IHE 2017

# Density dependent groundwater flow in the coastal zone

Gualbert Oude Essink

Lecture set-up:
- PowerPoint sheets
- Lecture Notes
- Practicals

http://freshsalt.deltares.nl

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

20-27-28-29 June 2017



## Curriculum Vitae

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

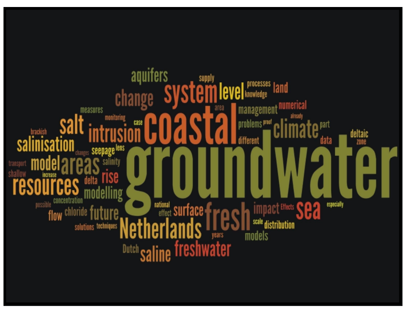
Qualifications:
- Groundwater resources management
- Density-dependent groundwater flow and coupled solute transport
- Salt water intrusion in coastal aquifers
- Assessment of climate change on groundwater resources
- Numerical Modeling
- Teaching and training

http://freshsalt.deltares.nl
Deltares: gualbert.oudeessink@deltares.nl

## 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

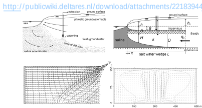



## Research on groundwater in the coastal zone

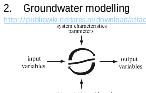
- 18 years experience in modelling variable-density dependent groundwater flow and coupled solute transport in the coastal zone
- Incorporating monitoring campaigns results in numerical modeling tools
- Research on new fresh-saline phenomenae: salty seepage boils and shallow freshwater lenses in saline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

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

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




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




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



## Practicals

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

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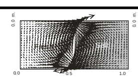
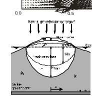
## Practicals

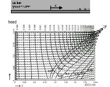
- Rotating sharp interface



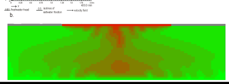
- Freshwater lens



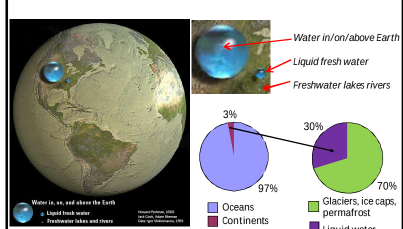
- Henry's case



- (Elder's case)



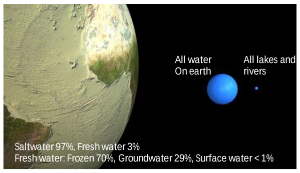
## Volumes of water on Earth: a scarce product




Source: Perlman, USGS; Shiklomanov, 1993

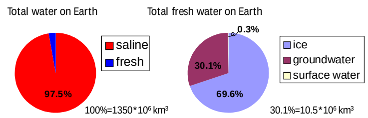
Water Energy Food Nexus
Global water scarcity

Fresh water is a scarce resource...






## Water on Earth

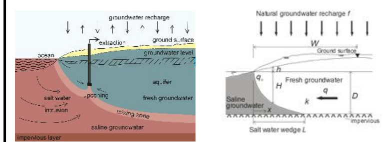



Demand for groundwater (now 30%) increases due to:

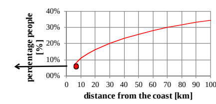
- increase world population & economical growth
- loss of surface water due to contamination
- great resource: available in large quantities
- still unpolluted (relative to surface water)

(Source: Cheng, 1998)

## Groundwater in the coastal zone



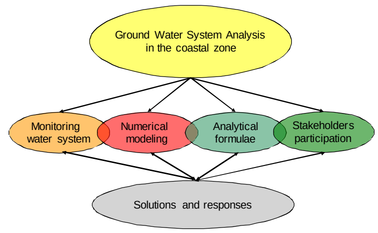

500 million people in the first 5km from the coastline



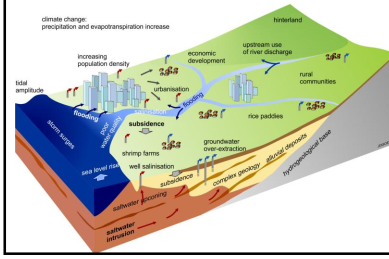



## Topics of density driven groundwater flow

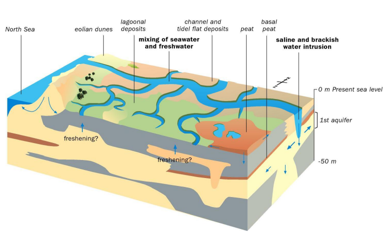
1. Introduction
   - water on earth
   - salt water intrusion
   - freshwater head
2. Interface between fresh and saline groundwater
   - analytical formulae (Badon Ghyben-Herzberg)
   - upconing example
3. Numerical modelling
   - mathematical background
   - Benchmark problems: Henry, Elder, Hydrocoin,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



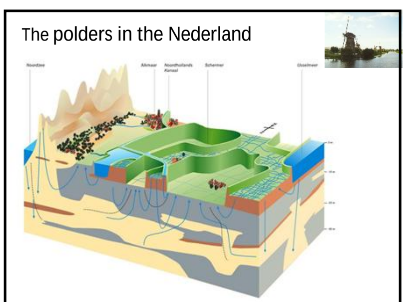

## Groundwater issues in the coastal zone/deltaic areas




## Past, before man




## The polders in the Nederland



## Groundwater in the future

We have to cope which...:

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

*Direct anthopogenic influence on groundwater is more important than climate effect*

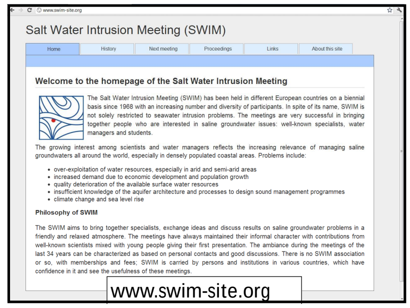
Salt Water Intrusion Meeting, since 1968

Salt Water Intrusion Meeting, since 1968

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

Themes

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


www.swim-site.org

Salt Water Intrusion Meeting (SWIM)

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

**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.

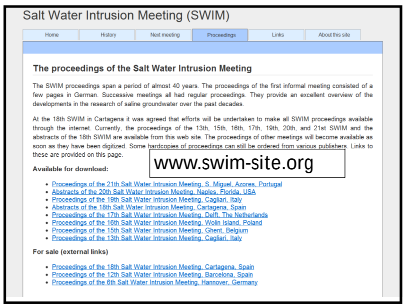
The growing interest among scientists and water managers reflects the increasing relevance of managing saline groundwaters all around the world, especially in densely populated coastal areas. Problems include:

- 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


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.

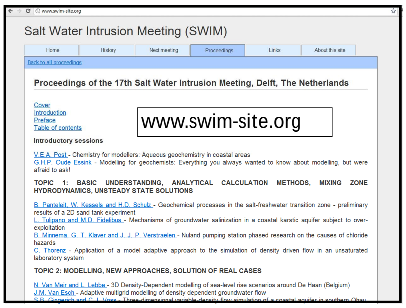
www.swim-site.org

**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
Table of contents

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**

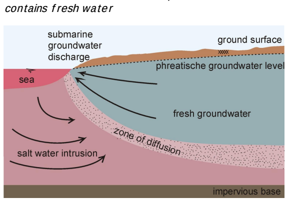
N. Van Meir and L. Lebbe - 3D Density-Dependent modelling of sea-level rise scenarios around De Haan (Belgium)
J.M. Van Esch - Adaptive multigrid modelling of density dependent groundwater flow

Introduction SWI



Definition of salt water intrusion

*Inflow of saline water into an aquifer which contains fresh water*






Origin of saline groundwater in the subsoil

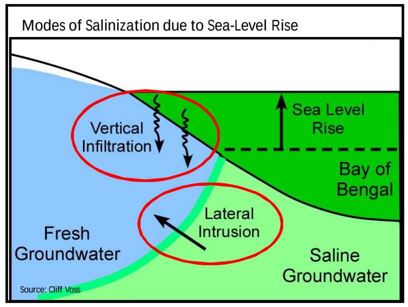
Geological causes:

-marine deposits during geological times
-trans- and regressions in coastal areas (deltas)
-salt/brine dome

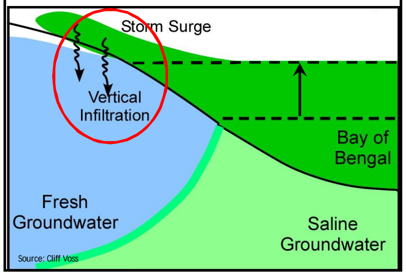
Anthropogenic causes:

-agriculture/irrigation (salt damage Middle East & Australia)
-upconing under extraction wells throughout the world
-upconing under low-lying areas (e.g. Dutch polders)

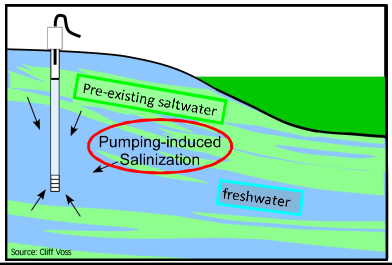
Modes of Salinization due to Sea-Level Rise



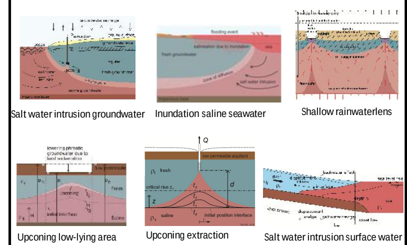
Modes of Salinization due to Sea-Level Rise



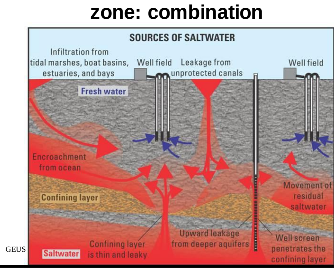

Salinization due to Pumping



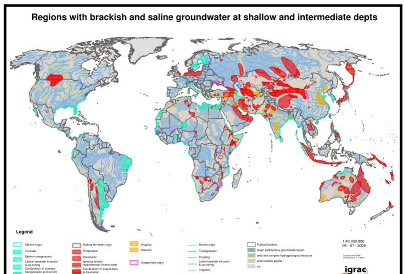

**Salinisation processes at local scale**

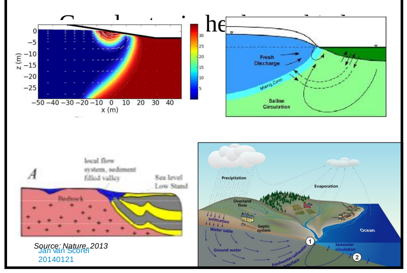


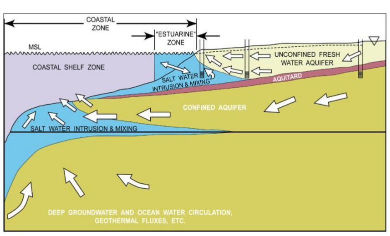

## Salinization processes in the coastal zone: combination



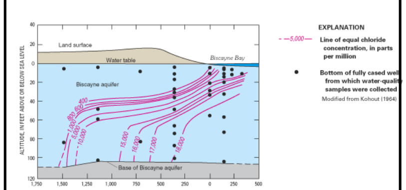

Regions with brackish and saline groundwater at shallow and intermediate depts



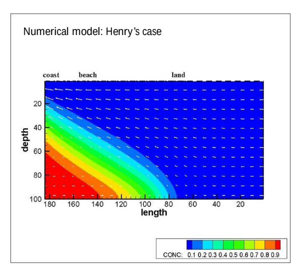




Biscayne aquifer, Florida USA: Henry's case




Definition of salt water intrusion



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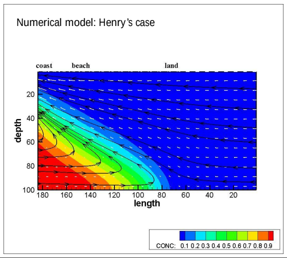
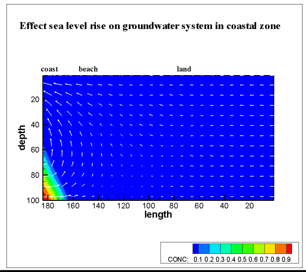
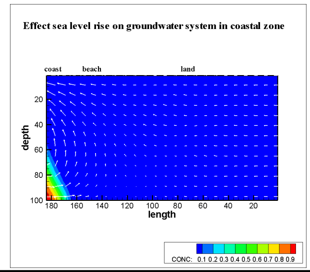


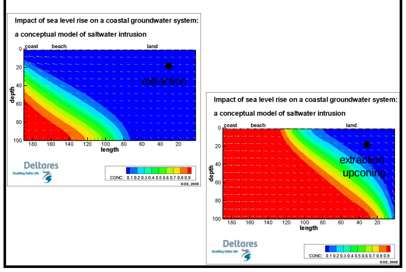

## Sea level rise and salt water intrusion



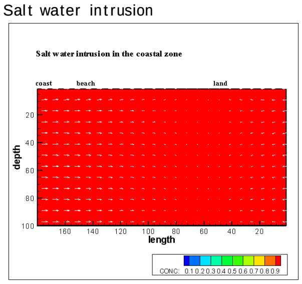

## Sea level rise and salt water intrusion



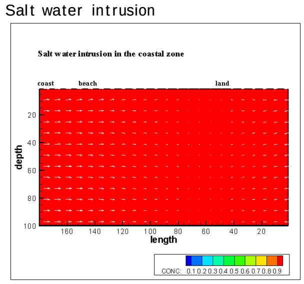

## Sea level rise and salt water intrusion




## Salt water intrusion




## Salt water intrusion




Introduction

## Water on Earth

Some serious developments:

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

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

In 1 liter ocean: about 35 gr salt

In 1 liter ocean: about 35 gr salt


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


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


Jan van Scorel
20140121

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


## Fresh-brackish-saline groundwater

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

## Definition fresh-brackish-saline groundwater

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

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

EOS

## Examples of equations of state

Knudsen (1902)

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

T<15 °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)

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

## Equation of state (SEAWAT)

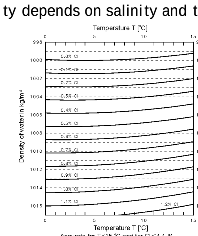
$$\rho_{i,j,k} = \rho_f + \frac{\partial \rho}{\partial C} C_{i,j,k}$$

e.g.:

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

EOS

## Density depends on salinity and temperature

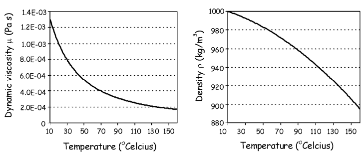


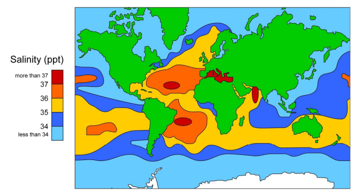

$$\rho_{(S,T)} = 1000 + 0.8054S - 0.0065(T - 4 + 0.2214S)^2$$ Knudsen (1902)

EOS

## Density and viscosity depend on temperature

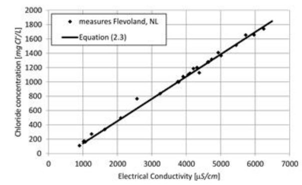
(10ºC-160 ºC)






## Close relation between chloride concentration and Electrical Conductivity



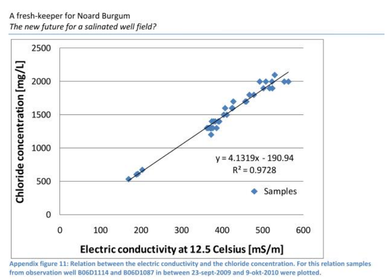

$$Cl^{-}(mg/L) = EC_{w}(mS/cm) \cdot 0.305 - 137$$

## Close relation between chloride concentration and Electrical Conductivity

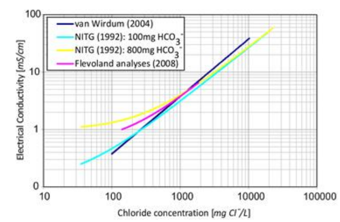
$10^6$ *μS/cm* = $10^3$ *mS/cm* = 1 *S/cm*
1 *μS/cm* = 100 *μS/m*

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

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

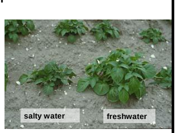



## EC-Chloride




## Salt in water is a problem







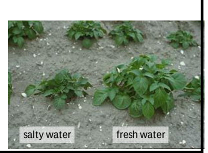

Introduction

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

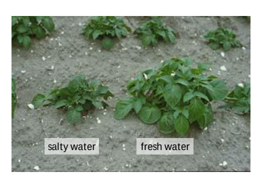
-drinking water:
- taste (100-300 mg Cl⁻/l)
- long term health effect
- norm: EC& WHO=150 mg Cl⁻/l (live stock=1500 mg Cl⁻/l)

-industry:
- corrosion pipes
- preparation food

-irrigation/agriculture:
- production crops
- salt damage

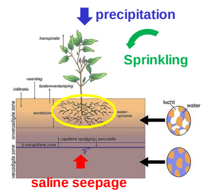


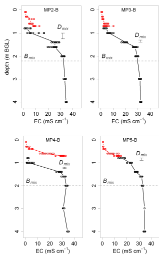

## Effects salinisation: salt damage




Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

## Salt-resistant crops



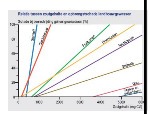

**Important parameter:**
Chloride concentration root zone
Land use
Sensitivity crops

## Salt damage to crops

Important parameters:
- Chloride concentration in the root zone
- Land use
- Sensitivity crops

