IHE 2023

Density dependent groundwater flow in the coastal zone

Gualbert Oude Essink, PhD

Lecture set-up: 14* 1 hr

- **PowerPoint sheets**
- **Lecture Notes**
- **Practicals numerical modelling**

Deltares

Universiteit Utrecht

http://freshsalt.deltares.nl

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

11-12-13 April 2023

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, Science Council
- 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

Independent research institute on water, soil and infrastructure

- We are the knowledge partner of the Dutch government
- We make our knowledge applicable worldwide
- We help to enhance the innovative strength of The Netherlands
- We are a strategic partner internationally
- We provide specialist consultancy internationally

Deltares

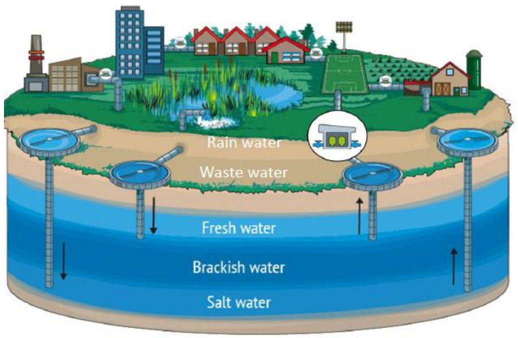

Our mission areas
Deltares
Future deltas
Sustainable deltas
Safe deltas
Resilient infrastructure
Deltares

We work on:

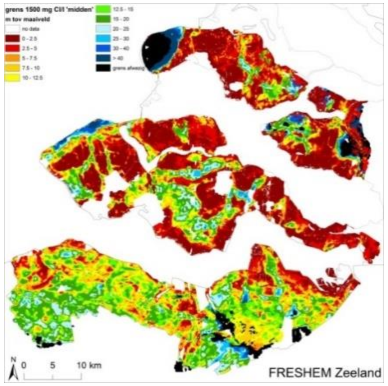
- **Flood risk management**
- **Healthy water and soil systems**
- **Water and soil resources**
- **Delta infrastructure**
- **Adaptive delta planning**
- **Enabling technologies**

Some of my present activities

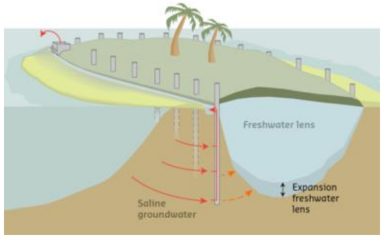
- Part of (national) research programmes **AquaConnect** and **GEOWAT**
  a. *Key technologies for safeguarding regional water provision in fresh water stressed deltas*
  b. A Global Assessment of the Limits of Groundwater Use
  c. impact of sea-level rise in coastal groundwater systems

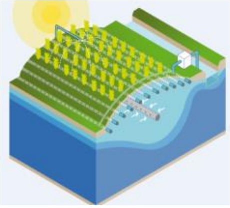


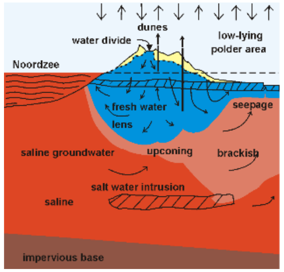
- Small-scale ASR pilot projects in Netherlands (GO-FRESH Zeeland), Vietnam (FAME)
- NUFFIC Egypt (Smart Water in Agriculture and Food Security Desert and Delta)
- Mapping fresh-saline groundwater by Airborne EM Surveys, FRESHEM

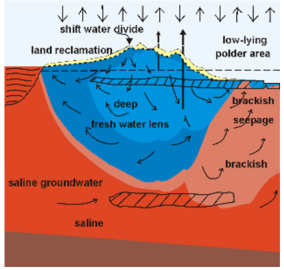


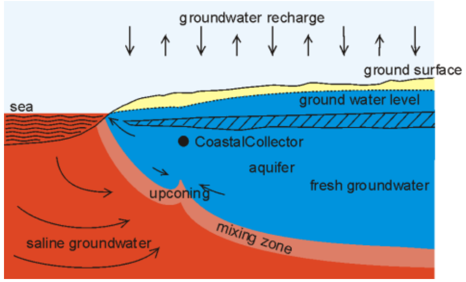
- Supervising MScs and 5 PhD on coastal groundwater issues: e.g.
  - field studies Mekong and Nile deltas on water saving in agriculture
  - modelling (parallel massive computing)
  - global groundwater modelling
  - innovative monitoring techniques (ERT, AHDTS)
- Joining innovations to improve freshwater supply in coastal zones
  - Desalinisation, solar energy and Aquifer Storage and Recovery!
  - Seepcat, Coastal Collectors











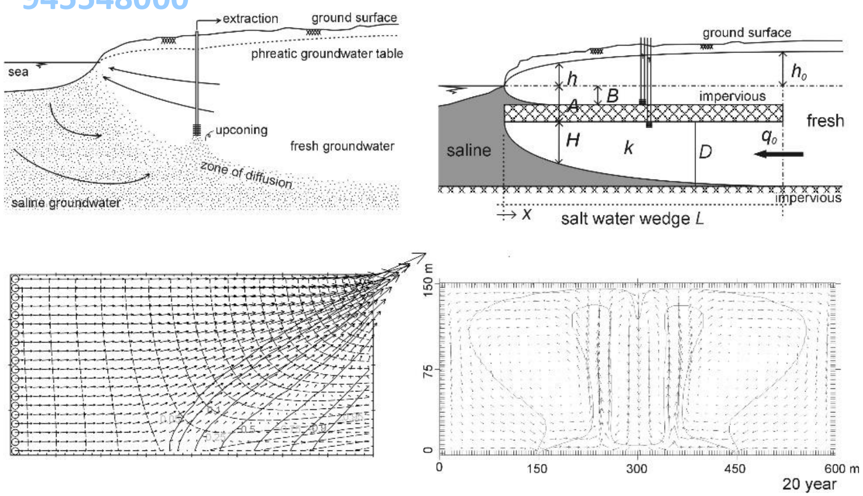
Research on groundwater in the coastal zone

- >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

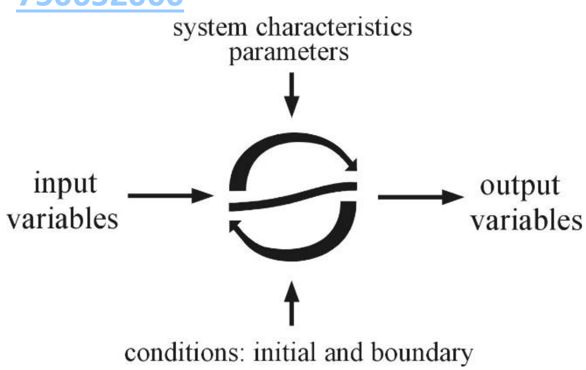
1. Density dependent groundwater flow

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: variable-density groundwater flow and salt transport
- 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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Possibilities for internships / MSc thesis at Deltares

1. Estimating geologic uncertainty in groundwater salinity modeling
2. How old is Dutch groundwater?
3. Exploring groundwater salinization effects of large-scale sea level rise adaptation in the Netherlands
4. Estimating groundwater salinity in the coastal zone of Africa, using machine learning techniques
5. Estimate groundwater use in Africa, using machine learning
6. Machine learning of airborne EM data to concurrently map groundwater salinity and lithology
7. Literature study of global surface water salinization
8. Model study on islands in the Pacific Ocean using the SIDS groundwater modelling framework
9. Comparison of 2D and 3D groundwater flow model estimations in deltaic regions (with Utrecht University)
10. Economical and technical feasibility of offshore groundwater pumping (with Utrecht University)

Topics of density driven groundwater flow

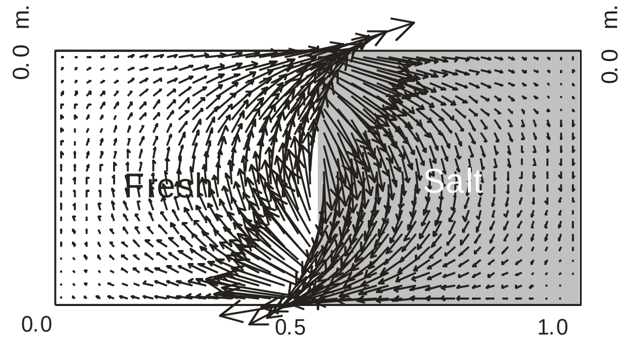
1. Introduction
   - water on earth
   - salt water intrusion
   - freshwater head
2. Interface between fresh and saline groundwater
   - analytical formulae (Badon Ghyben-Herzberg)
   - upconing example
3. Numerical modelling
   - mathematical background
   - paleo-reconstructions
   - benchmark problems: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

Examples of variable-density groundwater flow

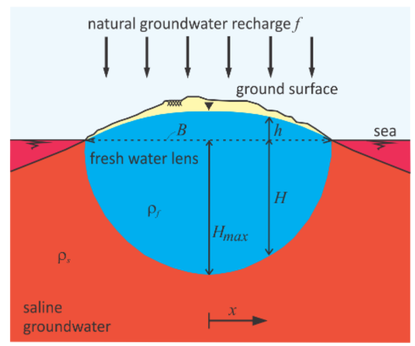
- Henry’s problem
- Dutch 2D cases
- Effect of Tsunami on groundwater resources
- Vertical interface
- Rotating interface
- Freshwater lenses
- Salt water pocket
- Rotating immiscible interface
- Hydrocoin
- Broad 14 Basin, North Sea
- Heat transport: Elder and Rayleigh=4000
- Dutch 3D cases

Practicals

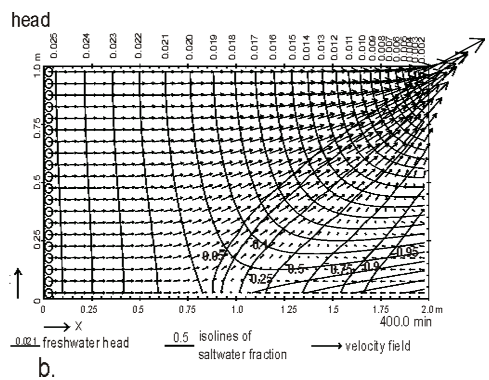
- Rotating sharp interface



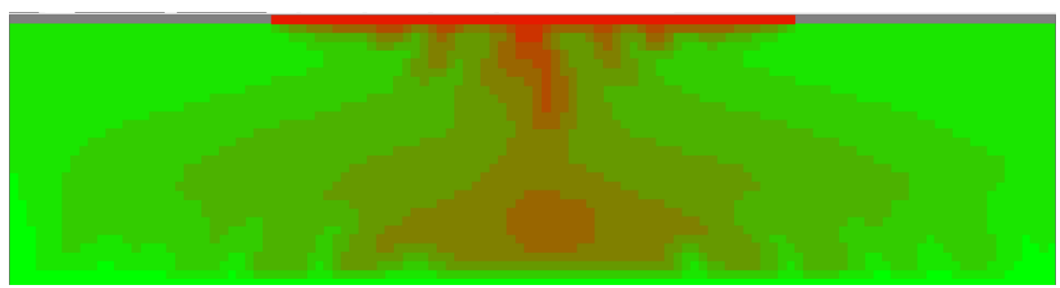
- Freshwater lens



- Henry’s case



- (Elder’s case)



Salt Water Intrusion Meeting, since 1968

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

Themes

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

Salt Water Intrusion Meeting (SWIM)

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

Welcome to the homepage of the Salt Water Intrusion Meeting

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

SWIM from Alphafilm & Kommunikation on Vimeo.

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

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

www.swim-site.org

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

Salt Water Intrusion Meeting (SWIM)

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

The proceedings of the Salt Water Intrusion Meeting

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

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

Available for download:

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

www.swim-site.org

For sale (external links)

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

Salt Water Intrusion Meeting (SWIM)

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

Back to all proceedings

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

www.swim-site.org

Preface

A.D. Werner

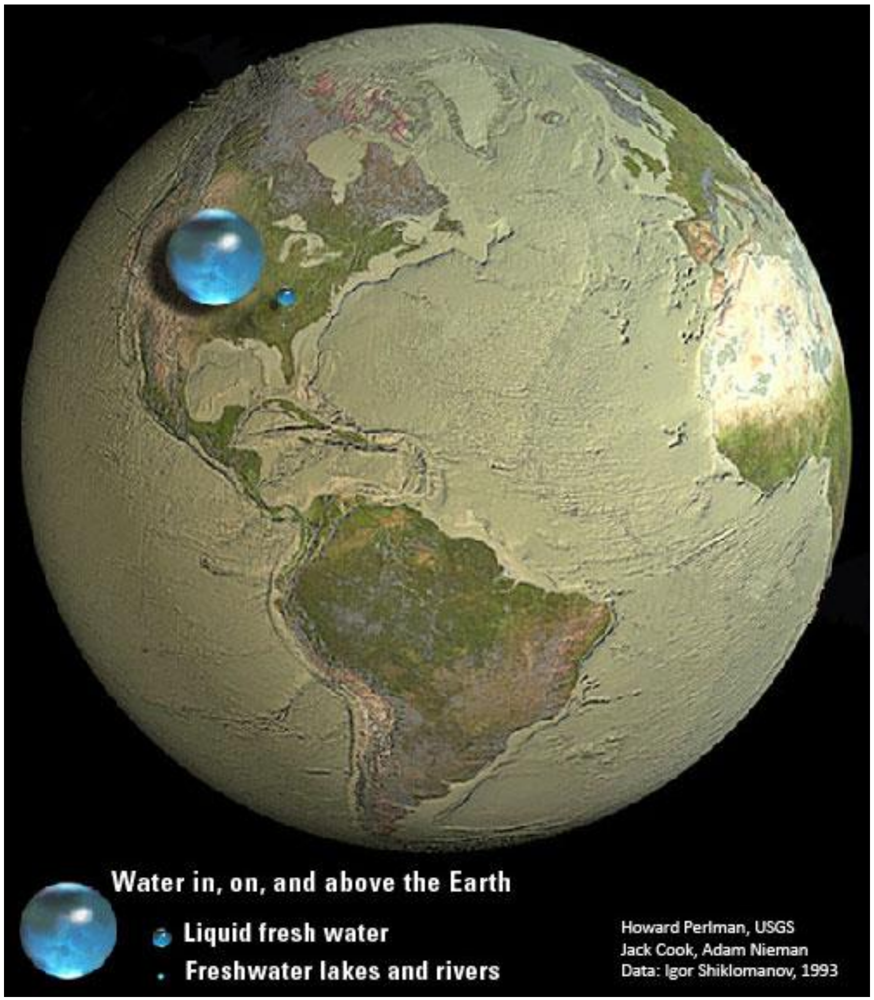
Posters

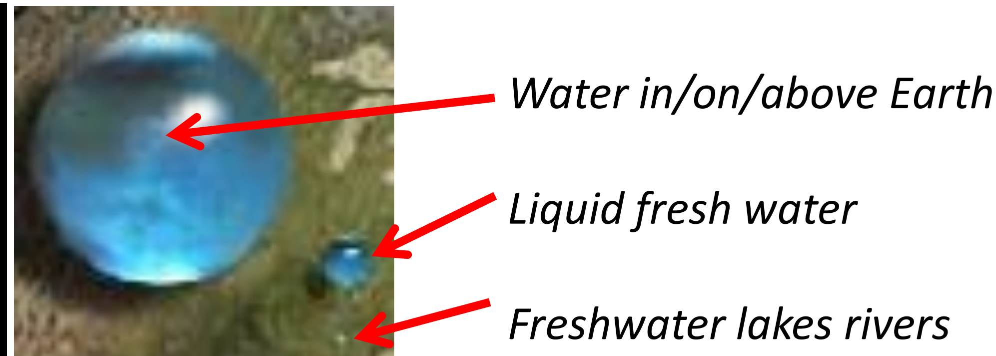
S. Fatema, A. Marandi, C. Schüth Seawater Intrusion of the Coastal Groundwater: A Case Study in Cox's Bazar, Bangladesh
A. Kawachi, C. Uchida, M. Kefi, J. Tarhouni, K. Kashiwagi Effect of Surface Water Use on Mitigation of GW Salinization in a Semi-Arid Coastal Shallow Aquifer Setting: A Case Study of 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

