IHE 2020

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

17-18-22-24 June 2020

Curriculum Vitae

- Delft University of Technology, Civil Engineering: till 1997

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

Qualifications:

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

http://freshsalt.deltares.nl

Deltares: gualbert.oudeessink@deltares.nl

Colleagues at Deltares
Groundwater in the Coastal Zone

http://zoetzout.deltares.nl

http://freshsalt.deltares.nl

Gualbert Oude Essink

Joost Delsman

Pieter Pauw

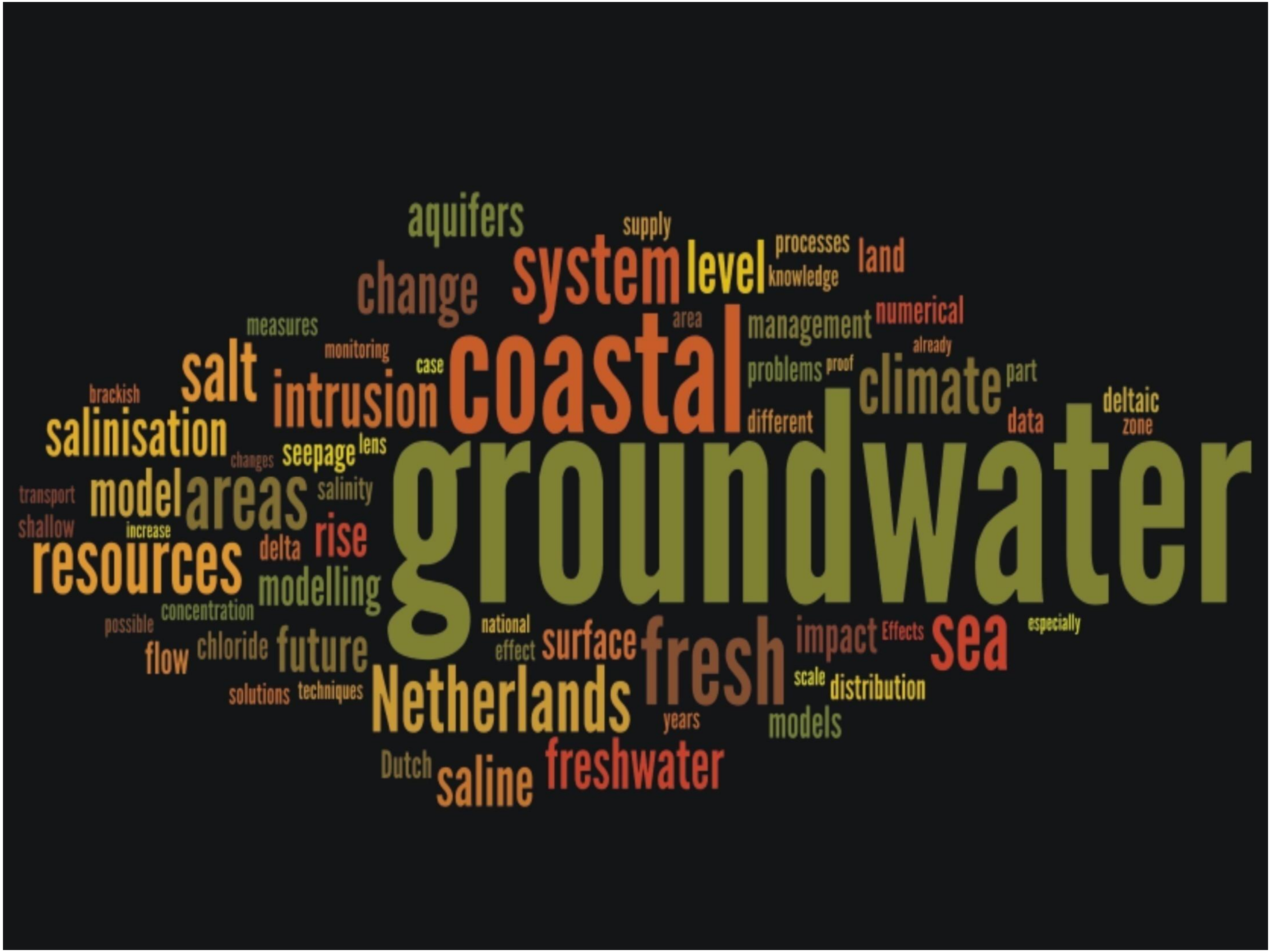
Tobias Mulder

Perry de Louw

Esther van Baaren

Jarno Verkaik

Marta Faneca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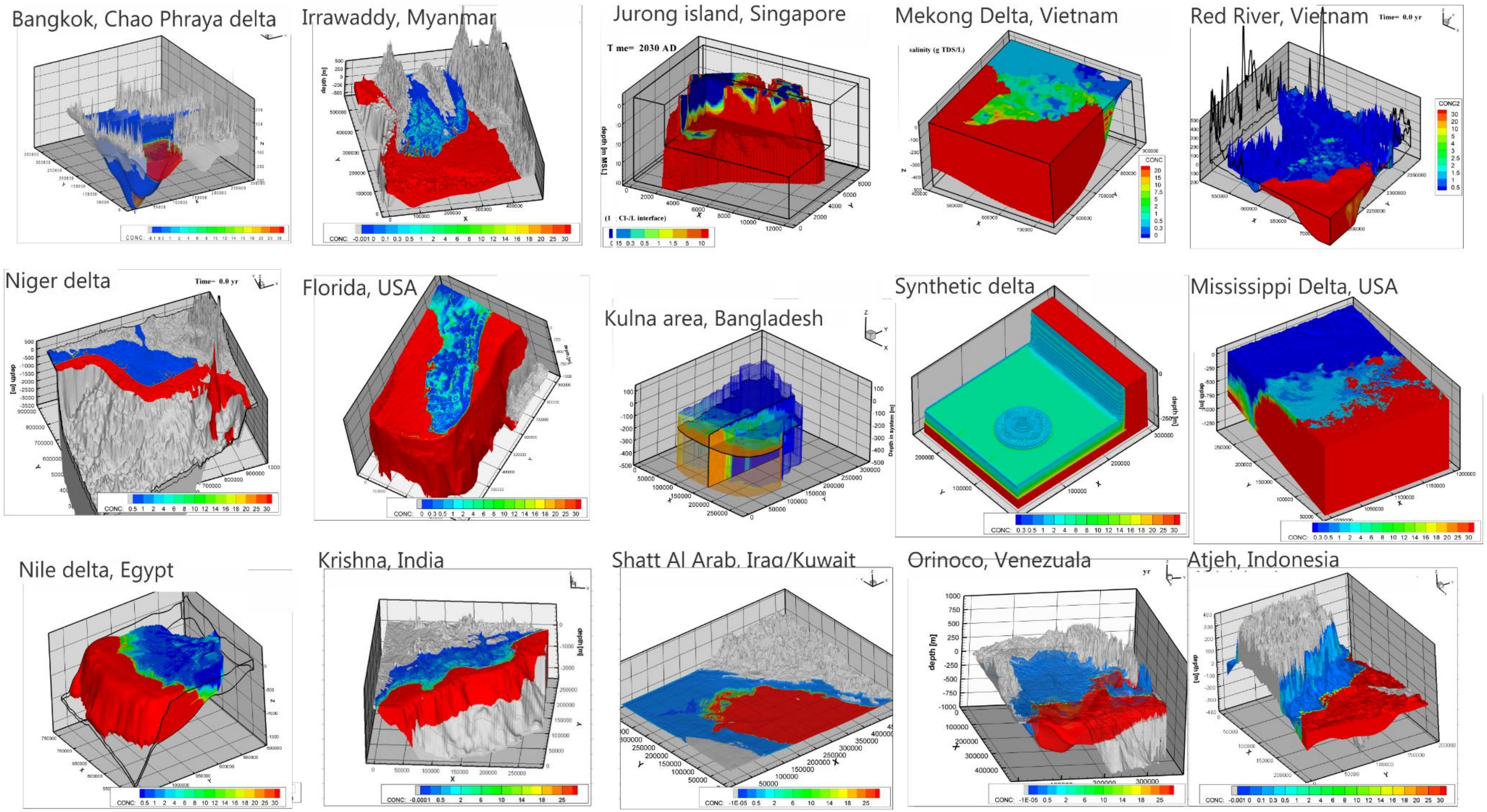

Bangkok, Chao Phraya delta
Irrawaddy, Myanmar
Jurong island, Singapore
Mekong Delta, Vietnam
Red River, Vietnam
Niger delta
Florida, USA
Kulna area, Bangladesh
Synthetic delta
Mississippi Delta, USA
Nile delta, Egypt
Krishna, India
Shatt Al Arab, Iraq/Kuwait
Orinoco, Venezuala
Atjeh, Indonesia

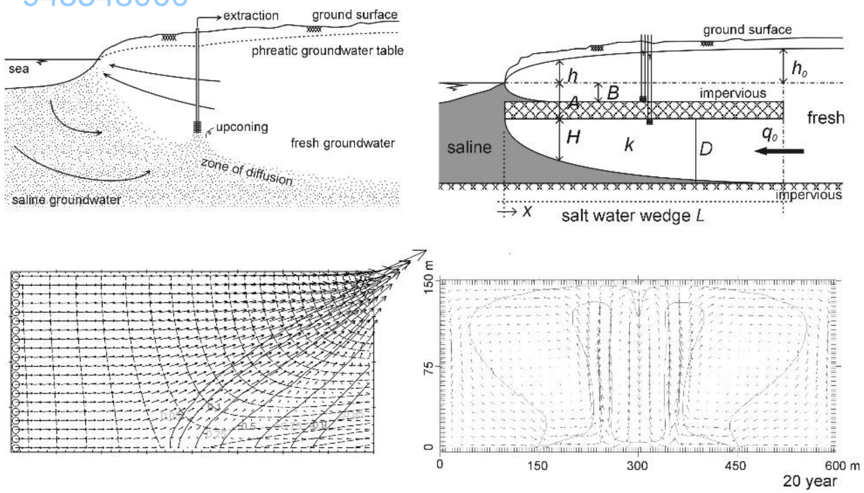
Research on groundwater in the coastal zone

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

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

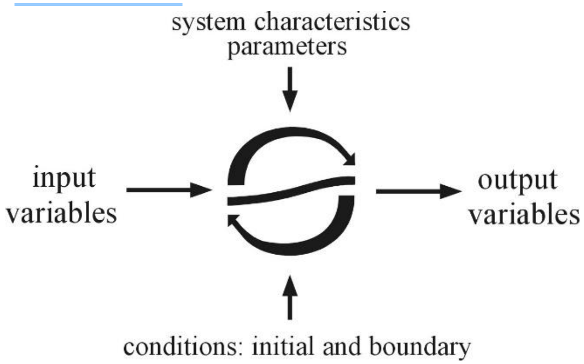
1. Density dependent groundwater flow

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



2. Groundwater modelling

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



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

Practicals numerical modelling

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

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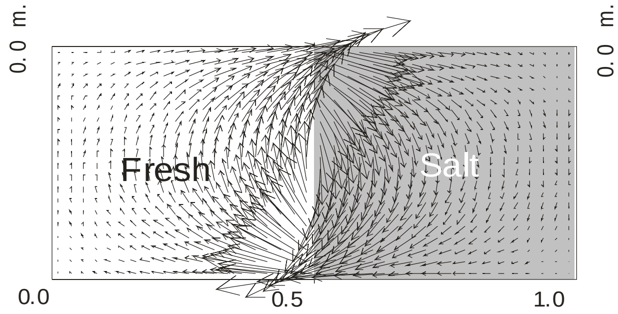
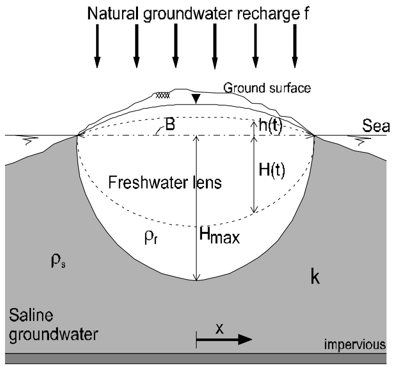
Practicals

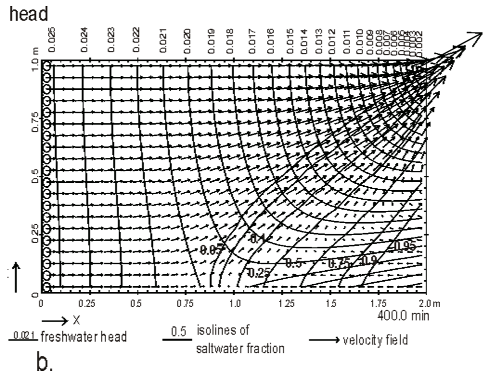
- Rotating sharp interface



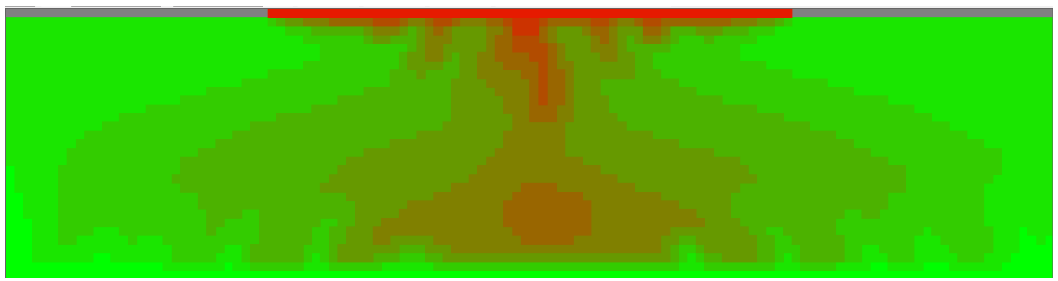
- Freshwater lens



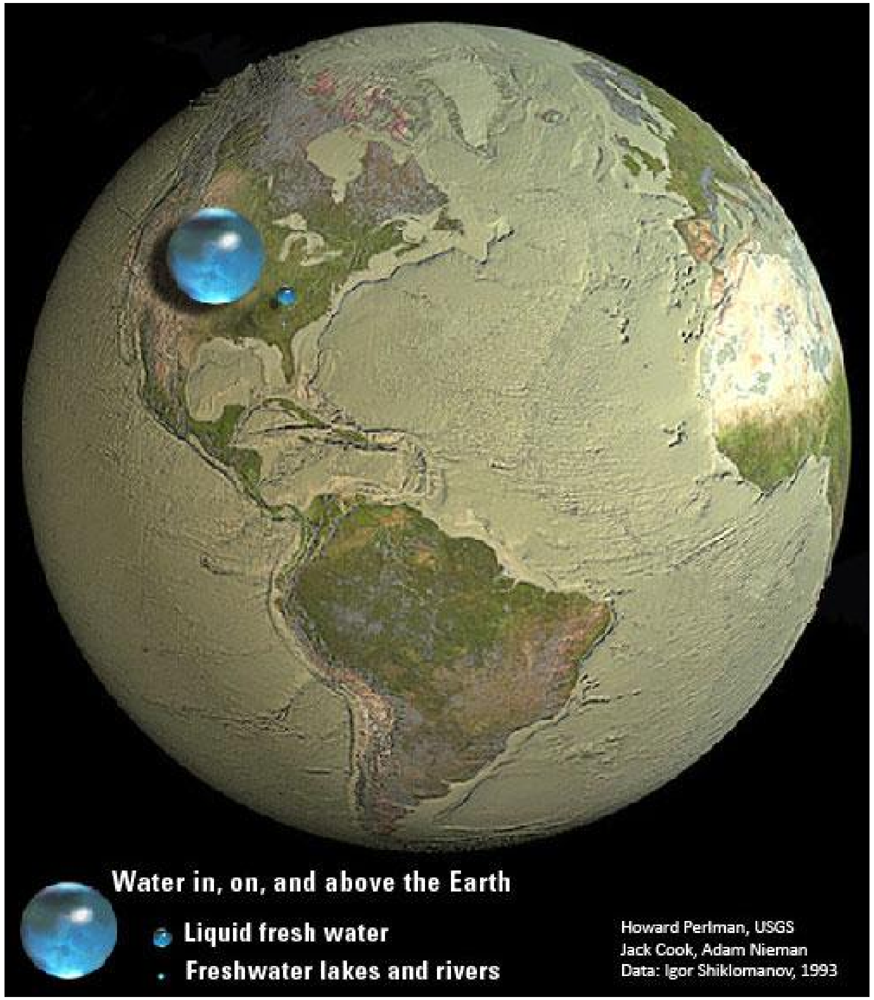
- Henry's case

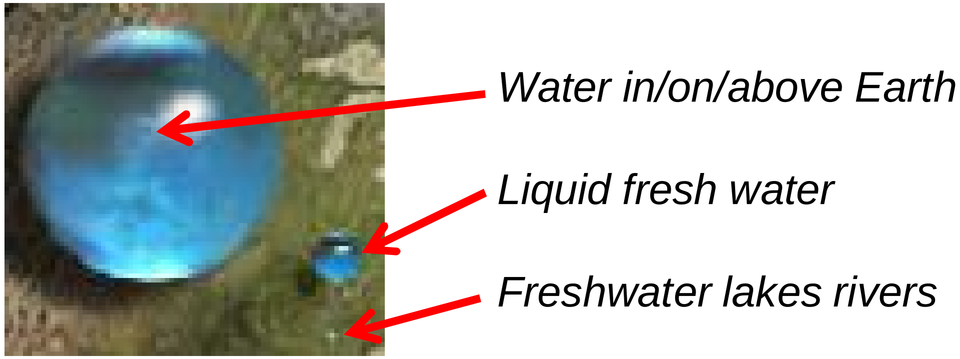


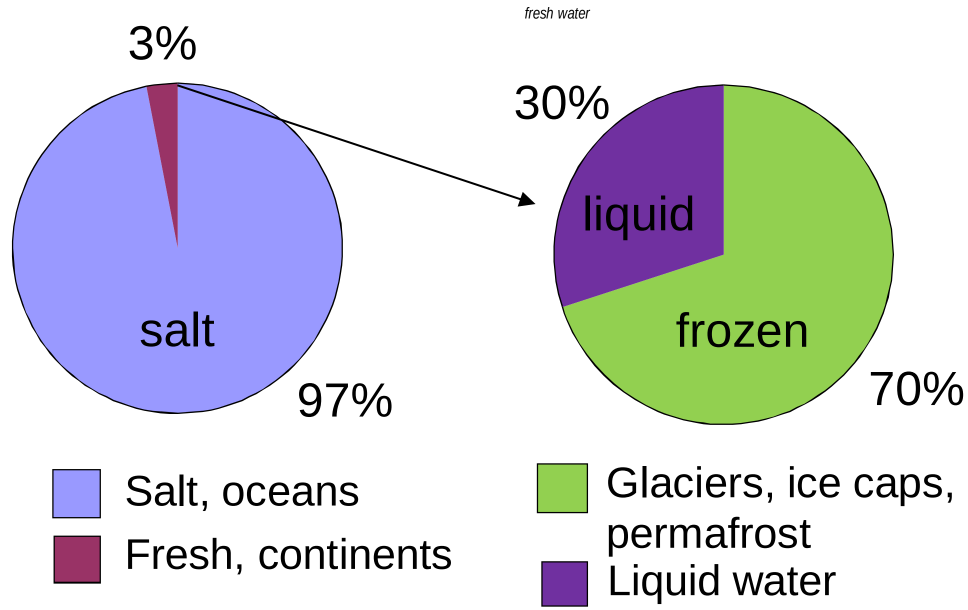
- (Elder's case)



Volumes of water on Earth: a scarce product



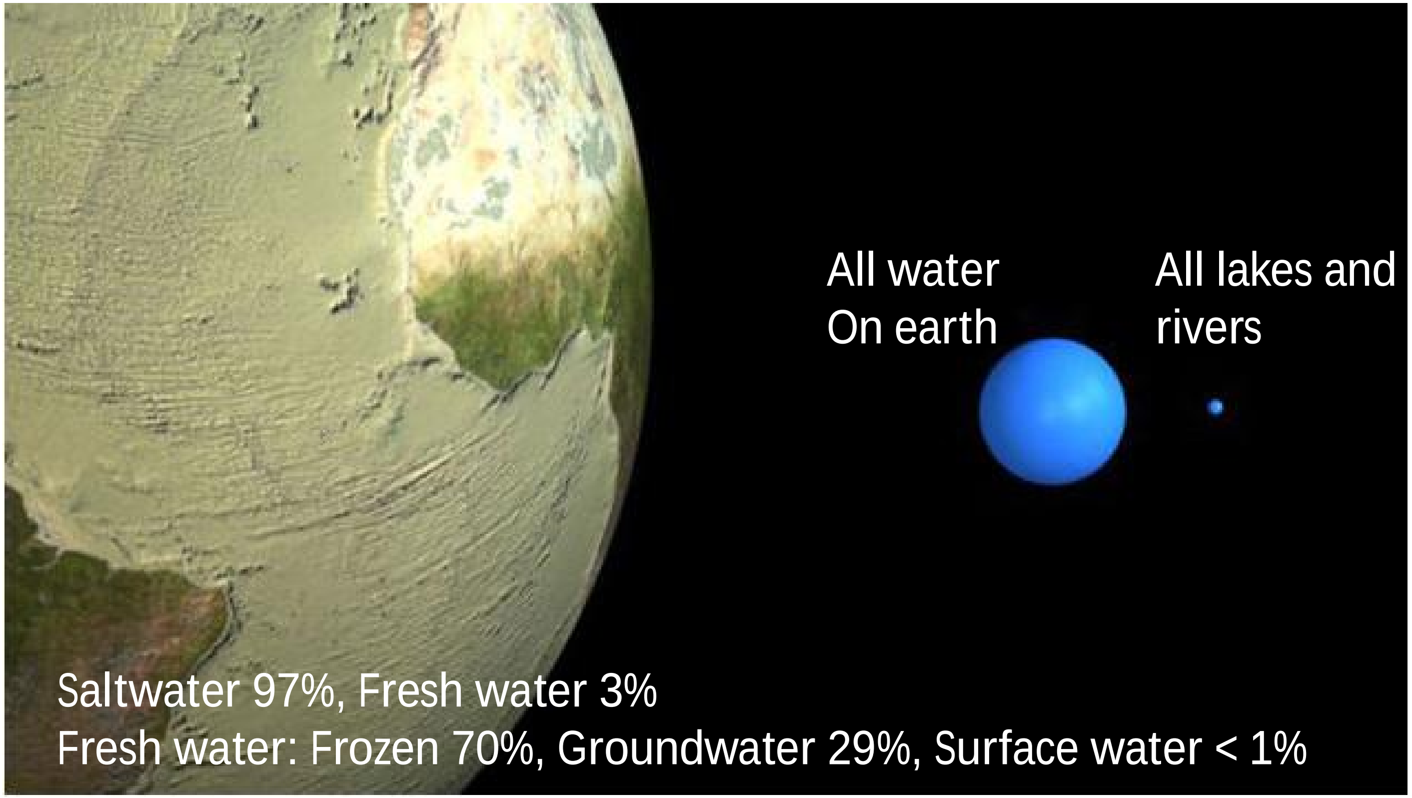




Source: Perlman, USGS; Shiklomanov, 1993

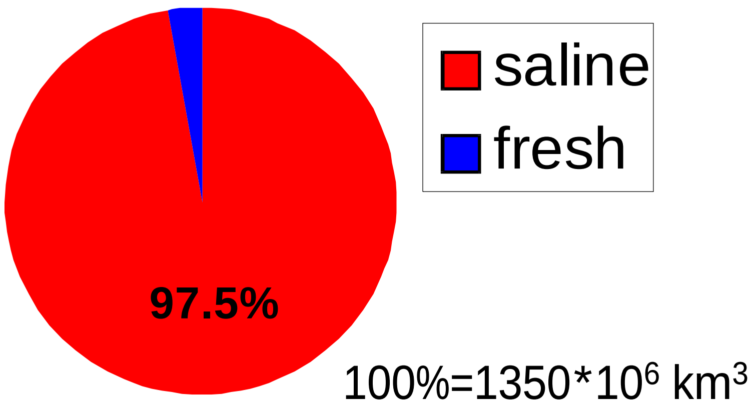
Water Energy Food Nexus
Global water scarcity

Fresh water is a scarce resource…

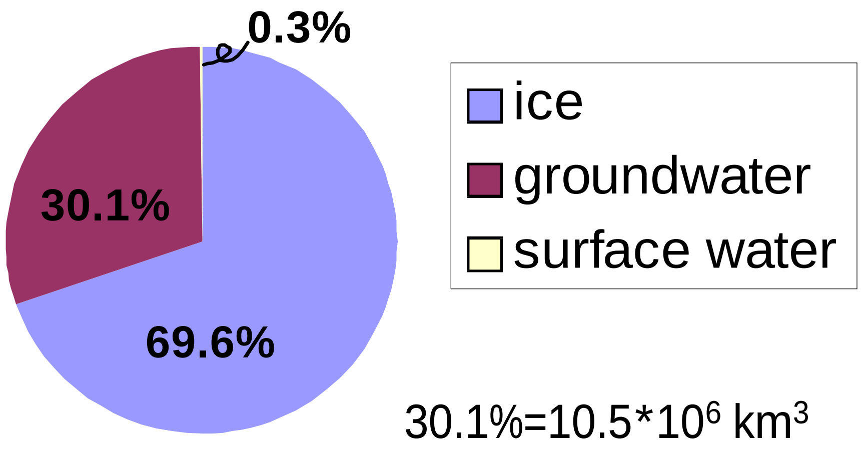


Water on Earth

Total water on Earth



Total fresh water on Earth

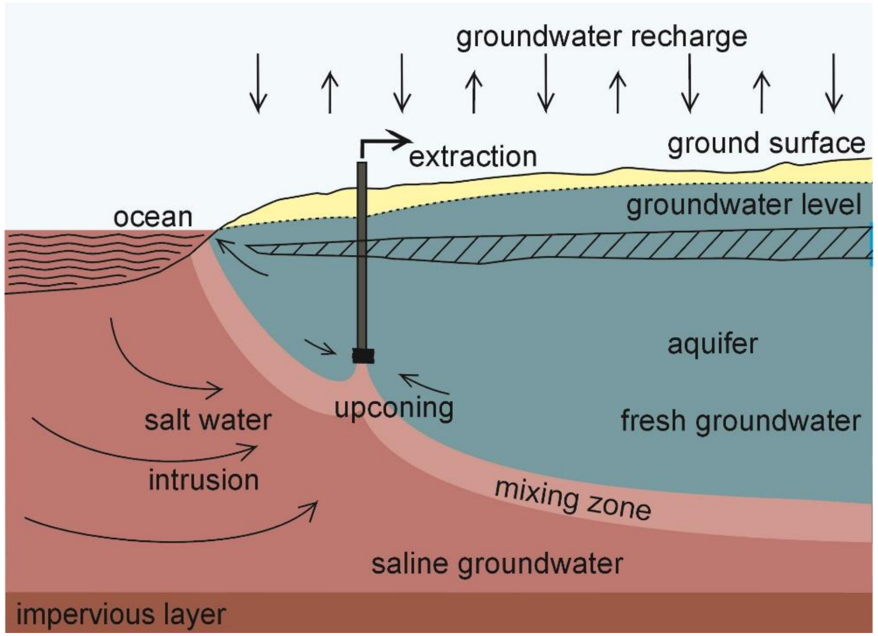


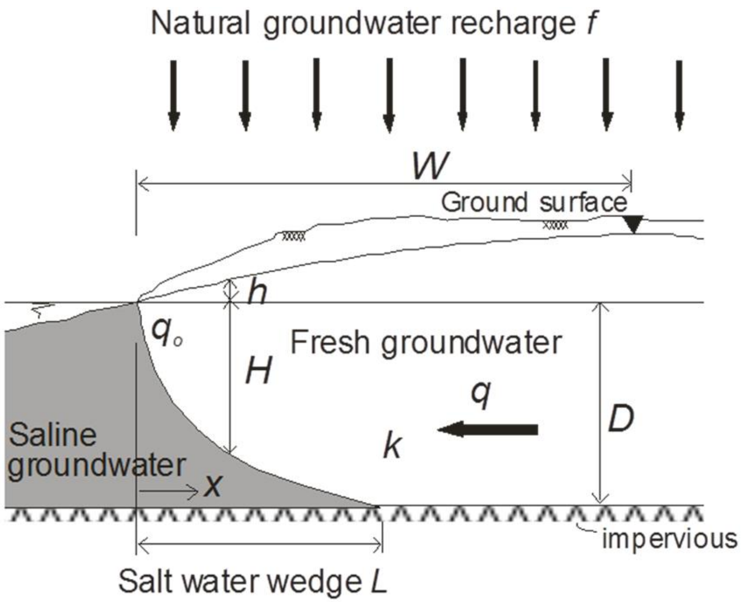
Demand for groundwater (now 30%) increases due to:

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

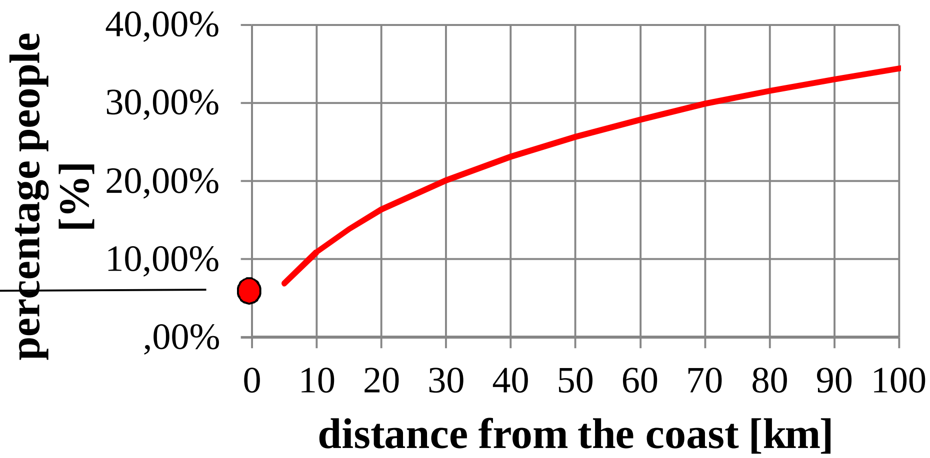
(Source: Cheng, 1998)

Groundwater in the coastal zone





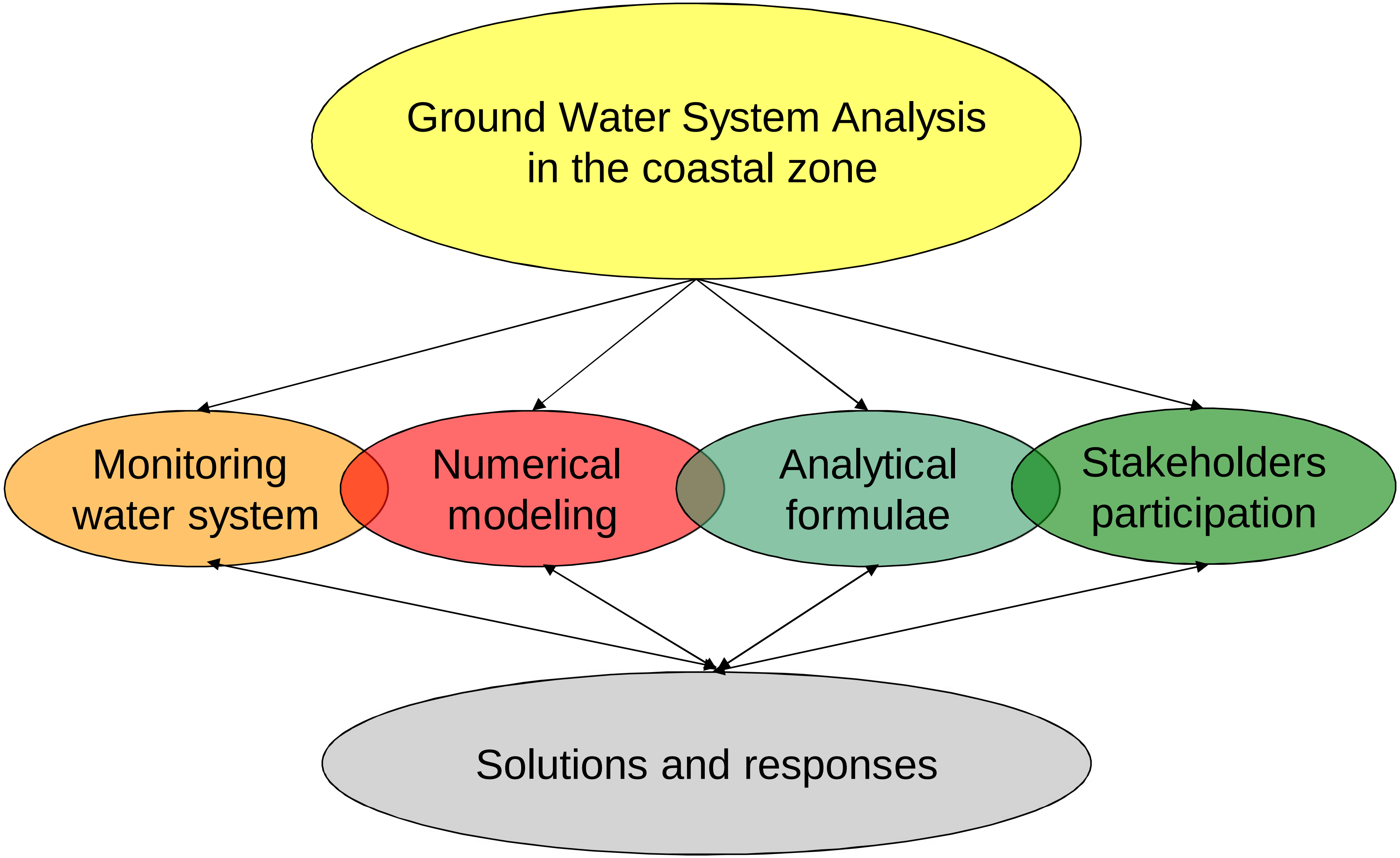
500 million people in the first 5km from the coastline



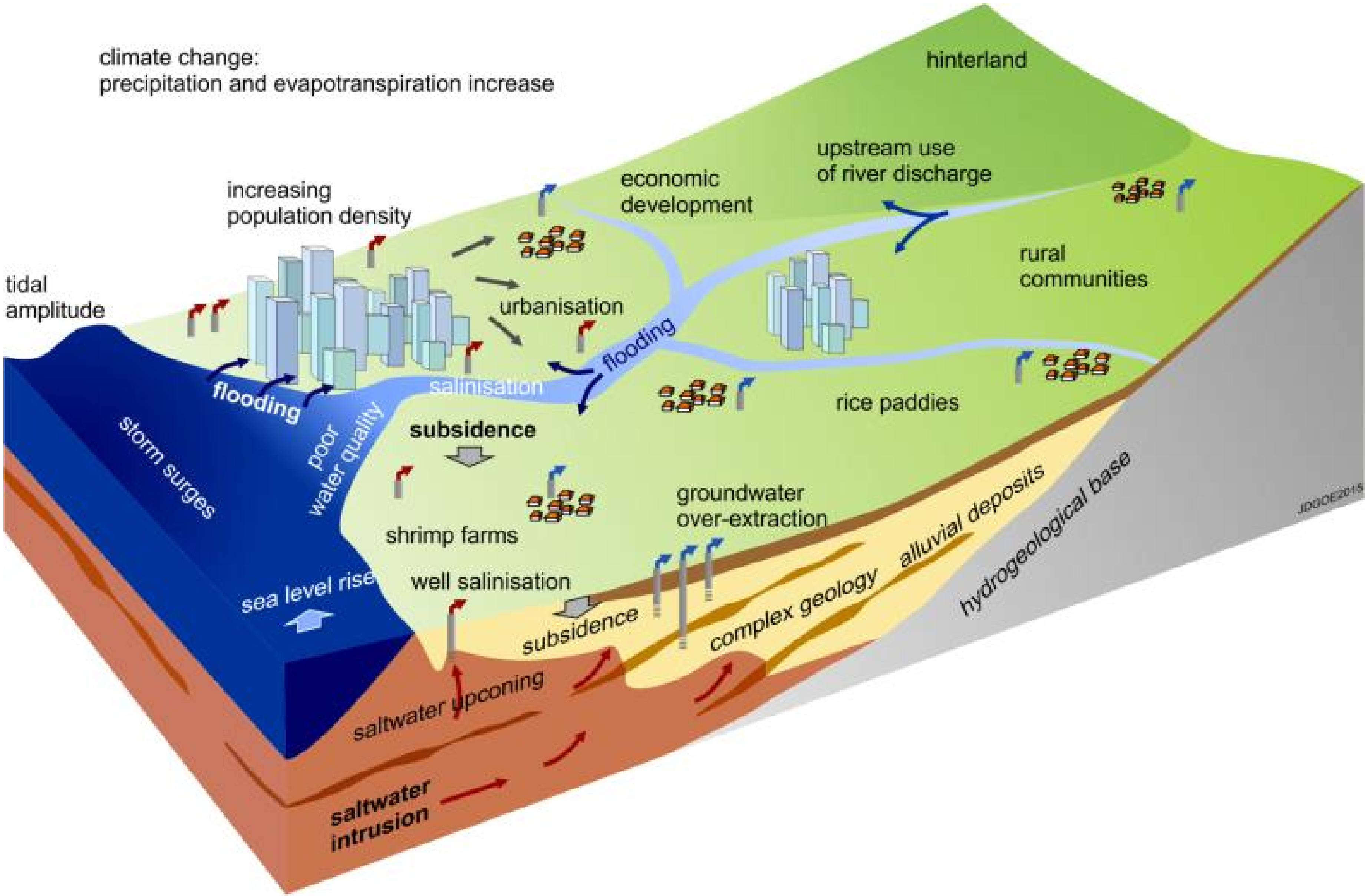
Topics of density driven groundwater flow

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

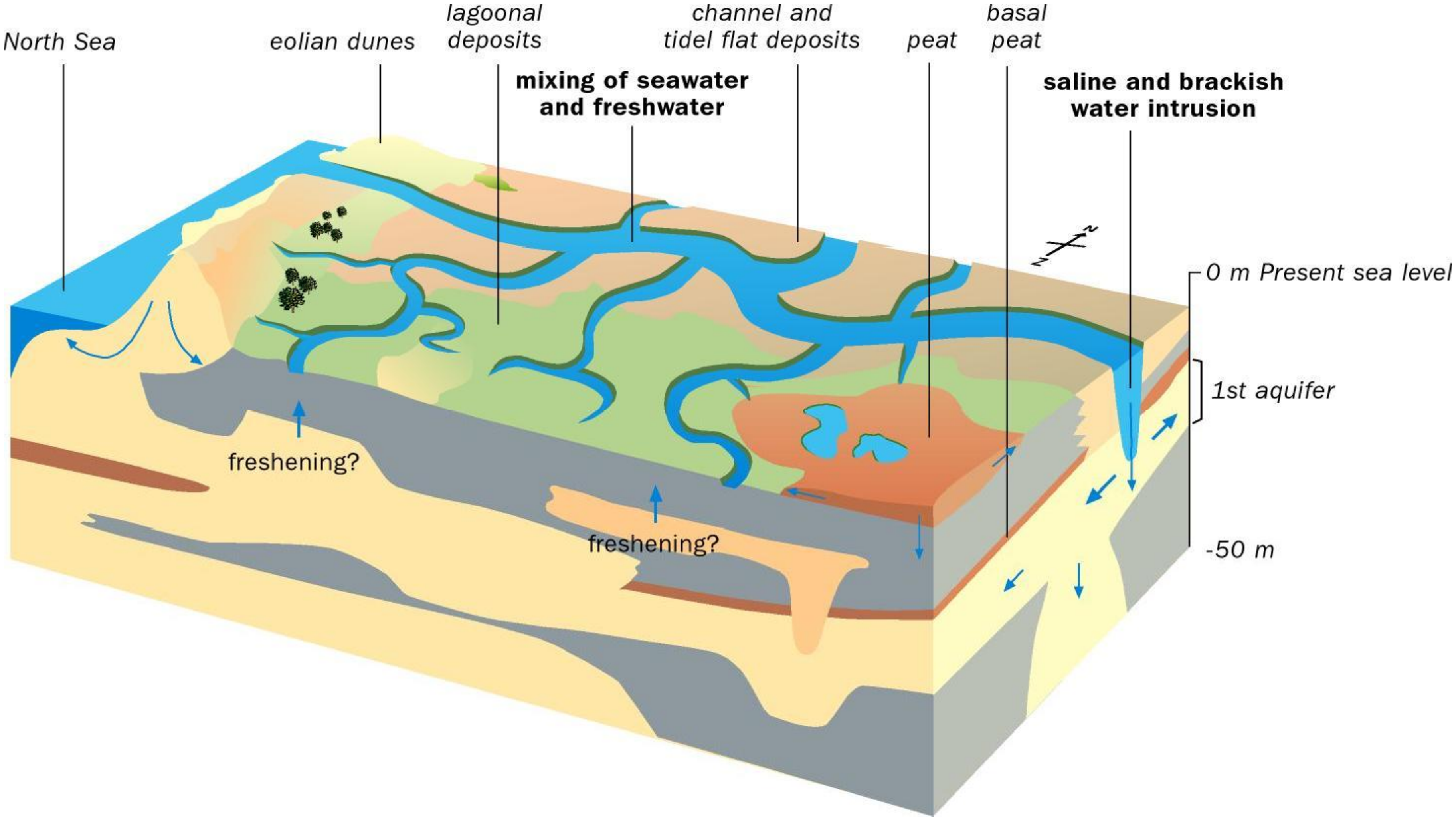
Work at Deltares



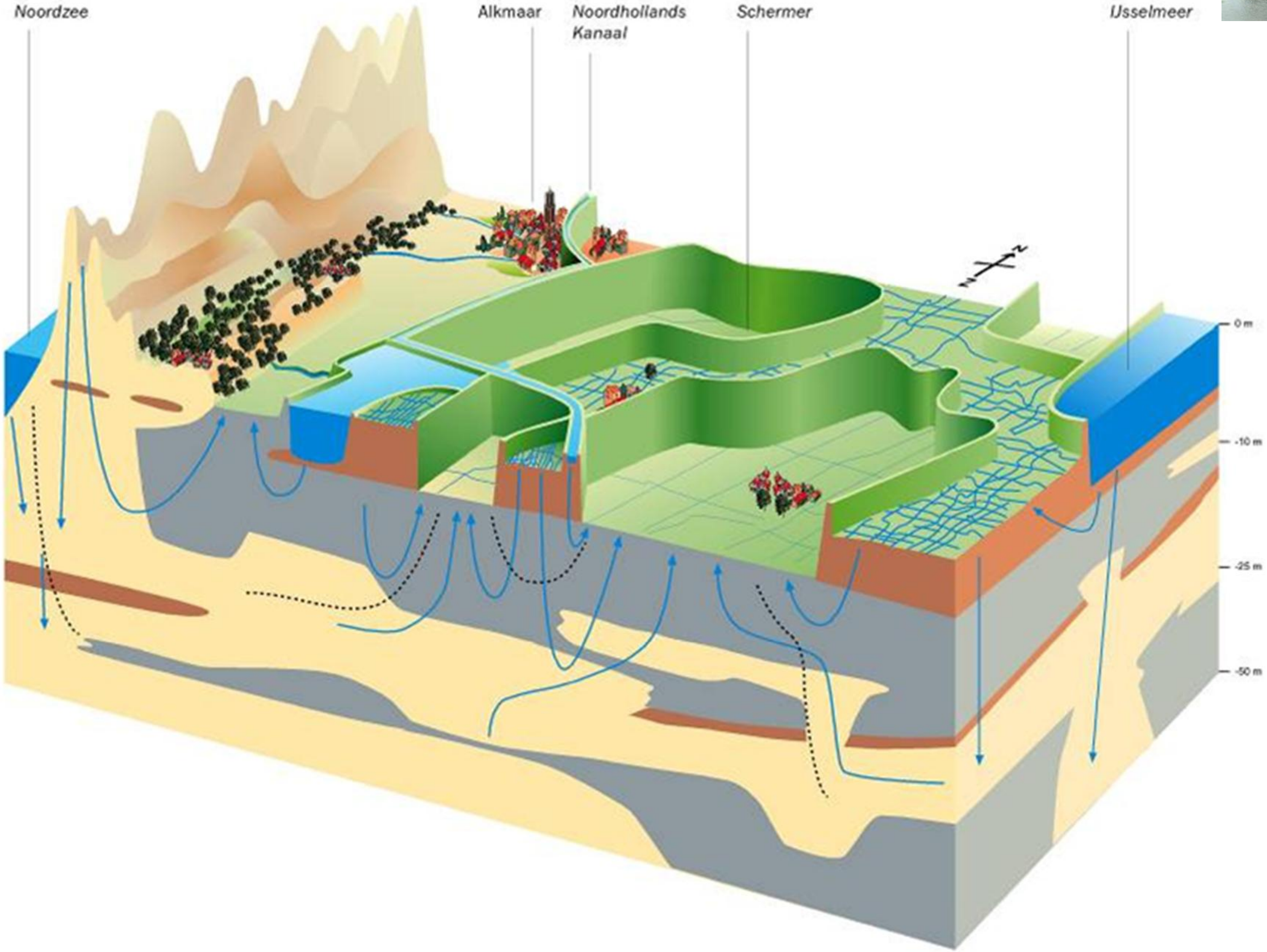
Groundwater issues in the coastal zone/deltaic areas



Past, before man



The polders in the Nederland



Groundwater in the future

We have to cope which…:

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

Direct anthopogenic influence on groundwater is more important than climate effect

Salt Water Intrusion Meeting, since 1968

Salt Water Intrusion Meeting, since 1968

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

Themes

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

Salt Water Intrusion Meeting (SWIM)

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

Welcome to the homepage of the Salt Water Intrusion Meeting

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

SWIM from Alphafilm & Kommunikation on Vimeo.

