

IHE 2019

Density dependent groundwater flow in the coastal zone

Gualbert Oude Essink, PhD

Lecture set-up:

- PowerPoint sheets
- Lecture Notes
- Practicals numerical modelling

<http://freshsalt.deltares.nl>

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



20-24-25-26 June 2019

Introduction

Curriculum Vitae

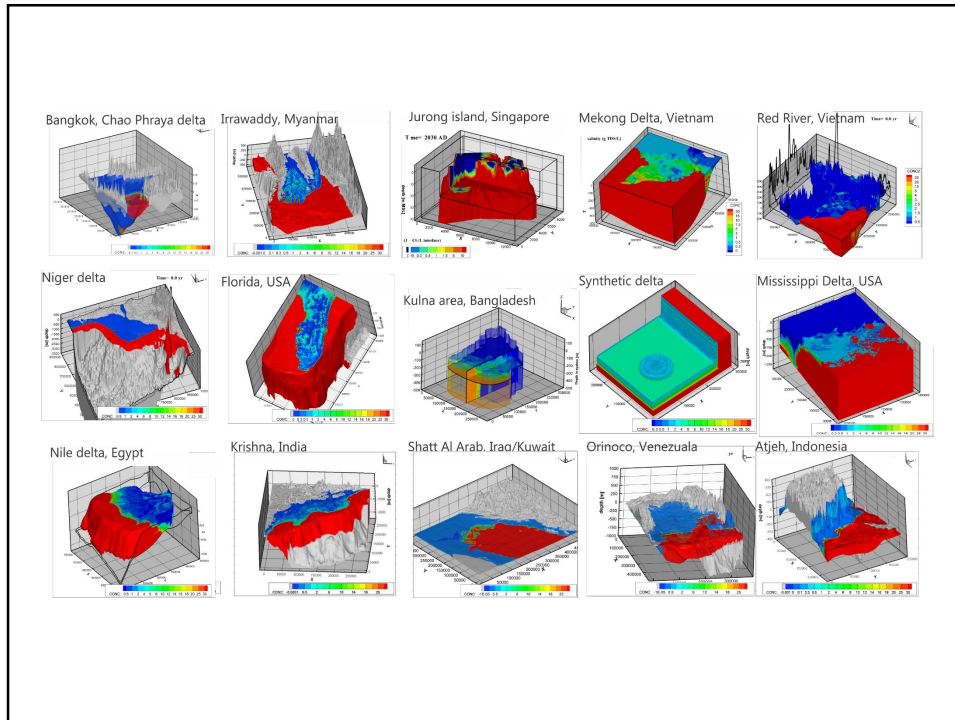
- Delft University of Technology, Civil Engineering: till 1997
Ph.D.-thesis: Impact of sea level rise on groundwater flow regimes
- Utrecht University, Earth Sciences: till 2002
- Free University of Amsterdam, Earth Sciences: till 2004
- Deltares
- Utrecht University (Associate Professor): from 2014

Qualifications:

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

<http://freshsalt.deltares.nl>

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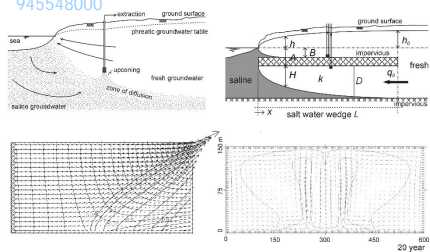
Research on groundwater in the coastal zone

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

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

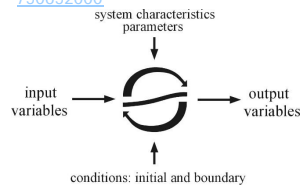
1. Density dependent groundwater flow

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



2. Groundwater modelling

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



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

Introduction

Practicals numerical modelling

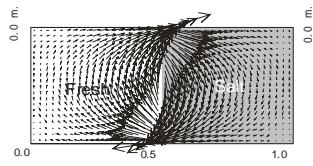
- PMWIN
- SEAWAT
- Cases:
 - Rotating sharp interface
 - Freshwater lens
 - Henry's case
 - (Elder's case)
- Setup practicals:
 - work in small groups of two persons
 - short report of findings (make screenshots)
 - deliver within one week after finish last lectures

<http://freshsalt.deltares.nl>

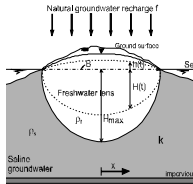
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Practicals

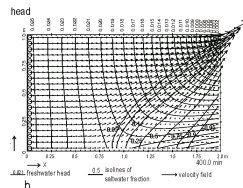
- Rotating sharp interface



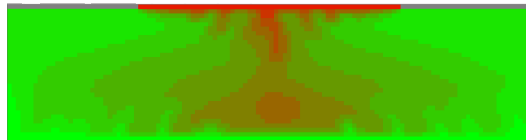
- Freshwater lens



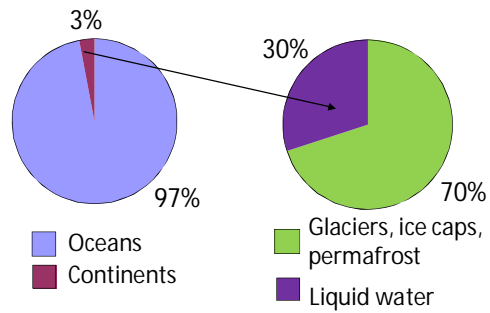
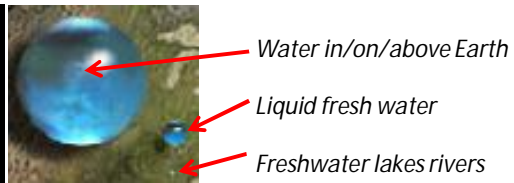
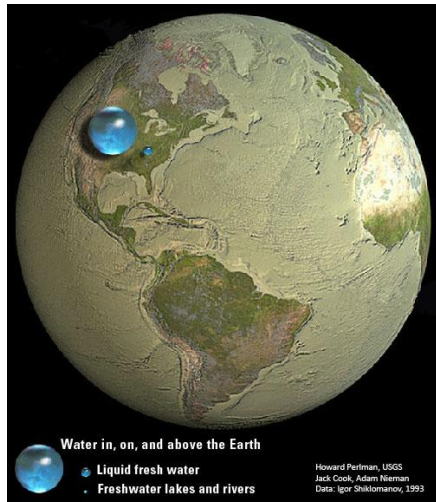
- Henry's case



- (Elder's case)



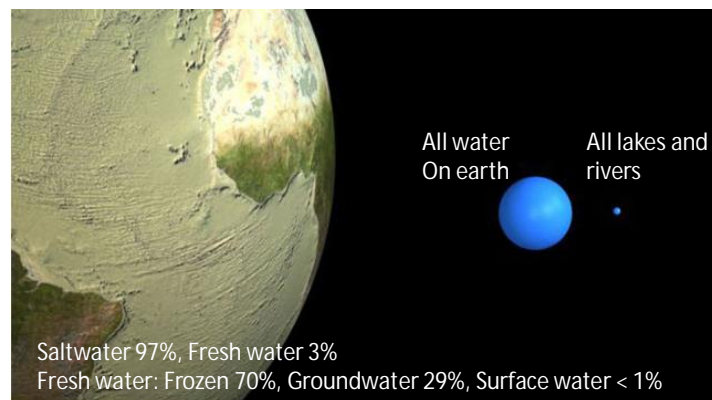
Volumes of water on Earth: a scarce product



Source: Perlman, USGS; Shiklomanov, 1993

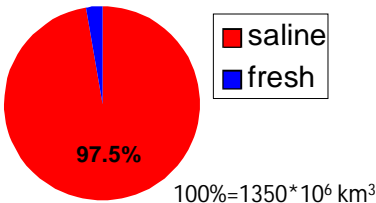
Water Energy Food Nexus Global water scarcity

Fresh water is a scarce resource...

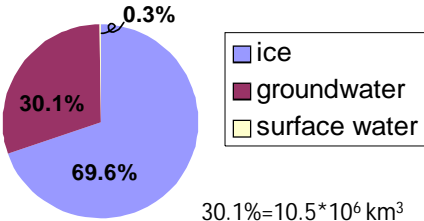


Water on Earth

Total water on Earth



Total fresh water on Earth

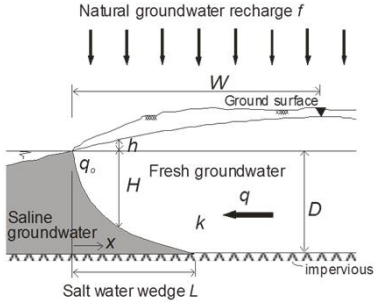
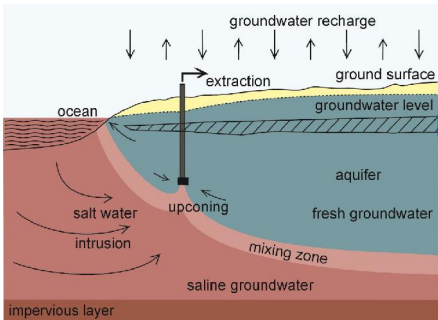


Demand for groundwater (now 30%) increases due to:

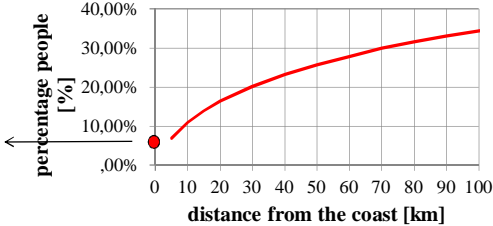
- increase world population & economical growth
- loss of surface water due to contamination
- great resource: available in large quantities
- still unpolluted (relative to surface water)

(Source: Cheng, 1998)

Groundwater in the coastal zone



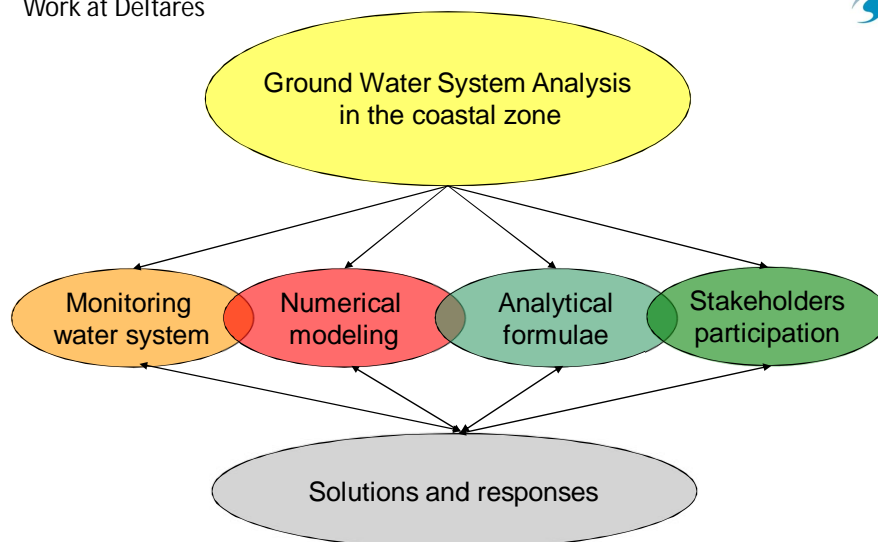
500 million people in the first 5km from the coastline



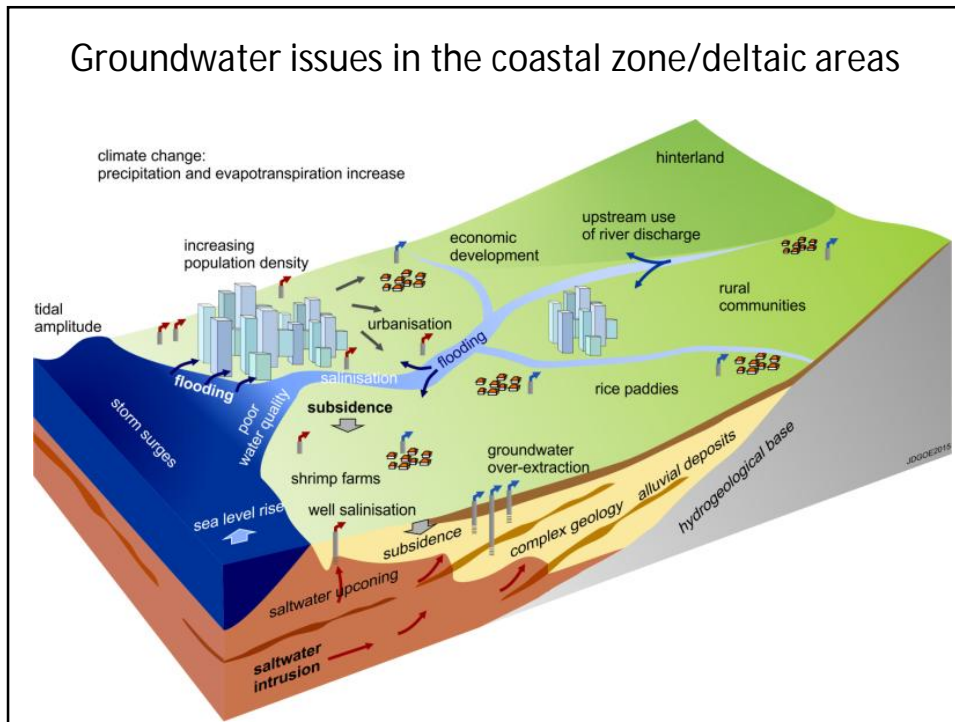
Topics of density driven groundwater flow

1. Introduction
 - water on earth
 - salt water intrusion
 - freshwater head
2. Interface between fresh and saline groundwater
 - analytical formulae (Badon Ghyben-Herzberg)
 - upcoming 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)

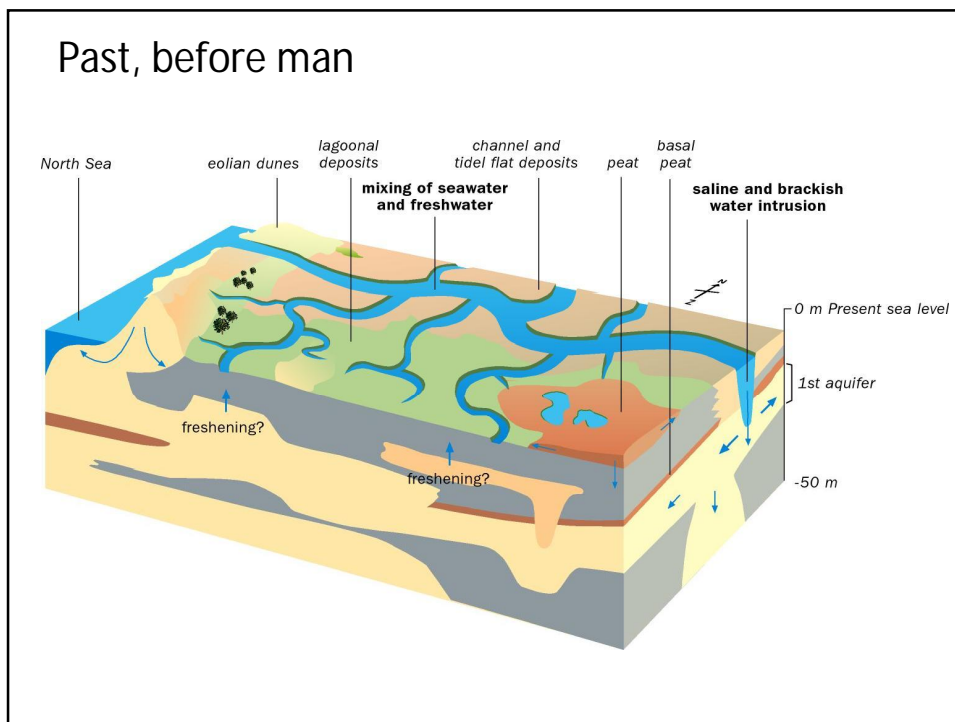
Work at Deltares



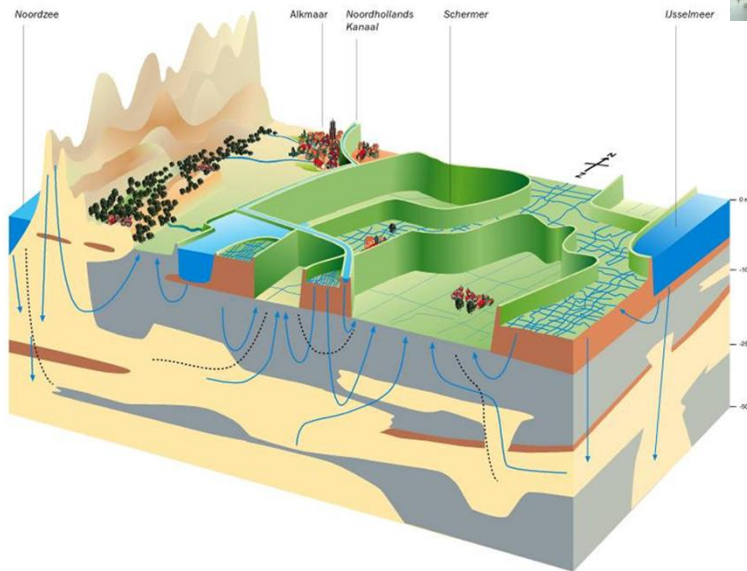
Groundwater issues in the coastal zone/deltaic areas



Past, before man



The polders in the Nederland



Groundwater in the future

We have to cope which...:

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

Direct anthropogenic 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 system analysis
- Monitoring
- Modelling
- Effects
- Solutions



Salt Water Intrusion Meeting (SWIM)

[Home](#) [History](#) [Philosophy](#) [Next meeting](#) [Proceedings](#) [Links](#)

Welcome to the homepage of the Salt Water Intrusion Meeting

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



[SWIM from Alphafilm & Kommunikation on Vimeo.](#)

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

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

www.swim-site.org

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

Salt Water Intrusion Meeting (SWIM)

[Home](#) [History](#) [Philosophy](#) [Next meeting](#) [Proceedings](#) [Links](#)

The proceedings of the Salt Water Intrusion Meeting

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

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

Available for download:

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

For sale (external links)

- [Proceedings of the 12th Salt Water Intrusion Meeting, Barcelona, Spain, 1992](#)
- [Proceedings of the 6th Salt Water Intrusion Meeting, Hannover, Germany, 1979](#)

www.swim-site.org

Salt Water Intrusion Meeting (SWIM)

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

Preface
[A.D. Werner](#)

Posters

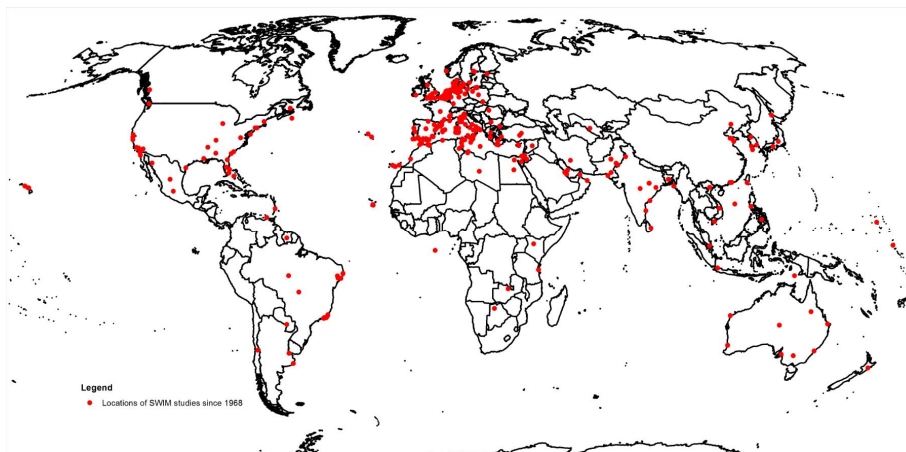
[S. Fatema, A. Marandi, C. Schuyf](#) Seawater Intrusion of the Coastal Groundwater: A Case Study in Cox's Bazar, Bangladesh
[A. Kawachi, C. Uchida, M. Kefi, J. Tarhouni, K. Kashiwagi](#) Effect of Surface Water Use on Mitigation of GW Salinization in a Semi-Arid Coastal Shallow Aquifer Setting: A Case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

Session 1 - Managing Coastal Groundwater I

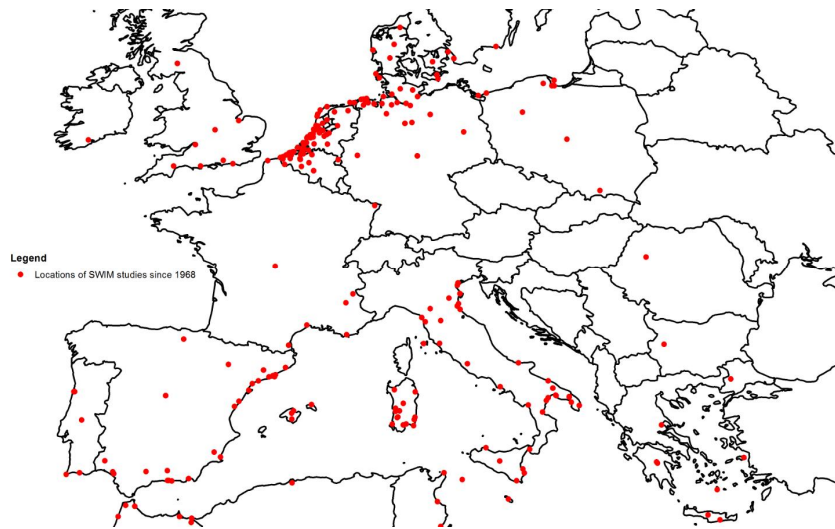
[G.H.P. Oude Essink](#) Fresh Groundwater Resources in Deltaic Areas Under Climate and Global Stresses, with Examples from Vietnam, Egypt, Bangladesh and The Netherlands

www.swim-site.org

Location of SWIM studies since 1968



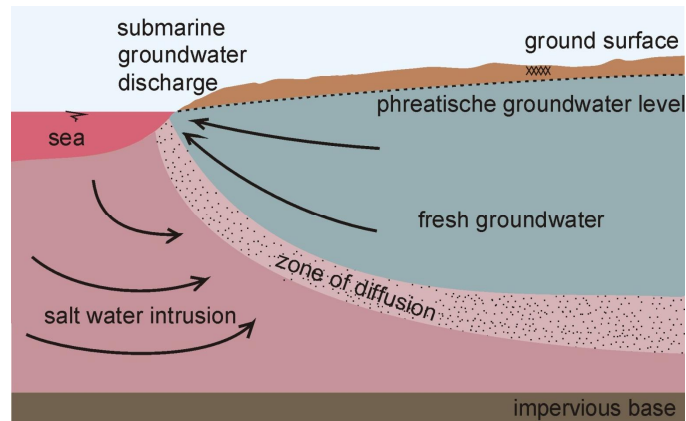
Location of SWIM studies since 1968



Introduction SWI

Definition of salt water intrusion

Inflow of saline water into an aquifer which contains fresh water



Origin of saline groundwater in the subsoil

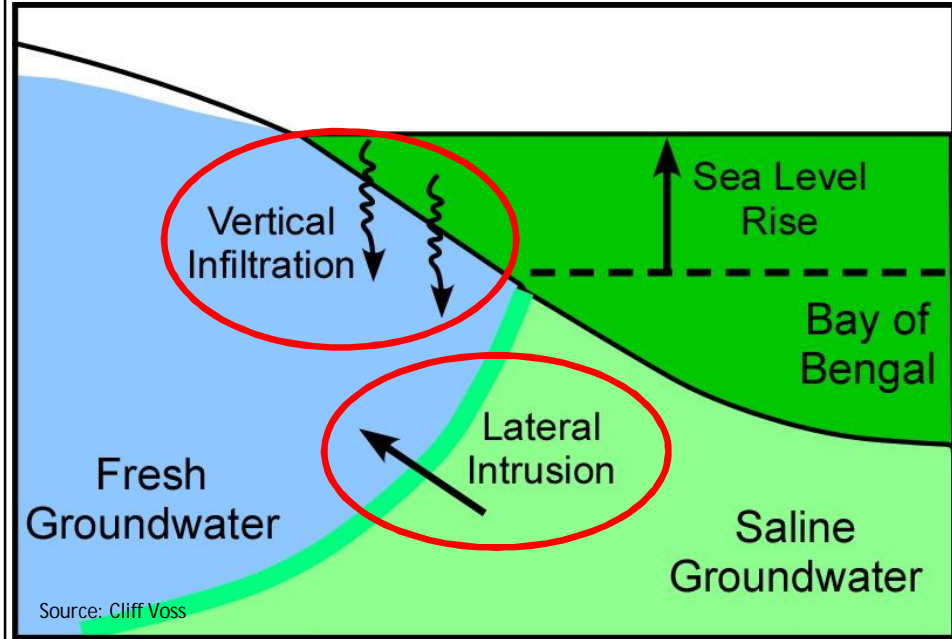
Geological causes:

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

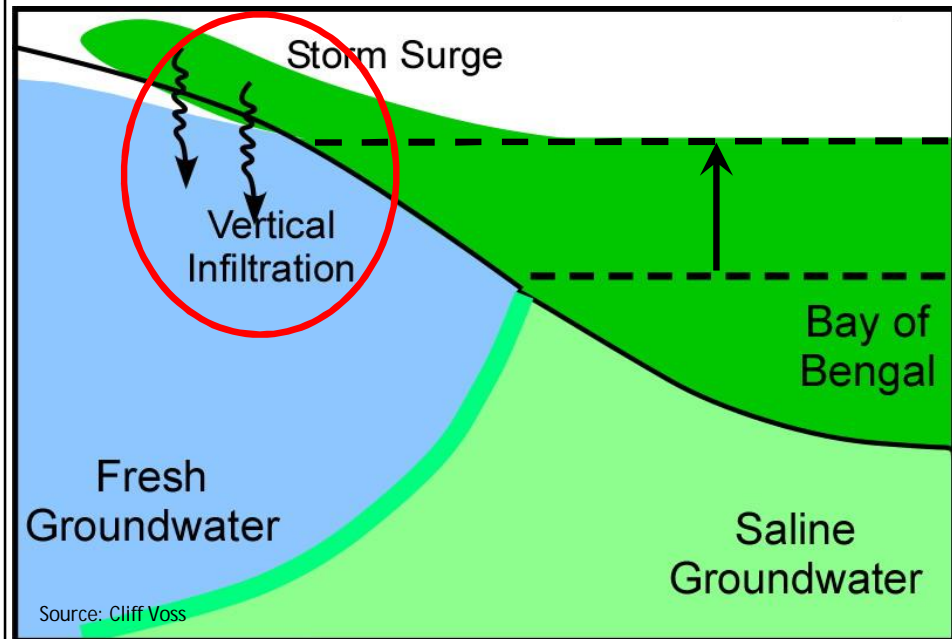
Anthropogenic causes:

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

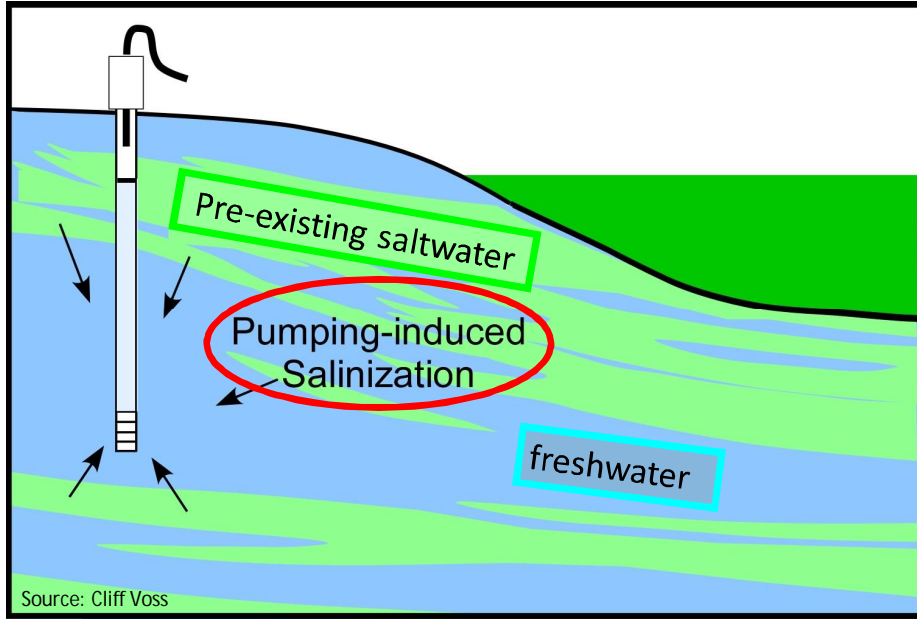
Modes of Salinization due to Sea-Level Rise



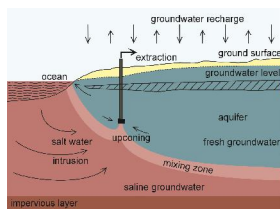
Modes of Salinization due to Sea-Level Rise