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

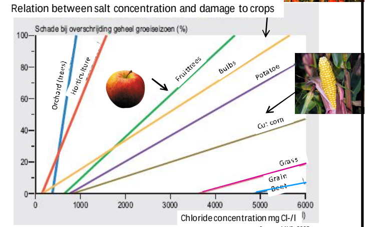
*Source: Roest et al., 2003 en Haskoning*




*Source: MNP, 2005*

## Salt damage to crops

Relation between salt concentration and damage to crops



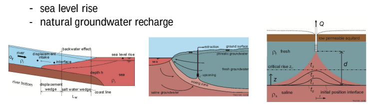

*Source: MNP, 2005*

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



## Why is salinisation a pressing problem?

- 30% of world population lives <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



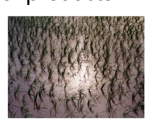


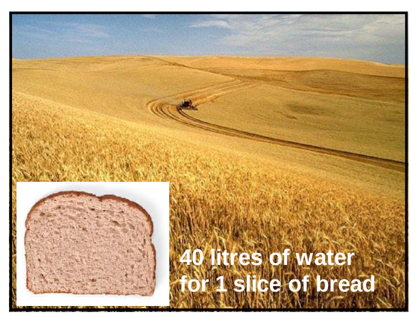
Processes that accelerate salt water intrusion:
- Sea level rise
- Land subsidence
- Human activities

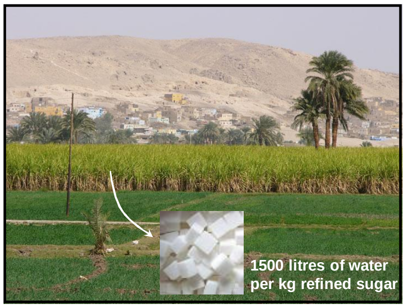
Threats for:
- drinking water supply in dunes:
  - upconing of saline groundwater
  - decrease of fresh groundwater resources
  - recharge areas reduction
- agriculture:
  - salt damage to crops: salt load and seepage
- water management low-lying areas:
  - flushing water channels
- ecology


## The water footprint of products

| | |
|---|---|
| 1 kg wheat | 1 m³ water |
| 1 kg rice | 3 m³ water |
| 1 kg milk | 1 m³ water |
| 1 kg cheese | 5 m³ water |
| 1 kg pork | 5 m³ water |
| 1 kg beef | 15 m³ water |











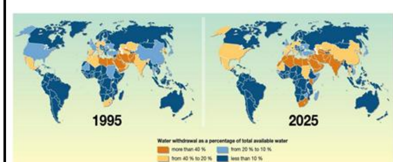


Question:

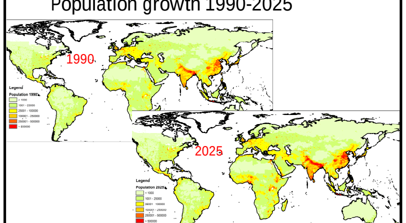
*Demand fresh water per capita per day in the Netherlands?:*

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

Water withdrawal as % of total available water




Population growth 1990-2025




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

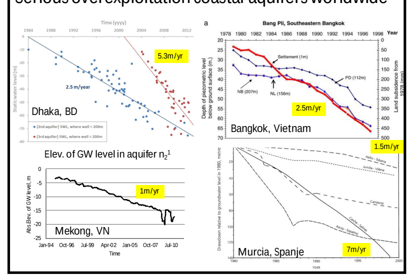


Reasons and drawbacks of using groundwater

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

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

Serious overexploitation coastal aquifers worldwide

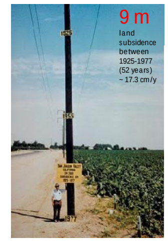


## Groundwater overexploitation in Mekong Delta


## Land subsidence

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

## Land subsidence San Joachim Valley, CA, USA




9 m since 1930s


## What causes the land to subside?

Natural causes (geological processes):

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

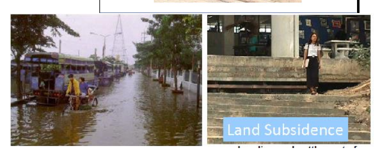
Anthropogenic causes (human-induced processes):

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

Why discriminating between human-induced and natural processes?

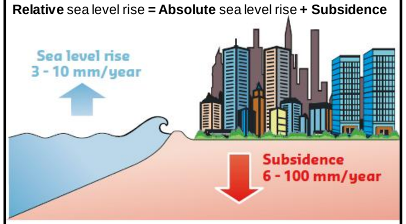
- Magnitude
- Cooping strategy (mitigation versus adaptation)


## Impacts

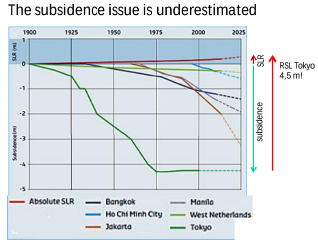

## Sinking delta cities

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

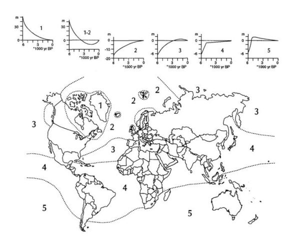



## Examples of some major coastal cities

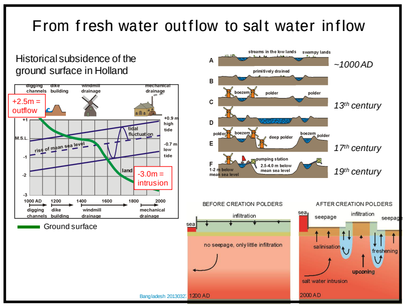
The subsidence issue is underestimated

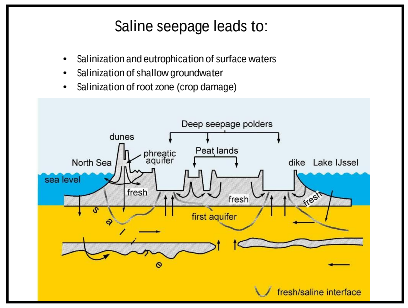


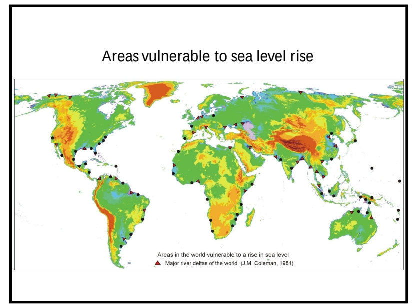

## Regional distribution of Holocene Sea-level Changes



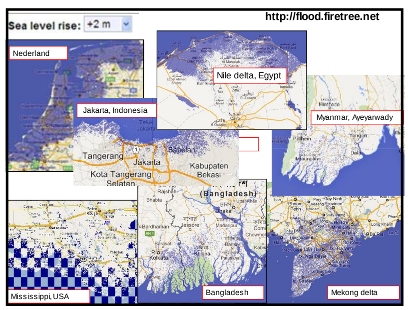
*Source: Pirazzoli, P.A. & Pluet, J., 1991. World Atlas of Holocene Sea-level Changes. Elsevier Oceanography Series, Vol. 58*

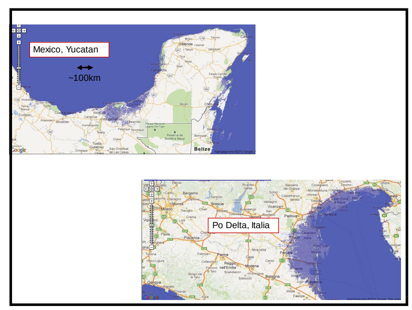

From fresh water outflow to salt water inflow
Historical subsidence of the ground surface in Holland
+2.5m = outflow
-3.0m = intrusion
Ground surface
~1000 AD
13th century
17th century
19th century
BEFORE CREATION POLDERS
AFTER CREATION POLDERS
no seepage, only little infiltration
1200 AD
2000 AD

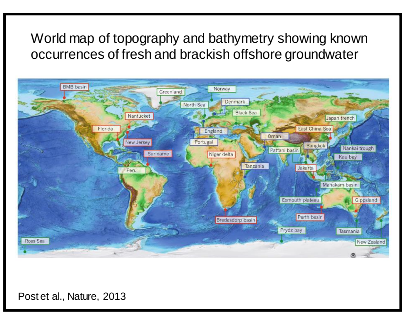

Saline seepage leads to:
• Salinization and eutrophication of surface waters
• Salinization of shallow groundwater
• Salinization of root zone (crop damage)
Deep seepage polders
dunes
Peat lands
phreatic aquifer
North Sea
dike
Lake IJssel
sea level
fresh
fresh
first aquifer
fresh/saline interface

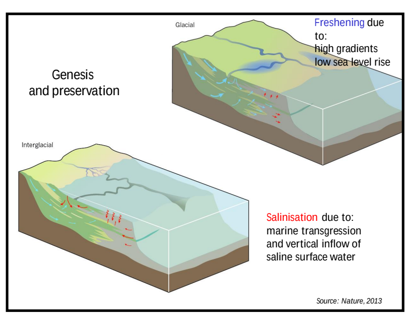

Areas vulnerable to sea level rise

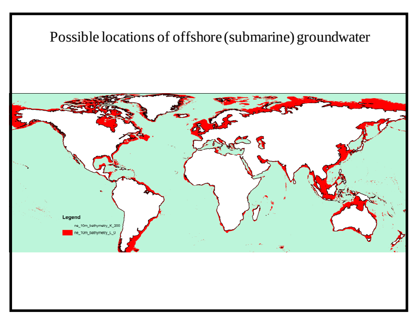

The Netherlands: low-lying lands
Sea level rise: +2 m
http://flood.firetree.net
~50km


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

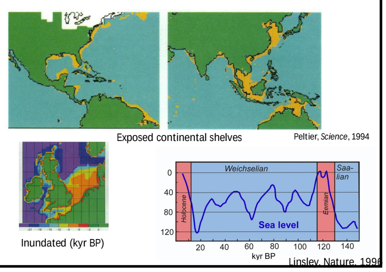

Mexico, Yucatan
~100km
Po Delta, Italia


World map of topography and bathymetry showing known occurrences of fresh and brackish offshore groundwater
Post et al., Nature, 2013

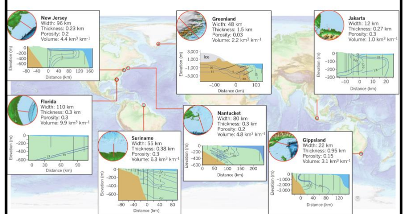

Genesis
and preservation
Glacial
Freshening due to:
high gradients
low sea level rise
Interglacial
Salinisation due to:
marine transgression
and vertical inflow of
saline surface water
Source: Nature, 2013


Possible locations of offshore (submarine) groundwater

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

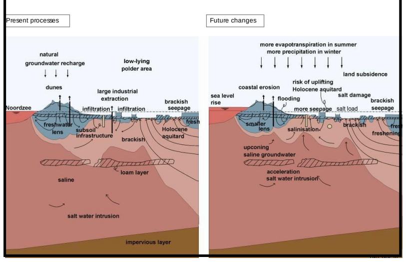



Global overview of inferred key metrics and cross sections of well-characterised vast meteoric groundwater reserves

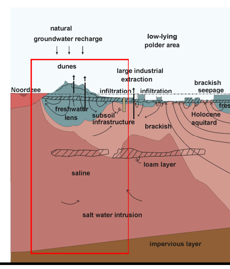



My first density dependent groundwater flow and solute transport model in 1990!

## The Dutch groundwater system under stress

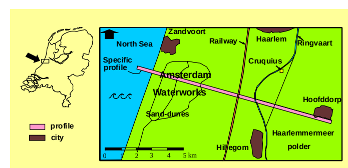



Saltwater intrusion in the Netherlands




Saltwater intrusion in the Dutch coastal zone

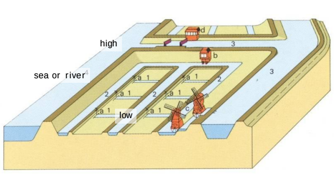
Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder




# The polder system

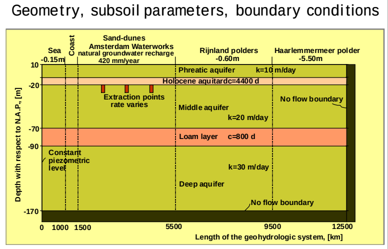
A polder is:

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



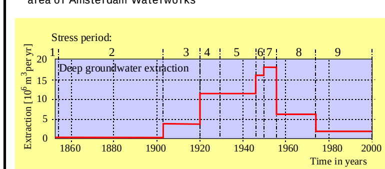

Upconing example

Geometry, subsoil parameters, boundary conditions

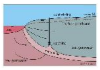


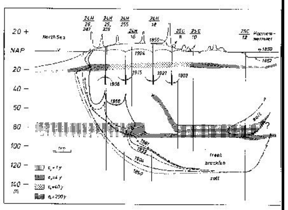

Saltwater intrusion in the Dutch coastal zone

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



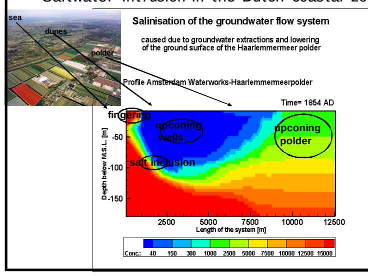
Upconing of brackish-saline groundwater



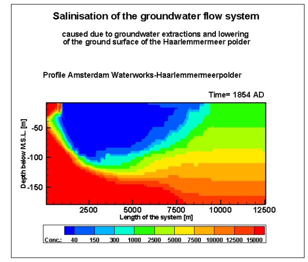



Stuyfzand, 1993

Saltwater intrusion in the Dutch coastal zone



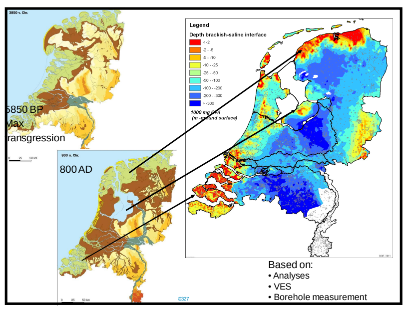

Saltwater intrusion in the Dutch coastal zone




**Palaeo hydrogeological modelling**

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

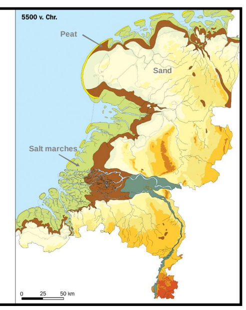
***J.R. Delsman, K. Hu-a-ng, P.C. Vos, P.G.B. de Louw, G.H.P. Oude Essink and M.F.P. Bierkens***

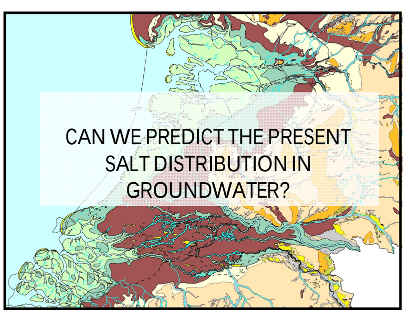


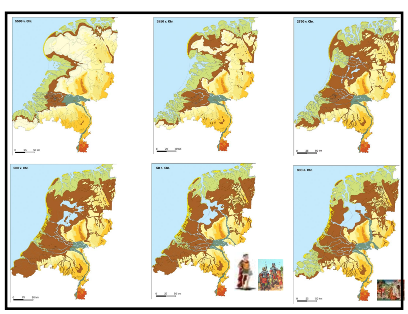

The Holocene transgressions

Major impact on present regional brackish groundwater systems

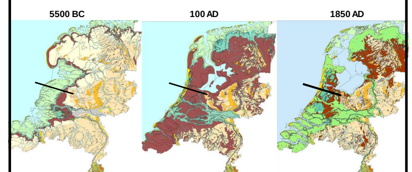
7500 BP



**Palaeogeographical development**



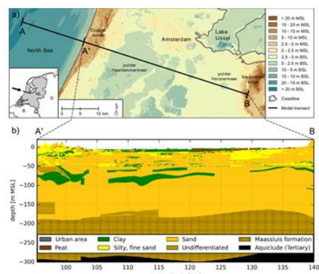

*Delsman, J.R., Hu-a-ng, K.R.M., Vos, P.C., De Louw, P.G.B., Oude Essink, G.H.P., Stuyfzand, P.J. and Bierkens, M.F.P. 2013, Palaeo-modeling of coastal salt water intrusion during the Holocene: an application to the Netherlands, Hydrol. Earth Syst. Sci. Discuss., 10, 13707–13742*

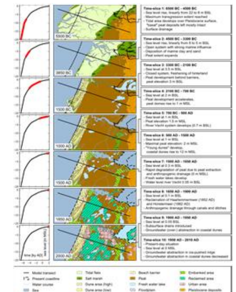
Atlas NL in het Holoceen (Vos et al, 2011)

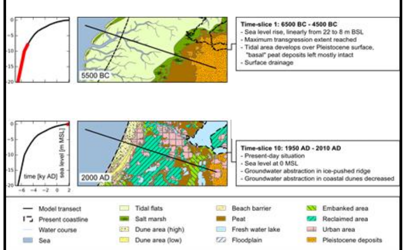
## Occurrence of salt under the polder Haarlemmermeer