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

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

www.swim-site.org

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

The proceedings of the Salt Water Intrusion Meeting

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

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

Available for download:

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

www.swim-site.org

For sale (external links)

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

Salt Water Intrusion Meeting (SWIM)

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

Back to all proceedings

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

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Preface

A.D. Werner

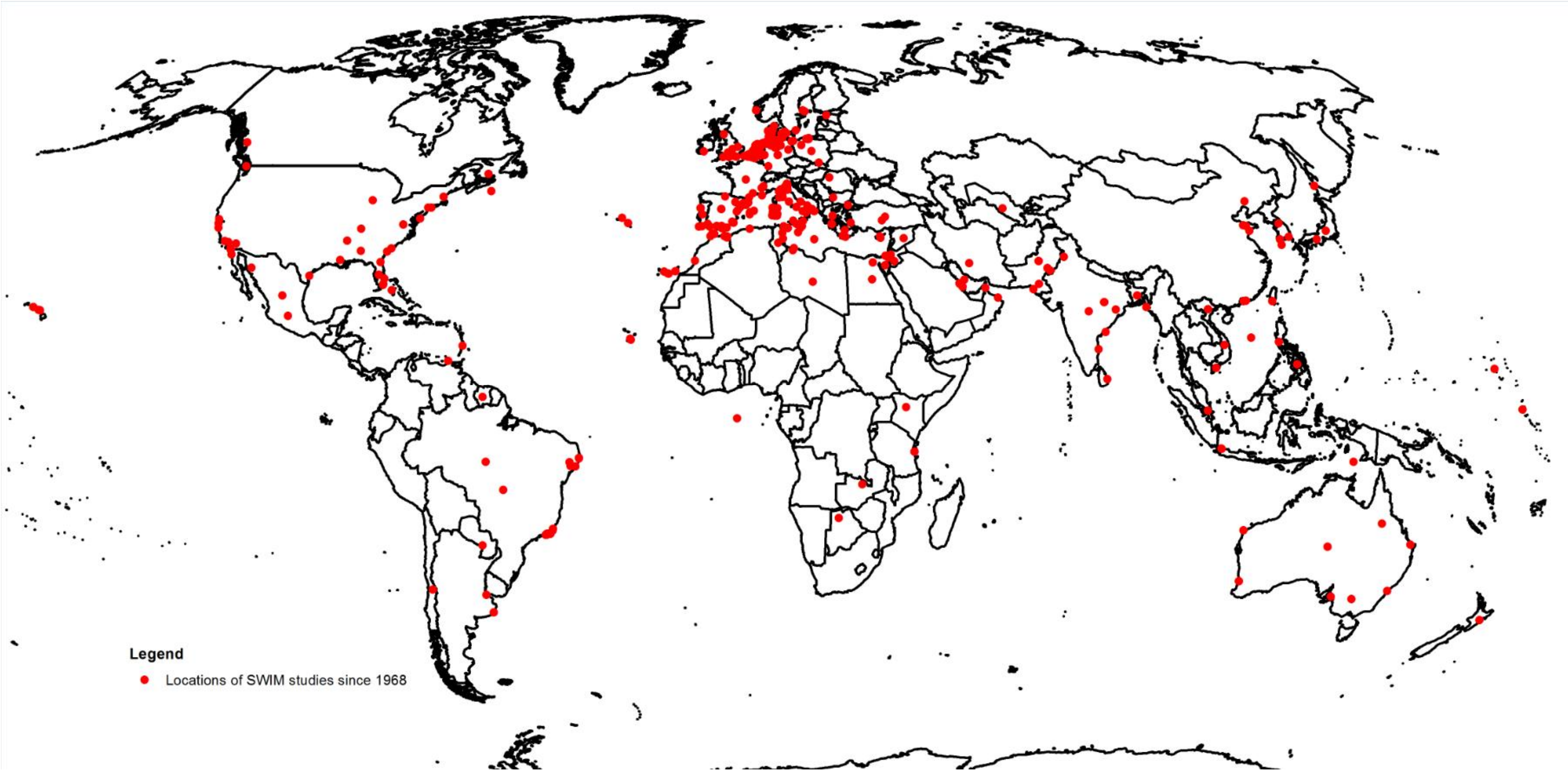
Posters

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

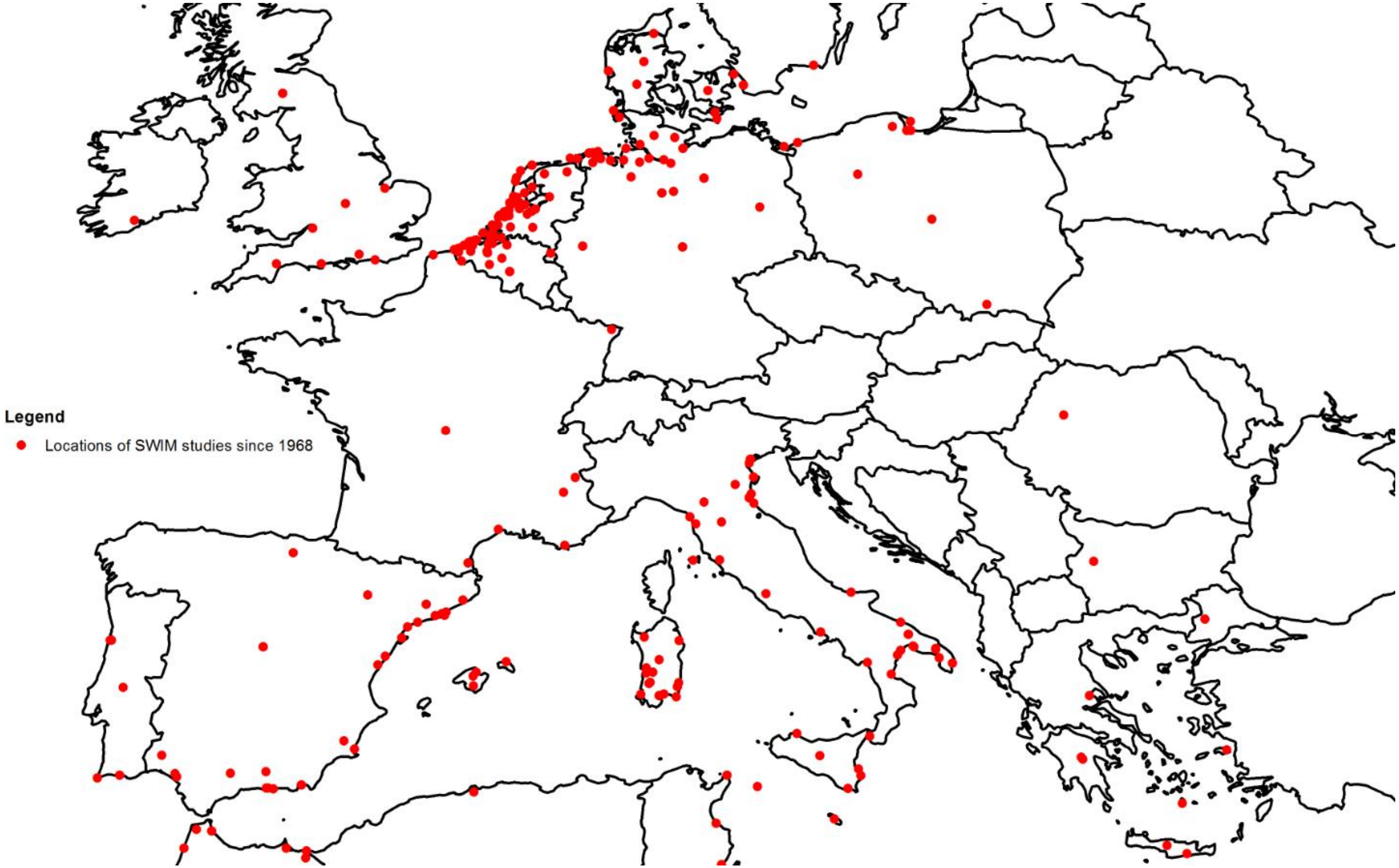
Session 1 - Managing Coastal Groundwater I

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

Location of SWIM studies since 1968



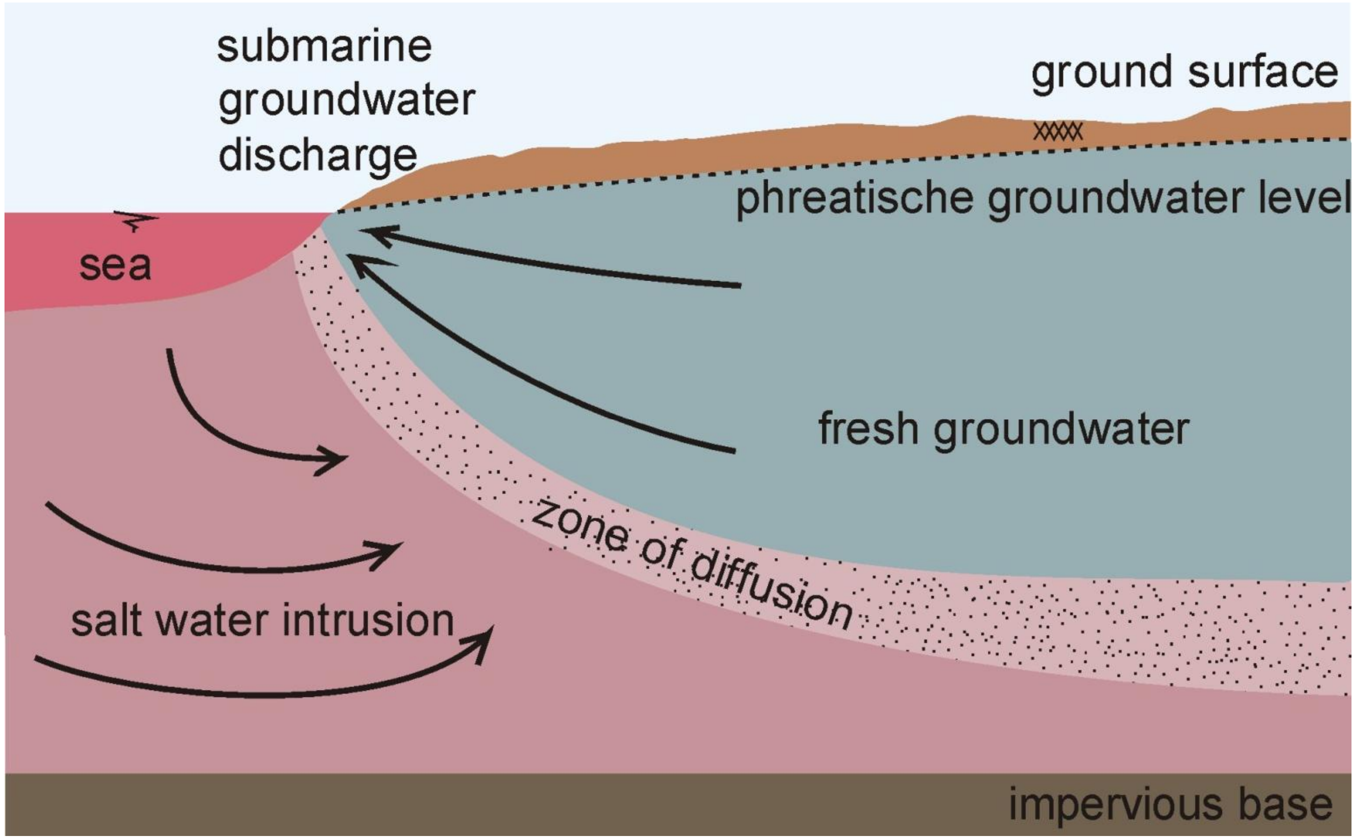
Location of SWIM studies since 1968



Introduction SWI

Definition of salt water intrusion

Inflow of saline water into an aquifer which contains fresh water



Origin of saline groundwater in the subsoil

Geological causes:

-marine deposits during geological times

-trans- and regressions in coastal areas (deltas)

-salt/brine dome

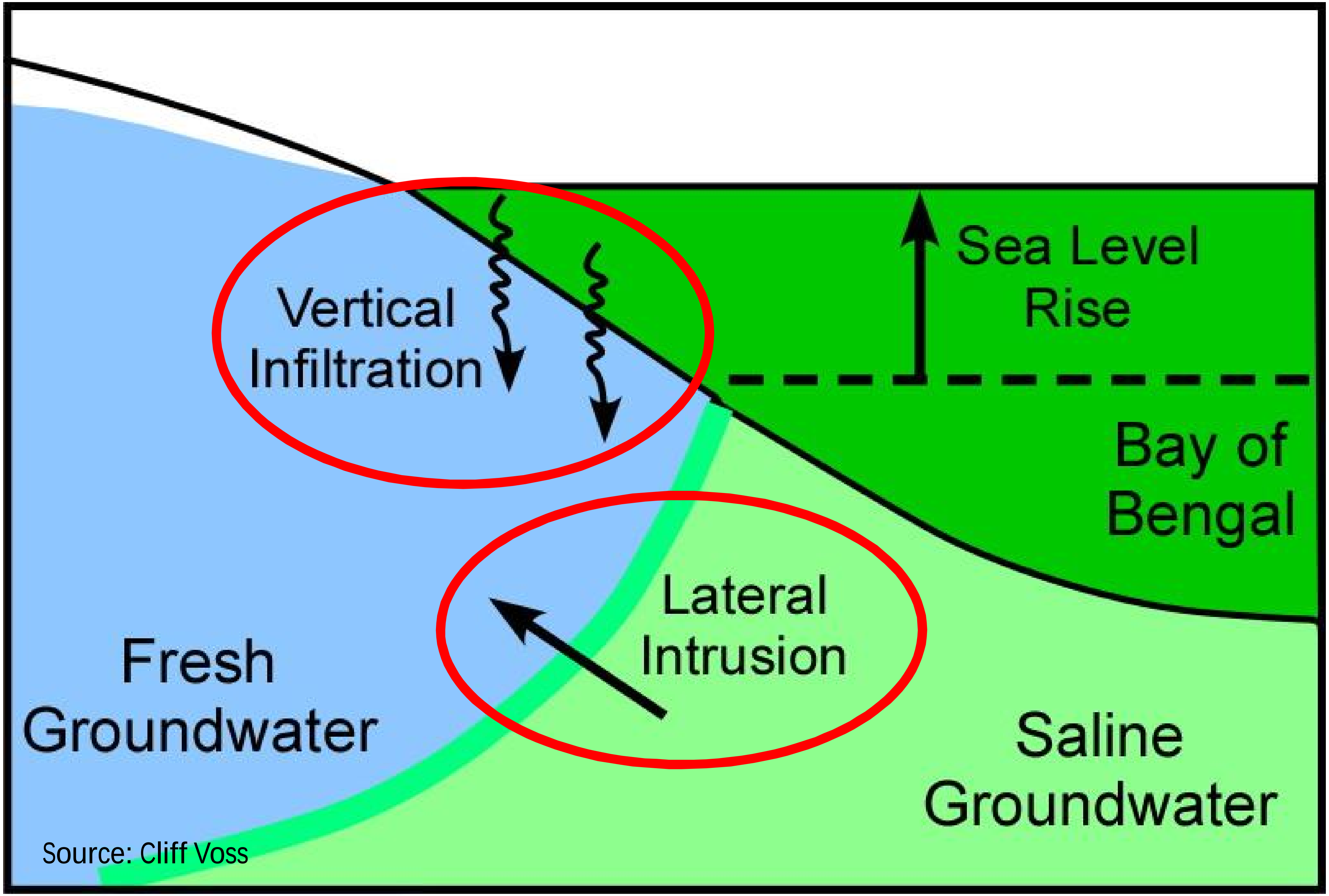
Anthropogenic causes:

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

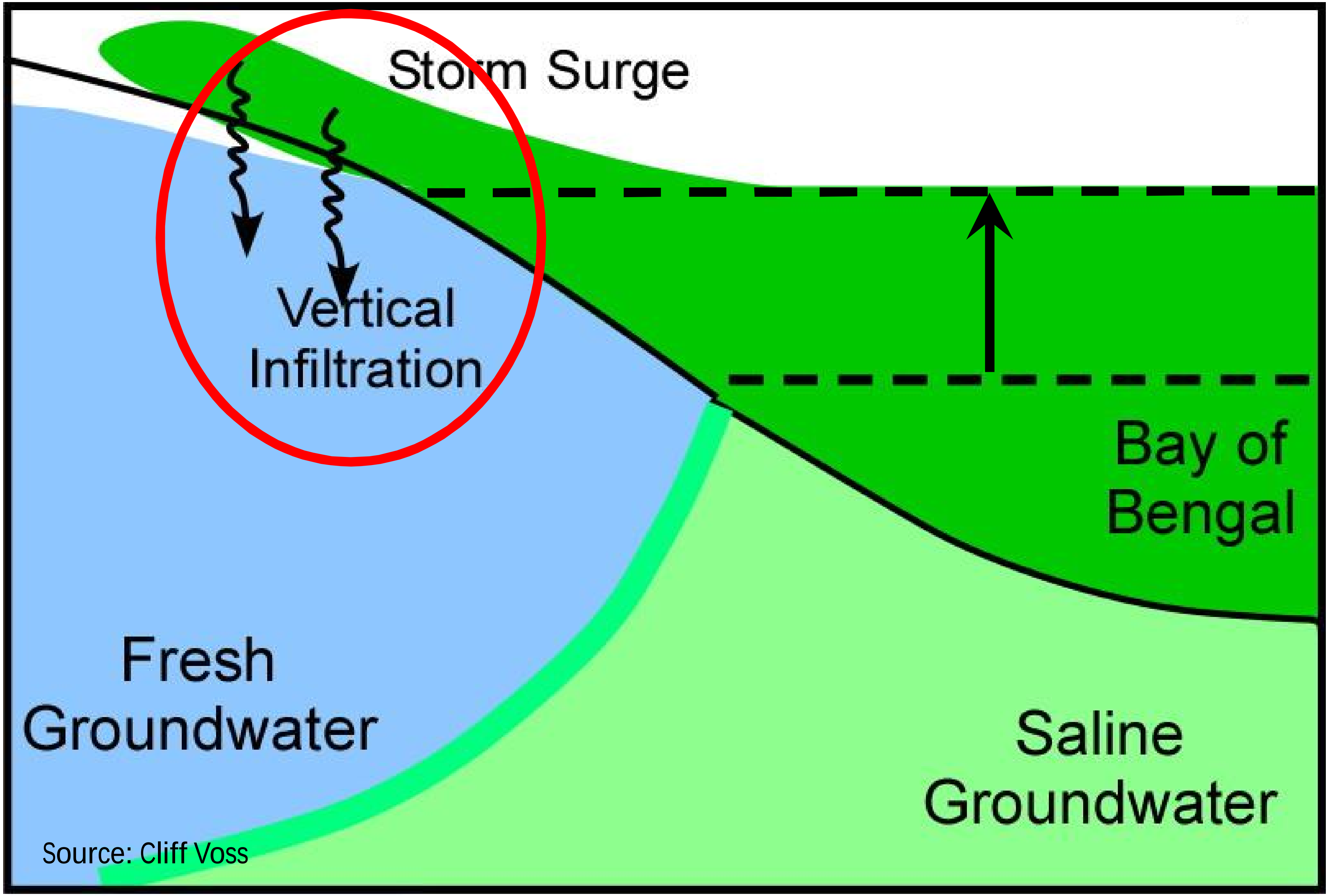
-upconing under extraction wells throughout the world

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

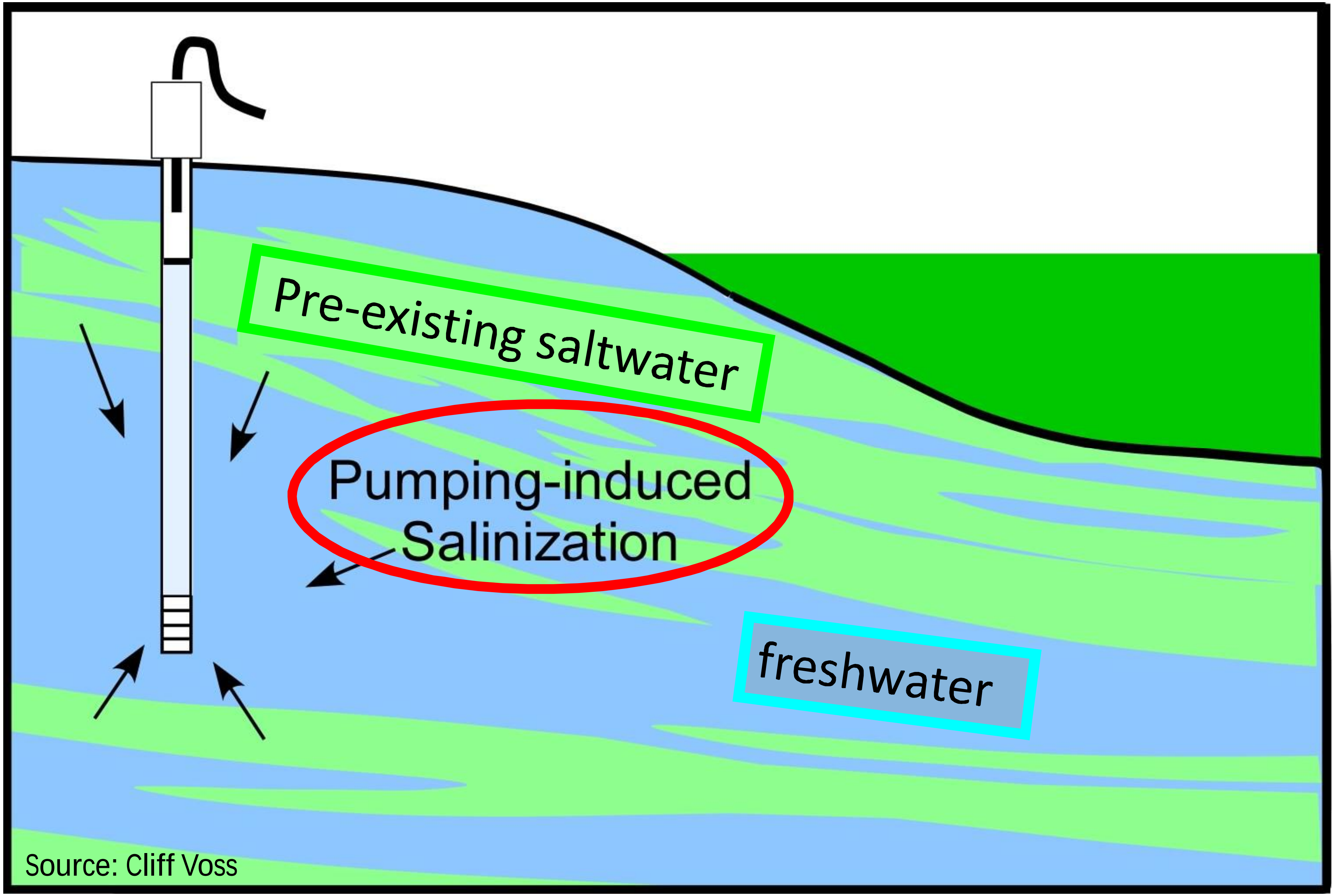
Modes of Salinization due to Sea-Level Rise



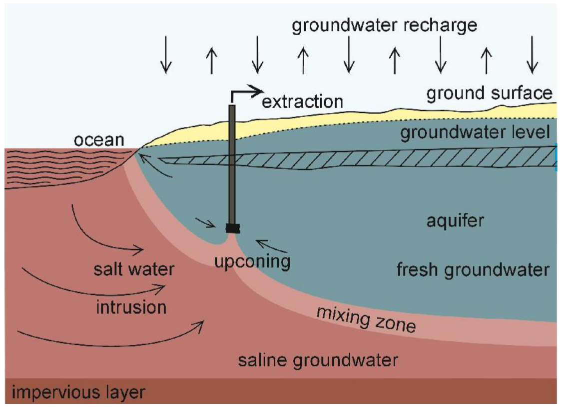
Modes of Salinization due to Sea-Level Rise



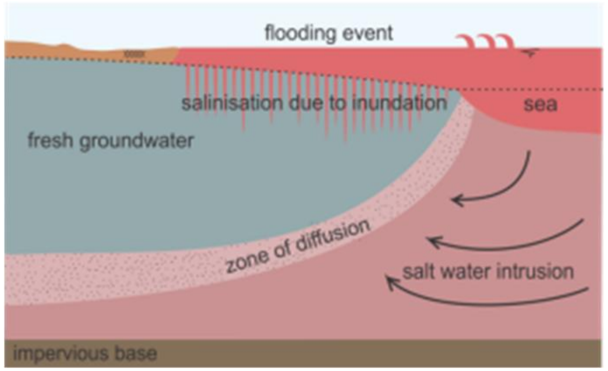
Salinization due to Pumping



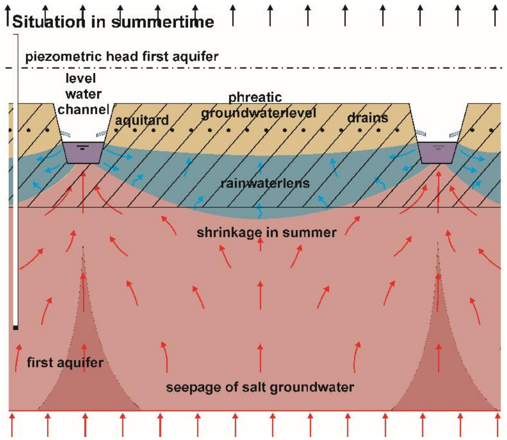
Salinisation processes at local scale



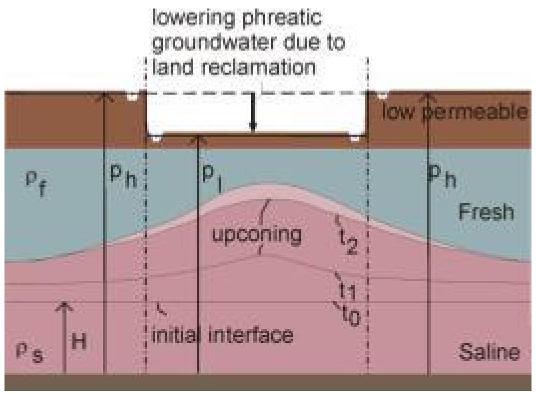
Salt water intrusion groundwater



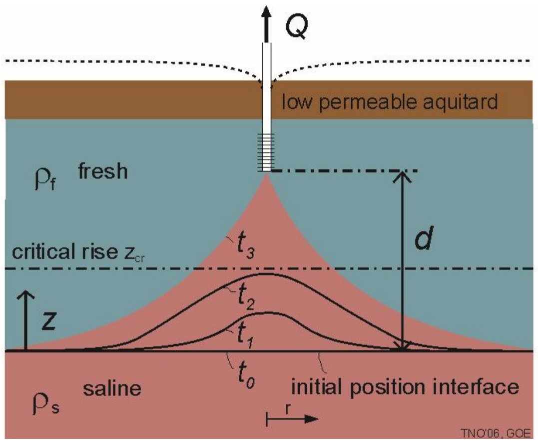
Inundation saline seawater



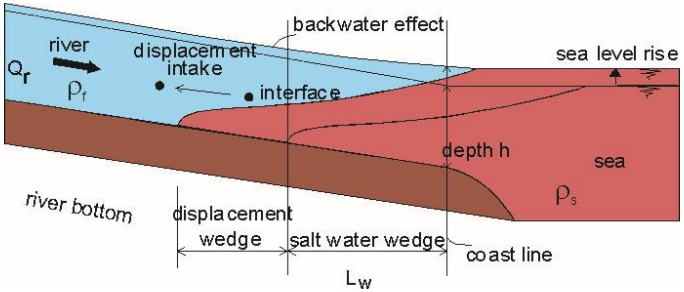
Shallow rainwaterlens



Upconing low-lying area

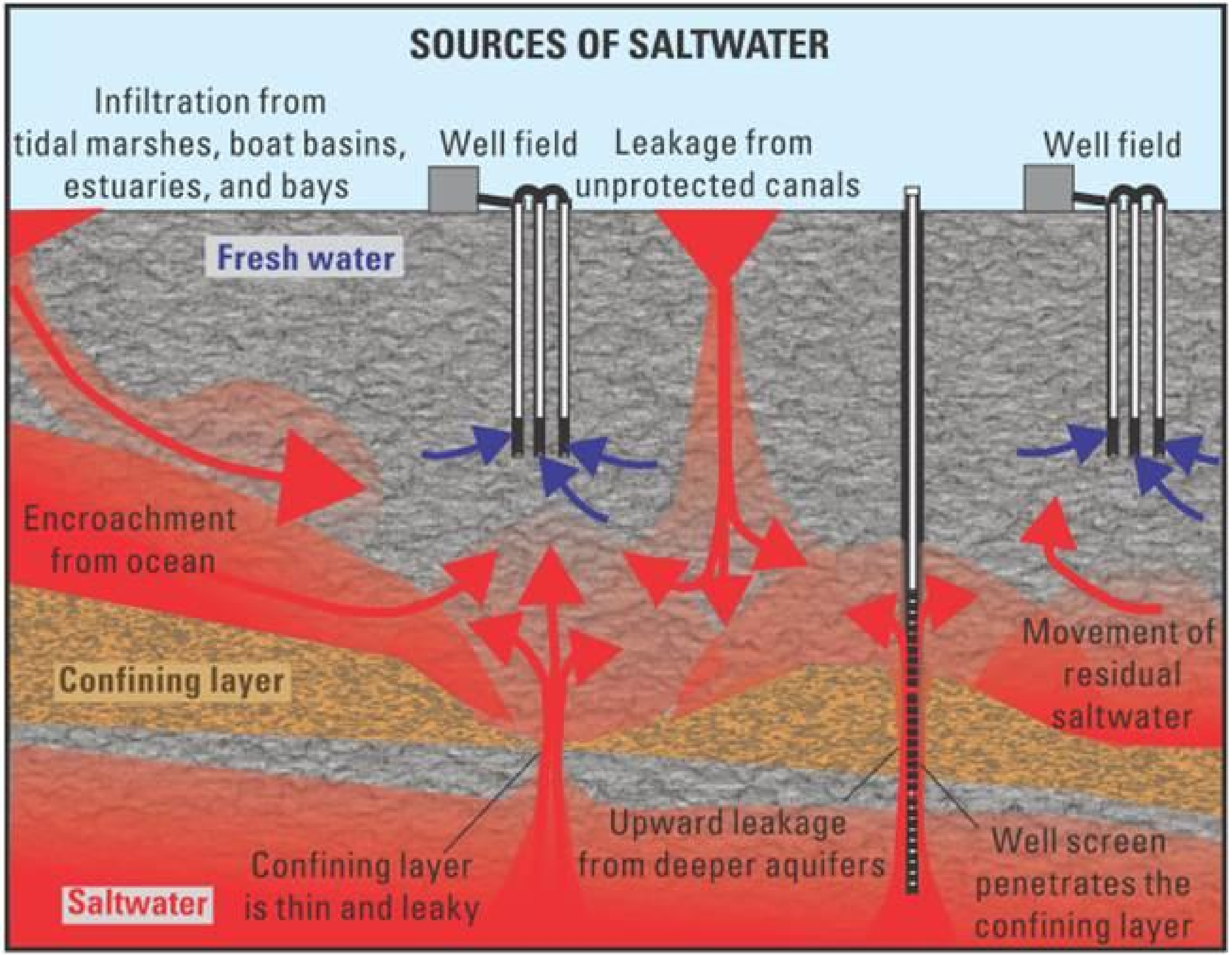


Upconing extraction



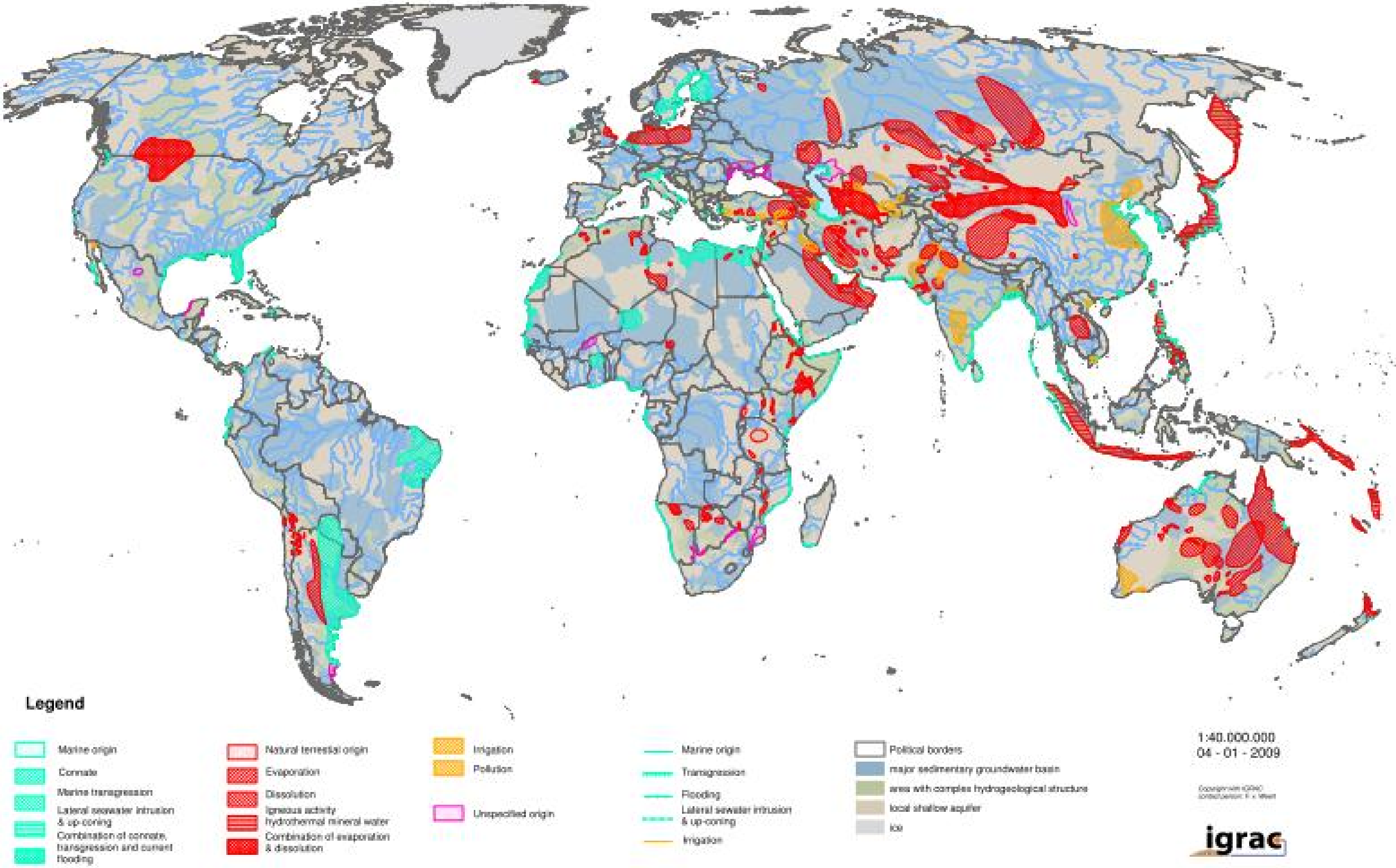
Salt water intrusion surface water

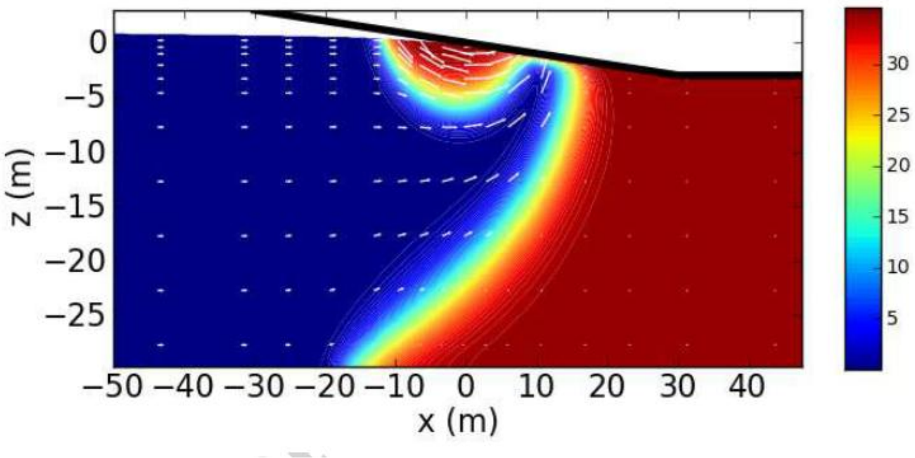
Salinization processes in the coastal zone: combination