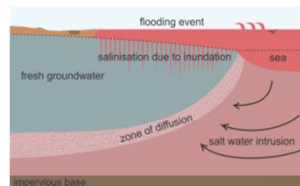
Salinization due to Pumping



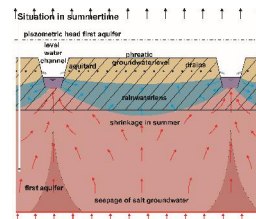
Salinisation processes at local scale



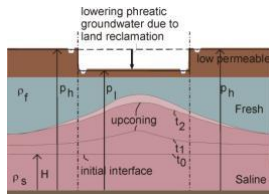
Salt water intrusion groundwater



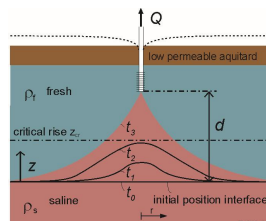
Inundation saline seawater



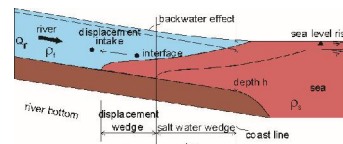
Shallow rainwaterlens



Upconing low-lying area

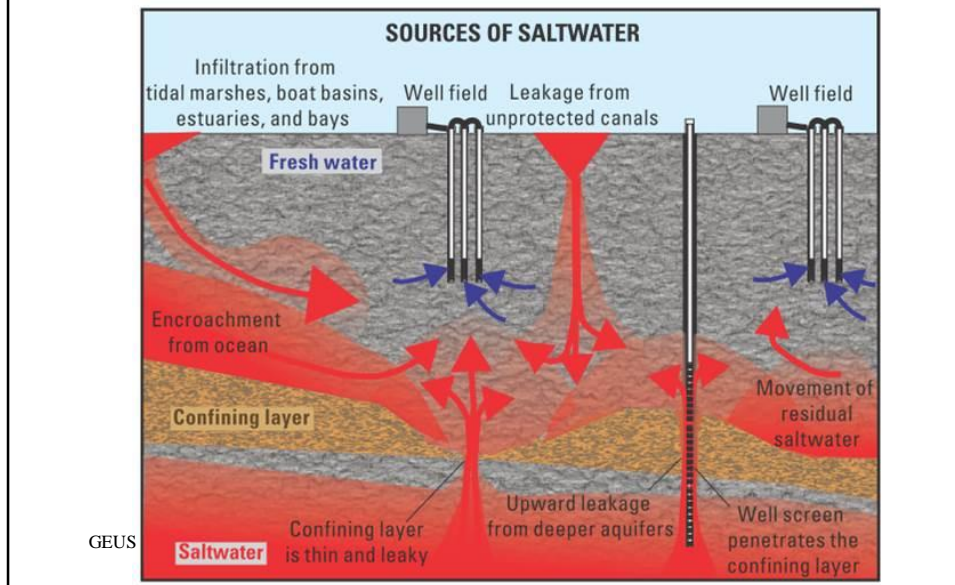


Upconing extraction

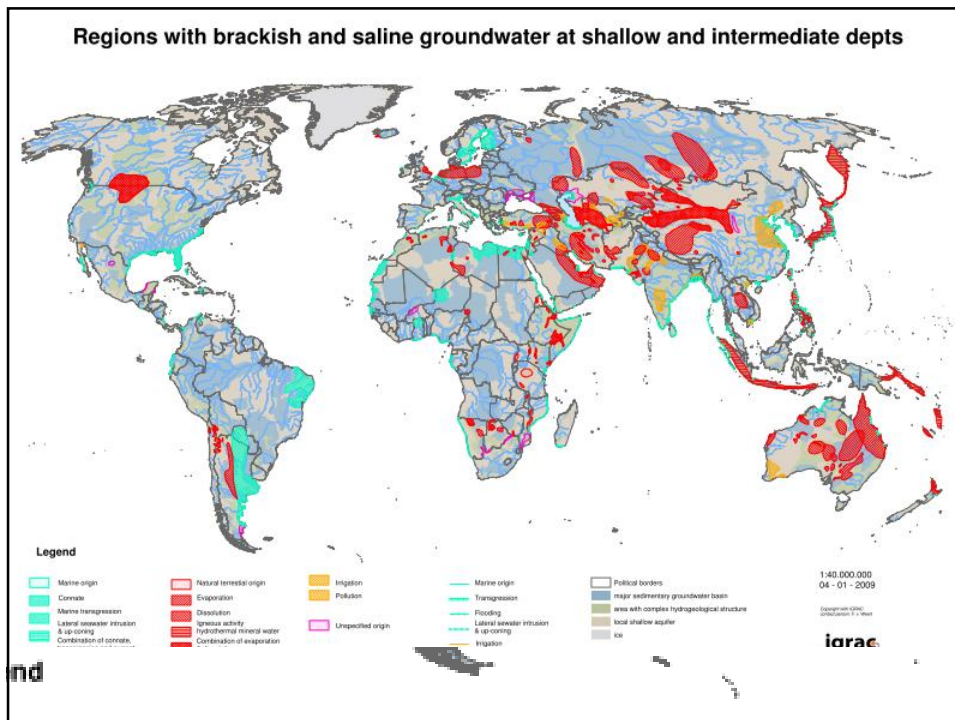


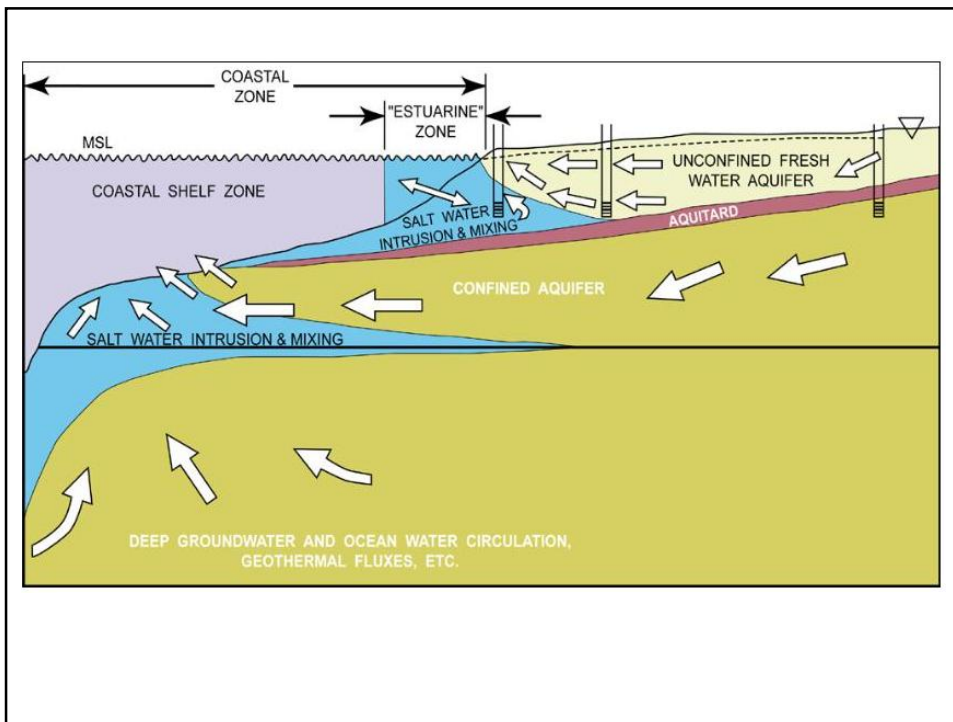
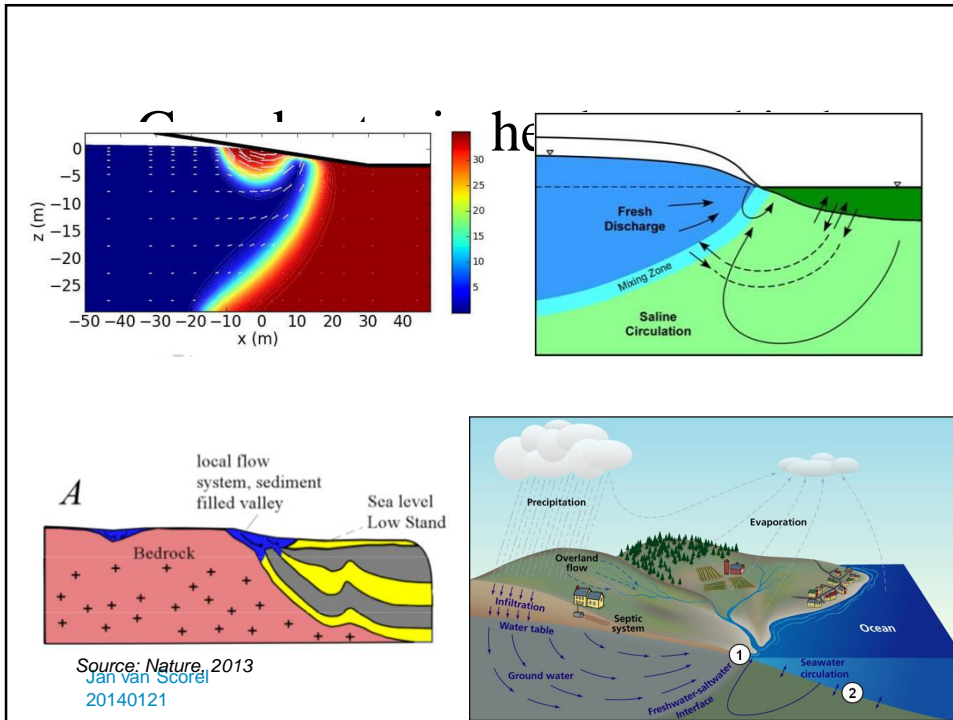
Salt water intrusion surface water

Salinization processes in the coastal zone: combination

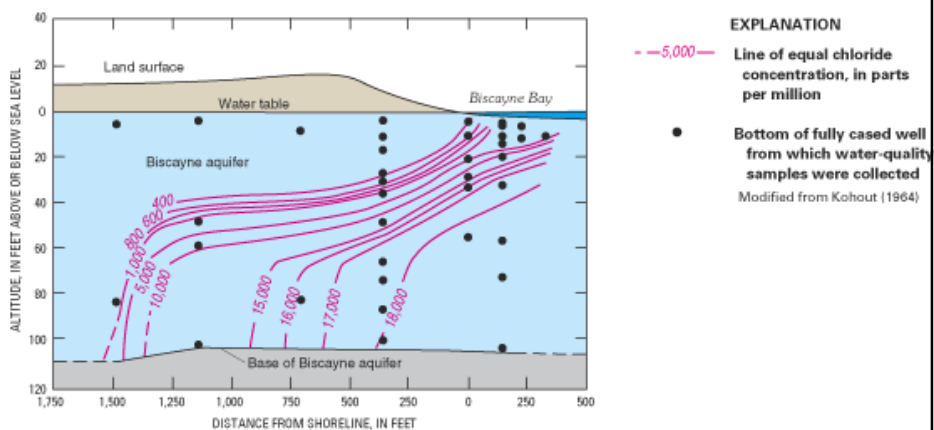


Regions with brackish and saline groundwater at shallow and intermediate depths



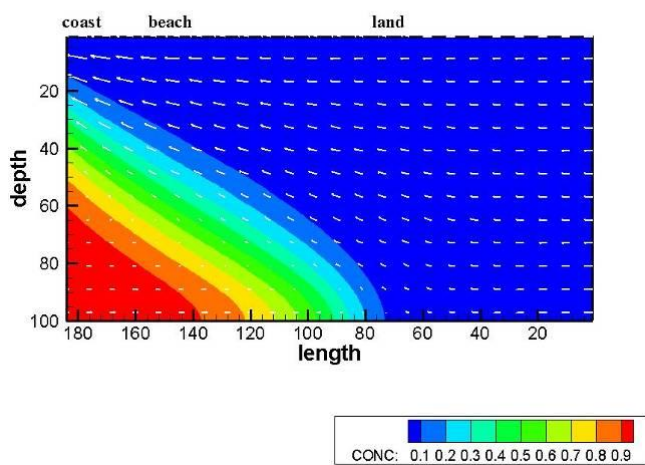


Biscayne aquifer, Florida USA: Henry's case



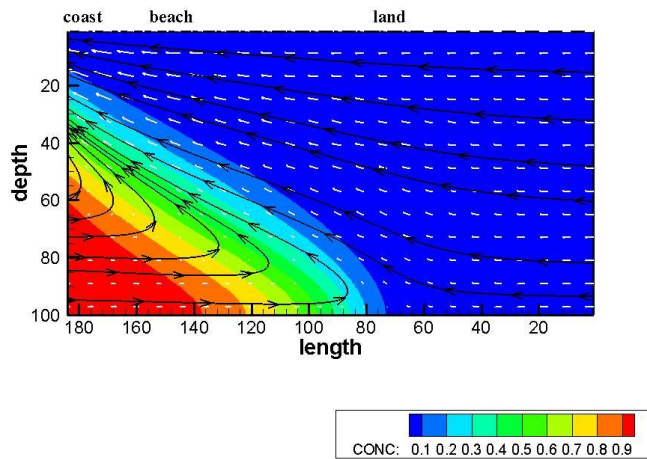
Definition of salt water intrusion

Numerical model: Henry's case



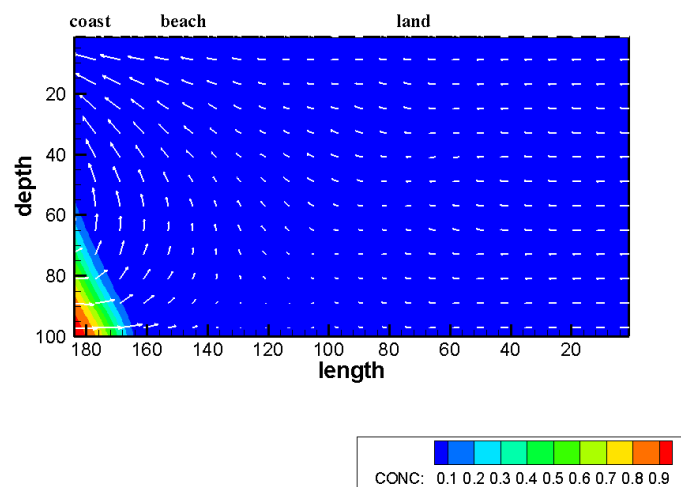
Definition of salt water intrusion

Numerical model: Henry's case



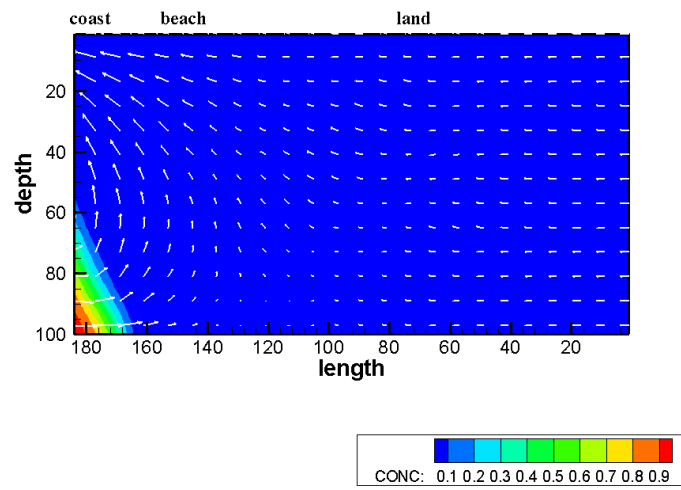
Sea level rise and salt water intrusion

Effect sea level rise on groundwater system in coastal zone



Sea level rise and salt water intrusion

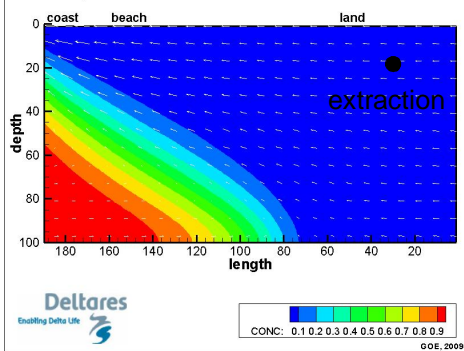
Effect sea level rise on groundwater system in coastal zone



Sea level rise and salt water intrusion

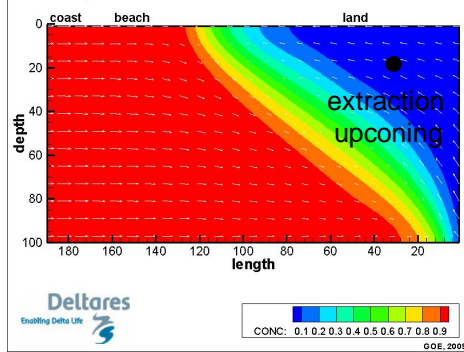
Impact of sea level rise on a coastal groundwater system:

a conceptual model of saltwater intrusion

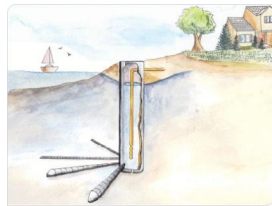
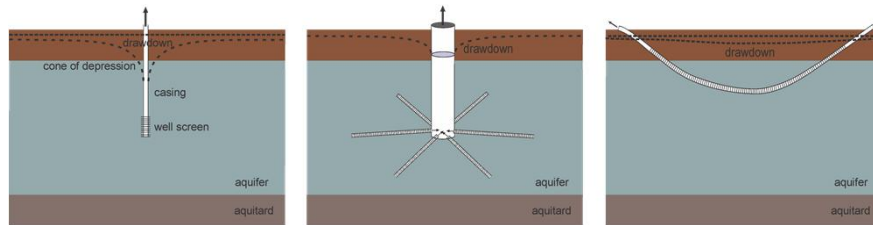


Impact of sea level rise on a coastal groundwater system:

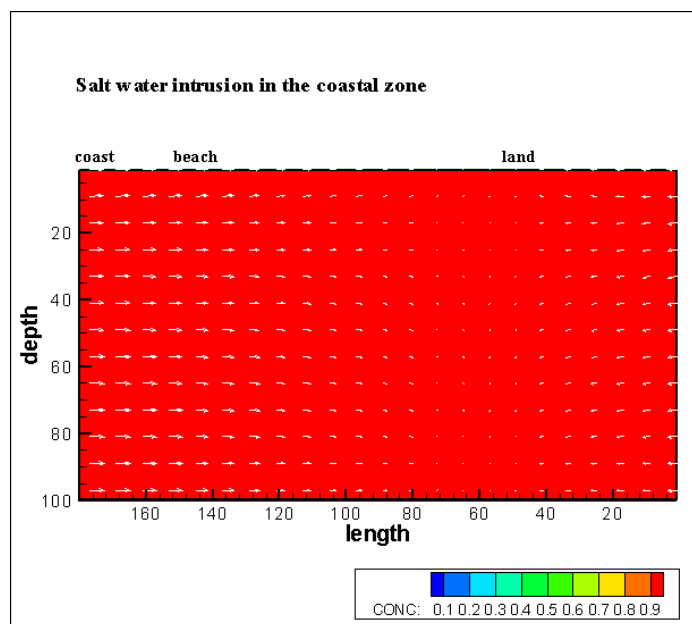
a conceptual model of saltwater intrusion

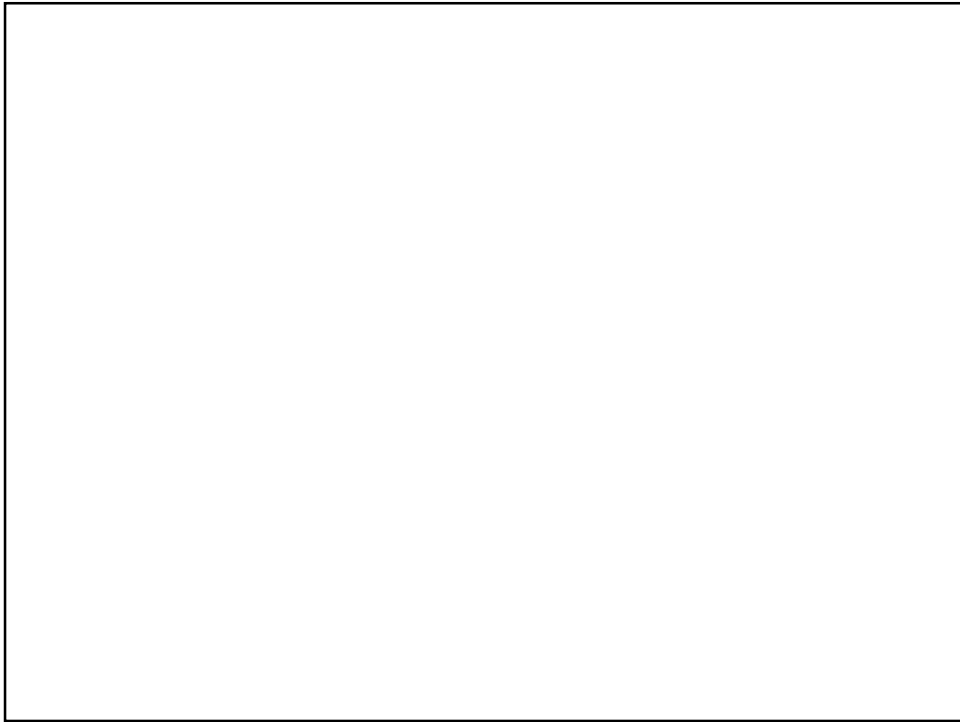


Types of extraction systems



Salt water intrusion





Water on Earth

Some serious developments:

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

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



In 1 liter ocean: about 35 gr salt



In 1 liter ocean: about 35 gr salt





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



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



Jan van Scorel
20140121



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



Fresh-brackish-saline groundwater

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

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

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)

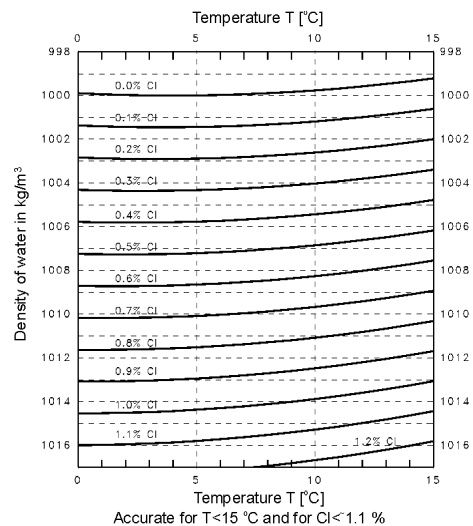
$$\rho_{i,j,k} = \rho_f + \frac{\partial \rho}{\partial C} C_{i,j,k}$$

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)

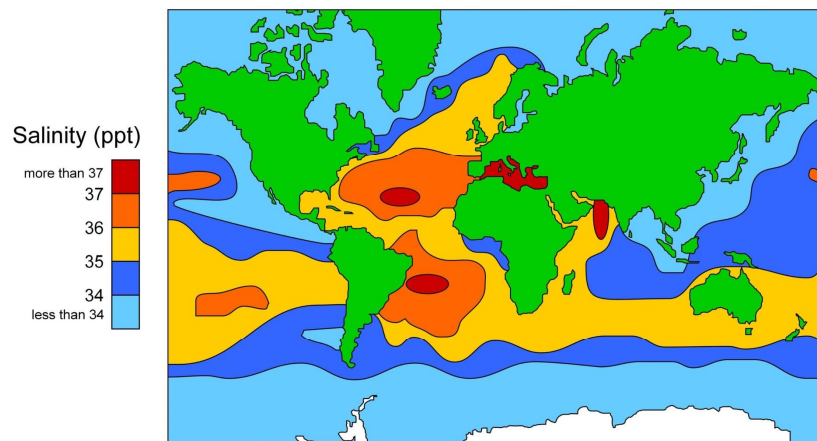
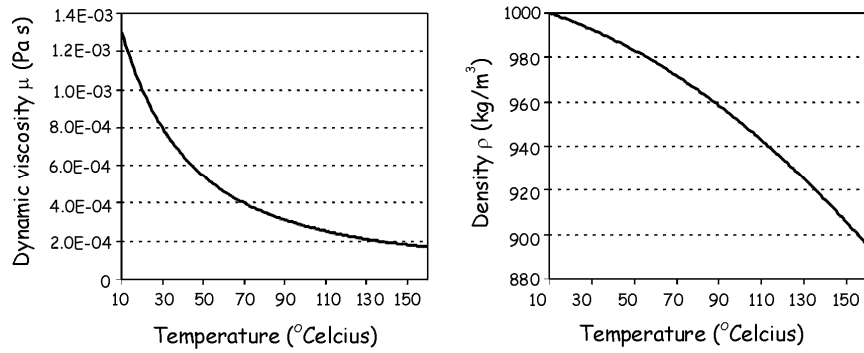
EOS

Density depends on salinity and temperature



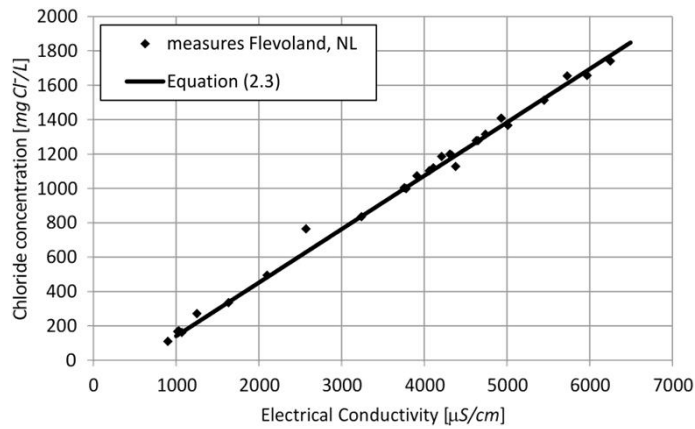
$$\rho_{(S,T)} = 1000 + 0.8054S - 0.0065(T - 4 + 0.2214S)^2 \quad \text{Knudsen (1902)}$$

Density and viscosity depend on temperature (10°C-160 °C)



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Close relation between chloride concentration and Electrical Conductivity



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

Close relation between chloride concentration and Electrical Conductivity

$$10^6 \mu S/cm = 10^3 mS/cm = 1 S/cm$$

$$1 \mu S/cm = 100 \mu S/m$$

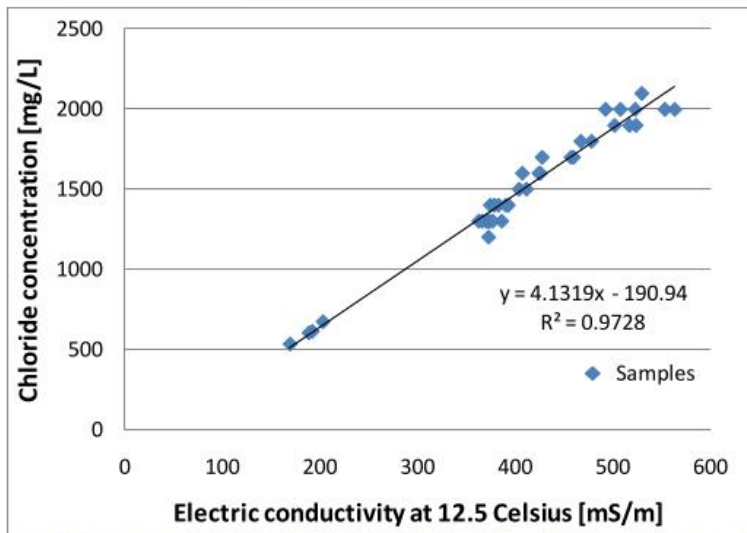
ocean water:

~19000 mg Cl-/L or ~34555 mg TDS/L

~5 S/m or ~48 mS/cm

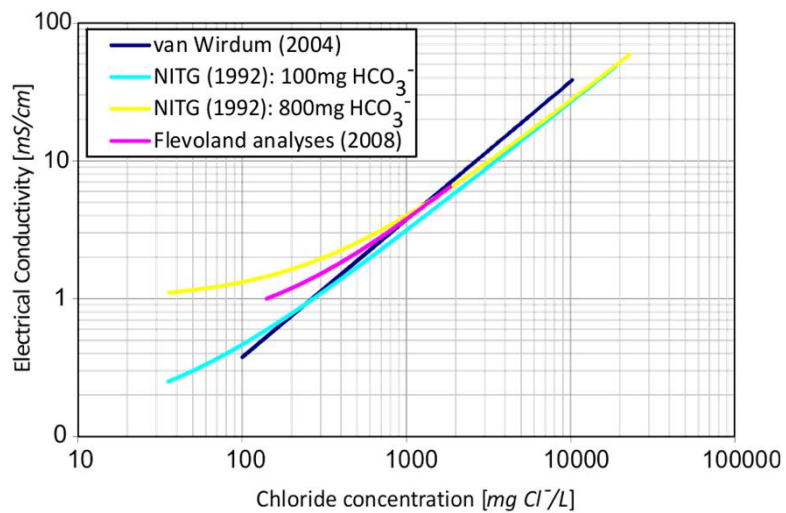
the ratio Cl⁻ over TDS equal to ~0.554, under stable normal seawater environments

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

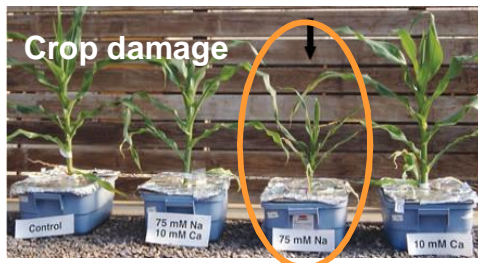
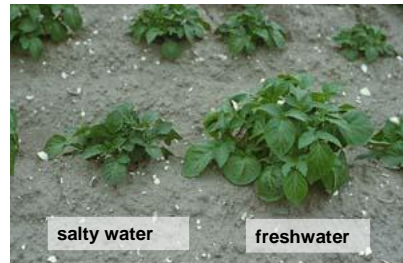


Appendix figure 11: Relation between the electric conductivity and the chloride concentration. For this relation samples from observation well B06D1114 and B06D1087 in between 23-sept-2009 and 9-okt-2010 were plotted.