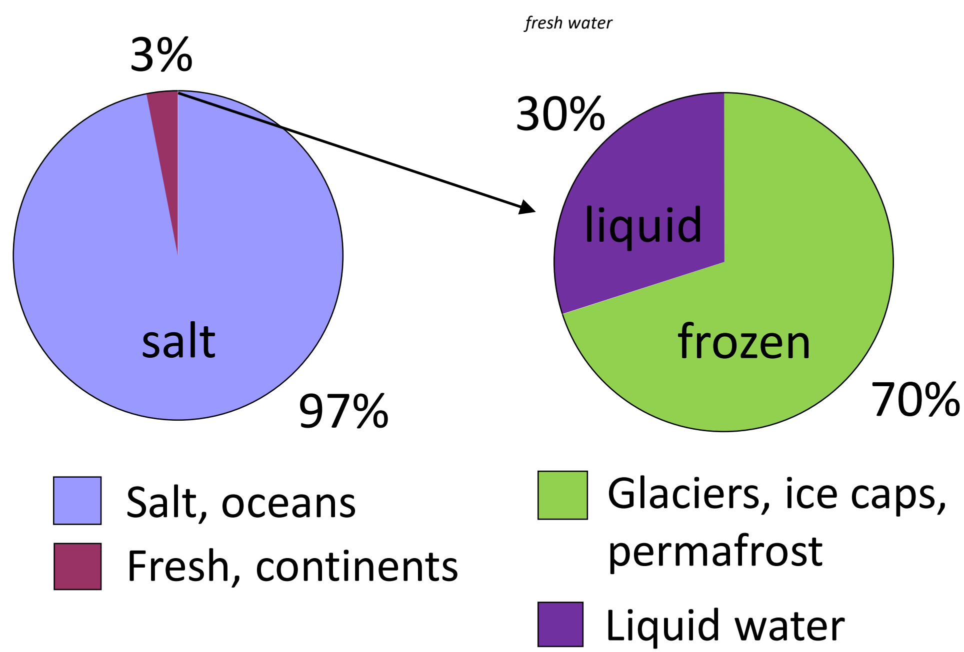
Session 1 - Managing Coastal Groundwater I

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

Volumes of water on Earth: a scarce product



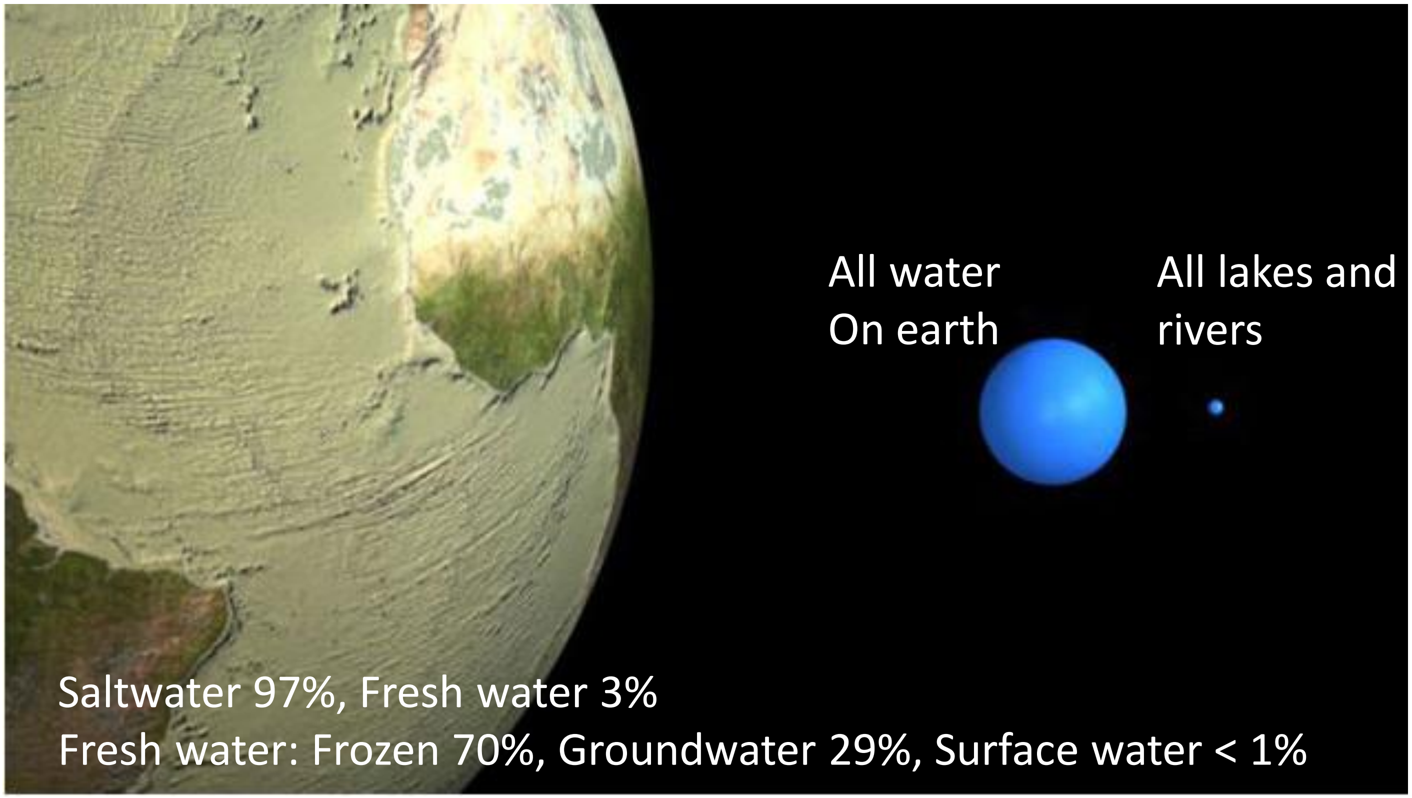




Source: Perlman, USGS; Shiklomanov, 1993

Water Energy Food Nexus
Global water scarcity

Fresh water is a scarce resource…



Fresh groundwater resources in delta's seriously under stress

Every year, about 2 million people worldwide die from diarrhea, caused by bad drinking water quality; this is more than people dying from flooding Events.

Groundwater is an important source of drinking water (now ~50% and increasing):

- increase world population & economical growth
- relatively easy-to-access and available in large quantities
- high quality and still unpolluted (relative to surface water)
- loss of surface water due to contamination

In the future, we have to cope which:

- climate change and sea-level rise
- increasing quantities groundwater extractions
- land subsidence
- politics, policy & watermanagement, affecting land use

Reasons and drawbacks of using groundwater

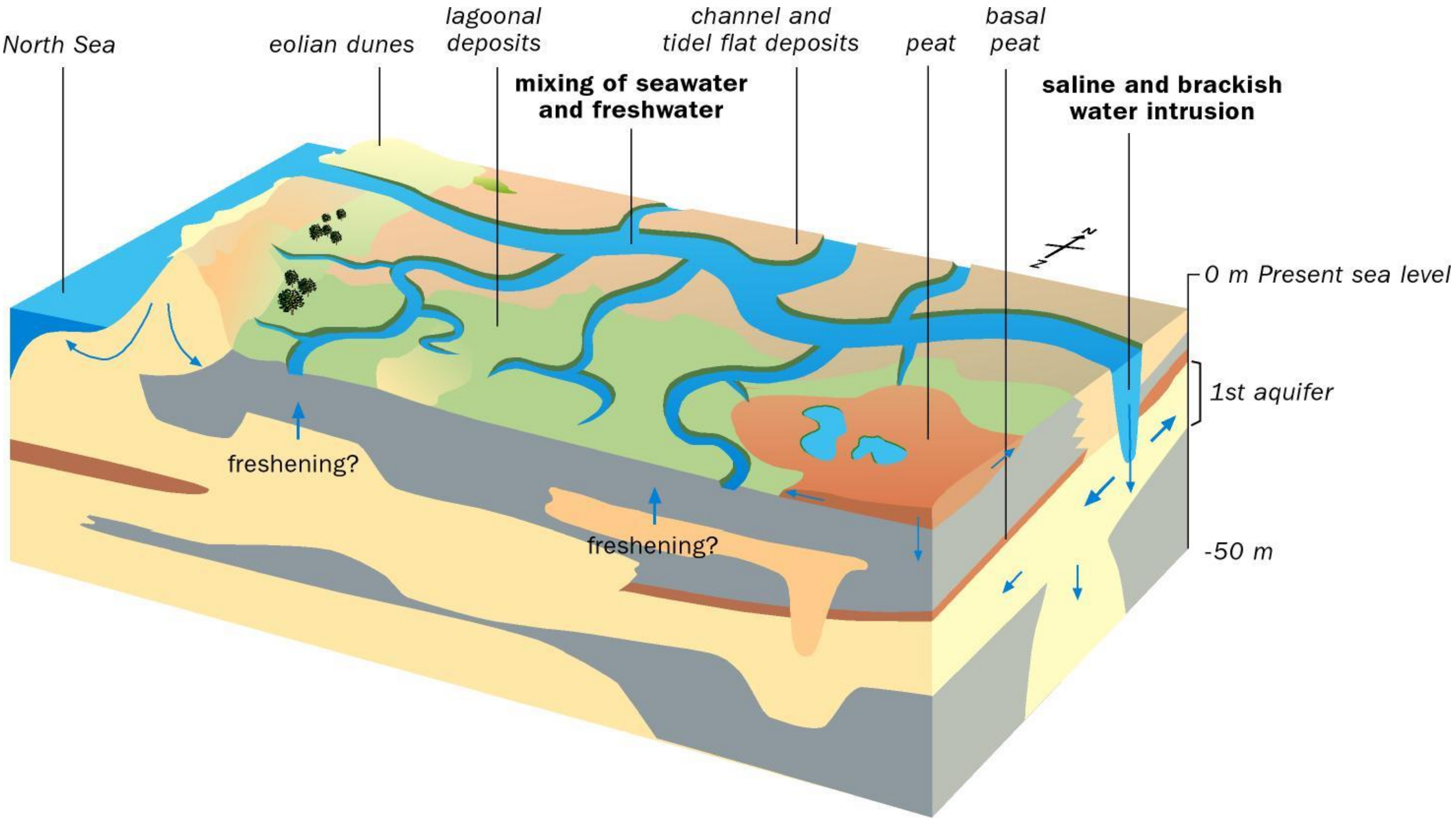
Advantage:

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

Disadvantage:

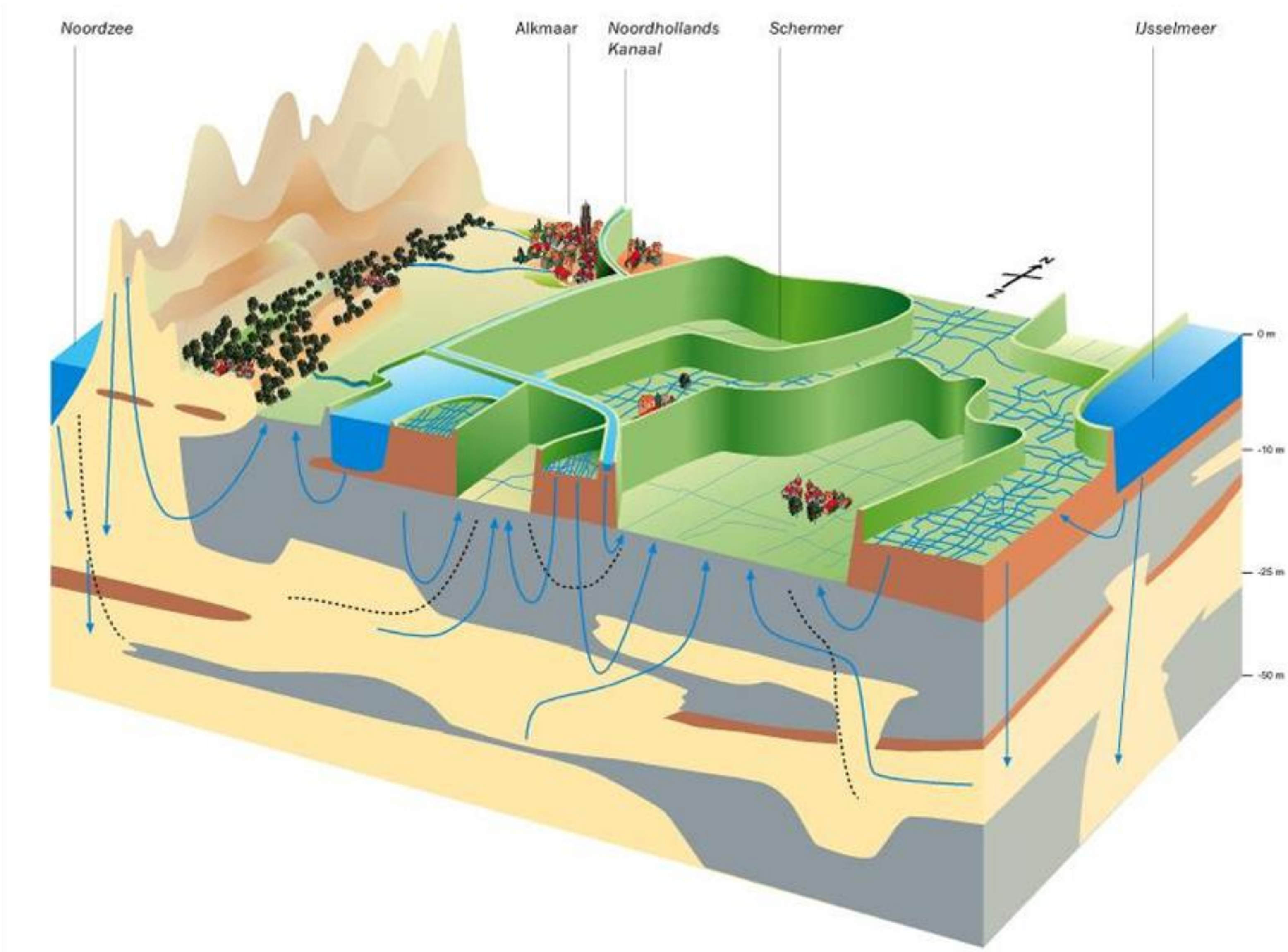
-high extraction costs
-local droughts
-high mineral content
-land subsidence….
-salt water intrusion !