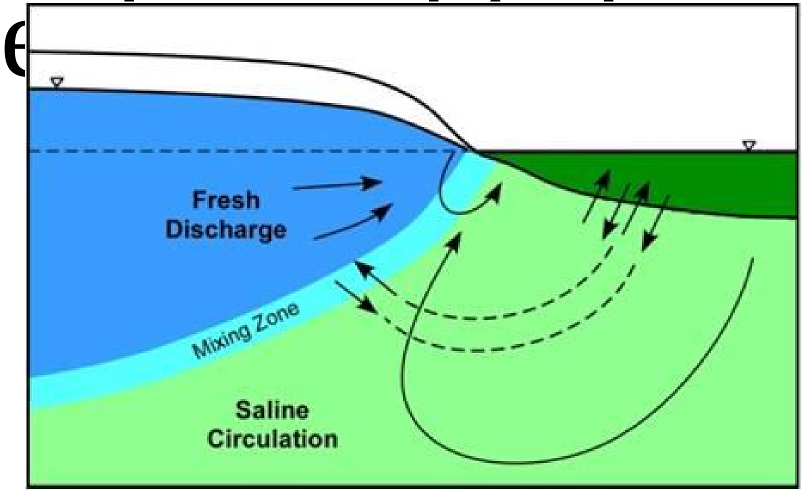


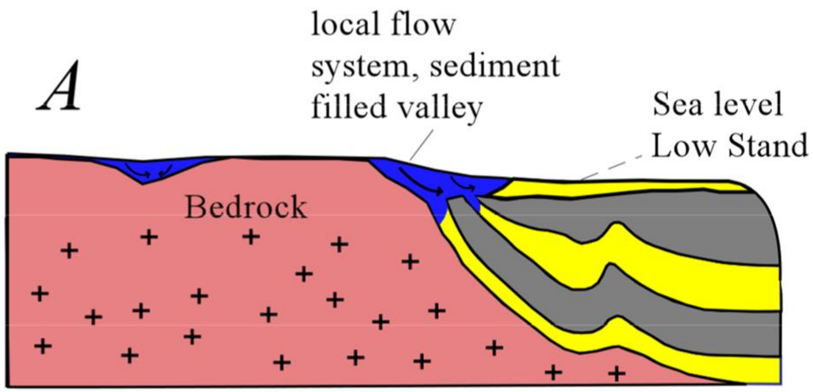
GEUS

Regions with brackish and saline groundwater at shallow and intermediate depts

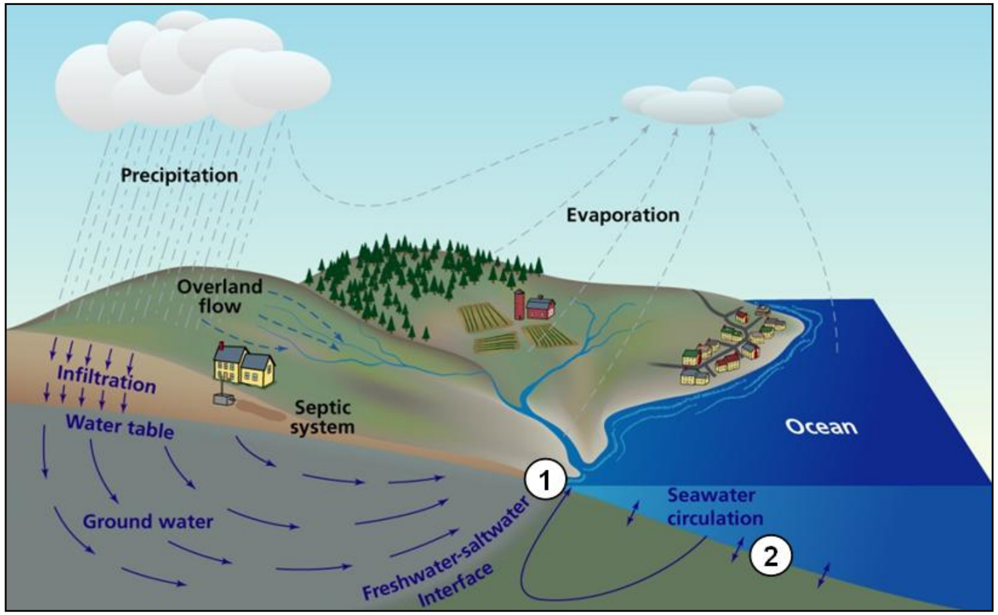


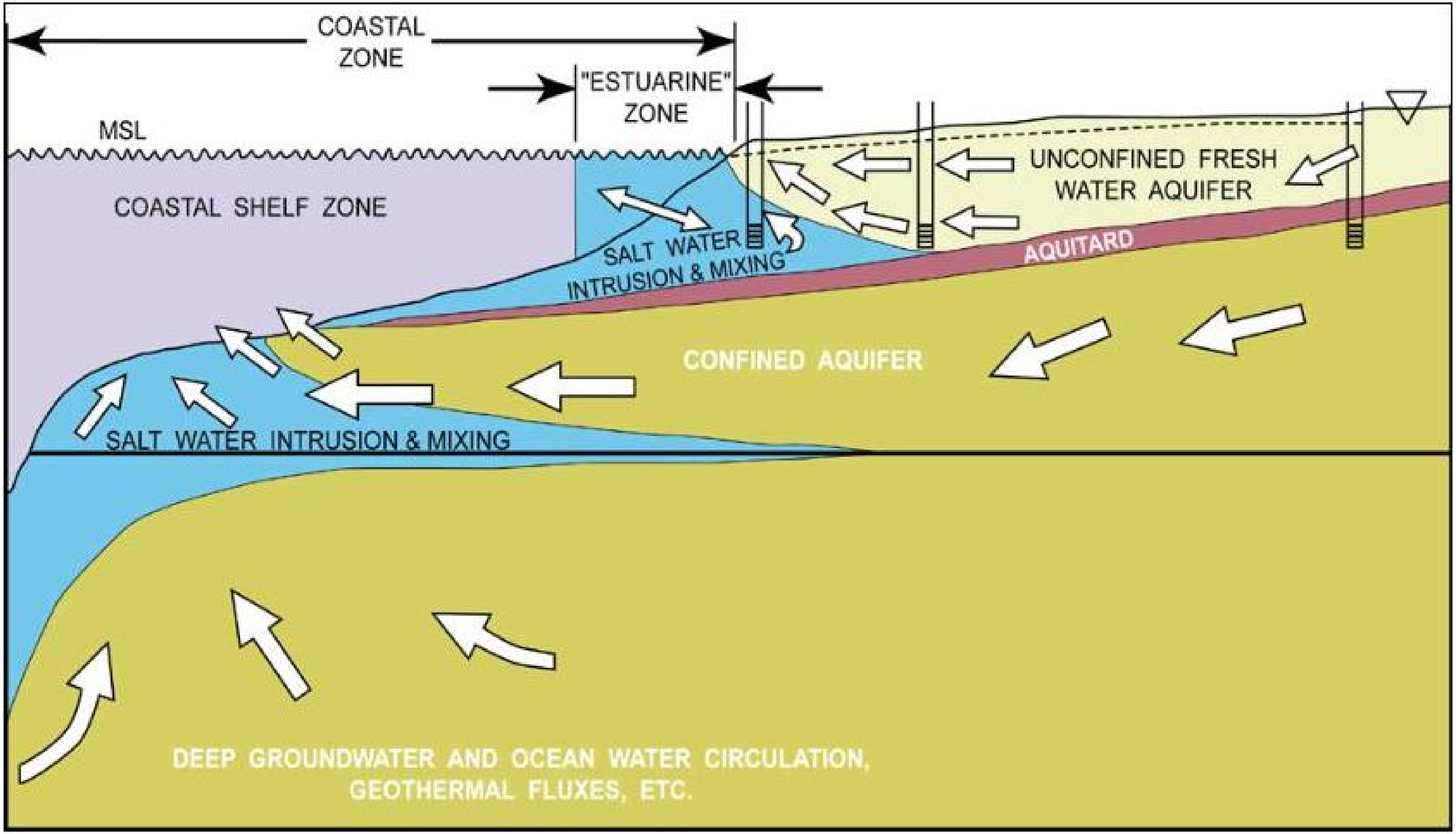




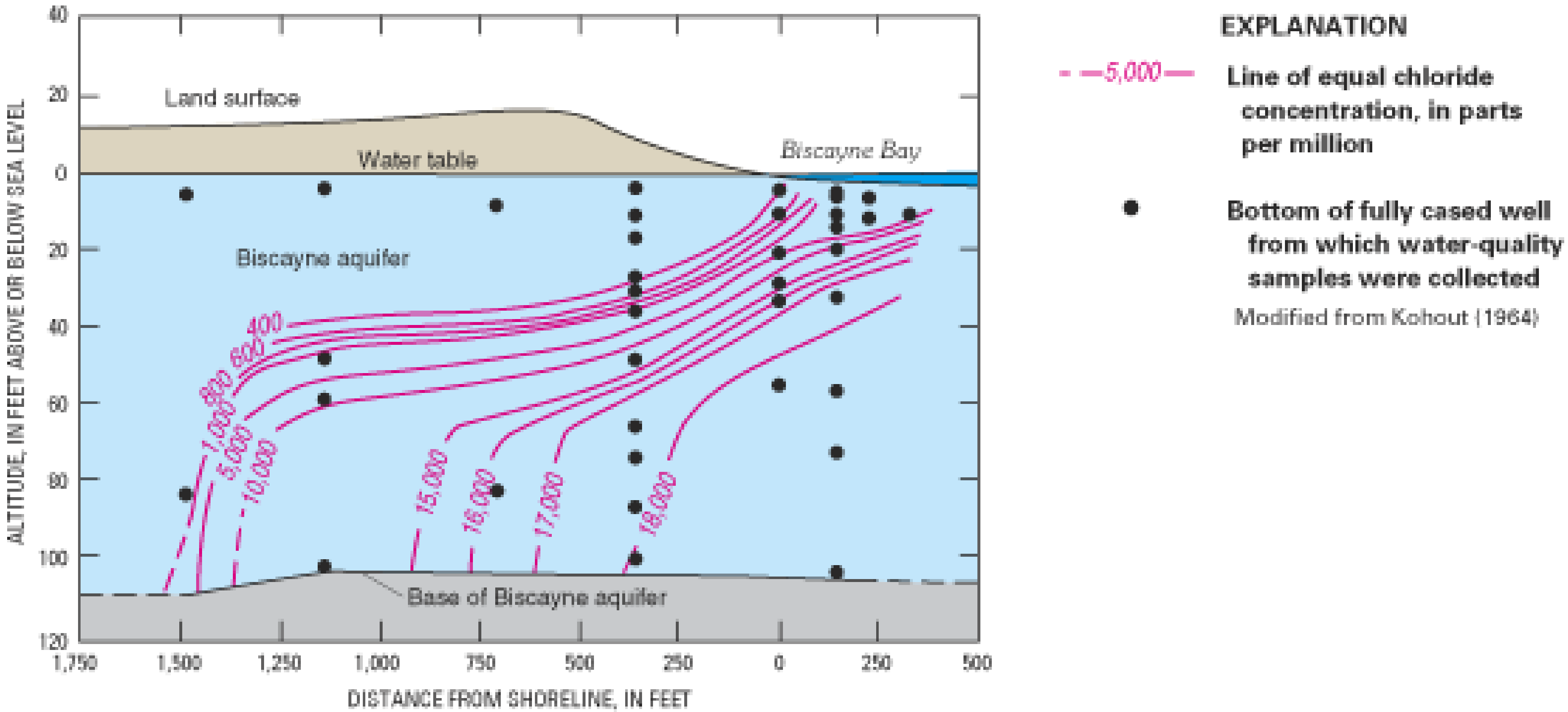


Source: Nature, 2013



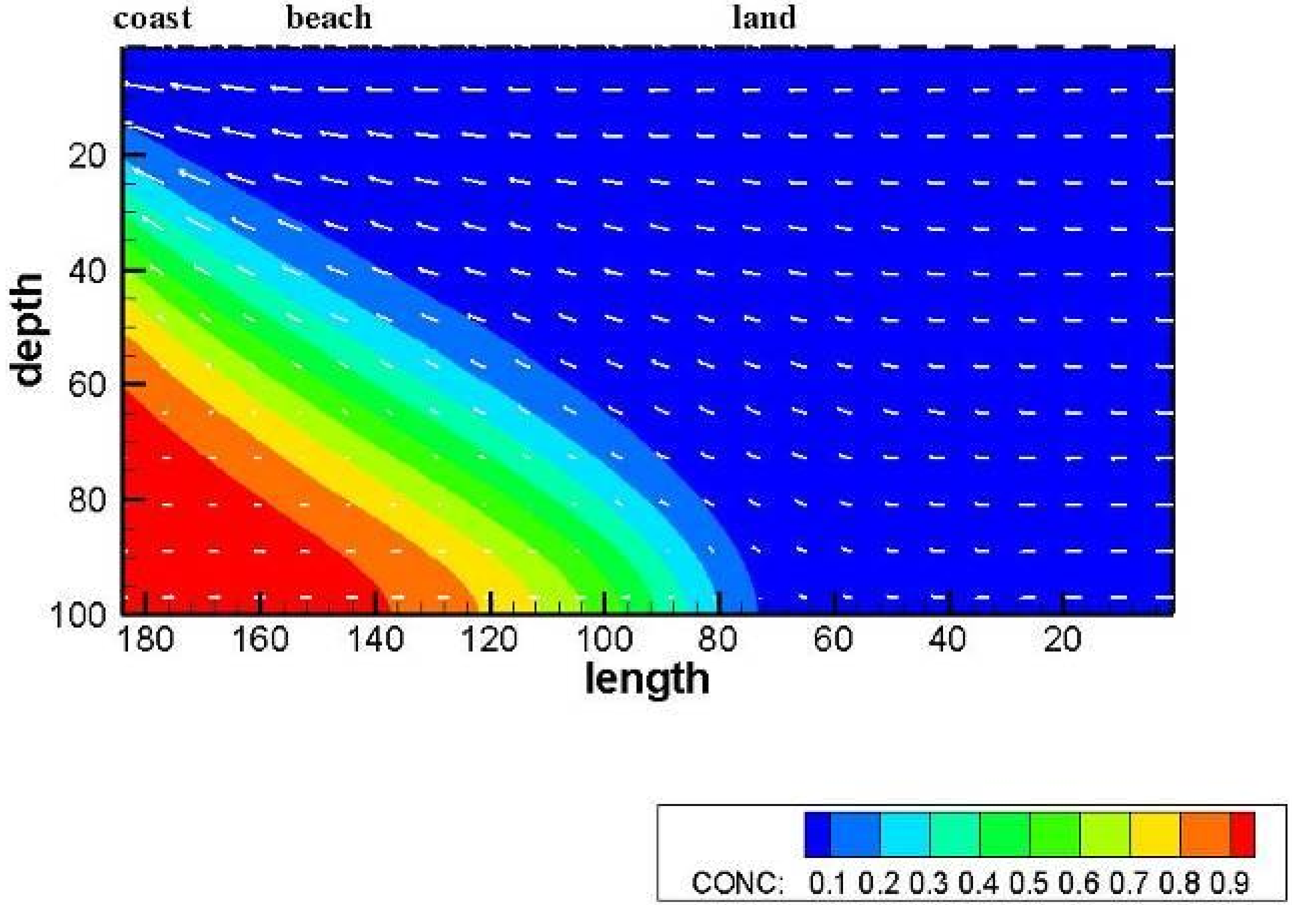

COASTAL ZONE
"ESTUARINE" ZONE
MSL
COASTAL SHELF ZONE
UNCONFINED FRESH WATER AQUIFER
SALT WATER INTRUSION & MIXING
AQUITARD
CONFINED AQUIFER
SALT WATER INTRUSION & MIXING
DEEP GROUNDWATER AND OCEAN WATER CIRCULATION, GEOTHERMAL FLUXES, ETC.

Biscayne aquifer, Florida USA: Henry’s case



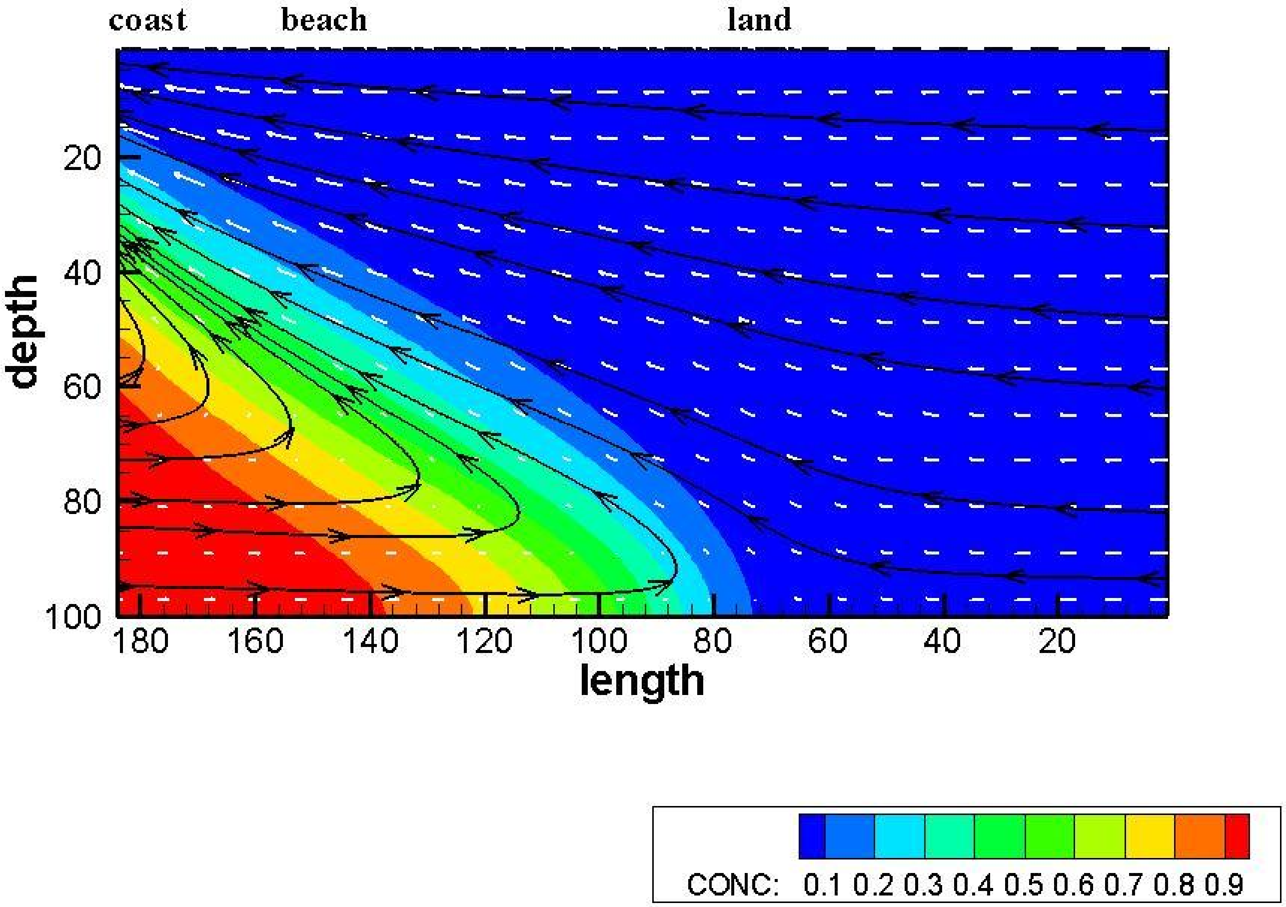
Definition of salt water intrusion

Numerical model: Henry's case

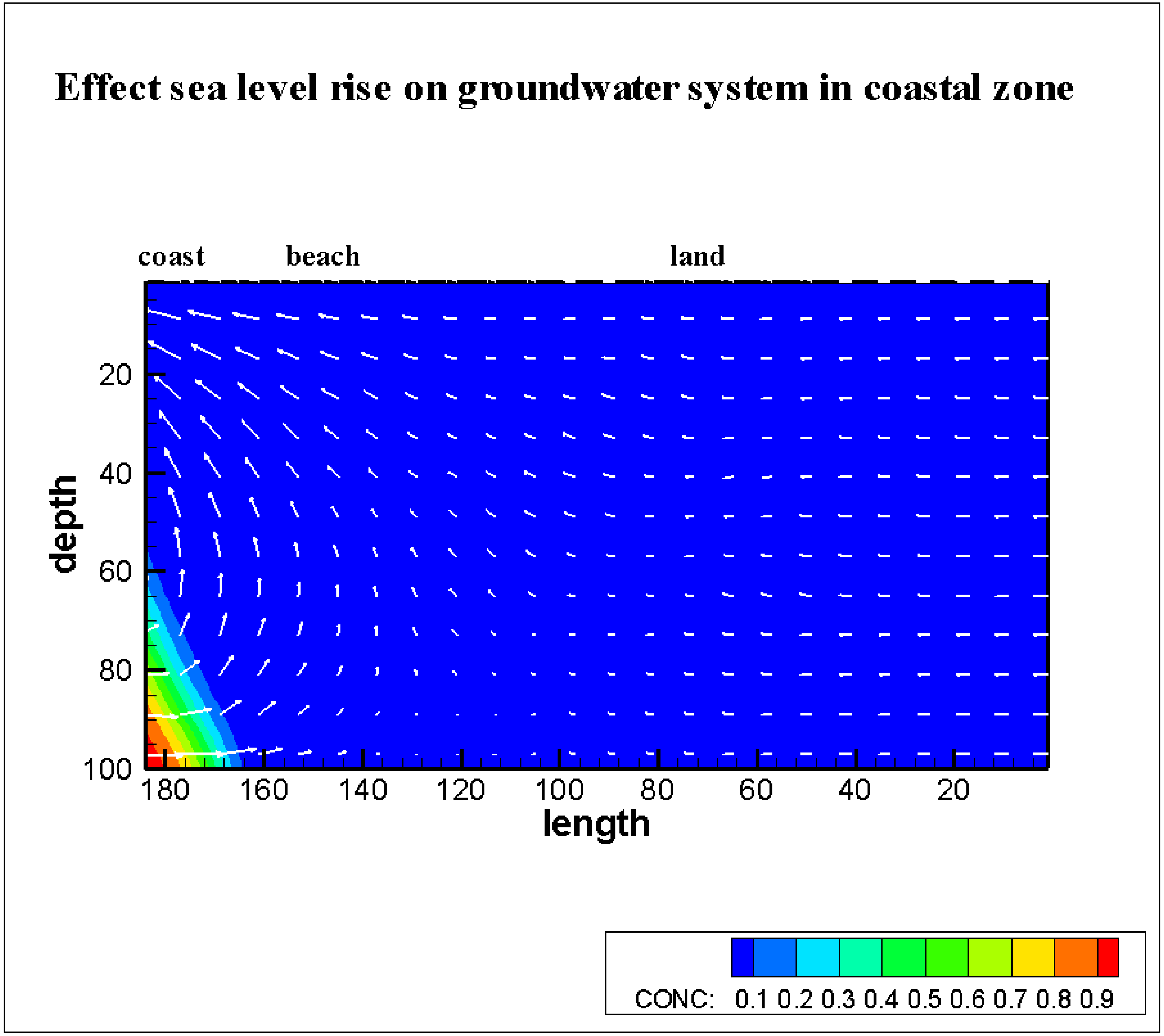


Definition of salt water intrusion

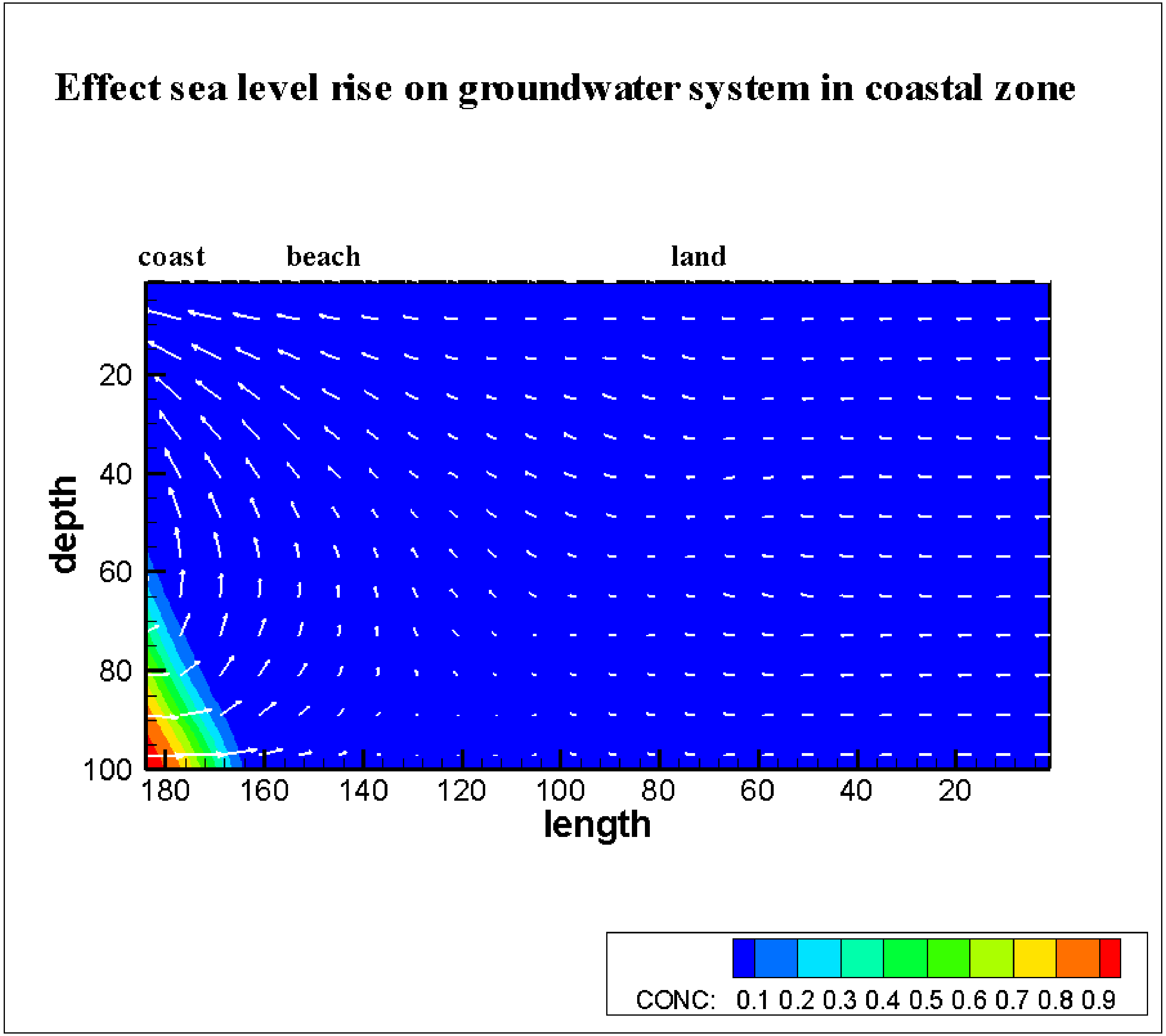
Numerical model: Henry’s case



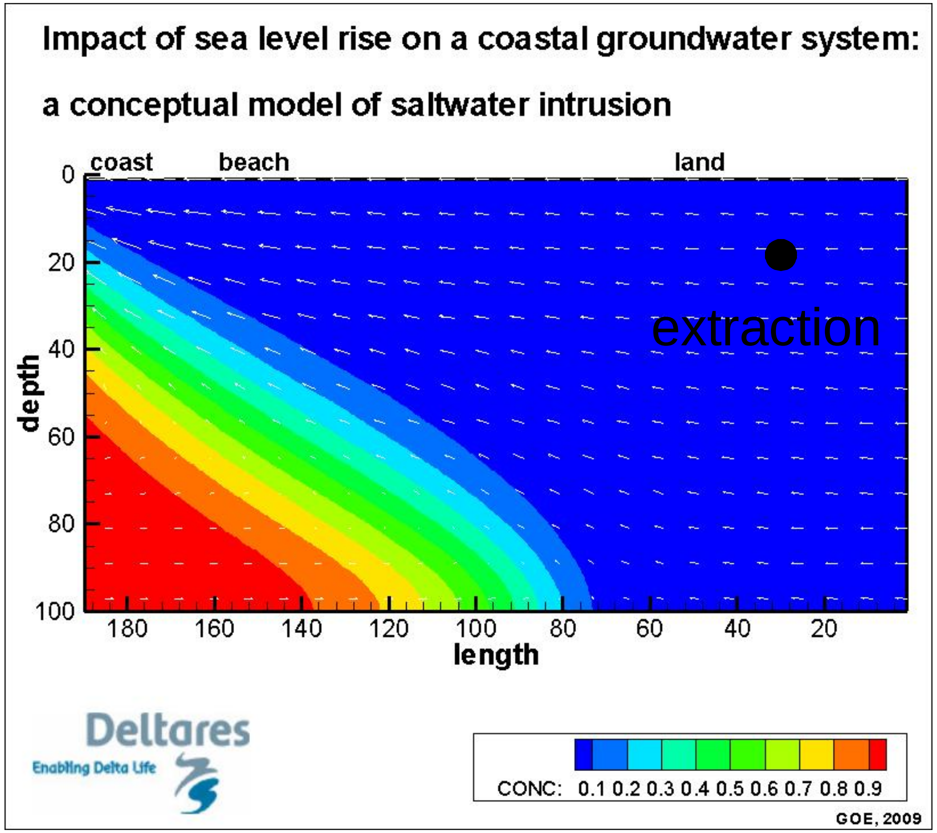
Sea level rise and salt water intrusion

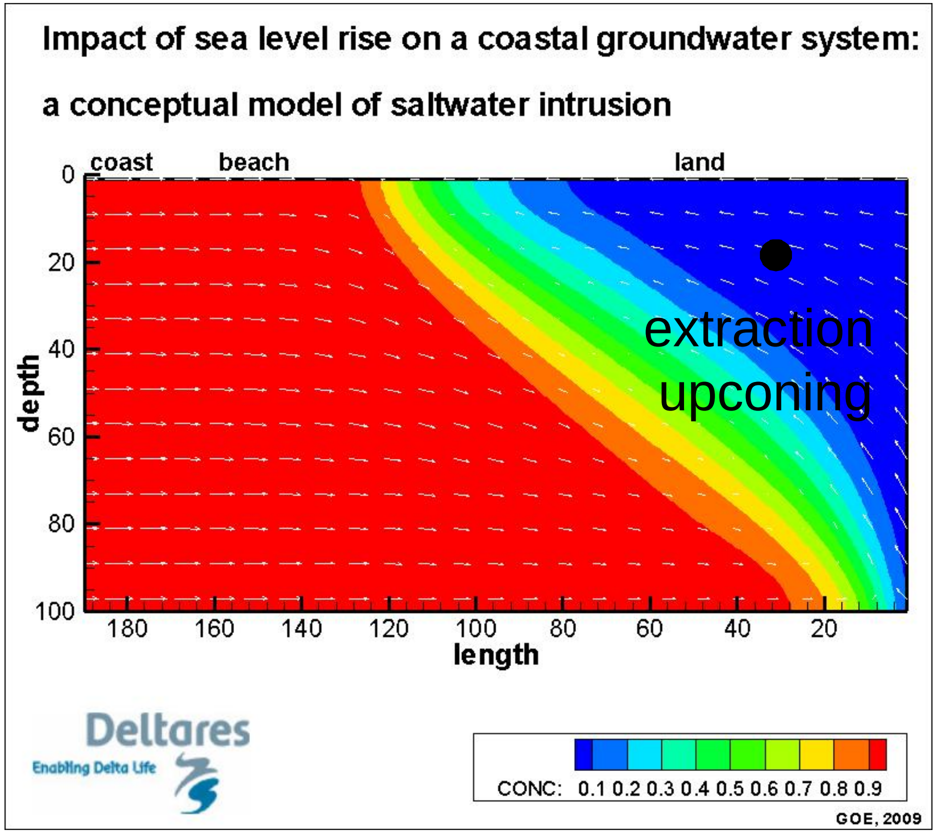


Sea level rise and salt water intrusion

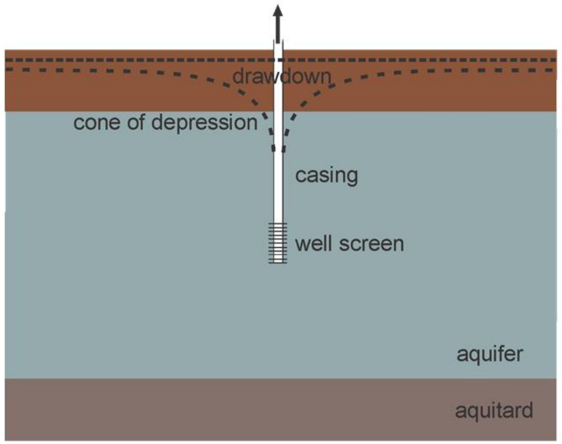


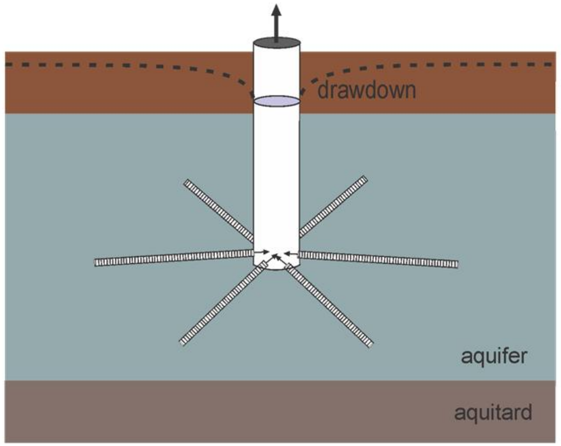
Sea level rise and salt water intrusion

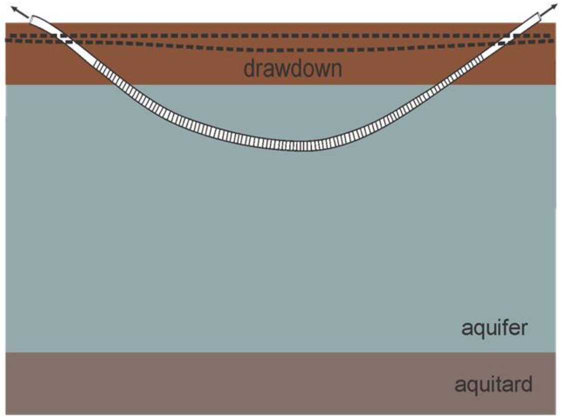


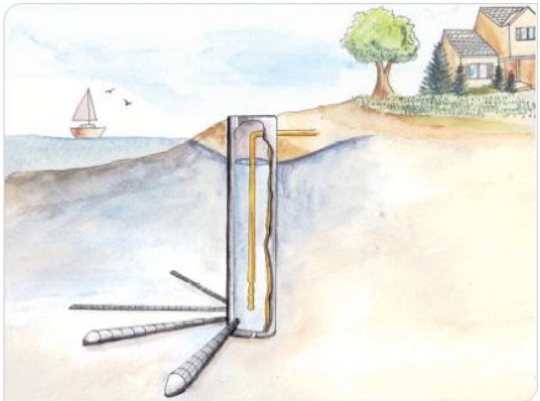


Types of extraction systems

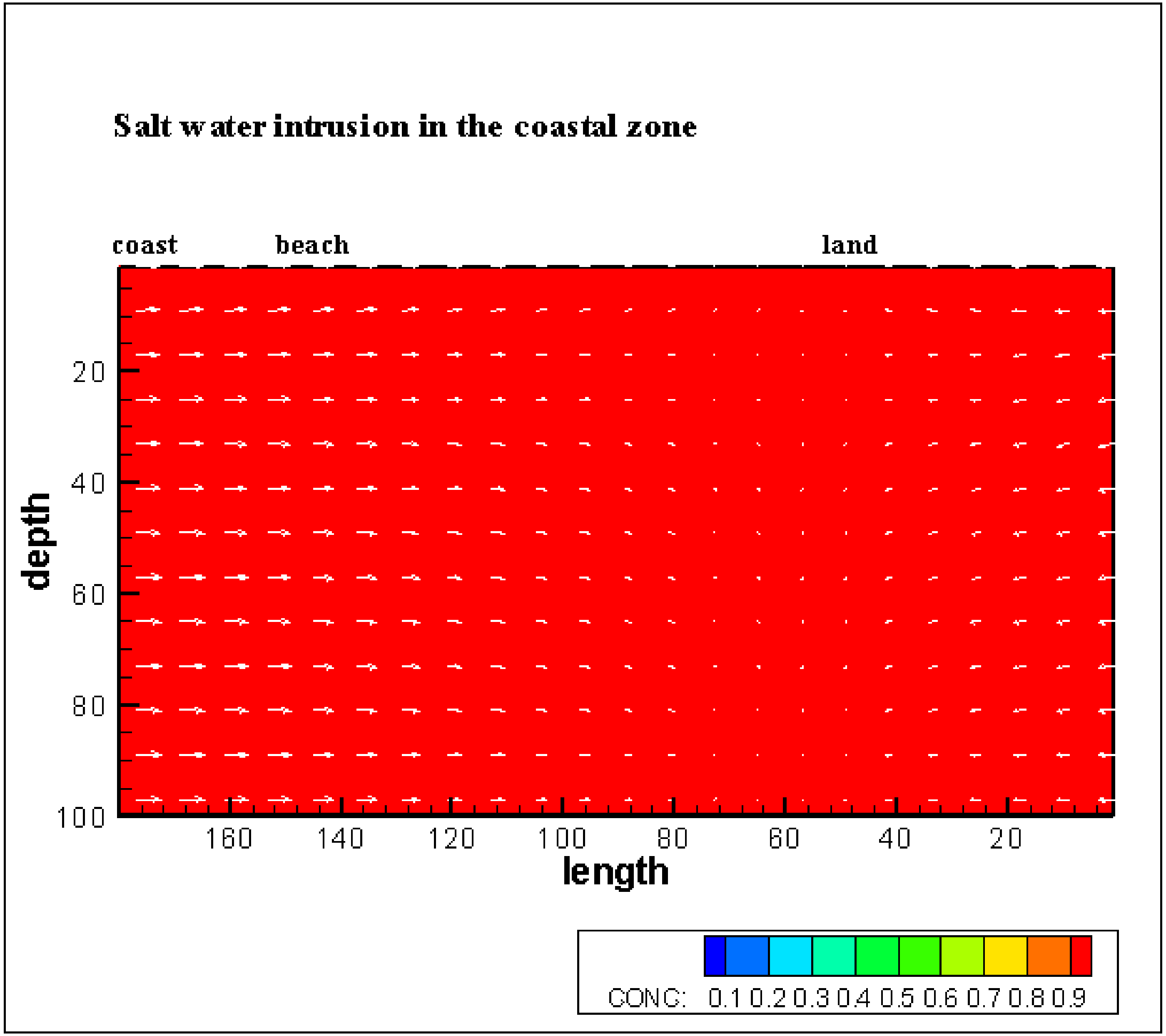








Salt water intrusion



Water on Earth

Some serious developments:

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

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

In 1 liter ocean: about 35 gr salt

In 1 liter ocean: about 35 gr salt

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

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

Jan van Scorel
20140121

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

Fresh-brackish-saline groundwater

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

Definition fresh-brackish-saline groundwater

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

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

Examples of equations of state

Knudsen (1902)

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

T<15 ºC, S<20 ppt

Linear (concentration)

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

where a=relative density difference

Linear (temperature)

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

Exponential (temperature, pressure, salt)

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

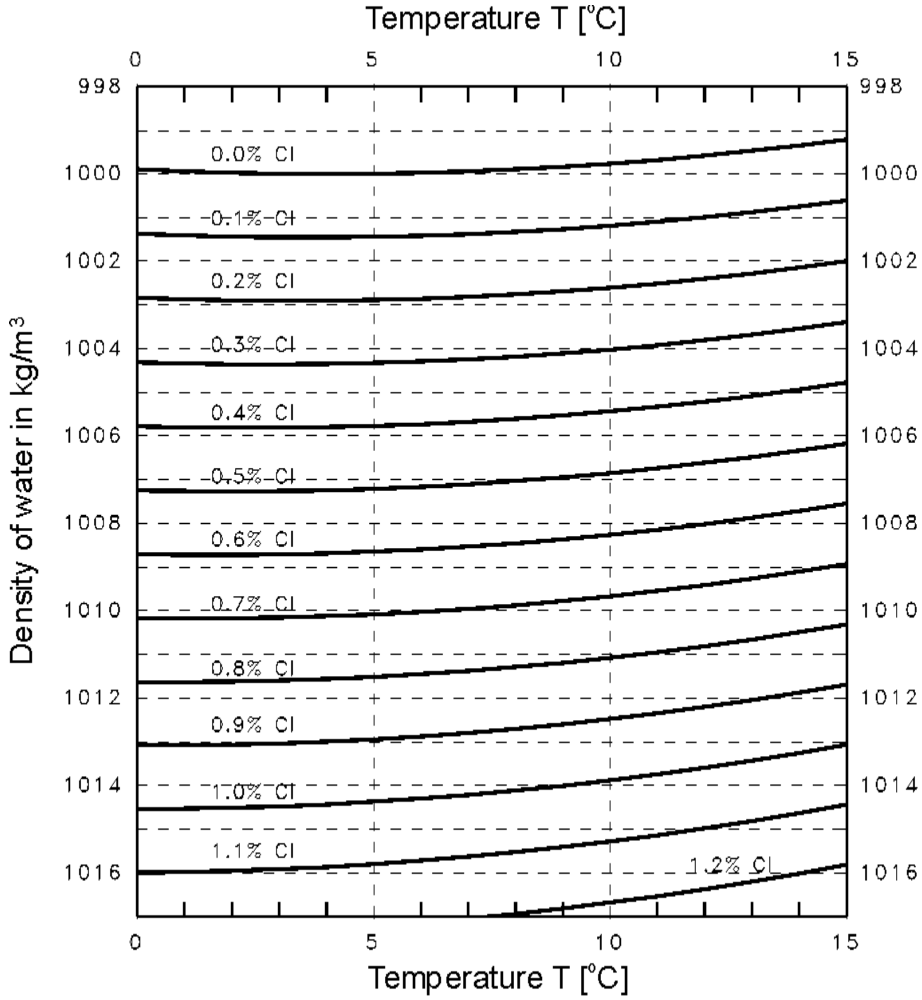
Equation of state (SEAWAT)

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

e.g.:

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

Density depends on salinity and temperature

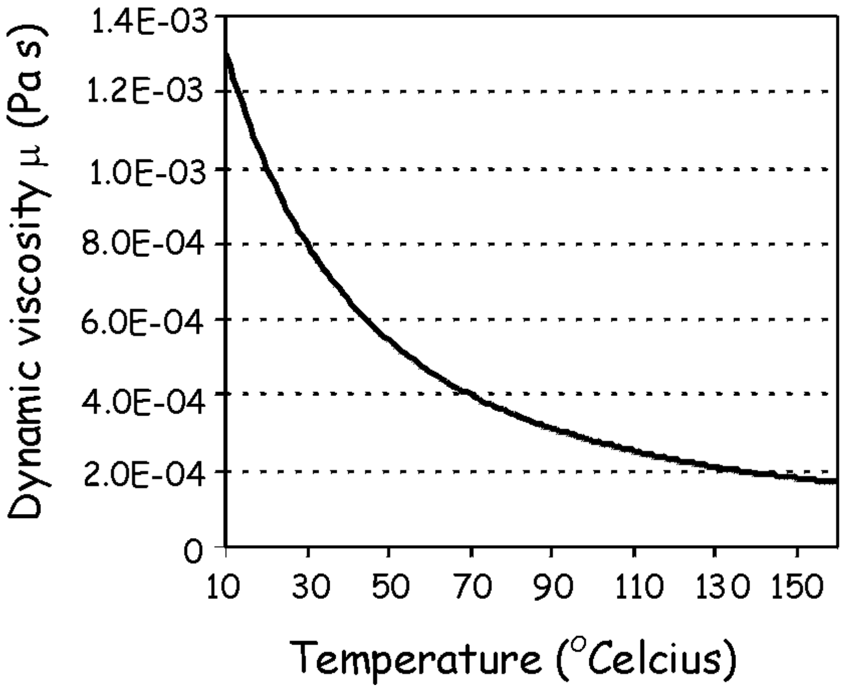


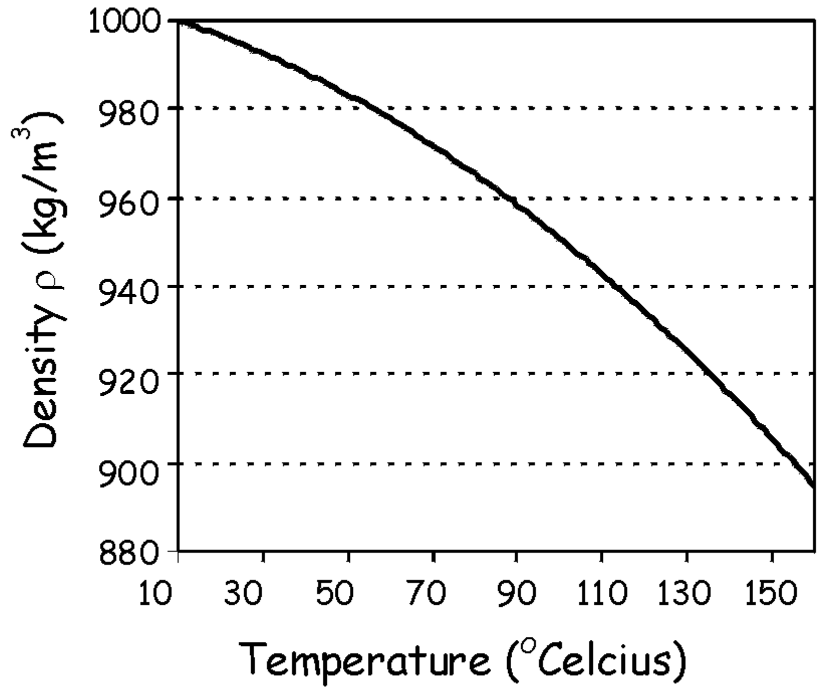
Accurate for T<15 °C and for Cl< 1.1 %

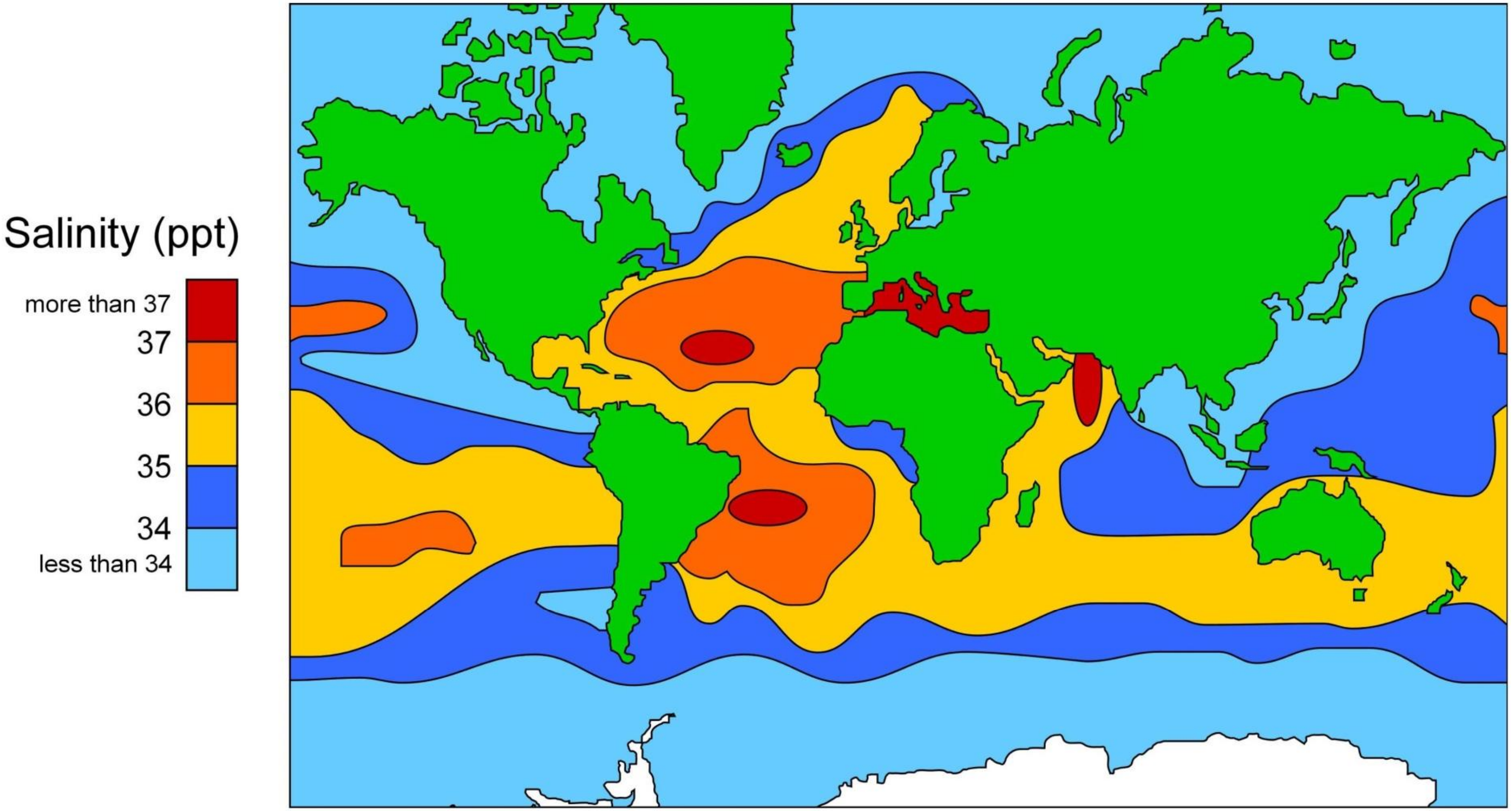
$$\rho_{(S,T)} = 1000 + 0.8054S - 0.0065(T - 4 + 0.2214S)^2$$ Knudsen (1902)

Density and viscosity depend on temperature

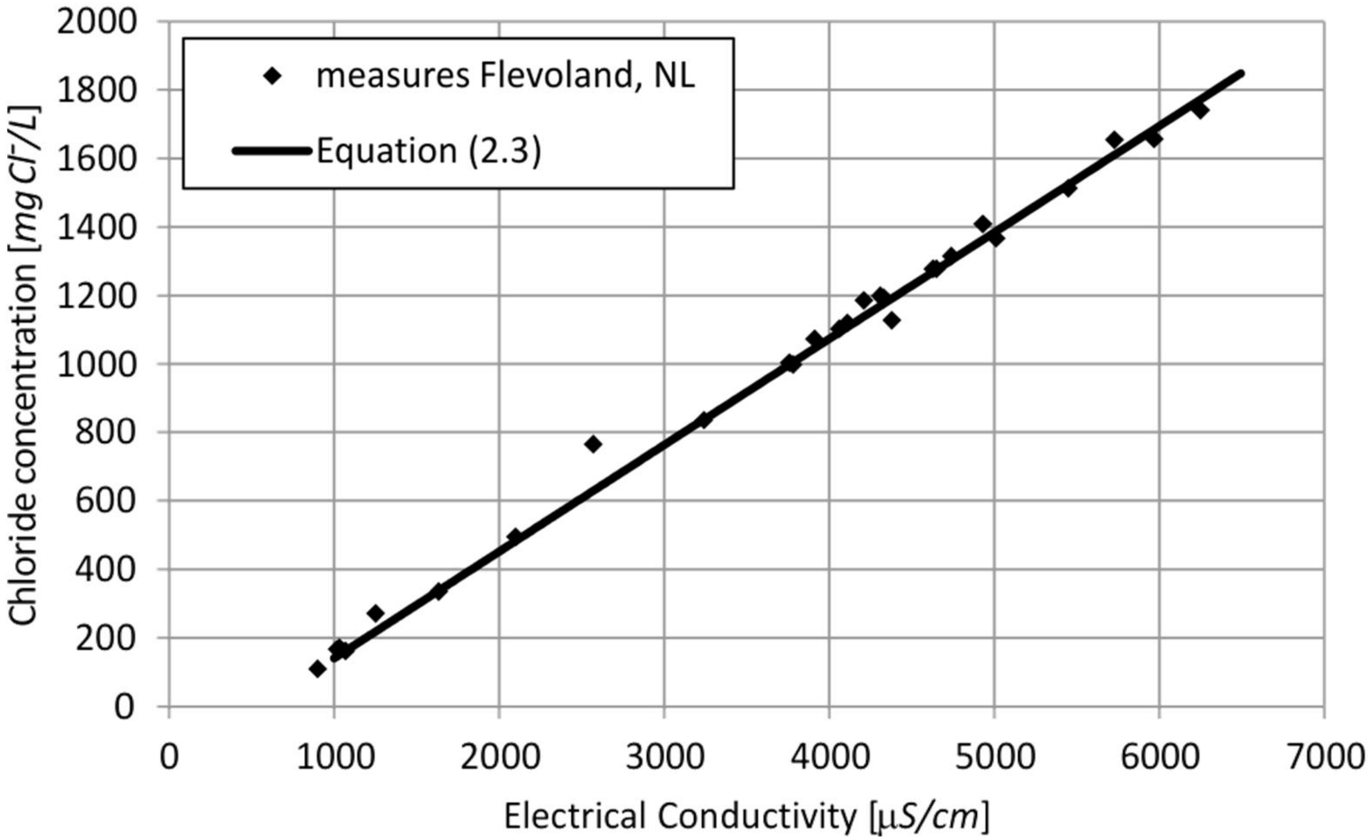
(10^{o}C-160 ^{o}C)






Salinity (ppt)
more than 37
37
36
35
34
less than 34

Close relation between chloride concentration and Electrical Conductivity



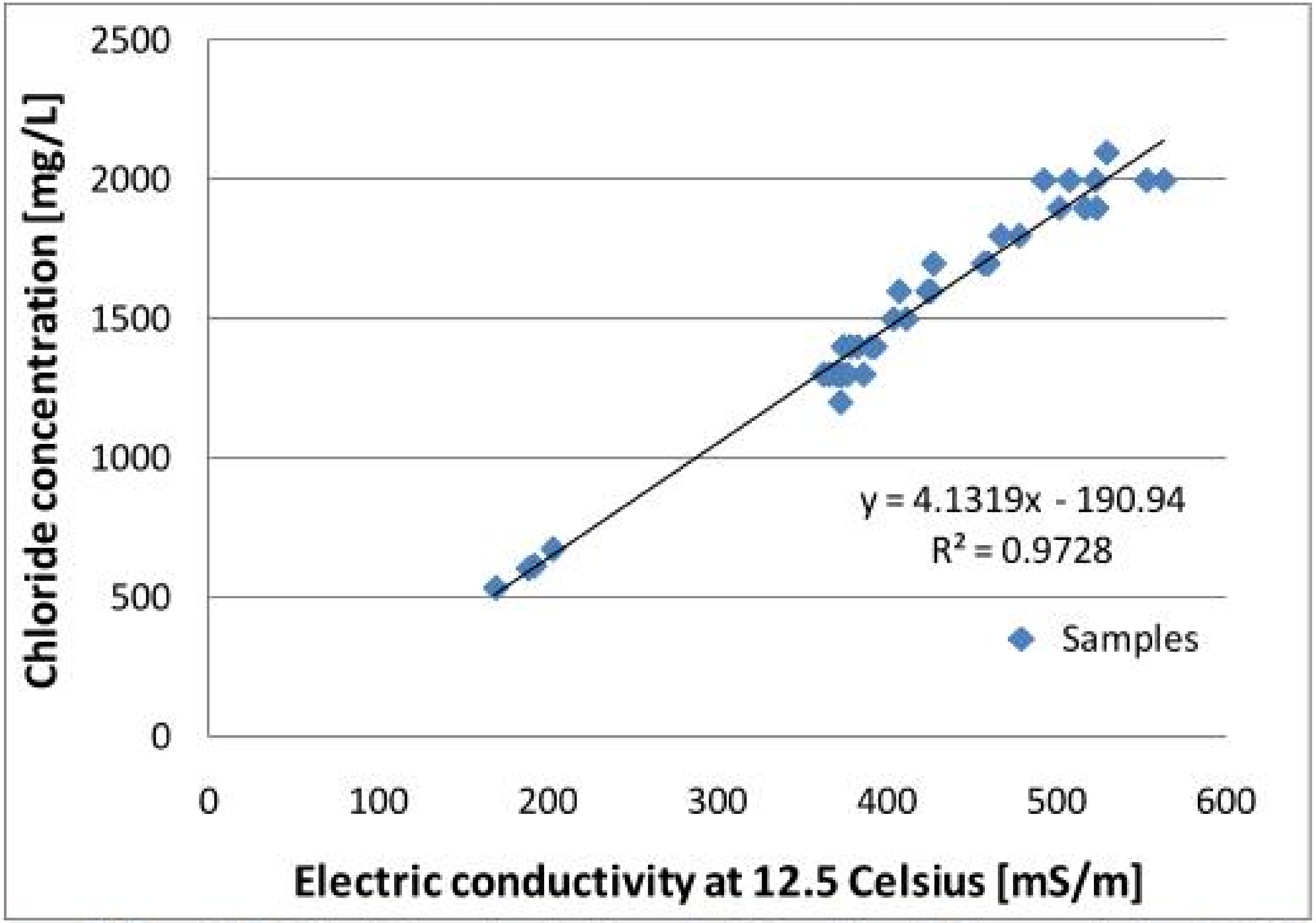
$$Cl^{-}(mg / L) = EC_{w}(\mu S / cm) \cdot 0.305 - 137$$

Close relation between chloride concentration and Electrical Conductivity

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

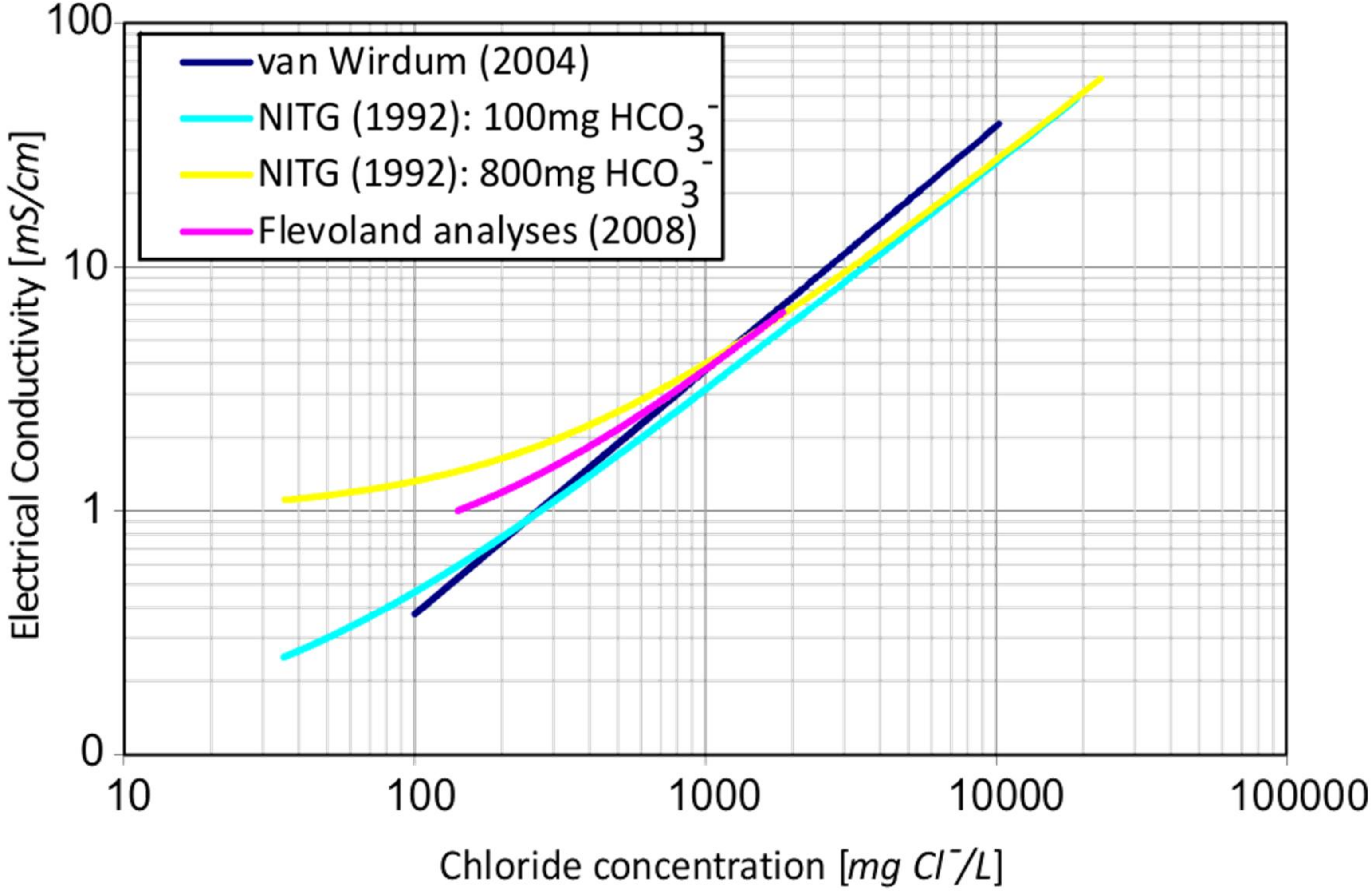
ocean water:
~19000 *mg Cl-/L* or ~34555 *mg TDS/L*
~5 *S/m* or ~48 *mS/cm*

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



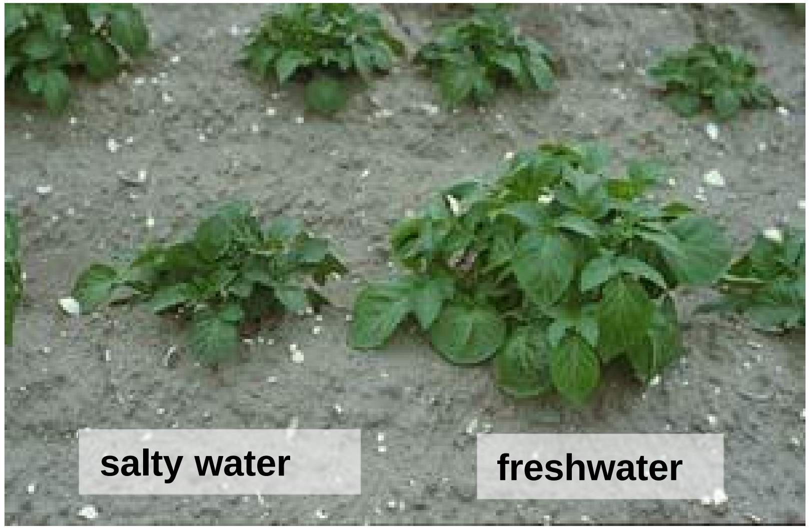
Appendix figure 11: Relation between the electric conductivity and the chloride concentration. For this relation samples from observation well B06D1114 and B06D1087 in between 23-sept-2009 and 9-okt-2010 were plotted.

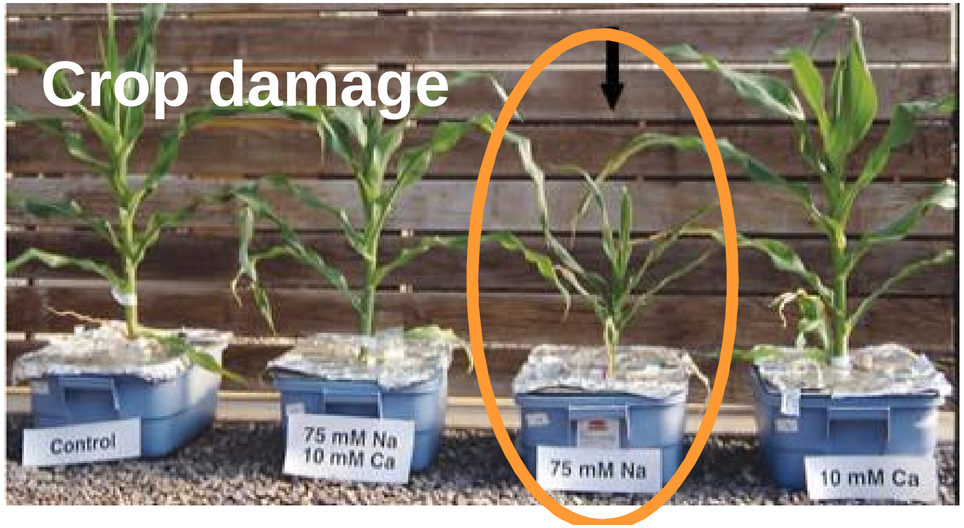
EC-Chloride



van Wirdum (2004)
NITG (1992): 100mg HCO3-
NITG (1992): 800mg HCO3-
Flevoland analyses (2008)
Electrical Conductivity [mS/cm]
100
10
1
0
10
100
1000
10000
100000
Chloride concentration [mg Cl-/L]

Salt in water is a problem





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

-drinking water:

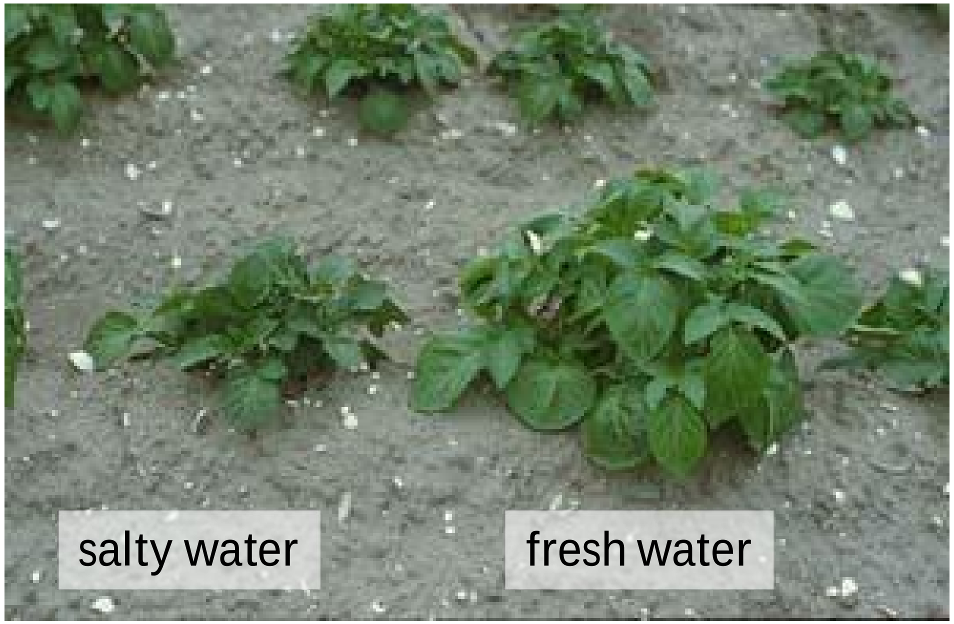
- taste (100-300 mg Cl^-/l)
- long term health effect
- norm: EC& WHO=150 mg Cl^-/l (live stock=1500 mg Cl^-/l)

-industry:

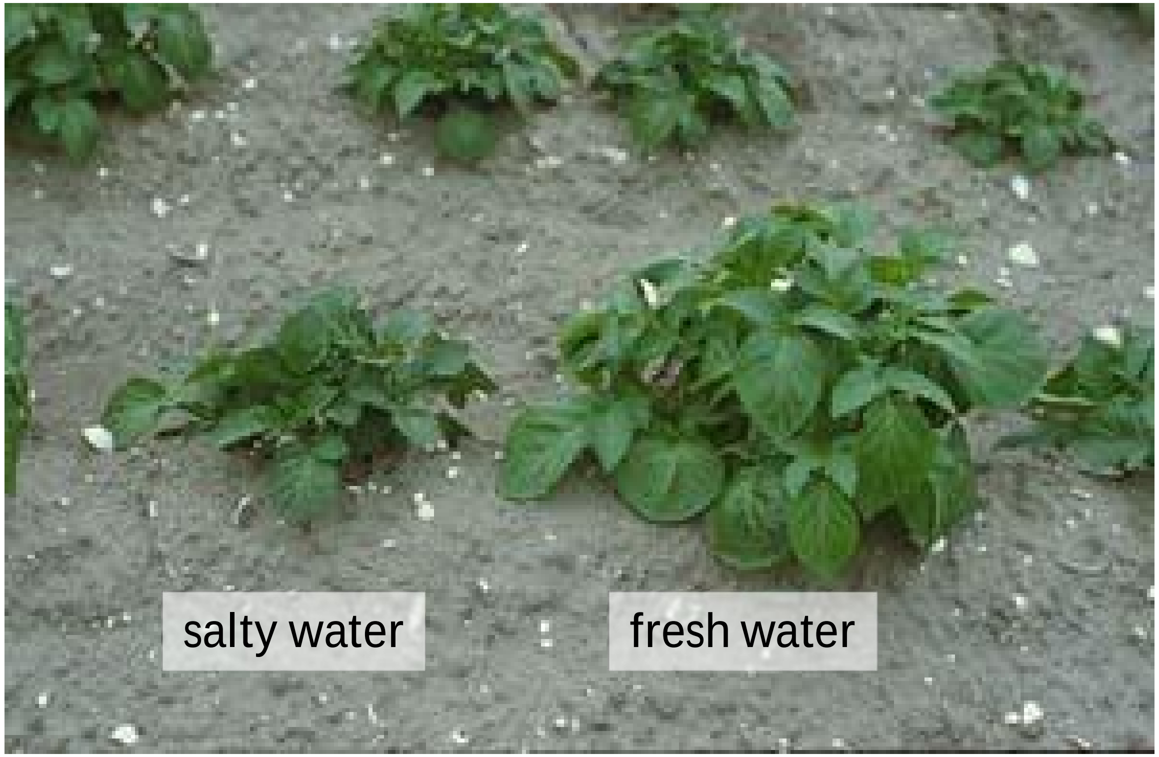
- corrosion pipes
- preparation food

-irrigation/agriculture:

- production crops
- salt damage

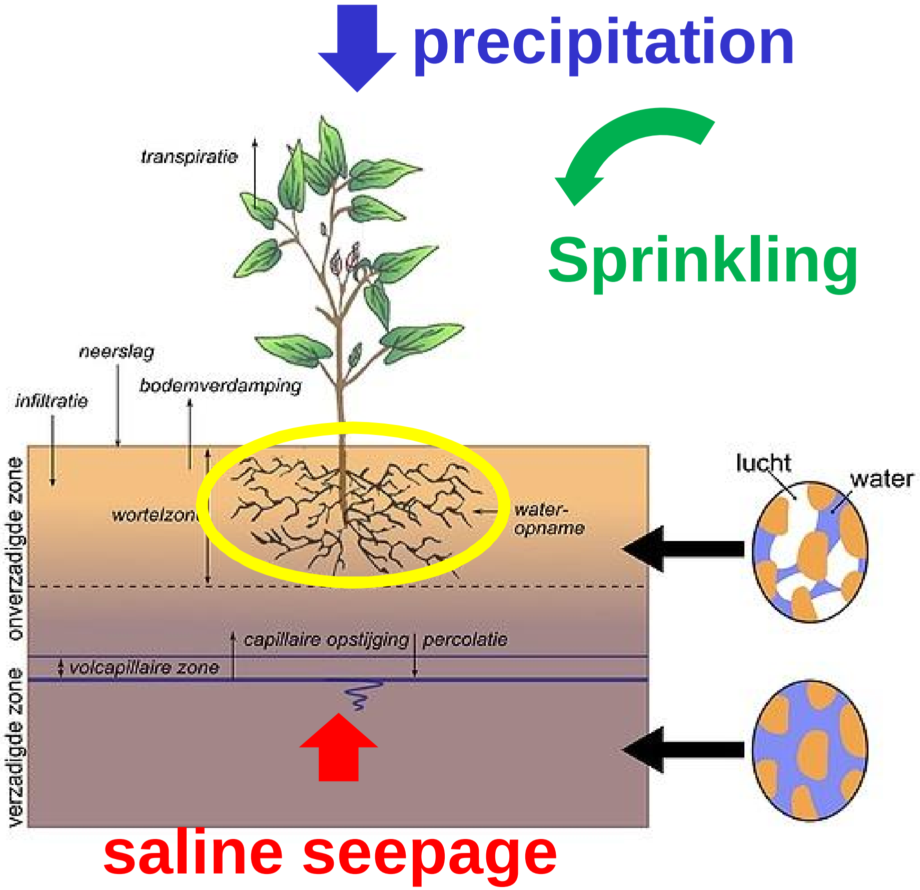


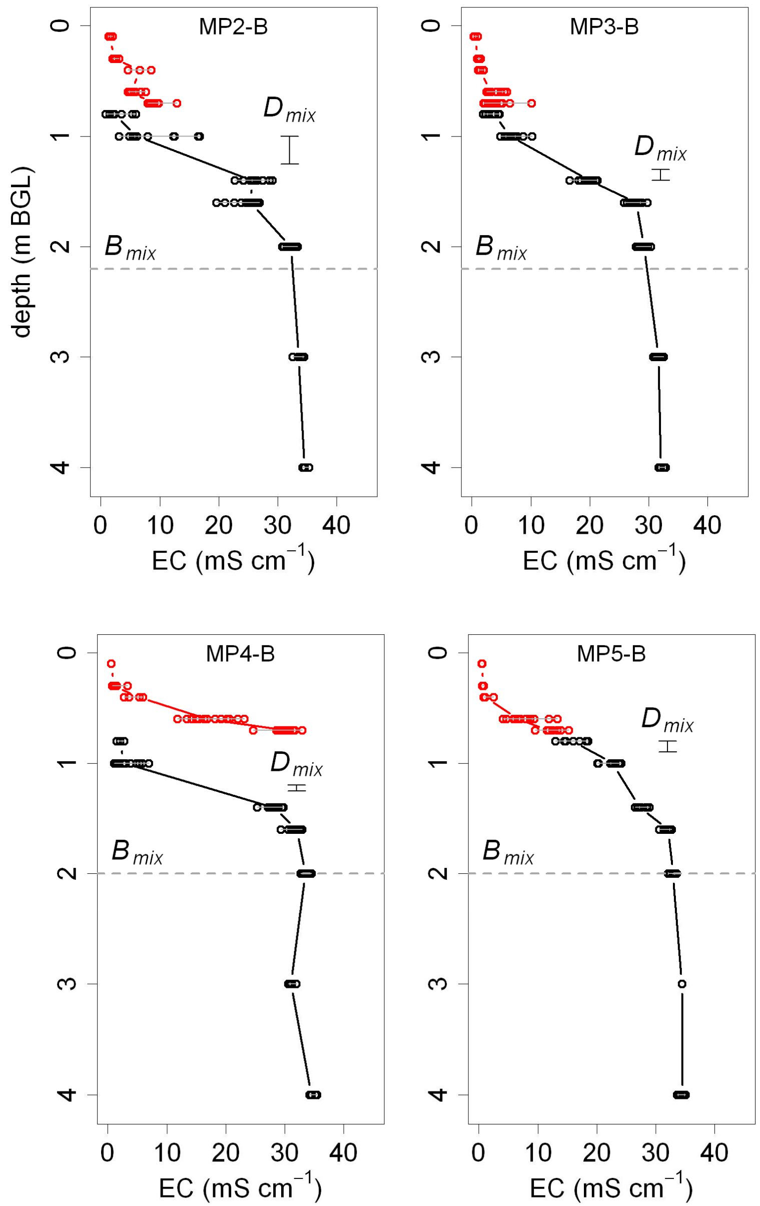
Effects salinisation: salt damage



Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

Salt-resistant crops





Important parameter:

- Chloride concentration root zone
- Land use
- Sensitivity crops

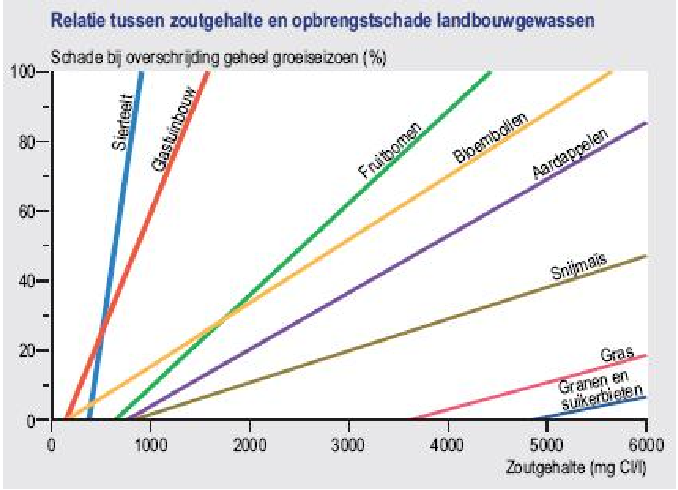
Salt damage to crops

Important parameters:

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

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

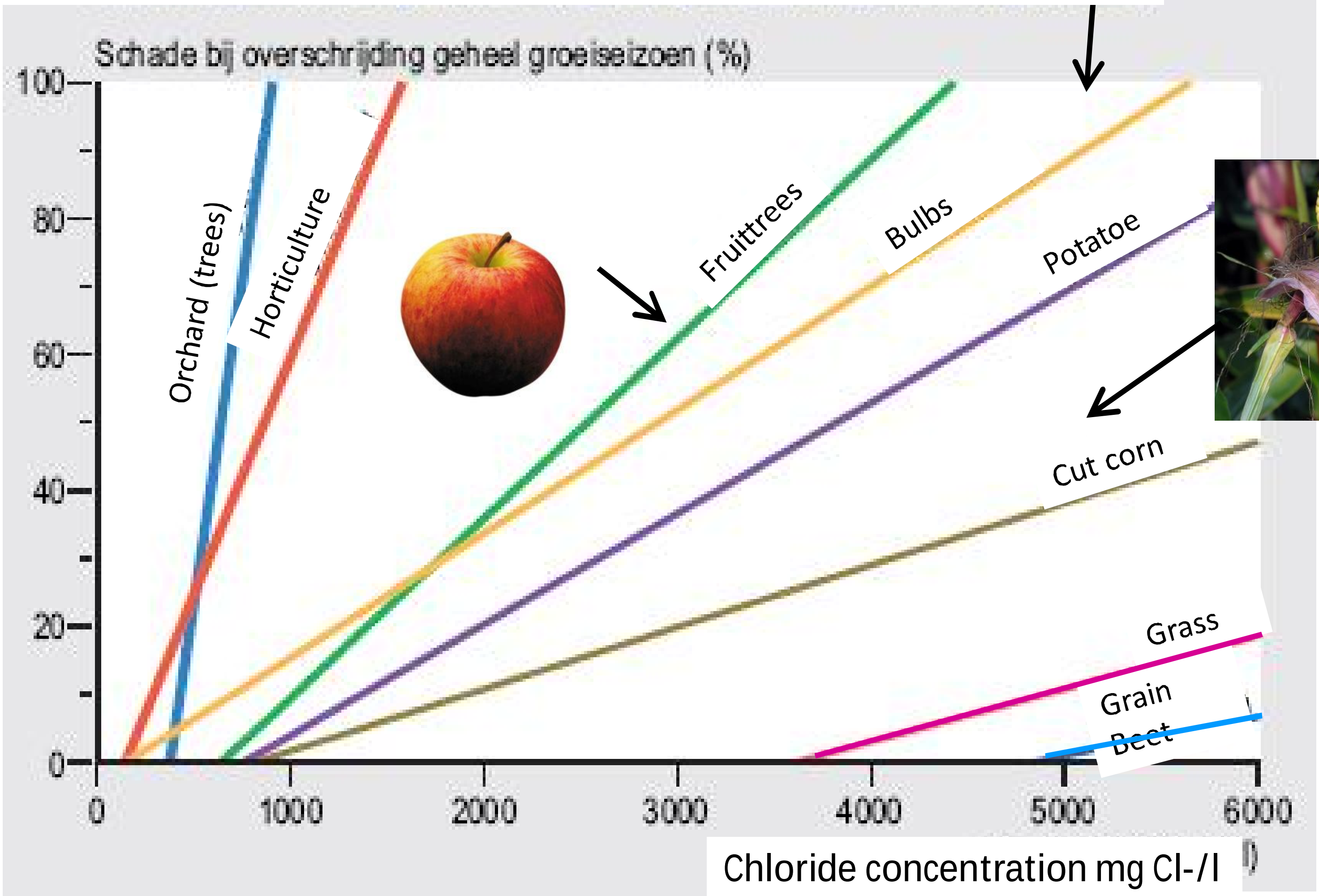
Source: Roest et al., 2003 en Haskoning



Source: MNP, 2005

Salt damage to crops

Relation between salt concentration and damage to crops

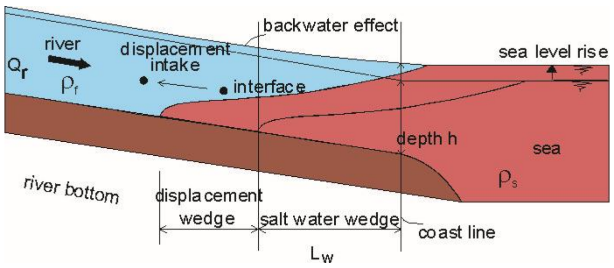


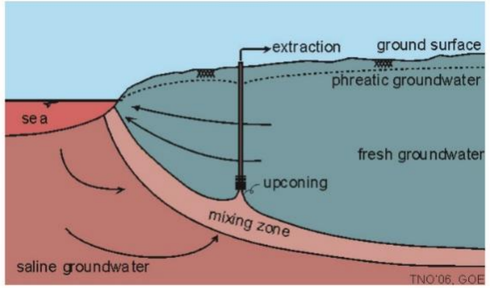
Source: MNP, 2005

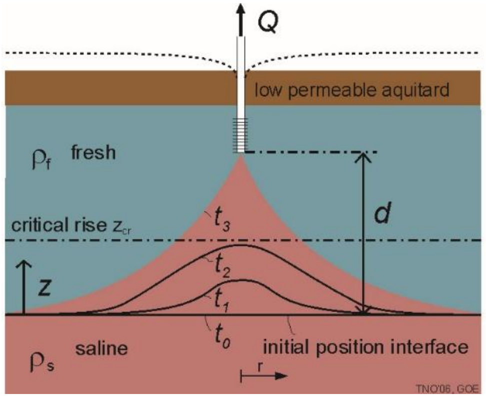
	Soil moisture		Irrigation water	
	Limi	Gradient	Limit	Gradient
Crop	mg/l Cl	%/mg/l Cl	mg/l Cl	%/mg/l Cl
Potatoe	756	0.0163	202	0.0610
Grass	3606	0.0078	962	0.0294
Sugar beat	4831	0.0057	1288	0.0212
Cut Corn	815	0.0091	217	0.0343
Grains	4831	0.0058	1288	0.0218
Fruit trees	642	0.0264	171	0.0991
Orchard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

Why is salinisation a pressing problem?