EC-Chloride



Salt in water is a problem



Introduction

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

-drinking water:

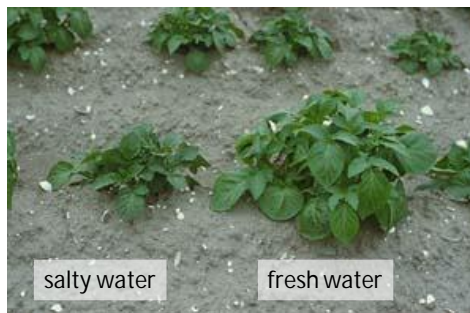
- taste (100-300 mg Cl⁻/l)
- long term health effect
- norm: EC& WHO=150 mg Cl⁻/l (live stock=1500 mg Cl⁻/l)

-industry:

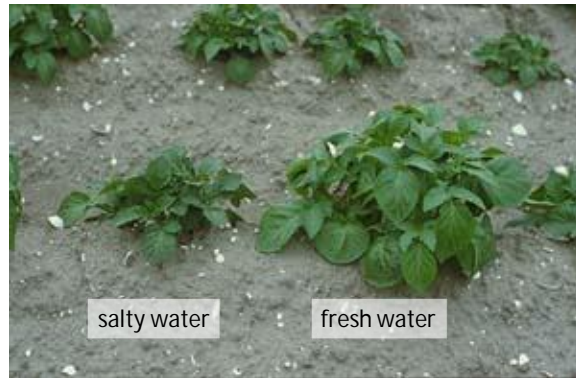
- corrosion pipes
- preparation food

-irrigation/agriculture:

- production crops
- salt damage

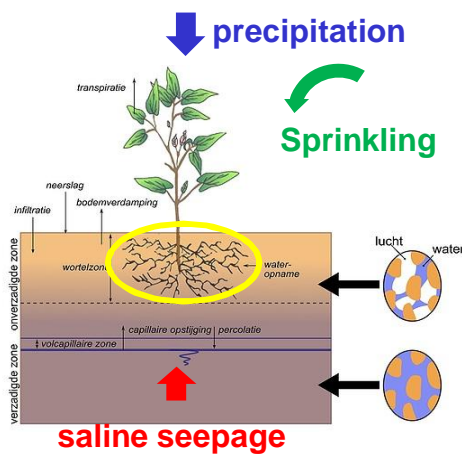


Effects salinisation: salt damage

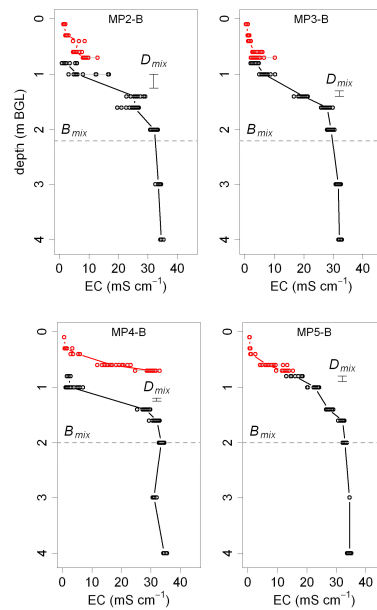


Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

Salt-resistant crops



Important parameter:
 Chloride concentration root zone
 Land use
 Sensitivity crops



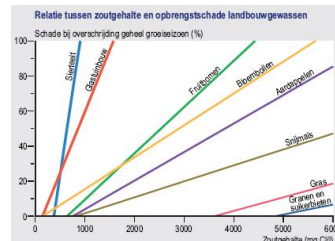
Salt damage to crops

Important parameters:

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

Land use	Threshold value	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

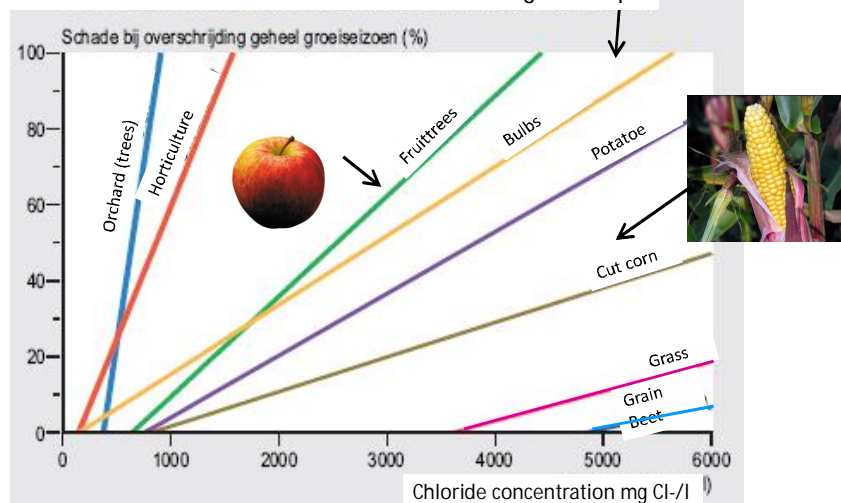


Source: MNP, 2005

Salt damage to crops



Relation between salt concentration and damage to crops

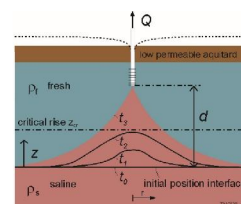
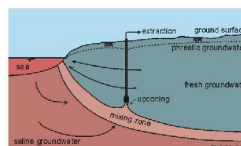
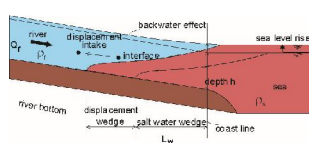


Source: MNP, 2005

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

Why is salinisation a pressing problem?

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



Processes that accelerate salt water intrusion:

- Sea level rise
- Land subsidence
- Human activities

Threats for:

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



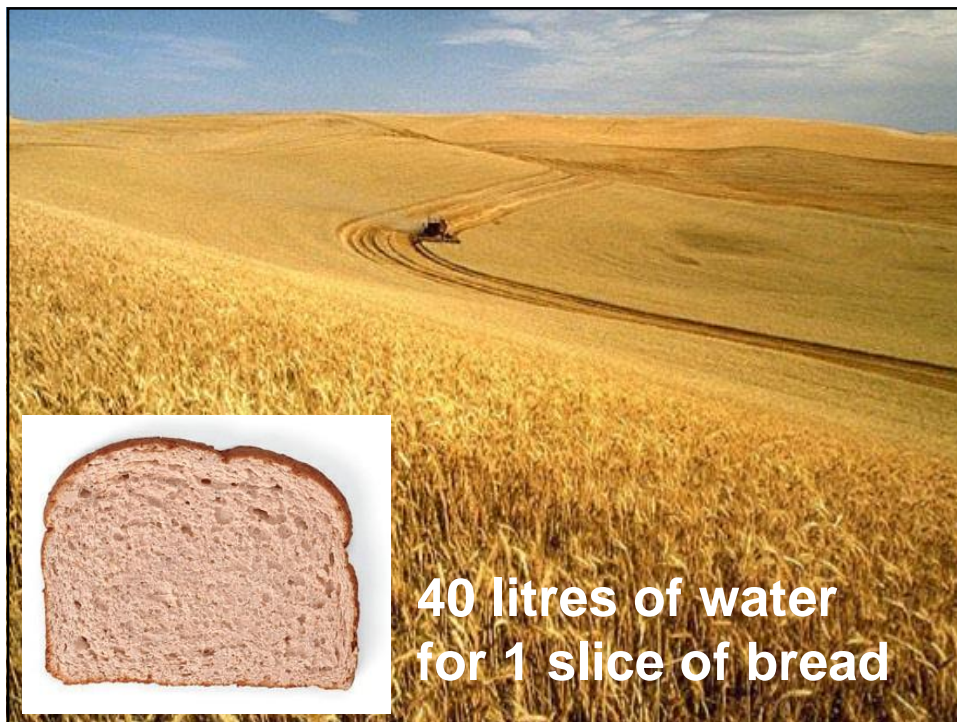
The water footprint of products

global averages

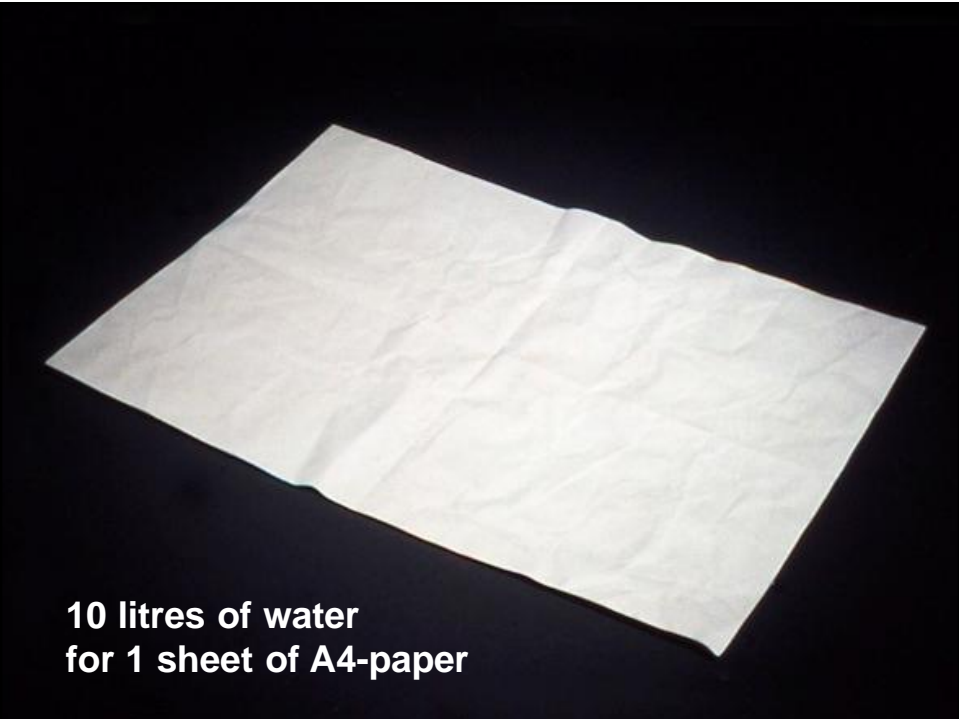
1 kg wheat	1 m³ water
1 kg rice	3 m³ water
1 kg milk	1 m³ water
1 kg cheese	5 m³ water
1 kg pork	5 m³ water
1 kg beef	15 m³ water



[Hoekstra & Chapagain, 2008]





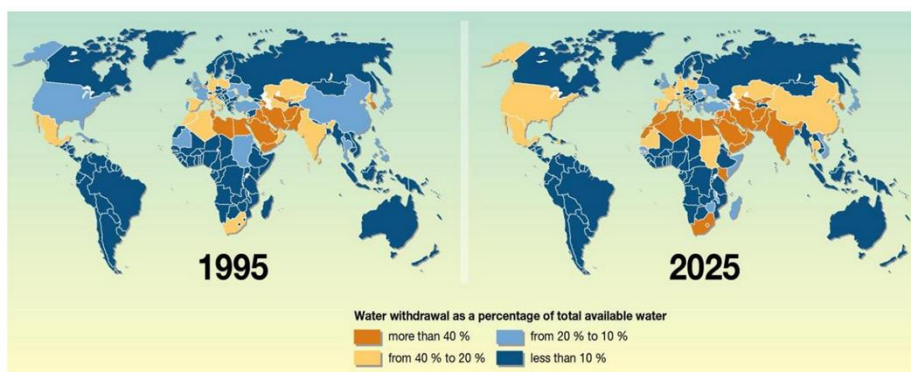


Question:

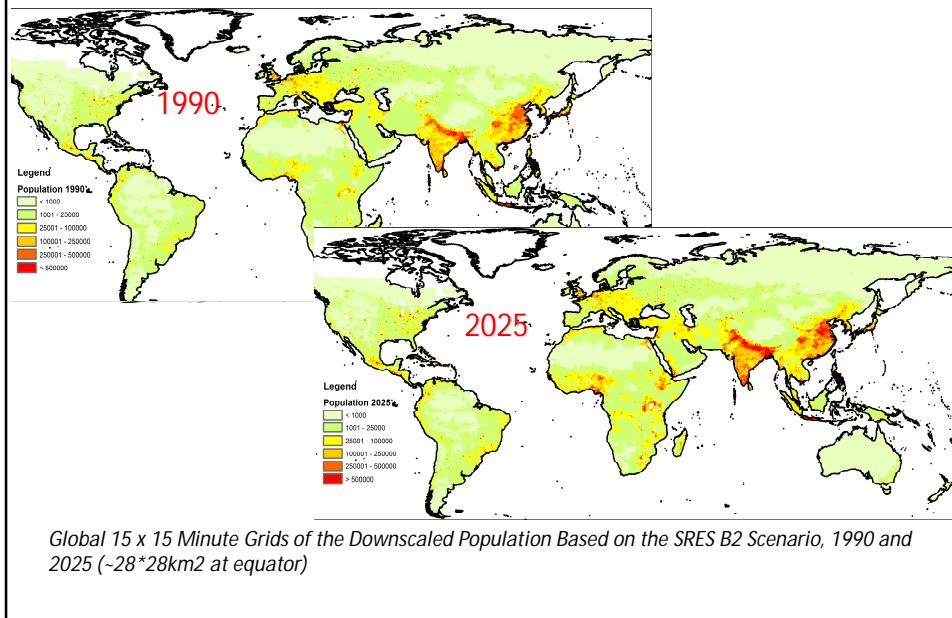
Demand fresh water per capita per day?:

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

Water withdrawal as % of total available water



Population growth 1990-2025



Introduction

Reasons and drawbacks of using groundwater

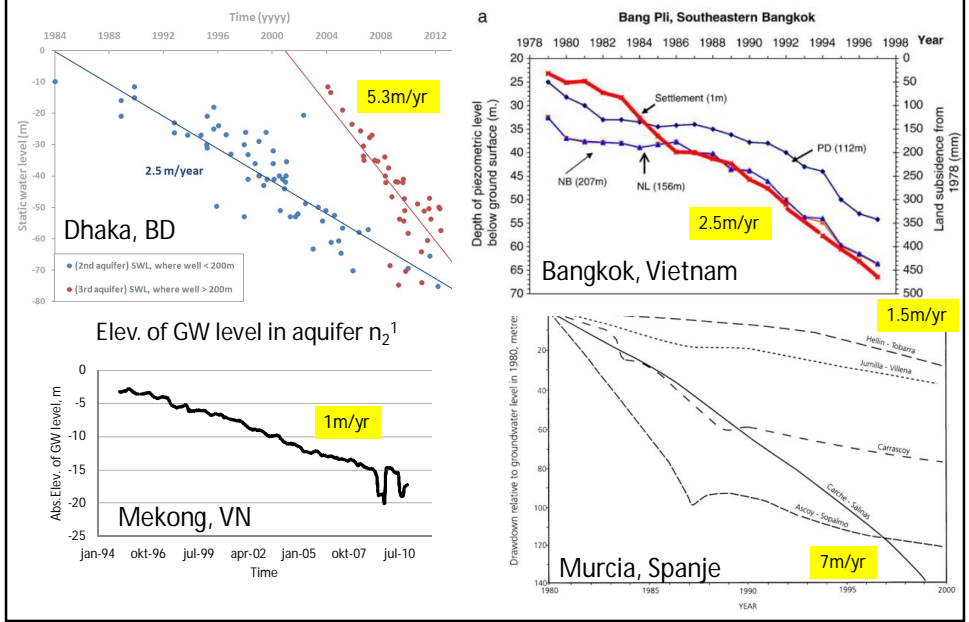
Advantage:

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

Disadvantage:

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

Serious overexploitation coastal aquifers worldwide



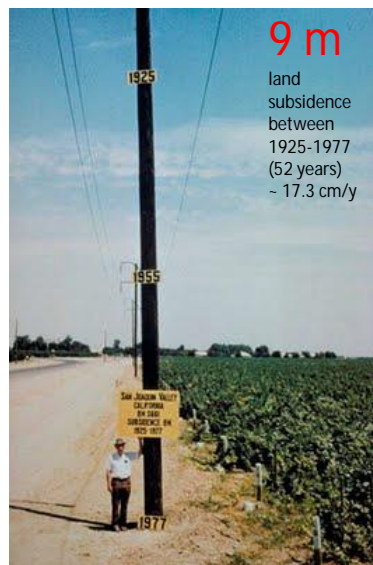
Groundwater overexploitation in Mekong Delta



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 \Rightarrow oxidation of peat, soil compaction

Why discriminating between human-induced and natural processes?

- Magnitude
- Cooping strategy (mitigation versus adaptation)

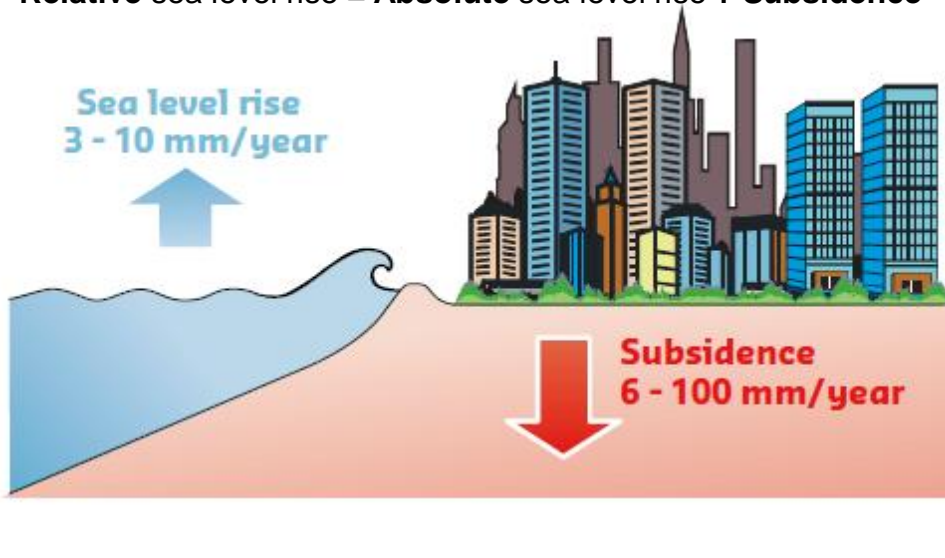


Impacts



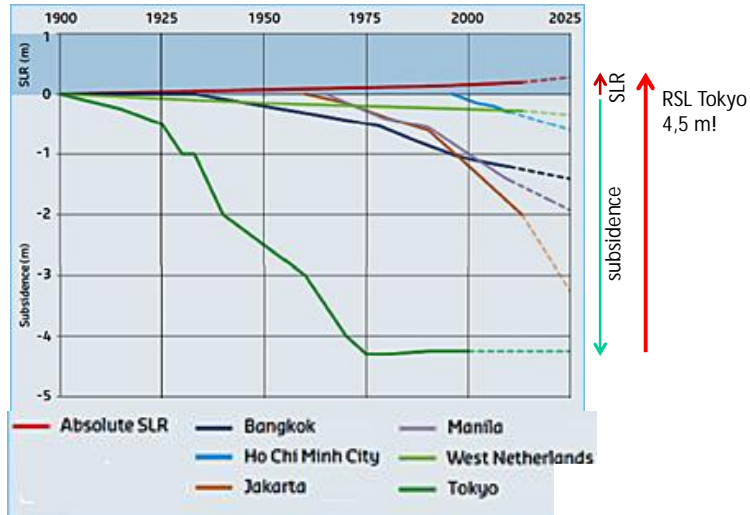
Sinking delta cities

$$\text{Relative sea level rise} = \text{Absolute sea level rise} + \text{Subsidence}$$

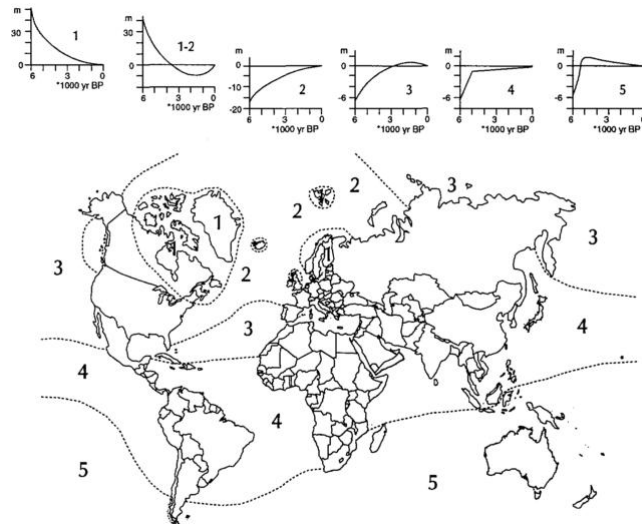


Examples of some major coastal cities

The subsidence issue is underestimated

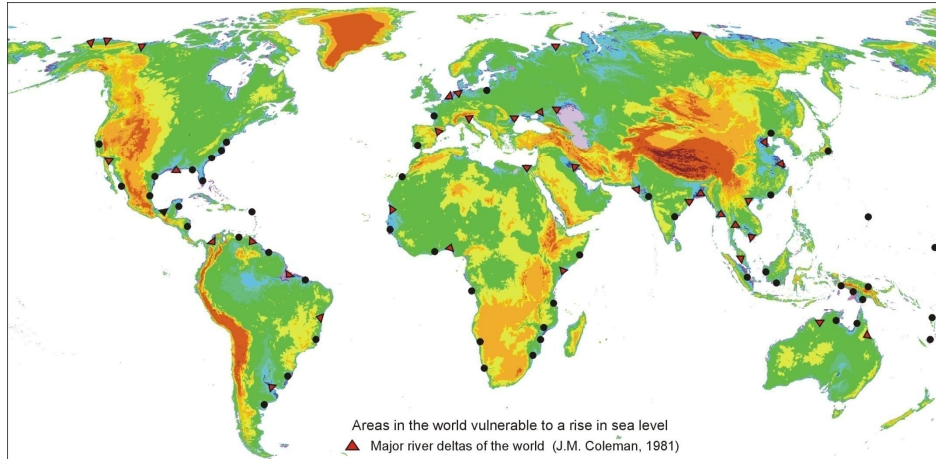


Regional distribution of Holocene Sea-level Changes

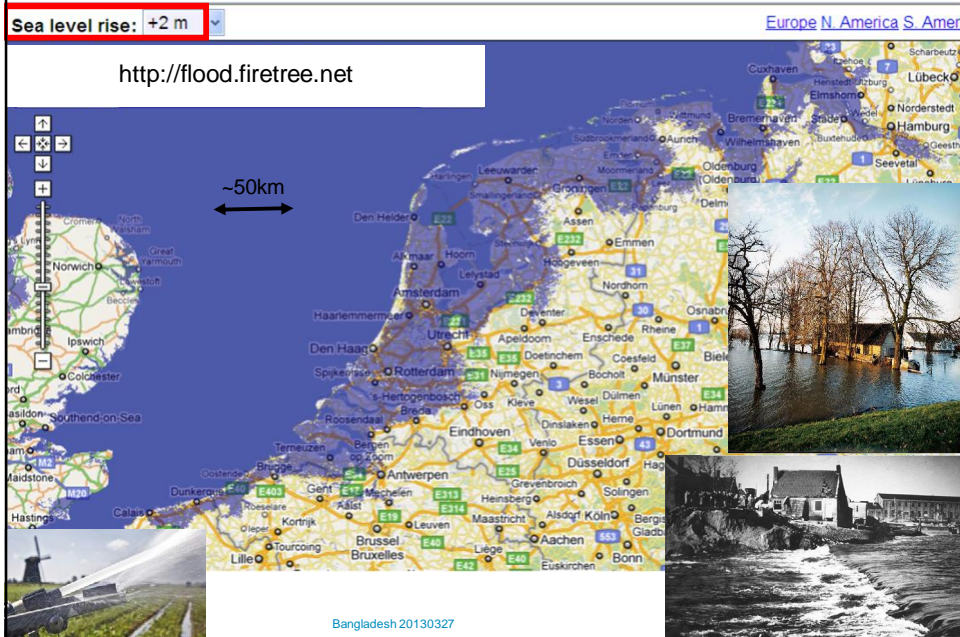


Source: Pirazzoli, P.A. & Pluett, J., 1991. *World Atlas of Holocene Sea-level Changes*. Elsevier Oceanography Series, Vol. 58

Areas vulnerable to sea level rise

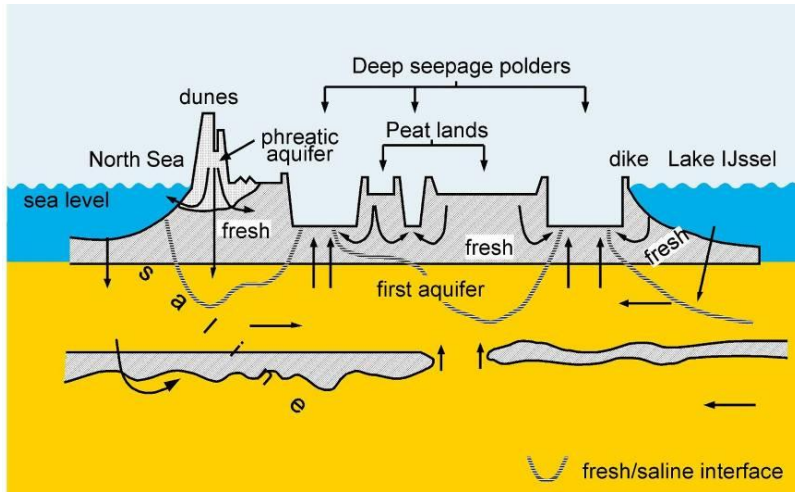


The Netherlands: low-lying lands



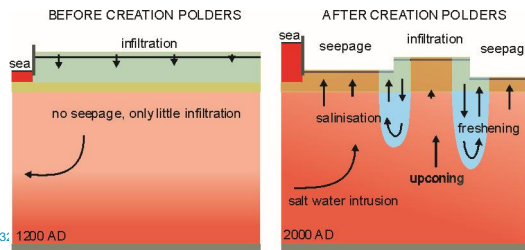
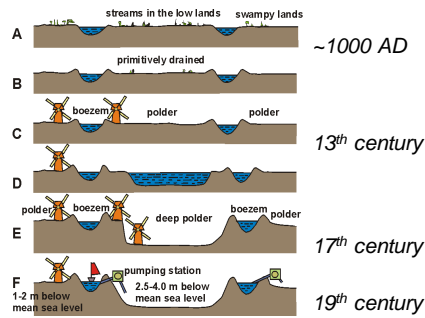
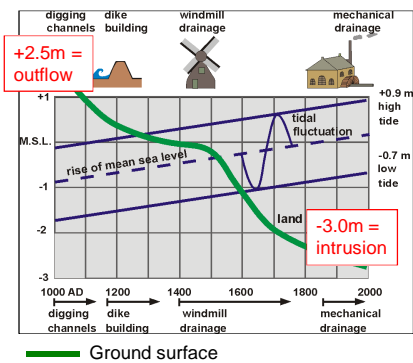
Saline seepage leads to:

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

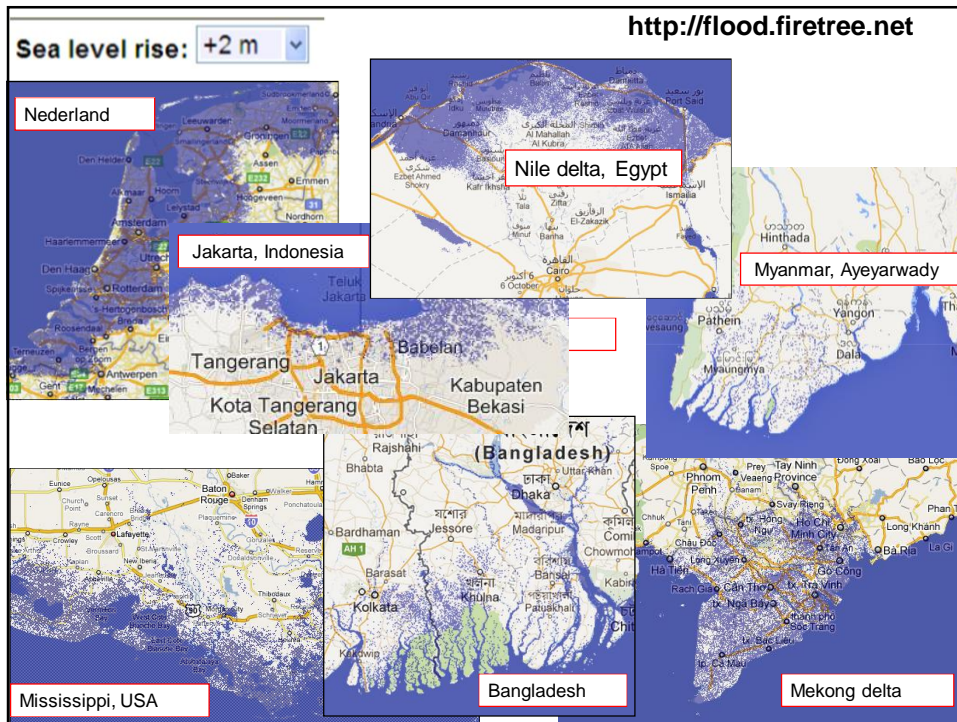


From fresh water outflow to salt water inflow

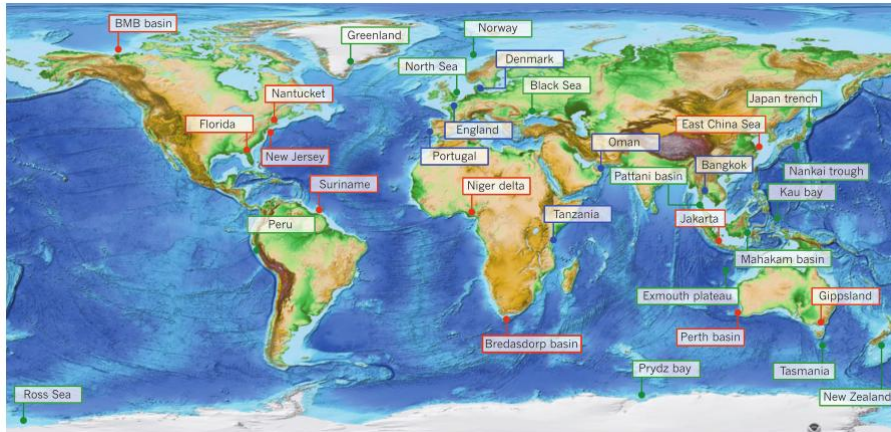
Historical subsidence of the ground surface in Holland