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

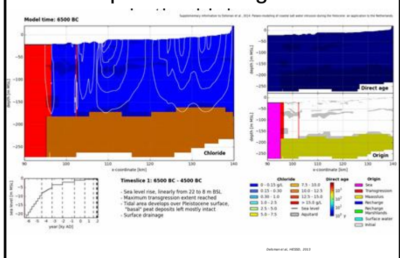

Delsman et al, HESS, 2013



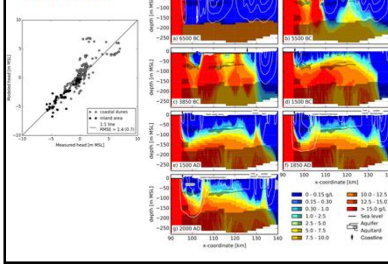



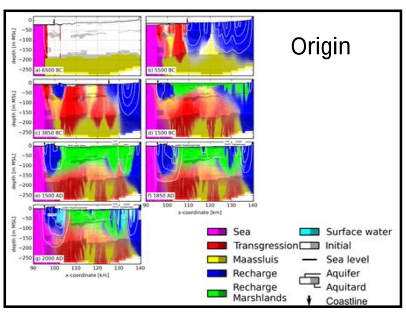


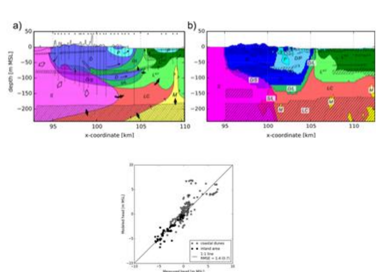

## Development saline groundwater



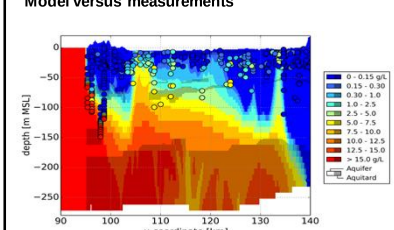

Model versus measurements





**Model versus measurements**



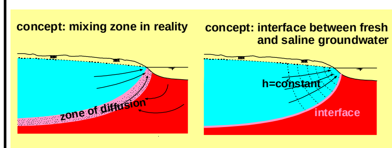
## Sharp interface between fresh and saline groudwater

---



### Badon Ghyben-Herzberg principle

Difference between reality and Badon Ghyben-Herzberg approximation

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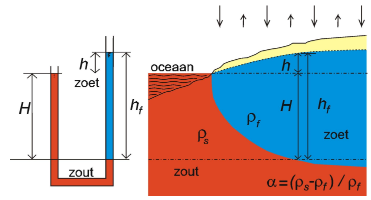
### Badon Ghijben-Herzberg principle

The principle suggests an interface between fresh and saline groundwater

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

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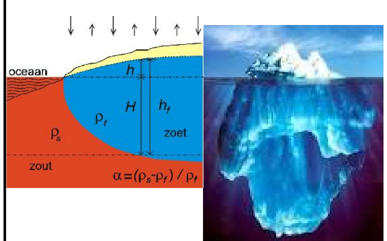


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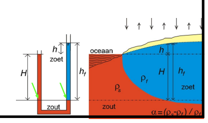
pressure saline groundwater=pressure fresh groundwater

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

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

$$h = \alpha H$$



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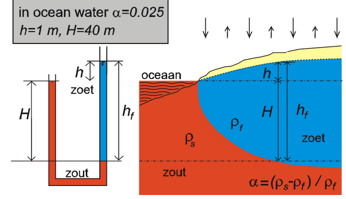
$$h = \alpha H$$

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

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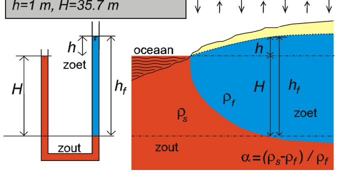
$$h = \alpha H$$

*h=αH*
Mediterranean Sea α=*0.028*
*h=1 m, H=35.7 m*

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### Badon Ghyben-Herzberg principle

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

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

---

### Badon Ghyben-Herzberg principle

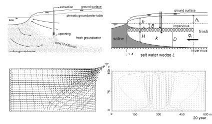
What is the case then h≠αH?

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

# Analytical solutions

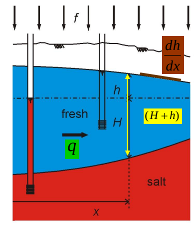
## Analytical solutions

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



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

## Unconfined aquifer (1D situation)




$$\frac{dh}{dx}$$

$$(H+h)$$

## Unconfined aquifer (1D situation)

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

(II) Continuity $dq = f dx$

(III) BGH $h = \alpha H$

## Unconfined aquifer (1D situation)

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

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

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

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

## Unconfined aquifer (1D situation)

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

integration gives

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

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

## Unconfined aquifer (1D situation)

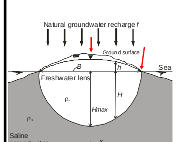
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}}$$

$$h = \alpha H$$

$$q = fx + C1$$

## Example 1: Elongated island

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

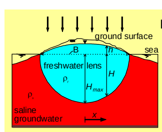



Boundary conditions

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

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

## Example of analytical solutions (I)




**Depth of fresh-saline interface H**

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

$$h = \alpha H$$

Maximal thickness lens

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

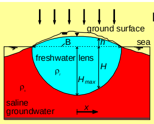
Volume lens

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

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

Lecture notes p. 32

## Example of analytical solutions (I)




**Depth of fresh-saline interface H**

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

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

$n_e = 0.35$

Maximal thickness lens

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

Volume lens (wrong in lectures notes)

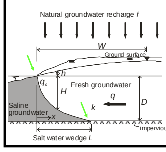
$V = 35203\text{m}^3/\text{m}'$

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

Lecture notes p. 32

## Example 2: salt water wedge

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




Boundary conditions

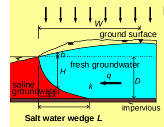
$x = 0 : q = q_0 \rightarrow q_0 = -fW \rightarrow C1 = q_0$

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

Length of salt water wedge

$x = L : H = D$

## Example of analytical solutions (II)




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

$q_0 = -fW$

$h = \alpha H$

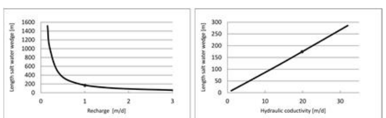
Example:

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

$L = 175.1\text{m}$

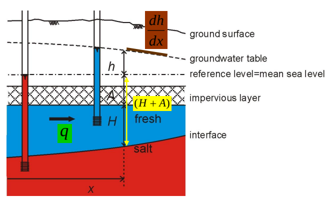
Lecture notes p. 33

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




*the dots resample with the example mentioned above*

## Confined aquifer (1D situation)




## Confined aquifer (1D situation)

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

(II) Continuity $q = q_0$

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

## Confined aquifer (1D situation)

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

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

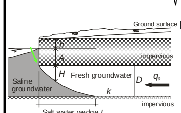
integration gives

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

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

## Example 3: salt water wedge confined aquifer

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




Boundary condition

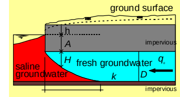
$x = 0 : H = 0 \rightarrow C = 0$

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

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

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

## Example of analytical solutions (III)




**Length of salt water wedge**

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

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

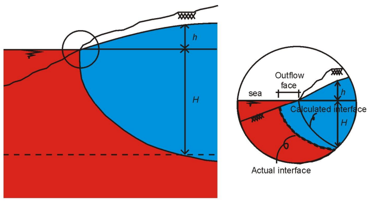
Example:

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

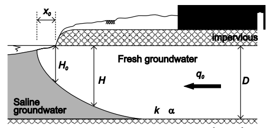
$L = 250\text{m}$

Lecture notes p. 35-36

## Outflow face (Submarine Groundwater Discharge)




## Outflow face (Submarine Groundwater Discharge)

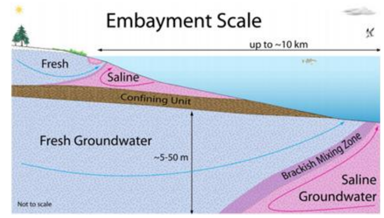



$$x_0 = \frac{q_0}{2k\alpha} \qquad H_0 = \frac{q_0}{k\alpha}$$ Glover (1959)

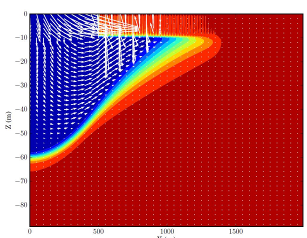
Example:
$x_0$= f*L/(2ka) = 0.001m/d*20000m/(2*20*0.025) = 20m (only!)

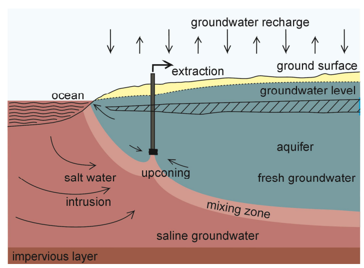
Note: no resistance layer offshore

## Outflow face (Submarine Groundwater Discharge)

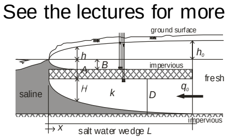


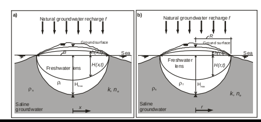

## Outflow face (Submarine Groundwater Discharge)




## See the lectures for more cases



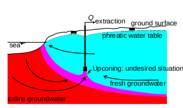



# Upconing processes

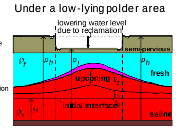


## Upconing of saline groundwater

Under an extraction well




Under a low-lying polder area

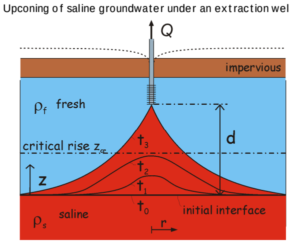



- movement of saline groundwater to extraction wells
- increase in salinity (>150-200 mg Cl-/l)
- lowering of the piezometric head (leads to land subsidence: e.g. Los Angeles: 9 m in the 1930's)

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

## Examples of analytical solutions (IV)

Upconing of saline groundwater under an extraction well

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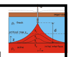
## Examples of analytical solutions (IV)



Upconing of saline groundwater under an extraction well

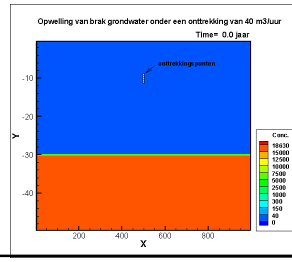
$$z(r,t) = \frac{Q}{2\pi\alpha k_x d}\left[\frac{1}{(1+R'^2)^{1/2}} - \frac{1}{[(1+\gamma')^2+R'^2]^{1/2}}\right]$$

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

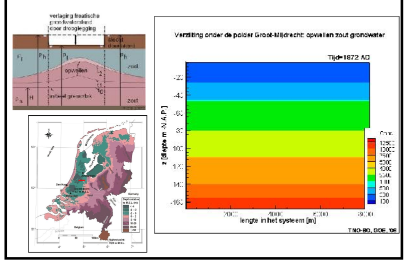
Dagan & Bear, 1968, J. Hydraul. Res 6, 1563-1573

Lecture notes p. 44

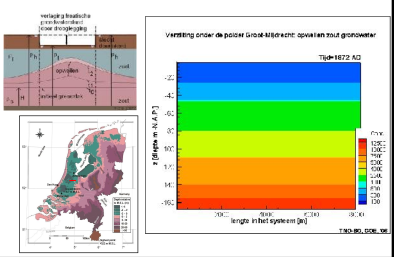
## Upconing of salt under an extraction



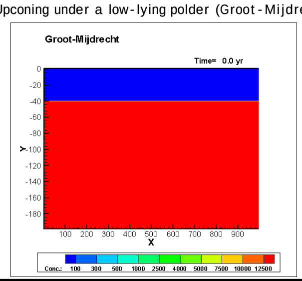

## Upconing under a low-lying polder (Groot-Mijdrecht)



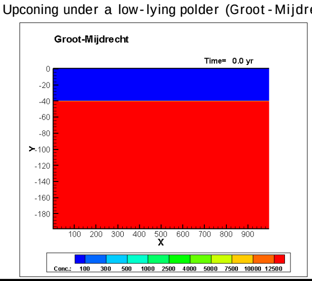

## Upconing under a low-lying polder (Groot-Mijdrecht)



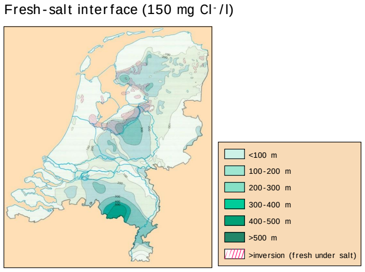

## Upconing under a low-lying polder (Groot-Mijdrecht)



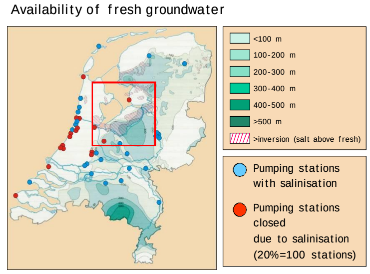

## Upconing under a low-lying polder (Groot-Mijdrecht)



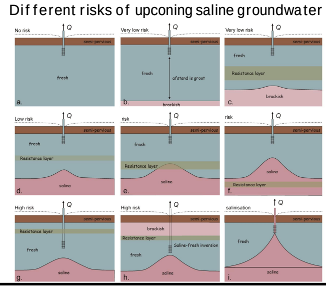

## Fresh-salt interface (150 mg Cl⁻/l)



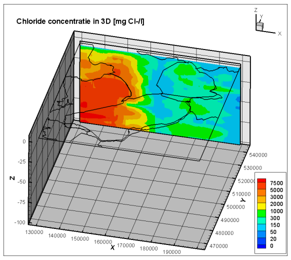

## Availability of fresh groundwater



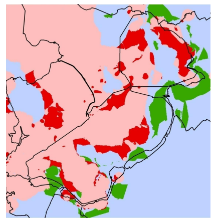

## Different risks of upconing saline groundwater



Animation 3D Chloride concentration




Upconing in Flevoland



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

High risk
Low risk
Very low risk

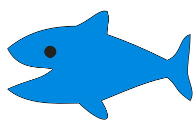
# Compensating measures

# Base idea

Many local solutions for fresh groundwater supply can have regional impact

# Starring

solution fresh groundwater supply



# Starring

Local solution fresh groundwater supply

# Starring

climate and global change

# Starring

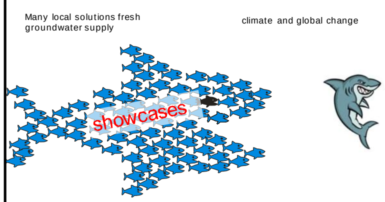
climate and global change

# Solutions and responses

Local solution fresh groundwater supply

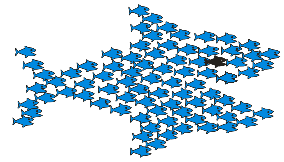
climate and global change

What should be the response?




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

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



Possible solutions to stop salt water intrusion:

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

Tools to understand salt water intrusion:

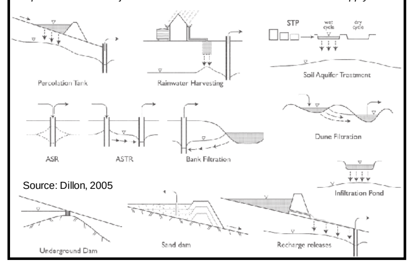
- Monitoring of salinities and piezometric levels
- Numerical modelling of salt water intrusion

Measures to compensate salt water intrusion

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

Aquifer Storage and Recovery

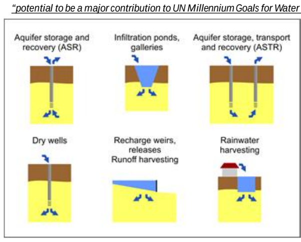
*"potential to be a major contribution to UN Millennium Goals for Water Supply"*




Source: Dillon, 2005

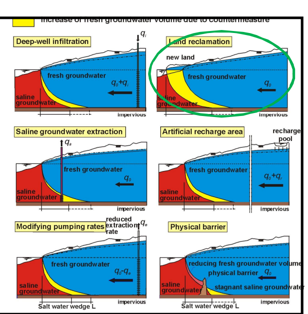
Aquifer Storage and Recovery / Managed Aquifer Recharge

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



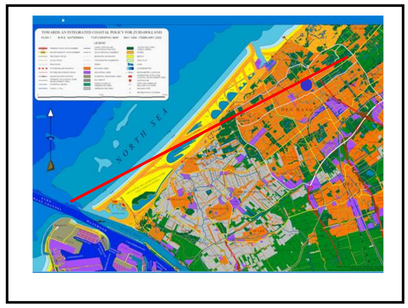

Source: Dillon, 2005

Technical measures to compensate salt water intrusion

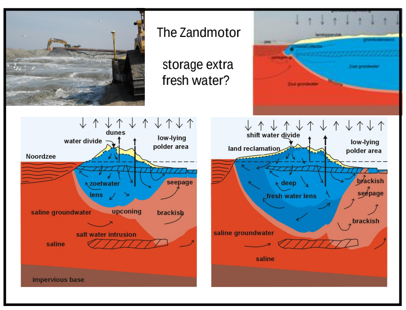



**Land reclamation**

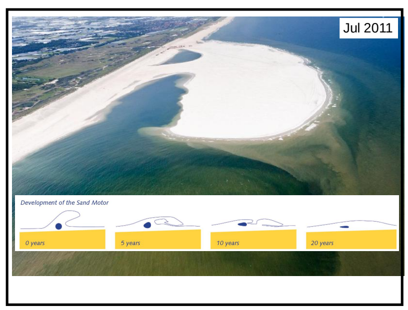
**The Zandmotor: effects at the hinterland?**