Coastal groundwater system, before man

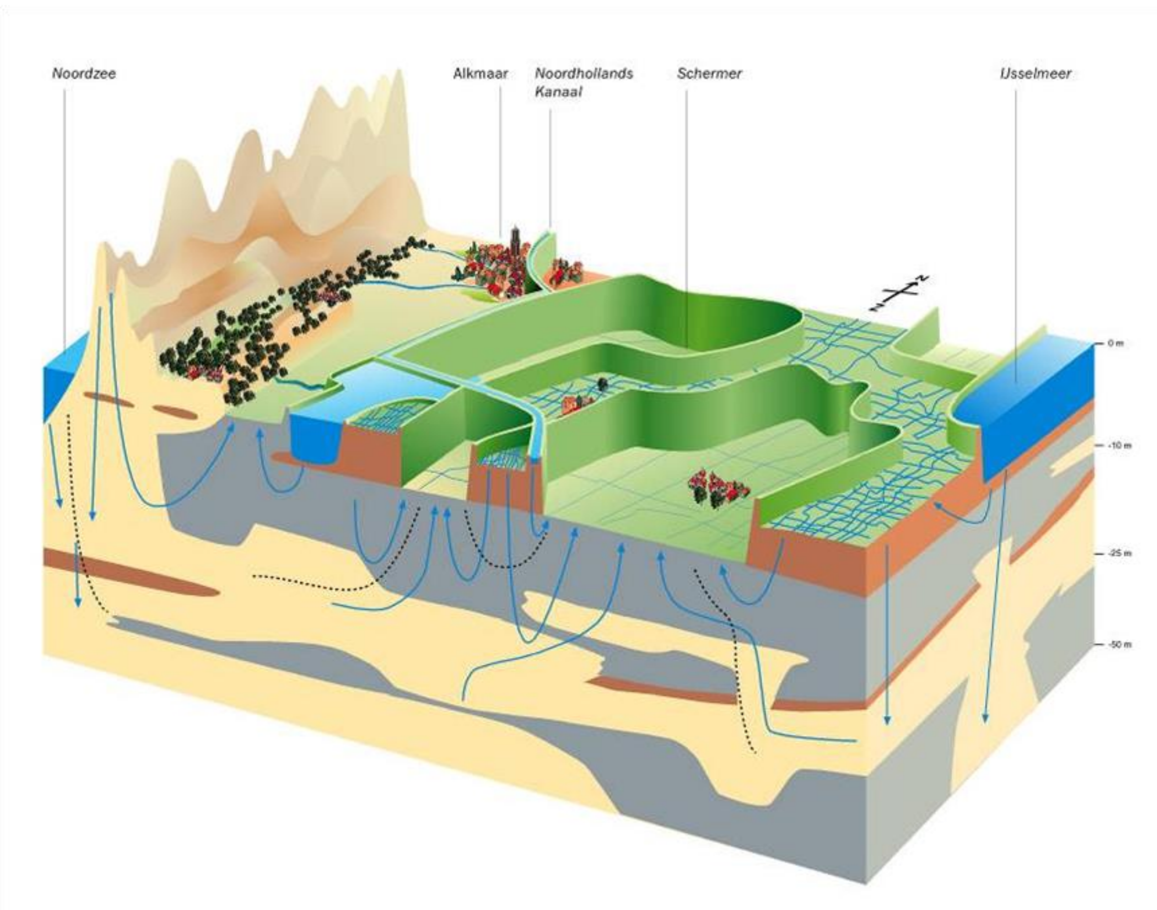


Coastal groundwater system, now

The polders in the Nederland



The current coastal groundwater system in the Netherlands



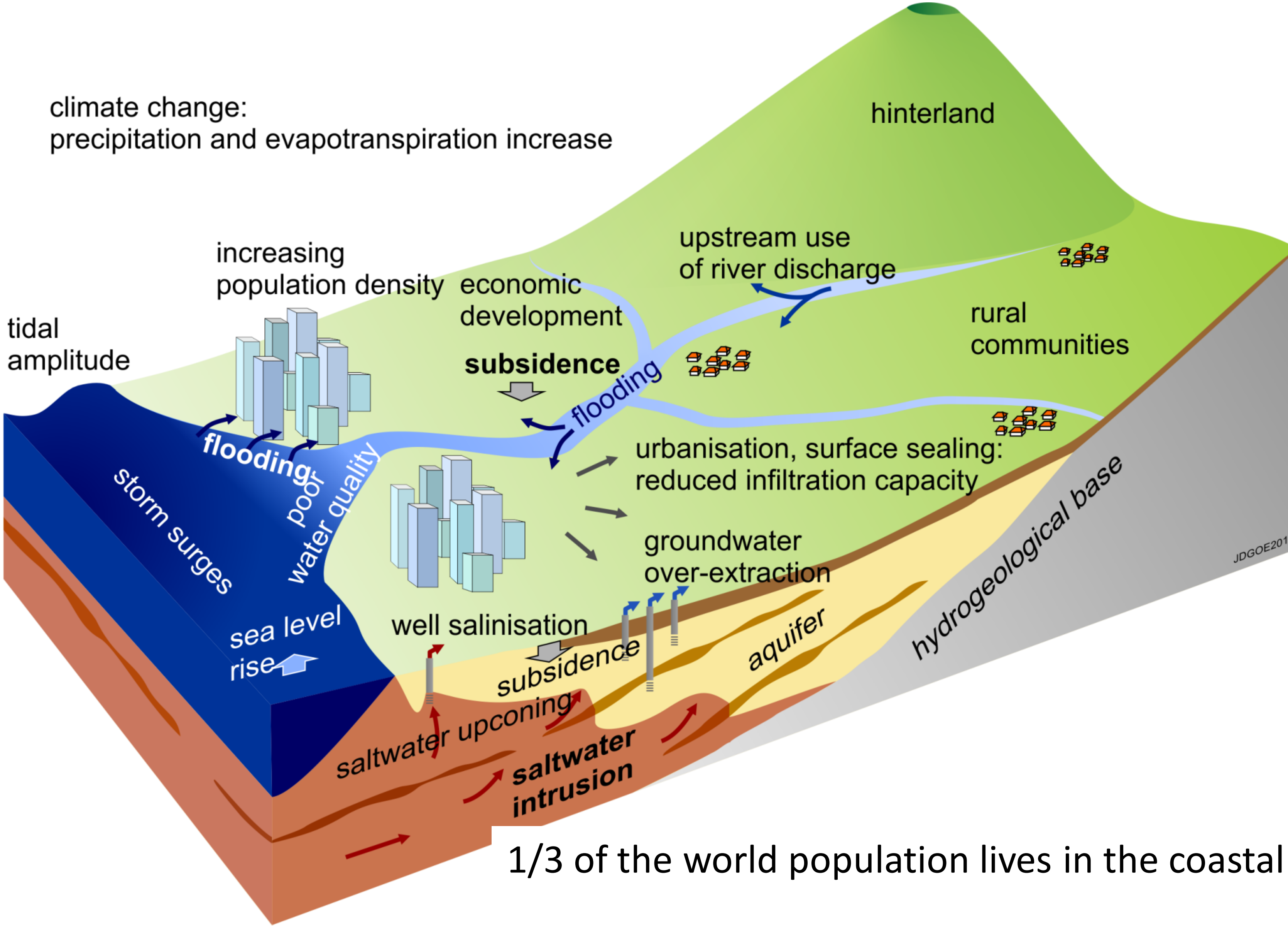
Level reductions in the past have caused groundwater flows inland

History (palaeohydrogeology) important: groundwater flow is a slow process

The past still influences the distribution of fresh-brackish-salt groundwater

Fresh-salt distribution can vary greatly over a short distance

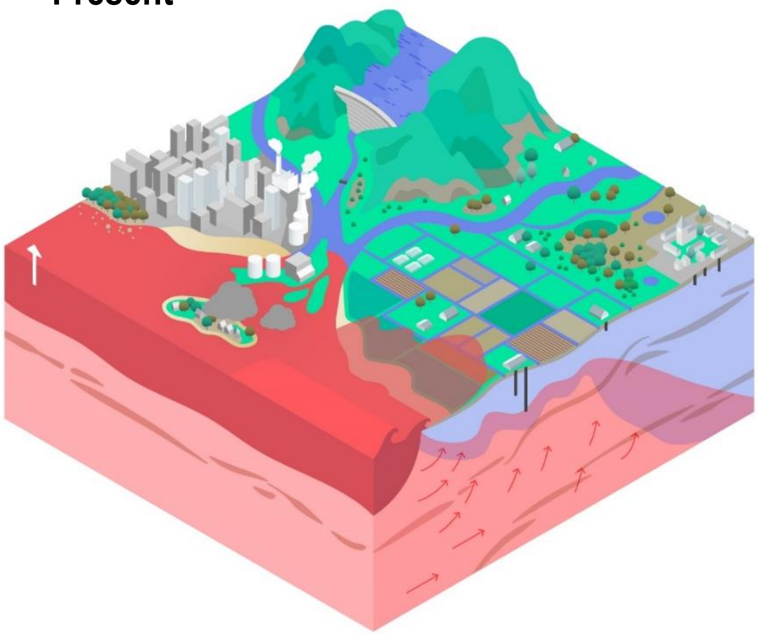
Threaths to deltas worldwide:
subsidence, salinisation, depletion, sealing, sea level rise, CC



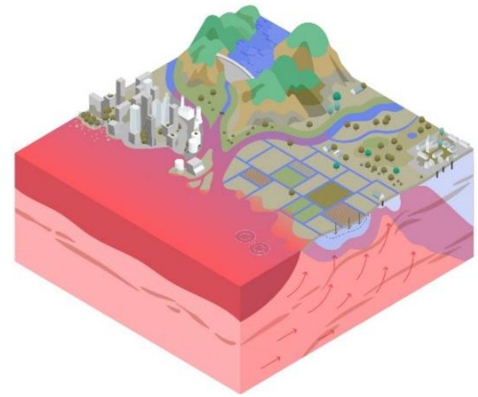
1/3 of the world population lives in the coastal zone

Fresh groundwater availability deltaic areas

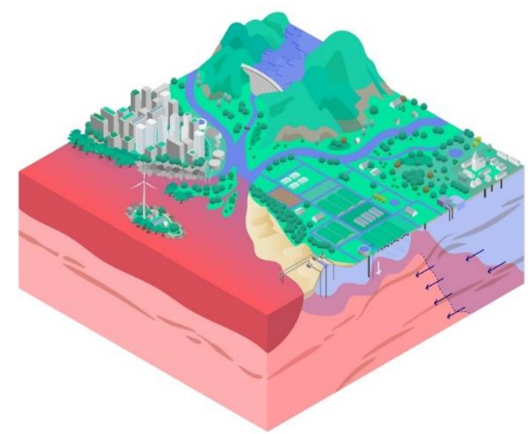
Present



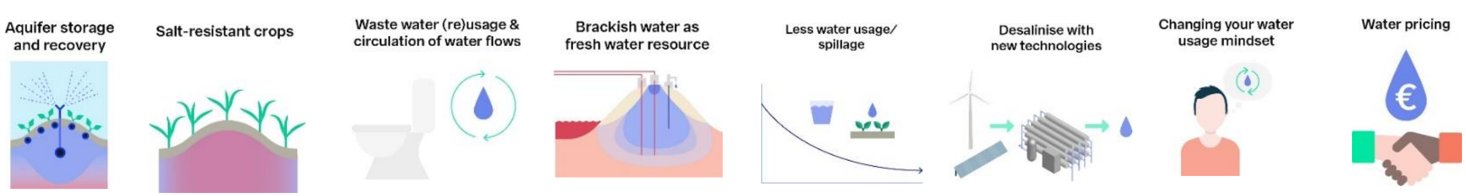
Future without measures



Future with measures



1/3 world population lives in the coastal zone



Fresh groundwater resources in deltas are seriously under stress

Every year, about 2 million people worldwide die from diarrhea, caused by bad drinking water quality; this is more than people dying from flooding events

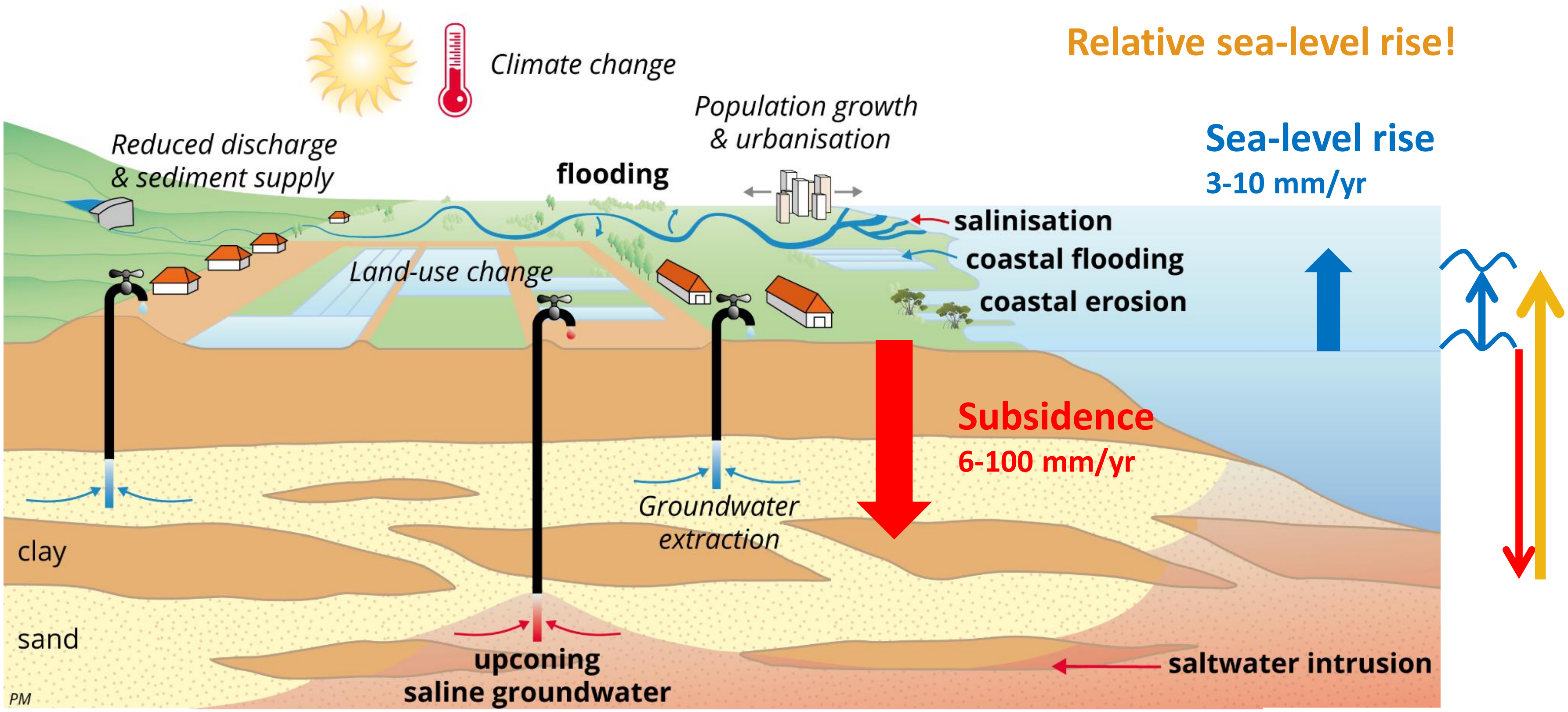
Groundwater is an key source for many agricultural, domestic and industrial water users in many countries, due to its high quality and relatively easy-to-access quantity (now ~50% and increasing)

In the future, delta's have to cope which…:

- more groundwater extractions
- land subsidence
- climate change and sea-level rise
- politics, policy & watermanagement, affecting land use

Many changes in the Mekong delta

(and other deltas around the world)



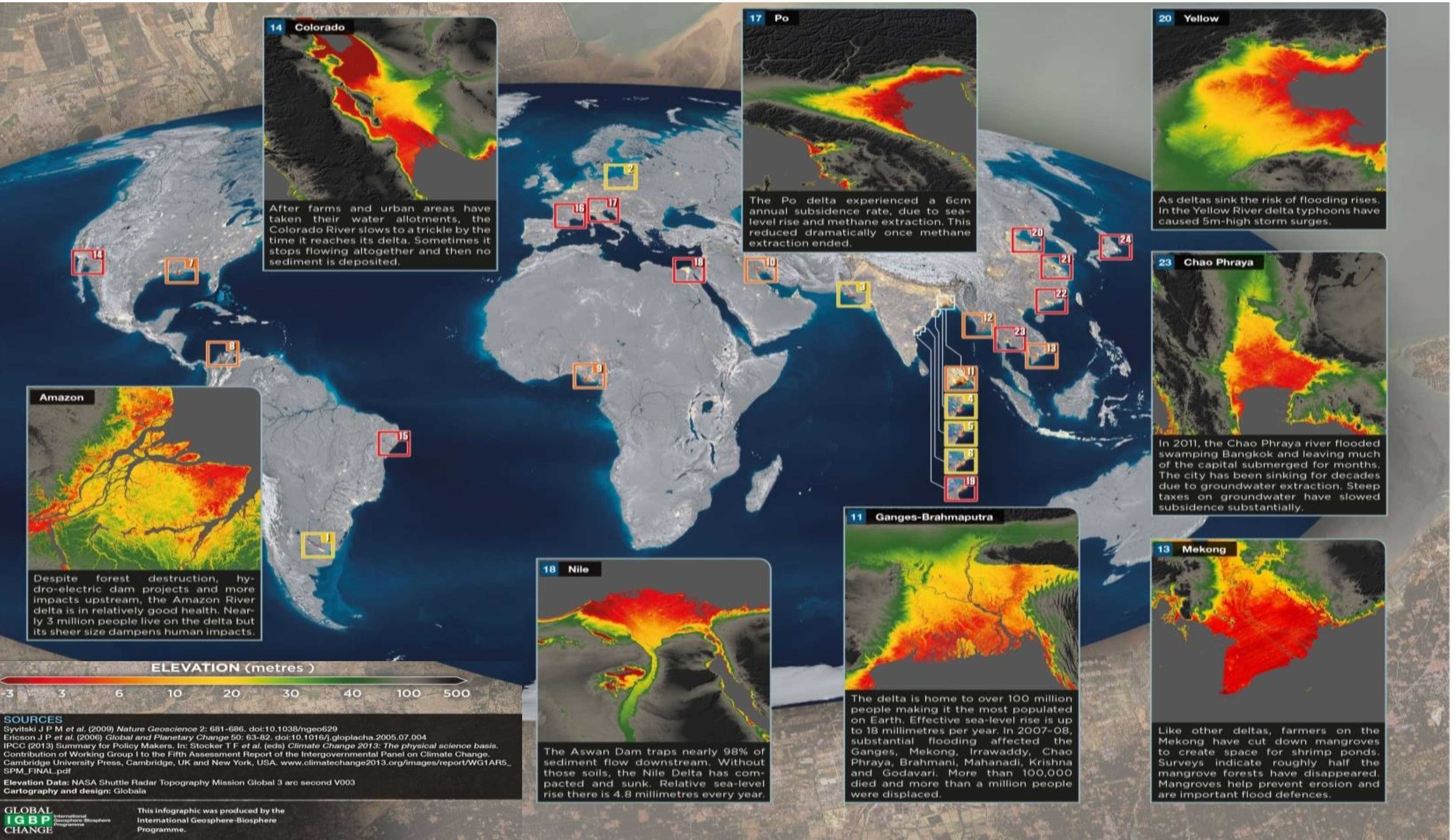
Minderhoud, 2019

Absolute Sea-level rise *versus* Subsidence

Deltas are densely populated areas: >500 million people worldwide
High economic value
Crucial to global food security*

