\phi^{t+\Delta t}_{i,j,k} + Q'_{i,j,k}$$

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

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

2. River package (III)

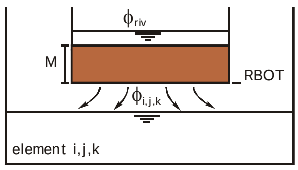
Determine the conductance of the river in one element:



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

2. River package (IV)

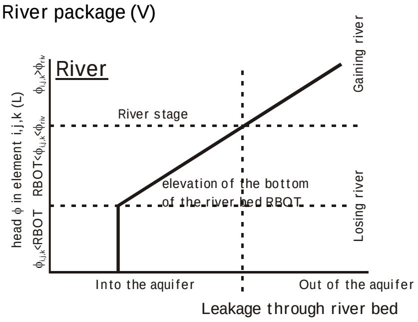
Leakage to the groundwater system



Special case:

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

2. River package (V)



MODFLOW

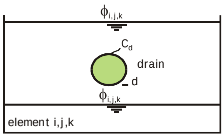
3. Recharge package

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

MODFLOW

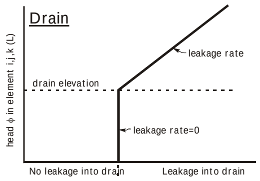
4. Drain package

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



Special case: →

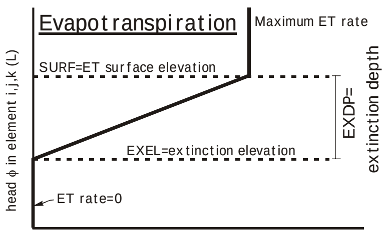
if $\phi_{i,j,k} < d$ than $Q_{drn} = 0$



Leakage into a drain

MODFLOW

5. Evapotranspiration package

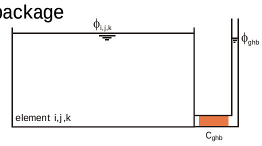


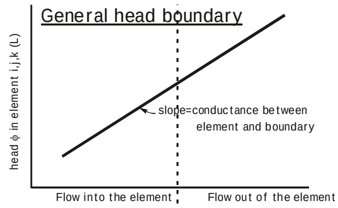
Evapotranspiration (ET)

MODFLOW

6. General head boundary package

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





Flow to a general head boundary

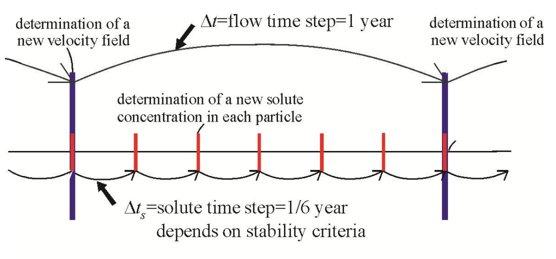
1 (name).bas-file
2 (name).bcf-file
3 (name).moc-file
4 (name).wel-file
5 (name).riv-file
6 (name).drn-file
7 (name).ghb-file
8 (name).sip-file
9 densin.dat-file
10 (name).nam-files

MODFLOW

Time indication MODFLOW

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

Flow time step and solute time step



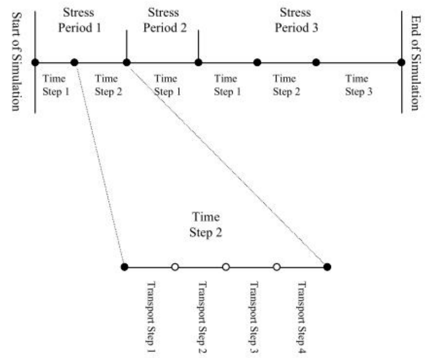
* velocity field remains constant during 1 year
* solute concentration changes during each solute time step