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







Processes that accelerate salt water intrusion:

- Sea level rise
- Land subsidence
- Human activities

Threats for:

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


2500 litres of water
for 1 cotton shirt

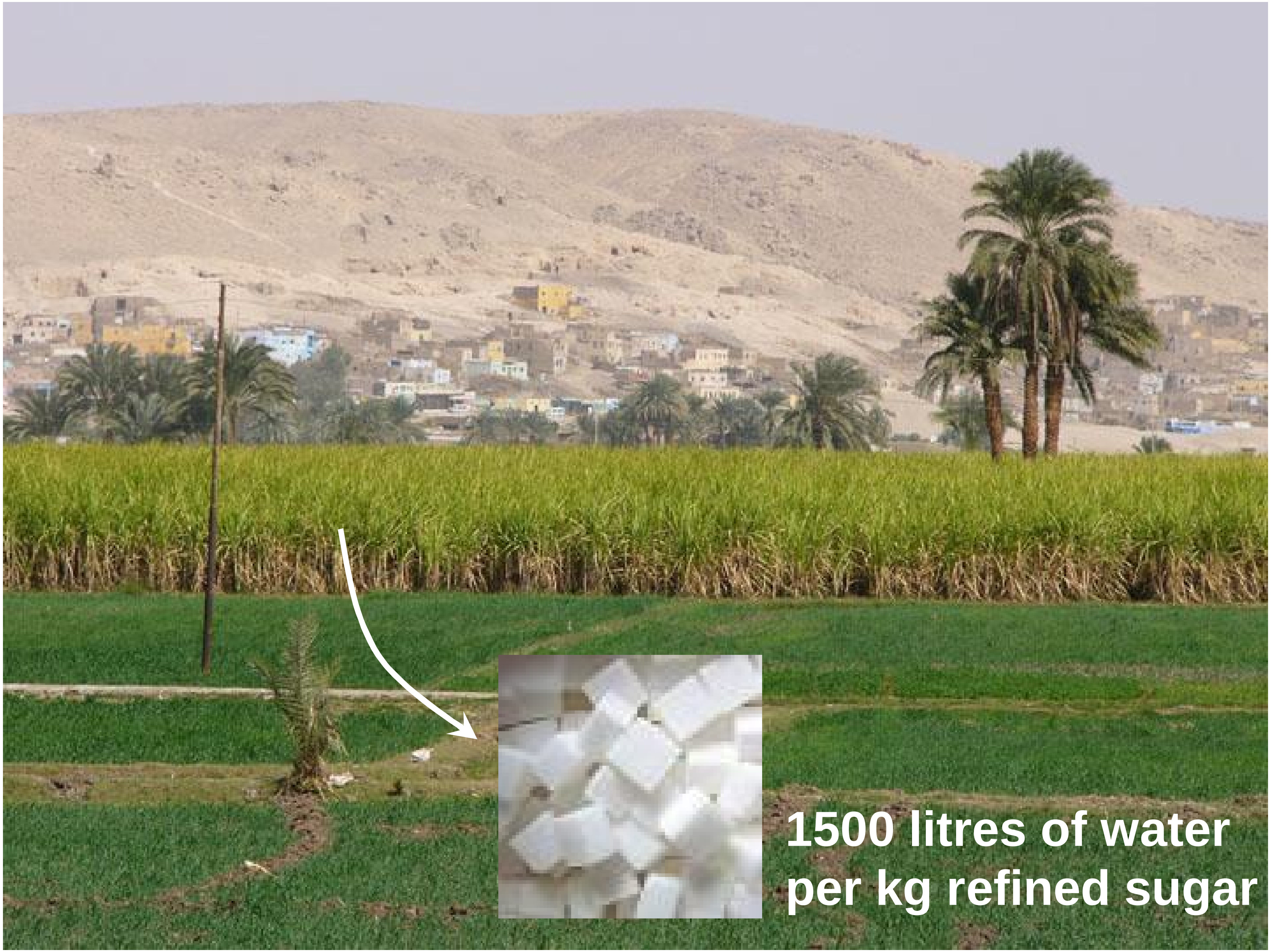
The water footprint of products

global averages

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

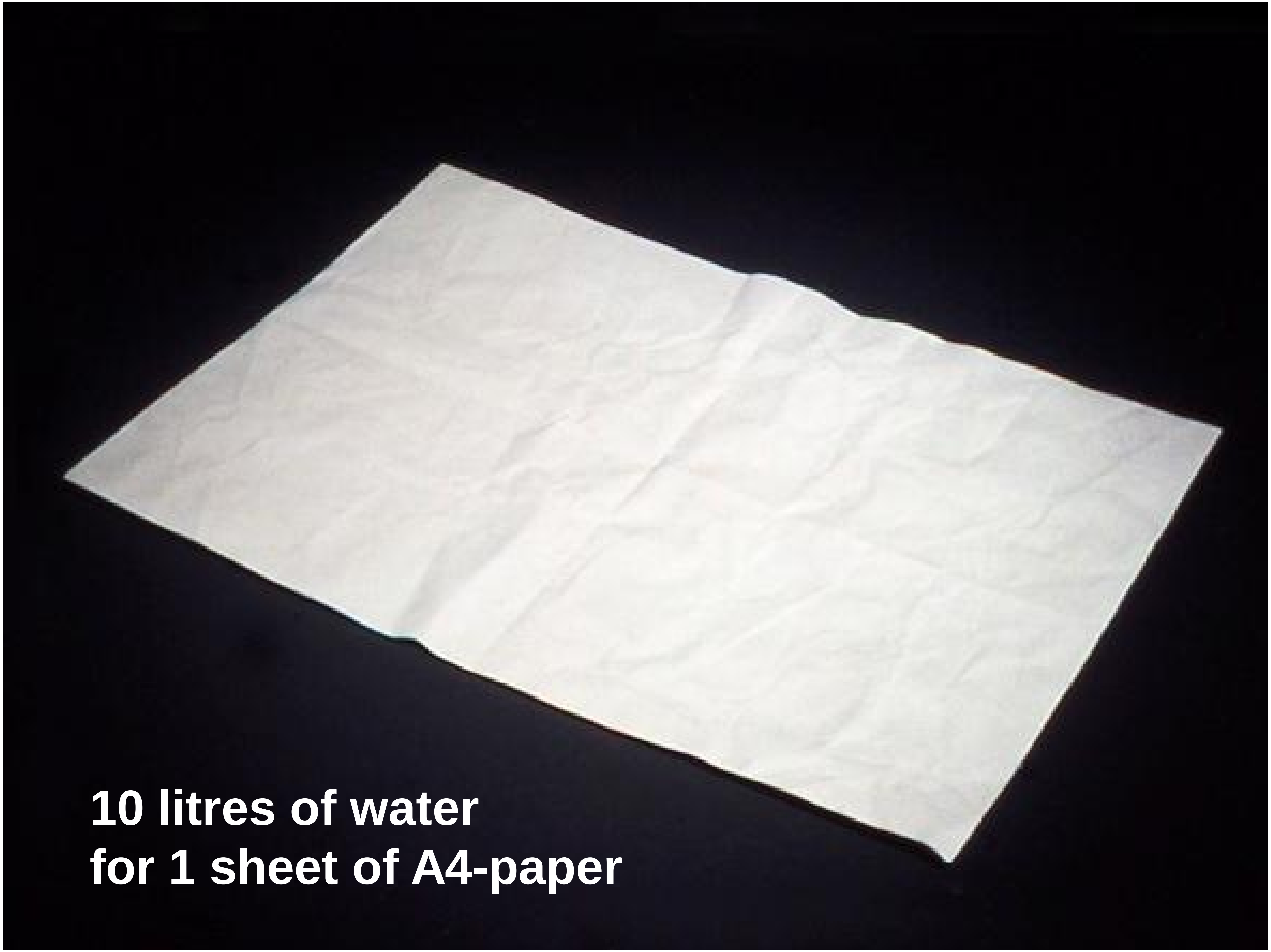
[Hoekstra & Chapagain, 2008]


40 litres of water
for 1 slice of bread


1500 litres of water
per kg refined sugar


2400 litres of water
for 1 hamburger

= 140 litres of water

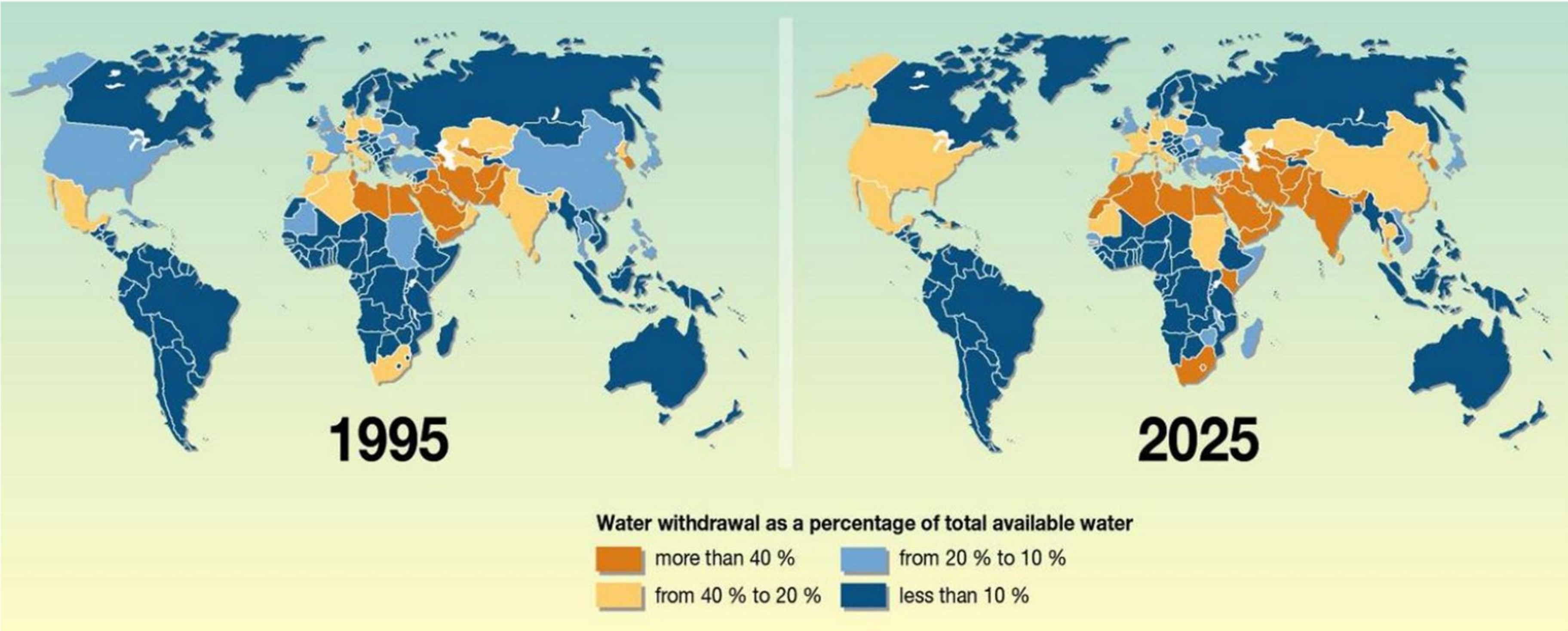

10 litres of water
for 1 sheet of A4-paper

Question:

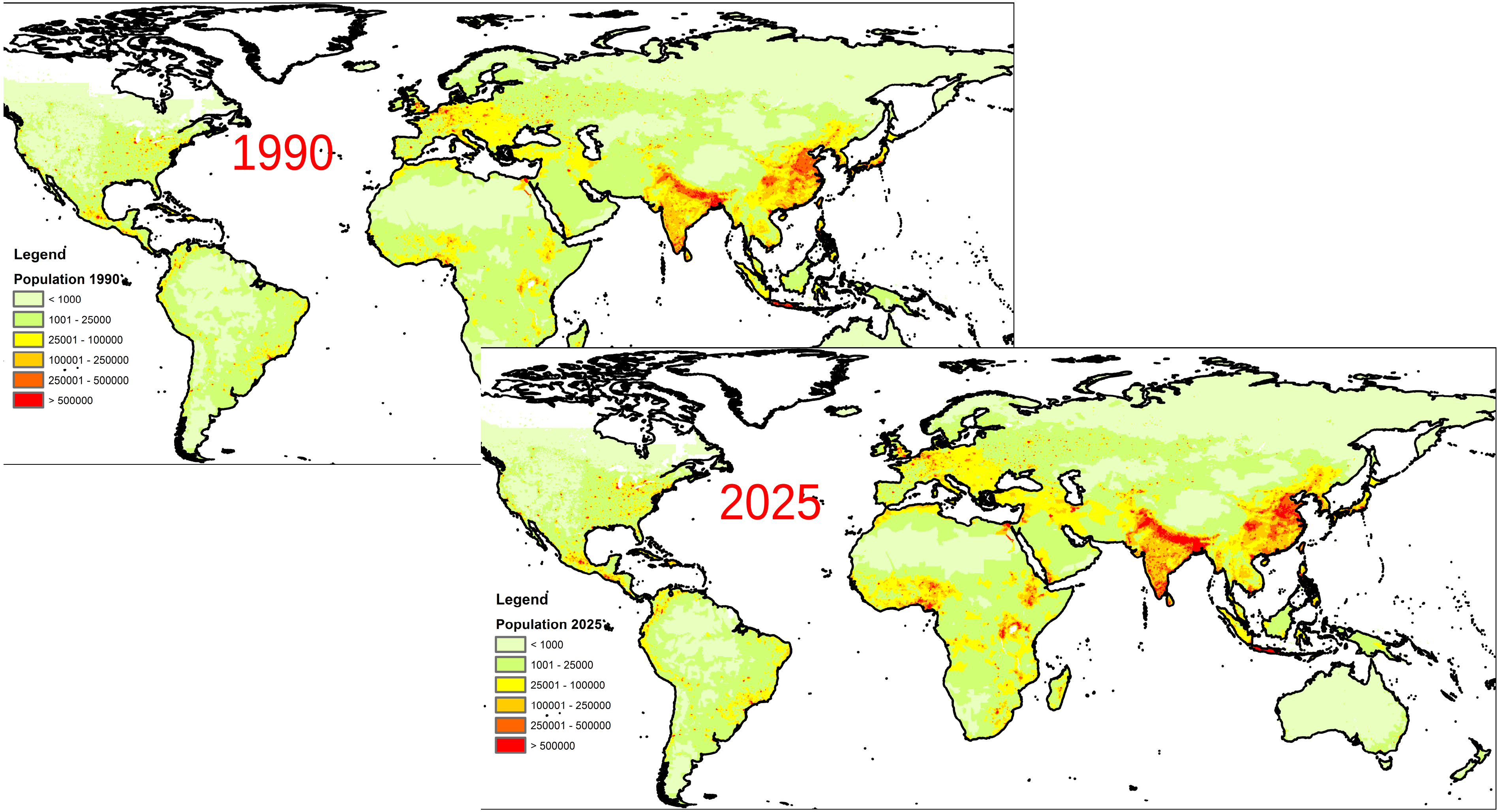
Demand fresh water per capita per day?:

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

Water withdrawal as % of total available water



Population growth 1990-2025



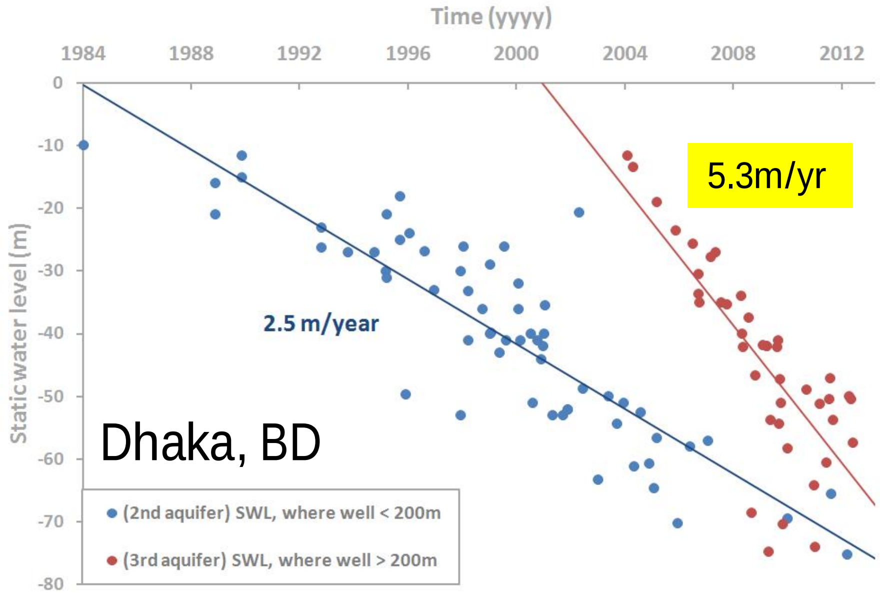
*Global 15 x 15 Minute Grids of the Downscaled Population Based on the SRES B2 Scenario, 1990 and 2025 (~28*28km2 at equator)*

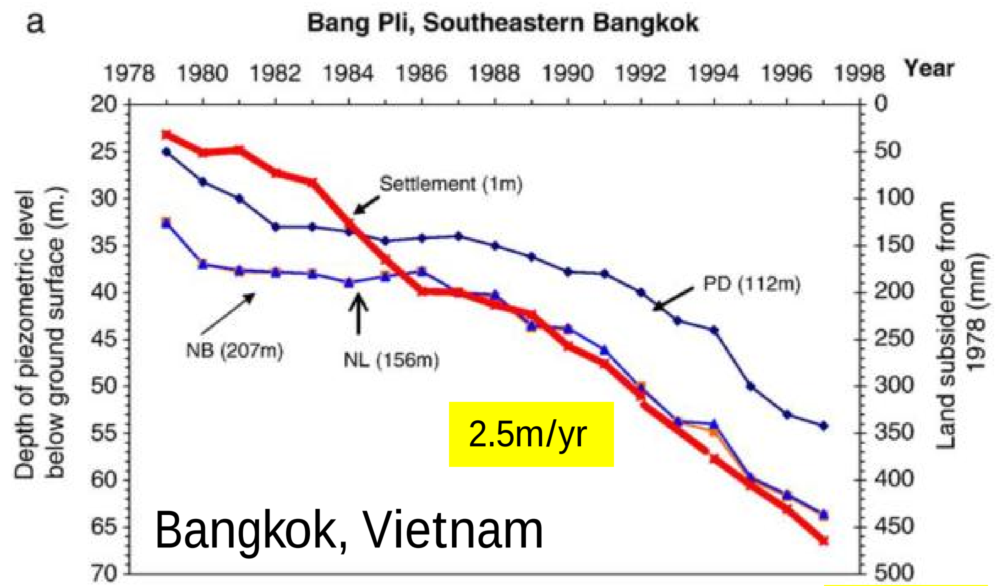
Reasons and drawbacks of using groundwater

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

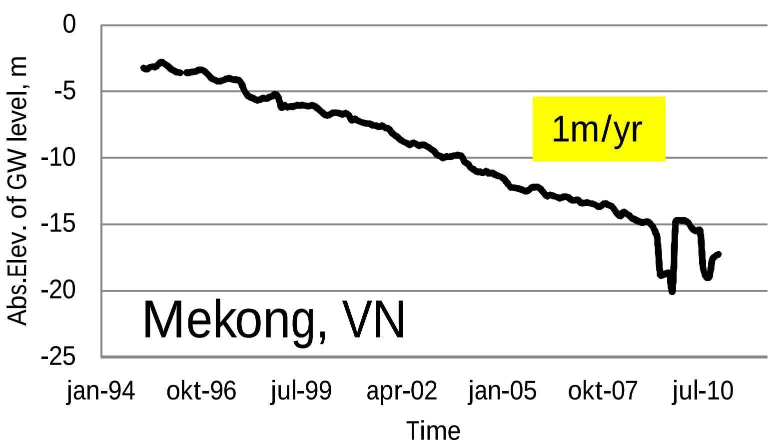
Disadvantage:
- high extraction costs
- local droughts
- high mineral content
- land subsidence....
- salt water intrusion !

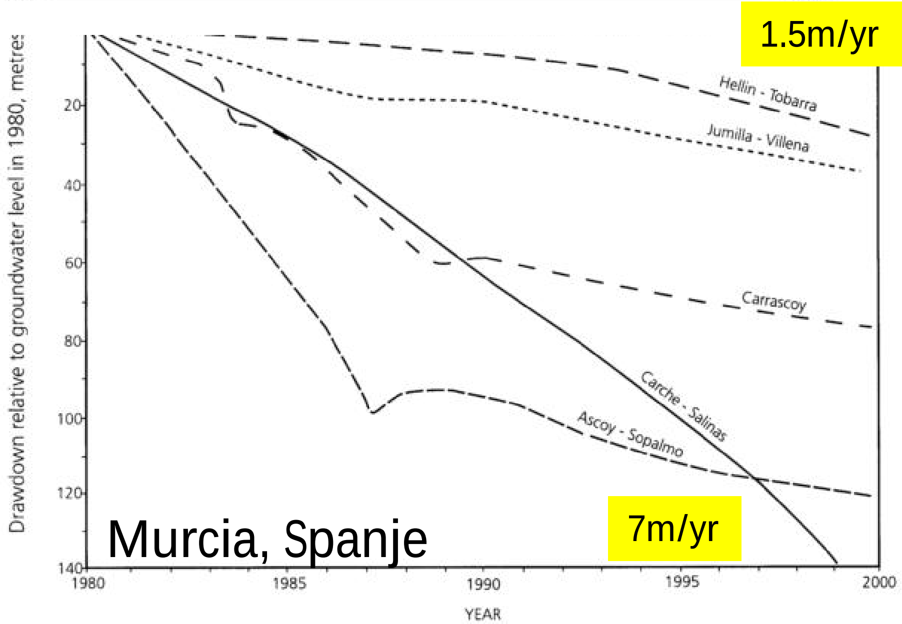
Serious overexploitation coastal aquifers worldwide





Elev. of GW level in aquifer n_2^1





Groundwater overexploitation in Mekong Delta

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

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

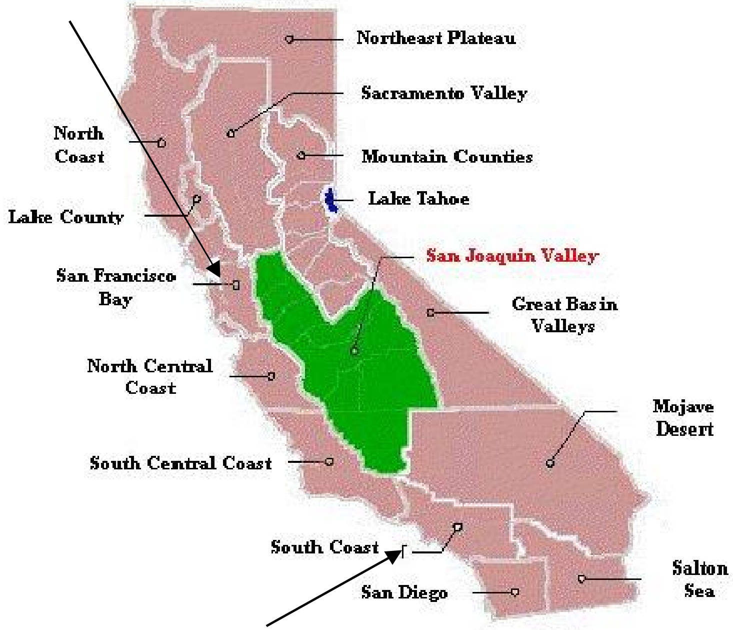
Land subsidence San Joachim Valley, CA, USA

9 m

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

9 m since 1930s

San Francisco



Los Angeles

What causes the land to subside?

Natural causes (geological processes):

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

Anthropogenic causes (human-induced processes):

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

Why discriminating between human-induced and natural processes?

- Magnitude
- Cooping strategy (mitigation versus adaptation)

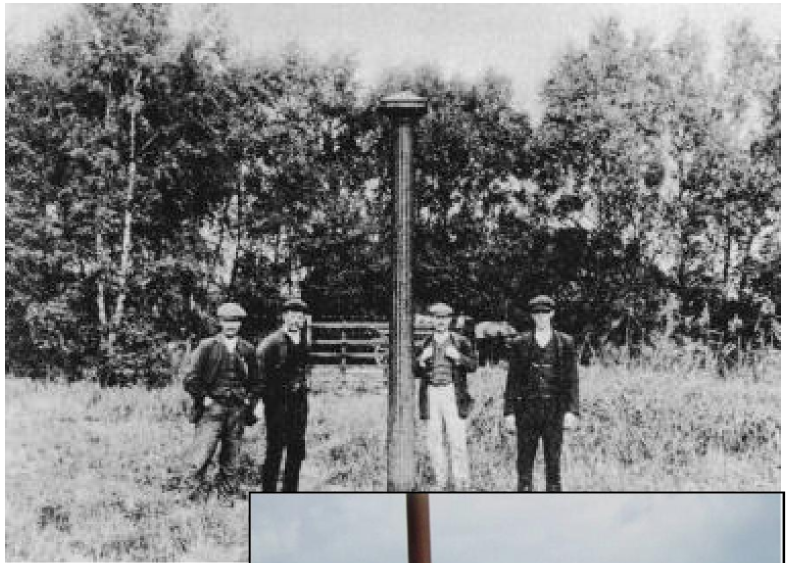
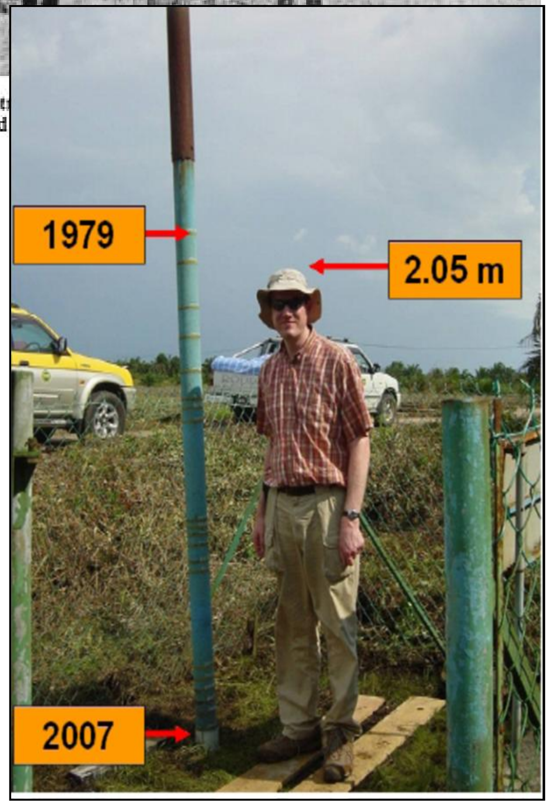


PLATE 4. Holme Post (prot
probably between 1910 and



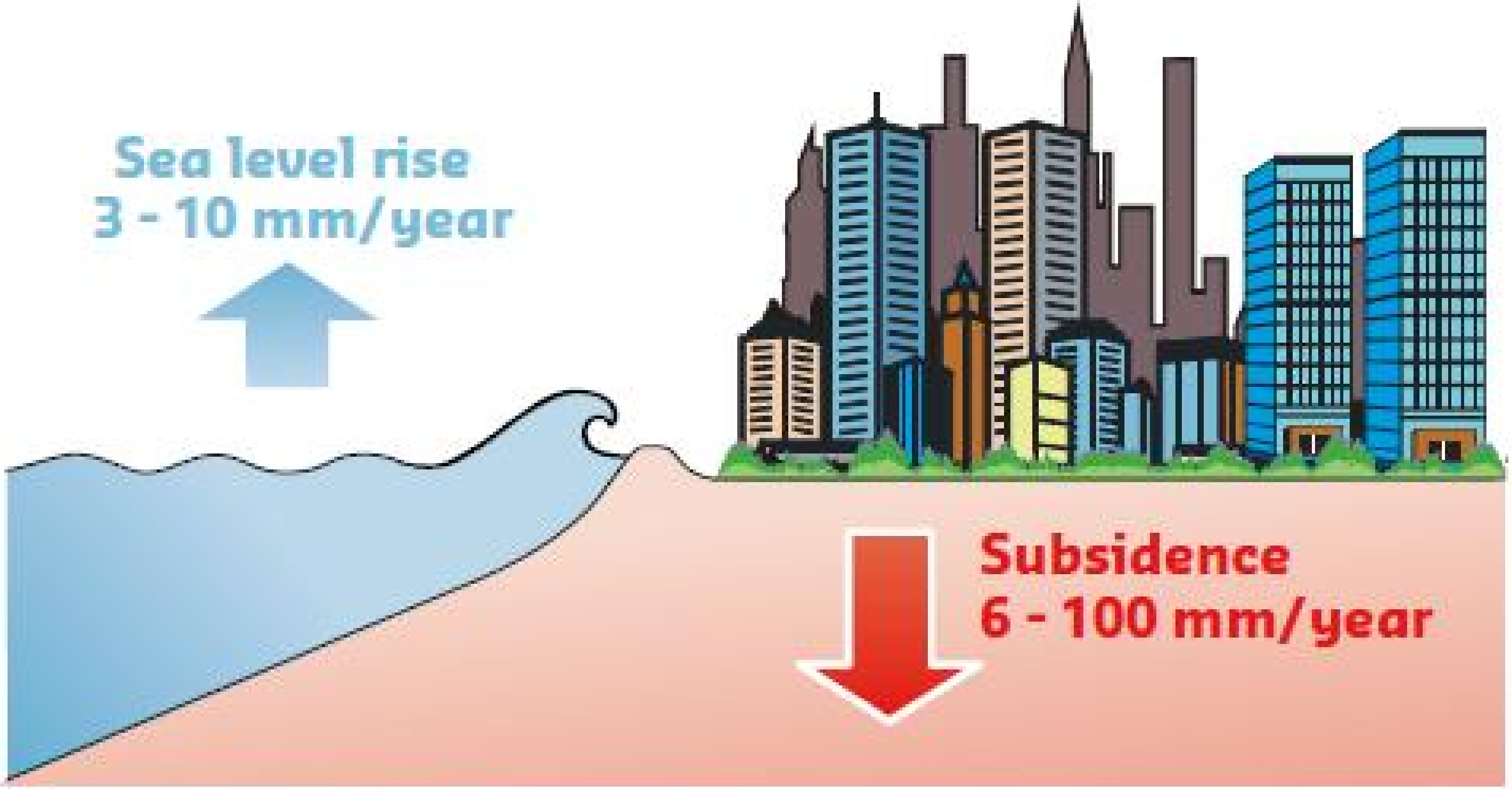
Impacts


Newly made road level
Abandon well head
Previous Road level
Subsidence of original road level
ระดับพื้นหมู่บ้าน


Land Subsidence

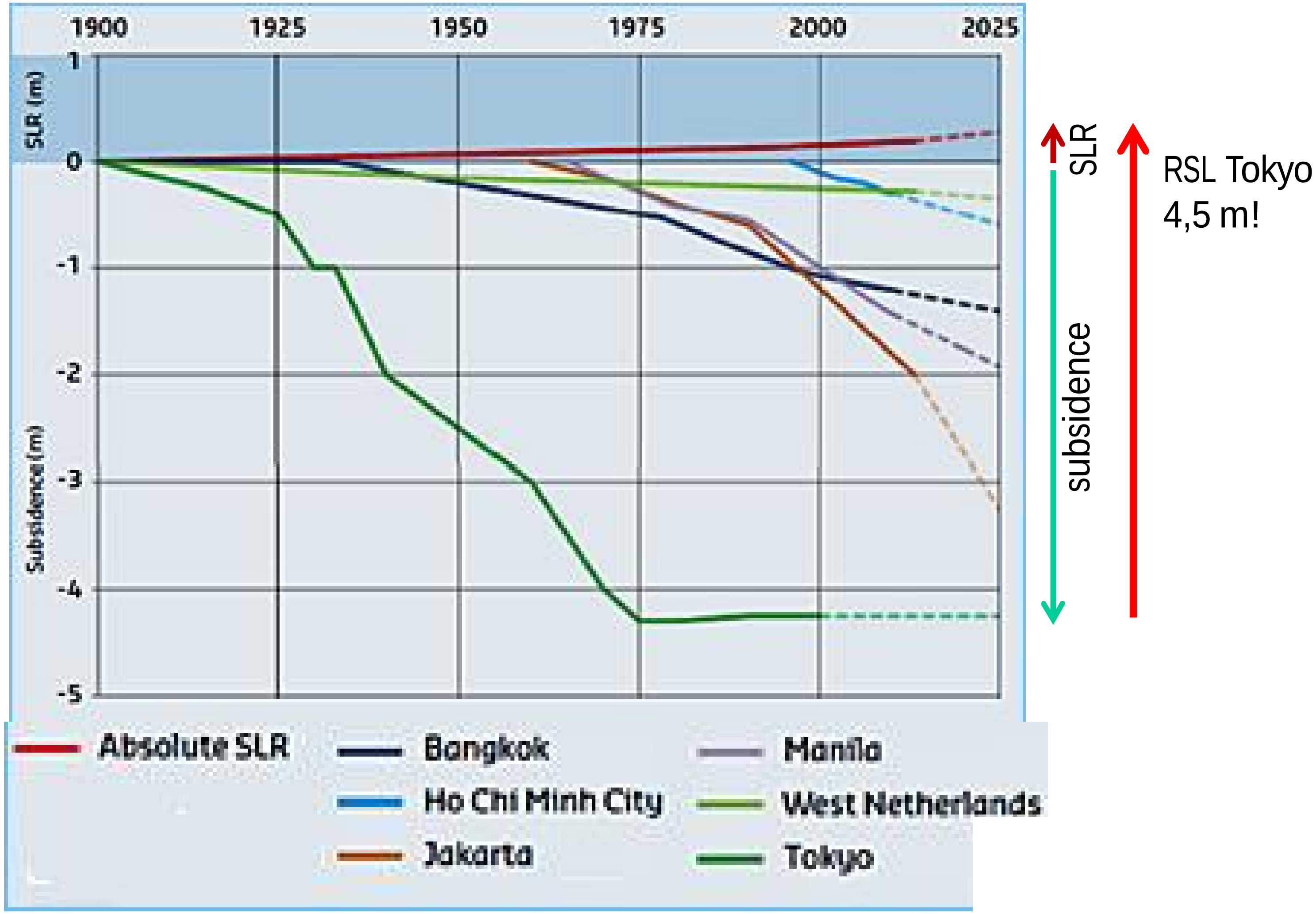
Sinking delta cities

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

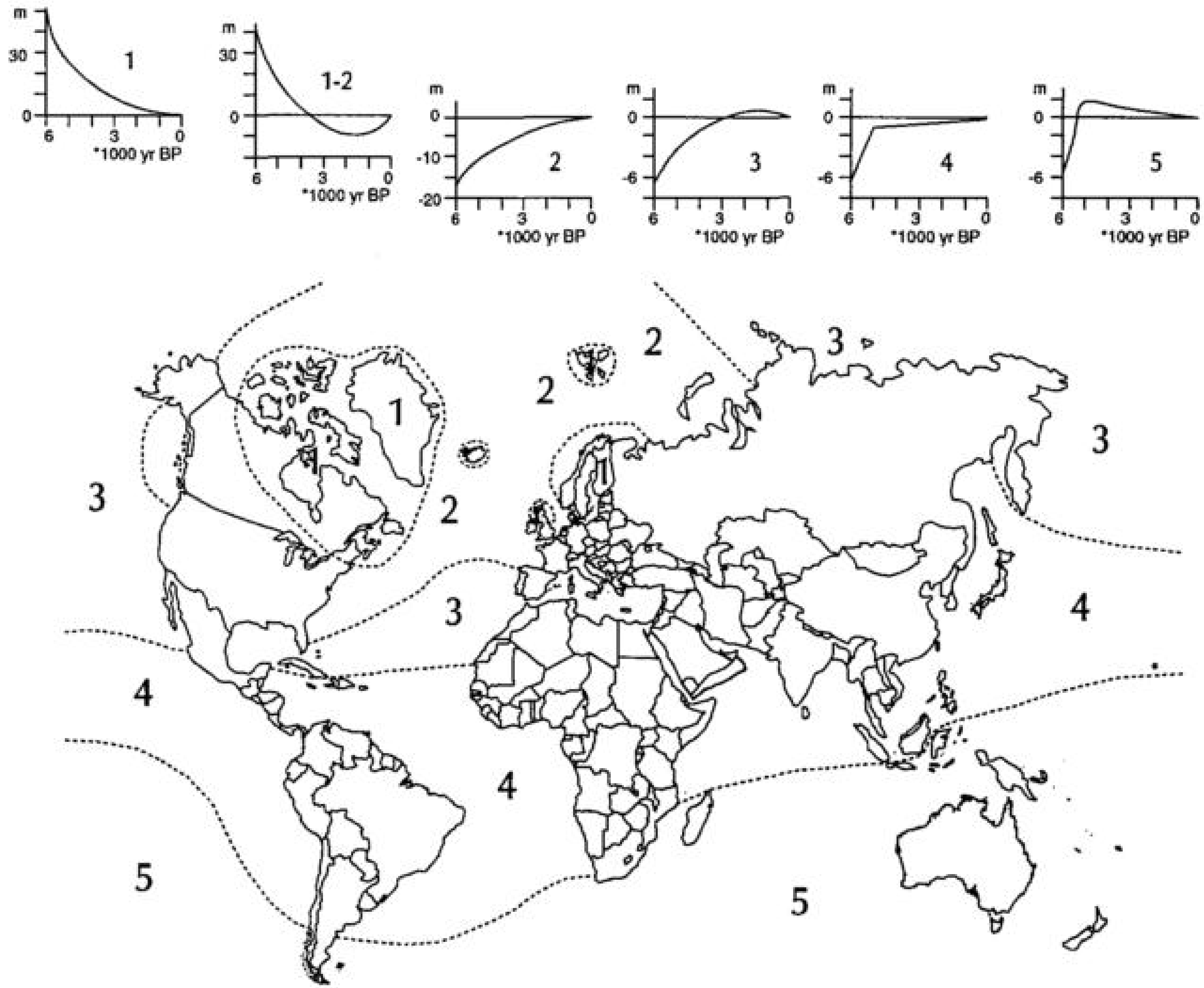


Examples of some major coastal cities

The subsidence issue is underestimated

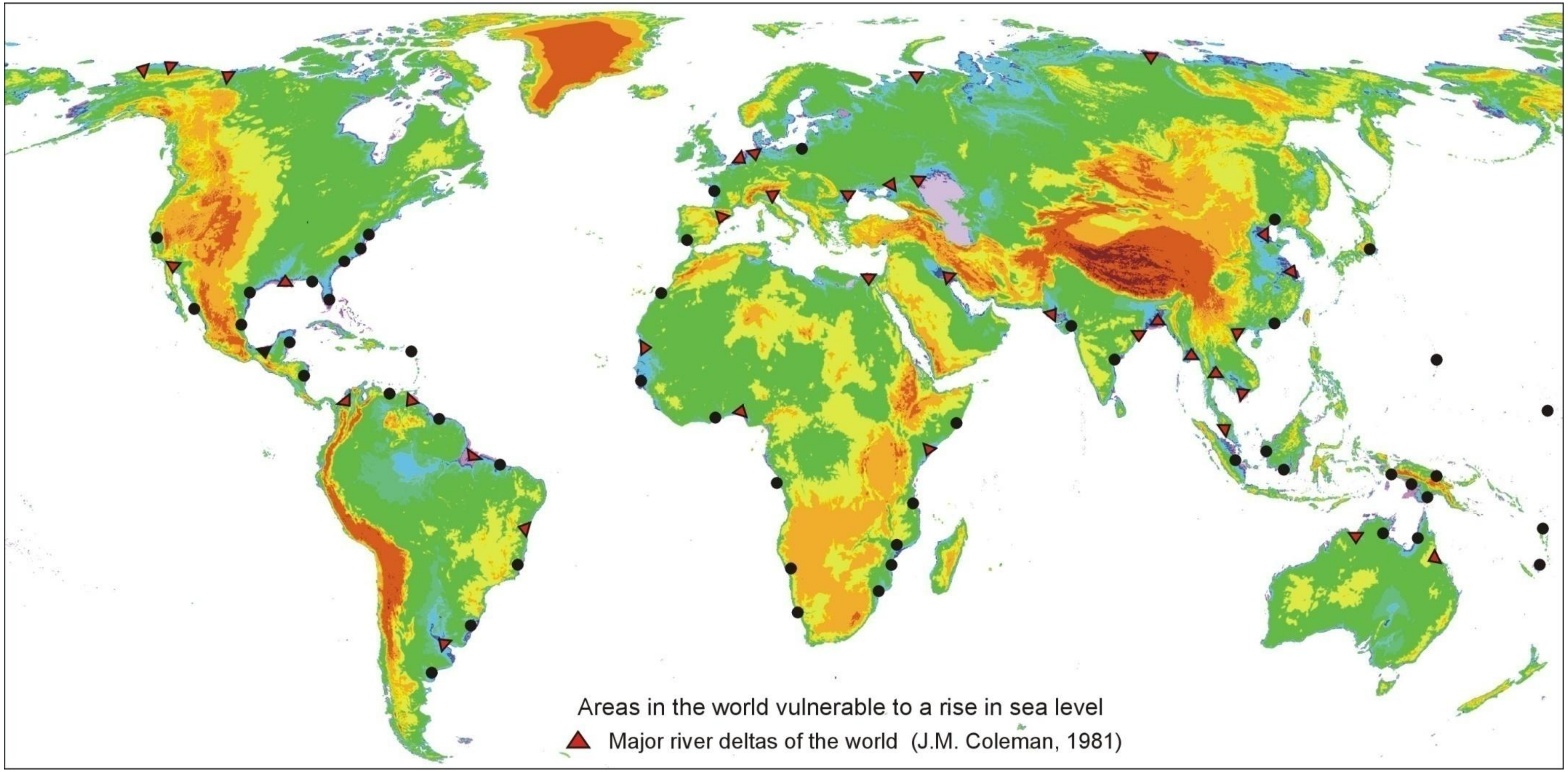


Regional distribution of Holocene Sea-level Changes



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

Areas vulnerable to sea level rise



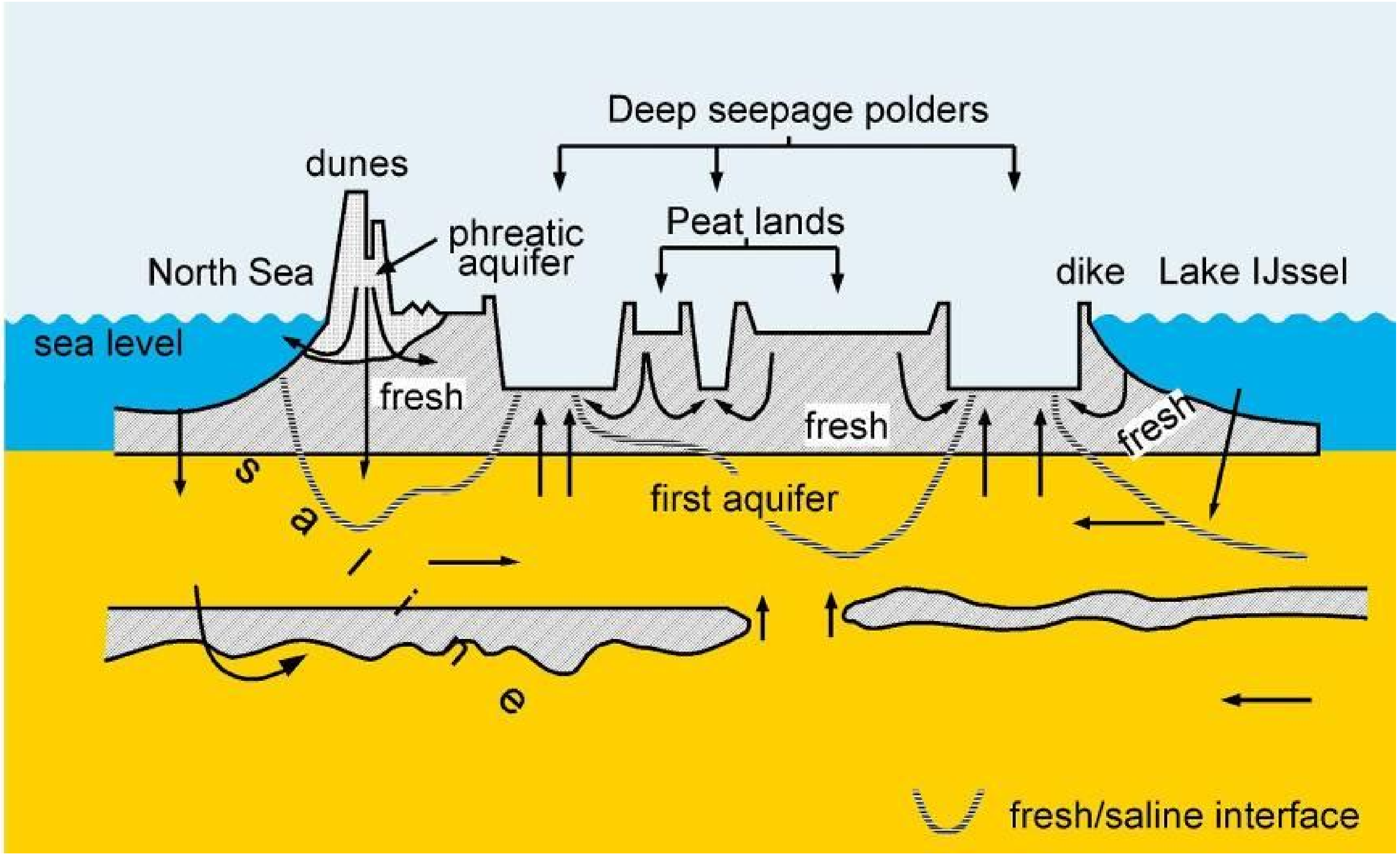
The Netherlands: low-lying lands

http://flood.firetree.net

~50km

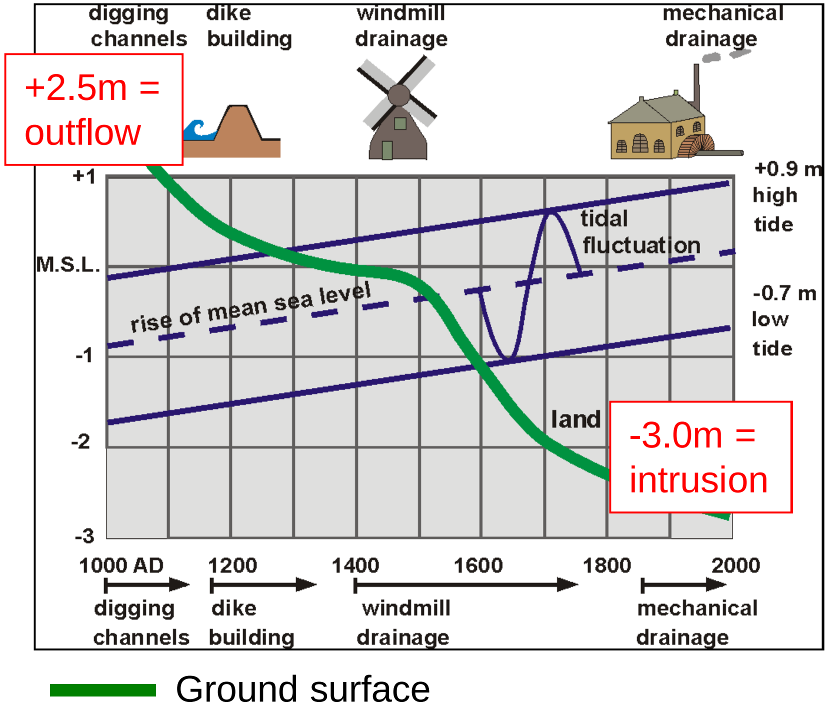
Saline seepage leads to:

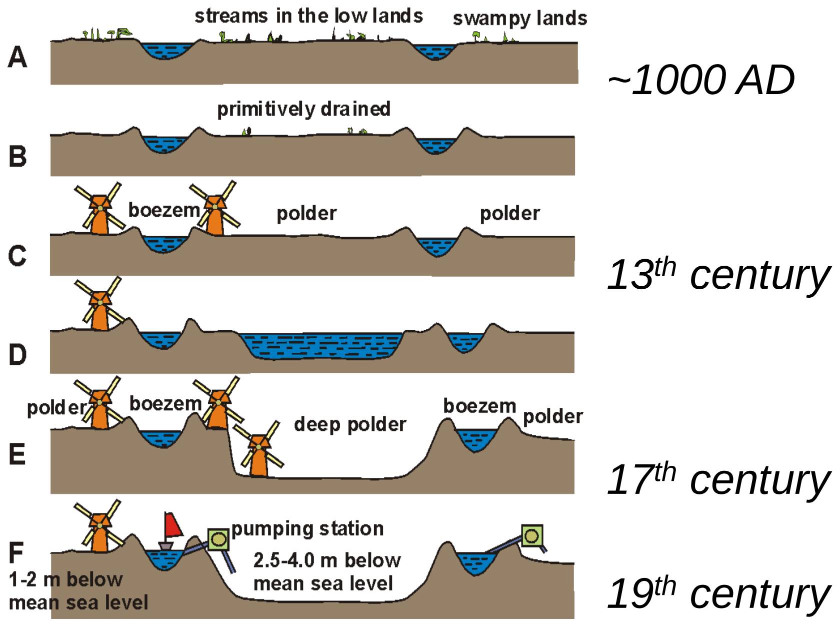
- Salinization and eutrophication of surface waters
- Salinization of shallow groundwater
- Salinization of root zone (crop damage)

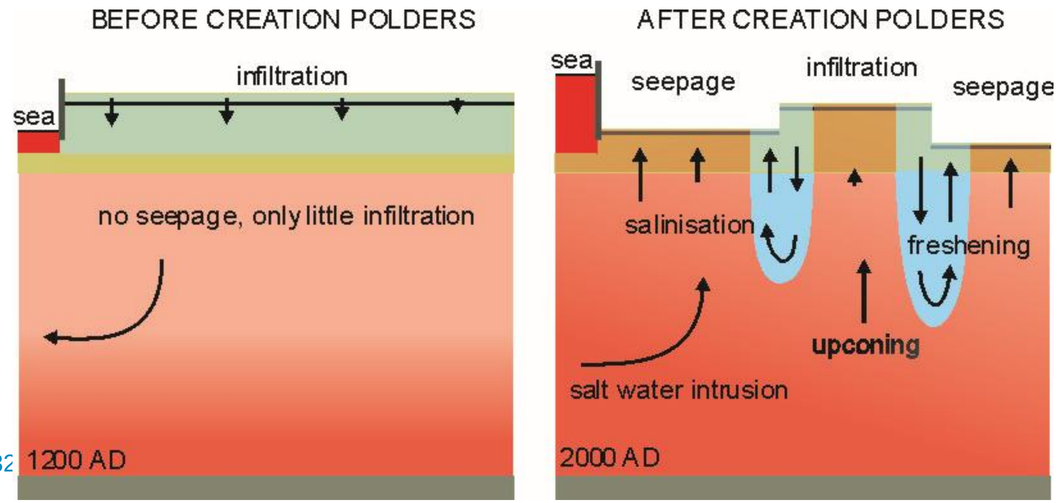


From fresh water outflow to salt water inflow

Historical subsidence of the ground surface in Holland

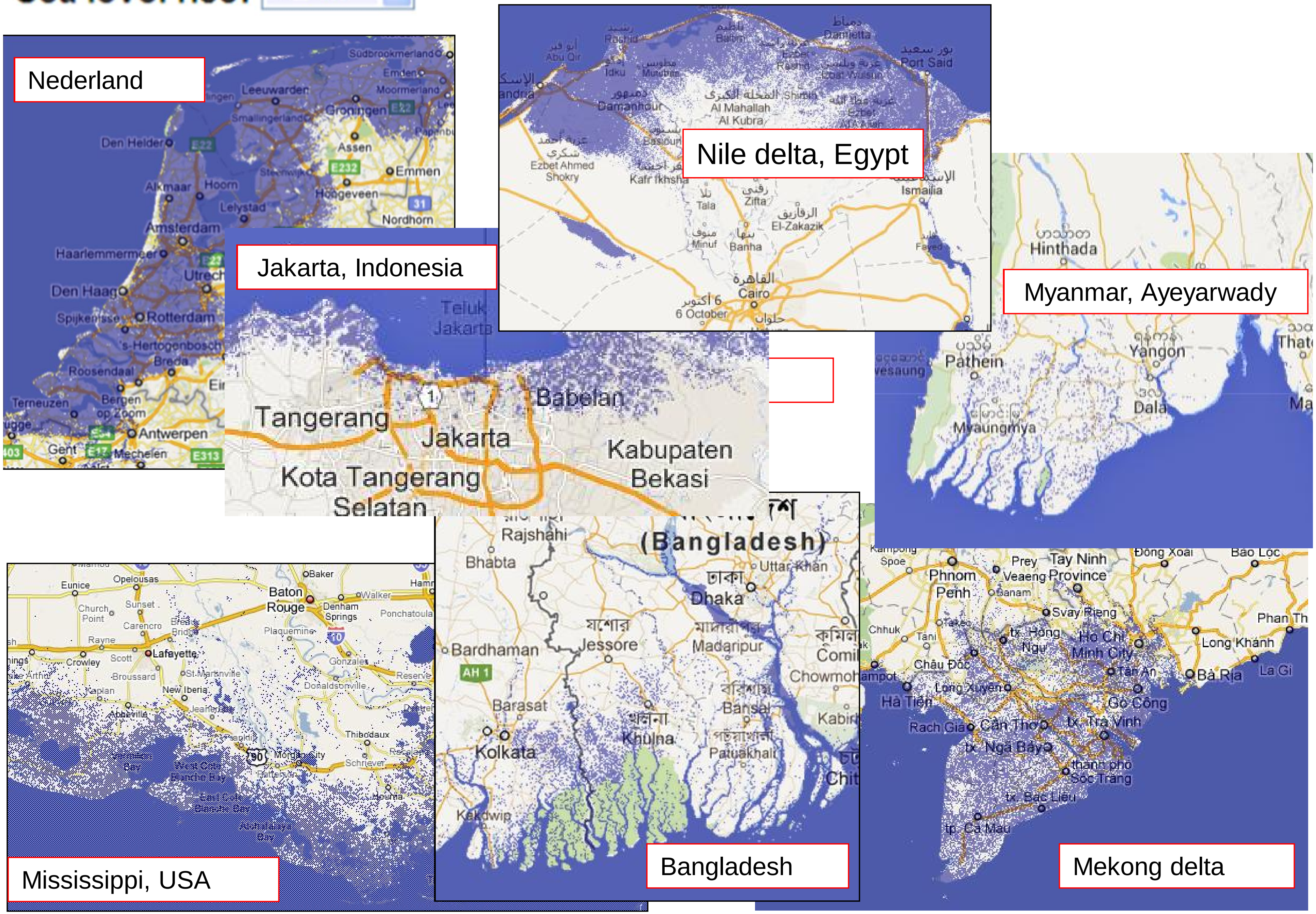


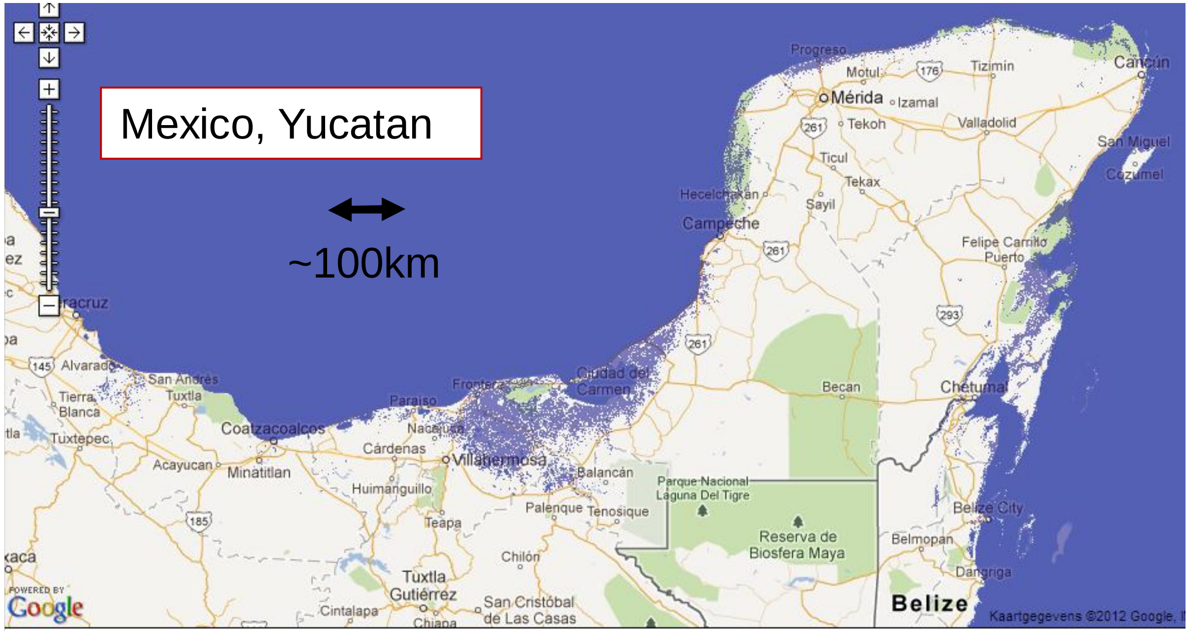




Sea level rise: +2 m

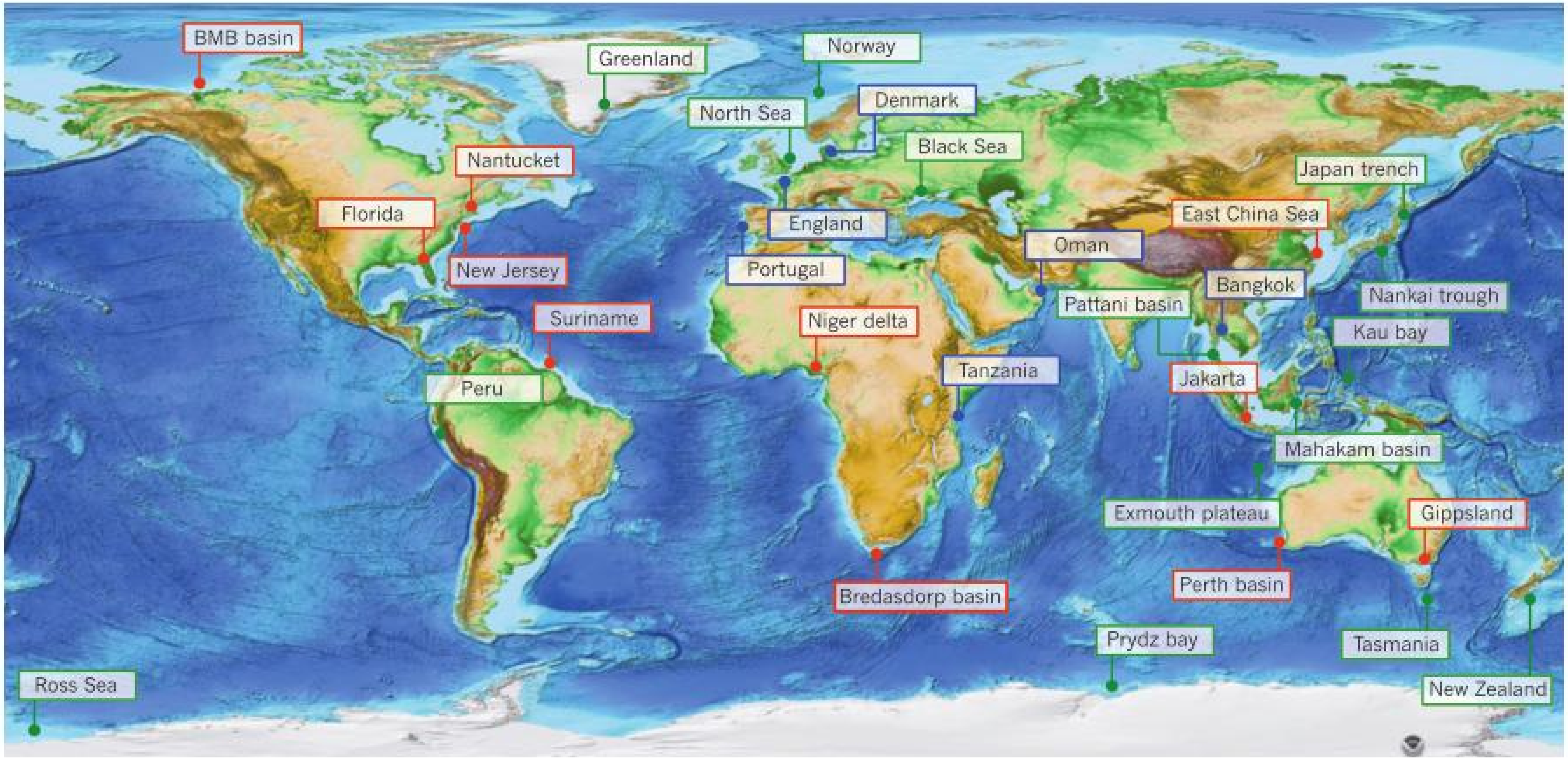
http://flood.firetree.net




Mexico, Yucatan
~100km
Progreso
Motul
Tizimín
Cancún
Mérida
Izamal
Tekoh
Valladolid
San Miguel
Cozumel
Ticul
Tekax
Hecelchakan
Sayil
Campeche
Felipe Carrillo
Puerto
Becan
Chetumal
Ciudad del
Carmen
Frontera
Paraiso
Alvarado
San Andrés
Tuxtla
Tierra
Blanca
Coatzacoalcos
Tuxtepec
Nacajuca
Cárdenas
Villahermosa
Acayucan
Minatitlán
Huimanguillo
Balancán
Parque Nacional
Laguna Del Tigre
Palenque
Tenosique
Teapa
Reserva de
Biosfera Maya
Belize City
Belmopan
Chilón
Tuxtla
Gutiérrez
San Cristóbal
de Las Casas
Cintalapa
Dangriga
Belize
Kaartgegevens ©2012 Google
POWERED BY
Google

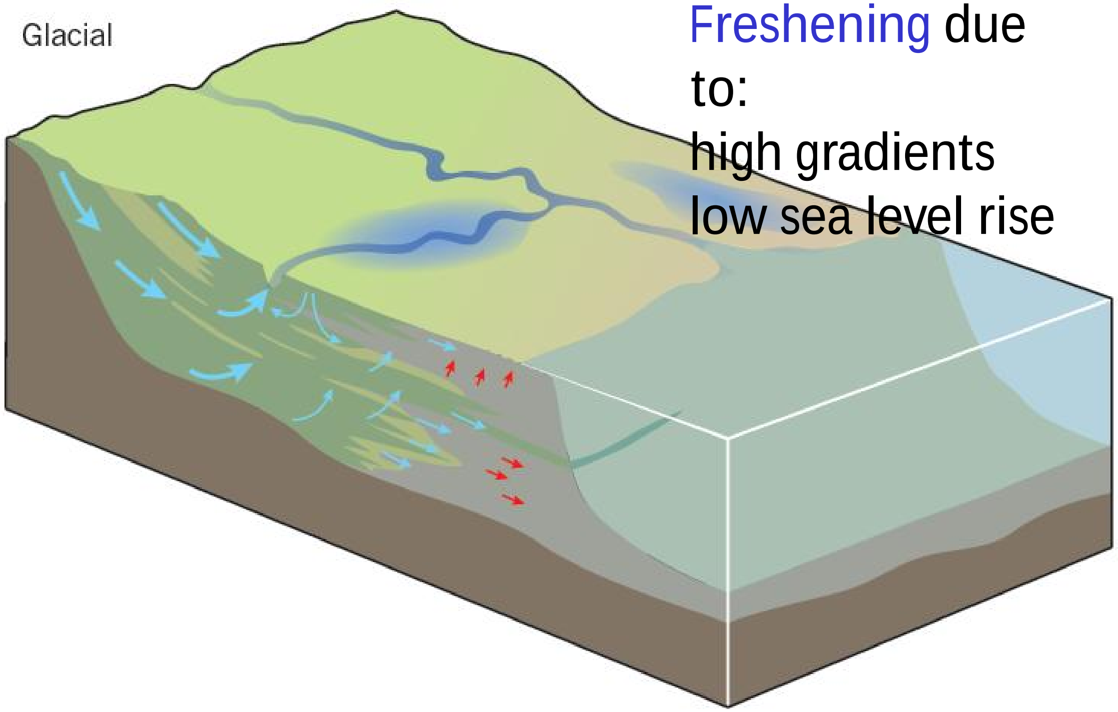

Po Delta, Italia
Como
Lecco
Riva del
Garda
Bassano
del Grappa
Conegliano
Vrtojba
Cantù
Bergamo
Sarezzo
Schio
Montebelluna
Castelfranco
Veneto
Saronno
Seregno
Dalmine
Valdagno
Treviso
San Donà
di Piave
Trieste
Koper
Monza
Brescia
Vicenza
Milano
Treviglio
Chiari
Rezzato
Bussolengo
San
Bonifacio
Mestre
Venezia
Lido di
Jesolo
Piran
Izola
Umag
Crema
Verona
Padova
Lodi
Mira
Vigevano
Chioggia
Cavarzere
Rovigo
Adria
Pavia
Cremona
Piacenza
Poreč
Rovinj
Voghera
Porto Tolle
Mesola
Pula
Tortona
Fidenza
Parma
Mirandola
Ferrara
Carpi
Novi Ligure
Collecchio
Reggio
nell'Emilia
Cento
Comacchio
Modena
Fornovo
di Taro
Scandiano
Formigine
Argenta
Lido di
Spina
Borgo Val
di Taro
Sassuolo
Bologna
Genova
Rapallo
Lugo
Ravenna
Chiavari
Imola
Cervia
Faenza
Google
Kaartgegevens ©2012 Google, Tele Atlas

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

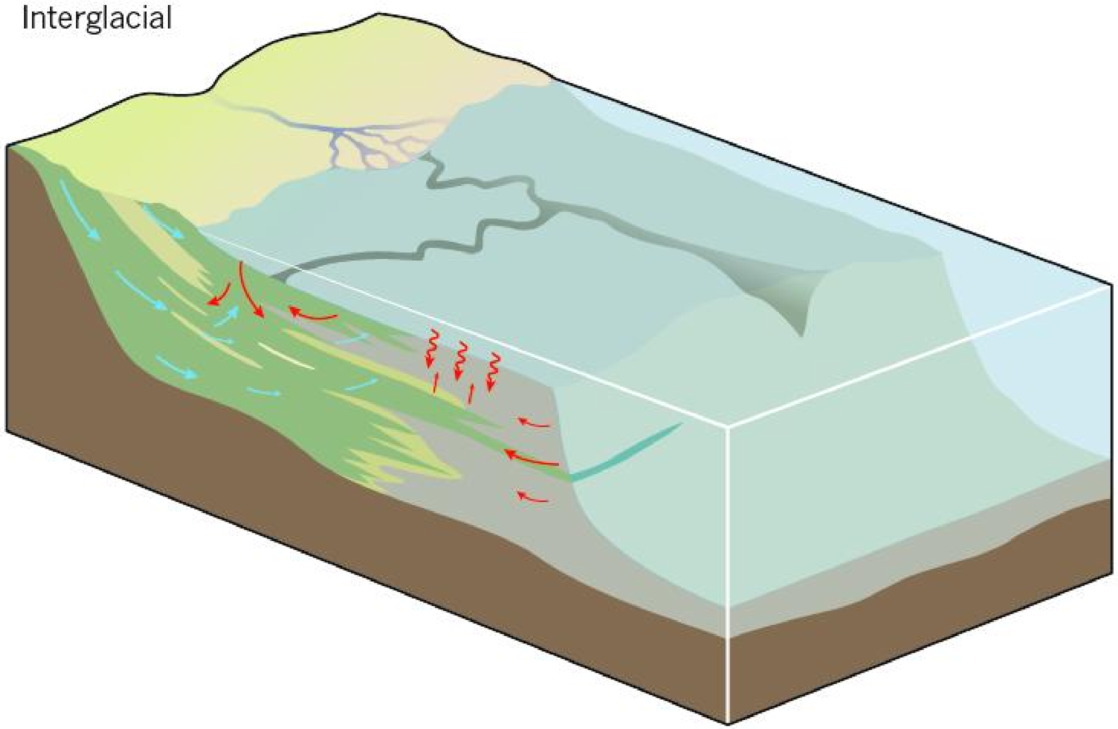


Post et al., Nature, 2013

Genesis
and preservation



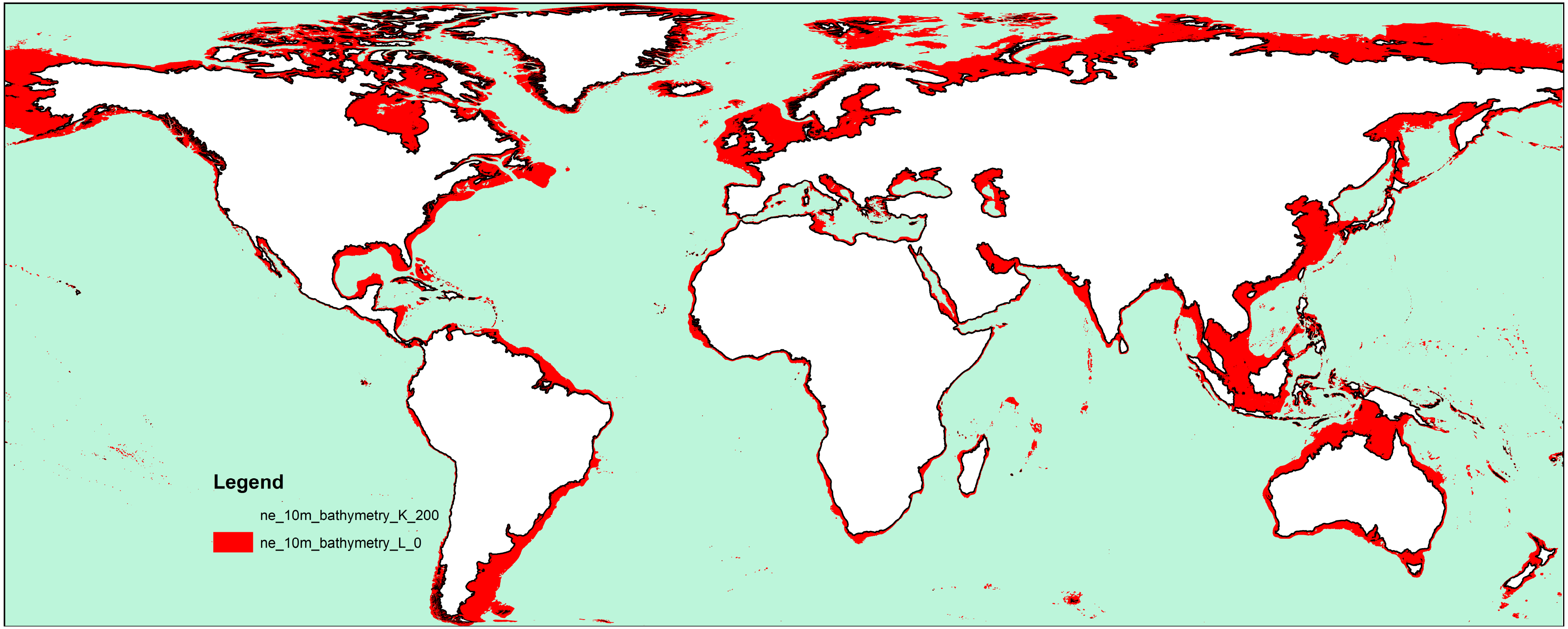
Freshening due to:
high gradients
low sea level rise



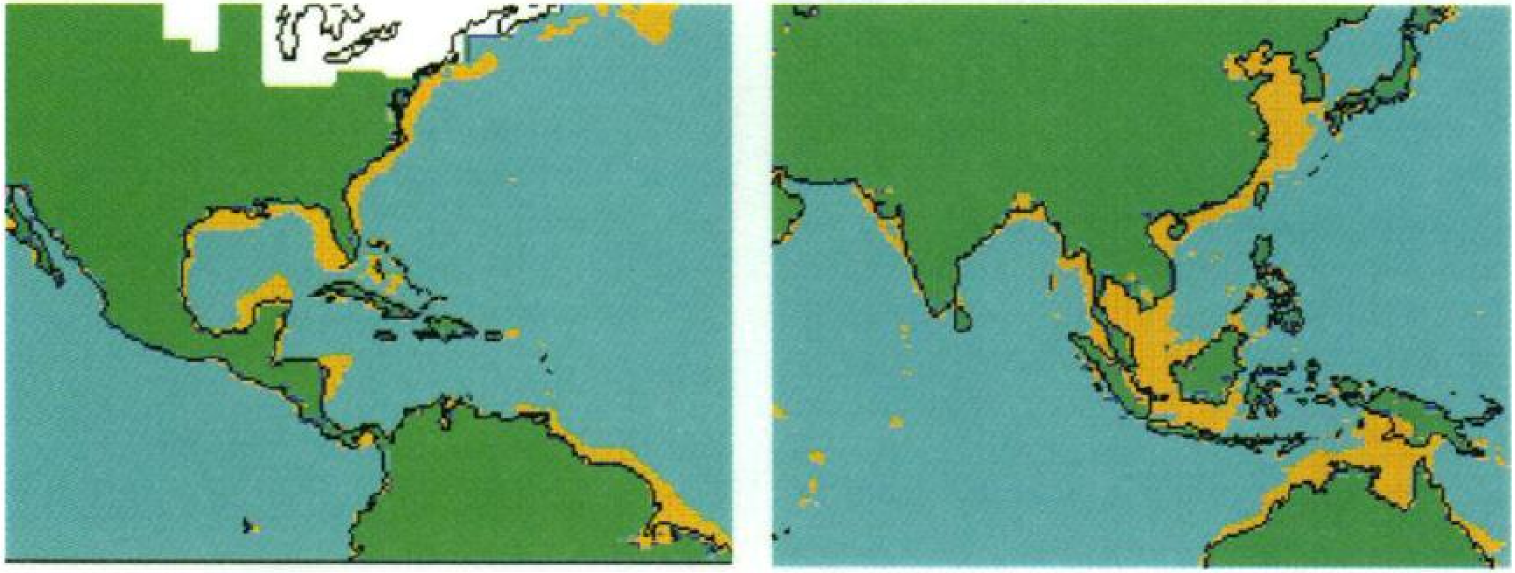
Salinisation due to:
marine transgression
and vertical inflow of
saline surface water

Source: Nature, 2013

Possible locations of offshore (submarine) groundwater

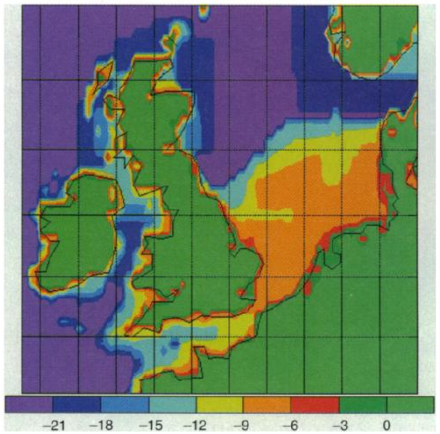


Coastal zone cases around the world
Occurrence related to dynamic sea-levels and coastlines

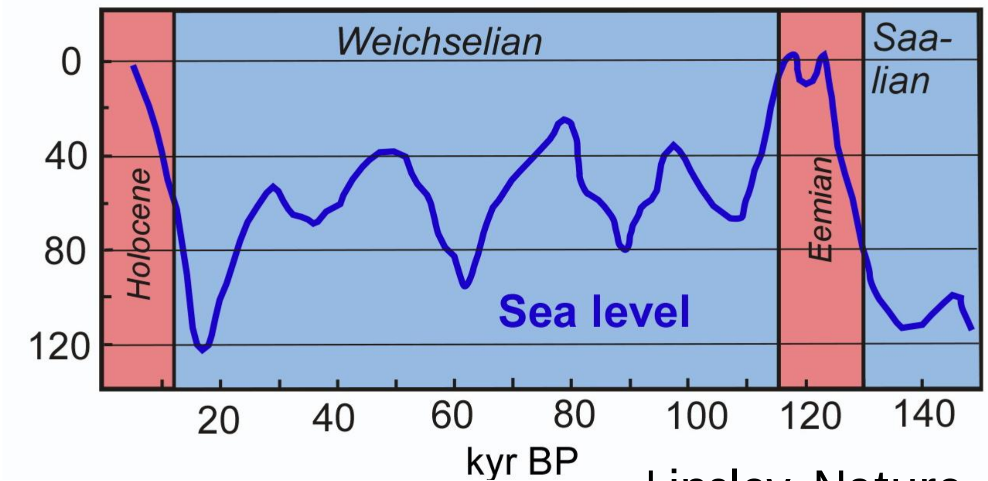


Exposed continental shelves

Peltier, *Science*, 1994

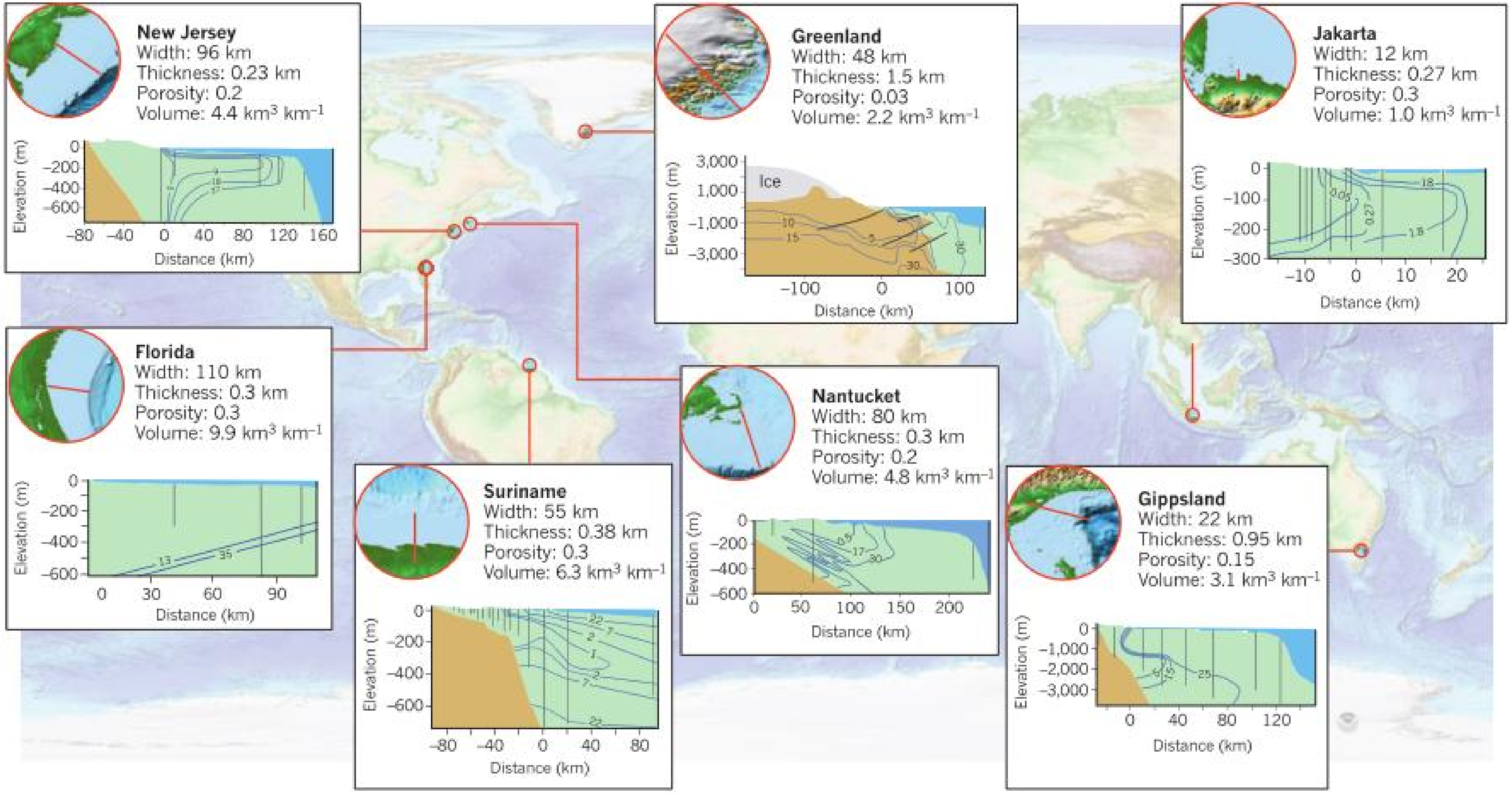


Inundated (kyr BP)



Linsley, Nature, 1996

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

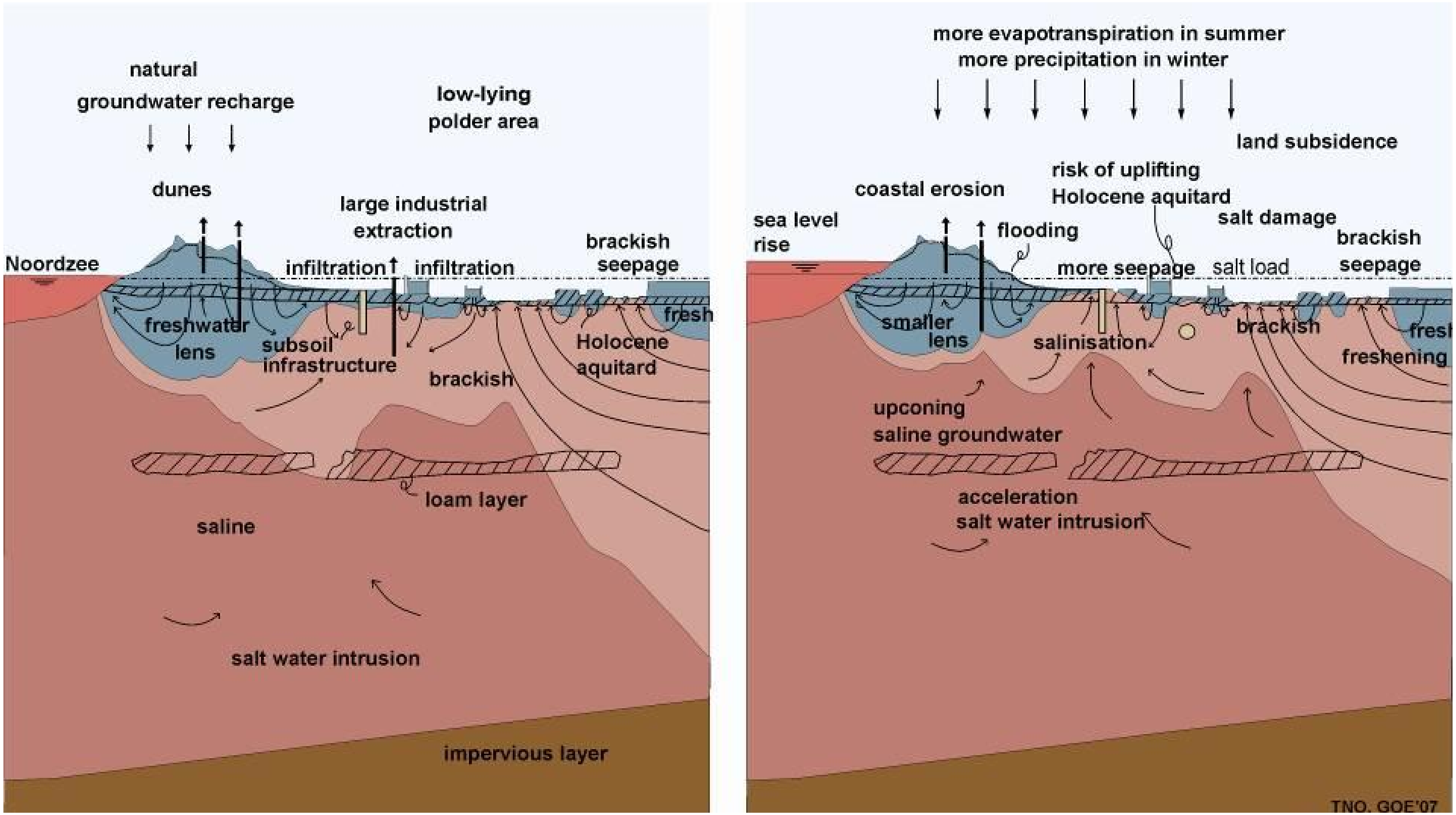


My first density dependent groundwater flow and solute transport model in 1990!