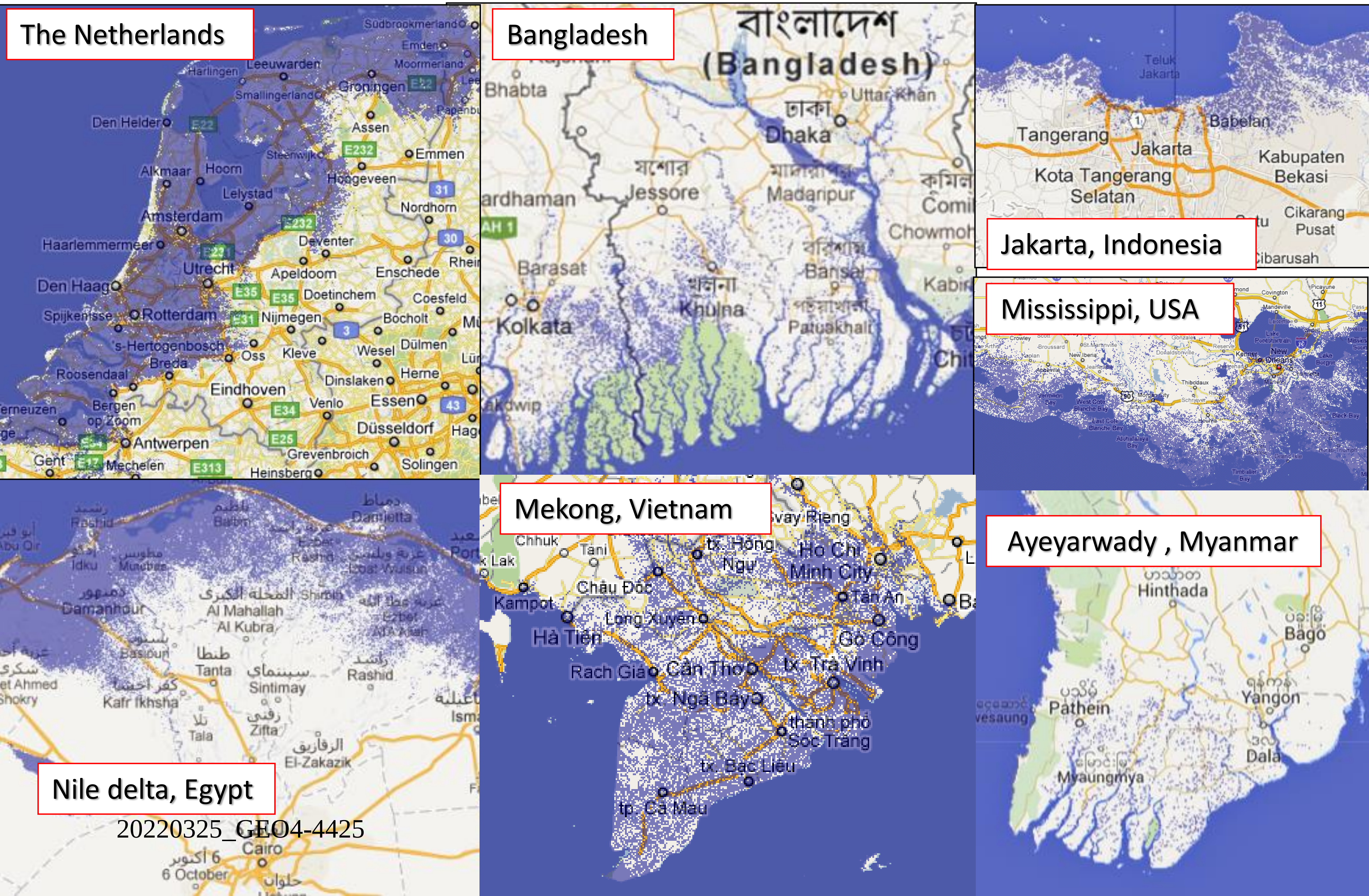
Deltas at risk

Deltaic areas are valuable areas:
→densely populated: >500 million people worldwide
→high economic value
→crucial to global food security



Sea level rise: +2 m

http://flood.firetree.net



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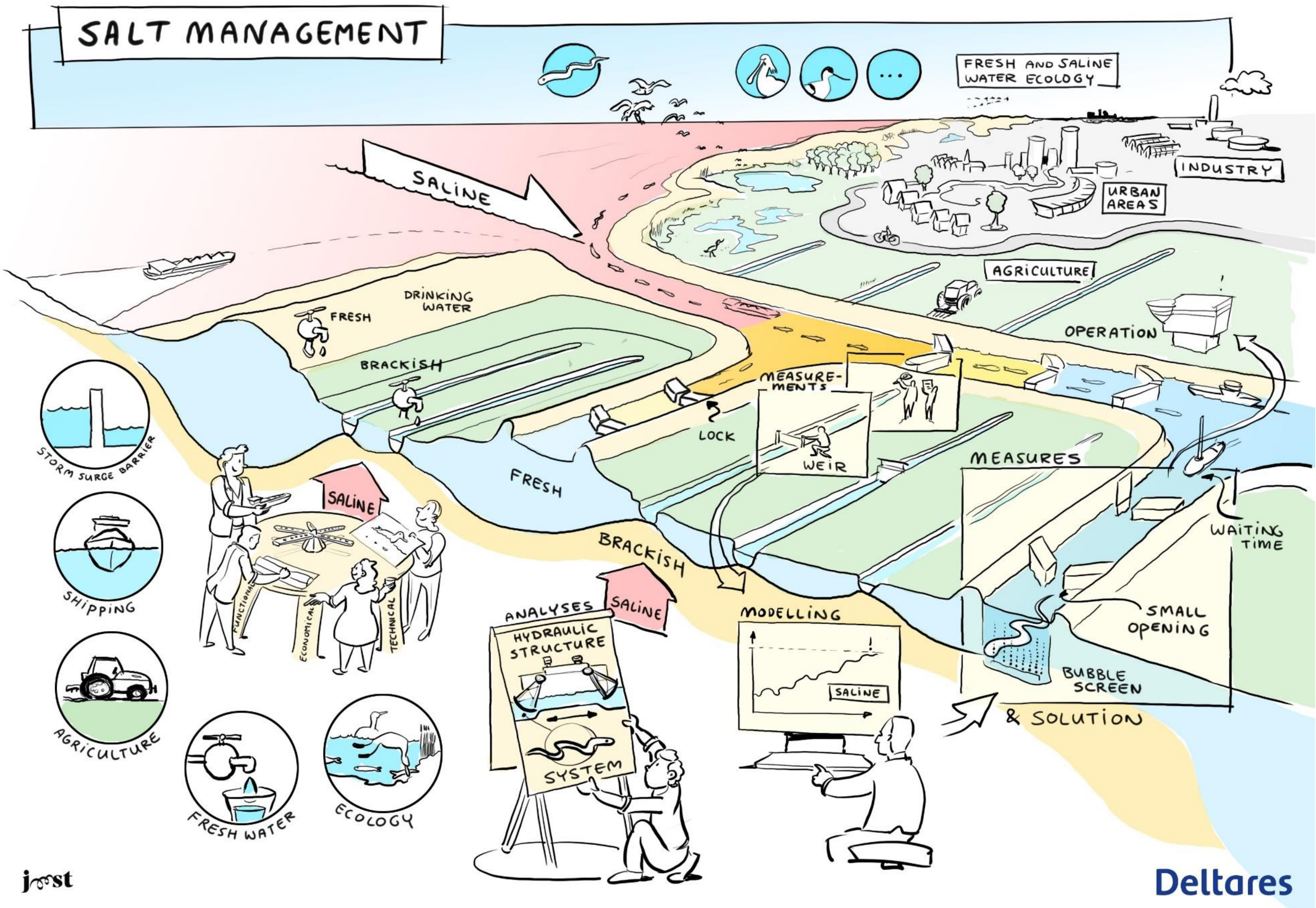

SALT MANAGEMENT
FRESH AND SALINE WATER ECOLOGY
INDUSTRY
URBAN AREAS
SALINE
AGRICULTURE
DRINKING WATER
FRESH
BRACKISH
OPERATION
MEASUREMENTS
LOCK
WEIR
MEASURES
WAITING TIME
FRESH
SALINE
BRACKISH
STORM SURGE BARRIER
SHIPPING
AGRICULTURE
FRESH WATER
ECOLOGY
FUNCTIONAL
ECONOMICAL
TECHNICAL
ANALYSES
SALINE
HYDRAULIC STRUCTURE
SYSTEM
MODELLING
SALINE
SMALL OPENING
BUBBLE SCREEN
& SOLUTION
joost
Deltares

Studies on fresh water availability issues around the world

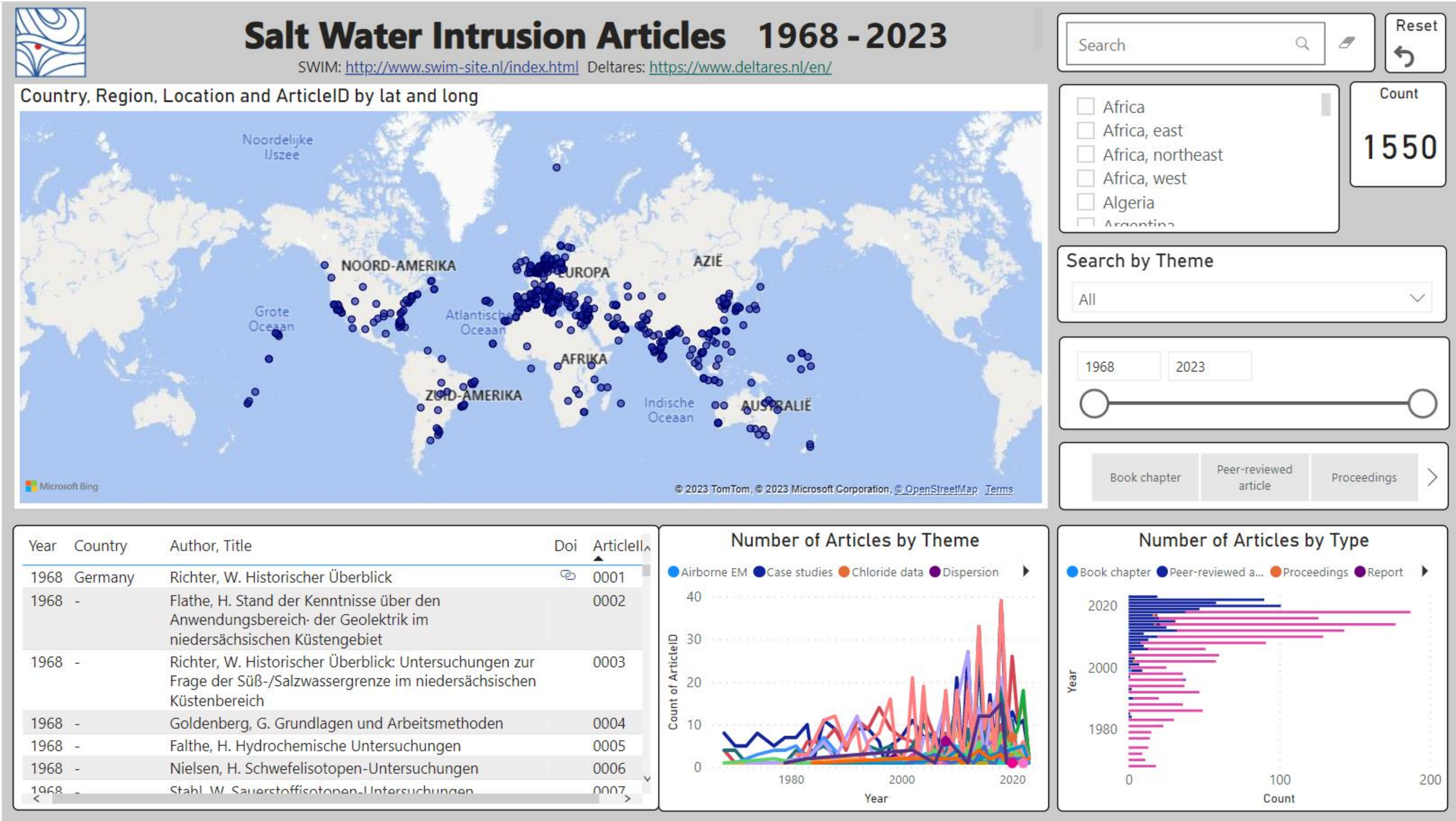
- 30% of global population lives within 100km of the coastline
- <5m Above Present Sea Level: 320 million people and 1.5 million km²

Source: Deltares

Database salt water intrusion articles

link

https://app.powerbi.com/view?r=eyJrIjoiOWU3NzMwZDgtYjQ5Yi00ODZmLWIxOTktMzViMTUyNTQyNTBkIiwidCI6IjE1ZjNmZTBlLWQ3MTItNDk4MS1iYzdjLWZlOTQ5YWYyMTViYiIsImMiOjh9&pageName=ReportSection



Introduction SWI

In 1 liter ocean: about 35 gr salt

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

In 1 liter drinking water: about 0.6 gr salt is allowed

Rice can grow well in water with a salt content less than about 2.0 gr salt in 1 liter water

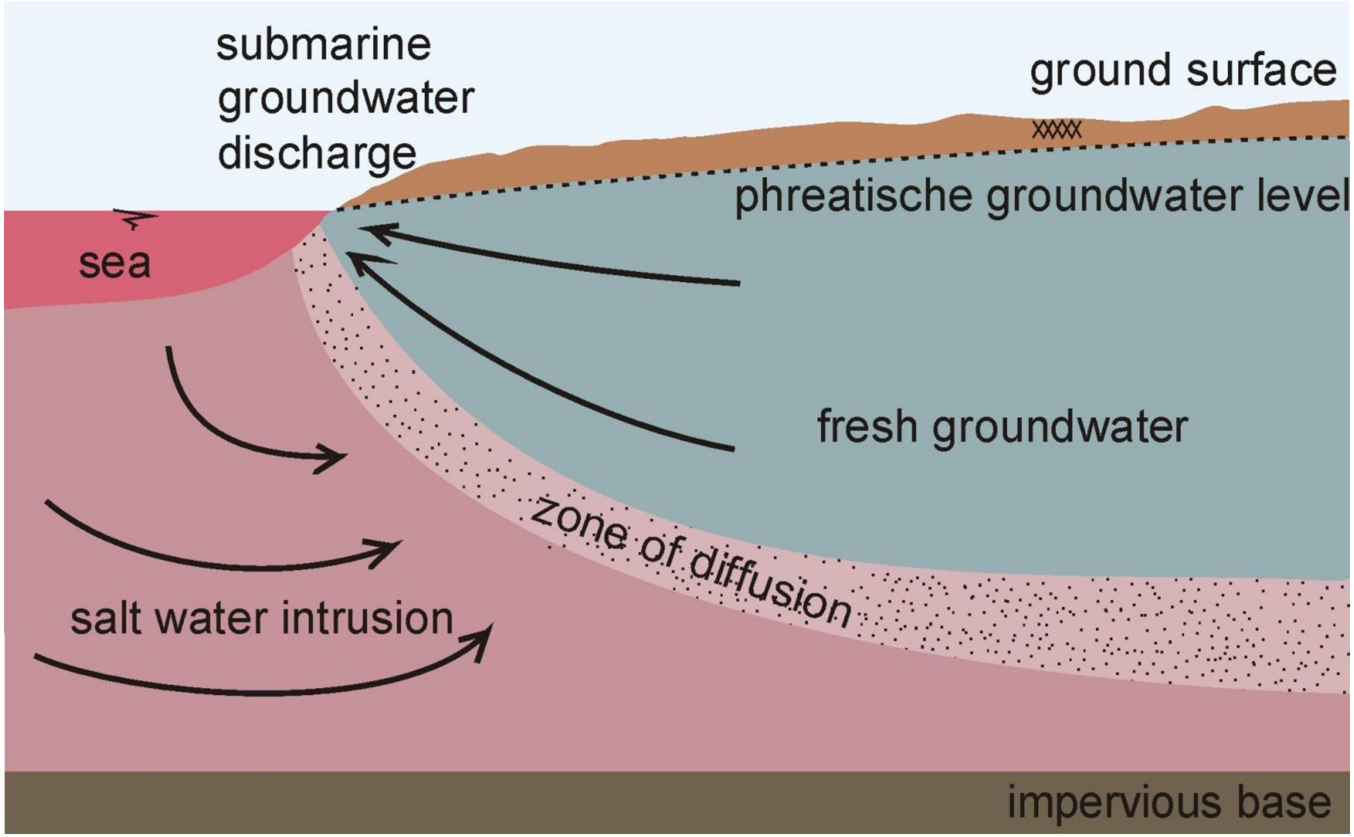
Definition of fresh and saline groundwater