Salt Water Intrusion Meeting, since 1968

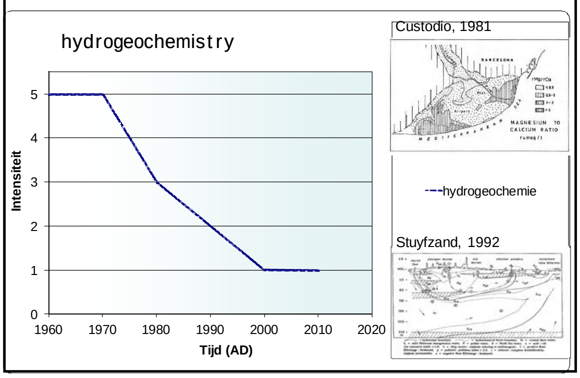
http://www.swim-site.org/

Subthemes:

- hydrogeochemistry
- monitoring (a.o. geophysical methods)
- fresh-saline interface modelling
- 2D modelling variable-density & solute transport
- submarine groundwater discharge
- sea level rise
- 3D modelling variable-density & solute transport
- solutions
- paleohydrogeology fresh-saline
- global analysis



Salt Water Intrusion Meeting, since 1968



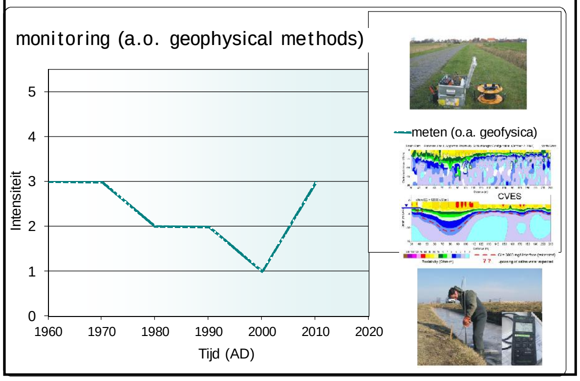
Salt Water Intrusion Meeting, since 1968

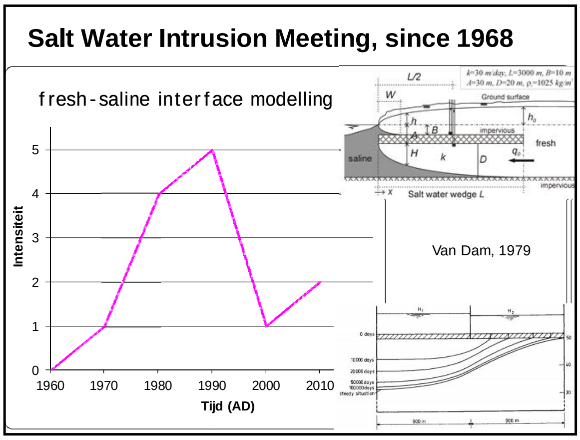
http://www.swim-site.org/

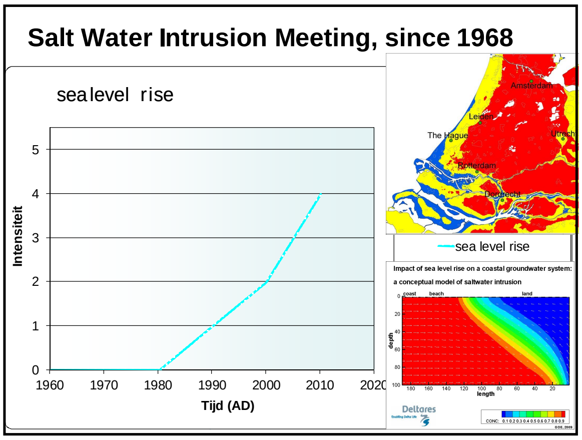
Themes

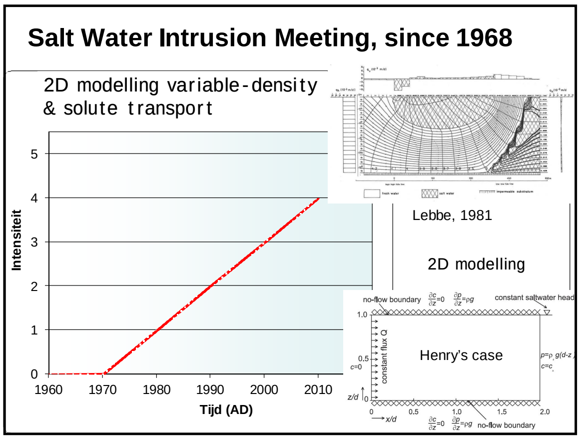
- **Water systeem analysis**
- **Monitoring**
- **Modelling**
- **Effects**
- **Solutions**