Bangladesh 201303

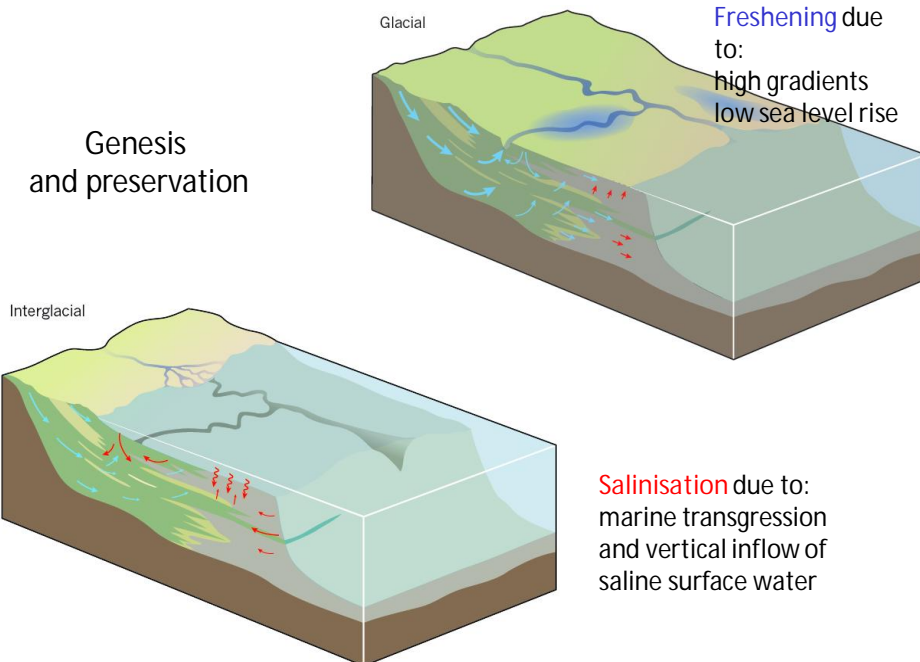


World map of topography and bathymetry showing known occurrences of fresh and brackish offshore groundwater



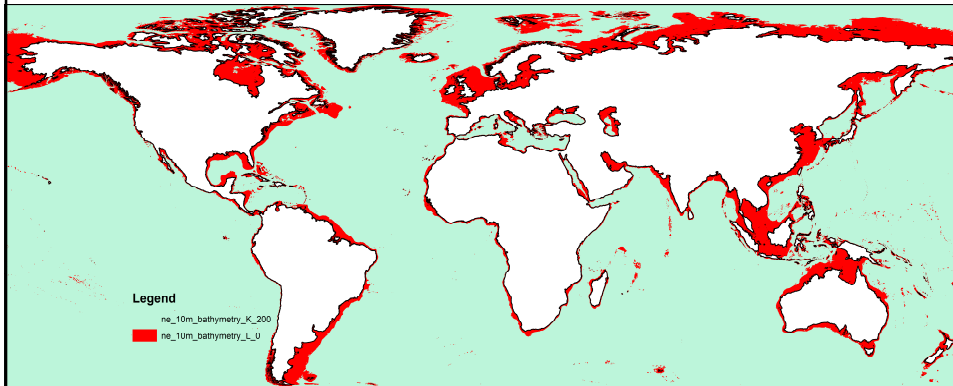
Post et al., Nature, 2013

Genesis and preservation

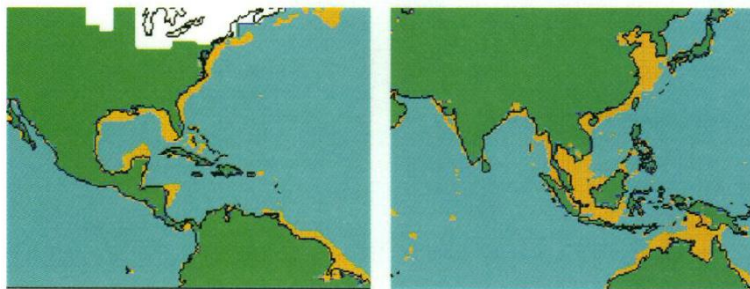


Source: Nature, 2013

Possible locations of offshore (submarine) groundwater

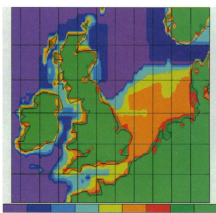


Coastal zone cases around the world Occurrence related to dynamic sea-levels and coastlines

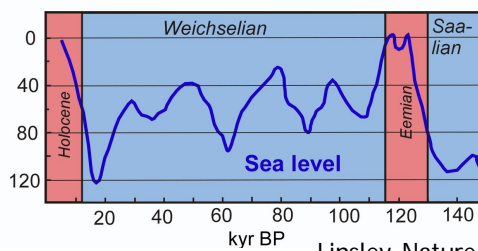


Exposed continental shelves

Peltier, *Science*, 1994

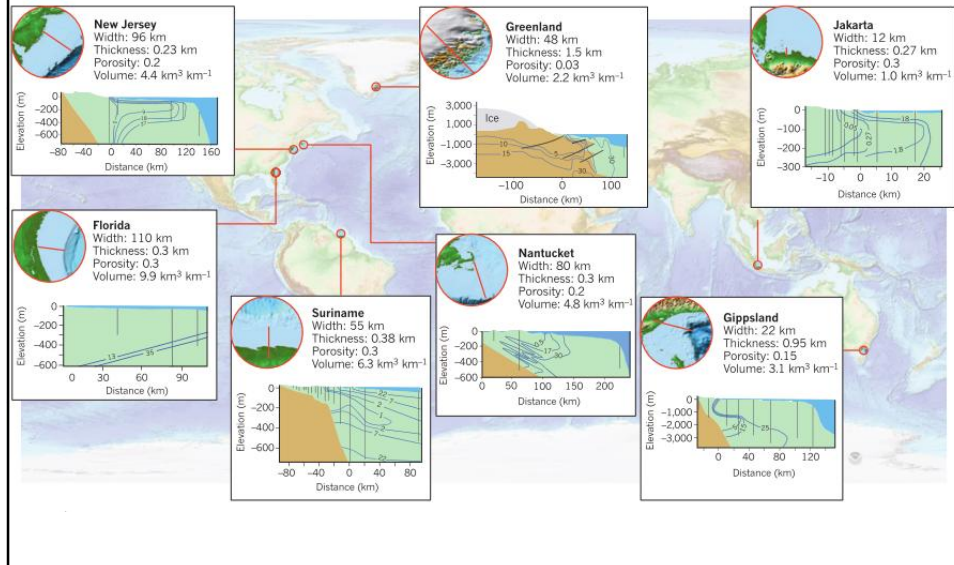


Inundated (kyr BP)



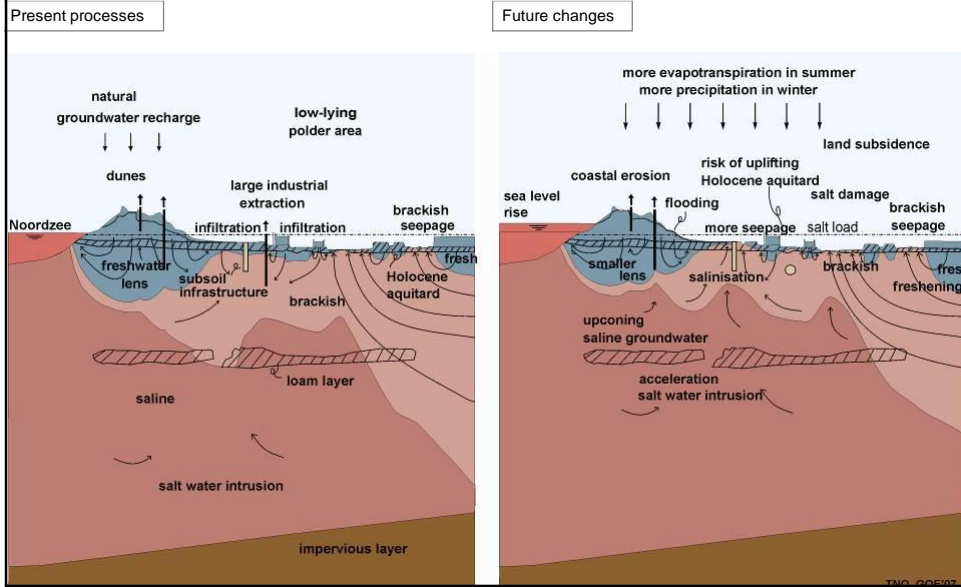
Linsley, *Nature*, 1996

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

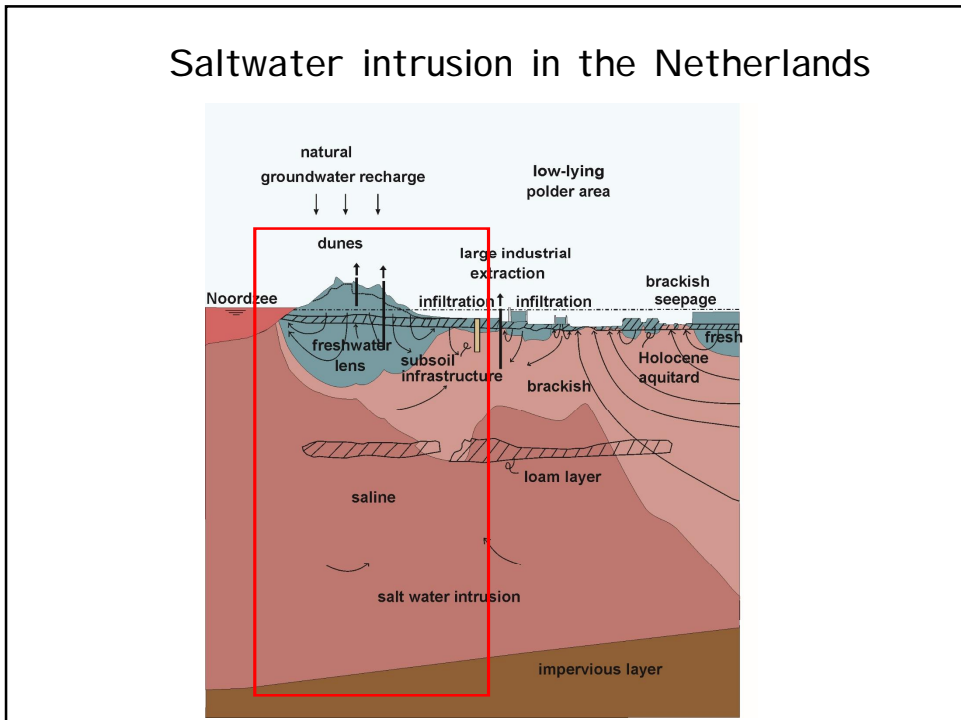


My first density dependent groundwater flow and solute transport model in 1990!

The Dutch groundwater system under stress

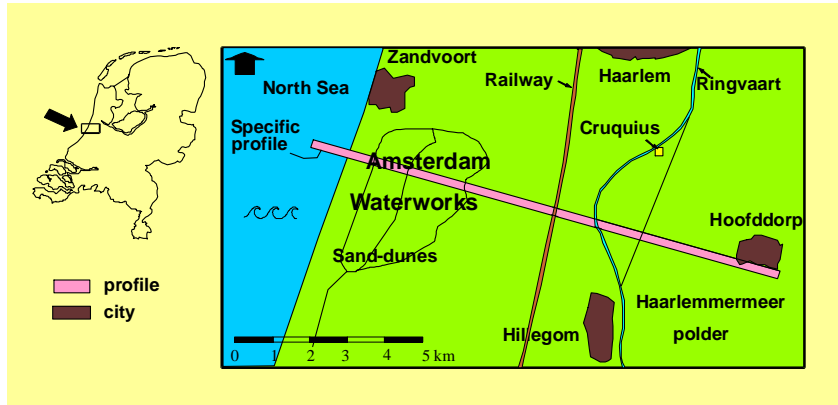


Saltwater intrusion in the Netherlands



Saltwater intrusion in the Dutch coastal zone

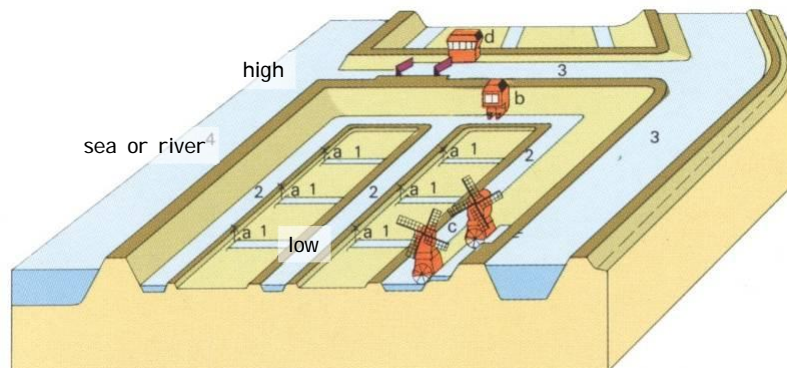
Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmeer polder



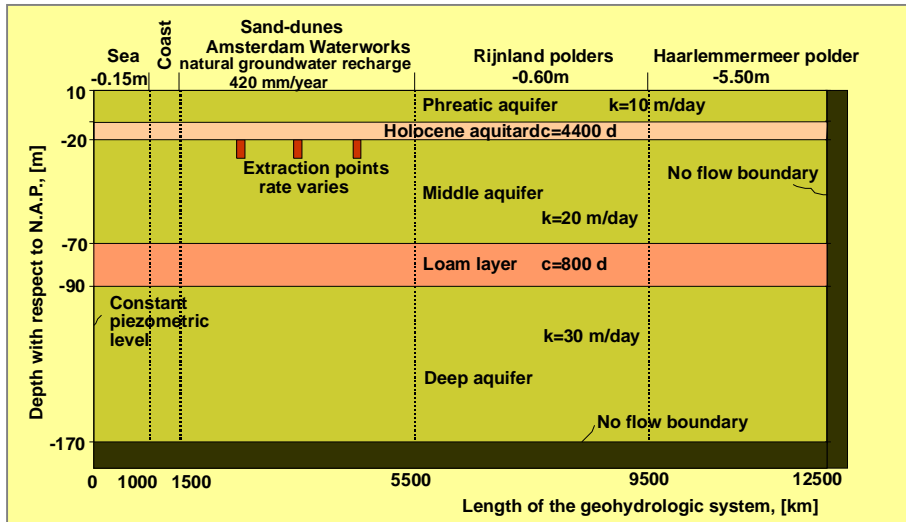
The polder system

A polder is:

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

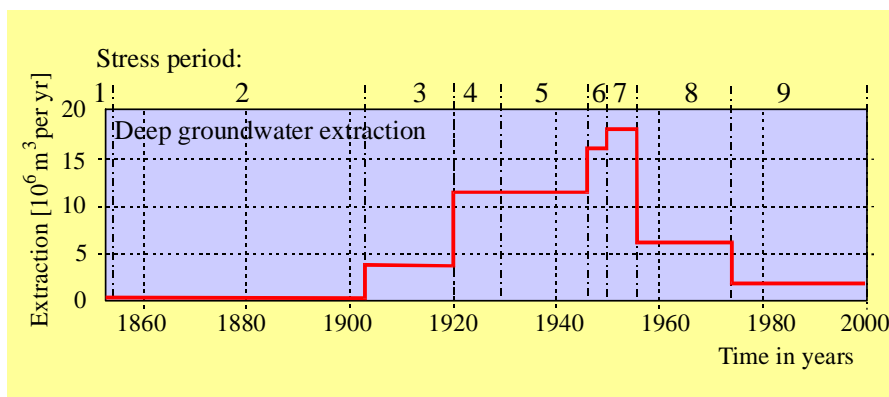


Geometry, subsoil parameters, boundary conditions

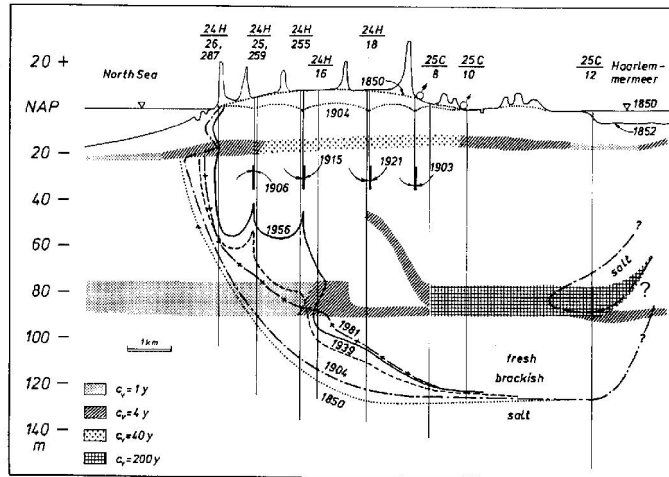
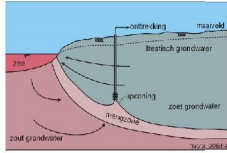


Saltwater intrusion in the Dutch coastal zone

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

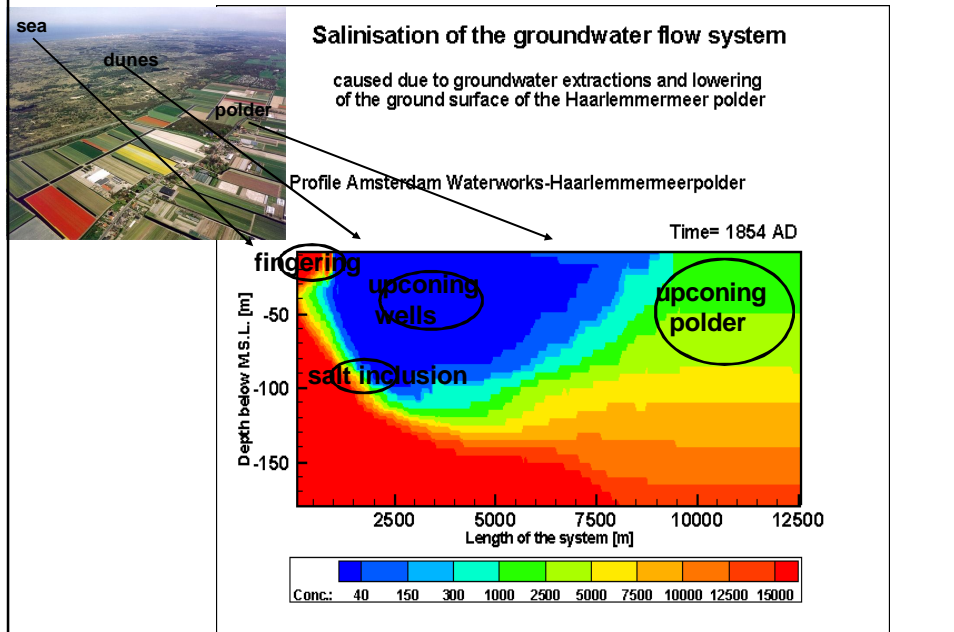


Upconing of brackish-saline groundwater

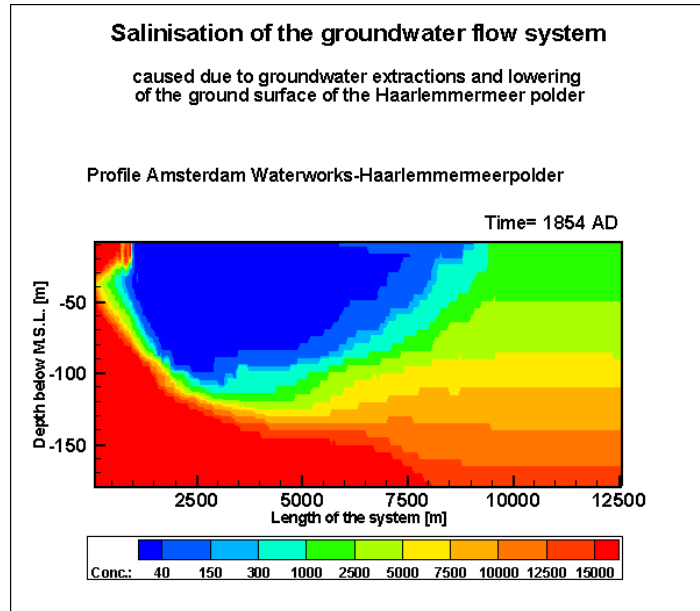


Stuyfzand, 1993

Saltwater intrusion in the Dutch coastal zone



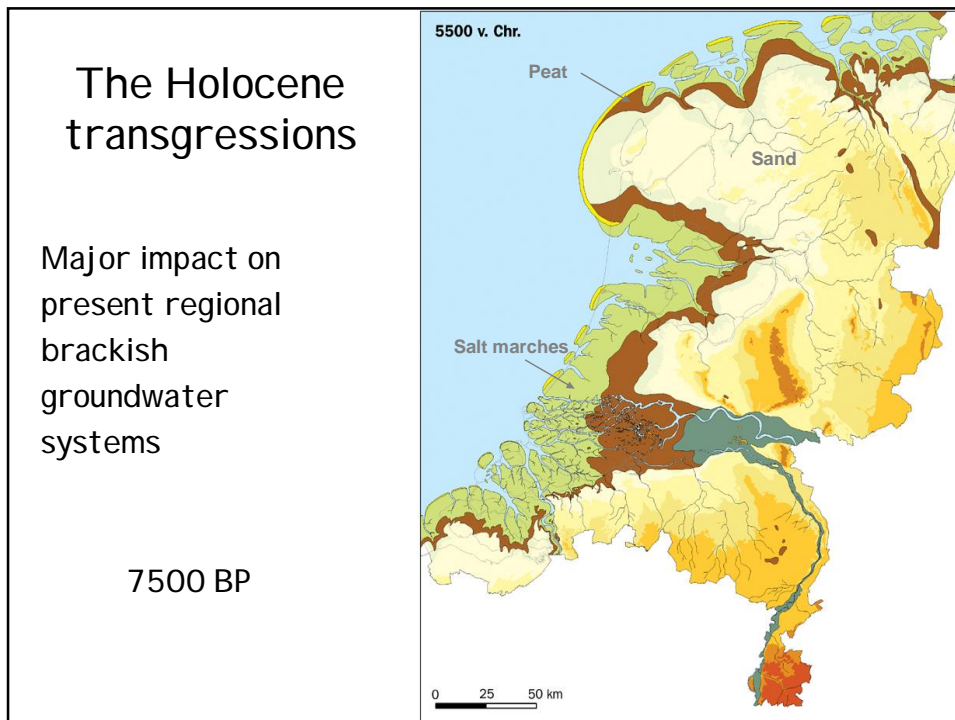
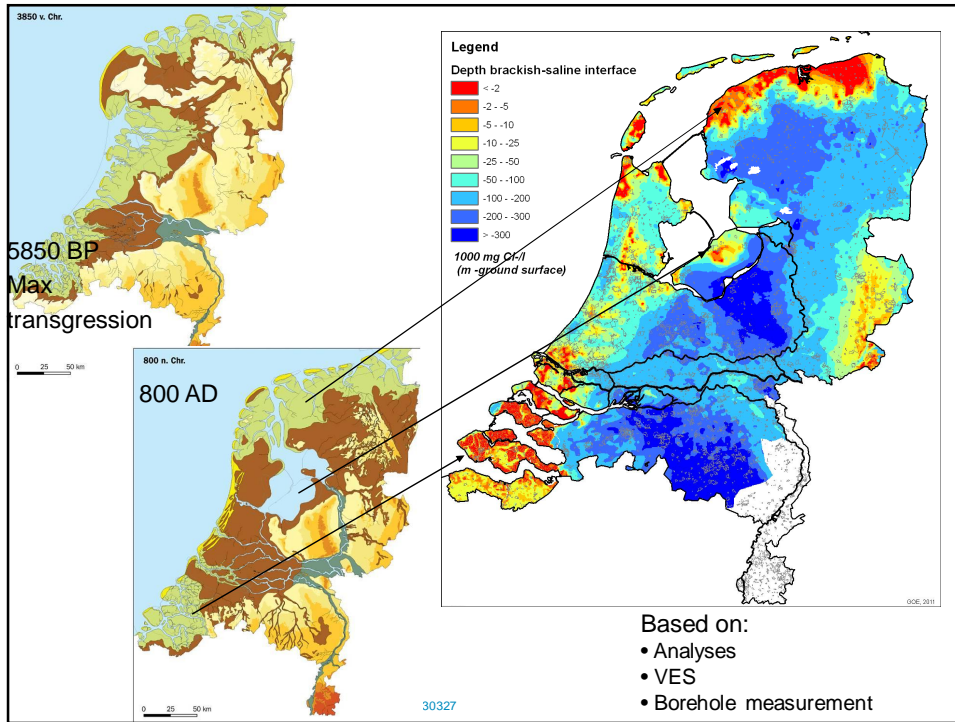
Saltwater intrusion in the Dutch coastal zone



Palaeo hydrogeological modelling

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

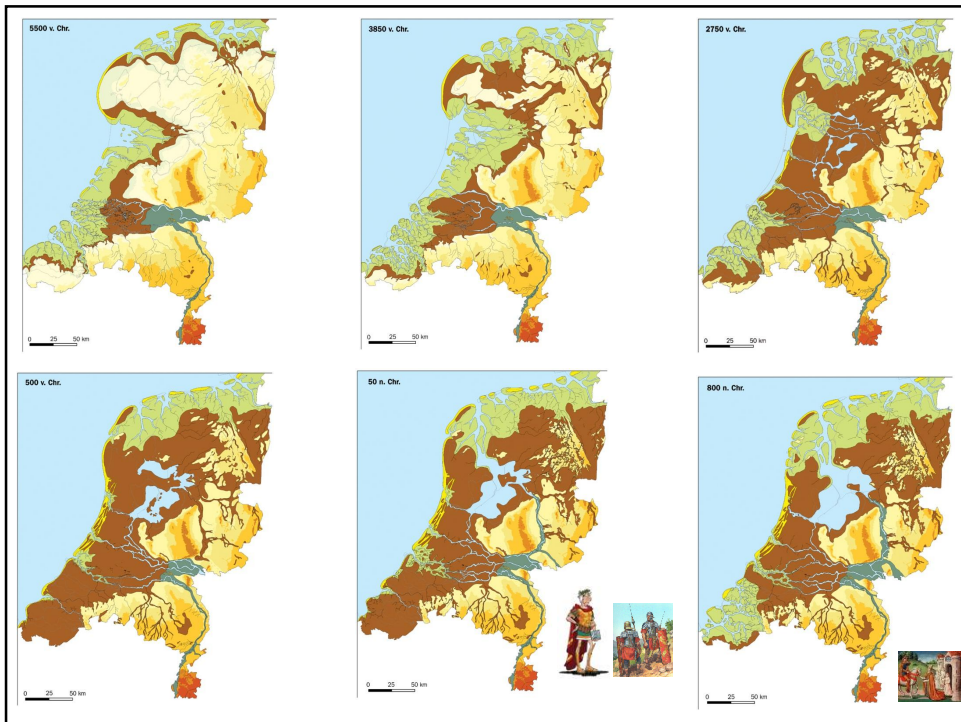
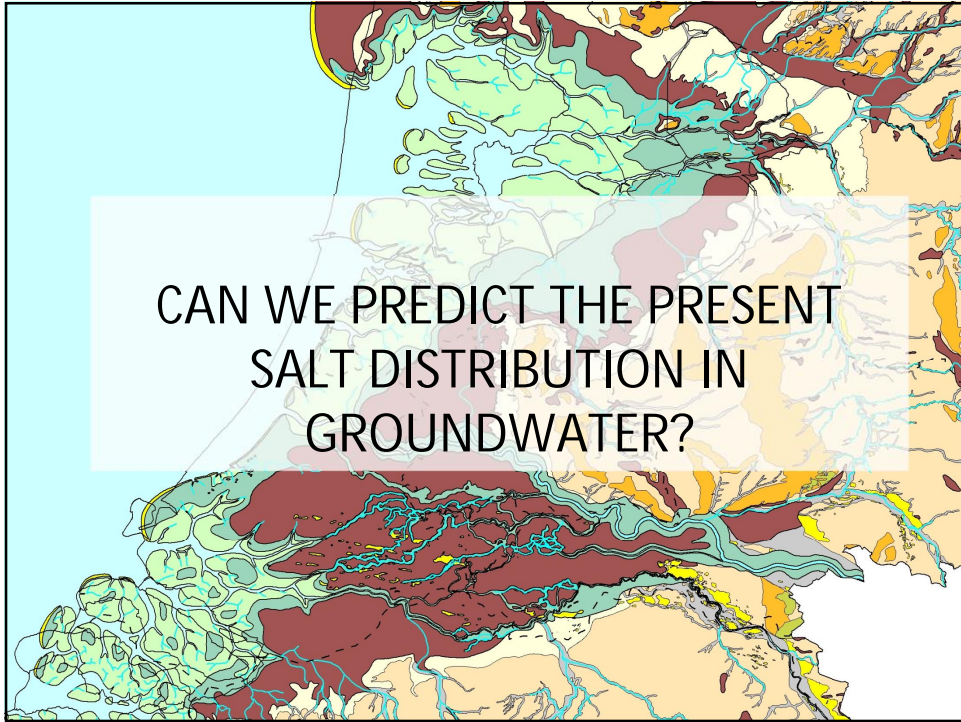
*J.R. Delsman, K. Hu-a-ng, P.C. Vos, P.G.B. de
Louw, G.H.P. Oude Essink and M.F.P. Bierkens*