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

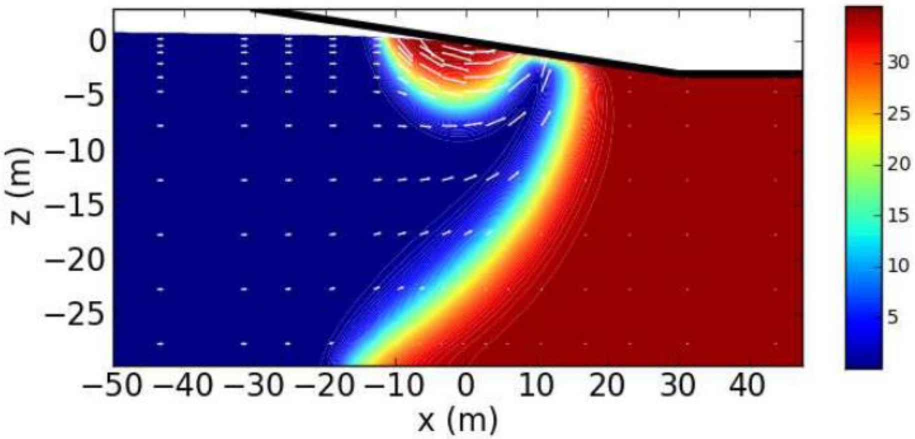
Bangladesh, 2014

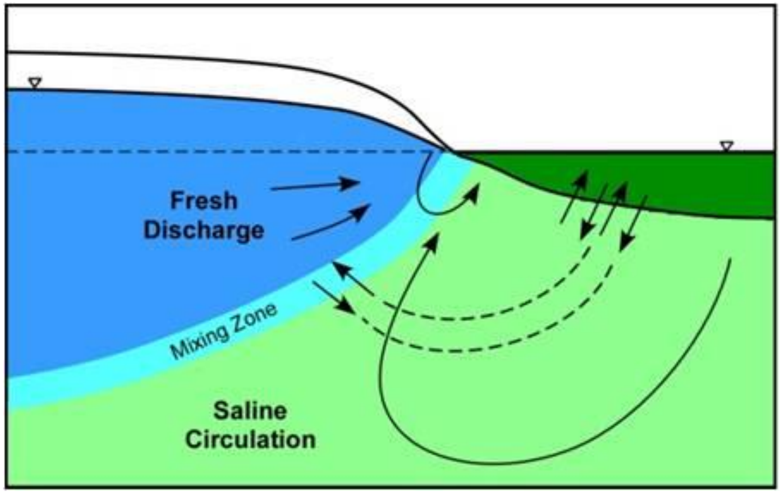
Definition of salt water intrusion

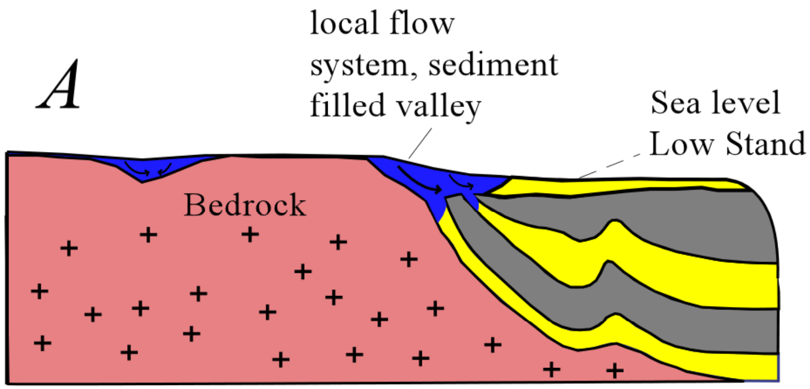
Inflow of saline water into an aquifer which contains fresh water



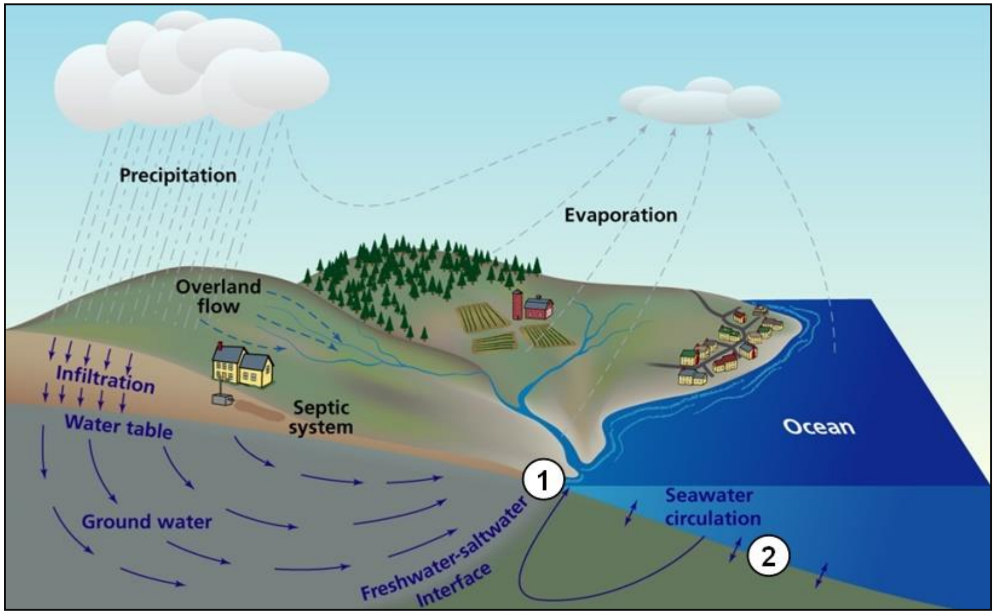
Groundwater in the coastal zone

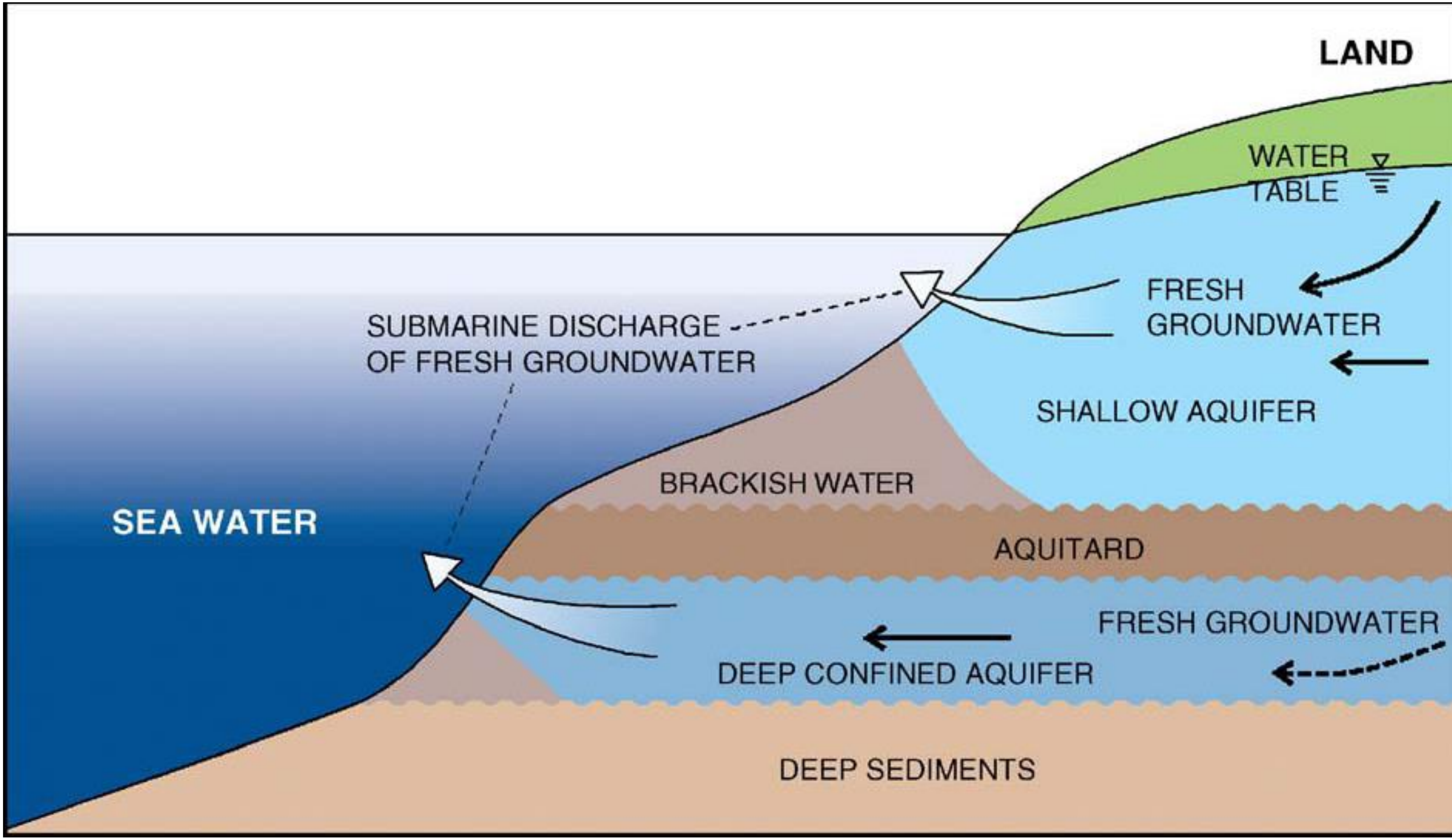






Source: Nature, 2013




LAND
WATER TABLE
FRESH GROUNDWATER
SUBMARINE DISCHARGE OF FRESH GROUNDWATER
SHALLOW AQUIFER
BRACKISH WATER
SEA WATER
AQUITARD
FRESH GROUNDWATER
DEEP CONFINED AQUIFER
DEEP SEDIMENTS

Origin of saline groundwater in the subsoil

Geological causes:

-marine deposits during geological times

-trans- and regressions in coastal areas (deltas)

-salt/brine dome

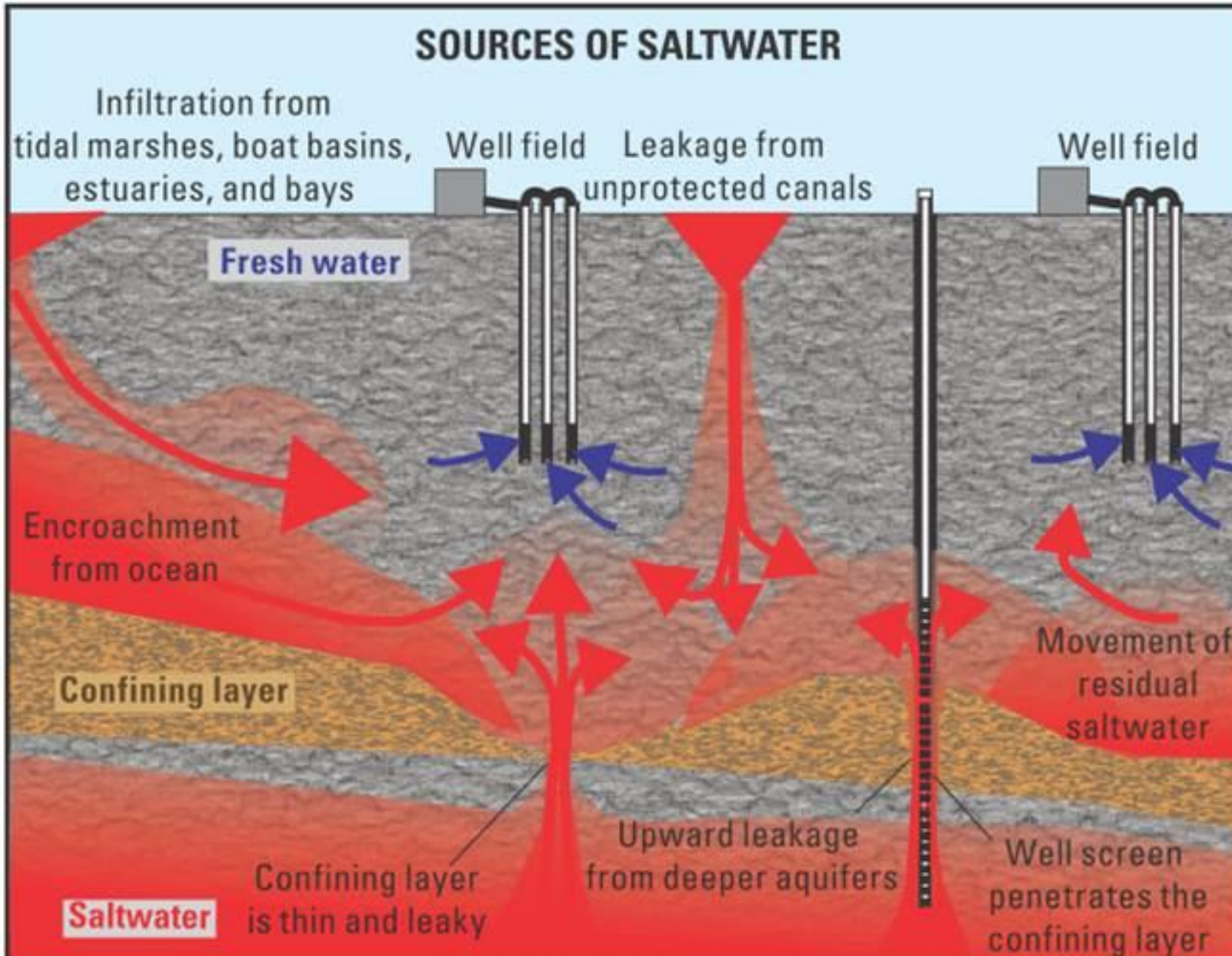
Anthropogenic causes:

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

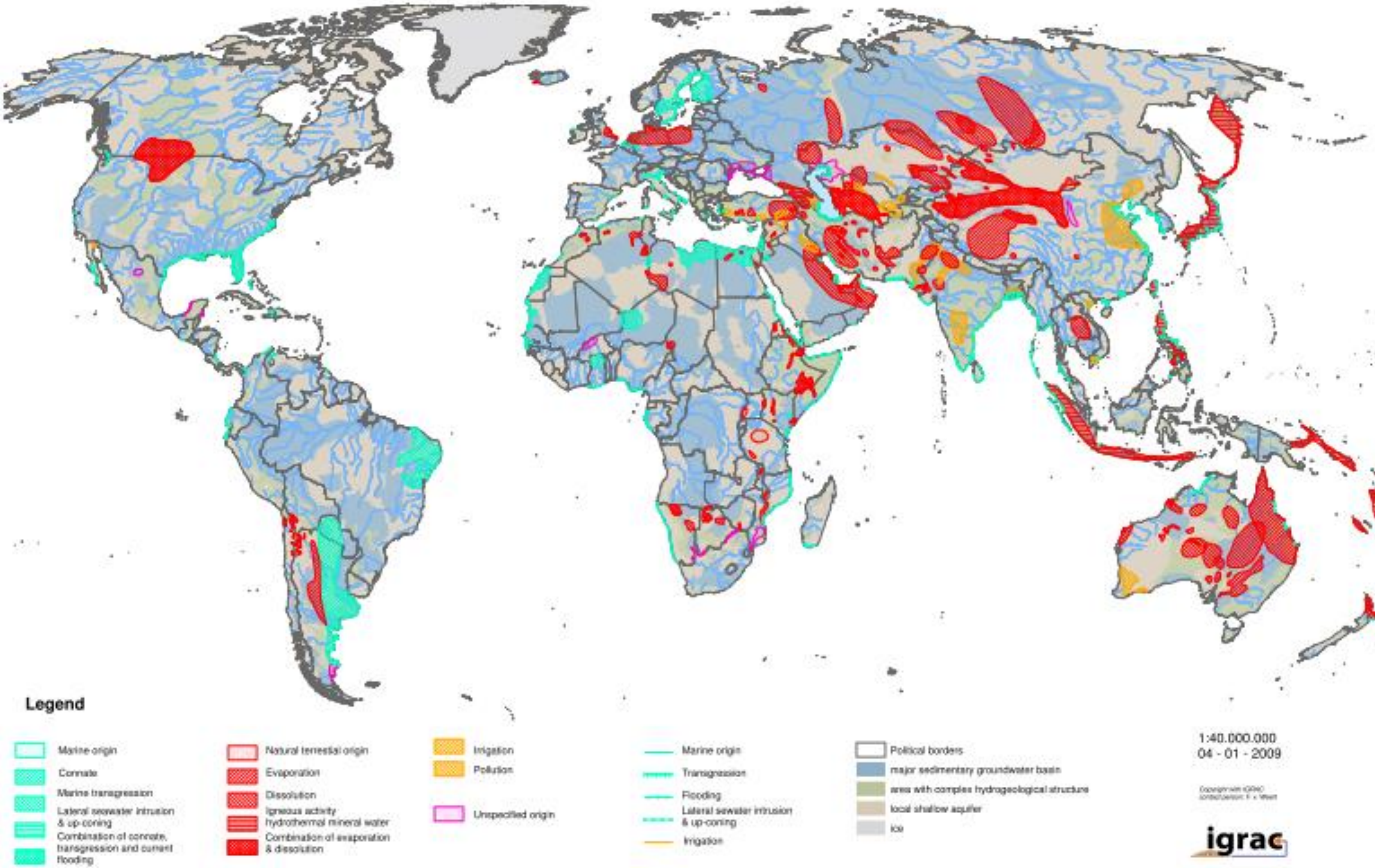
-upconing under extraction wells throughout the world