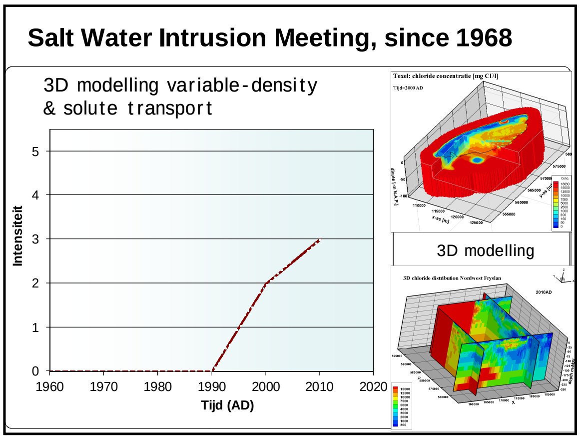
Salt Water Intrusion Meeting, since 1968

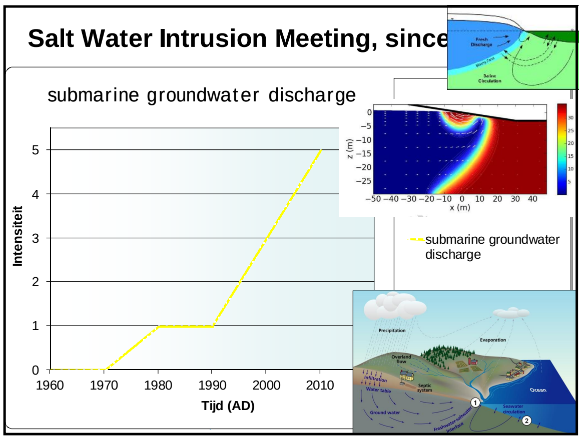


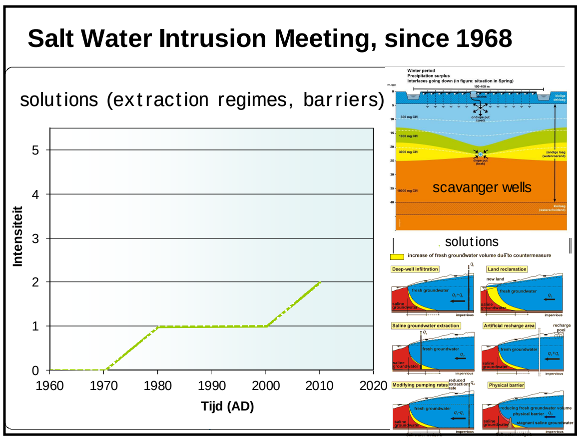

Salt Water Intrusion Meeting, since 1968
fresh-saline interface modelling
Intensiteit
Tijd (AD)
saline
fresh
Ground surface
impervious
Salt water wedge L
Van Dam, 1979

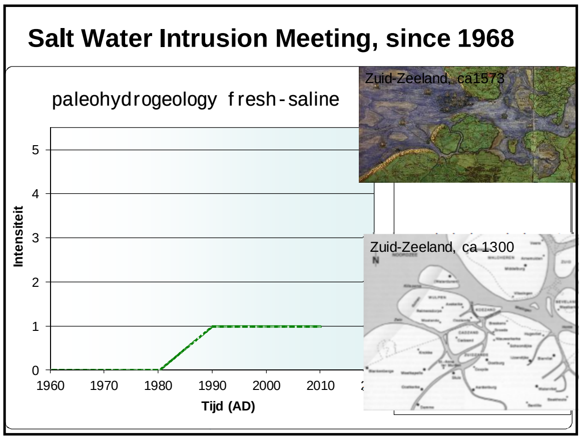

Salt Water Intrusion Meeting, since 1968
sealevel rise
Intensiteit
Tijd (AD)
Amsterdam
Leiden
The Hague
Rotterdam
sea level rise
Impact of sea level rise on a coastal groundwater system: a conceptual model of saltwater intrusion
Deltares