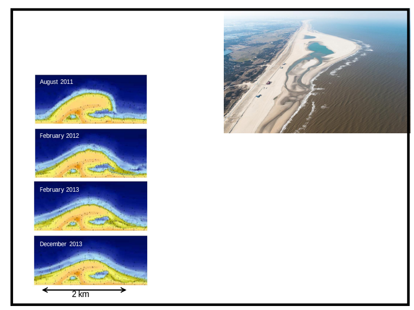
The Zandmotor: effects at the hinterland?
2D model profile

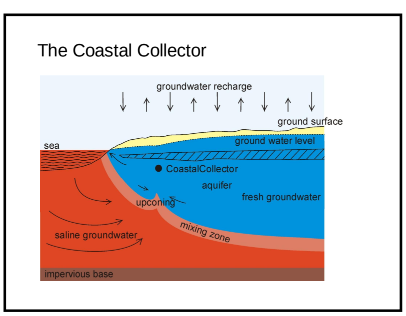
The Zandmotor
storage extra fresh water?
water divide
dunes
low-lying polder area
Noordzee
zoetwater lens
seepage
upconing
brackish
saline groundwater
salt water intrusion
saline
impervious base
shift water divide
land reclamation
deep fresh water lens

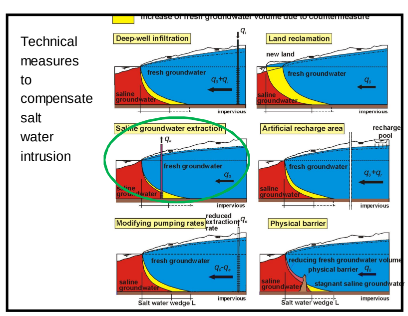
Jul 2011
Development of the Sand Motor
0 years
5 years
10 years
20 years

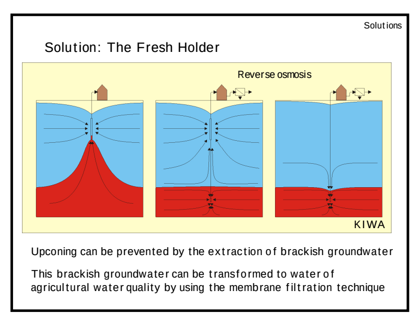
August 2011
February 2012
February 2013
December 2013
2 km

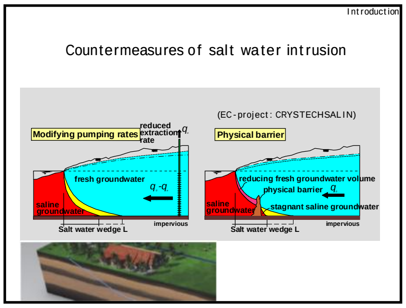
The Coastal Collector
groundwater recharge
ground surface
sea
ground water level
CoastalCollector
aquifer
fresh groundwater
upconing
mixing zone
saline groundwater
impervious base

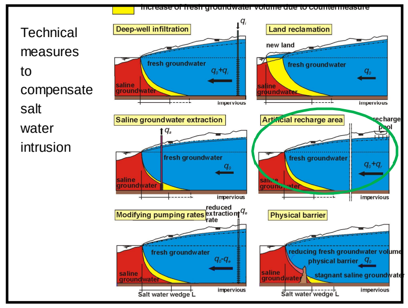



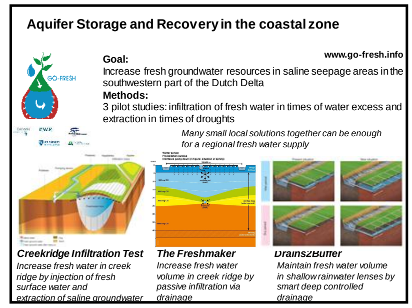
Technical measures to compensate salt water intrusion
Deep-well infiltration
Land reclamation
new land
fresh groundwater
saline groundwater
impervious
Saline groundwater extraction
Artificial recharge area
recharge pool
Modifying pumping rates
reduced extraction rate
Physical barrier
reducing fresh groundwater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

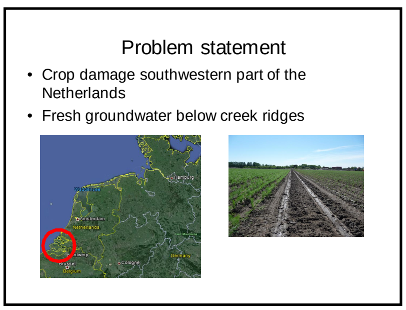



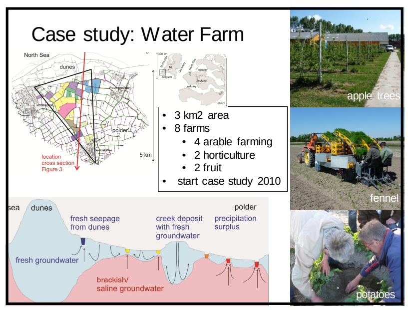
Solutions
Solution: The Fresh Holder
Reverse osmosis
KIWA
Upconing can be prevented by the extraction of brackish groundwater
This brackish groundwater can be transformed to water of agricultural water quality by using the membrane filtration technique

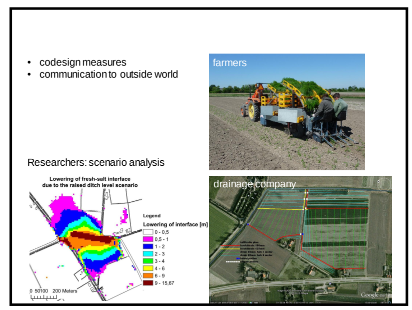

Introduction
Countermeasures of salt water intrusion
(EC-project: CRYSTECHSALIN)
Modifying pumping rates
Physical barrier
fresh groundwater
saline groundwater
reducing fresh groundwater volume
physical barrier
stagnant saline groundwater
Salt water wedge L
impervious

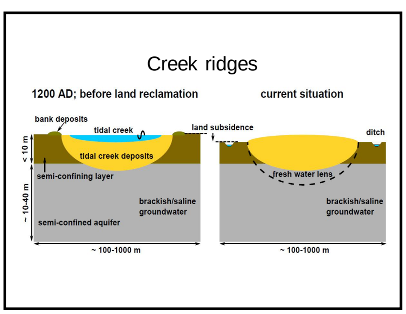

Technical measures to compensate salt water intrusion
Deep-well infiltration
Land reclamation
Saline groundwater extraction
Artificial recharge area
Modifying pumping rates
Physical barrier
fresh groundwater
saline groundwater
Salt water wedge L
impervious

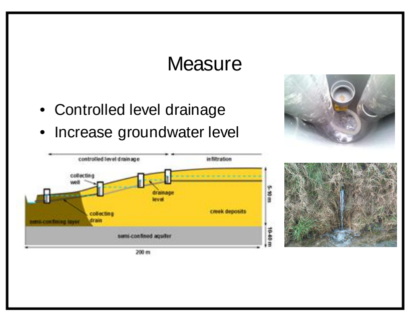

Aquifer Storage and Recovery in the coastal zone
www.go-fresh.info
Goal:
Increase fresh groundwater resources in saline seepage areas in the southwestern part of the Dutch Delta
Methods:
3 pilot studies: infiltration of fresh water in times of water excess and extraction in times of droughts
Many small local solutions together can be enough for a regional fresh water supply
Creekridge Infiltration Test
Increase fresh water in creek ridge by injection of fresh surface water and extraction of saline groundwater
The Freshmaker
Increase fresh water volume in creek ridge by passive infiltration via drainage
Drains2Buffer
Maintain fresh water volume in shallow rainwater lenses by smart deep controlled drainage

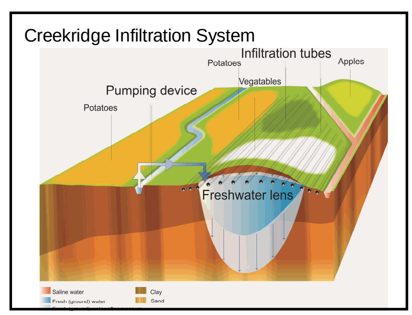

Problem statement
• Crop damage southwestern part of the Netherlands
• Fresh groundwater below creek ridges


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

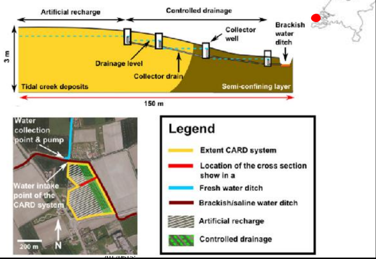

• codesign measures
• communication to outside world
farmers
Researchers: scenario analysis
drainage company


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


Measure
• Controlled level drainage
• Increase groundwater level


Creekridge Infiltration System
Infiltration tubes
Potatoes
Apples
Vegetables
Pumping device
Freshwater lens

## Concept of CARD and pilot layout



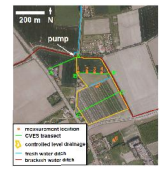

## Installation of drainage and monitoring network


various types of field measurements

## Different types of field measurements applied

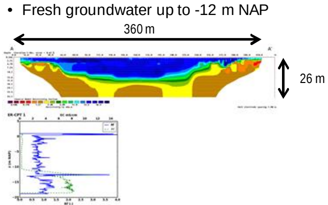
| Measurement type | Purpose |
|---|---|
| Pressure transducers[a] | Groundwater levels |
| Sampling using piezometer nest | $EC_{w20}$ |
| SLIMFLEX[b] | $EC_{bulk}$ |
| CPT[c] | Lithology and $EC_{bulk}$ |
| CVES[d] | $EC_{bulk}$ |
| SMD[e] | $EC_{bulk}$ |

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



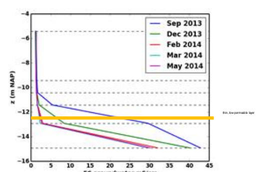

## Key field observations (1)

- Fresh groundwater up to -12 m NAP

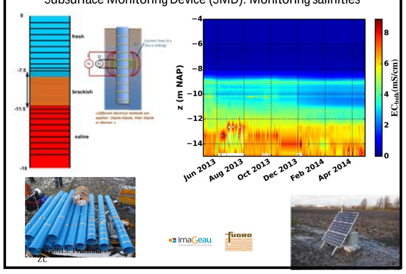



## Key field observations (2)

- Freshening up to 2m

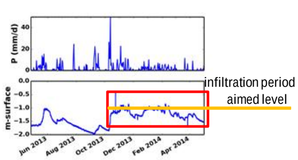



## Subsurface Monitoring Device (SMD): Monitoring salinities

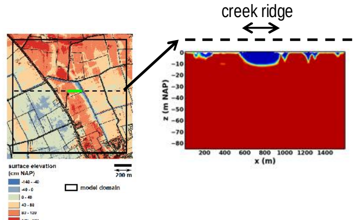



## Key field observations (3)

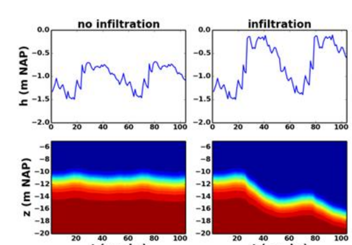
- Groundwater levels and precipitation




## Modeling

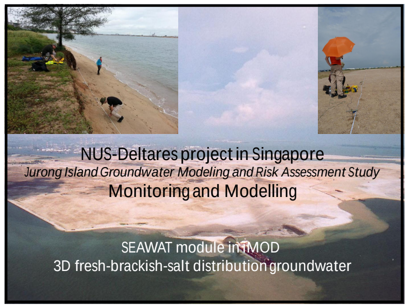



## Influence of infiltration

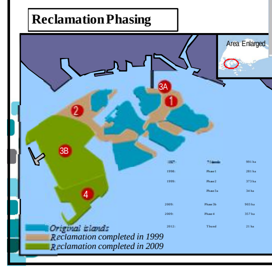


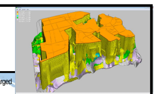
## Singapore Jurong Island

Aquifer Storage and Recovery



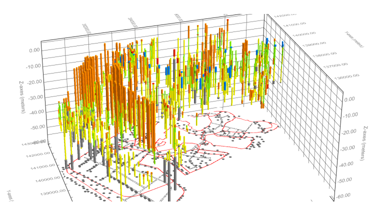

## Transformation of Jurong Island



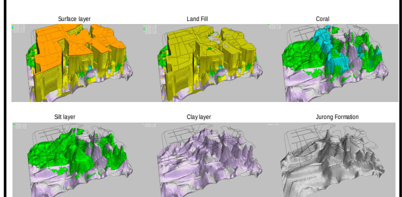



- In 1980s, 7 islands were reclaimed individually to a total land area of 991 ha. *(1960s was 118 ha).*
- Full-scale reclamation began from **1995** to form Jurong Island.
- Phases 1, 2, 3a completed in 1999; Phases 3b and 4 was completed in 2009.
- Current land area about **2960 ha.**

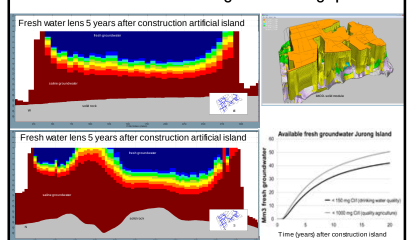
## Boreholes



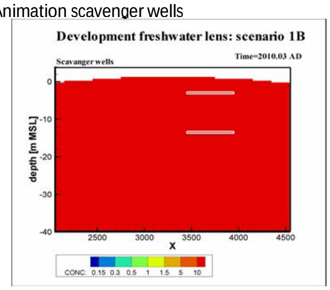
## SubSoil Model

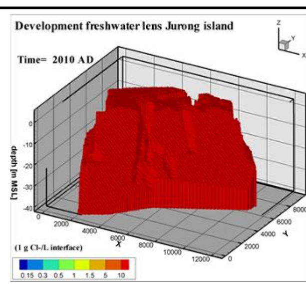


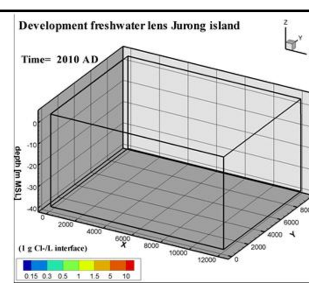

## iMOD-SEAWAT Jurong Island Singapore




## Animation scavenger wells



# Modelling

salt water intrusion

density dependent groundwater flow



Why mathematical modelling anyway?

A model is only a schematisation of the reality!



Why mathematical modelling anyway?

+:

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

-:

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



Numerical modelling variable density flow

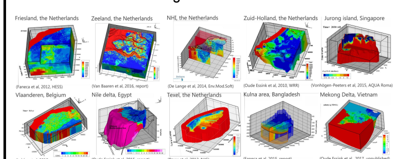
Type:

- sharp interface models
- solute transport models

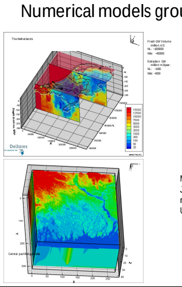
State of the art:

- three-dimensional
- solute transport
- transient

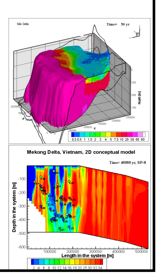
## Numerical models groundwater coastal zone




## Numerical models groundwater coastal zone




Mekong,
Just started
research
UDW project






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)

**Restrictions 3D saltwater intrusion modelling**

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

## Restrictions 3D salt water intrusion modelling 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

---



## Length flow time step

NOT EQUAL TO SOLUTE TIME STEP !