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

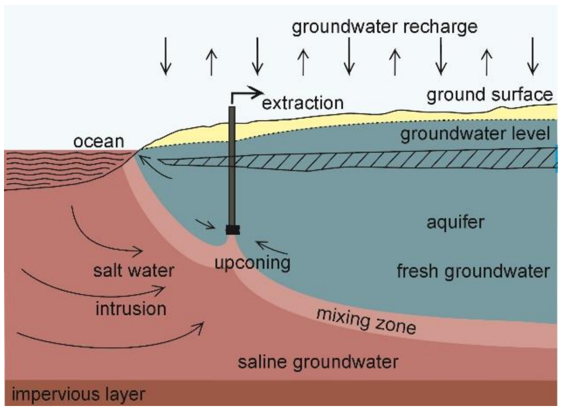
Combining salinization processes in the coastal zone



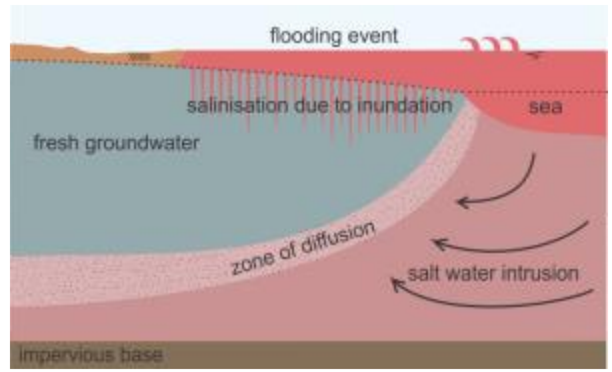
Regions with brackish and saline groundwater at shallow and intermediate depts



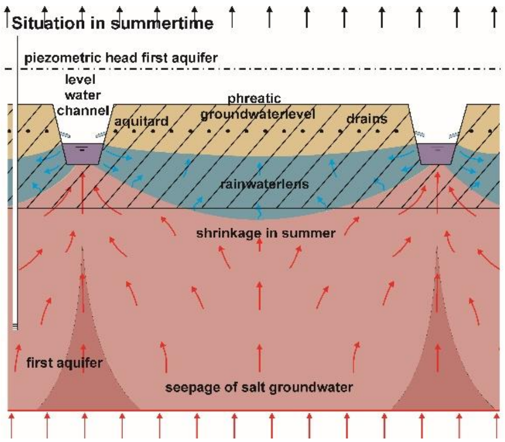
Salinisation processes at local scale



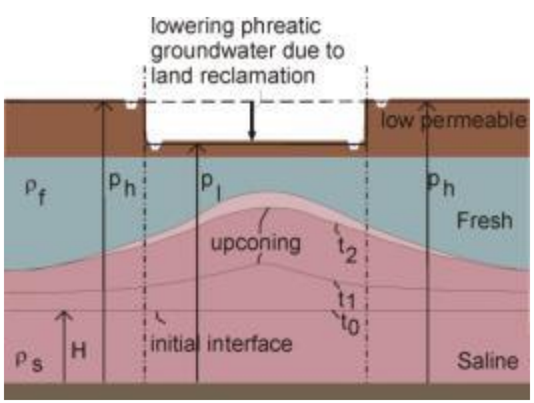
Salt water intrusion groundwater



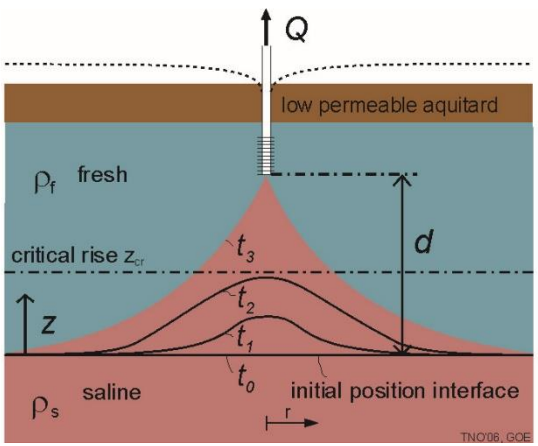
Inundation saline seawater



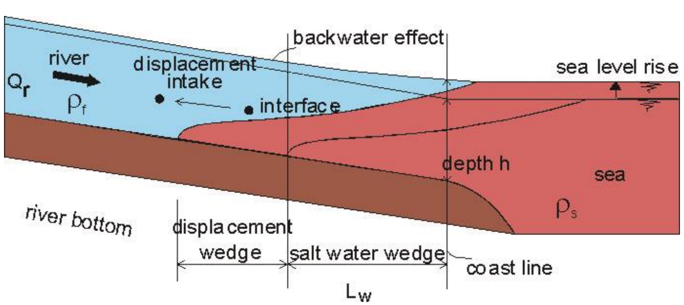
Shallow rainwaterlens



Upconing low-lying area



Upconing extraction

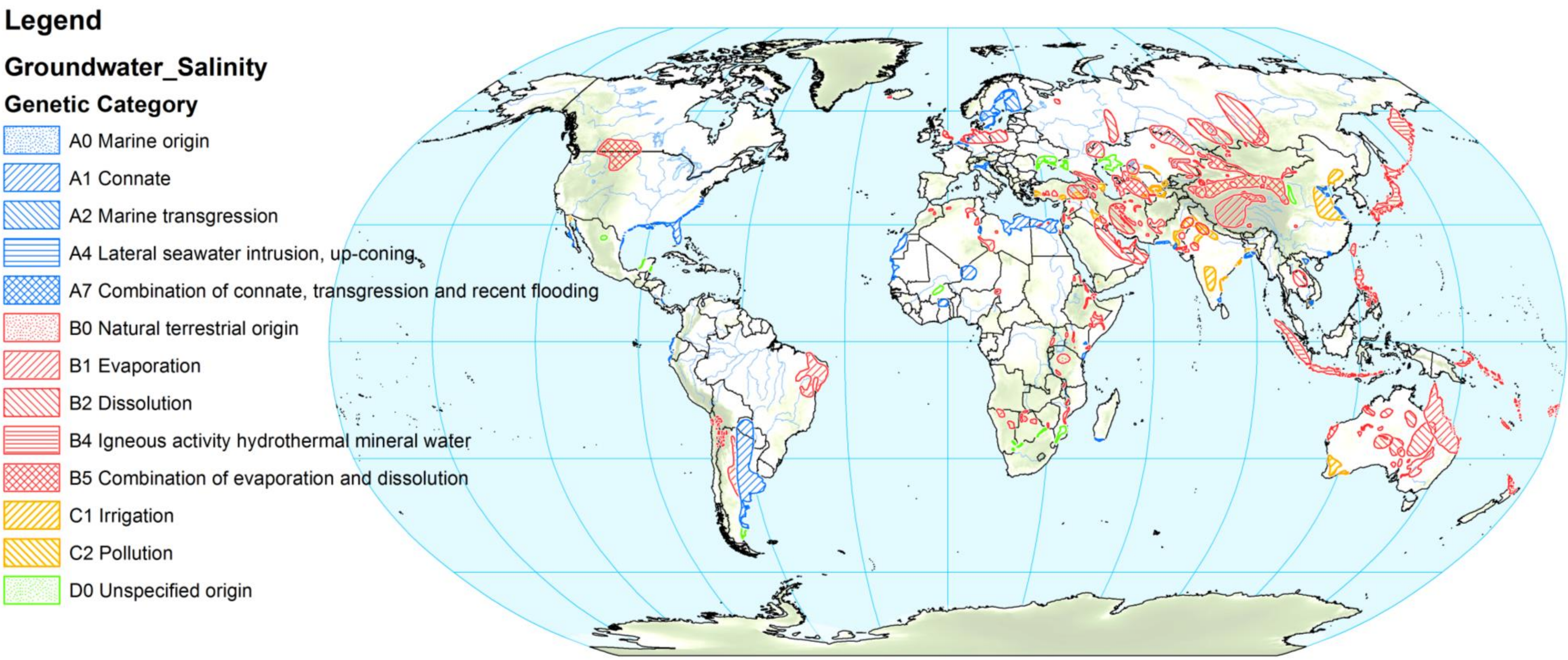


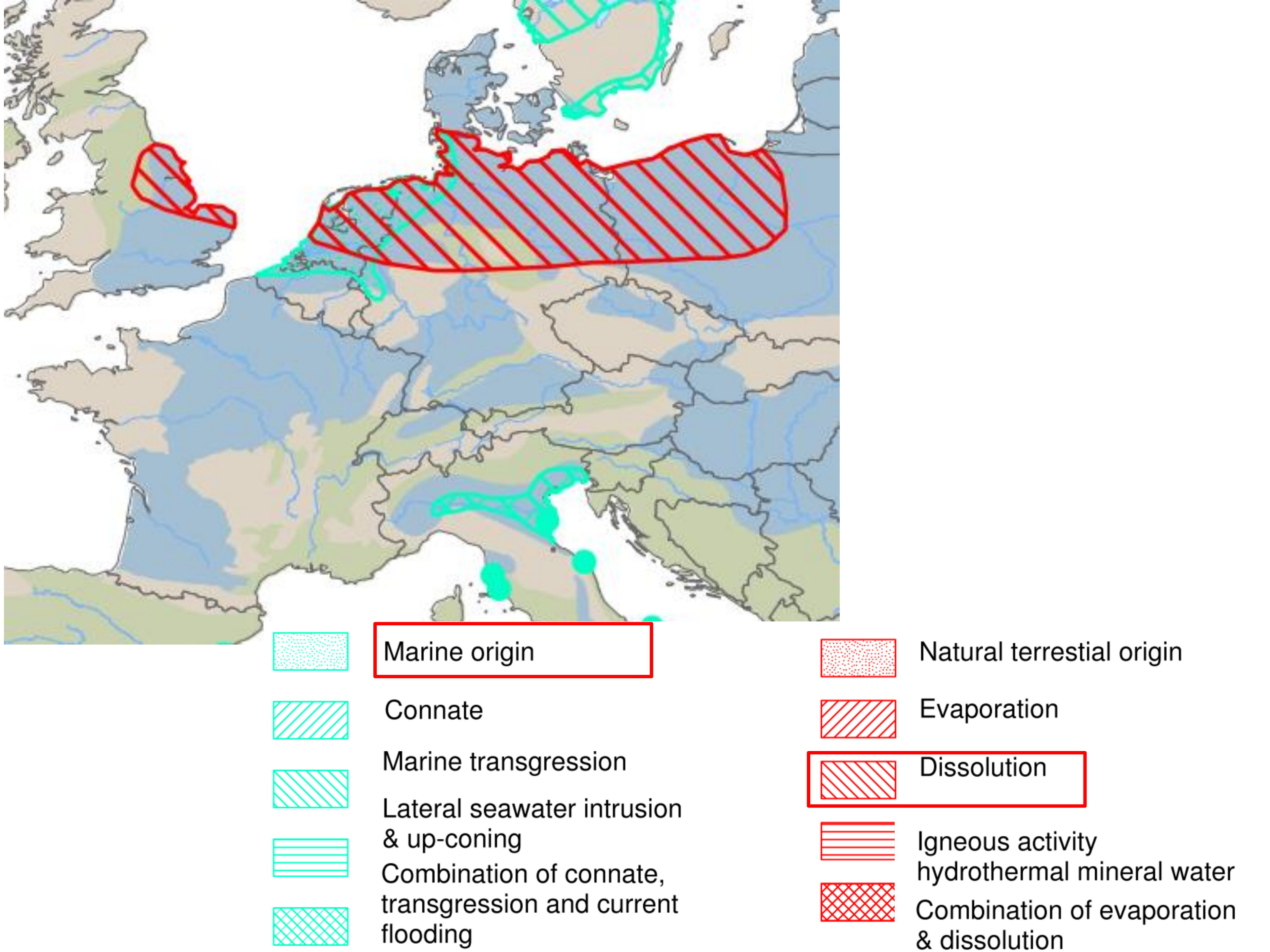
Salt water intrusion surface water

Stress 1: there is salt everywhere

Regions with brackish-saline groundwater at shallow and intermediate depths

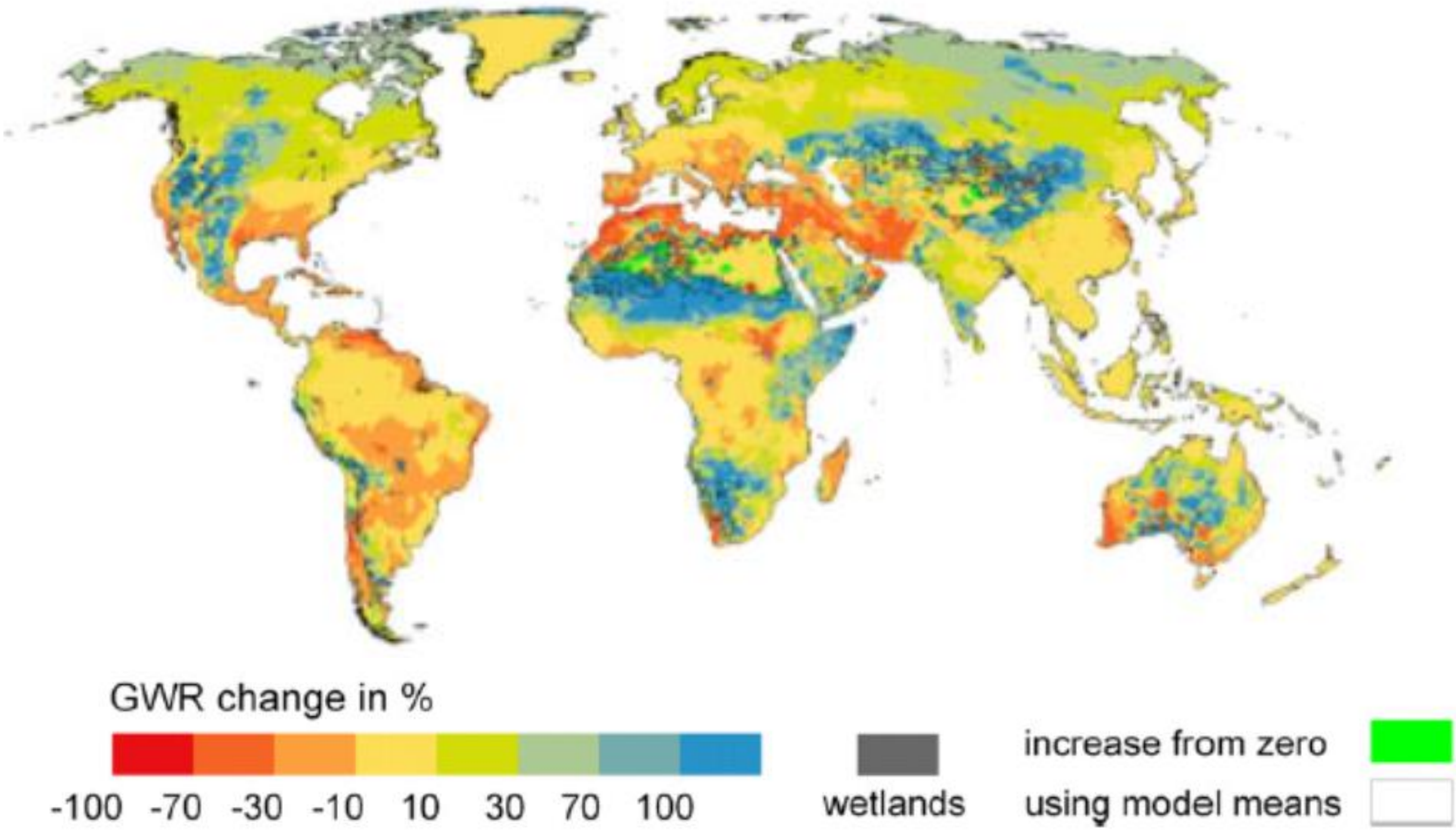
Saline Groundwater of the World





Marine origin
Connate
Marine transgression
Lateral seawater intrusion & up-coning
Combination of connate, transgression and current flooding
Natural terrestial origin
Evaporation
Dissolution
Igneous activity hydrothermal mineral water
Combination of evaporation & dissolution