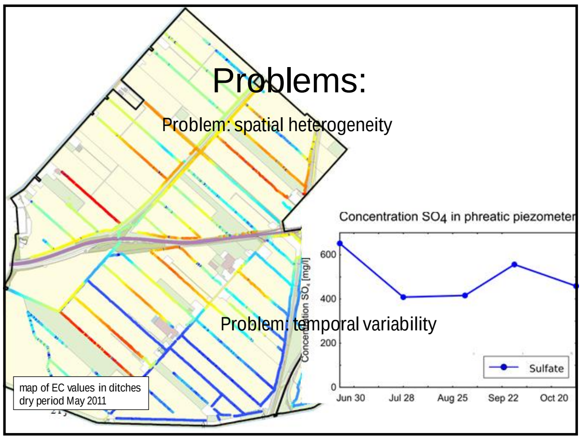

Salt Water Intrusion Meeting, since 1968
2D modelling variable-density & solute transport
Intensiteit
Tijd (AD)
Lebbe, 1981
2D modelling
no-flow boundary
constant saltwater head
Henry's case
constant flux Q
no-flow boundary

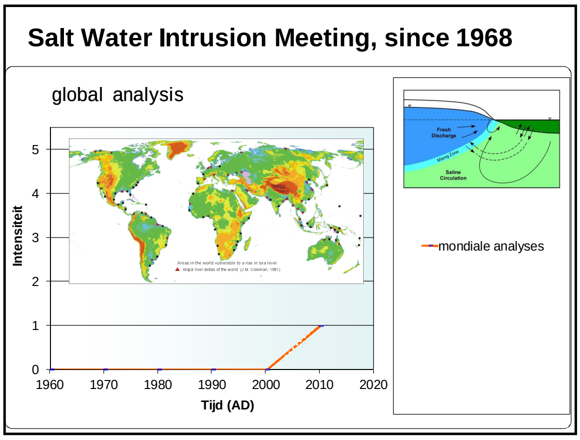

Salt Water Intrusion Meeting, since 1968
3D modelling variable-density & solute transport
Intensiteit
Tijd (AD)
3D modelling

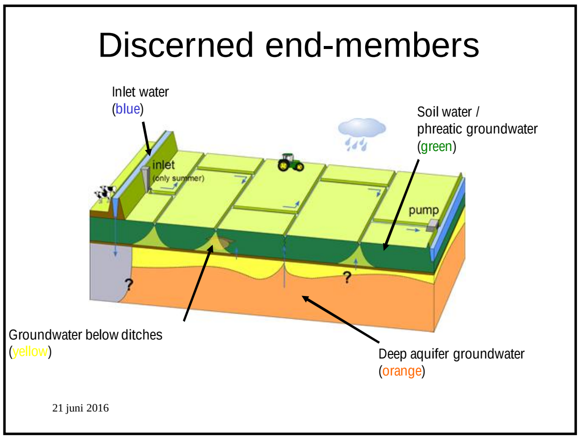

Salt Water Intrusion Meeting, since
submarine groundwater discharge
Intensiteit
Tijd (AD)
submarine groundwater discharge
Precipitation
Evaporation
Ocean

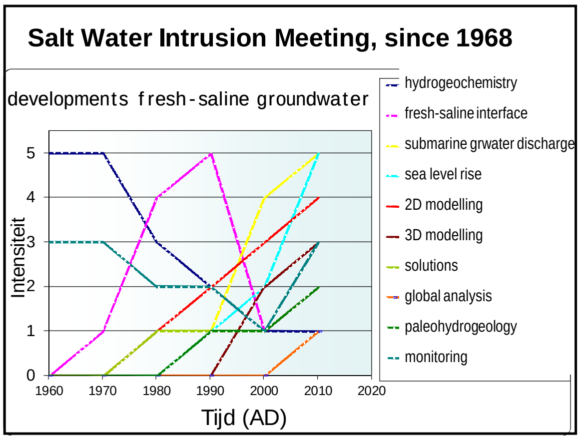

Salt Water Intrusion Meeting, since 1968
solutions (extraction regimes, barriers)
Intensiteit
Tijd (AD)
scavanger wells
solutions