Stability criteria for solute transport equation (I)

1. Neumann criterion:

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

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

---



## Stability criteria for solute transport equation (II)

2. Mixing criterion:

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

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

---



## Stability criteria for solute transport equation (III)

3. Courant criterion:

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

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

---

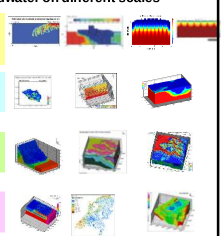
## Modelling fresh-salt groundwater on different scales

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

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

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

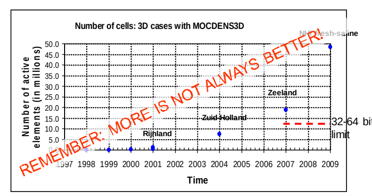
**National:** salt load
Bangladesh, Zuid-Holland, NHI
**cell size=250m-2km**



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

---

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

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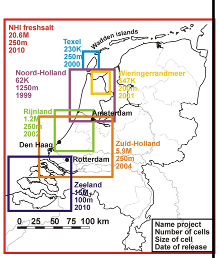
## Modelling effect climate change on fresh-salt groundwater

**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

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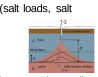
## Fields of application of fresh-saline groundwater models

- Water system analysis in brackish-saline environments (salt loads, salt boils, freshwater lenses)
- Quantifying effects of climate change & sea level rise



- Drinking water issues: upconing saline groundwater under extraction wells
- Developing measurements to stop salinization groundwater systems (e.g. fresh keeper, coastal collectors, freshwater storage underground)
- Impact of the disasters as tsunamis on fresh groundwater resources
- Submarine Groundwater Discharge (marine water pollution, Harmful Algae)

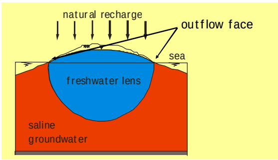
---



## Difficulties with variable density groundwater flow

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

## Outflow face at the coast is difficult to model




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

This is numerically difficult to handle

---

## A good initial density distribution is essential

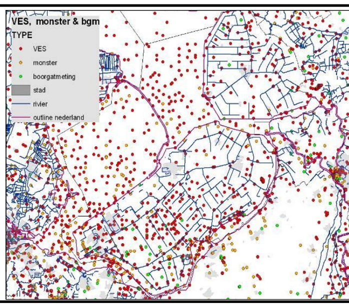
- Because groundwater and solute transport are coupled, the density influences grondwater velocities
- Numerous density measurements are necessary to get a reliable 3D density matrix

---

## 'Procedure' to improve initial density distribution

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

---

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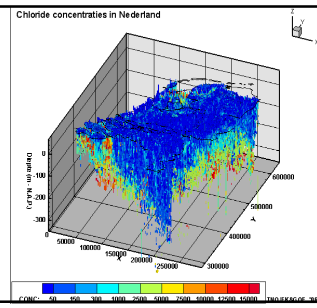


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## Mapping brackish-saline interface Zeeland

•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

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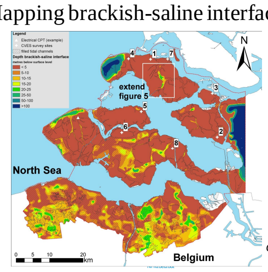
## Mapping brackish-saline interface




*Goes et al, 2009*

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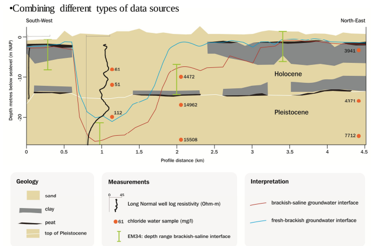
## Mapping brackish-saline interface

•Combining different types of data sources

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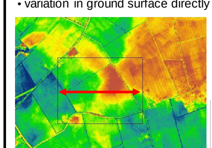
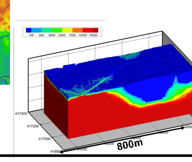
## Use variable-density groundwater flow modelling

**Why a model?**

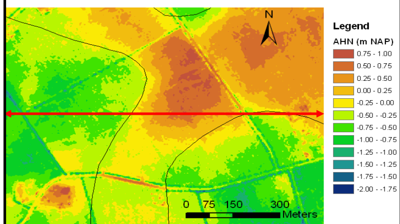
- variation in ground surface directly affects fresh-saline disribution






20150322 DGG

## Use variable-density groundwater flow modelling

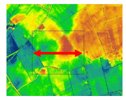


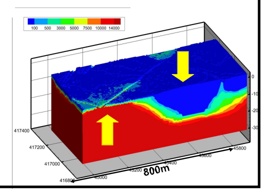

20150322 DGG

## Use variable-density groundwater flow modelling

**Why a model?**

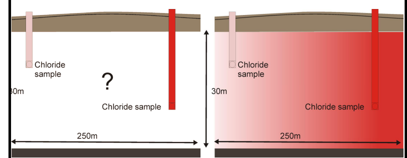
• variation in ground surface directly affects fresh-saline disribution





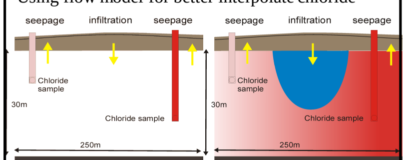

20150322 DGG

## Interpolation chloride



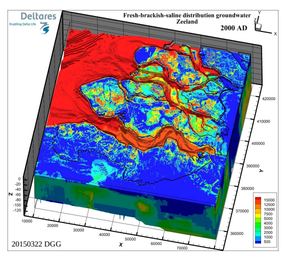

20150322 DGG

## Using flow model for better interpolate chloride




20150322 DGG

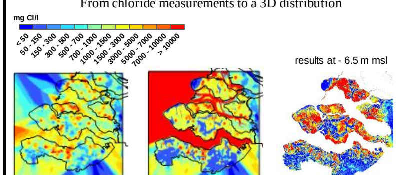
## 3D fresh-saline groundwater distribution




20150322 DGG

## 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*

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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

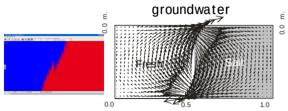
cases

## Rotating immiscible interfaces

Conclusion:

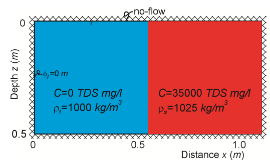
To check the variable-density component of your code, this immiscible interface benchmark can be used.

## Case 1: Vertical interface between fresh and saline groundwater



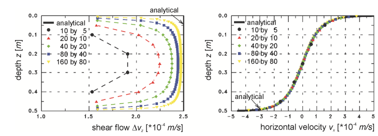

| Parameters | | | |
|---|---|---|---|
| Layers | 20 | $K_{hor}$ | $1\ 10^{-3}$ m/s |
| Rows | 1 | T | $2.5\ 10^{-5}$ m/s |
| Columns | 40 | Anisotropy $K_{hor}/K_{ver}$ | 1 |
| $\Delta x$ | 0.025 m | $n_e$ | 0.1 |
| $\Delta y$ | 1 m | $\alpha_L$ | 0 m |
| $\Delta z$ | 0.025 m | $\alpha_T$ | 0 m |
| Stress periods | 15 | | |
| Initial concentration | 0 and 35000 mg/l | | |
| bouyancy | 0.025 | | |

## Vertical interface




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

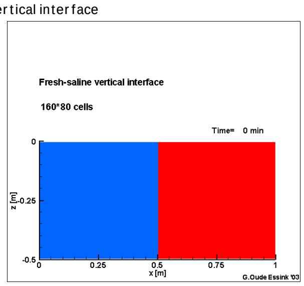
## Effect of the number of cells on the shear flow at the interface at t=0



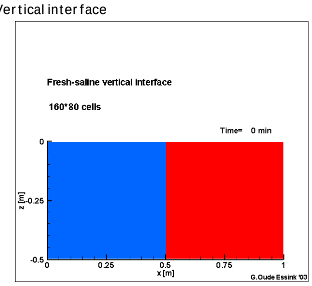

$$\Delta v_z = \frac{k}{n_e}\left(\frac{\rho_s - \rho_f}{\rho_f}\right)$$

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

## Vertical interface




## Vertical interface




## The effect of numerical solvers on the salt transport

Examples

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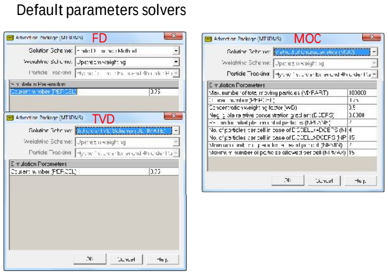
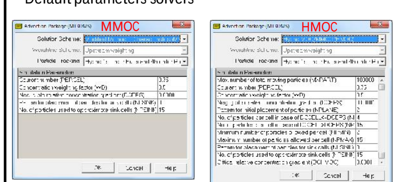
## Default parameters solvers

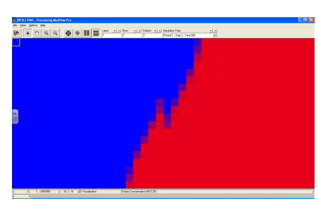



## Default parameters solvers




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

1 particle per cell



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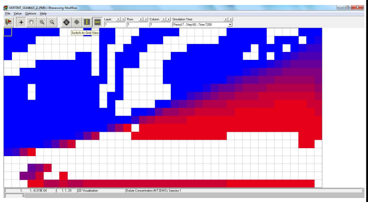
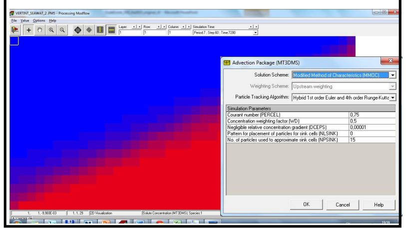
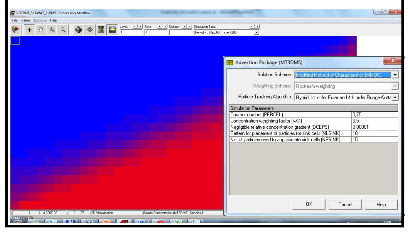
ULTIMATE



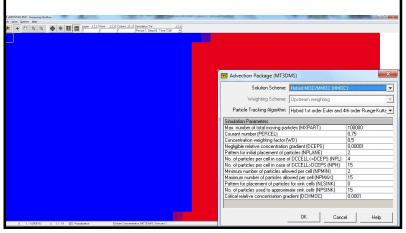
MMOC, NPLANE=0



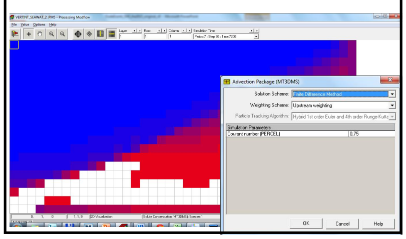
MMOC, NPLANE=10



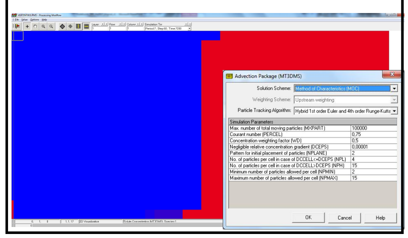
HMOC



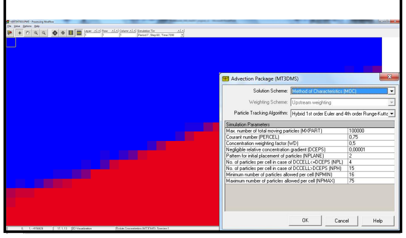
Finite Difference Method



MOC

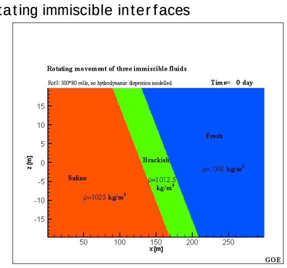


MOC



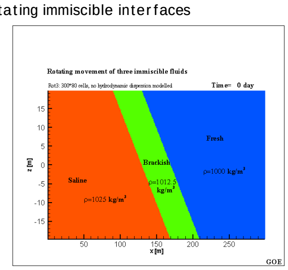
cases

Rotating immiscible interfaces



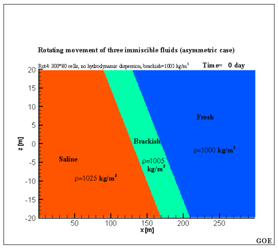

cases

Rotating immiscible interfaces



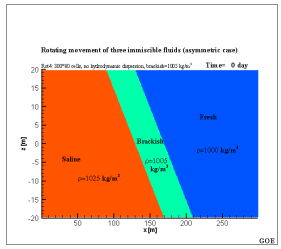
cases

## Rotating immiscible interfaces (asymmetric)




cases

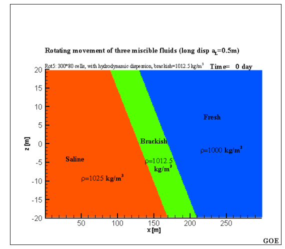
## Rotating immiscible interfaces (asymmetric)




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

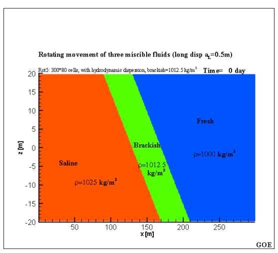
cases

## Rotating interfaces with dispersion $\alpha_L$=0.5m



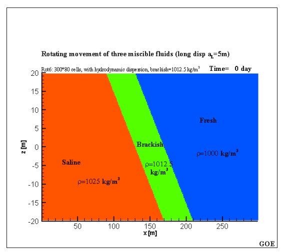

cases

## Rotating interfaces with dispersion $\alpha_L$=0.5m



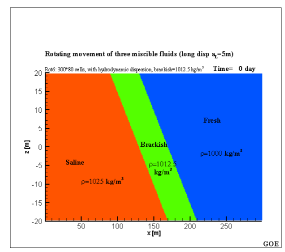

cases

## Rotating interfaces with dispersion $\alpha_L$=5m




cases

## Rotating interfaces with dispersion $\alpha_L$=5m




## Salt water pocket in a fresh environment

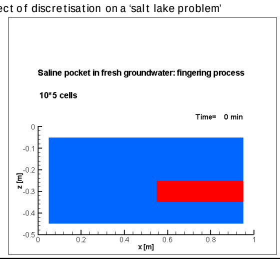
Grid convergence

Time step

cases

## Salt water pocket in a fresh environment (I)

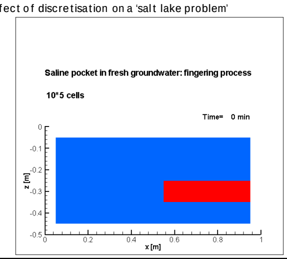
Effect of discretisation on a 'salt lake problem'

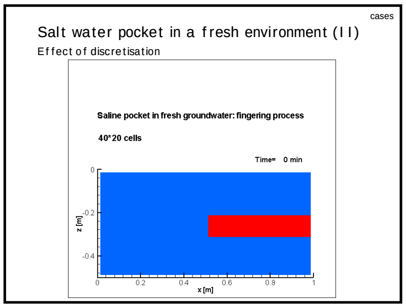


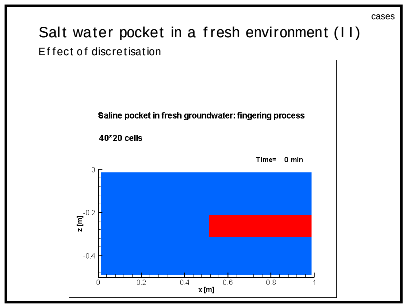

cases

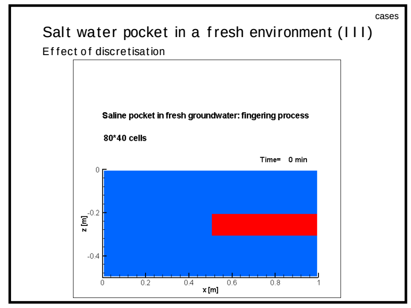
## Salt water pocket in a fresh environment (I)

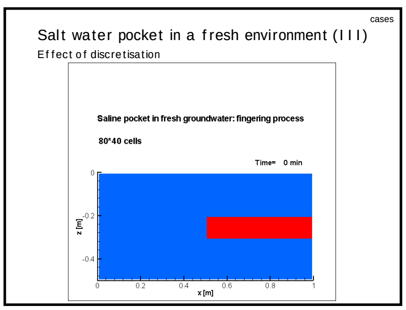
Effect of discretisation on a 'salt lake problem'

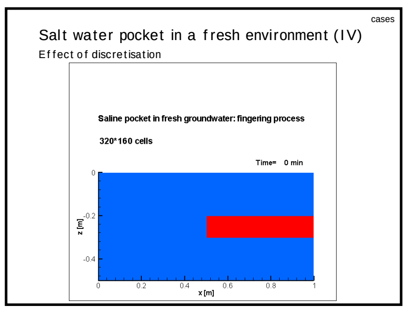


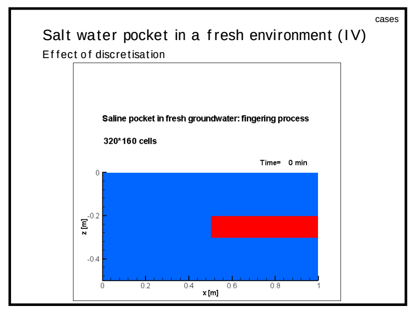

cases
Salt water pocket in a fresh environment (II)
Effect of discretisation
Saline pocket in fresh groundwater: fingering process
40*20 cells
Time= 0 min
z [m]
x [m]

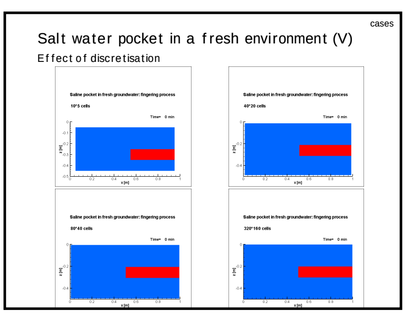

cases
Salt water pocket in a fresh environment (II)
Effect of discretisation
Saline pocket in fresh groundwater: fingering process
40*20 cells
Time= 0 min
z [m]
x [m]

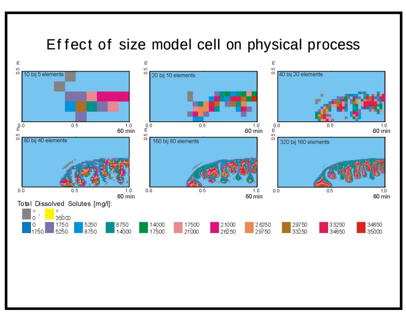

cases
Salt water pocket in a fresh environment (III)
Effect of discretisation
Saline pocket in fresh groundwater: fingering process
80*40 cells
Time= 0 min
z [m]
x [m]

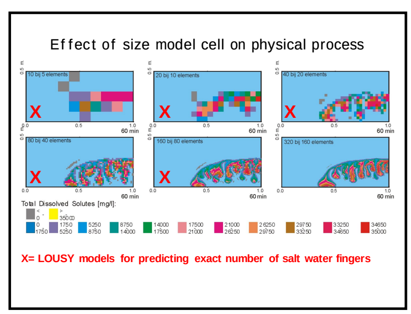

cases
Salt water pocket in a fresh environment (III)
Effect of discretisation
Saline pocket in fresh groundwater: fingering process
80*40 cells
Time= 0 min
z [m]
x [m]


cases
Salt water pocket in a fresh environment (IV)
Effect of discretisation
Saline pocket in fresh groundwater: fingering process
320*160 cells
Time= 0 min
z [m]
x [m]

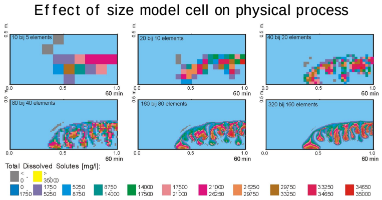

cases
Salt water pocket in a fresh environment (IV)
Effect of discretisation
Saline pocket in fresh groundwater: fingering process
320*160 cells
Time= 0 min
z [m]
x [m]


cases
Salt water pocket in a fresh environment (V)
Effect of discretisation


Effect of size model cell on physical process
60 min
Total Dissolved Solutes [mg/l]:

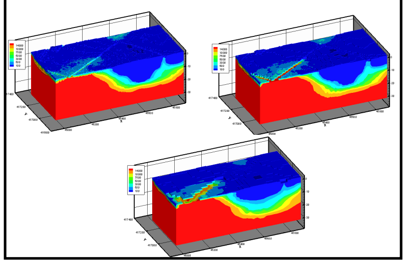

Effect of size model cell on physical process
X
60 min
Total Dissolved Solutes [mg/l]:
X= LOUSY models for predicting exact number of salt water fingers

## Effect of size model cell on physical process



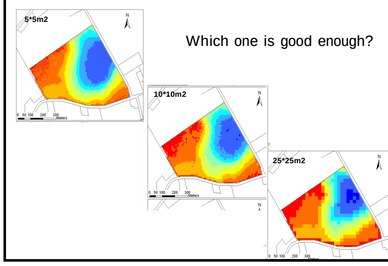

**BUT: all models are GOOD for predicting moment of touching bottom!**

## Different model scales: 5, 10, 25m2

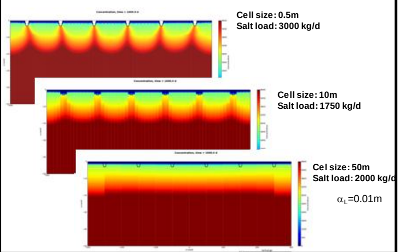


## Different model scales

Which one is good enough?