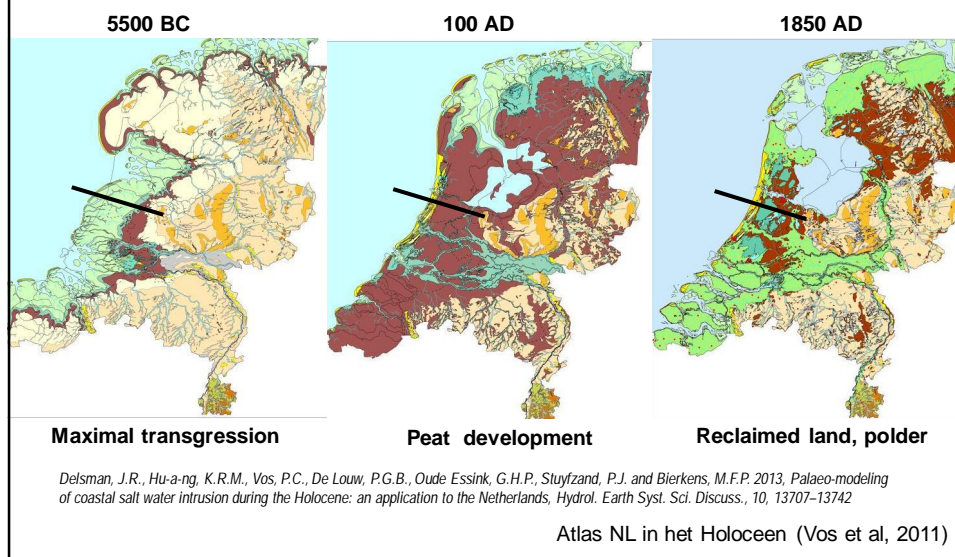
The Holocene transgressions

Major impact on present regional brackish groundwater systems

7500 BP

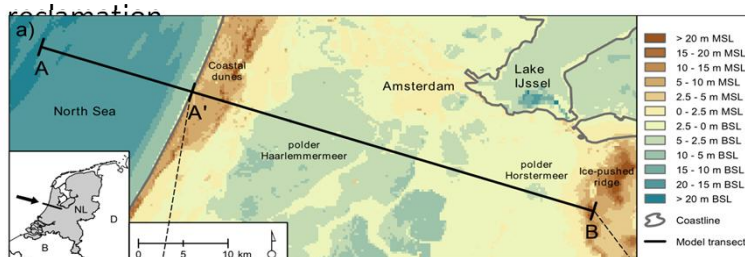


Palaeogeographical development

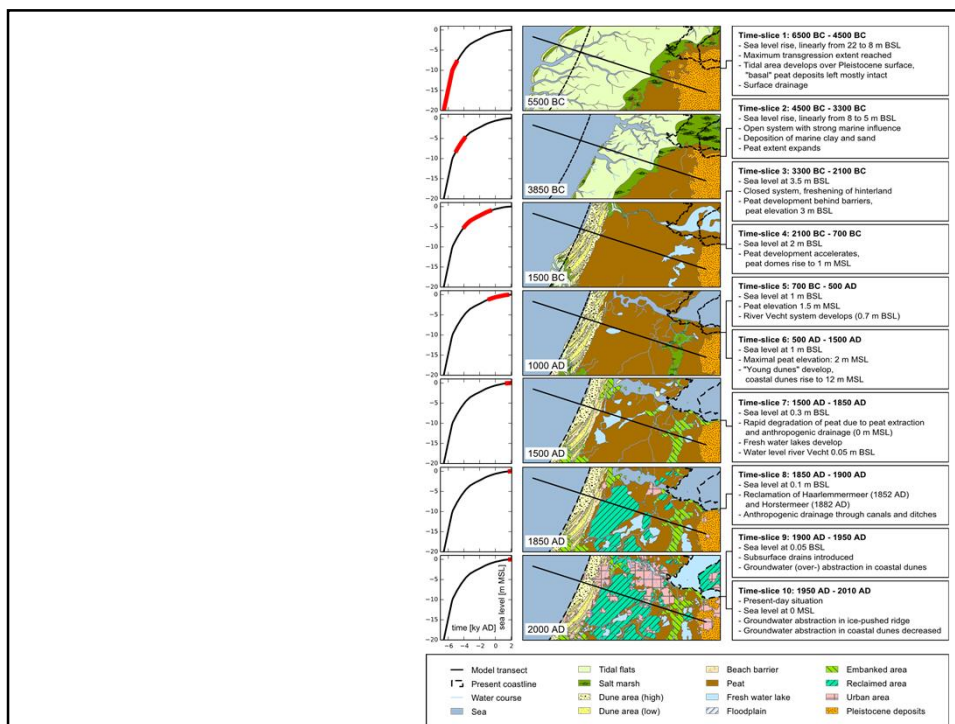
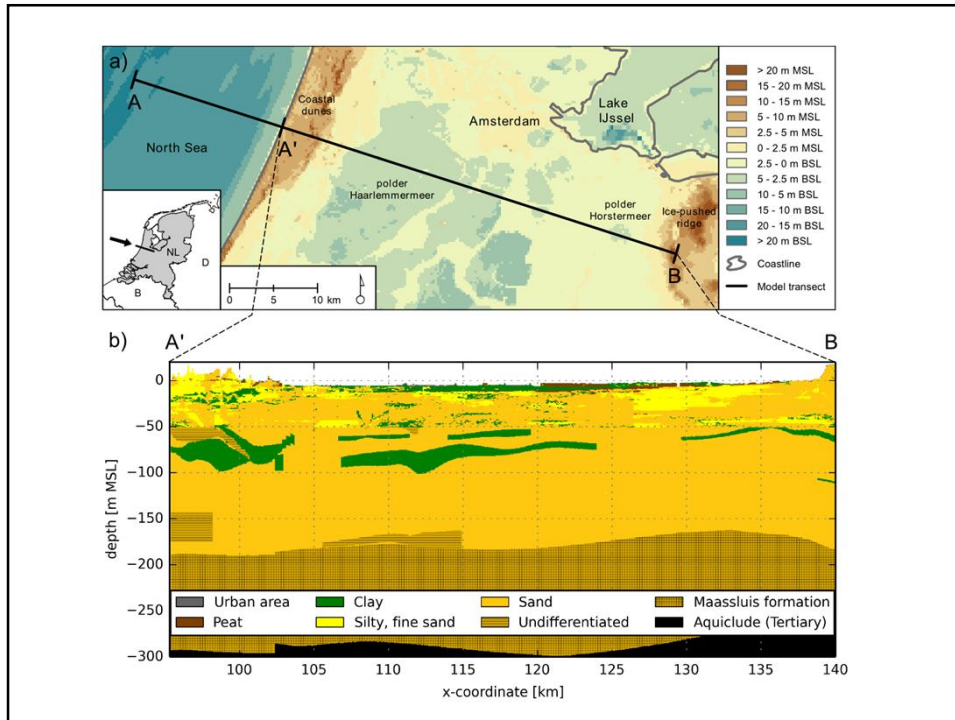


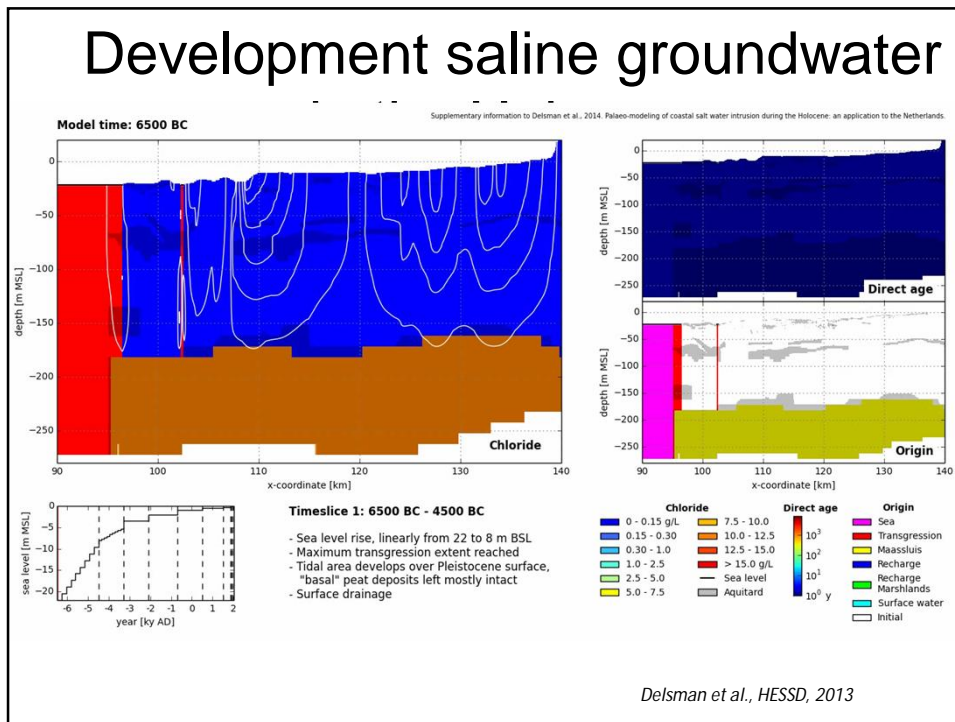
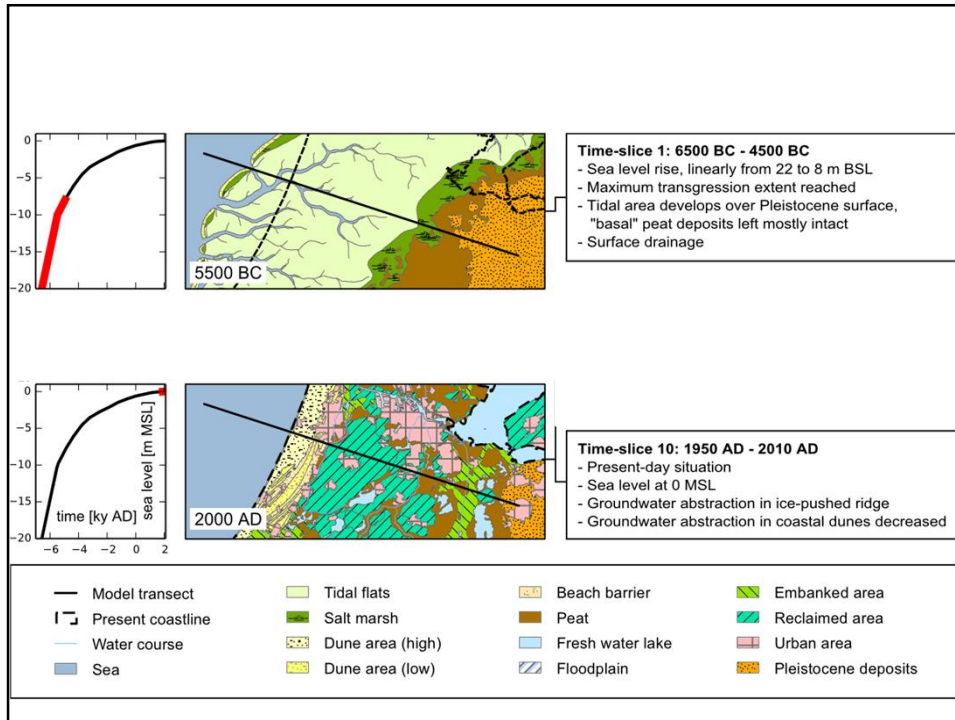
Occurrence of salt under the polder Haarlemmermeer

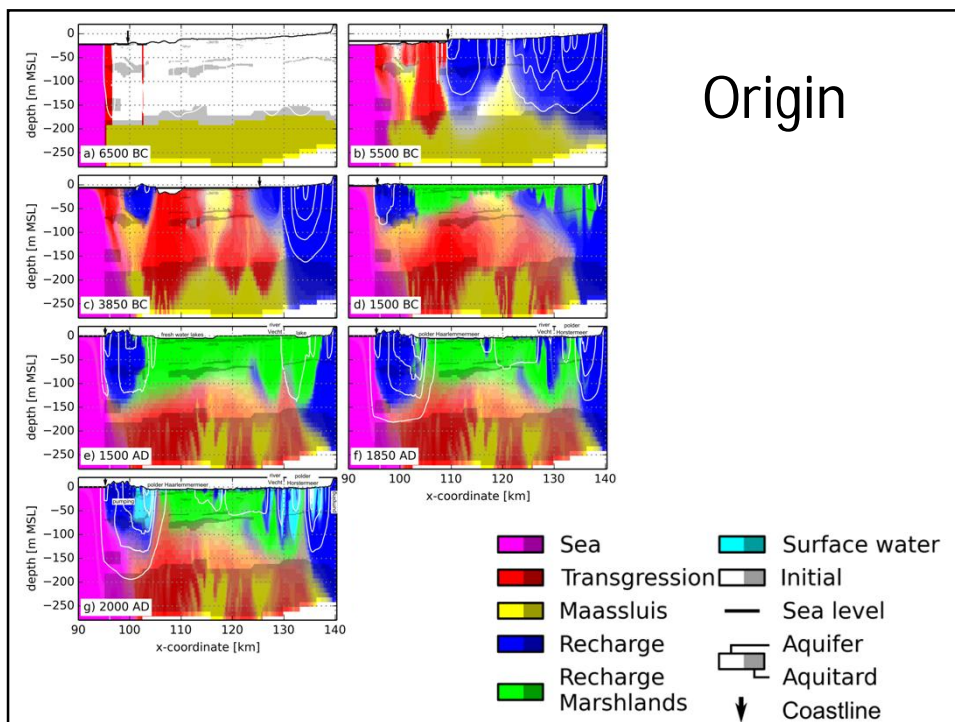
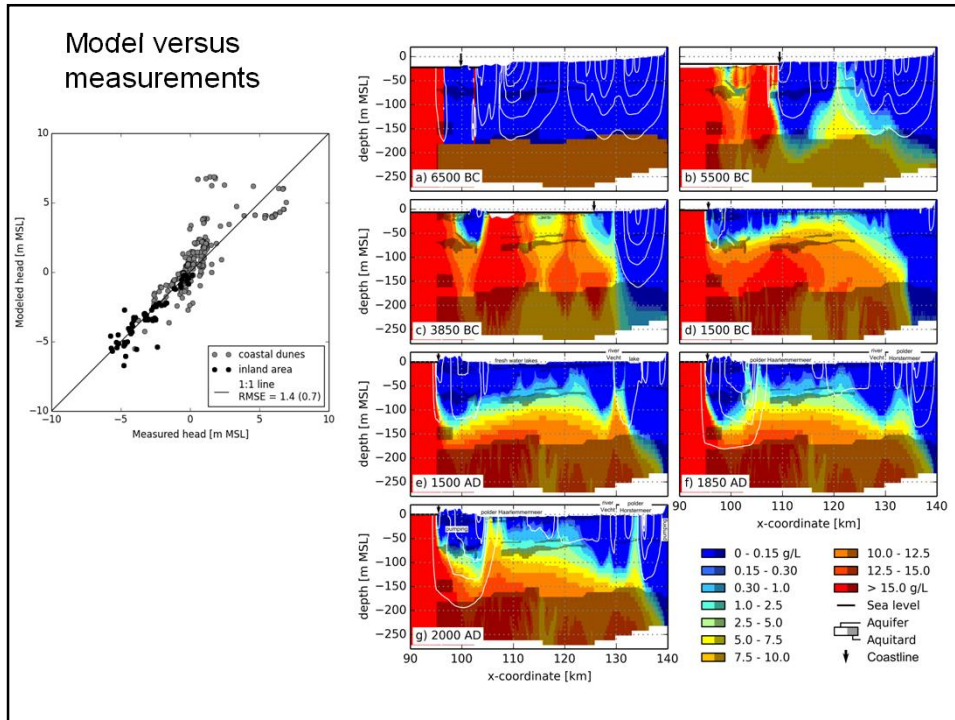
- Model profile Zandvoort - Hoofddorp – Hilversum
- Palaeogeographical development (Vos et al, 2011)
- 6500 BC - 2010 AD
- marine transgression
- Peat development, peat degradation, drainage, reclamation

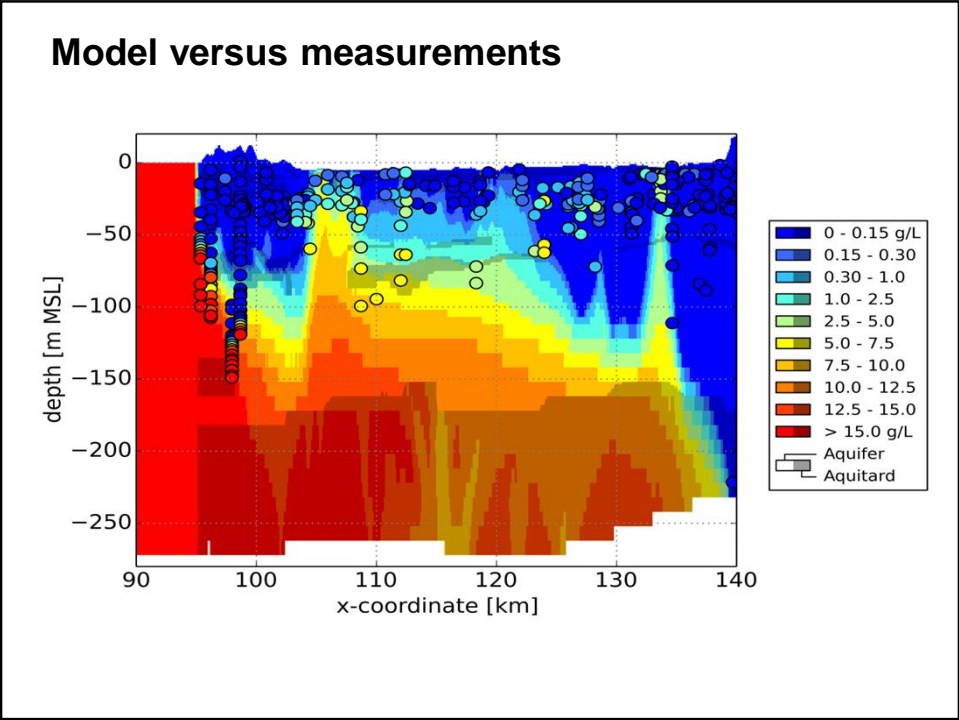
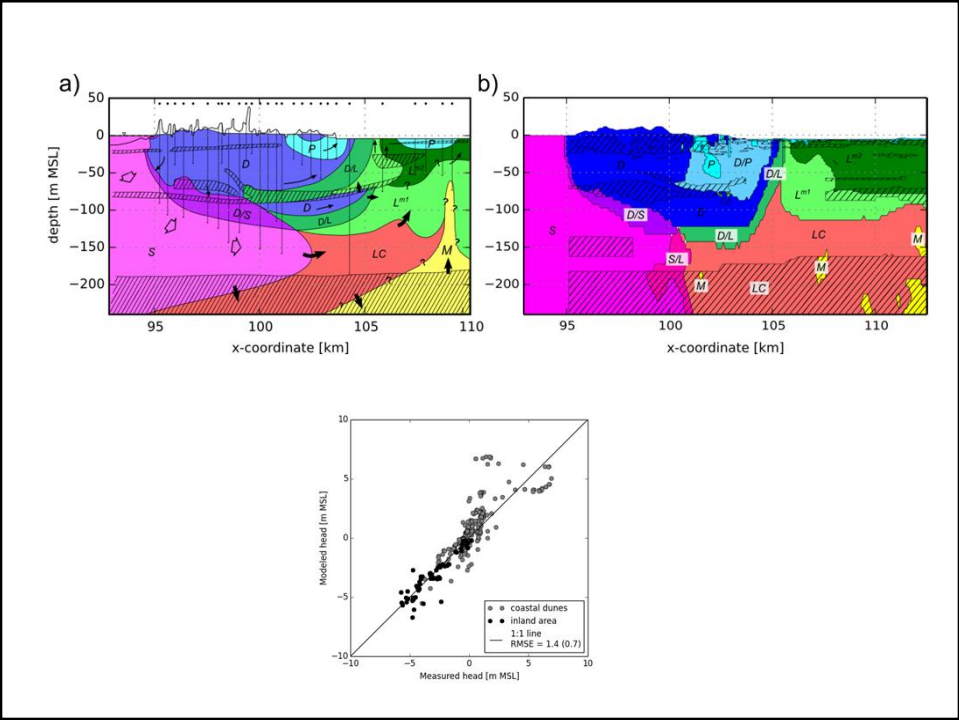


Delsman et al., HESS, 2013









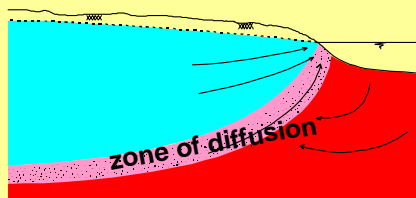
Sharp interface between fresh and saline groundwater

Introduction

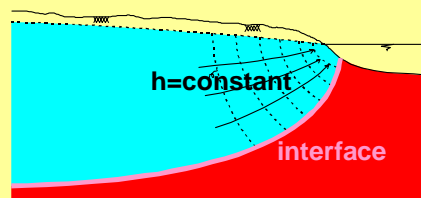
Badon Ghyben-Herzberg principle

Difference between reality and Badon Ghyben-Herzberg approximation

concept: mixing zone in reality



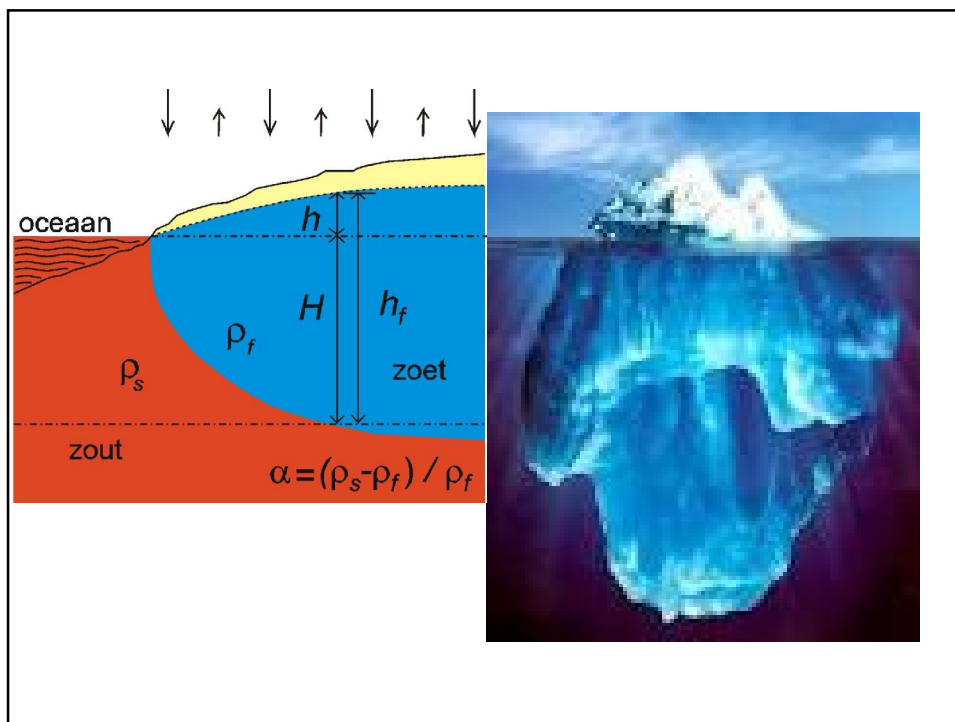
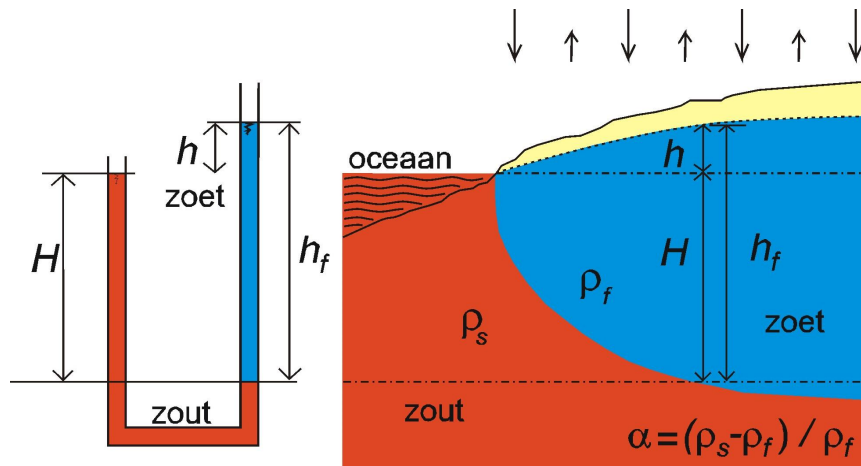
concept: interface between fresh and saline groundwater



Badon Ghijben-Herzberg principle

The principle suggests an interface between fresh and saline groundwater

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

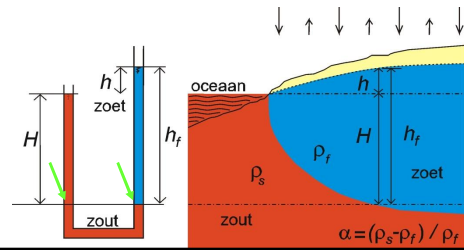


pressure saline groundwater = pressure fresh groundwater

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

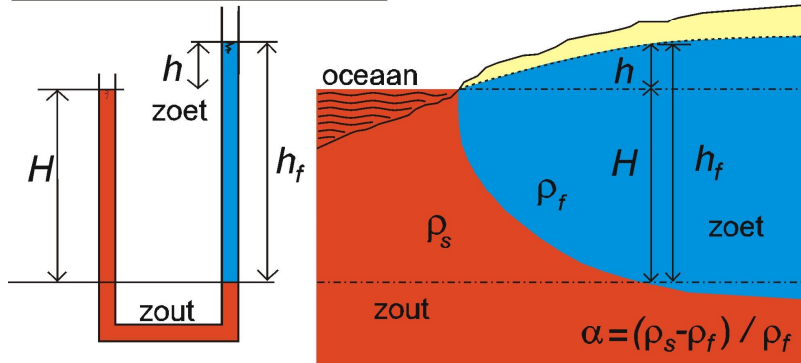
$$h = \frac{\rho_s - \rho_f}{\rho_f} H$$

$$h = \alpha H$$

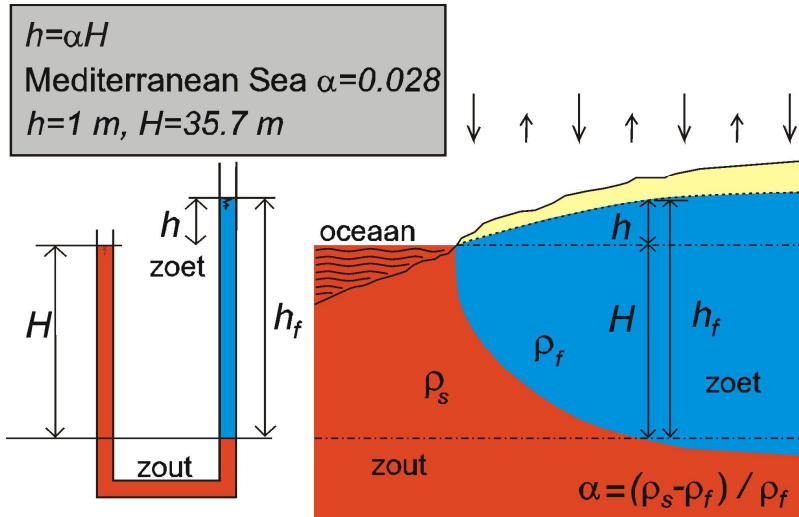


$$h = \alpha H$$

$h = \alpha H$
 in ocean water $\alpha = 0.025$
 $h = 1 \text{ m}, H = 40 \text{ m}$



$$h = \alpha H$$



Badon Ghyben-Herzberg principle

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

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

Badon Ghyben-Herzberg principle

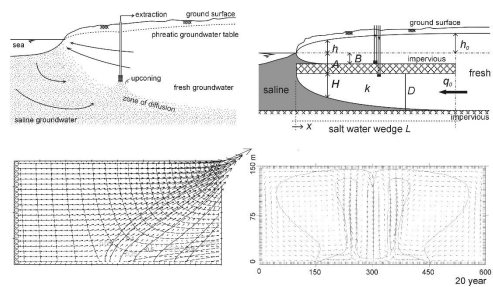
What is the case then $h \neq \alpha H$?