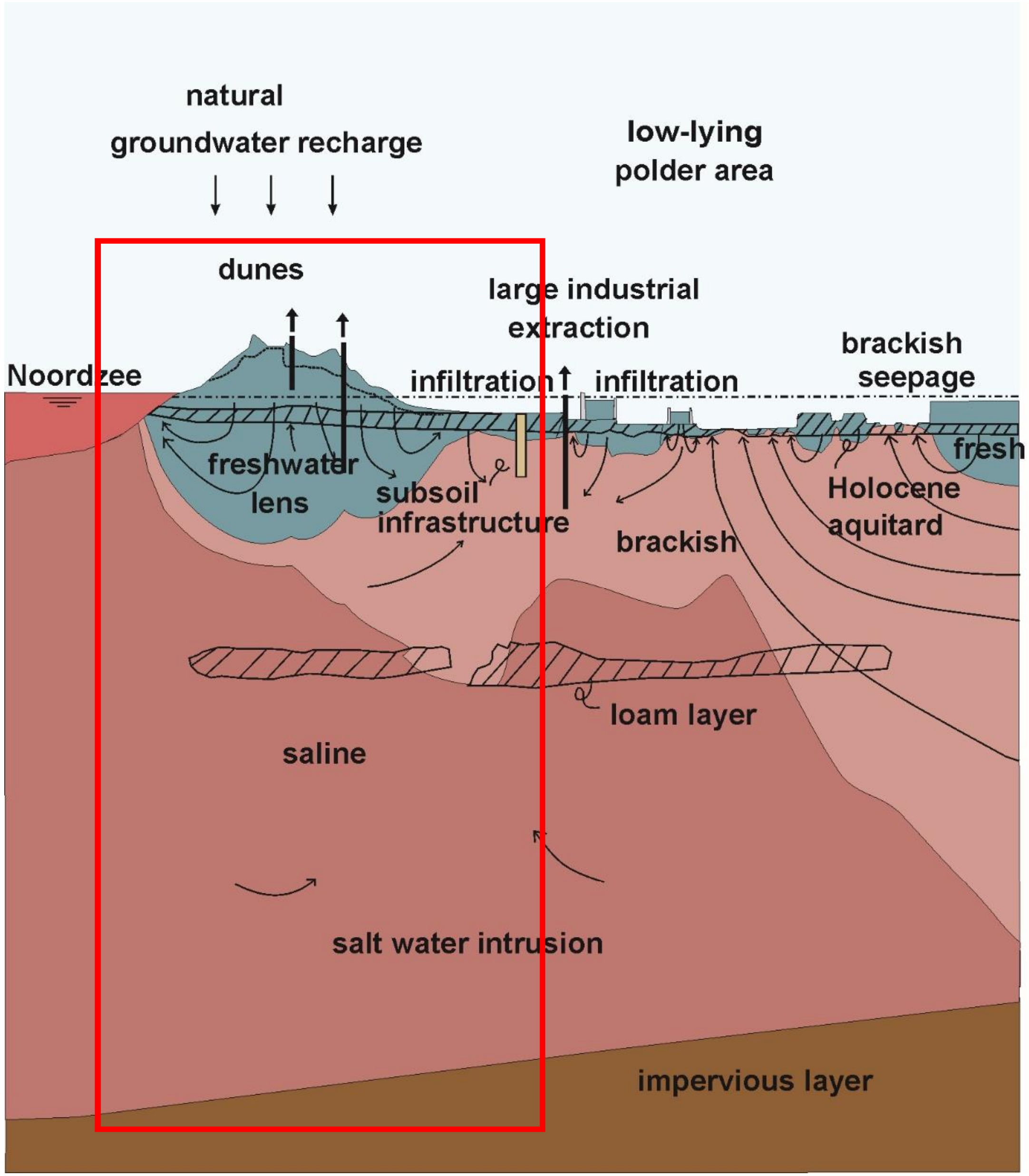
The Dutch groundwater system under stress

Present processes

Future changes

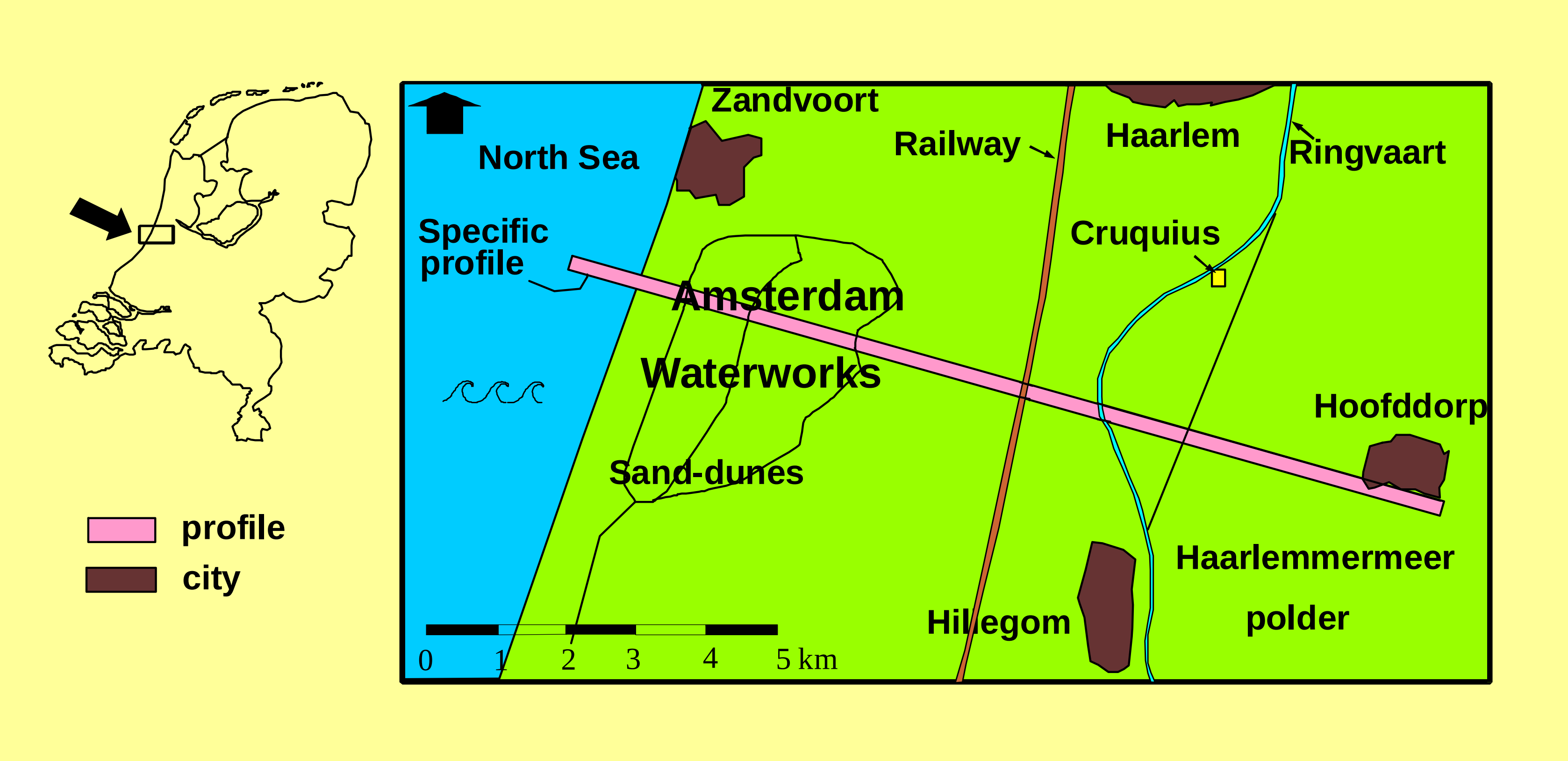


Saltwater intrusion in the Netherlands



Saltwater intrusion in the Dutch coastal zone

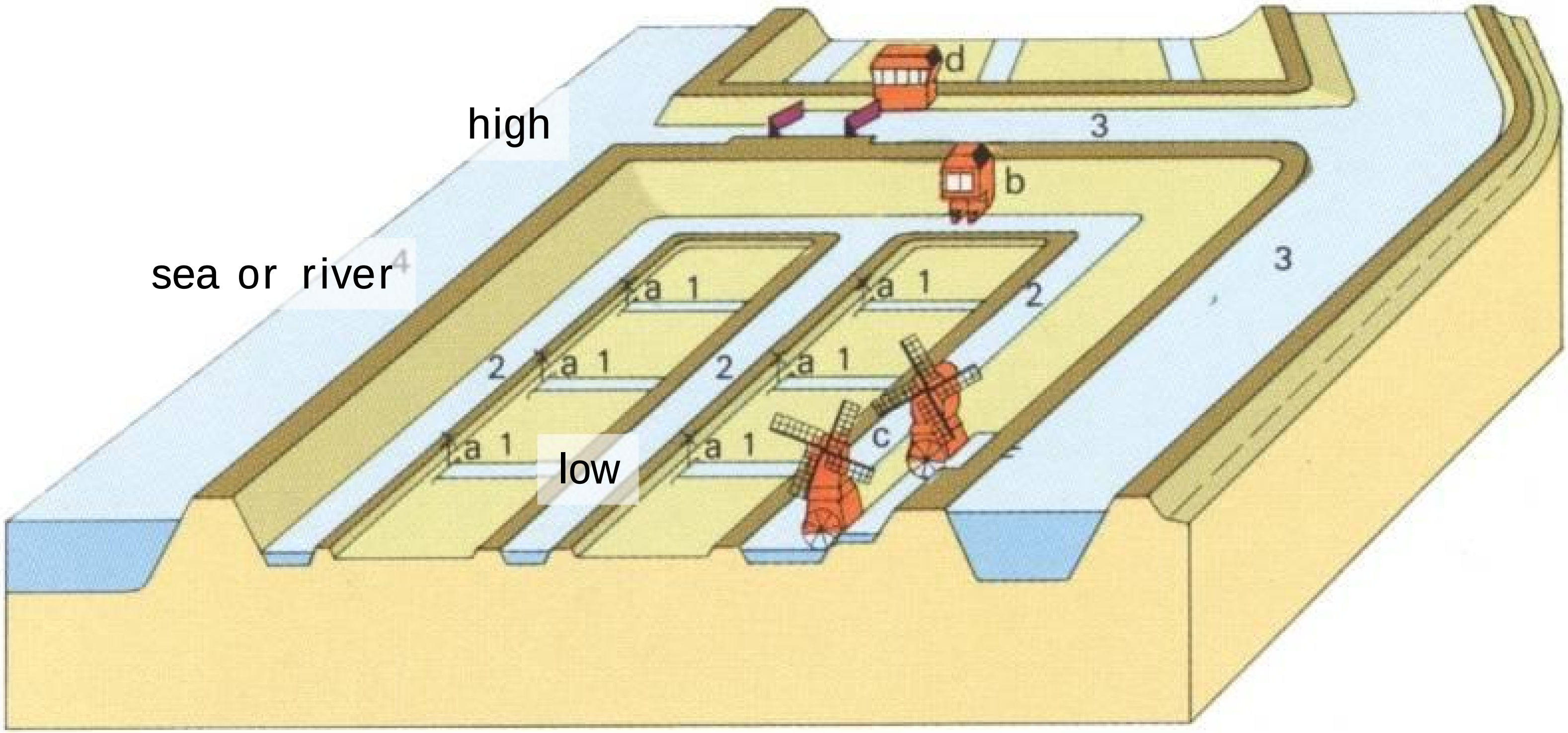
Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



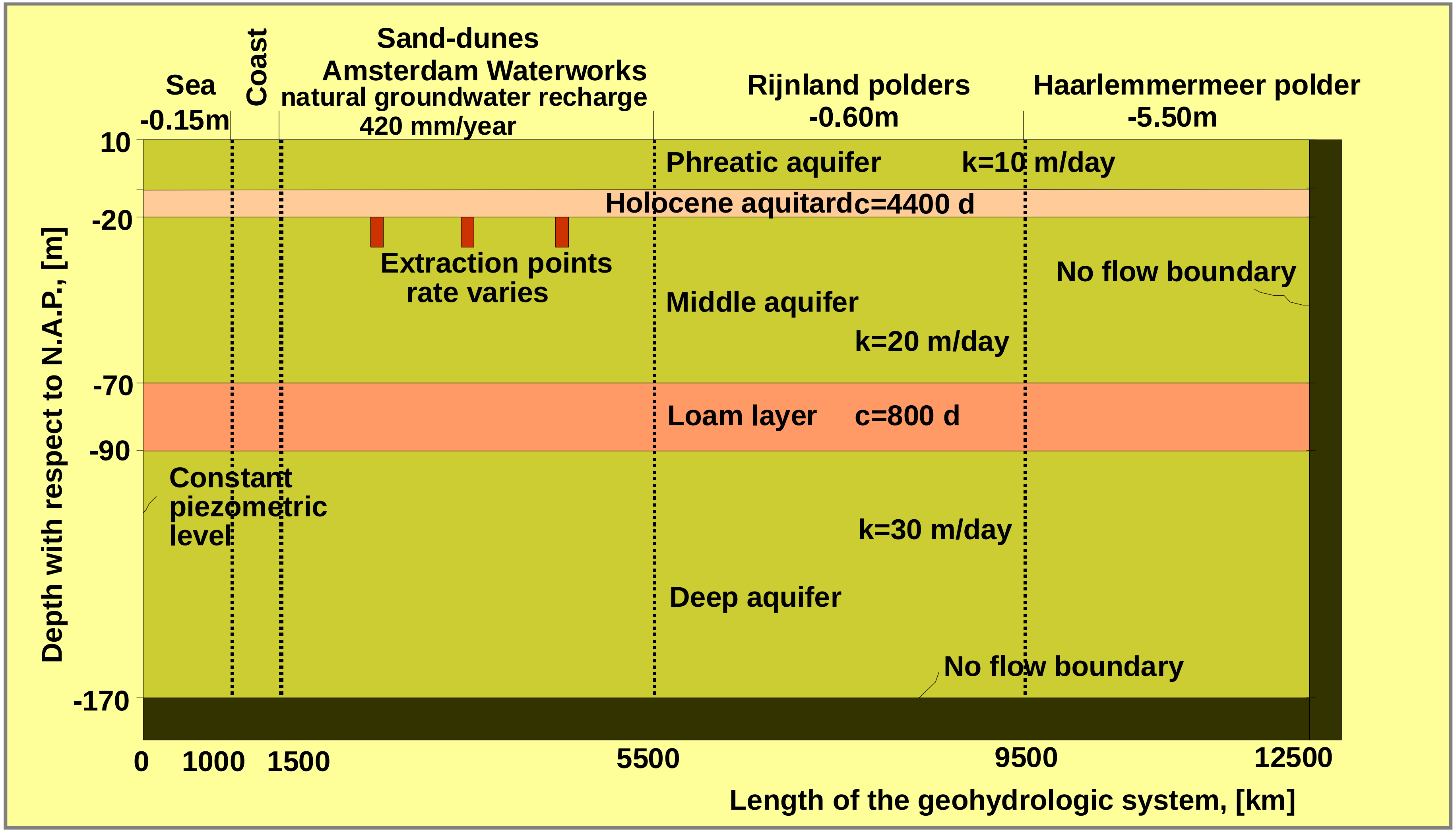
The polder system

A polder is:

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

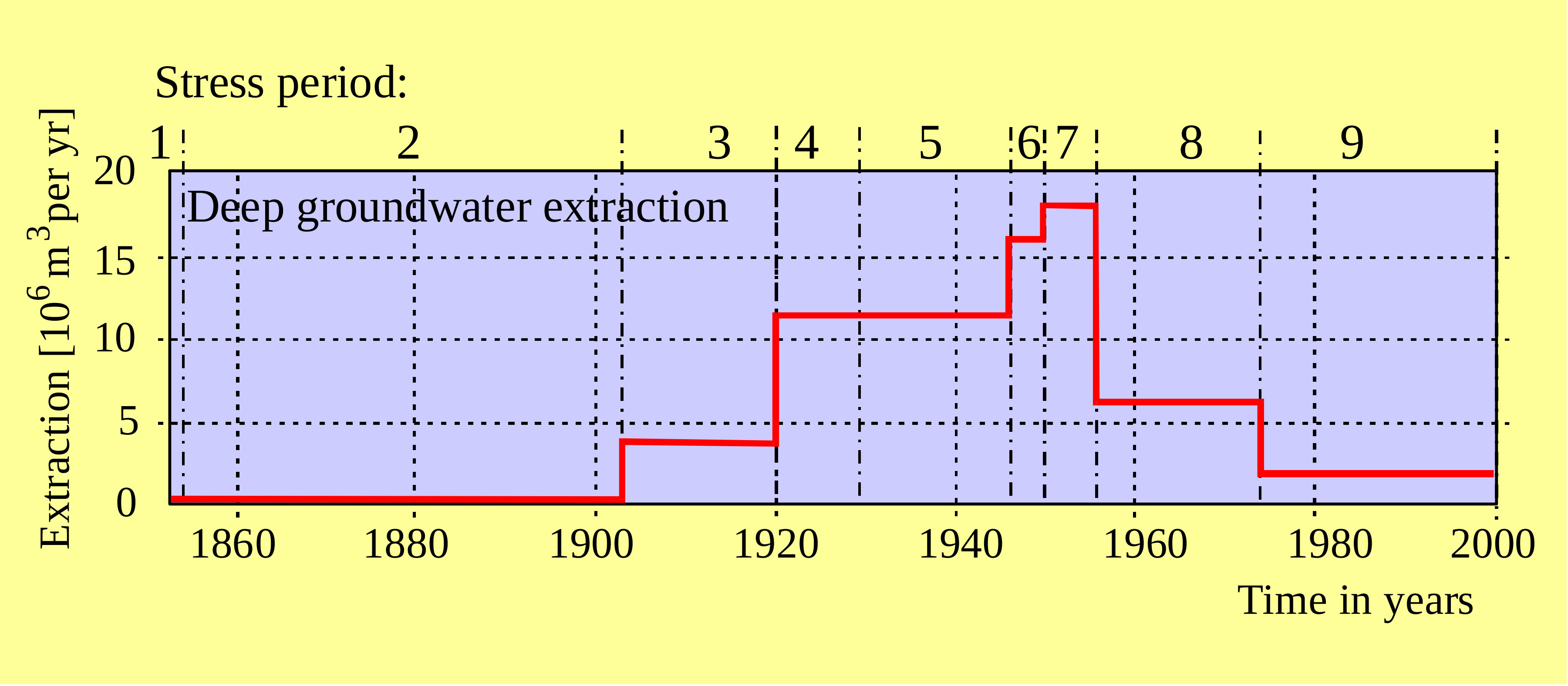


Geometry, subsoil parameters, boundary conditions

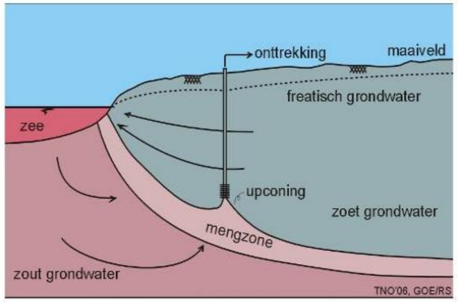


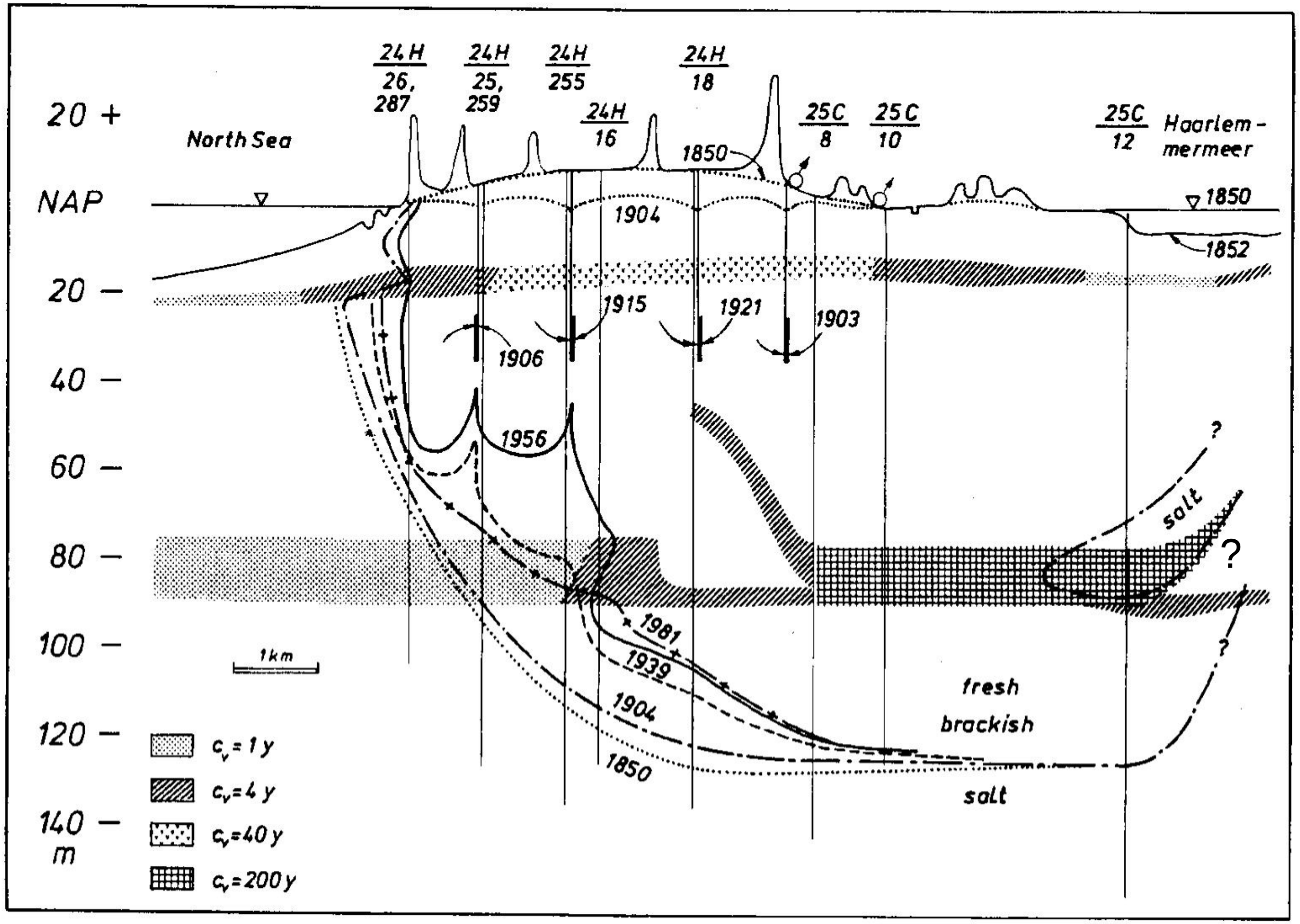
Saltwater intrusion in the Dutch coastal zone

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



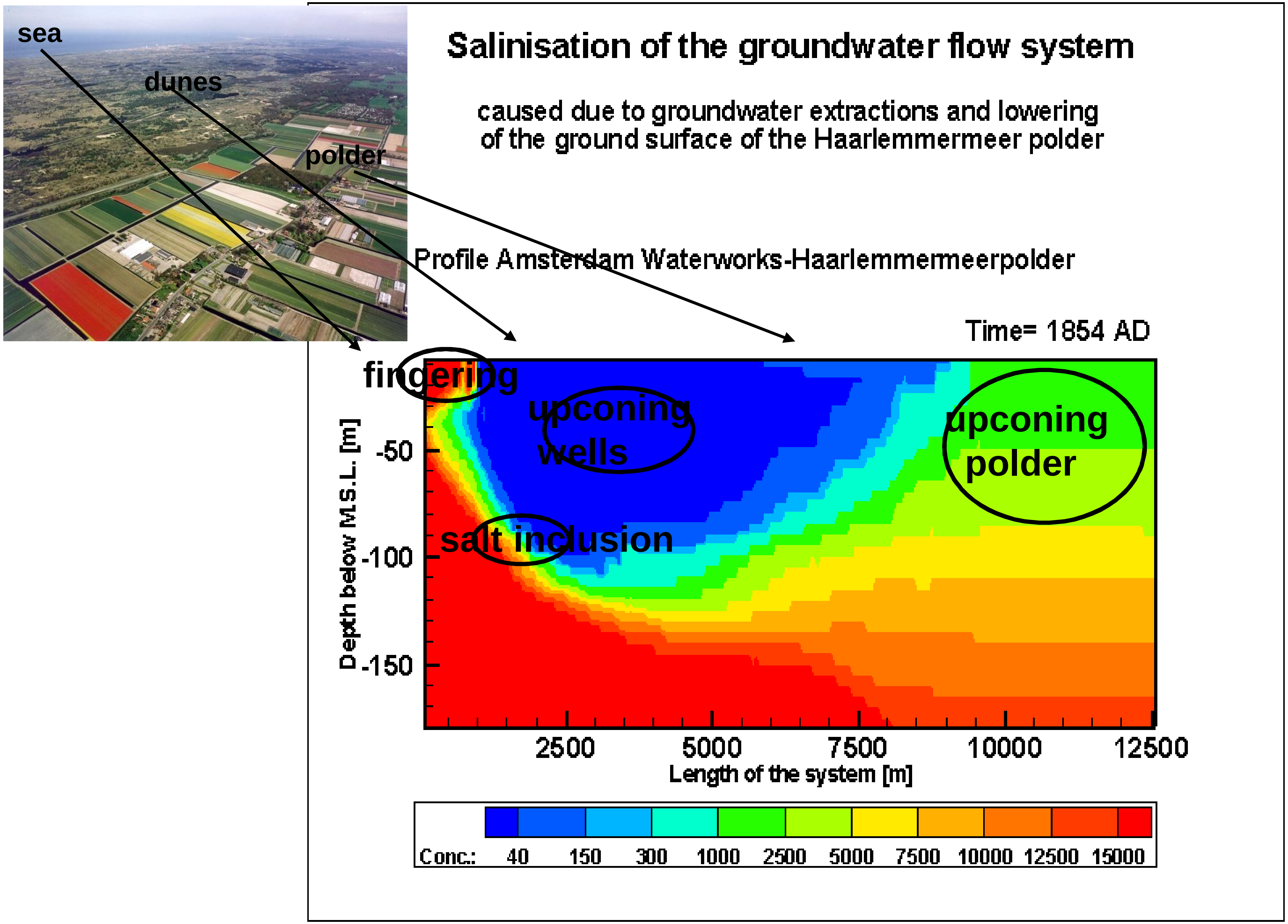
Upconing of brackish-saline groundwater



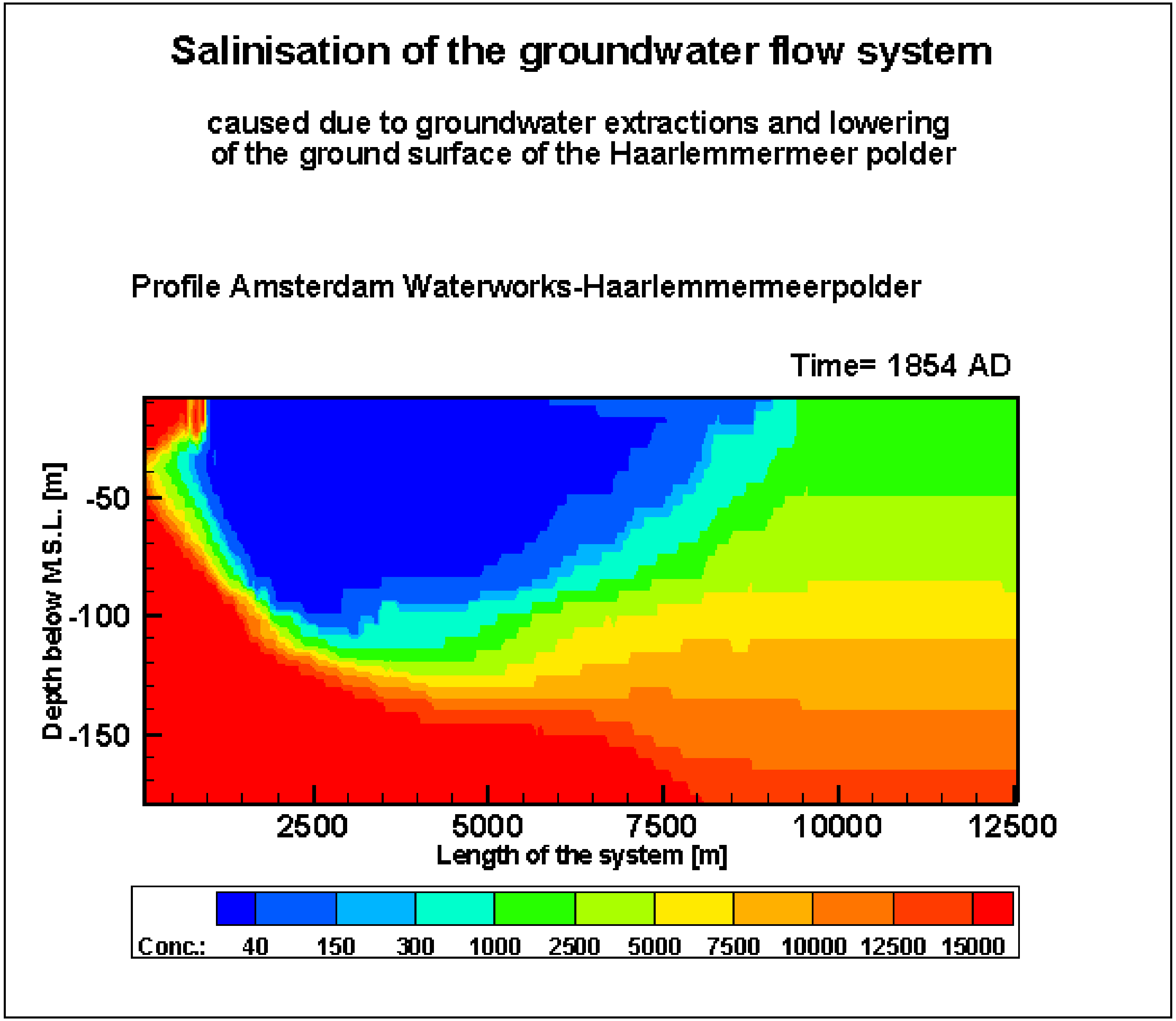


Stuyfzand, 1993

Saltwater intrusion in the Dutch coastal zone



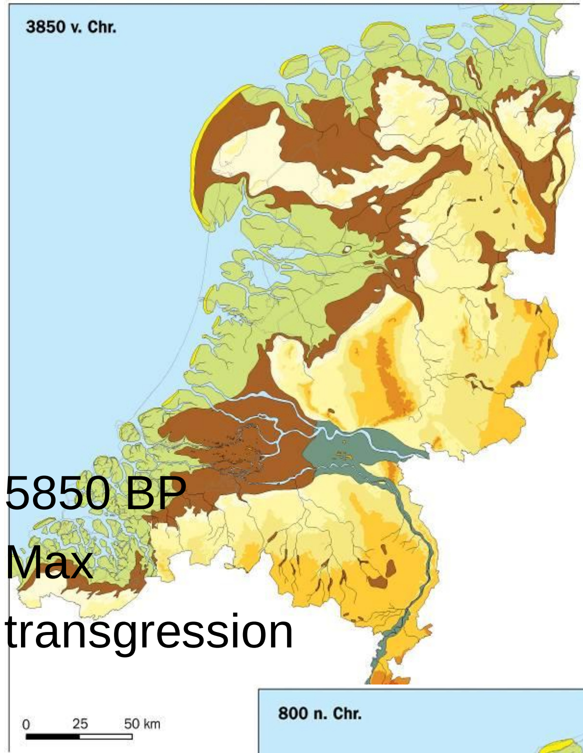
Saltwater intrusion in the Dutch coastal zone



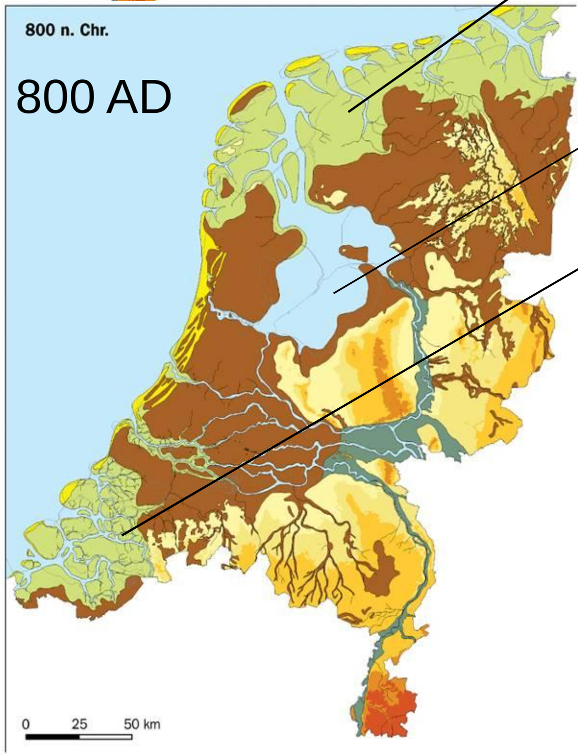
Palaeo hydrogeological modelling

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

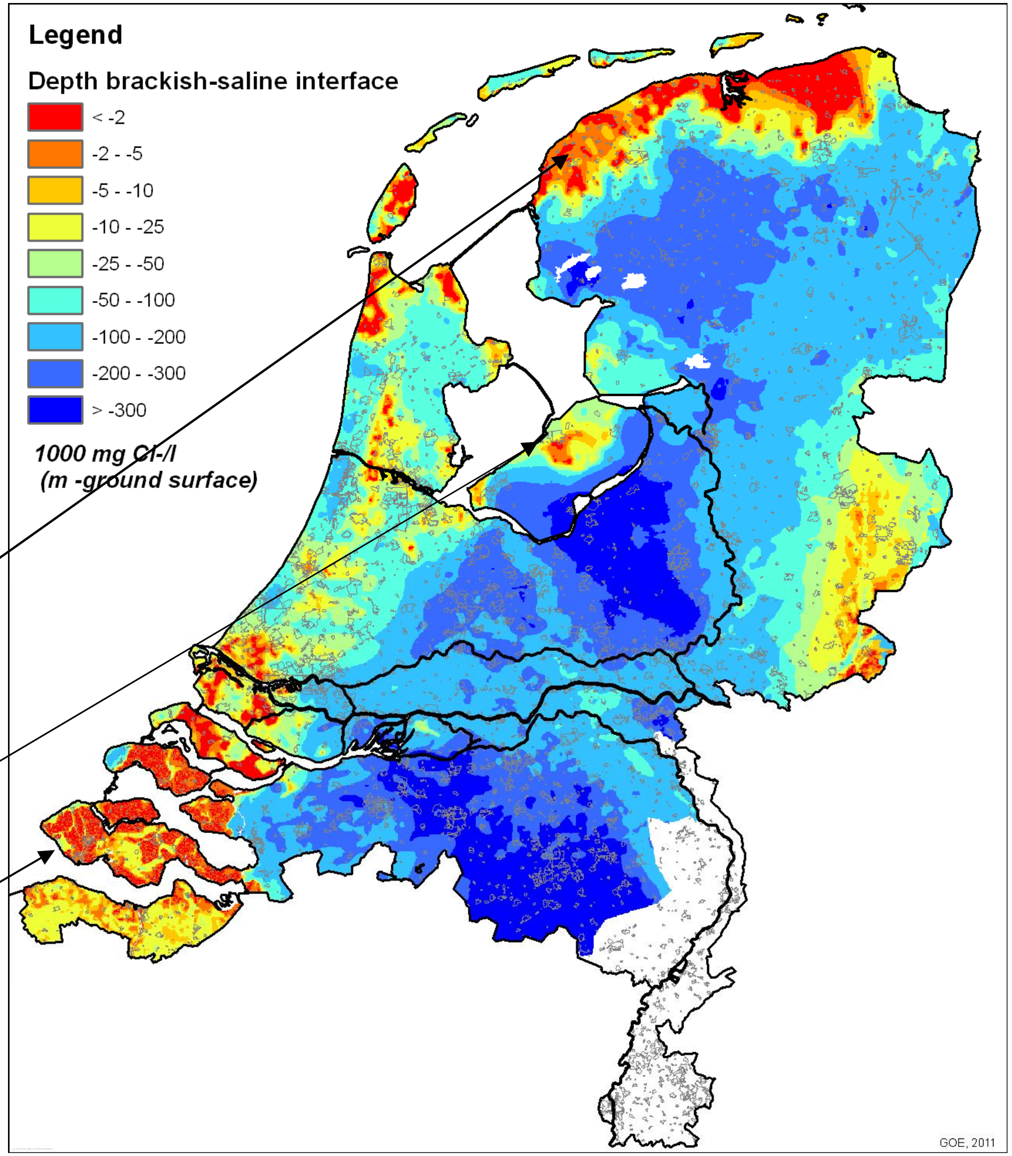
J.R. Delsman, K. Hu-a-ng, P.C. Vos, P.G.B. de Louw, G.H.P. Oude Essink and M.F.P. Bierkens



5850 BP
Max
transgression



800 AD



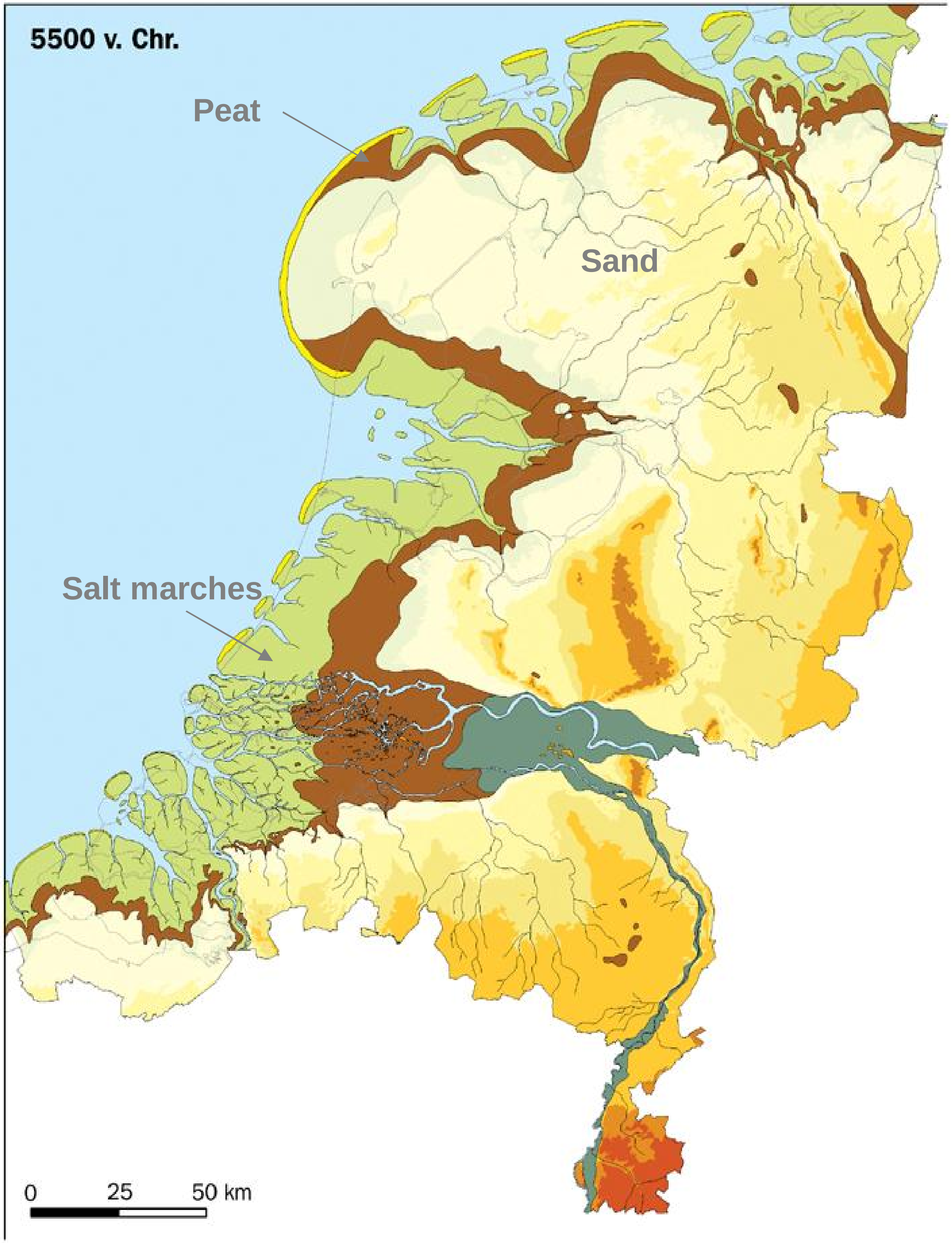
Based on:

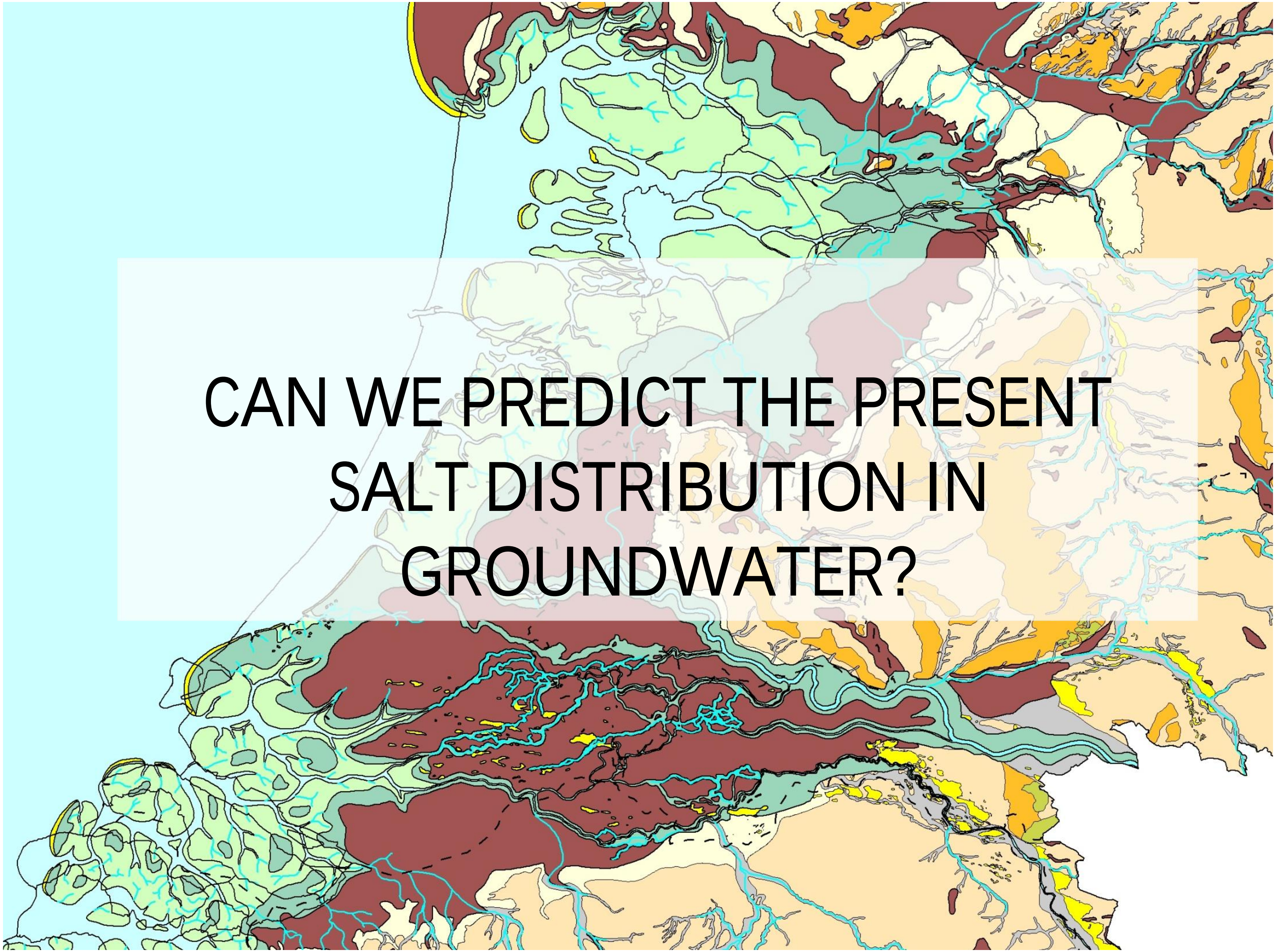
- Analyses
- VES
- Borehole measurement

The Holocene transgressions

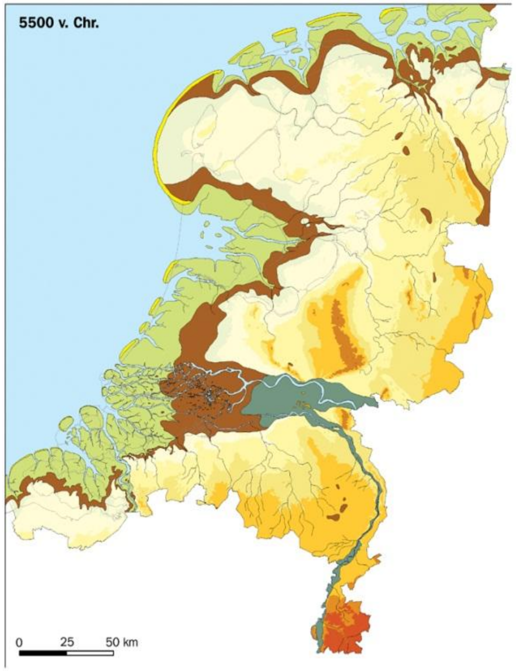
Major impact on present regional brackish groundwater systems

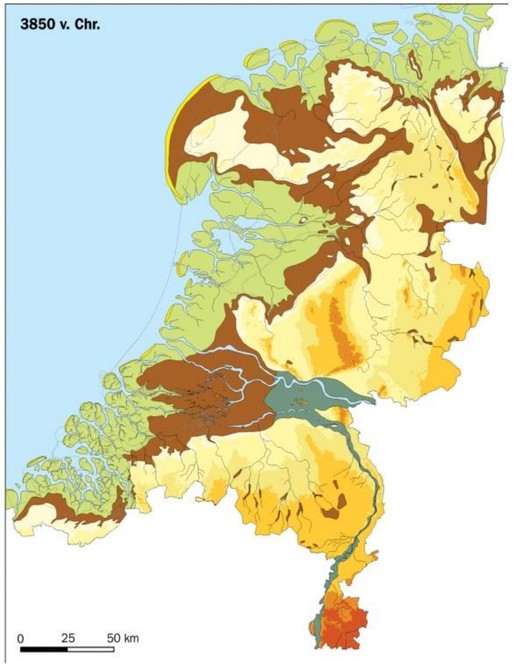
7500 BP

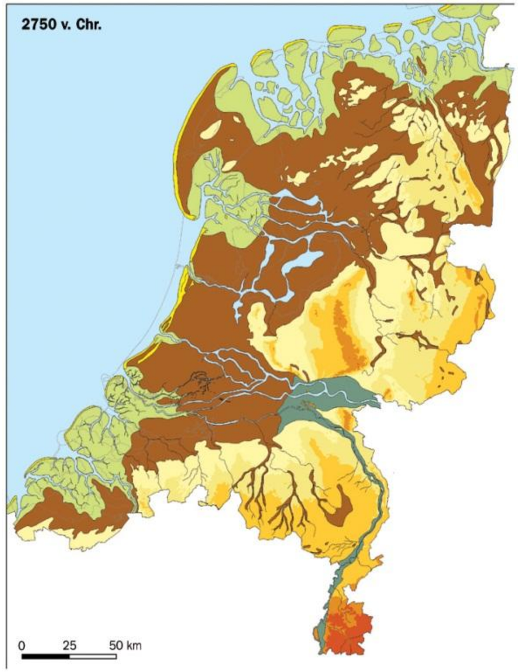


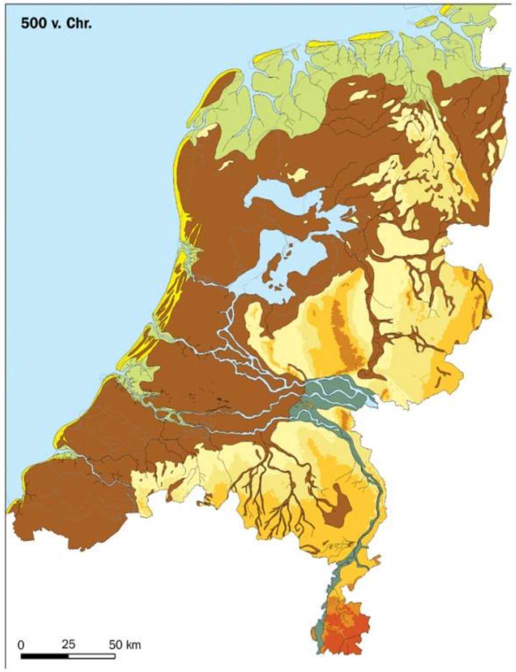


CAN WE PREDICT THE PRESENT SALT DISTRIBUTION IN GROUNDWATER?