## Upscaling issues: upconing under ditch



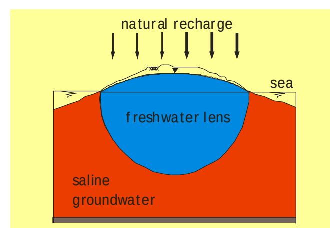

cases

## Salt water pocket in a fresh environment (VI)

Conclusion:

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

## Evolution of a freshwater lens




cases

## Question:

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

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

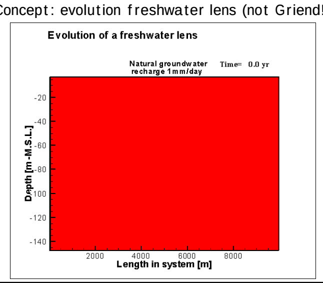
**T = specific time scale**

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

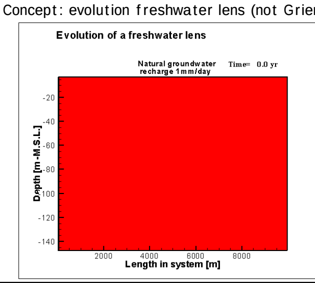
In the Netherlands: T = 75-200 jaar,

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

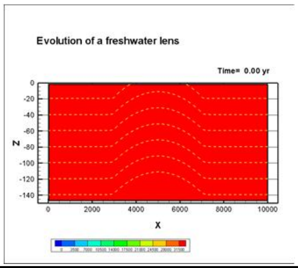
## Concept: evolution freshwater lens (not Griend!)



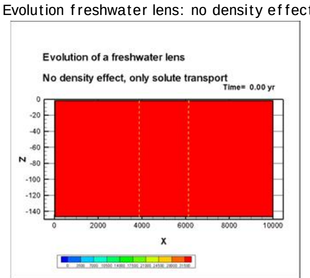

## Concept: evolution freshwater lens (not Griend!)



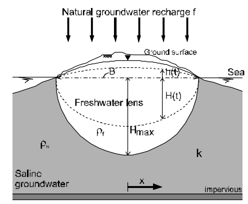
## Evolution freshwater lens



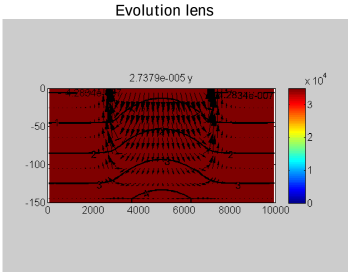

## Evolution freshwater lens: no density effects



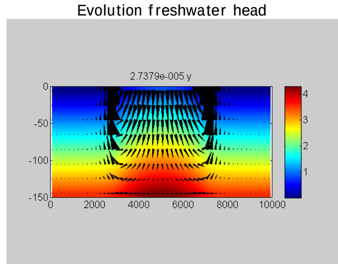

## Case 2: Development of a freshwater lens




## Evolution lens




## Evolution freshwater head

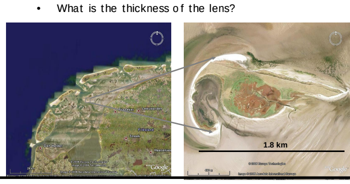



## Evolution freshwater head

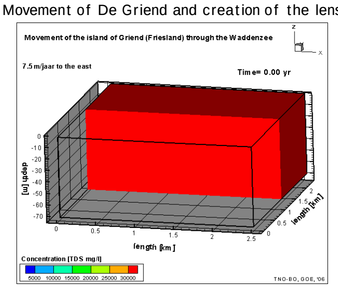
## The island of Griend

Issues:

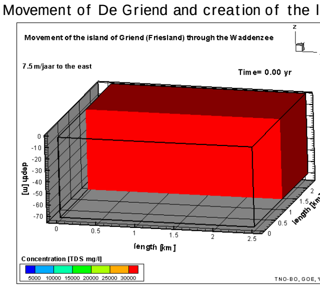
1. Small island moves ~7.5m per year to the east
2. Effect on the volume of the freshwater lens:
   - Can a lens be developed?
   - What is the thickness of the lens?



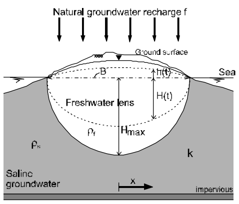

## Movement of De Griend and creation of the lens



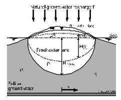

## Movement of De Griend and creation of the lens



Case 2: Development of a freshwater lens

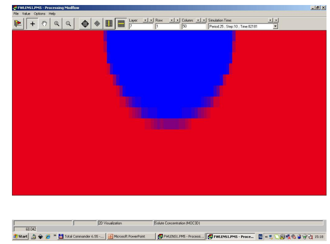



Case 2: Development of a freshwater lens

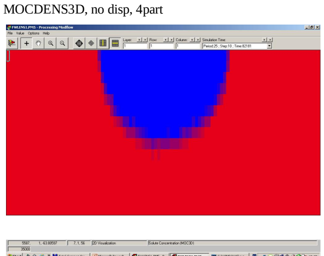


| Parameters | | | |
|---|---|---|---|
| Layers | 15 | $K_{hor}$ | 20 m/d |
| Rows | 1 | T | 200 m/d |
| Columns | 100 | Anisotropy $K_{hor}/K_{ver}$ | 10 |
| $\Delta x$ | 100 m | ne | 0.35 |
| $\Delta y$ | 10 m | $\alpha L$ | 0 m |
| $\Delta z$ | 10 m | $\alpha T$ | 0 m |
| Stress periods | 10 | recharge | 360 mm/y |
| Initial concentration | 35000 mg/l | Recharge concentration | 0 mg/l |
| bouyancy | 0.025 | | |

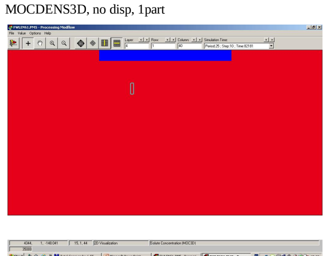
MOCDENS3D, no disp, 16part



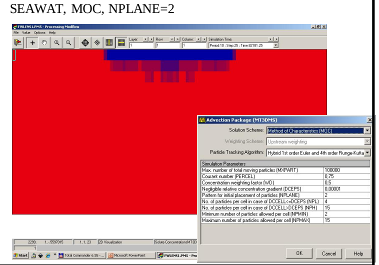
MOCDENS3D, no disp, 4part



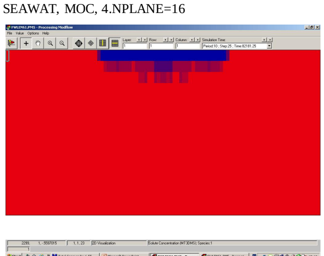
MOCDENS3D, no disp, 1part



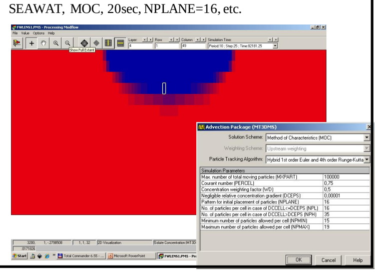
SEAWAT, MOC, NPLANE=2



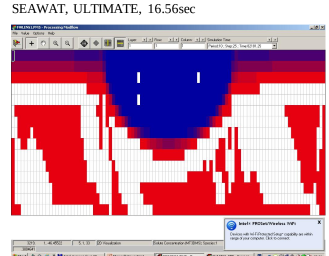
SEAWAT, MOC, 4.NPLANE=16



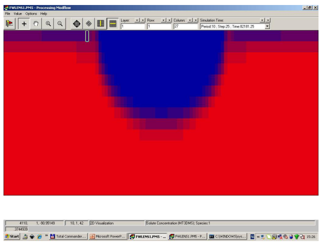
SEAWAT, MOC, 20sec, NPLANE=16, etc.



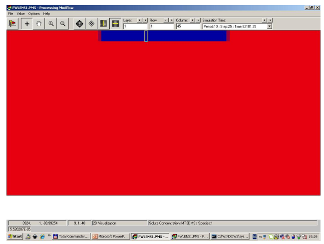
SEAWAT, ULTIMATE, 16.56sec



SEAWAT, MMOC, 8.5sec

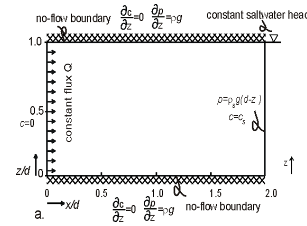


SEAWAT, HMOC, 6.8sec



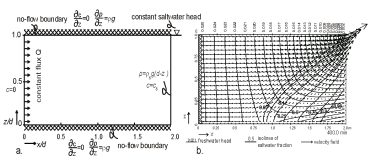


Henry's problem (1964)



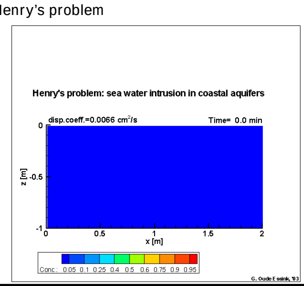



Henry's problem






Henry's problem





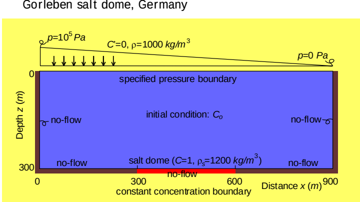

Henry's problem

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



Hydrocoin:

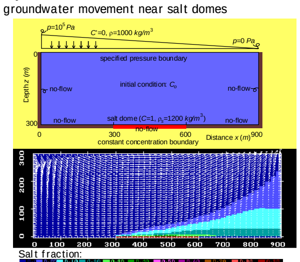
disposal of high-level nuclear waste
groundwater movement near salt domes
Gorleben salt dome, Germany






Hydrocoin:

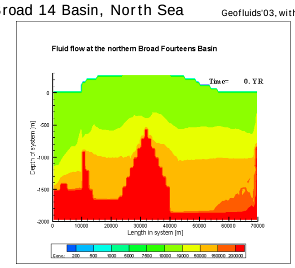
groundwater movement near salt domes






Broad 14 Basin, North Sea

Geofluids'03, with L. Bouw

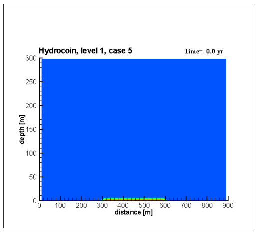



Bouw, L. & Oude Essink, G.H.P. 2003. Development of a freshwater lens in the inverted Broad Fourteens Basin, Netherlands offshore. J. of Geochemical Exploration (78-79), 321-325.

cases

## Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

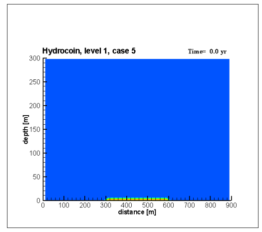



*recirculation type*

cases

## Hydrocoin: effect of boundary condition (I)

supply of brine through advection and hydrodynamic dispersion

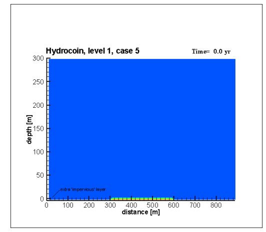



*recirculation type*

cases

## Hydrocoin: effect of boundary condition (II)

supply of brine through only hydrodynamic dispersion

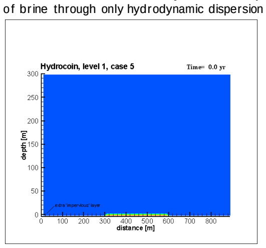



*swept-forward type*

cases

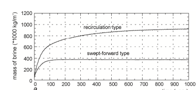
## Hydrocoin: effect of boundary condition (II)

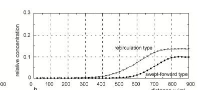
supply of brine through only hydrodynamic dispersion




*swept-forward type*

## Hydrocoin: difference recirculation vs swept forward



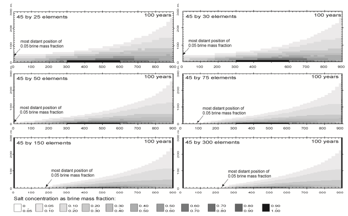




total mass of brine

brine conc at depth=200m

*Lecture notes, p. 86-91*

## Hydrocoin: effect of vertical grid size

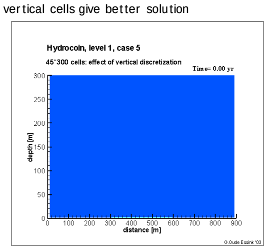



Recirculation type

cases

## Hydrocoin: effect of vertical discretization (III)

more vertical cells give better solution

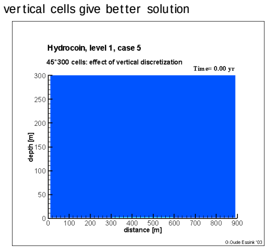



*like the swept-forward type*

cases

## Hydrocoin: effect of vertical discretization (III)

more vertical cells give better solution

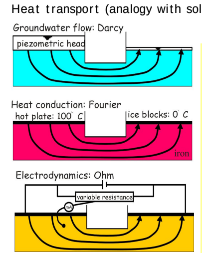



*like the swept-forward type*

cases

## Analogy physical processes

Heat transport (analogy with solute transport)




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

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

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

## Conduction and convection of heat

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

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

thermal conductivity [Joule/(ms °C)]

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

continuity equation

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

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

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



## Analogy solute and heat transport

Solute: advection-dispersion equation

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

Heat: convection-conduction equation

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



## Analogy heat and solute transport

Heat transport

Convection-conduction equation

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

Equation of state: relation density & temperature

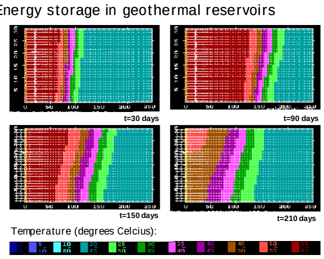
$$\rho_{i,j,k} = \rho_f (1 - \alpha_f T_{i,j,k})$$

Analogy between solute and heat transport

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



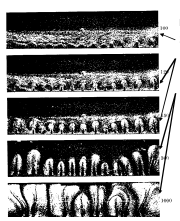
## Energy storage in geothermal reservoirs






## Elder problem (I)

It is originally a heat transport problem



Phases:

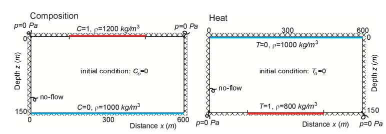
1. Stable growth diffusive boundary layer
2. Development flow cells embedded in boundary layer
3. Emergence of disturbances that grow into fingers

Convection of heat occurs when:
Rayleigh number > $4\pi^2$

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

## Elder problem (II)

Anology composition and heat

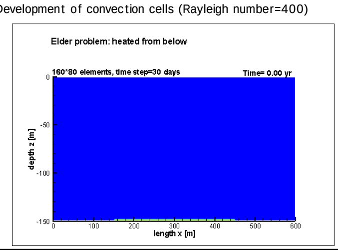



*Lecture notes, p. 91-96*



## Elder problem (III)

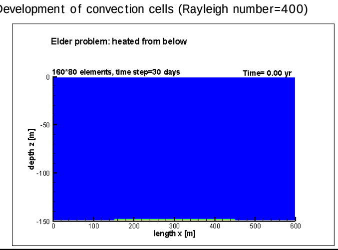
Development of convection cells (Rayleigh number=400)