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

Analytical solutions

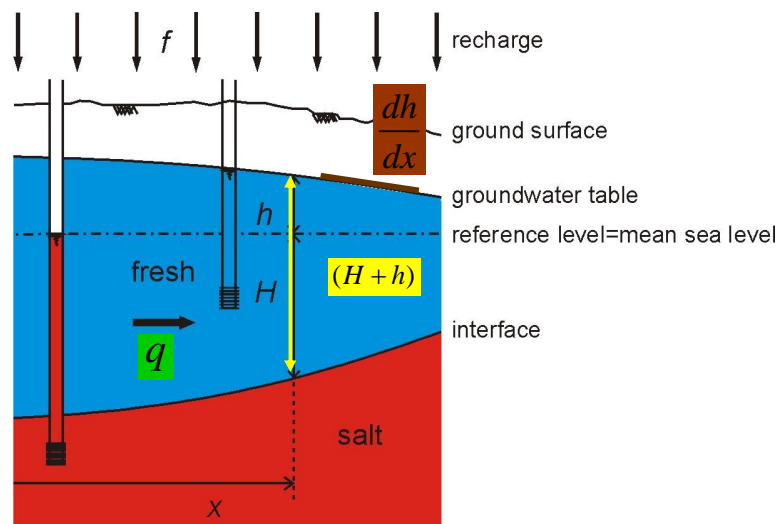
Analytical solutions

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



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

Unconfined aquifer (1D situation)



Unconfined aquifer (1D situation)

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

(II) Continuity $dq = f dx$

(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)

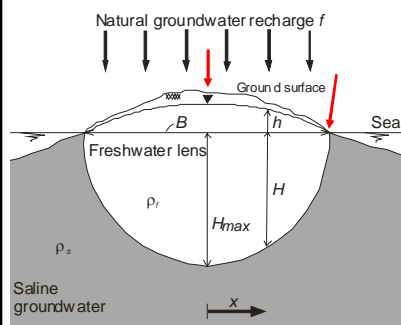
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}}$$

$$h = \alpha H$$

$$q = fx + C1$$

Example 1: Elongated island

$$H = \sqrt{\frac{-fx^2 - 2C_1x + 2C_2}{k\alpha(1+\alpha)}} \quad q = fx + C_1$$

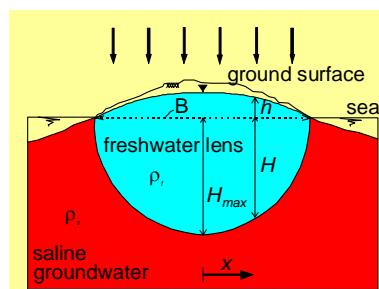


Boundary conditions

$$x = 0 : q = 0 \rightarrow C_1 = 0$$

$$x = 0.5B : H = 0 \rightarrow C_2 = fB^2 / 8$$

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

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

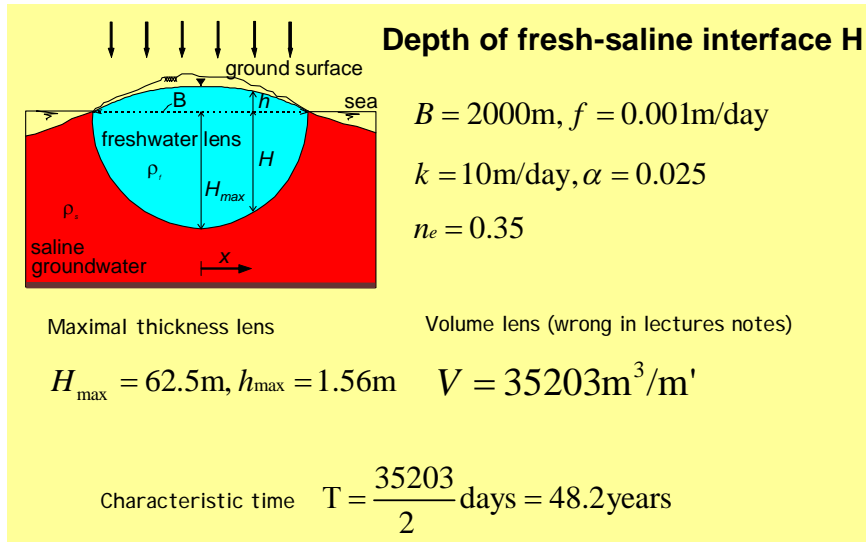
Volume lens

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

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

Lecture notes p. 32

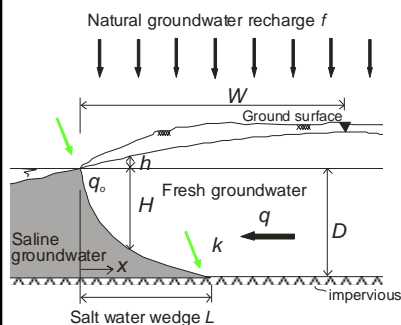
Example of analytical solutions (I)



Lecture notes p. 32

Example 2: salt water wedge

$$H = \sqrt{\frac{-fx^2 - 2C_1x + 2C_2}{k\alpha(1+\alpha)}} \quad q = fx + C_1$$



Boundary conditions

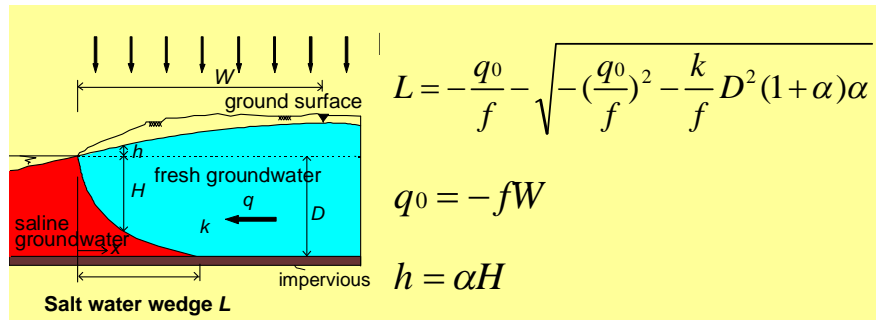
$$x = 0: q = q_0 \rightarrow q_0 = -fW \rightarrow C_1 = q_0$$

$$x = 0: H = 0 \rightarrow C_2 = 0$$

Length of salt water wedge

$$x = L: H = D$$

Example of analytical solutions (II)



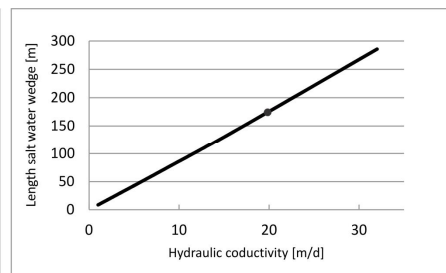
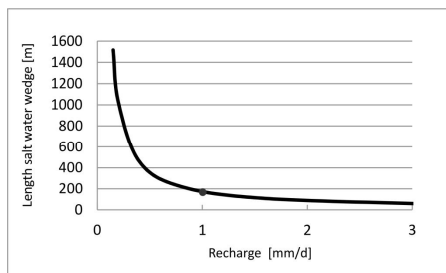
Example:

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

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

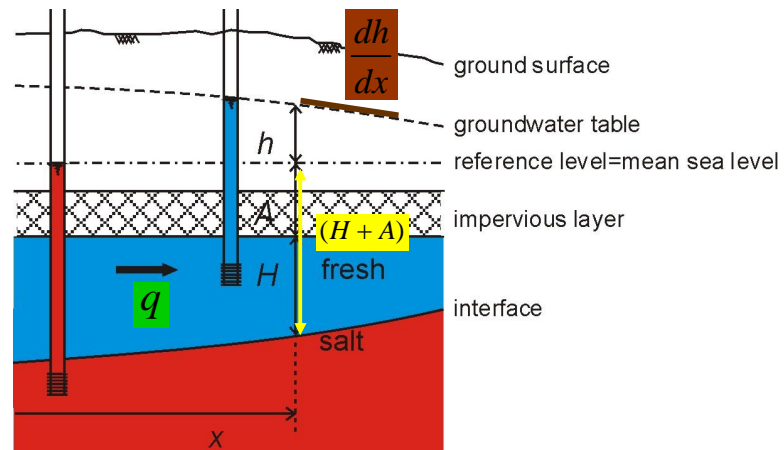
Lecture notes p. 33

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



the dots resample with the example mentioned above

Confined aquifer (1D situation)



Confined aquifer (1D situation)

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

(II) Continuity $q = q_0$

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

Confined aquifer (1D situation)

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

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

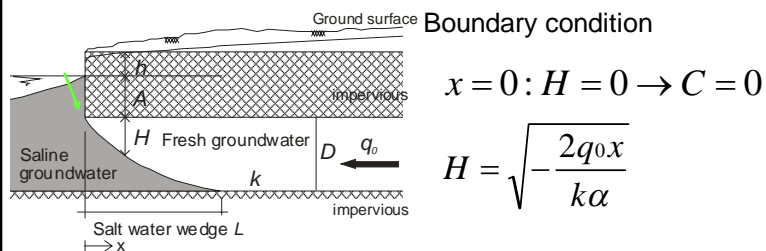
integration gives

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

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

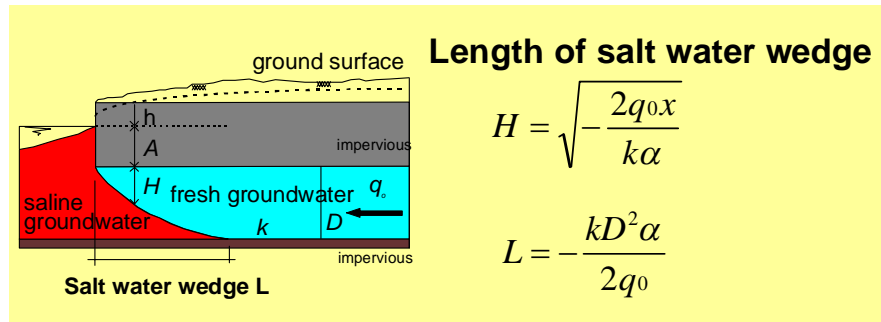
Example 3: salt water wedge confined aquifer

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



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

Example of analytical solutions (III)



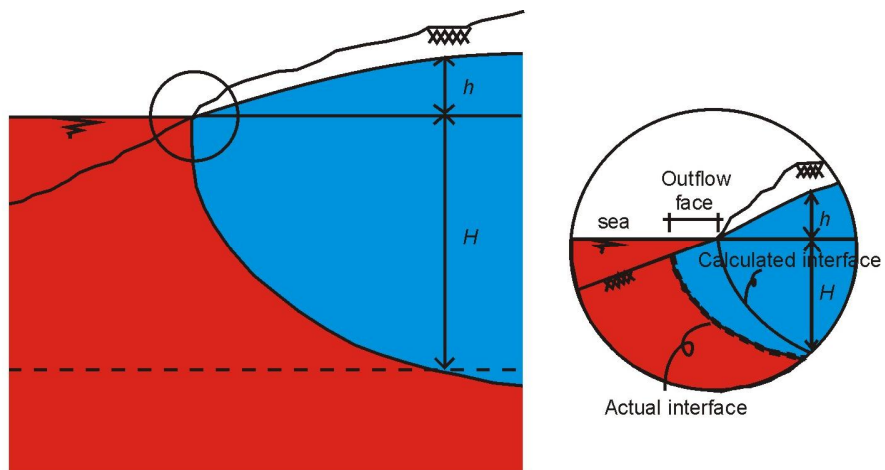
Example:

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

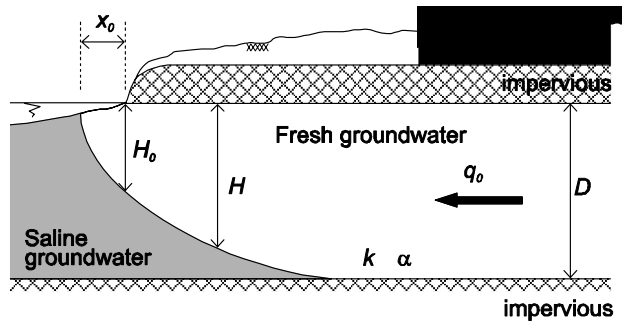
$L = 250\text{m}$

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Outflow face (Submarine Groundwater Discharge)



Outflow face (Submarine Groundwater Discharge)



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

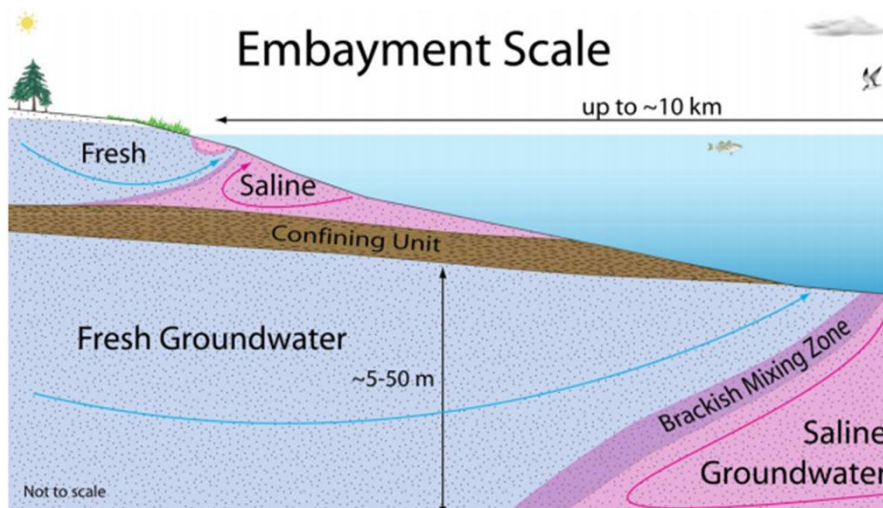
Example:

$$x_0 = \frac{f \cdot L}{2ka} = \frac{0.001 \text{ m/d} \cdot 20000 \text{ m}}{(2 \cdot 20 \cdot 0.025)} = 20 \text{ m (only!)}$$

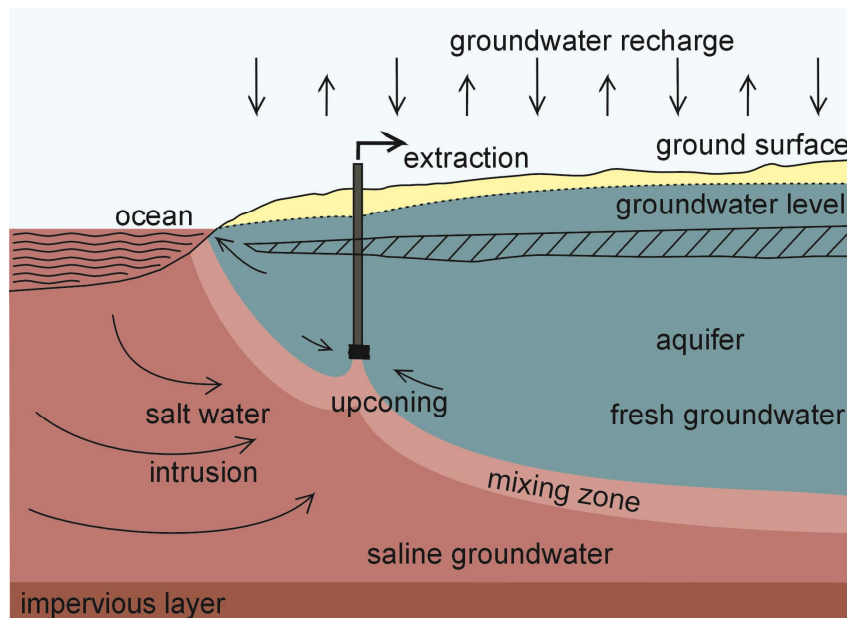
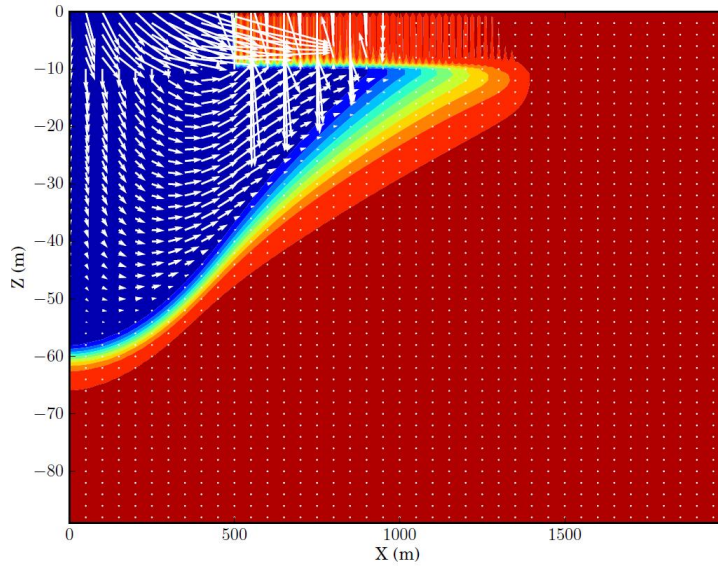
Note: no resistance layer offshore

Outflow face (Submarine Groundwater Discharge)

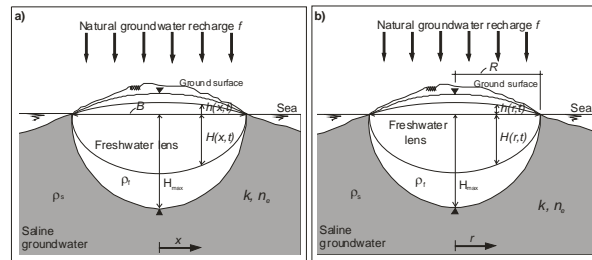
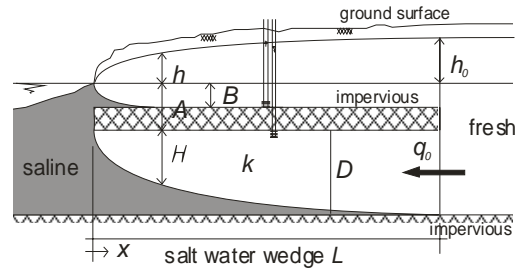
Embayment Scale



Outflow face (Submarine Groundwater Discharge)



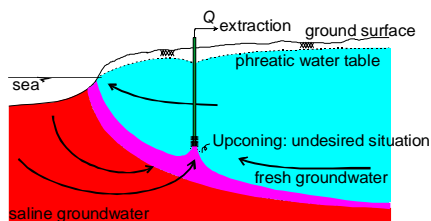
See the lectures for more cases



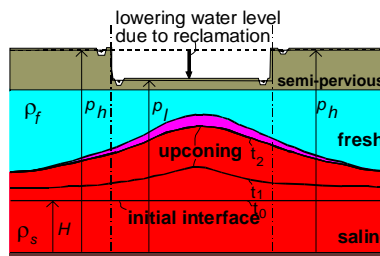
Upconing processes

Upconing of saline groundwater

Under an extraction well



Under a low-lying polder area

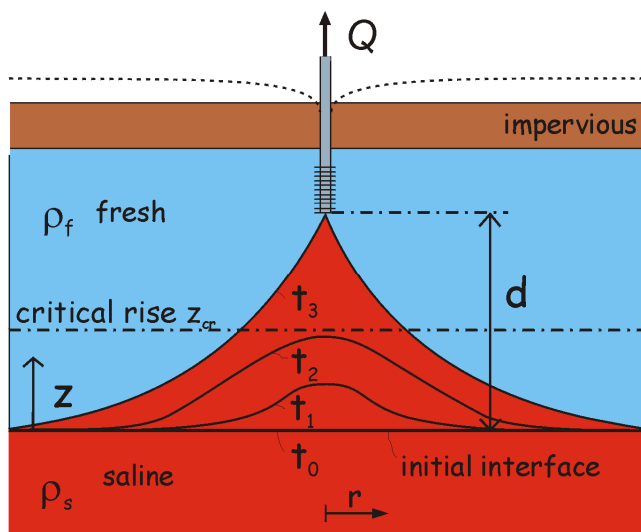


- movement of saline groundwater to extraction wells
- increase in salinity (>150-200 mg Cl-/l)
- lowering of the piezometric head (leads to land subsidence: e.g. Los Angeles: 9 m in the 1930's)

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

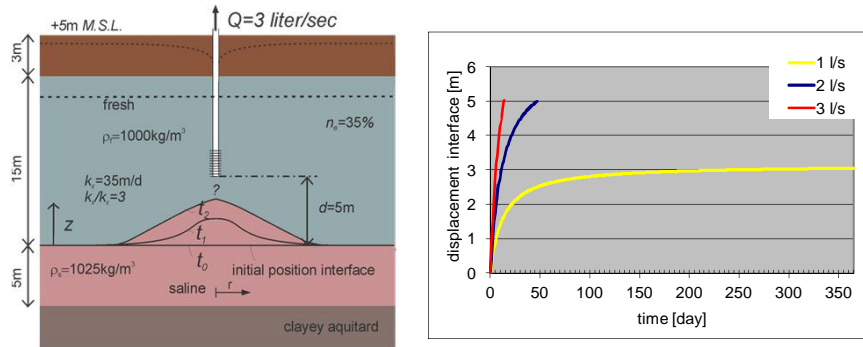
Examples of analytical solutions (IV)

Upconing of saline groundwater under an extraction well



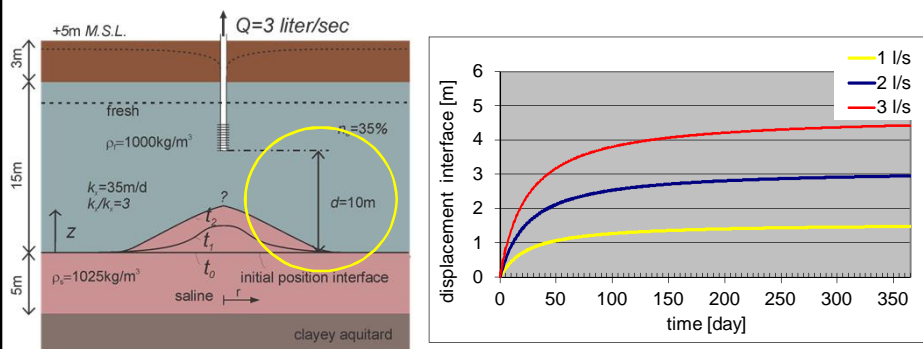
Lecture notes p. 44

Situation Jurong Island: pilot extraction well



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

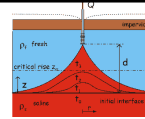
Situation Jurong Island: pilot extraction well: d=10m!



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

Examples of analytical solutions (IV)

Upconing of saline groundwater under an extraction well



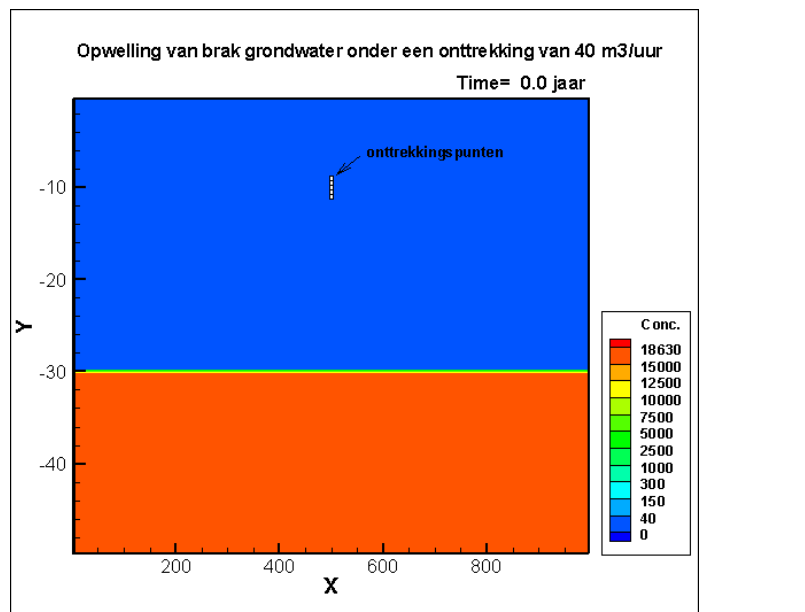
$$z(r, t) = \frac{Q}{2\pi\alpha k_x d} \left[\frac{1}{(1 + R'^2)^{1/2}} - \frac{1}{[(1 + \gamma')^2 + R'^2]^{1/2}} \right]$$

$$R' = \frac{r k_z}{d k_x} \quad \gamma' = \frac{\alpha k_z}{2n_e d} t$$

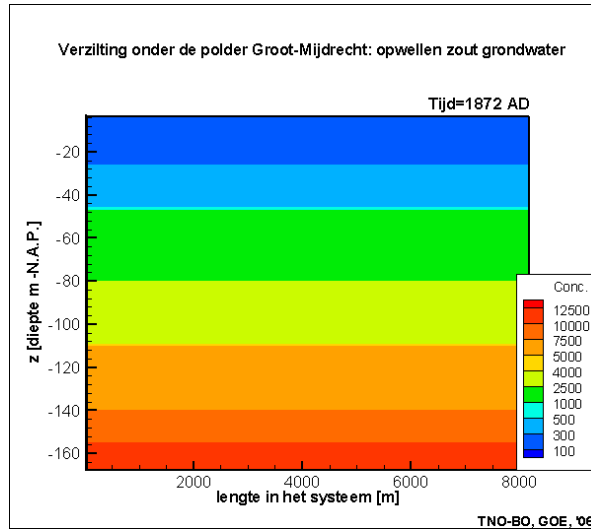
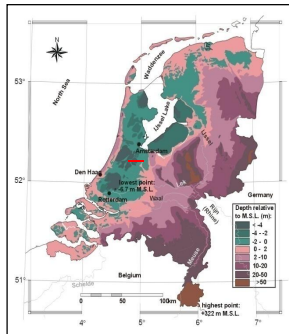
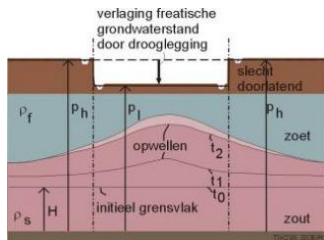
Dagan & Bear, 1968, J. Hydraul. Res 6, 1563-1573

Lecture notes p. 44

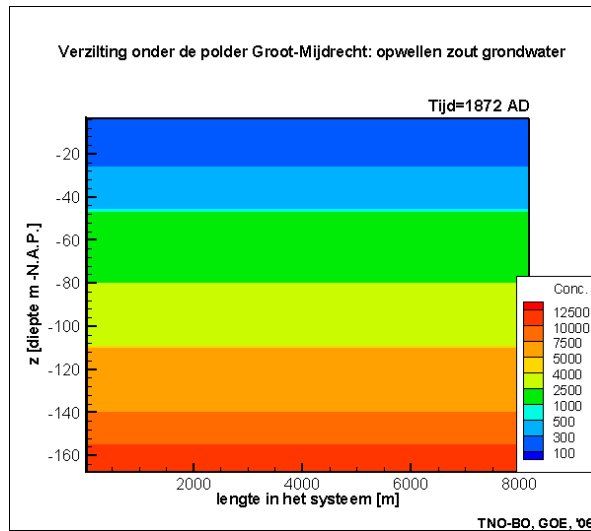
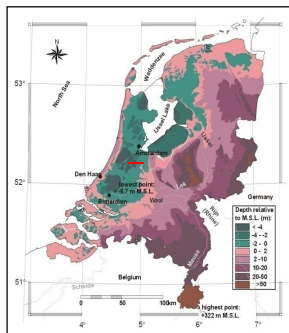
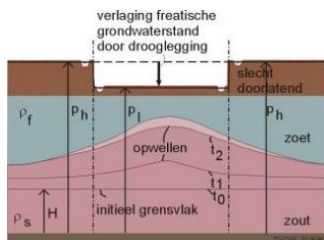
Upconing of salt under an extraction



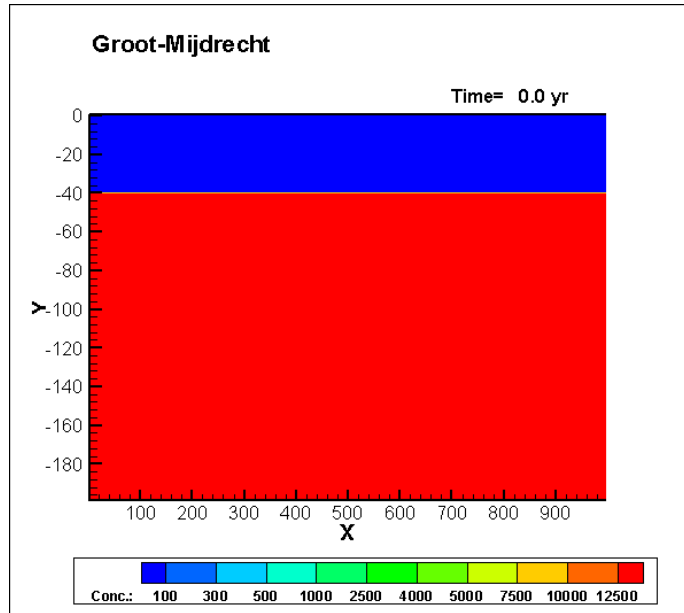
Upconing under a low-lying polder (Groot-Mijndrecht)