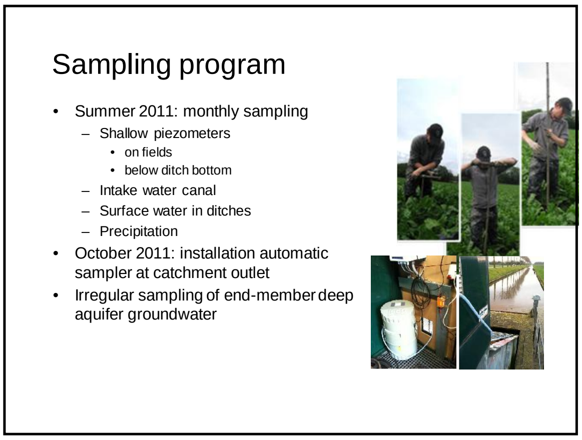

Salt Water Intrusion Meeting, since 1968
paleohydrogeology fresh-saline
Zuid-Zeeland, ca1573
Zuid-Zeeland, ca 1300
Intensiteit
5
4
3
2
1
0
1960
1970
1980
1990
2000
2010
Tijd (AD)


Problems:
Problem: spatial heterogeneity
Concentration SO4 in phreatic piezometer
Problem: temporal variability
Sulfate
600
400
200
0
Jun 30
Jul 28
Aug 25
Sep 22
Oct 20
map of EC values in ditches
dry period May 2011

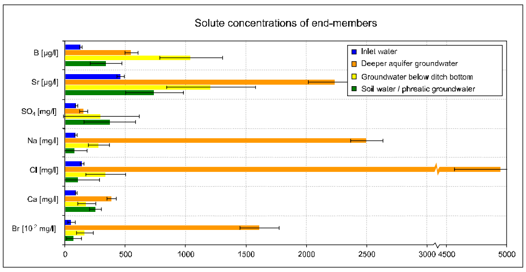

Salt Water Intrusion Meeting, since 1968
global analysis
Intensiteit
5
4
3
2
1
0
1960
1970
1980
1990
2000
2010
2020
Tijd (AD)
mondiale analyses


Discerned end-members
Inlet water
(blue)
Soil water /
phreatic groundwater
(green)
inlet
(only summer)
pump
Groundwater below ditches
(yellow)
Deep aquifer groundwater
(orange)
21 juni 2016


Salt Water Intrusion Meeting, since 1968
developments fresh-saline groundwater
hydrogeochemistry
fresh-saline interface
submarine grwater discharge
sea level rise
2D modelling
3D modelling
solutions
global analysis
paleohydrogeology
monitoring
Intensiteit
5
4
3
2
1
0
1960
1970
1980
1990
2000
2010
2020
Tijd (AD)


Sampling program
• Summer 2011: monthly sampling
– Shallow piezometers
• on fields
• below ditch bottom
– Intake water canal
– Surface water in ditches
– Precipitation
• October 2011: installation automatic sampler at catchment outlet
• Irregular sampling of end-member deep aquifer groundwater

End-member chemical signature



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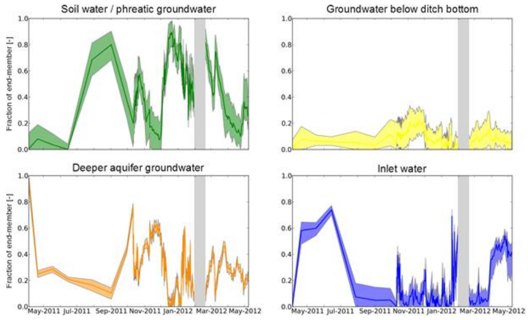
Result: End-member fractions +



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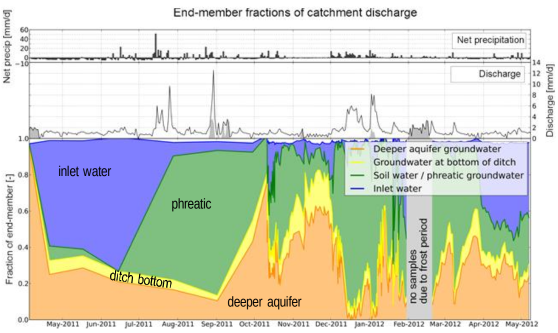
End-member fractions



21 juni 2016