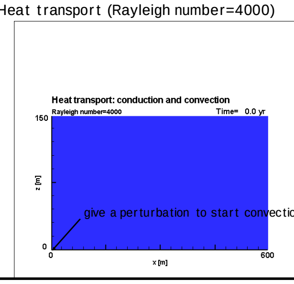

## Elder problem (III)

Development of convection cells (Rayleigh number=400)






## Heat transport (Rayleigh number=4000)



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

Sri Lanka
Some days after December 26th, 2004

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

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

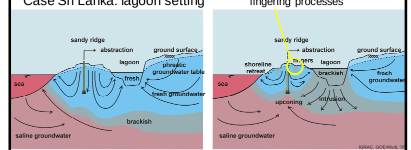
1. Fingering processes in the subsoil
2. Evolution of a freshwater lens after flooding by sea water
3. Freshwater lens in a coastal aquifer with a brackish lagoon

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

## Concept 1: Fingering processes in the subsoil

Case Sri Lanka: lagoon setting

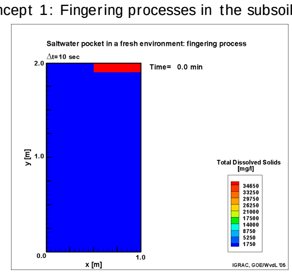
fingering processes



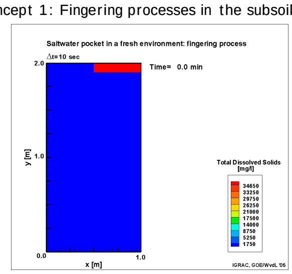

Before the Tsunami

After the Tsunami

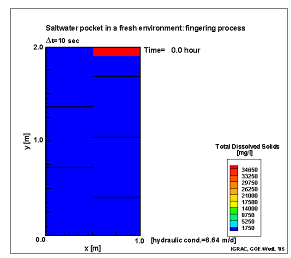
## Concept 1: Fingering processes in the subsoil



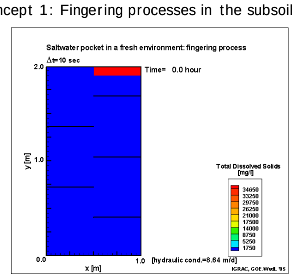

## Concept 1: Fingering processes in the subsoil



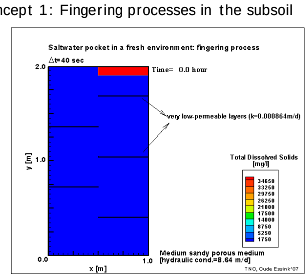

## Concept 1: Fingering processes in the subsoil



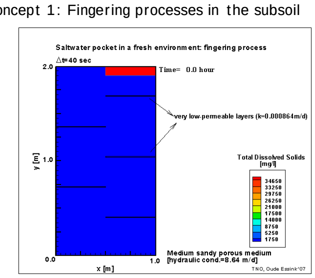

## Concept 1: Fingering processes in the subsoil



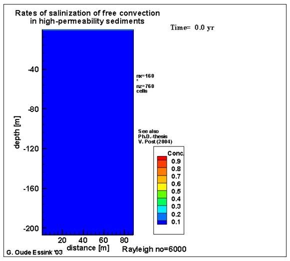

## Concept 1: Fingering processes in the subsoil



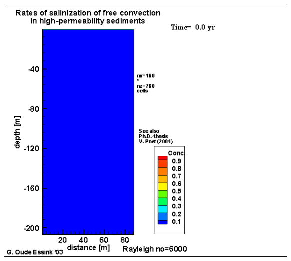

## Concept 1: Fingering processes in the subsoil



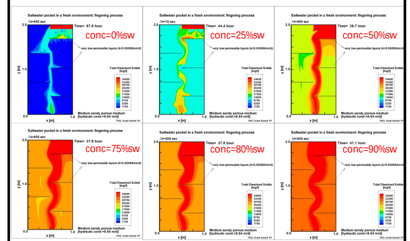
## Concept 1: Fingering processes in the subsoil



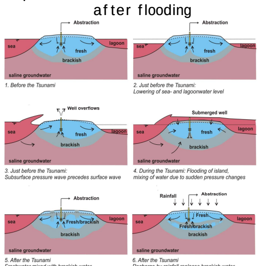

## Concept 1: Fingering processes in the subsoil




## Fingering processes in the subsoil




## Concept 2: Evolution of a freshwater lens after flooding

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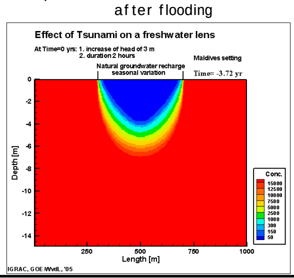
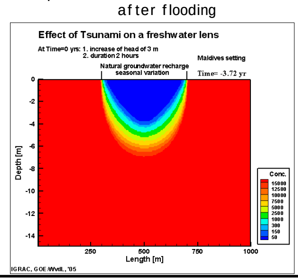
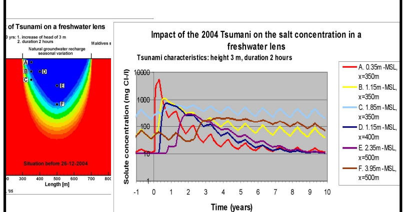



## Concept 2: Evolution of a freshwater lens after flooding

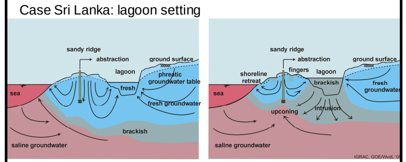



## Concept 2: Evolution of a freshwater lens after flooding

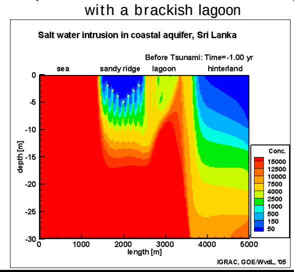



## Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

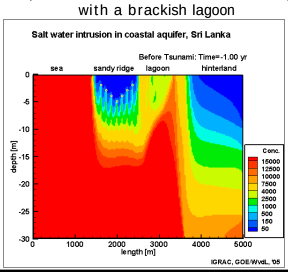
Case Sri Lanka: lagoon setting



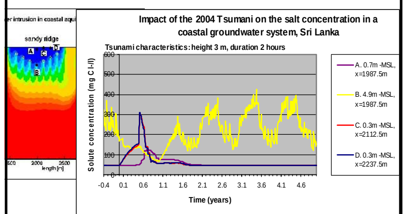

## Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon



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




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

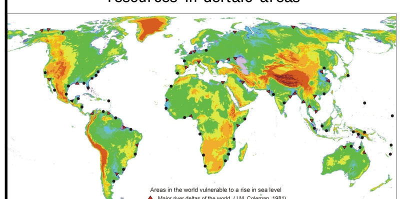



# Effect sea level rise

## Effects of sea level rise on groundwater resources in deltaic areas

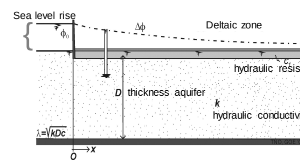
1. Increase of salt water intrusion
2. Increase of upconing under groundwater extraction wells
3. Increase of piezometric head
4. Increase of seepage and salt load to the surface water system
5. Risk of instable Holocene aquitards
6. [Decrease of fresh groundwater reservoirs due to decrease in natural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

## Effects of sea level rise on groundwater resources in deltaic areas




Digital Elevation Model (DEM)

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



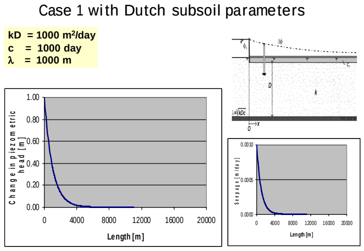

$$\Delta\phi(x)=\phi_0 e^{-x/\lambda}$$

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

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

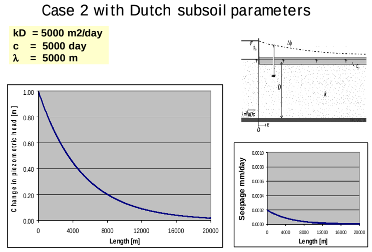
## Effect of sea level rise: Case 1 with Dutch subsoil parameters

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



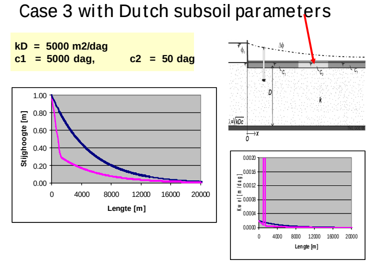

## Effect of sea level rise: Case 2 with Dutch subsoil parameters

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



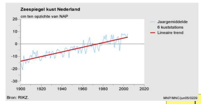

## Case 3 with Dutch subsoil parameters

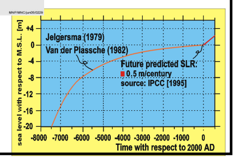
**kD = 5000 m2/dag**
**c1 = 5000 dag, c2 = 50 dag**



## Climate change is HOT!

## Past and future sea level rise in the Netherlands



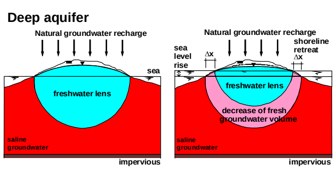




## Implementing new KNMI06 climate scenarios

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

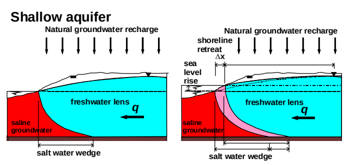


## Effect of a relative sea level rise (1):



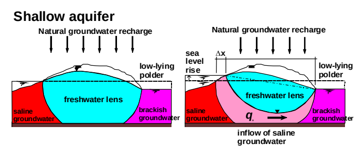



## Effect of a relative sea level rise (2):

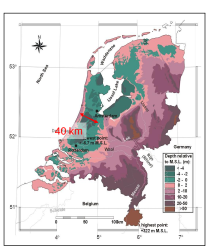


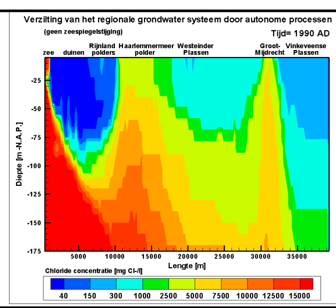


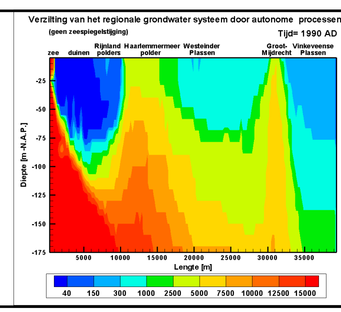

## Effect of a relative sea level rise (3):

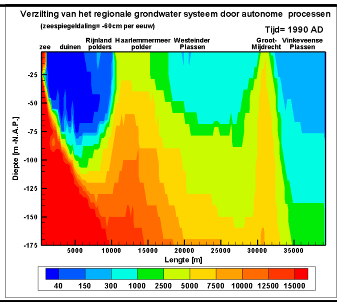


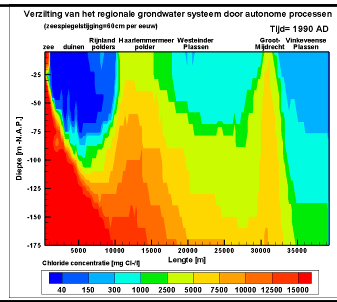

## 2D Profile and effect sea level rise

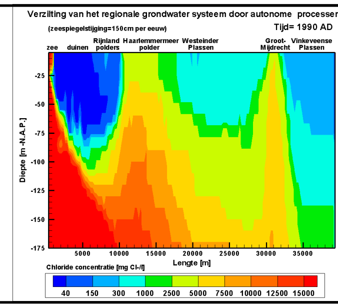


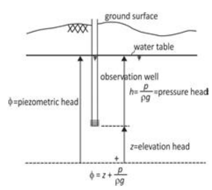



## Point water head and Freshwater head $\phi_f$

## Piezometric head $\phi$




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

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

## Freshwater head $\phi_f$

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

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

## Freshwater head $\phi_f$

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

$$\phi_f = h_f + z$$

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

e.g.:
$\rho_s$=1025kg/m3
$h$=10m
$\phi_f$=10.25m

## Special case: hydrostatic pressure: $q_z$=0

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

*no vertical flow*

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

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

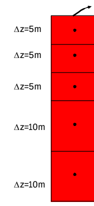
$$\phi_{f2} = \phi_{f1} - \frac{\rho - \rho_f}{\rho_f}(z2 - z1)$$

↓+

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

## Hydrostatic boundary condition at the sea

Water level=+0m MSL




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

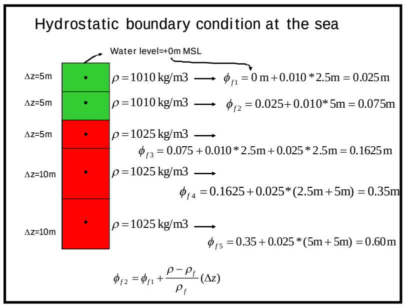
$\rho = 1025$ kg/m3 → $\phi_{f2} = 0.0625 + 0.025 * 5\text{m} = 0.1875\text{m}$

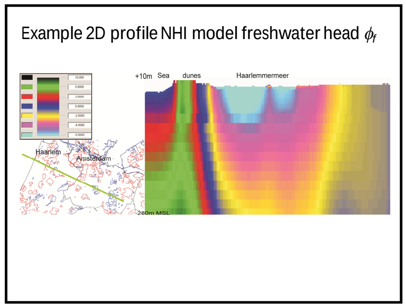
$\rho = 1025$ kg/m3 → $\phi_{f3} = 0.1875 + 0.025 * 5\text{m} = 0.3125\text{m}$

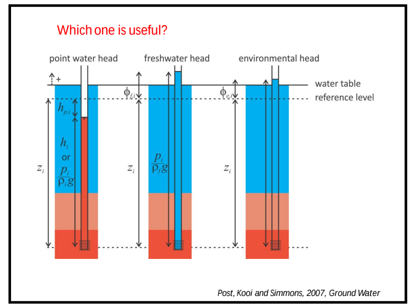
$\rho = 1025$ kg/m3 → $\phi_{f4} = 0.3125 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.50\text{m}$

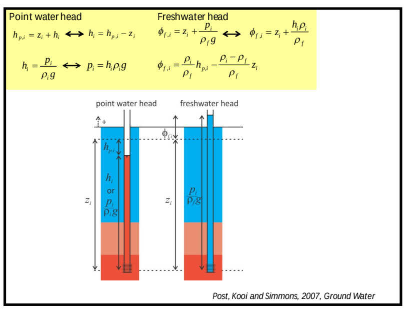
$\rho = 1025$ kg/m3 → $\phi_{f5} = 0.50 + 0.025 * (5\text{m} + 5\text{m}) = 0.75\text{m}$

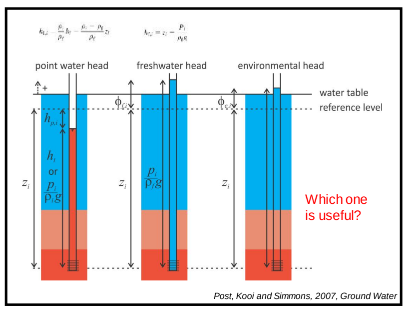
$$\phi_{f2} = \phi_{f1} + \frac{\rho - \rho_f}{\rho_f}(\Delta z)$$

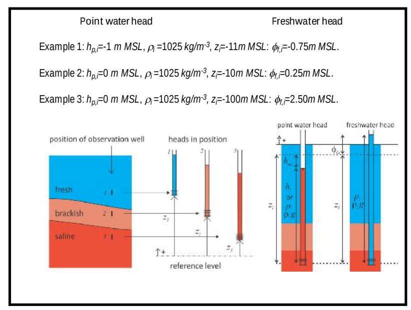

Hydrostatic boundary condition at the sea
Water level=+0m MSL
Δz=5m
Δz=5m
Δz=5m
Δz=10m
Δz=10m
$\rho = 1010$ kg/m3 ⟶ $\phi_{f1} = 0\,\text{m} + 0.010 * 2.5\text{m} = 0.025\text{m}$
$\rho = 1010$ kg/m3 ⟶ $\phi_{f2} = 0.025 + 0.010 * 5\text{m} = 0.075\text{m}$
$\rho = 1025$ kg/m3 ⟶ $\phi_{f3} = 0.075 + 0.010 * 2.5\text{m} + 0.025 * 2.5\text{m} = 0.1625\text{m}$
$\rho = 1025$ kg/m3 ⟶ $\phi_{f4} = 0.1625 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.35\text{m}$
$\rho = 1025$ kg/m3 ⟶ $\phi_{f5} = 0.35 + 0.025 * (5\text{m} + 5\text{m}) = 0.60\text{m}$
$\phi_{f2} = \phi_{f1} + \frac{\rho - \rho_f}{\rho_f}(\Delta z)$

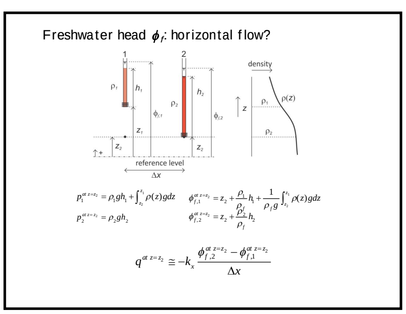

Example 2D profile NHI model freshwater head $\phi_f$
+10m
Sea
dunes
Haarlemmermeer
Haarlem
Amsterdam
-260m MSL