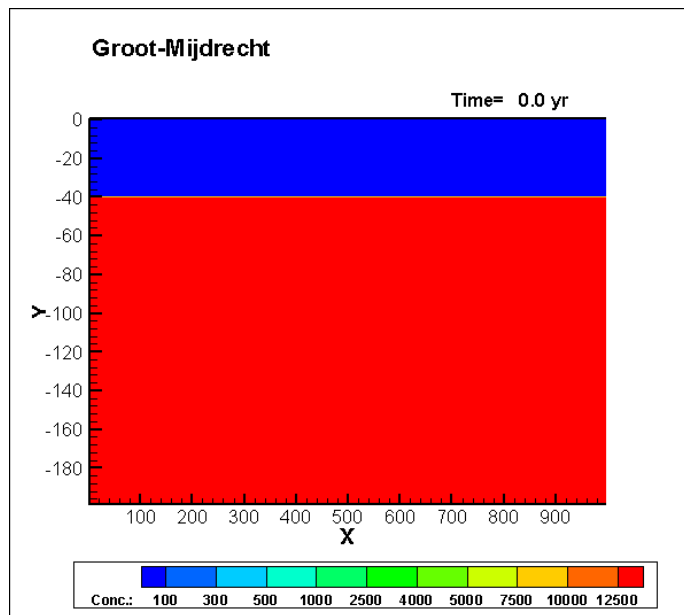
Upconing under a low-lying polder (Groot-Mijndrecht)



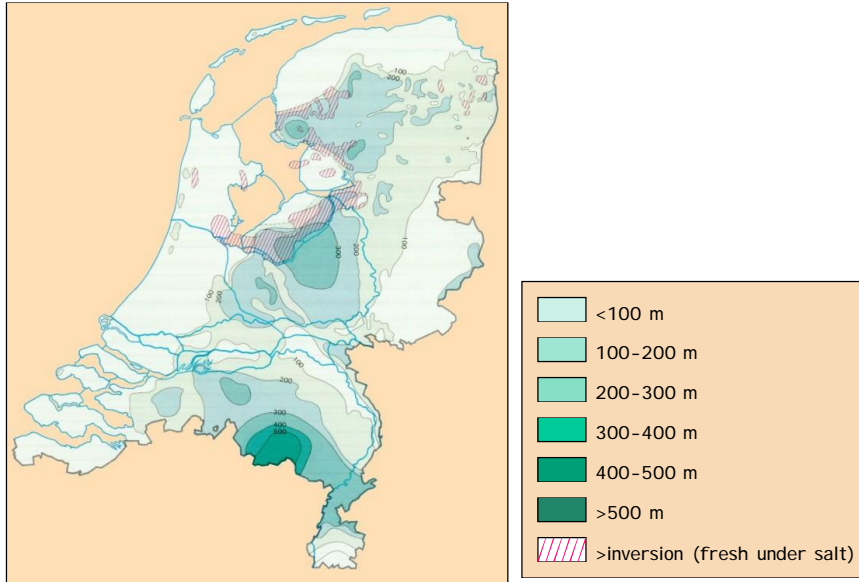
Upconing under a low-lying polder (Groot-Mijdrecht)



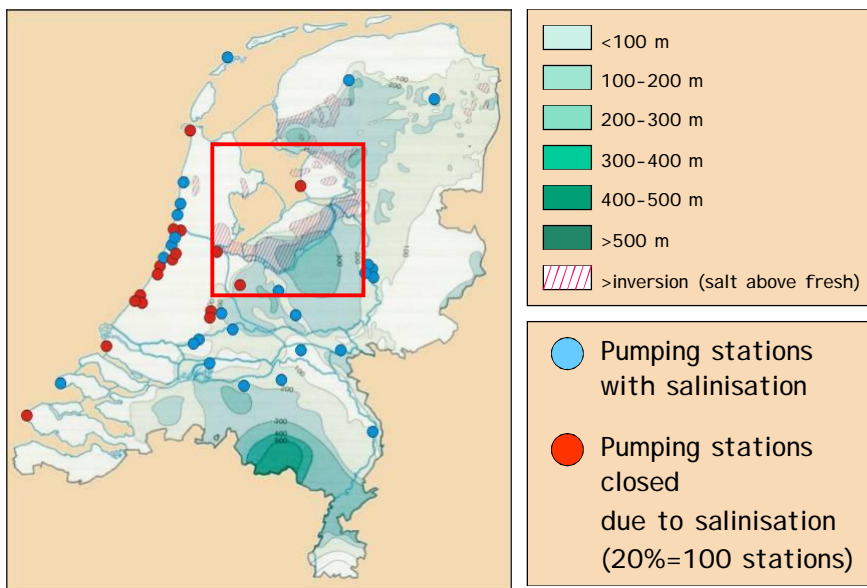
Upconing under a low-lying polder (Groot-Mijdrecht)



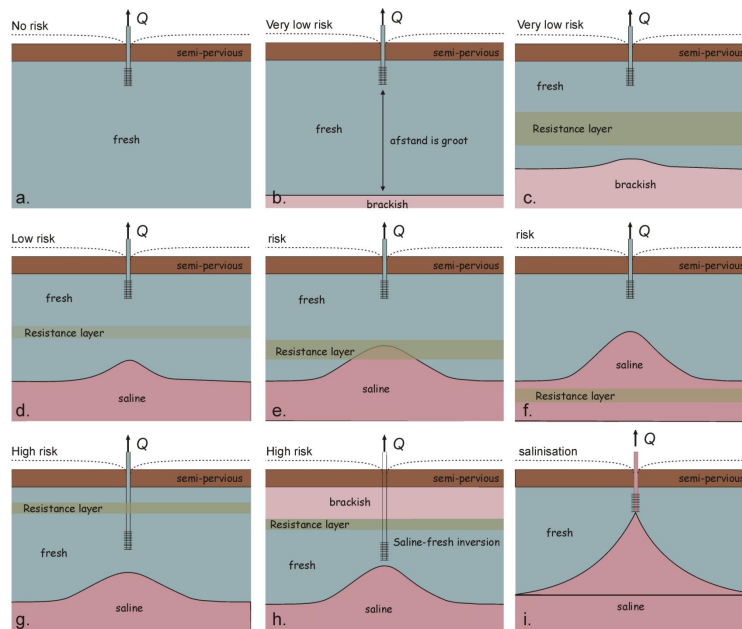
Fresh-salt interface (150 mg Cl⁻/l)



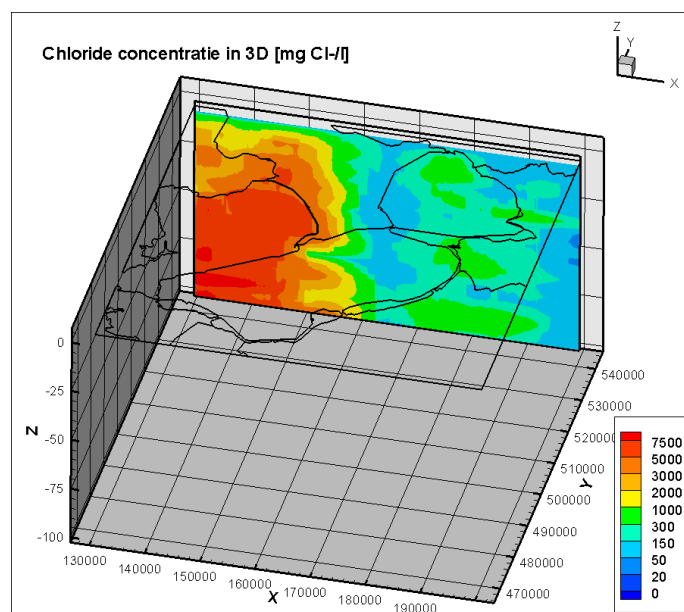
Availability of fresh groundwater



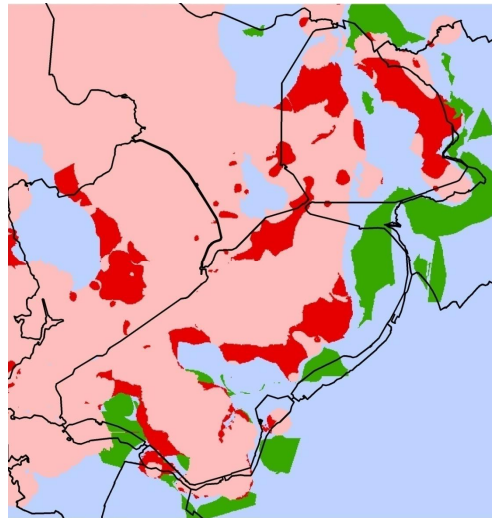
Different risks of upconing saline groundwater



Animation 3D Chloride concentration



Upconing in Flevoland




Risk depends on:

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

 High risk

 Low risk

 Very low risk

Compensating measures

Possible solutions to stop salt water intrusion:

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

Tools to understand salt water intrusion:

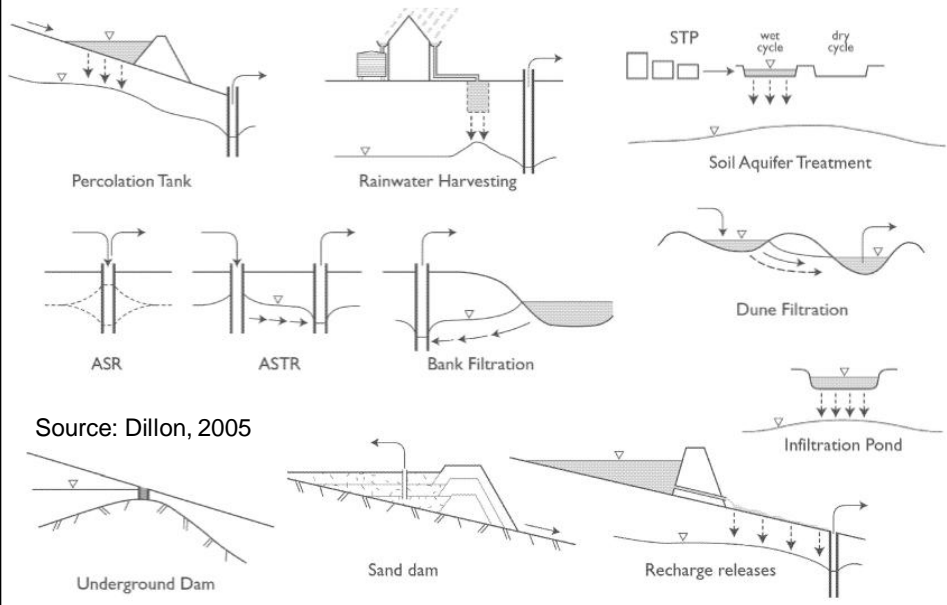
- Monitoring of salinities and piezometric levels
- Numerical modelling of salt water intrusion

Measures to compensate salt water intrusion

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

Aquifer Storage and Recovery

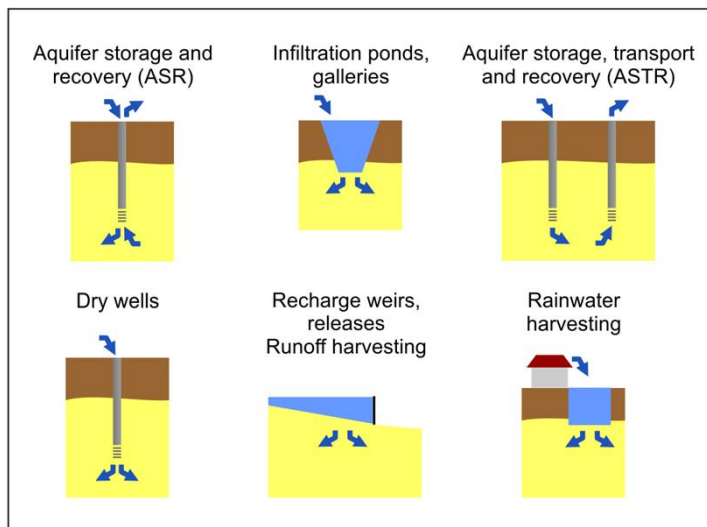
"potential to be a major contribution to UN Millennium Goals for Water Supply"



Source: Dillon, 2005

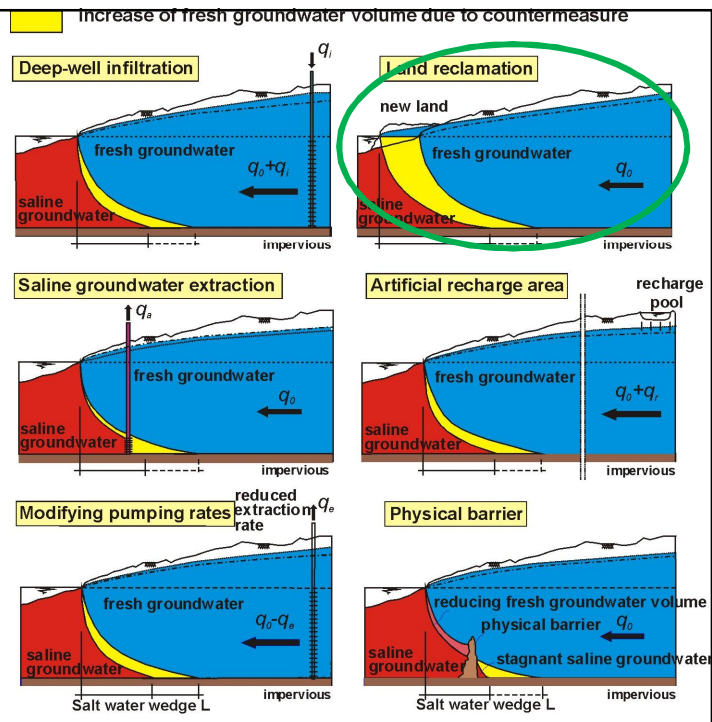
Aquifer Storage and Recovery / Managed Aquifer Recharge

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



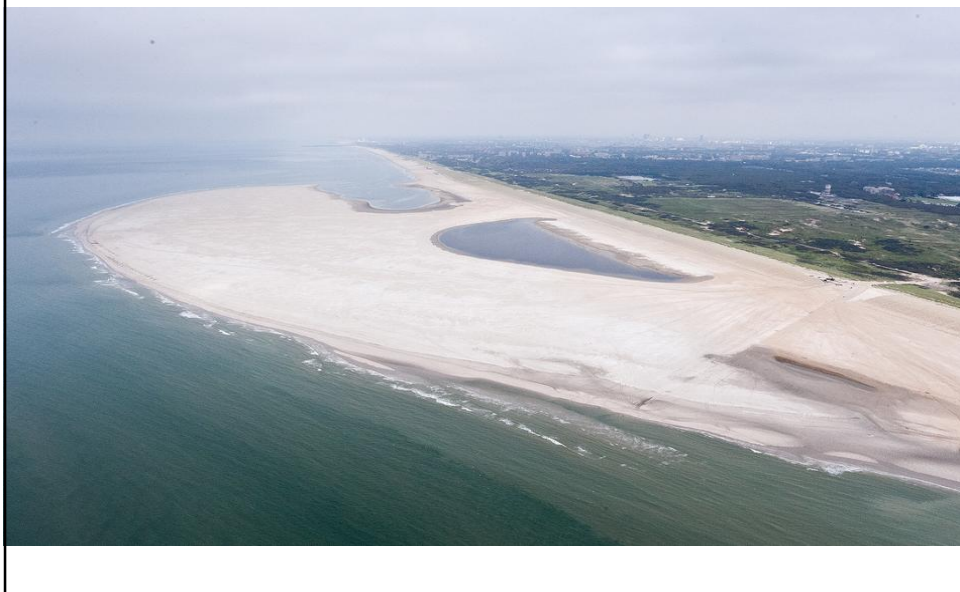
Source: Dillon, 2005

Technical measures to compensate salt water intrusion

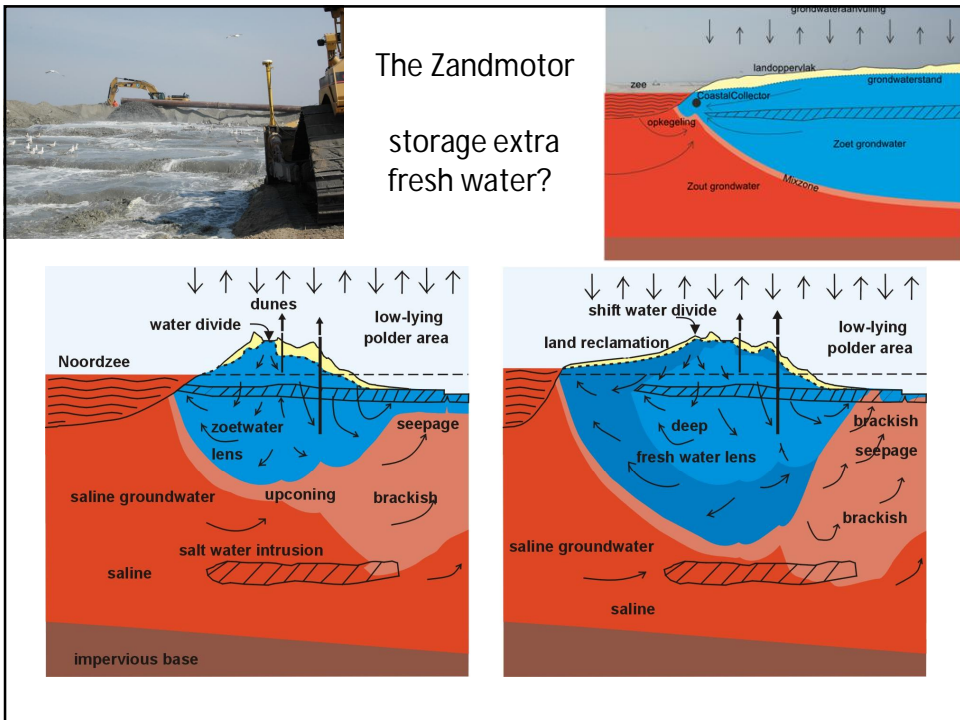


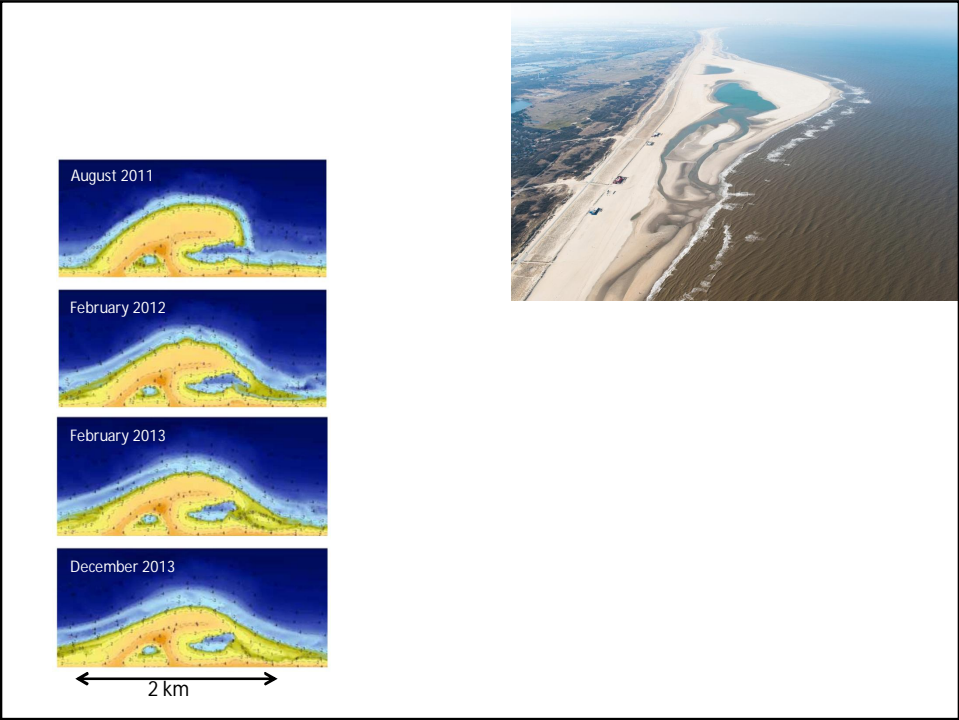
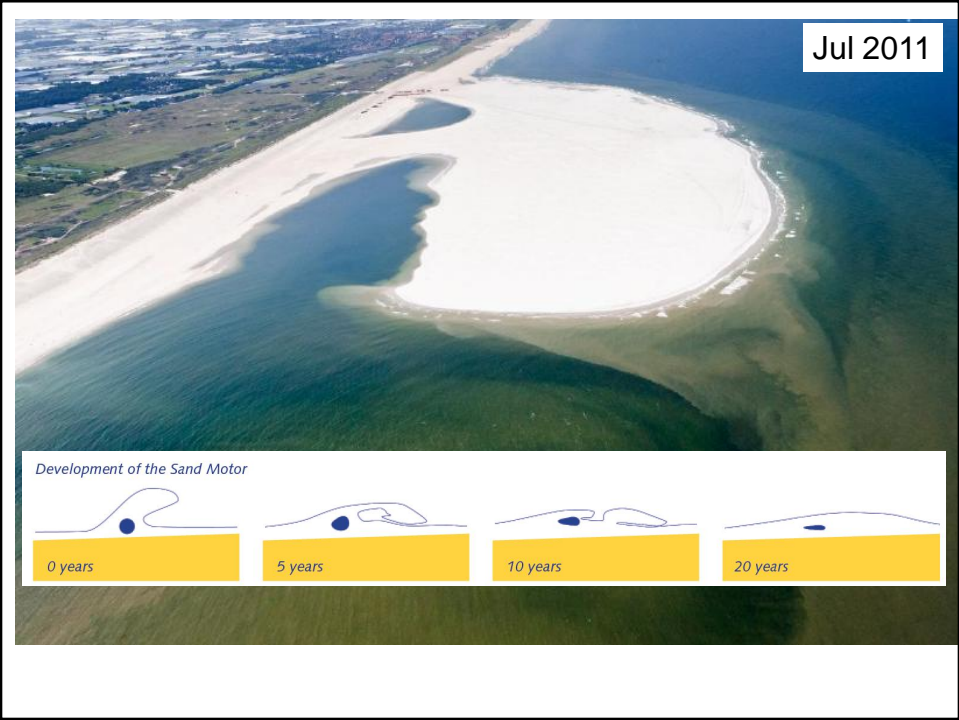
Land reclamation

The Zandmotor: effects at the hinterland?

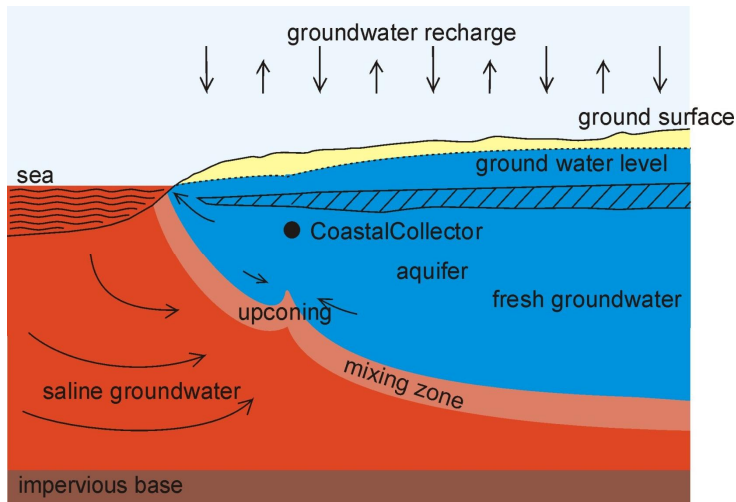


The Zandmotor: effects at the hinterland?



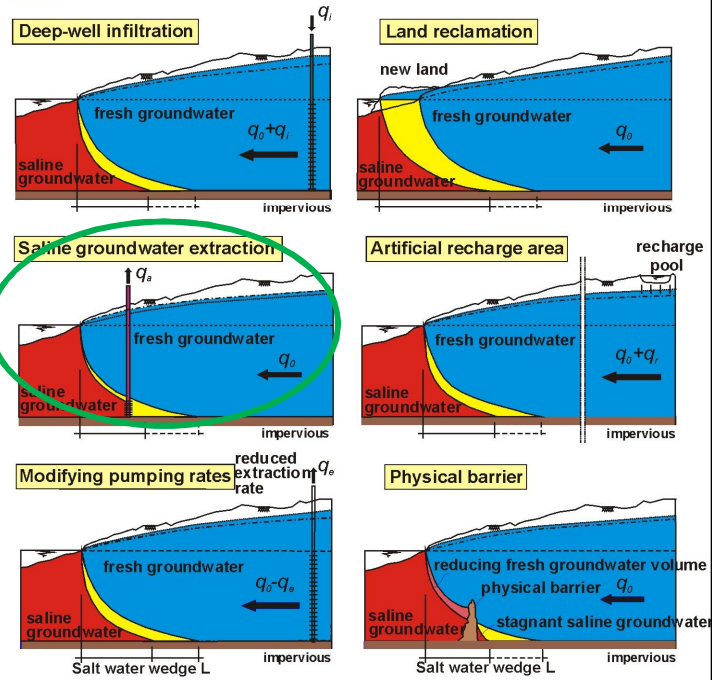


The Coastal Collector

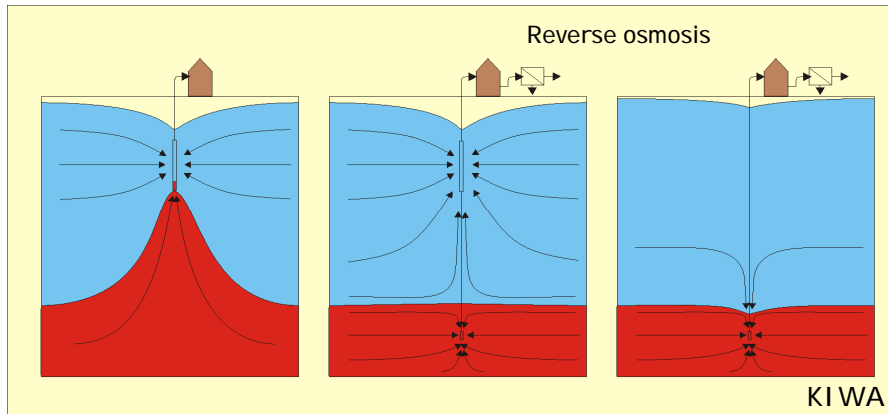


Technical measures to compensate salt water intrusion

increase of fresh groundwater volume due to countermeasure

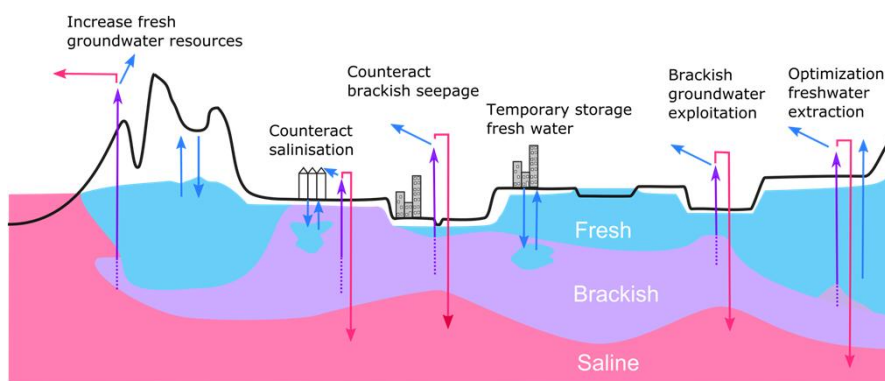


Solution: The Fresh Holder

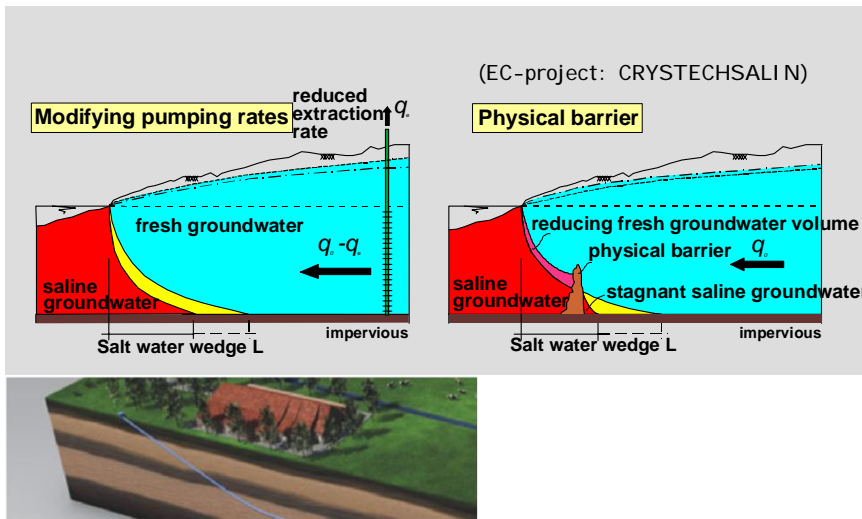


Upconing can be prevented by the extraction of brackish groundwater
 This brackish groundwater can be transformed to water of agricultural water quality by using the membrane filtration technique

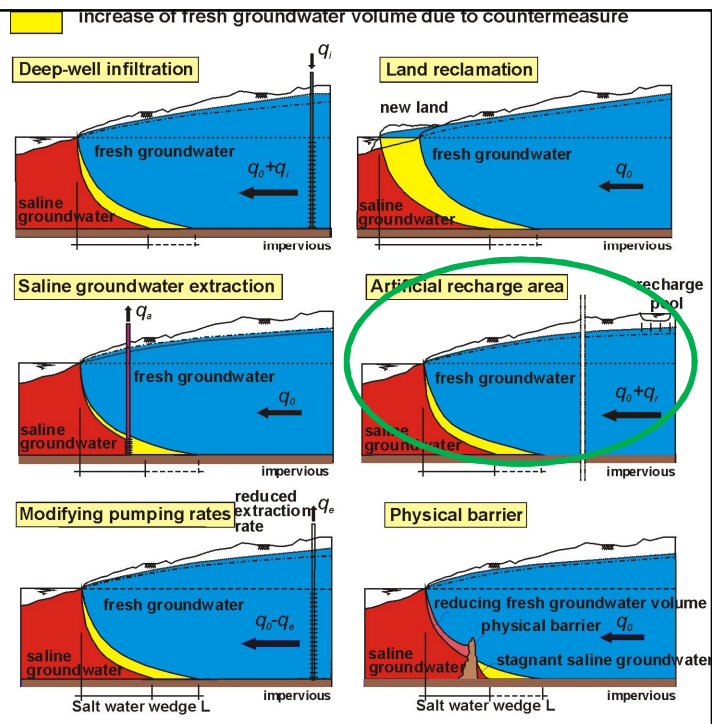
COASTAR: COastal Aquifer STORAGE And Recovery



Countermeasures of salt water intrusion



Technical measures to compensate salt water intrusion

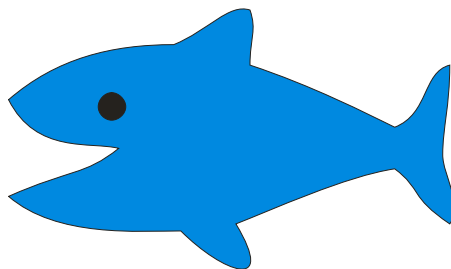


Base idea

Many local solutions for fresh groundwater supply can have regional impact

Starring

solution fresh groundwater supply



Starring

Local solution fresh groundwater supply



Starring

climate and global change



Starring

climate and global change



Solutions and responses

Local solution fresh
groundwater supply

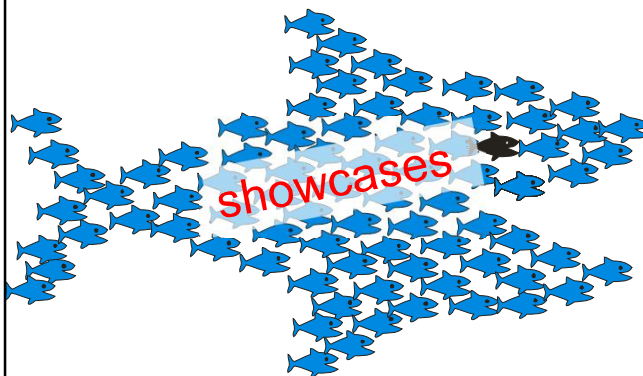
climate and global change



What should be the response?