5500 v. Chr.
0
25
50 km


3850 v. Chr.
0
25
50 km


2750 v. Chr.
0
25
50 km

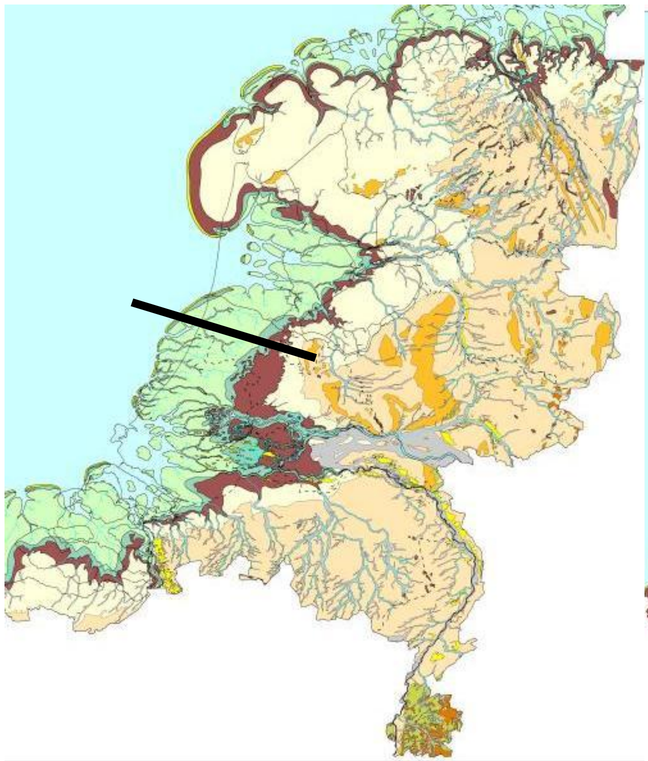

500 v. Chr.
0
25
50 km


50 n. Chr.
0
25
50 km


800 n. Chr.
0
25
50 km

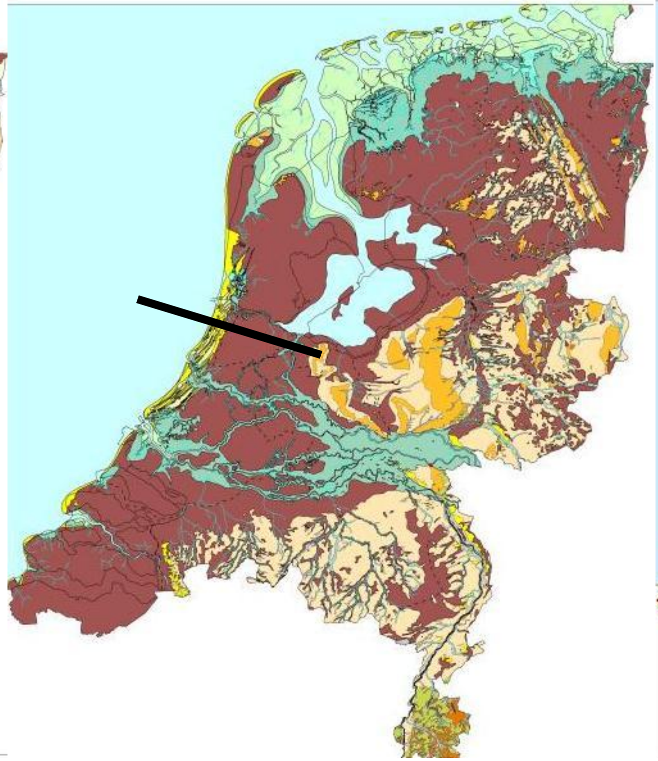
Palaeogeographical development

5500 BC



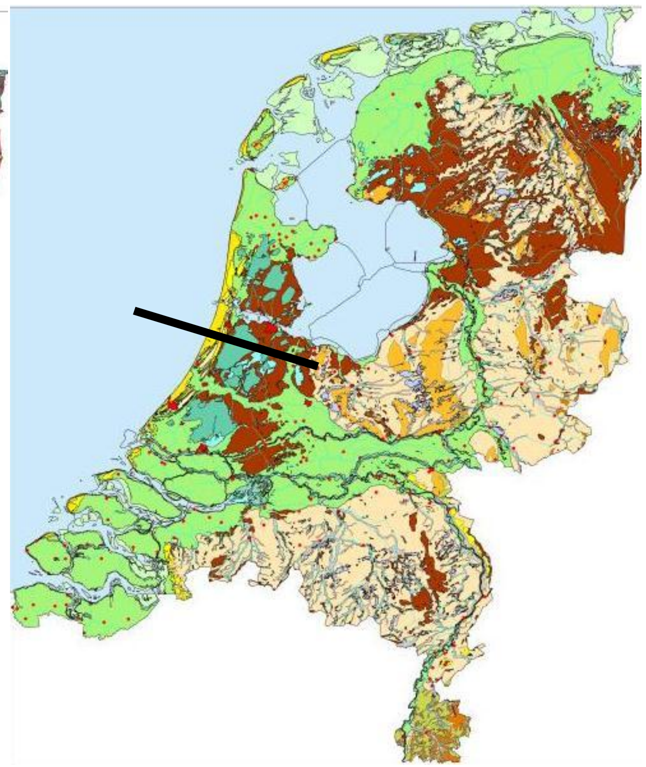
Maximal transgression

100 AD



Peat development

1850 AD



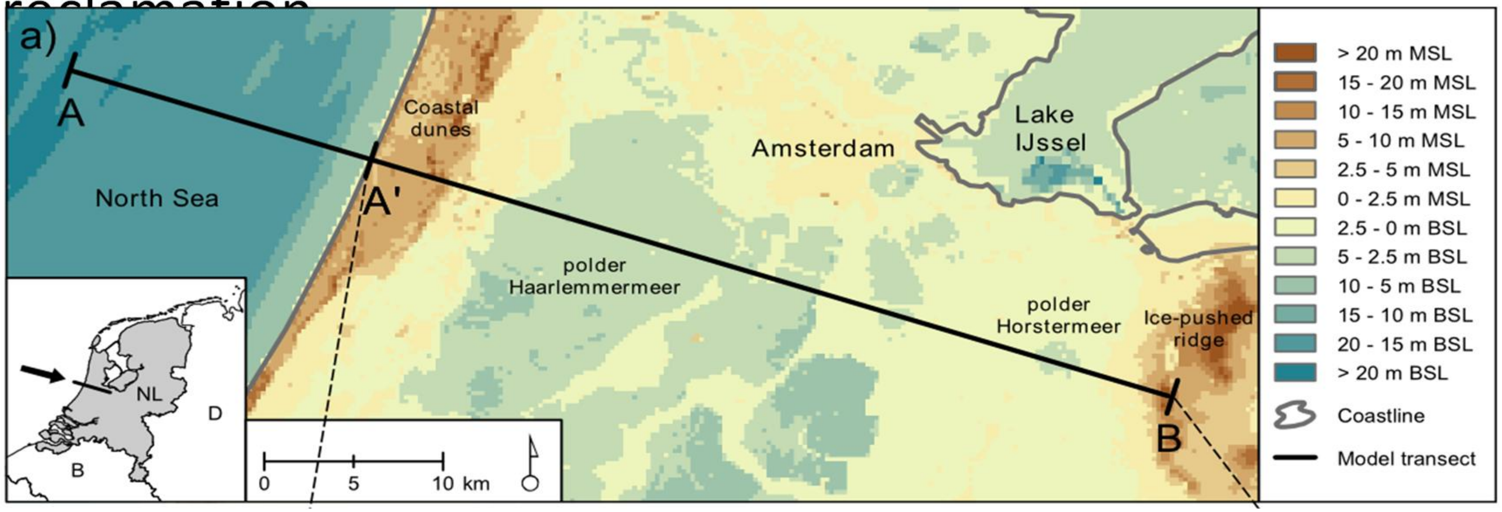
Reclaimed land, polder

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

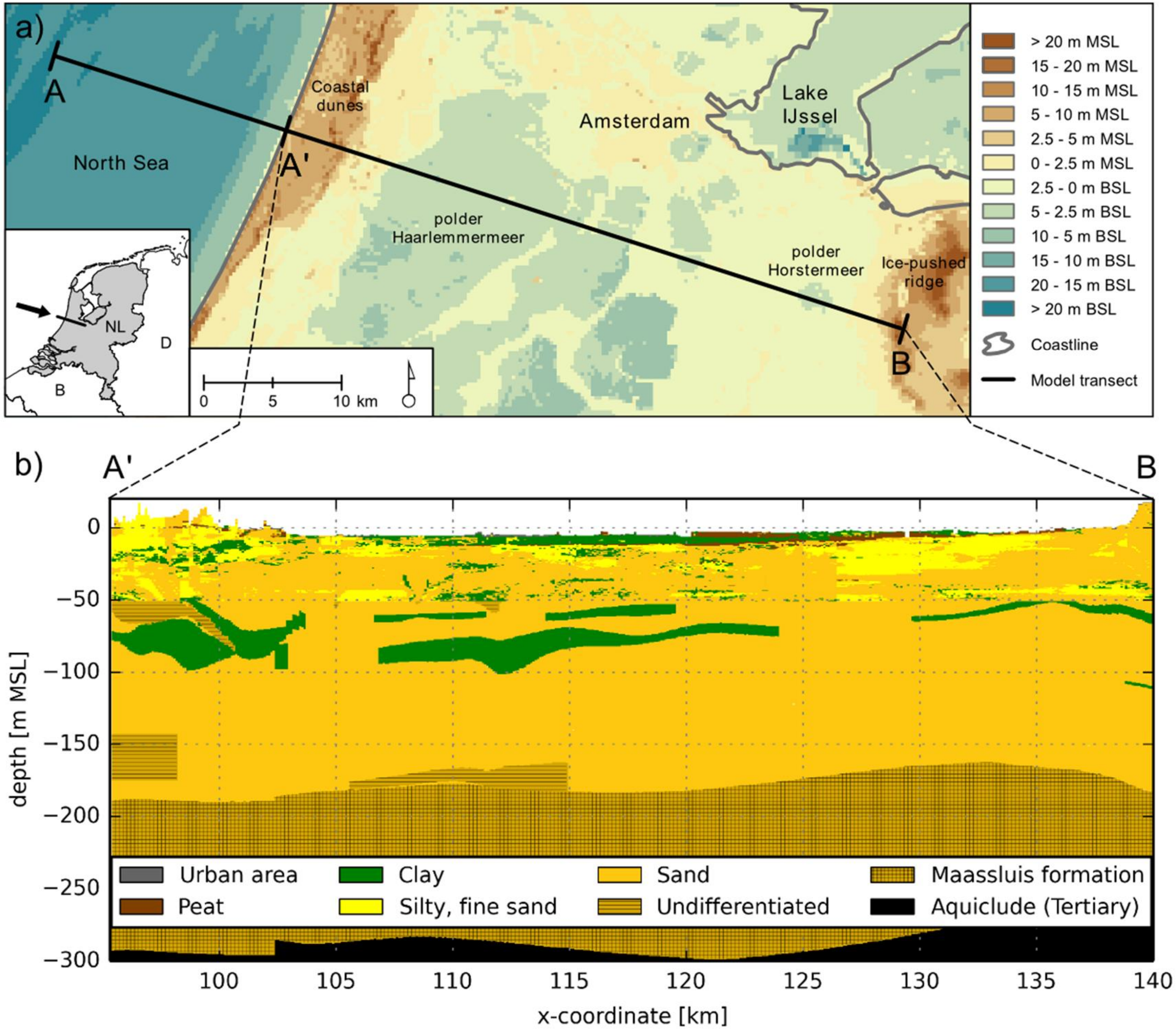
Atlas NL in het Holoceen (Vos et al, 2011)

Occurrence of salt under the polder Haarlemmermeer

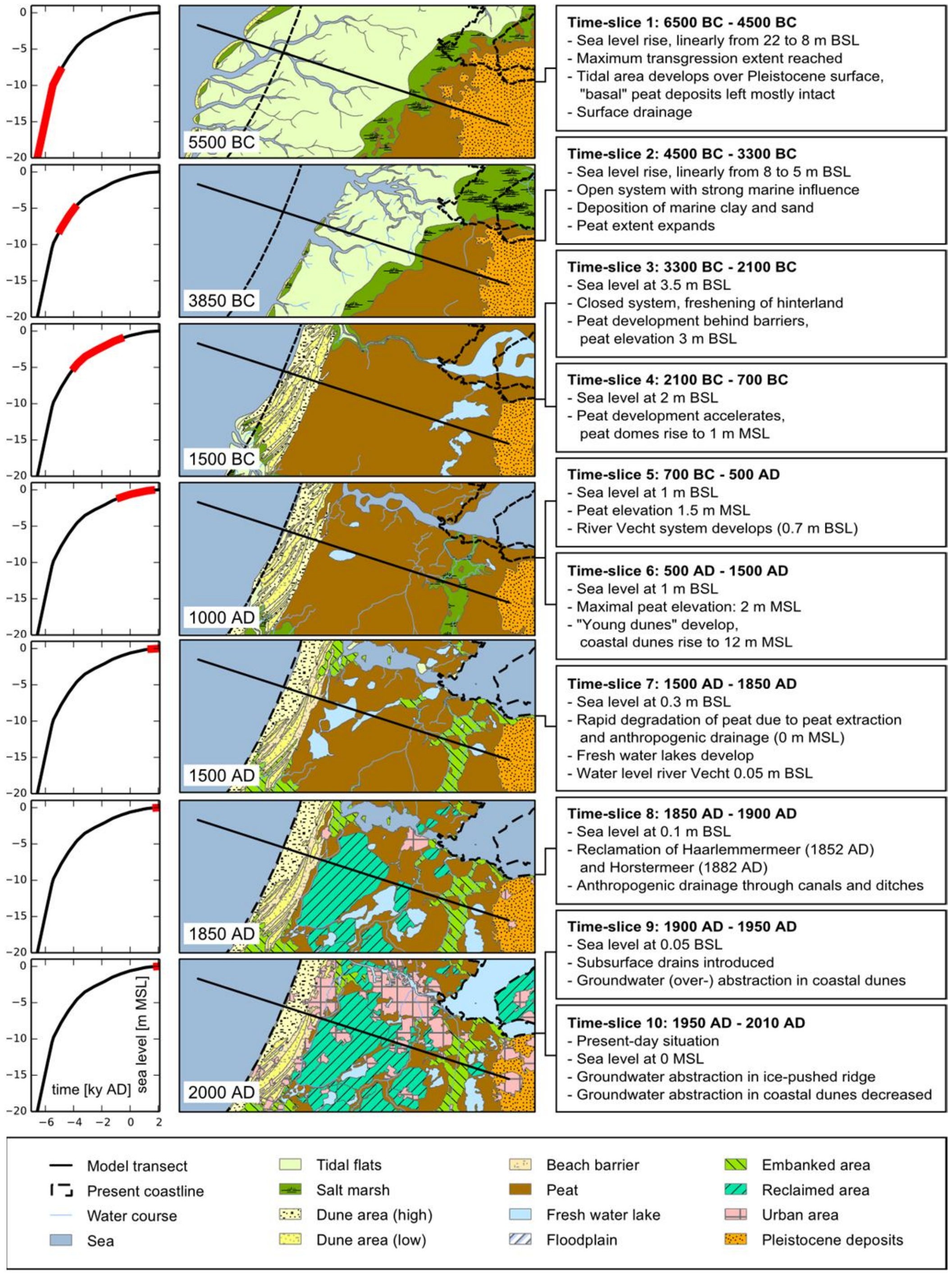
- Model profile Zandvoort - Hoofddorp – Hilversum
- Palaeogeographical development (Vos et al, 2011)
- 6500 BC - 2010 AD
- marine transgression
- Peat development, peat degradation, drainage, reclamation

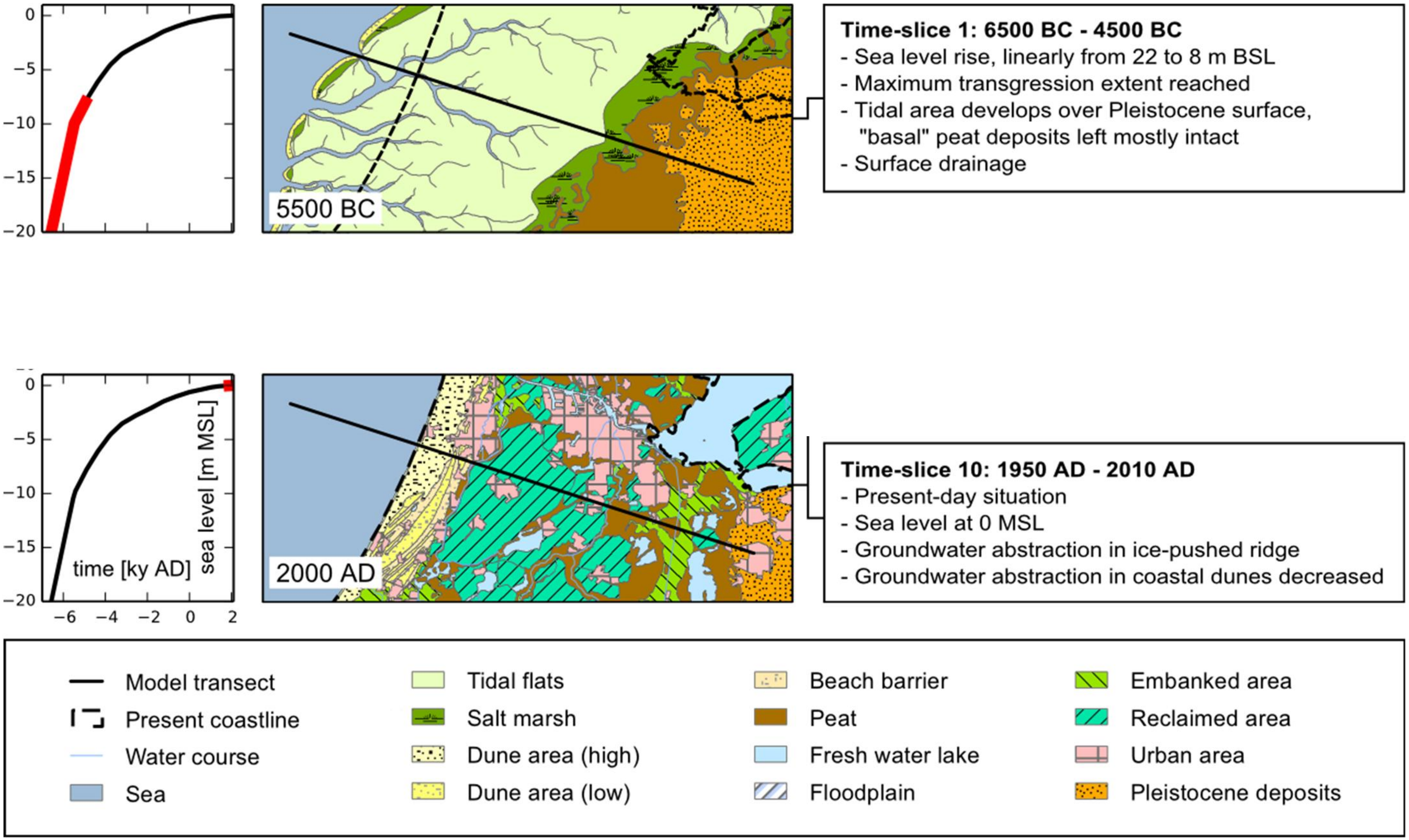


Delsman et al., HESS, 2013



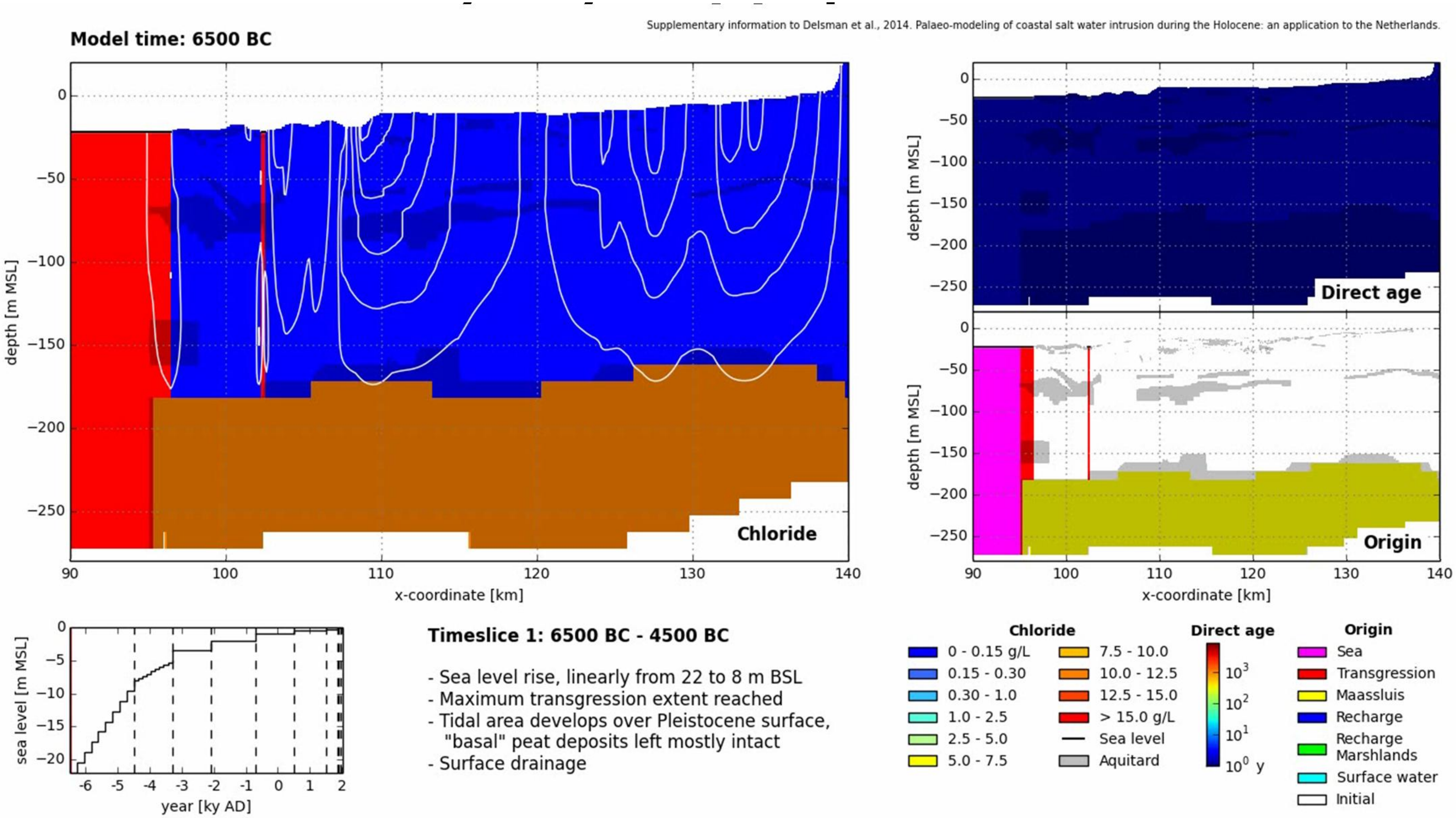
a)
A
A'
B
North Sea
Coastal dunes
Amsterdam
Lake IJssel
polder Haarlemmermeer
polder Horstermeer
Ice-pushed ridge
NL
D
B
0
5
10 km
> 20 m MSL
15 - 20 m MSL
10 - 15 m MSL
5 - 10 m MSL
2.5 - 5 m MSL
0 - 2.5 m MSL
2.5 - 0 m BSL
5 - 2.5 m BSL
10 - 5 m BSL
15 - 10 m BSL
20 - 15 m BSL
> 20 m BSL
Coastline
Model transect
b)
A'
B
depth [m MSL]
0
−50
−100
−150
−200
−250
−300
100
105
110
115
120
125
130
135
140
x-coordinate [km]
Urban area
Peat
Clay
Silty, fine sand
Sand
Undifferentiated
Maassluis formation
Aquiclude (Tertiary)


5500 BC
3850 BC
1500 BC
1000 AD
1500 AD
1850 AD
2000 AD
time [ky AD]
sea level [m MSL]
Time-slice 1: 6500 BC - 4500 BC
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage
Time-slice 2: 4500 BC - 3300 BC
- Sea level rise, linearly from 8 to 5 m BSL
- Open system with strong marine influence
- Deposition of marine clay and sand
- Peat extent expands
Time-slice 3: 3300 BC - 2100 BC
- Sea level at 3.5 m BSL
- Closed system, freshening of hinterland
- Peat development behind barriers, peat elevation 3 m BSL
Time-slice 4: 2100 BC - 700 BC
- Sea level at 2 m BSL
- Peat development accelerates, peat domes rise to 1 m MSL
Time-slice 5: 700 BC - 500 AD
- Sea level at 1 m BSL
- Peat elevation 1.5 m MSL
- River Vecht system develops (0.7 m BSL)
Time-slice 6: 500 AD - 1500 AD
- Sea level at 1 m BSL
- Maximal peat elevation: 2 m MSL
- "Young dunes" develop, coastal dunes rise to 12 m MSL
Time-slice 7: 1500 AD - 1850 AD
- Sea level at 0.3 m BSL
- Rapid degradation of peat due to peat extraction and anthropogenic drainage (0 m MSL)
- Fresh water lakes develop
- Water level river Vecht 0.05 m BSL
Time-slice 8: 1850 AD - 1900 AD
- Sea level at 0.1 m BSL
- Reclamation of Haarlemmermeer (1852 AD) and Horstermeer (1882 AD)
- Anthropogenic drainage through canals and ditches
Time-slice 9: 1900 AD - 1950 AD
- Sea level at 0.05 BSL
- Subsurface drains introduced
- Groundwater (over-) abstraction in coastal dunes
Time-slice 10: 1950 AD - 2010 AD
- Present-day situation
- Sea level at 0 MSL
- Groundwater abstraction in ice-pushed ridge
- Groundwater abstraction in coastal dunes decreased
Model transect
Present coastline
Water course
Sea
Tidal flats
Salt marsh
Dune area (high)
Dune area (low)
Beach barrier
Peat
Fresh water lake
Floodplain
Embanked area
Reclaimed area
Urban area
Pleistocene deposits



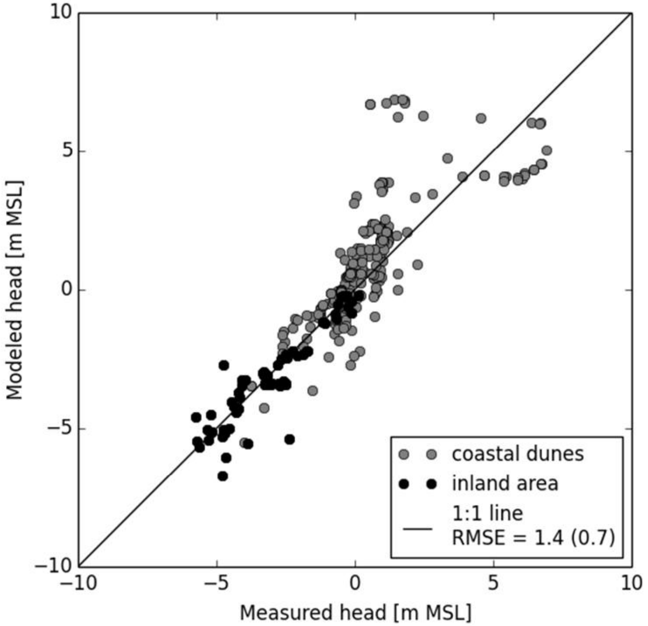
0
−5
−10
−15
−20
5500 BC
Time-slice 1: 6500 BC - 4500 BC
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage
0
−5
−10
−15
−20
−6
−4
−2
0
2
time [ky AD]
sea level [m MSL]
2000 AD
Time-slice 10: 1950 AD - 2010 AD
- Present-day situation
- Sea level at 0 MSL
- Groundwater abstraction in ice-pushed ridge
- Groundwater abstraction in coastal dunes decreased
Model transect
Present coastline
Water course
Sea
Tidal flats
Salt marsh
Dune area (high)
Dune area (low)
Beach barrier
Peat
Fresh water lake
Floodplain
Embanked area
Reclaimed area
Urban area
Pleistocene deposits

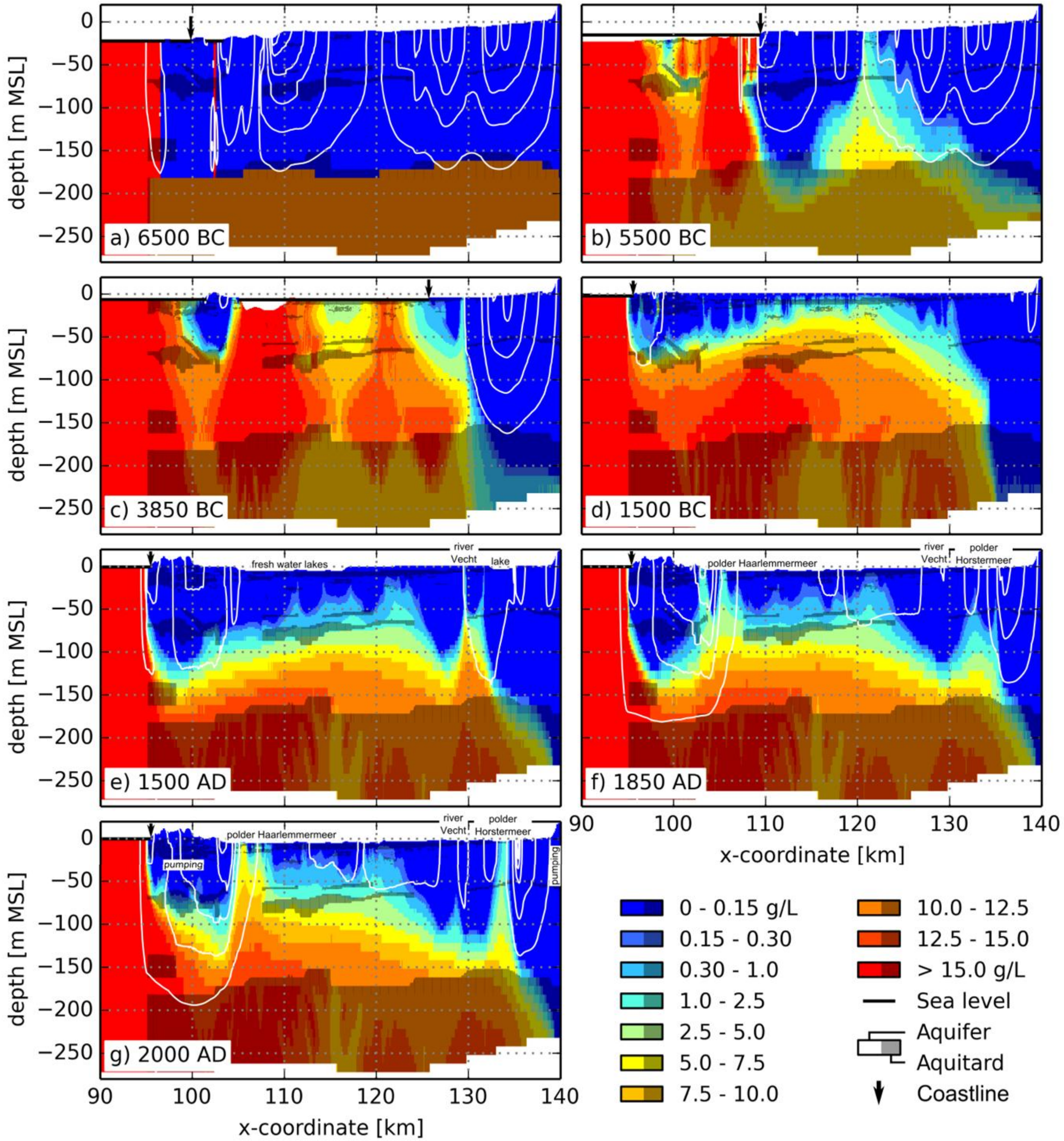
Development saline groundwater



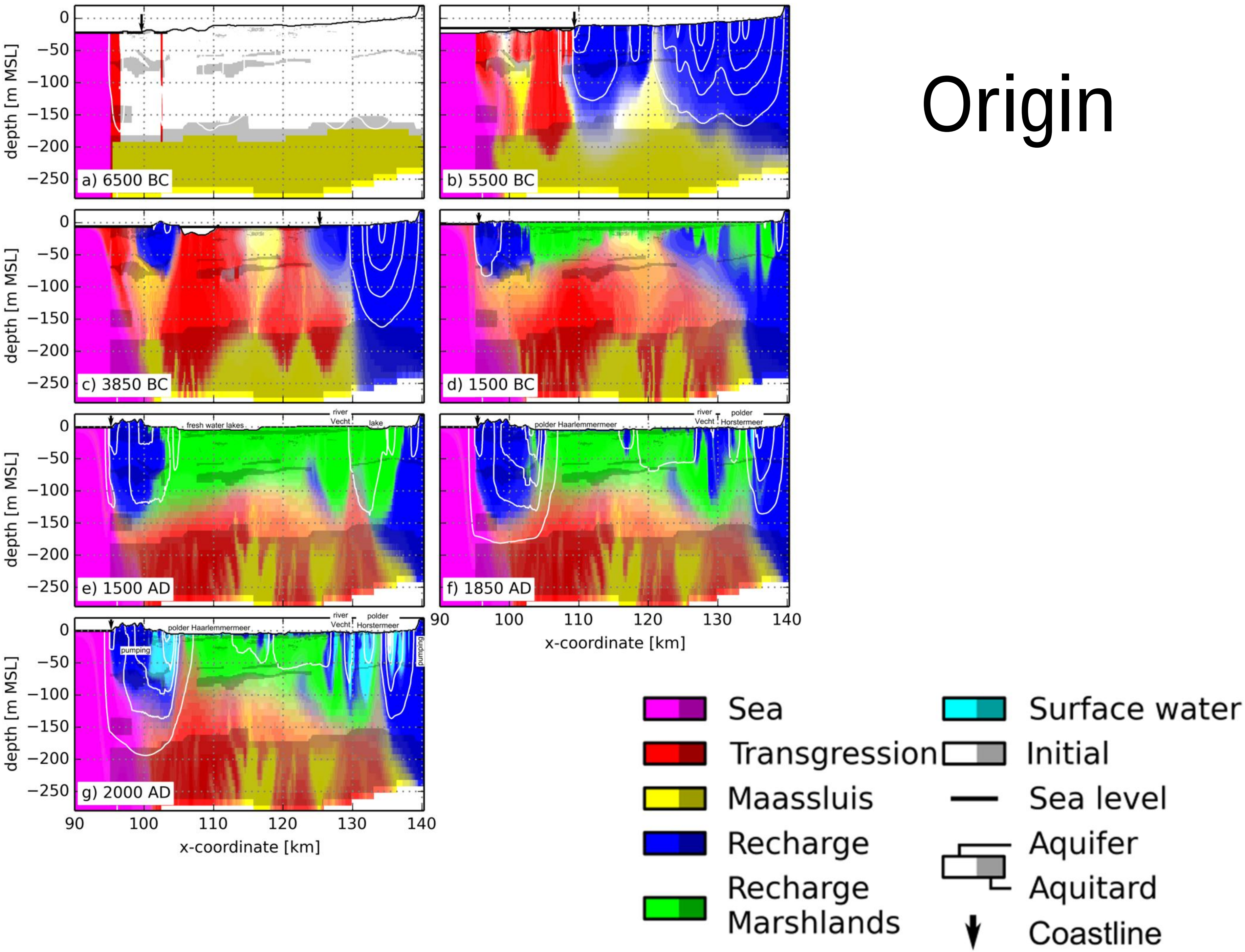
Delsman et al., HESSD, 2013

Model versus measurements

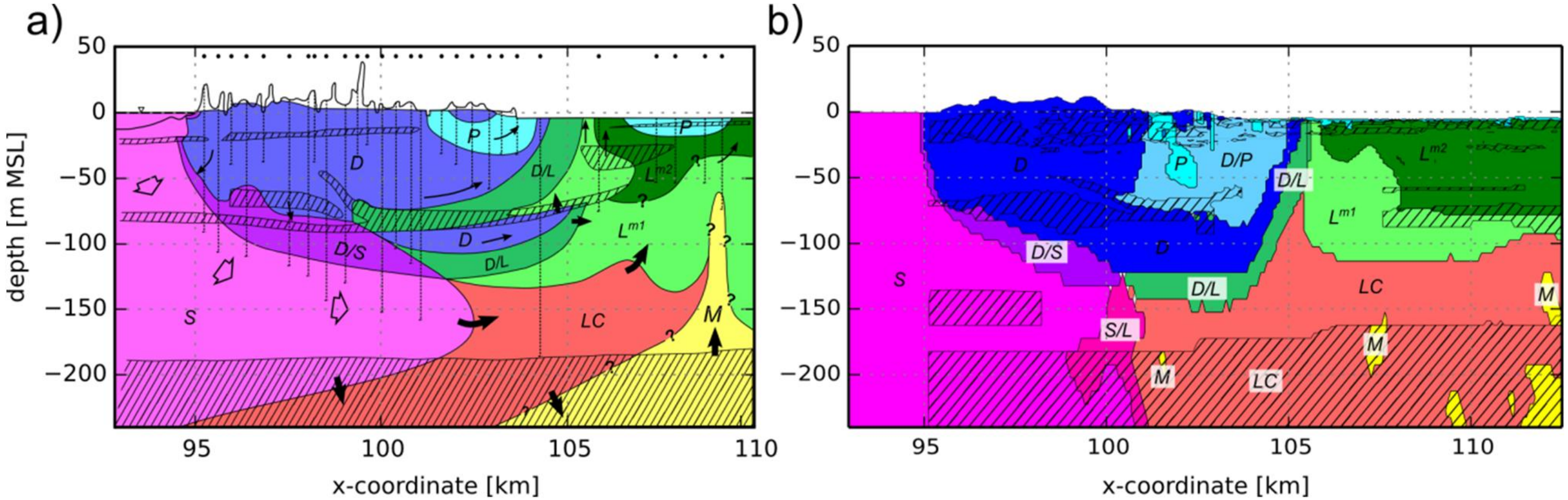


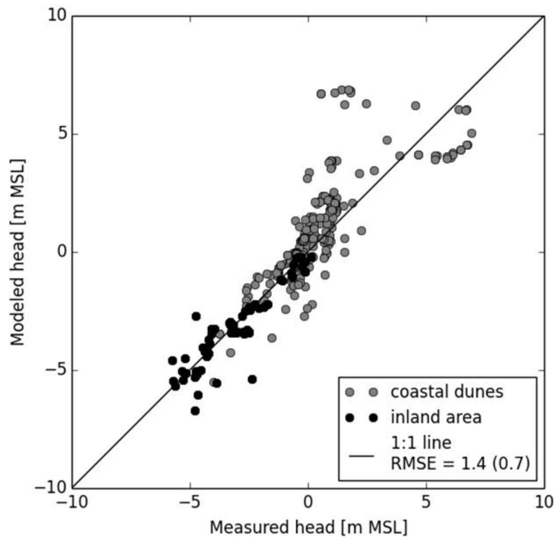


Origin



a) 6500 BC
b) 5500 BC
c) 3850 BC
d) 1500 BC
e) 1500 AD
f) 1850 AD
g) 2000 AD
depth [m MSL]
x-coordinate [km]
fresh water lakes
river Vecht
lake
polder Haarlemmermeer
polder Horstermeer
pumping
Sea
Transgression
Maassluis
Recharge
Recharge Marshlands
Surface water
Initial
Sea level
Aquifer
Aquitard
Coastline


a)
b)
depth [m MSL]
x-coordinate [km]
50
0
−50
−100
−150
−200
95
100
105
110
S
D
P
D/L
D/S
LC
M
L^m1
L^m2
D/P
S/L


Modeled head [m MSL]
Measured head [m MSL]
10
5
0
−5
−10
coastal dunes
inland area
1:1 line
RMSE = 1.4 (0.7)

Model versus measurements