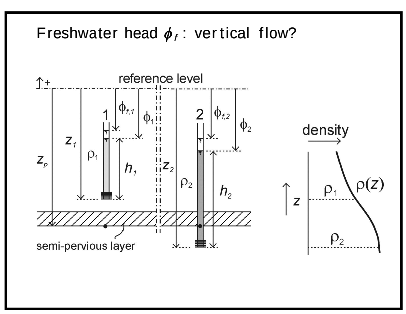

Which one is useful?
point water head
freshwater head
environmental head
water table
reference level
Post, Kooi and Simmons, 2007, Ground Water

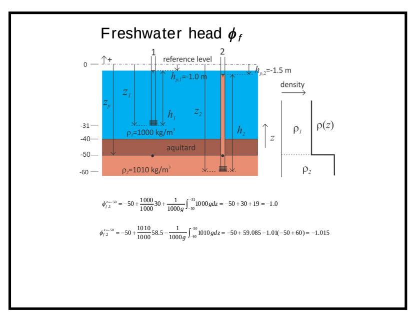

Point water head
Freshwater head
$h_{p,i} = z_i + h_i \leftrightarrow h_i = h_{p,i} - z_i$
$\phi_{f,i} = z_i + \frac{p_i}{\rho_f g} \leftrightarrow \phi_{f,i} = z_i + \frac{h_i \rho_i}{\rho_f}$
$h_i = \frac{p_i}{\rho_i g} \leftrightarrow p_i = h_i \rho_i g$
$\phi_{f,i} = \frac{\rho_i}{\rho_f} h_{p,i} - \frac{\rho_i - \rho_f}{\rho_f} z_i$
point water head
freshwater head
Post, Kooi and Simmons, 2007, Ground Water

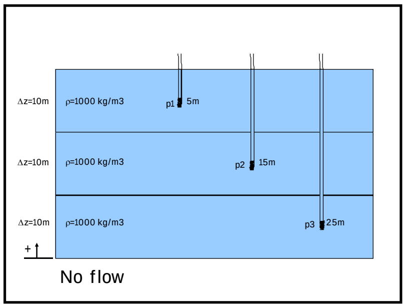

point water head
freshwater head
environmental head
water table
reference level
Which one is useful?
Post, Kooi and Simmons, 2007, Ground Water

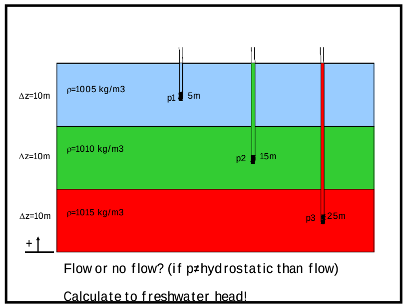

Point water head
Freshwater head
Example 1: $h_{p,i}$=-1 m MSL, $\rho_i$=1025 kg/m$^{-3}$, $z_i$=-11m MSL: $\phi_{f,i}$=-0.75m MSL.
Example 2: $h_{p,i}$=0 m MSL, $\rho_i$=1025 kg/m$^{-3}$, $z_i$=-10m MSL: $\phi_{f,i}$=0.25m MSL.
Example 3: $h_{p,i}$=0 m MSL, $\rho_i$=1025 kg/m$^{-3}$, $z_i$=-100m MSL: $\phi_{f,i}$=2.50m MSL.
position of observation well
heads in position
fresh
brackish
saline
reference level
point water head
freshwater head

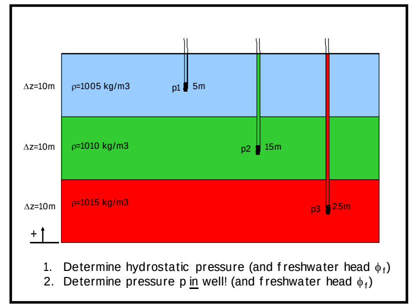

Freshwater head $\phi_f$: horizontal flow?
density
reference level
$\Delta x$
$q^{at\ z=z_2} \cong -k_x \frac{\phi_{f,2}^{at\ z=z_2} - \phi_{f,1}^{at\ z=z_2}}{\Delta x}$

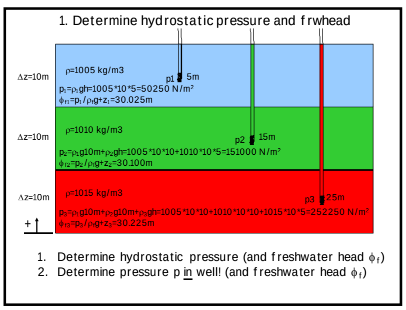

Freshwater head $\phi_f$ : vertical flow?
reference level
density
semi-pervious layer
$\rho(z)$

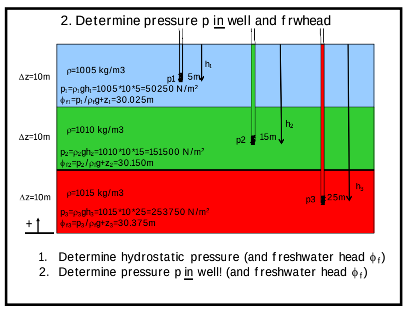

Freshwater head $\phi_f$
reference level
density
aquitard
$\rho_f$=1000 kg/m$^3$
$\rho_s$=1010 kg/m$^3$

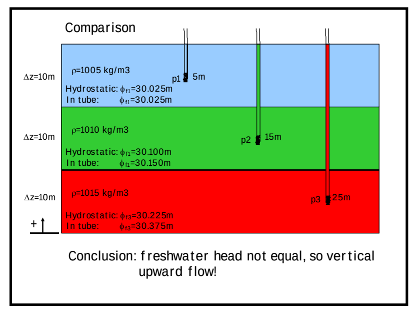


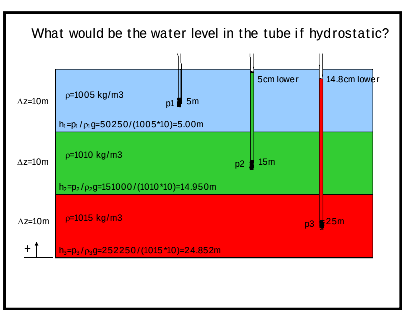



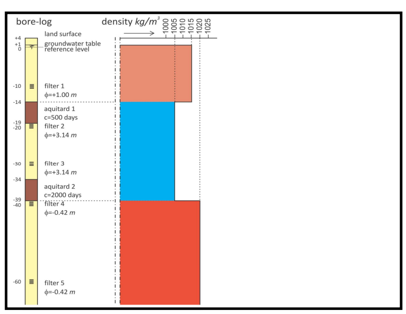



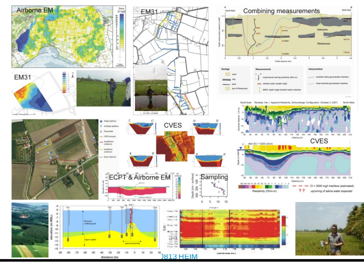




## Take home message

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

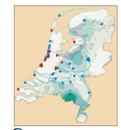
# Monitoring

Different (fresh-salt) monitoring techniques




## Monitoring salt in groundwater

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



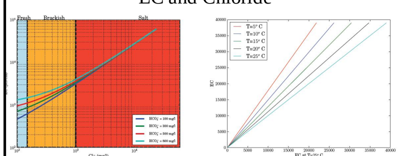
Pumpingstations with salinisation

Pumpingstations closed due to salinisation

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

Source: V. Post, 2007

## EC and Chloride




EC-Cl at different $HCO_3^-$ concentrations. (b) EC and temperature standardized EC.

P. Pauw, 2009

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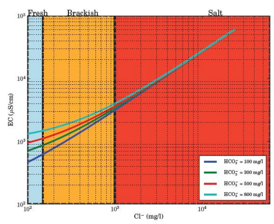
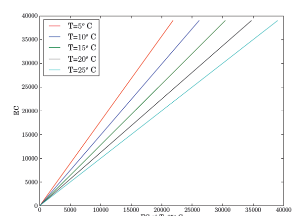
## EC and Chloride




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

## EC and Chloride




2( (b) EC and temperature standardized EC.

## Airborne measurements

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

*Source: Koos Groen*

## Surface measurements

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

Source: Koos Groen

## Cone Penetration Tests

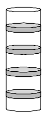
| Measuring system | Physical parameter | Geology/terrain information |
|---|---|---|
| mechanical CPT | Cone resistance<br>Friction resistance | Lithology<br>Geotechnical parameters |
| Electrical conductivity | Electrical formation conductivity | Water salinity |
| Contnuous water pressure | Water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

*Source: Koos Groen*

## Monitoring salt in groundwater: Direct methods

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

Direct methods 1 and 2



Source: V. Post, 2007

## Monitoring salt in groundwater: Indirect methods

Indirect methods measure the **conductance** of:

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

AND

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

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

Source: V. Post, 2007

## Monitoring salt in groundwater: Indirect methods

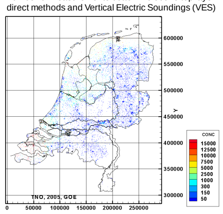
| **Method** | **Advantages** | **Disadvantages** |
|---|---|---|
| 1. Electrical conductance measurements | •High resolution (3D)<br>•Depth ~200 m | •Time consuming |
| 2. Electromagnetic measurements | •Fast | •Limited vertical resolution<br>•Sensitive for underground conductors (pipes) |
| 3. Satellites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

Source: V. Post, 2007

## Method used at Deltares

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

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




Source: Oude Essink et al (2005)

## Electrical conductance measurements

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

Source: TNO

Source: V. Post, 2007

## Electrical conductance measurements

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

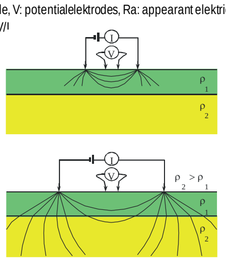
Source: Vitens

Source: V. Post, 2007

Principle geo-elektrical measurement

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

Ra = constant * V/I

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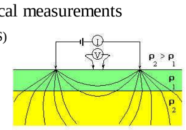
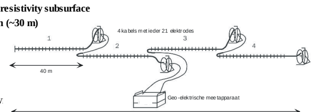
## Types geo-electrical measurements

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



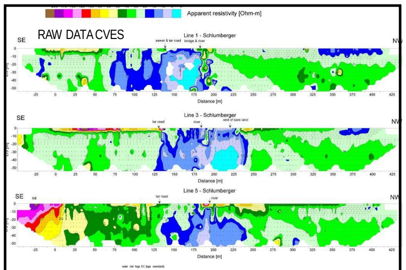

- II Continue Vertical Elektrical Sounding (CVES)
- **>80 elektrodes at surface**
- **2D elektrical resistivity subsurface**
- **Limited depth (~30 m)**

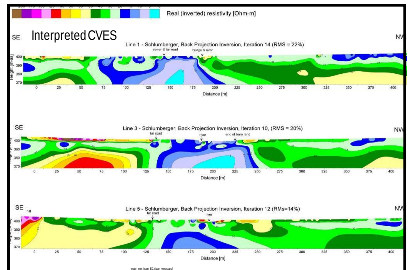


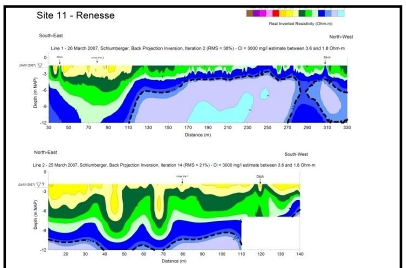

20120622 SW

VES measurement end 1950s/begin 1960s

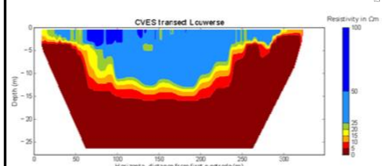
CVES measurements 2010s




Possible measures for sandy creeks




Monitoring salt in groundwater: Indirect methods

- Electrical conductance measurements

$\rho_s = F^* \rho_w$

$\rho_s$ = resistance subsoil & groundwater
$\rho_w$ = resistance groundwater
F = formation factor

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

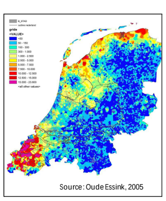
→ *F varies with the resistance of the groundwater*

If the lithology is known AND the measurement is in an aquifer
→ $\rho_w$ can be calculated

VES measurements are used in combination with borehole logging

Source: Oude Essink, 2005

Result: chloride concentration bottom Holocene toplayer



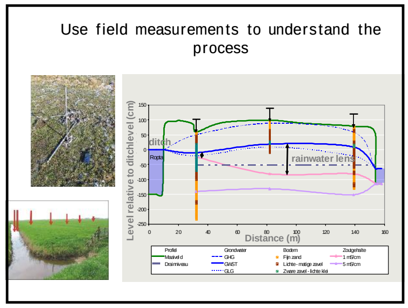
Source: Oude Essink, 2005

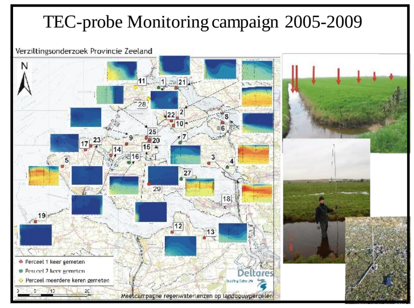
- Software Geological Survey of the Netherlands (TNO) is used to determine the salt concentration of the groundwater in the measurements
- Inter- and extrapolation is used to make a continuous field
- 2D Result is an combination of:
  1. Direct measurements (3500)
  2. Electrical conductance in boreholes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

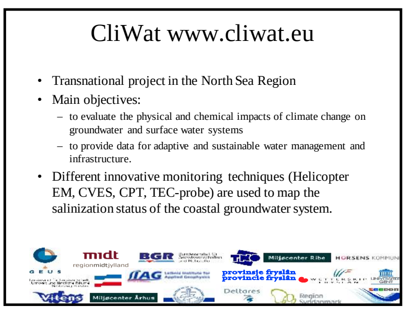
T-EC probe

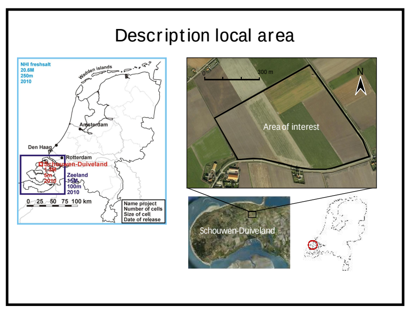
T EC fieldwork

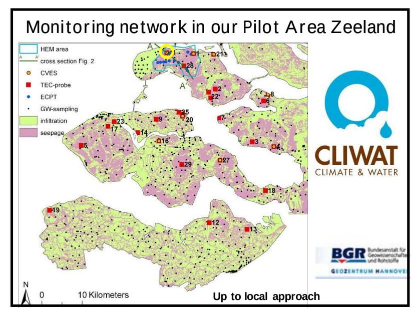
Altitude measurements

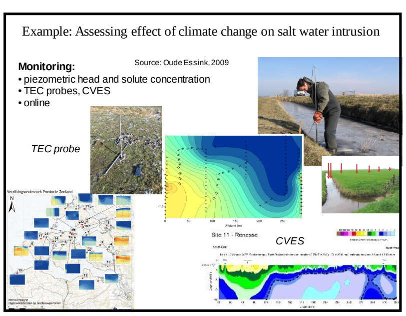

Use field measurements to understand the process
Level relative to ditchlevel (cm)
Distance (m)
ditch
rainwater lens

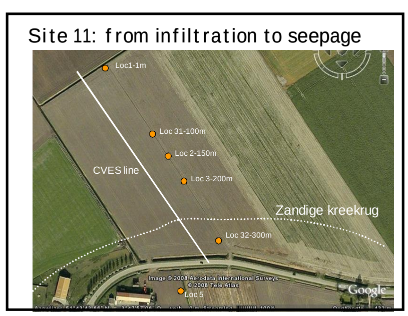

TEC-probe Monitoring campaign 2005-2009
Verziltingsonderzoek Provincie Zeeland
Deltares

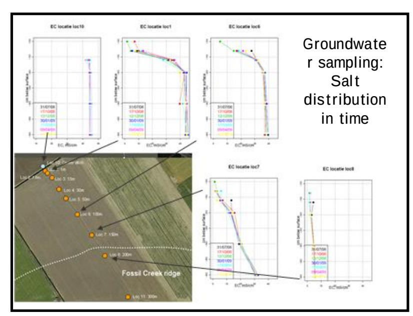

CliWat www.cliwat.eu
• Transnational project in the North Sea Region
• Main objectives:
– to evaluate the physical and chemical impacts of climate change on groundwater and surface water systems
– to provide data for adaptive and sustainable water management and infrastructure.
• Different innovative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


Description local area
Area of interest
Schouwen-Duiveland


Monitoring network in our Pilot Area Zeeland
HEM area
cross section Fig. 2
CVES
TEC-probe
ECPT
GW-sampling
infiltration
seepage
CLIWAT
CLIMATE & WATER
10 Kilometers
Up to local approach


Example: Assessing effect of climate change on salt water intrusion
Monitoring:
Source: Oude Essink, 2009
• piezometric head and solute concentration
• TEC probes, CVES
• online
TEC probe
CVES


Site 11: from infiltration to seepage
Loc1-1m
Loc 31-100m
Loc 2-150m
CVES line
Loc 3-200m
Zandige kreekrug
Loc 32-300m
Google


Groundwater sampling: Salt distribution in time
Fossil Creek ridge