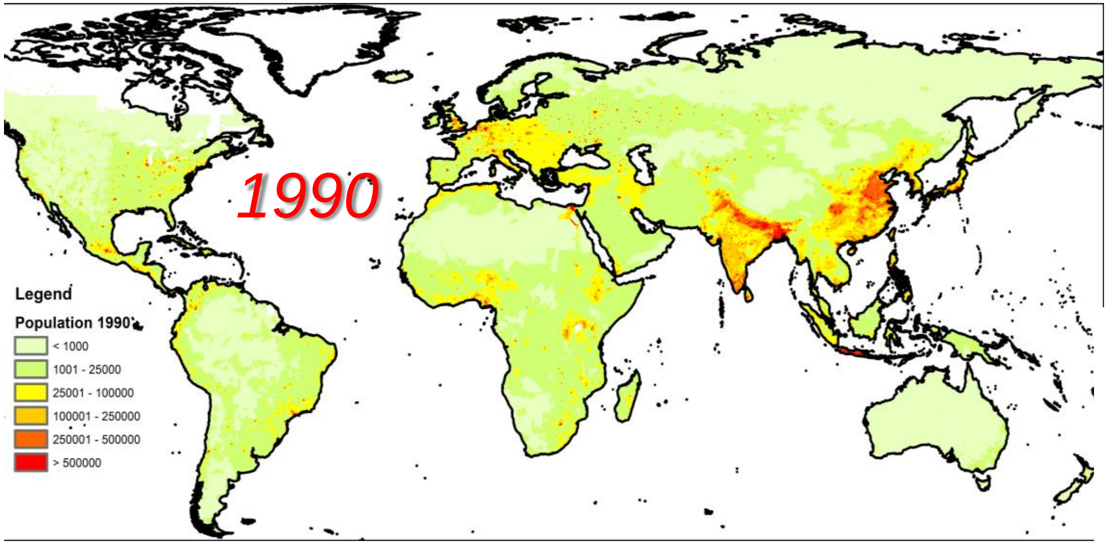
Stress 2: Change in groundwater recharge by end of century



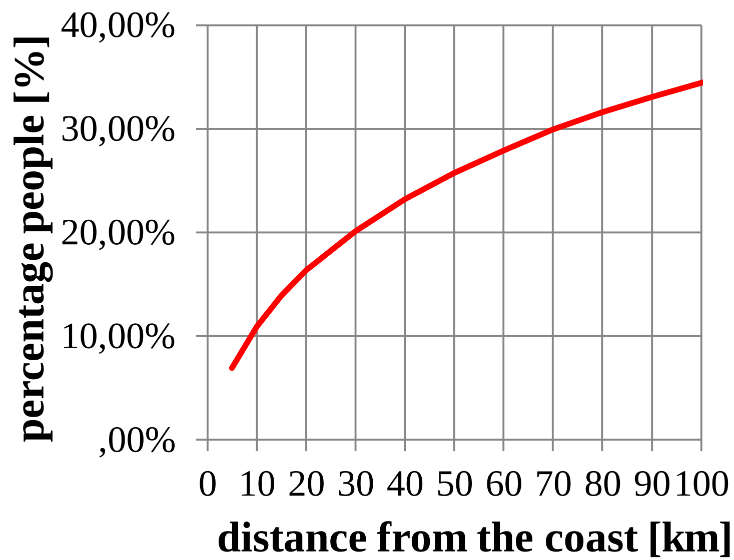
Projected percent changes of groundwater recharge by the end of this century with respect to present (1971–2000)
WaterGAP model with five different GCMs for RCP8.5

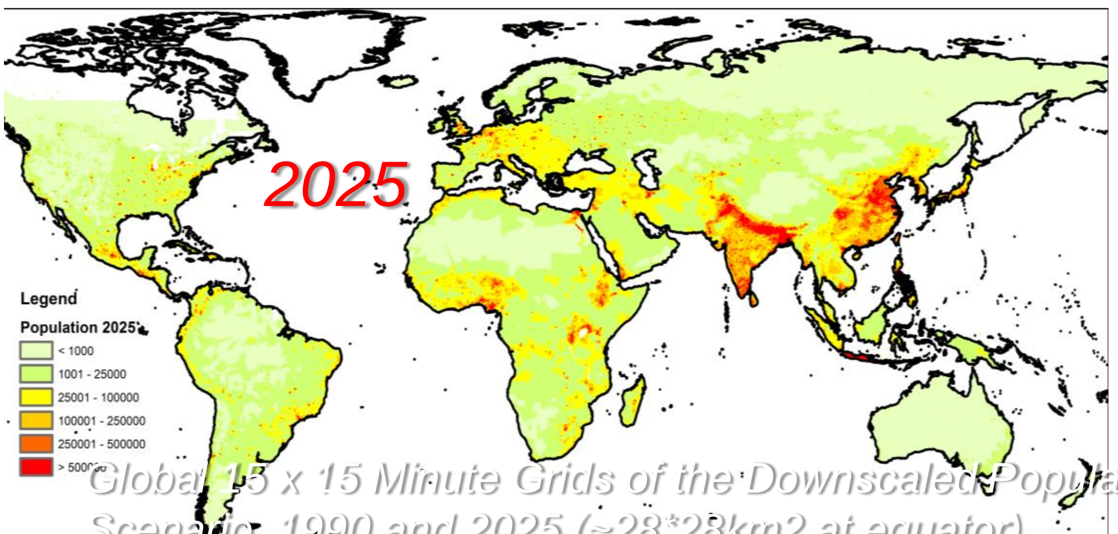
Portmann et al, 2013, ERL
From: Wada

Stress 3: Population growth 1990-2025, needing water



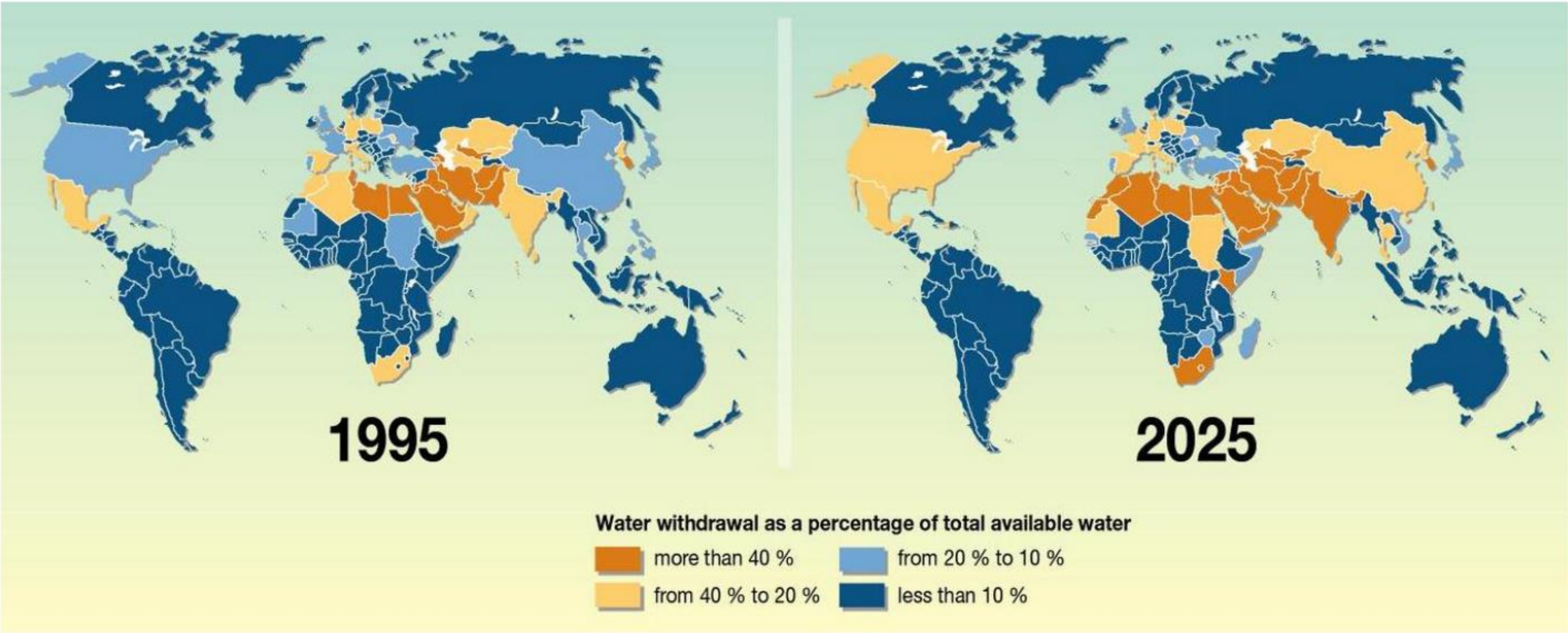
2100 million people in the first 70km from the coastline



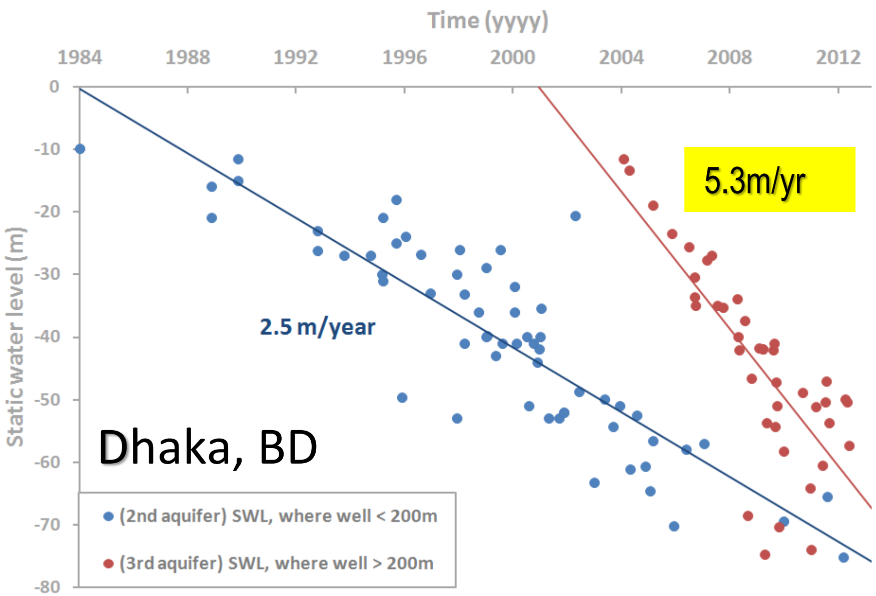


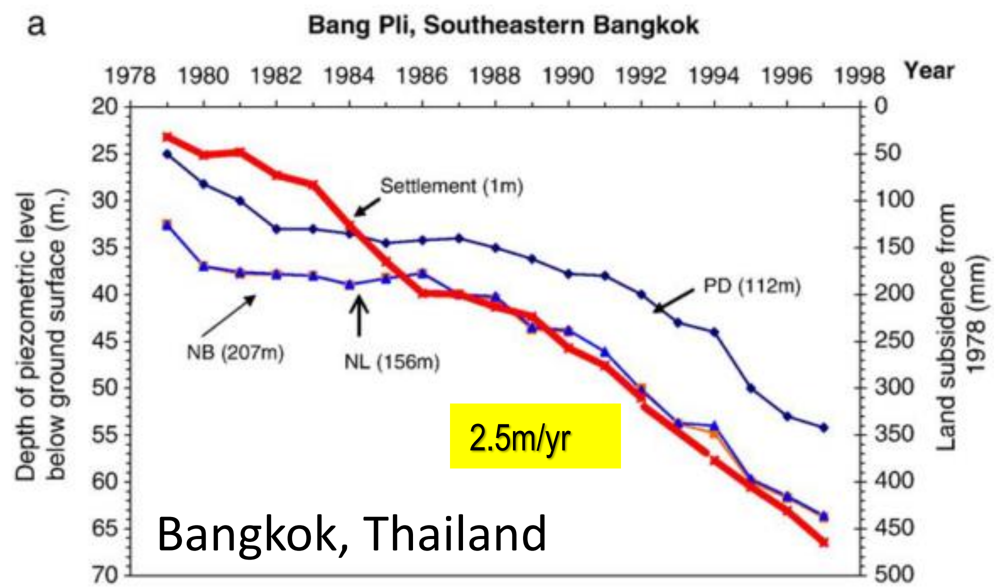
*Global 15 x 15 Minute Grids of the Downscaled Population Based on the SRES B2 Scenario, 1990 and 2025 (~28*28km2 at equator).*

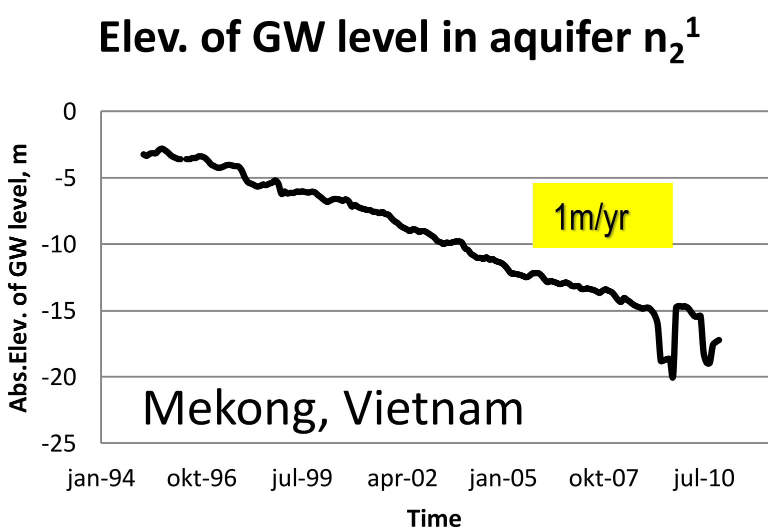
Water withdrawal as % of total available water

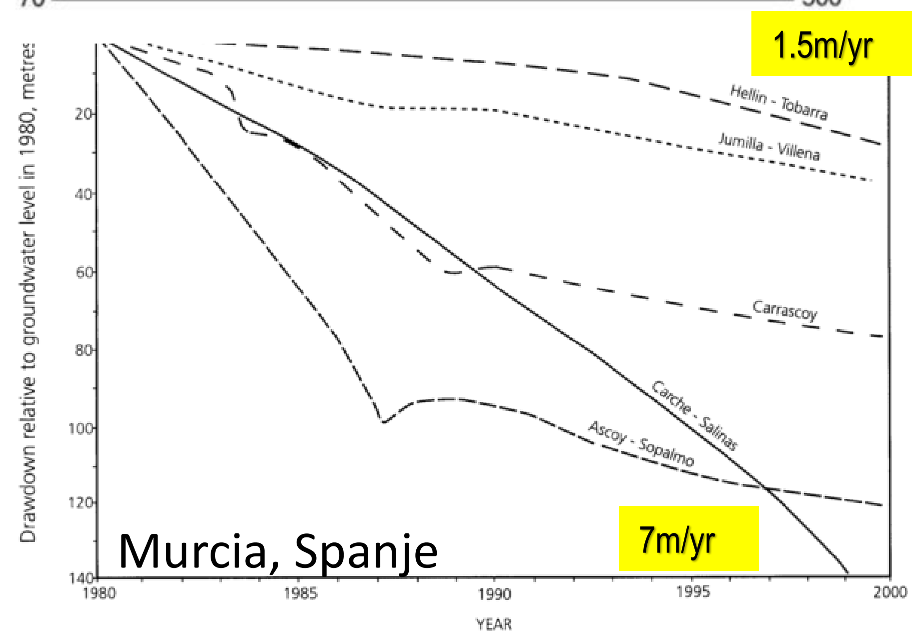


Stress 4: Serious overexploitation coastal aquifers worldwide









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?