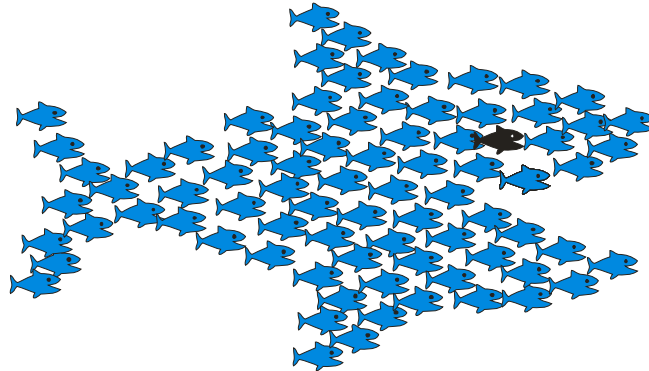
Many local solutions fresh groundwater supply

climate and global change



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

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



Aquifer Storage and Recovery in the coastal zone



Goal:

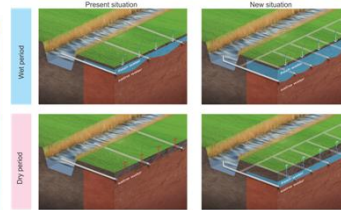
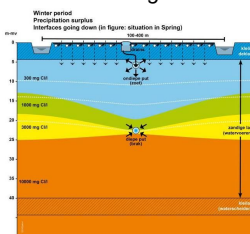
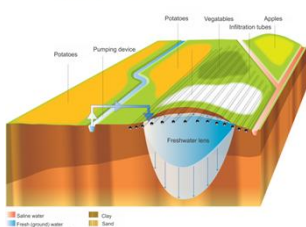
Increase fresh groundwater resources in saline seepage areas in the southwestern part of the Dutch Delta

Methods:

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

www.go-fresh.info

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



Creekridge Infiltration Test

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

The Freshmaker

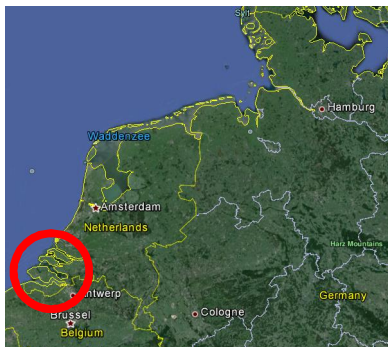
Increase fresh water volume in creek ridge by passive infiltration via drainage

Drains2Buffer

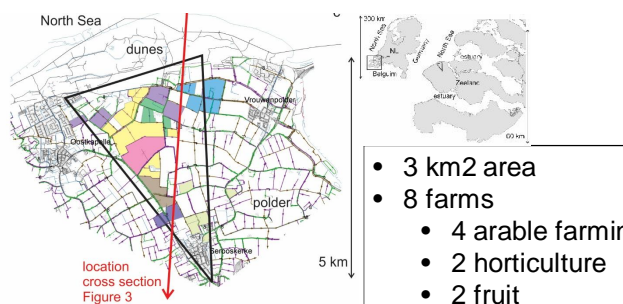
Maintain fresh water volume in shallow rainwater lenses by smart deep controlled drainage

Problem statement

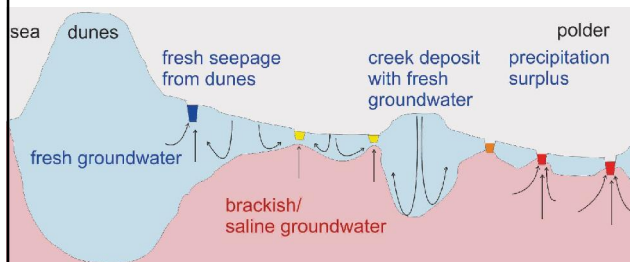
- Crop damage southwestern part of the Netherlands
- Fresh groundwater below creek ridges



Case study: Water Farm



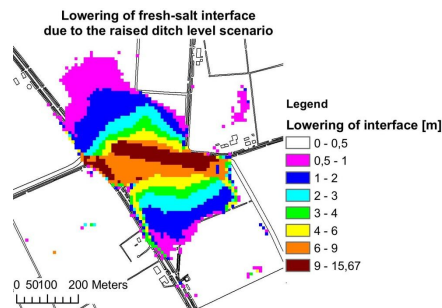
- 3 km² area
- 8 farms
 - 4 arable farming
 - 2 horticulture
 - 2 fruit
- start case study 2010



- codesign measures
- communication to outside world



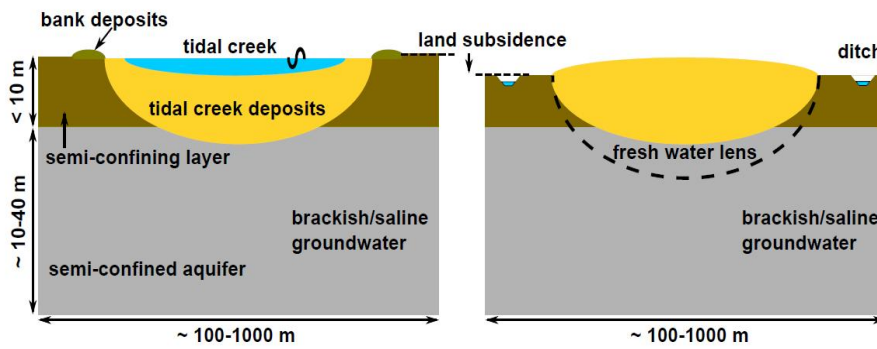
Researchers: scenario analysis



Creek ridges

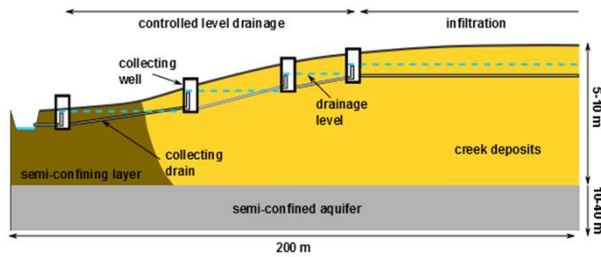
1200 AD; before land reclamation

current situation

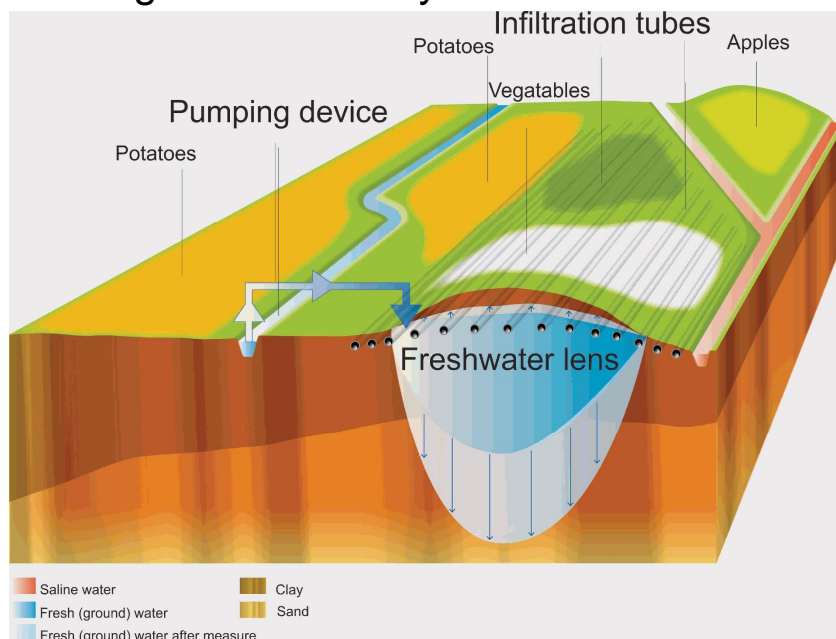


Measure

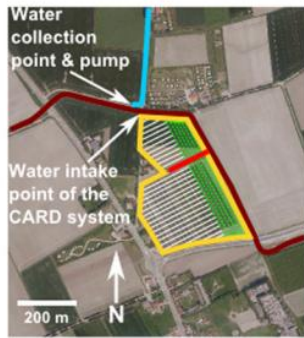
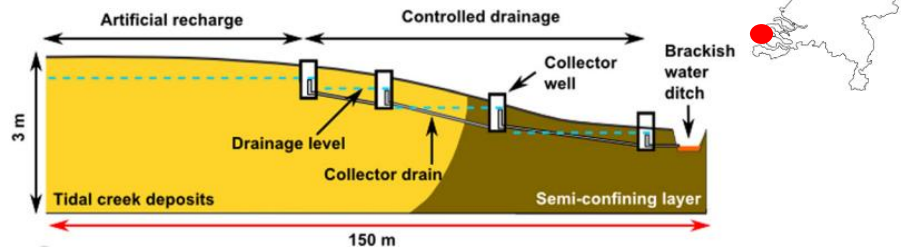
- Controlled level drainage
- Increase groundwater level



Creekridge Infiltration System



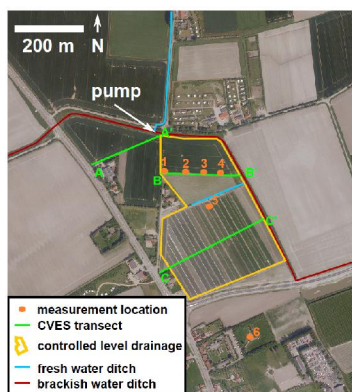
Concept of CARD and pilot layout



Legend

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

Installation of drainage and monitoring network

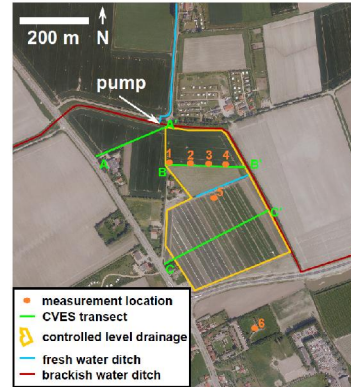


various types of field measurements

Different types of field measurements applied

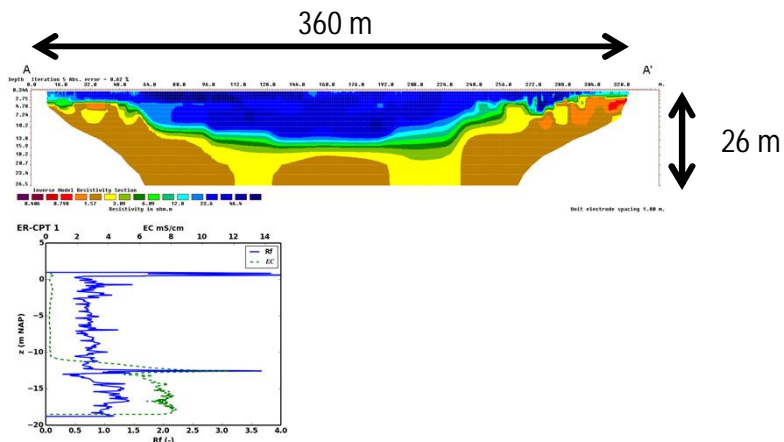
Measurement type	Purpose
Pressure transducers ^a	Groundwater levels
Sampling using piezometer nest	EC _{w20}
SLIMFLEX ^b	EC _{bulk}
CPT ^c	Lithology and EC _{bulk}
CVES ^d	EC _{bulk}
SMD ^e	EC _{bulk}

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



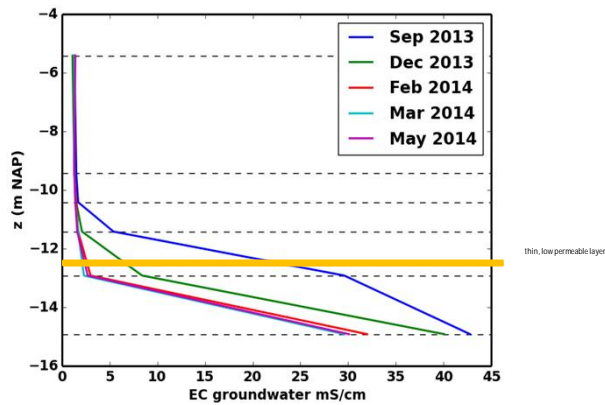
Key field observations (1)

- Fresh groundwater up to -12 m NAP

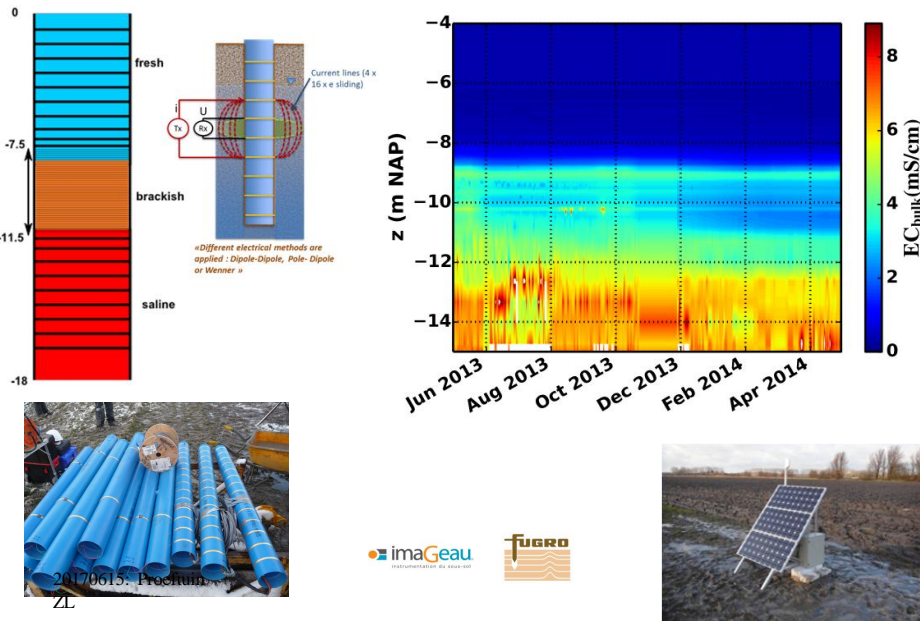


Key field observations (2)

- Freshening up to 2m

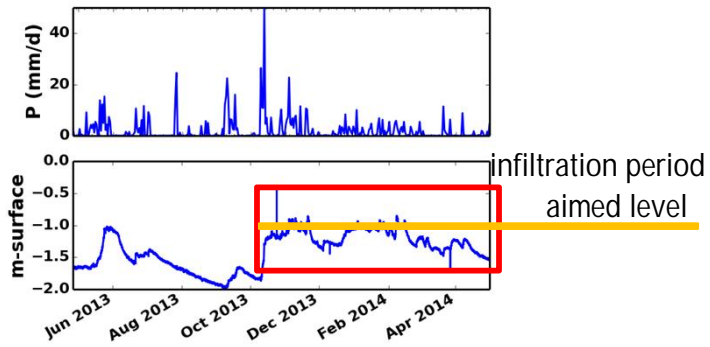


Subsurface Monitoring Device (SMD): Monitoring salinities

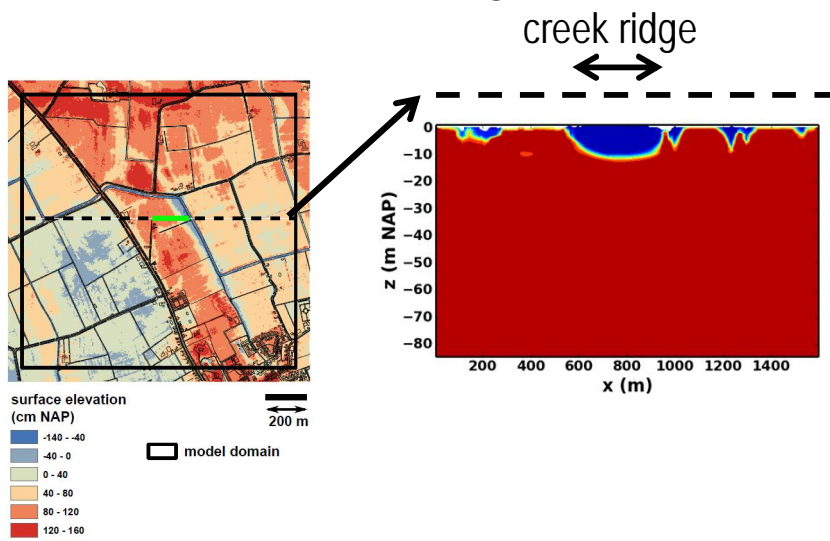


Key field observations (3)

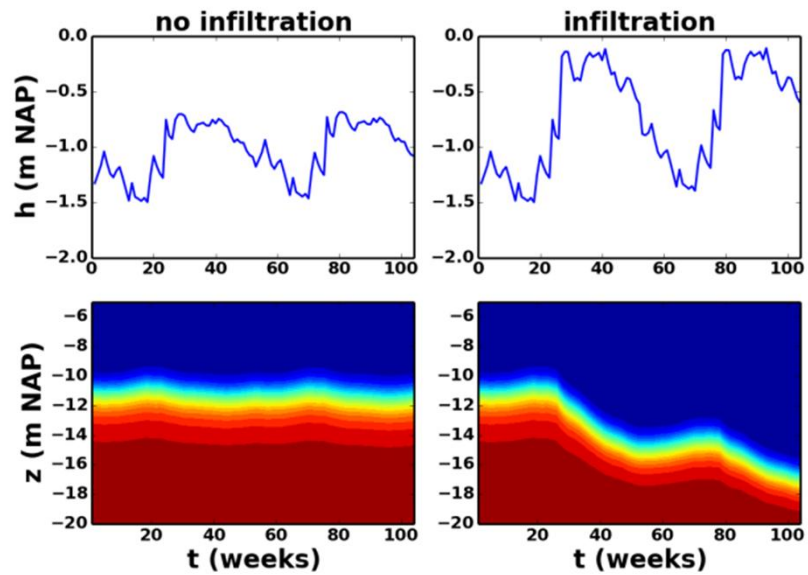
- Groundwater levels and precipitation



Modeling

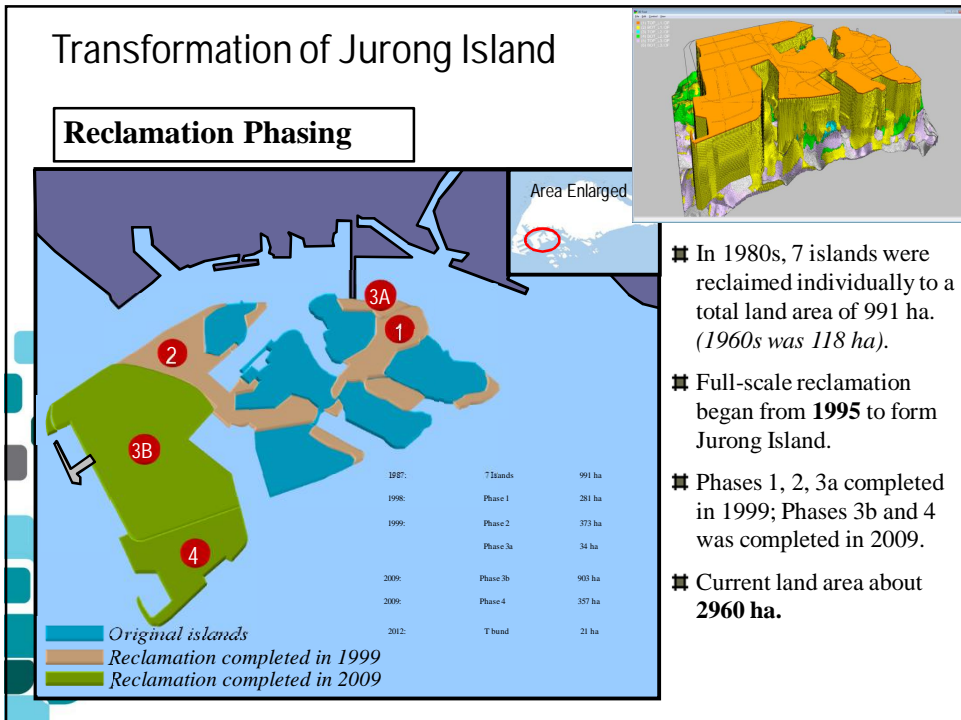
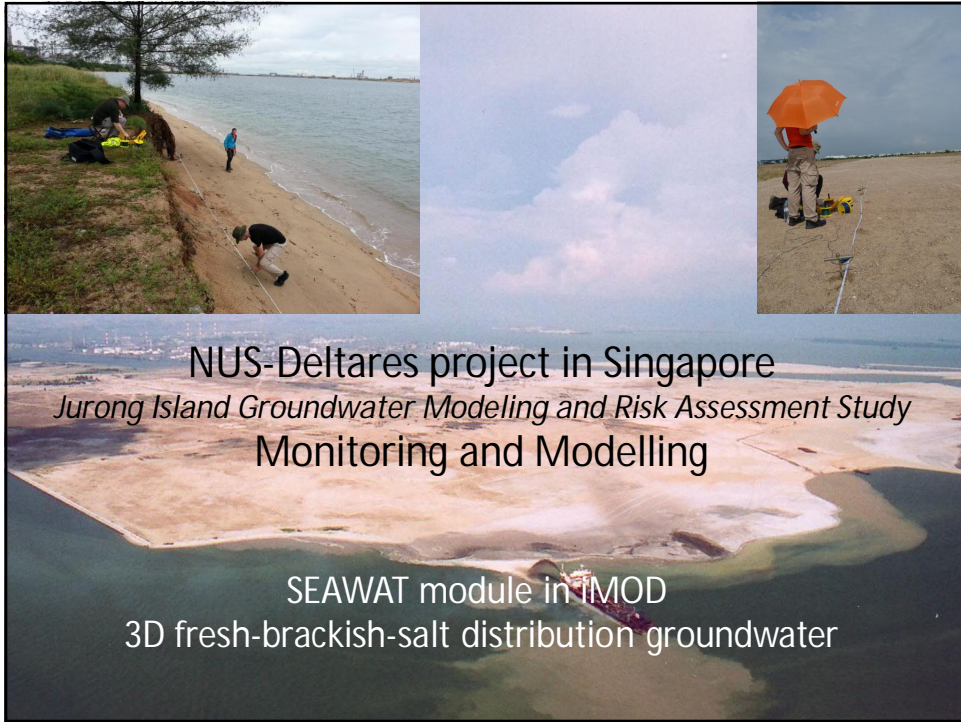


Influence of infiltration

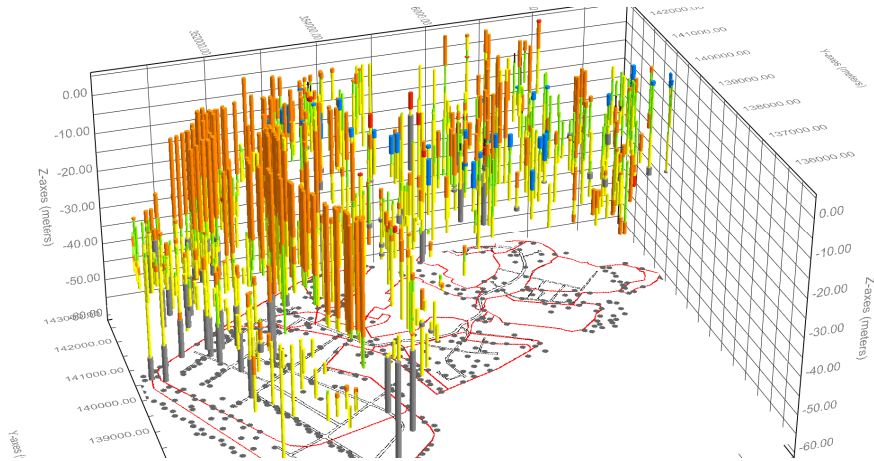


Singapore Jurong Island

Aquifer Storage and Recovery

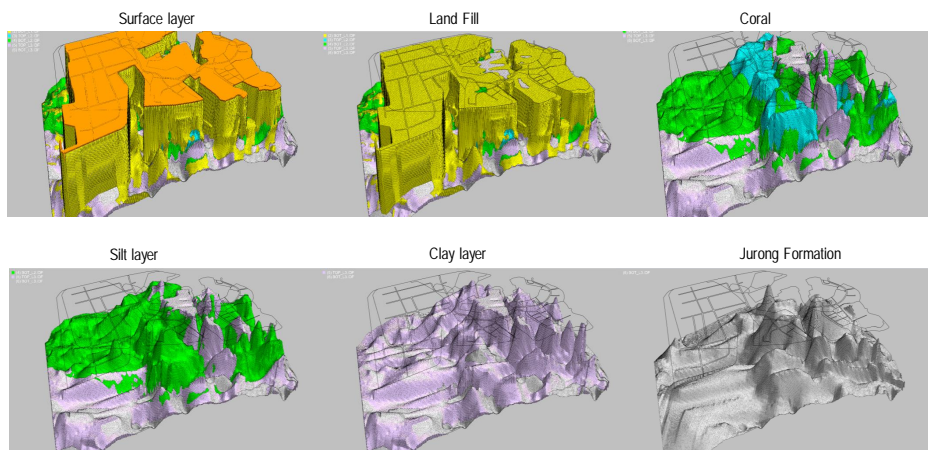


Boreholes

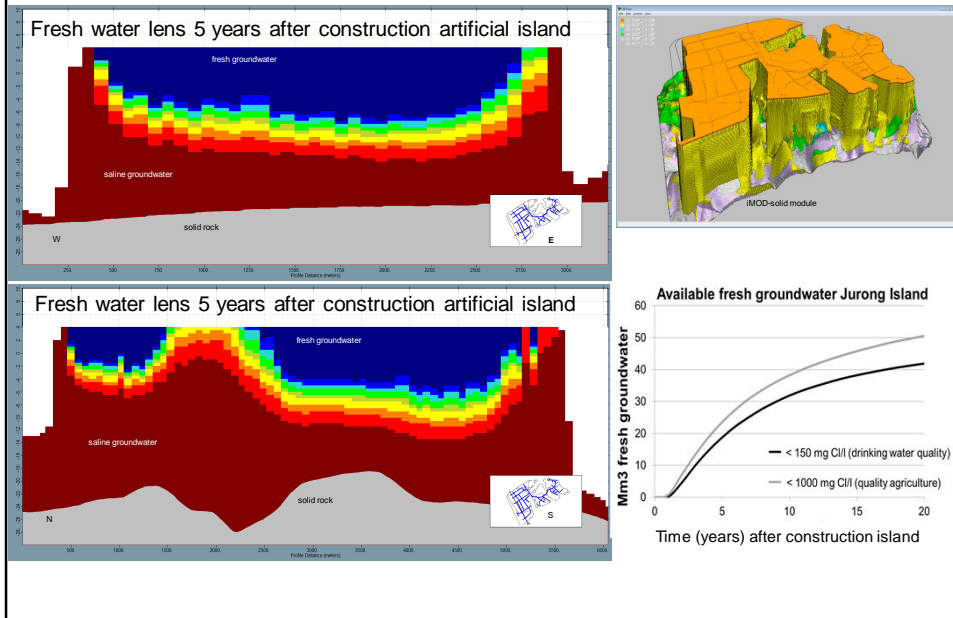


509 boreholes were converted from PDF to IFF, the format that MOD can read

SubSoil Model



iMOD-SEAWAT Jurong Island Singapore



Animation scavenger wells