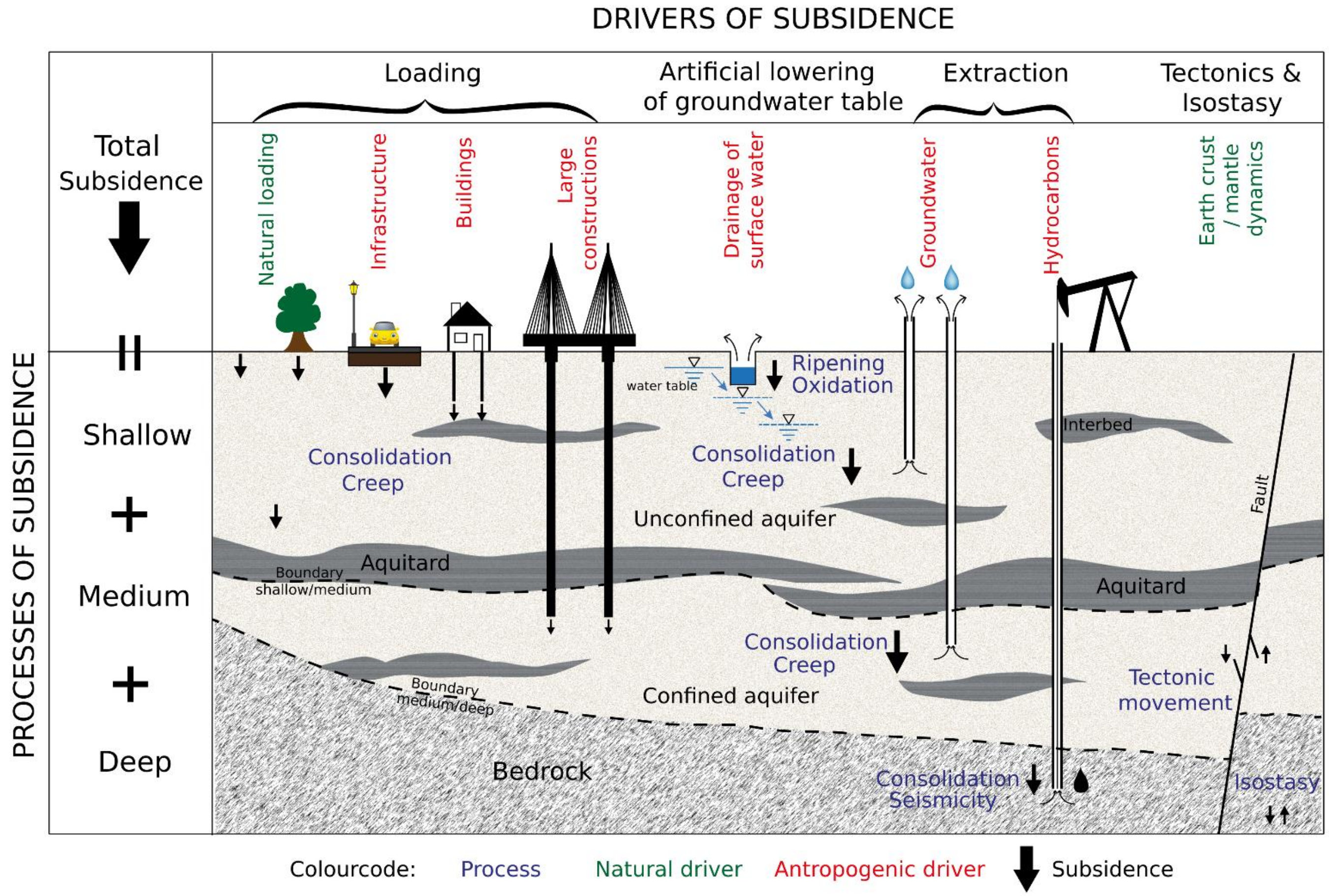
- Magnitude
- Cooping strategy (mitigation versus adaptation)

Possible causes of land subsidence in the Mekong

Land subsidence is natural process in deltas.

Land subsidence can be **accelerated** by human activities that increase physical loading or change the hydrogeological situation

Total subsidence is the cumulative effect of all processes.



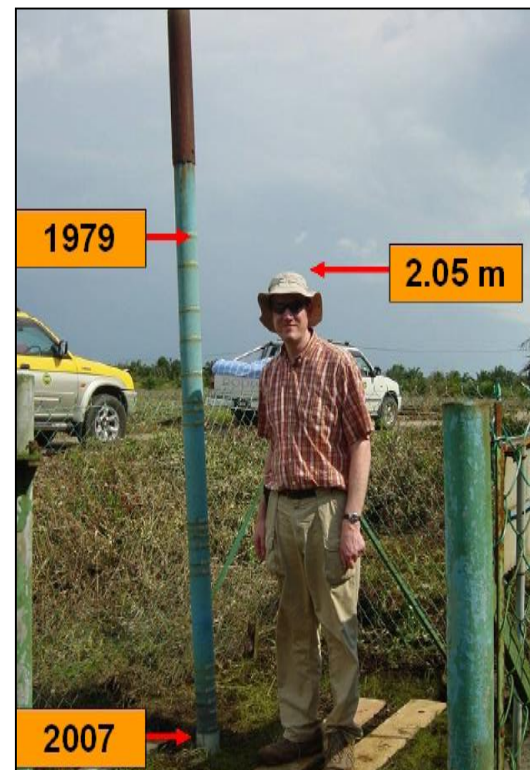
Minderhoud et al. 2015

Impacts


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

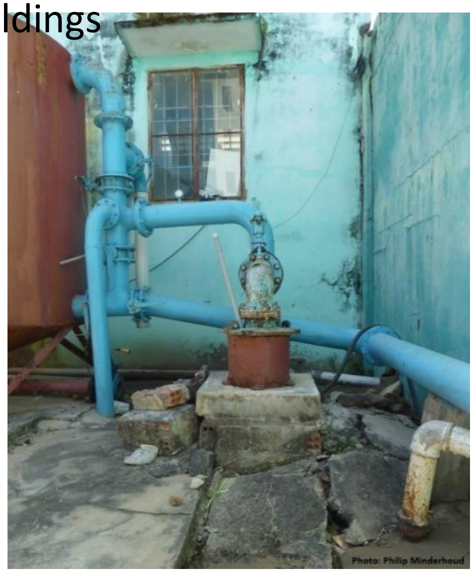

Photo: Philip Minderhoud


Photo: Philip Minderhoud


1979
2.05 m
2007

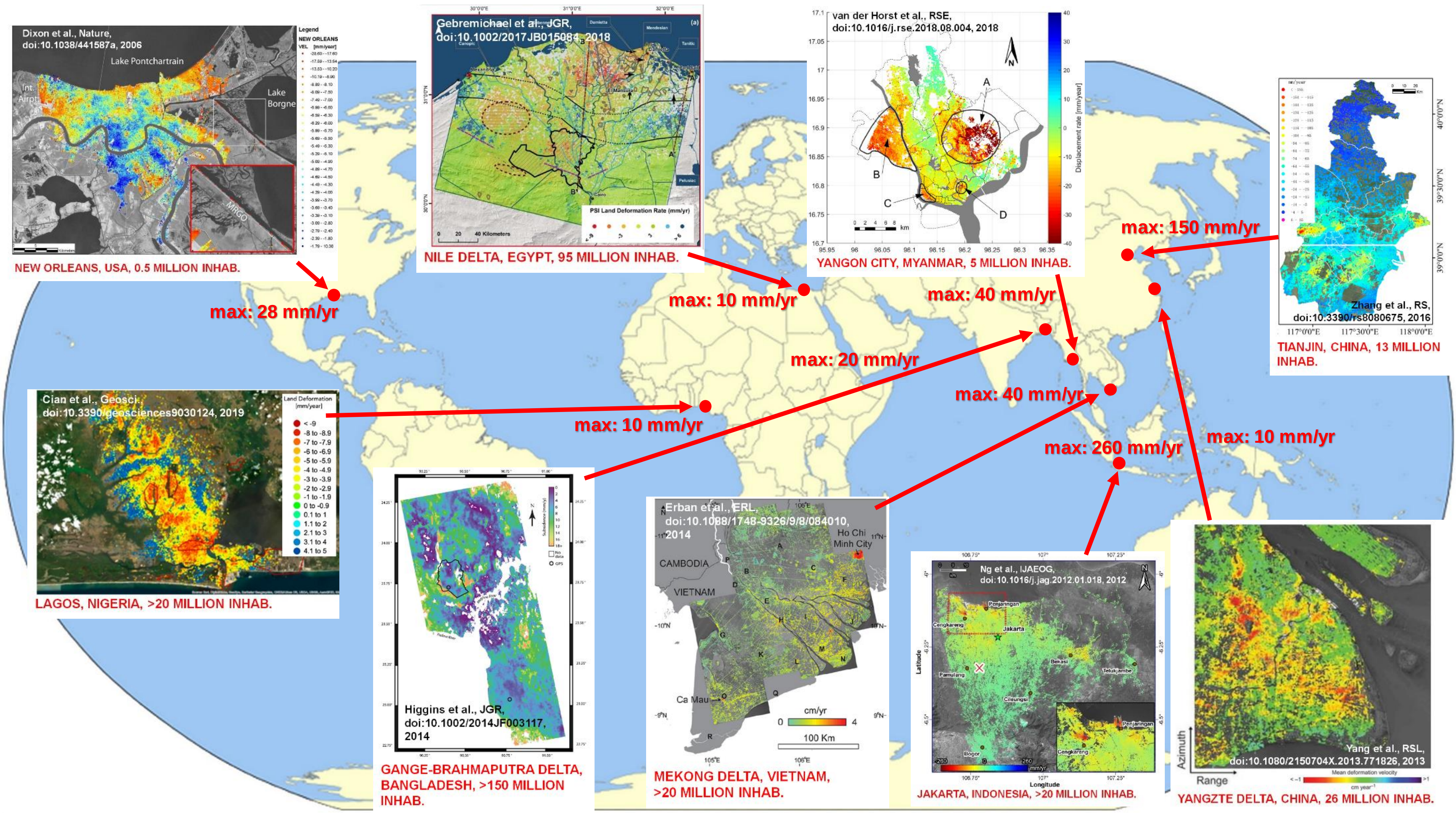
Evidence of subsidence in the Mekong delta

Shallow subsidence, visible around founded bridges and buildings



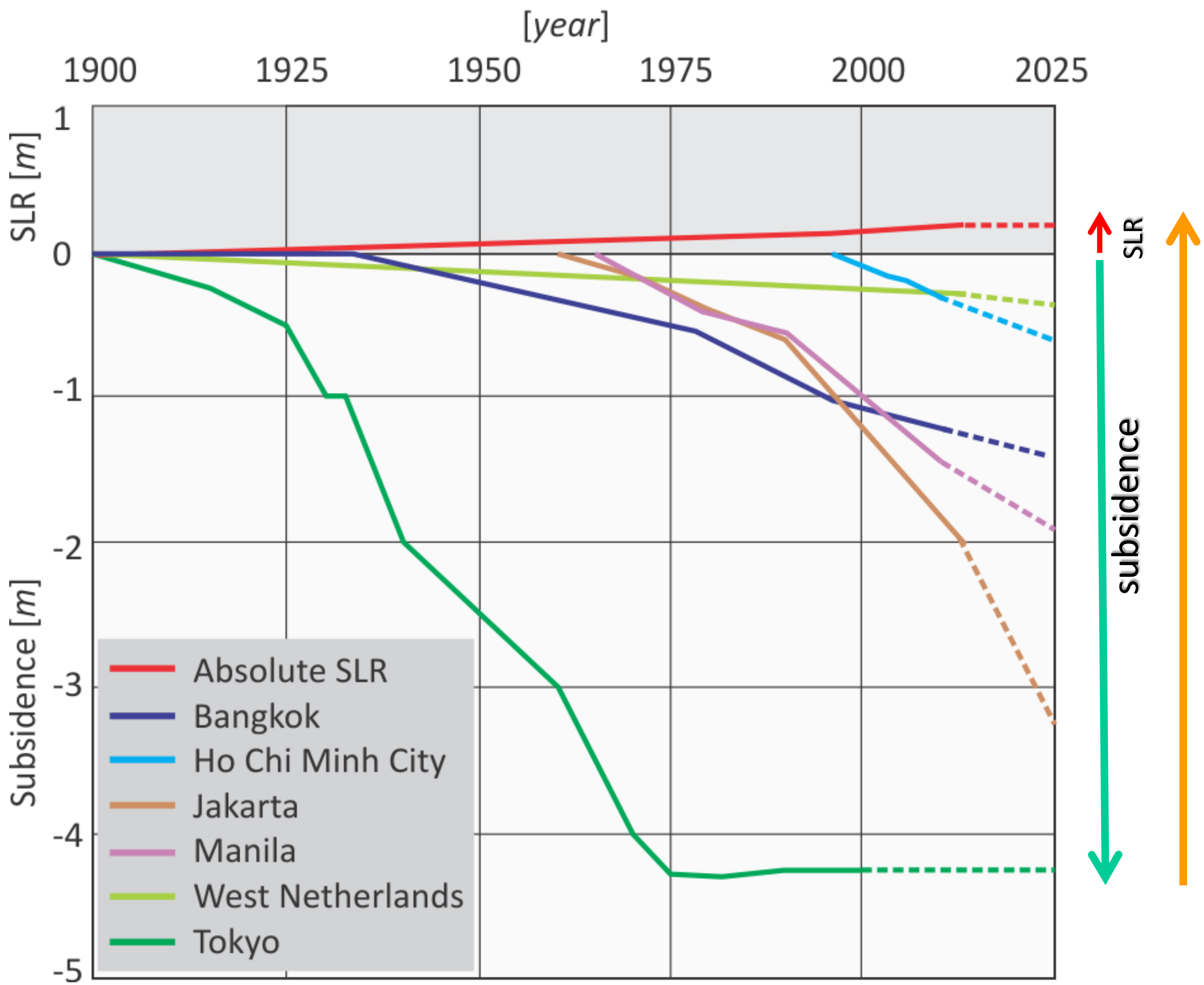
Deeper subsidence, visible by protruding pumping wells

Land subsidence in deltas is a global problem



Courtesy of Pietro Teatini

Stress 5: Land subsidence in some major coastal areas



Relative SLR
Tokyo is 4.5 m!

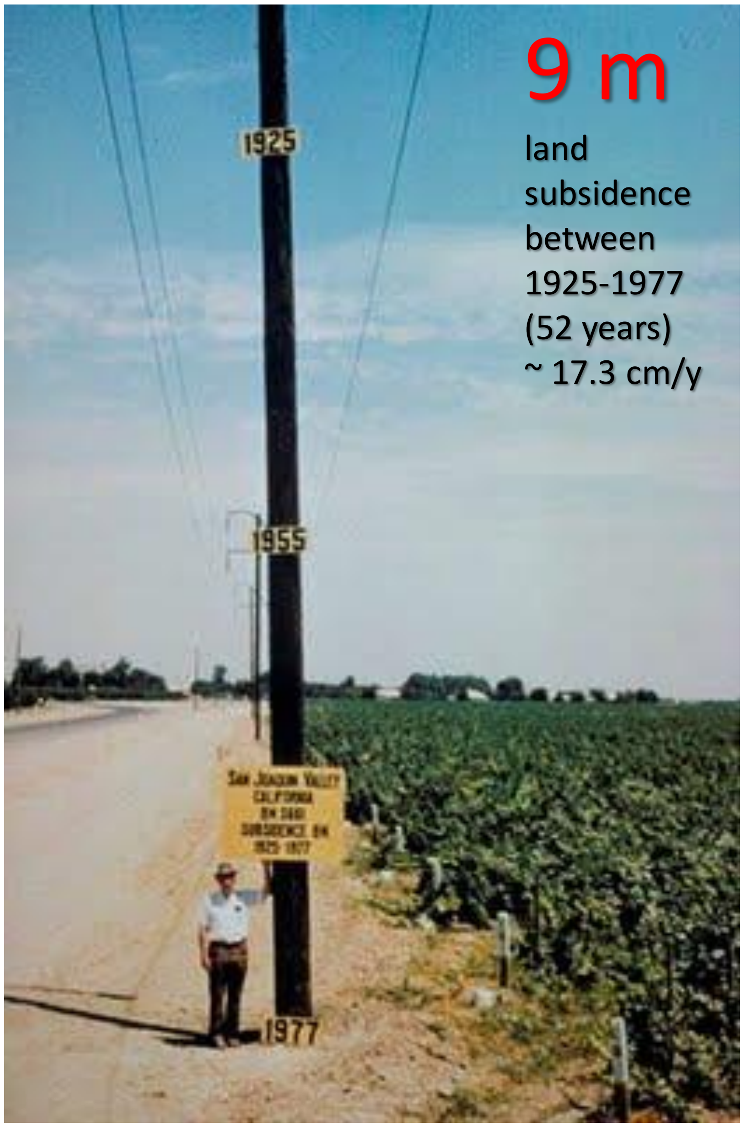
Subsidence issues are underestimated

Four case studies

What lessons can we learn:

1. California, USA
2. Bangkok, Thailand: implementing policies to reduce extraction
   - Groundwater act (1977)
   - Mitigation of Groundwater Crisis and Land subsidence (1983)
   - Groundwater Tariff and Conservation Fee (1985)
3. Jakarta, Indonesia: until today no mitigation measures on groundwater extraction
4. Mekong Delta, Vietnam

Case 1: Land subsidence San Joachim Valley, CA, USA

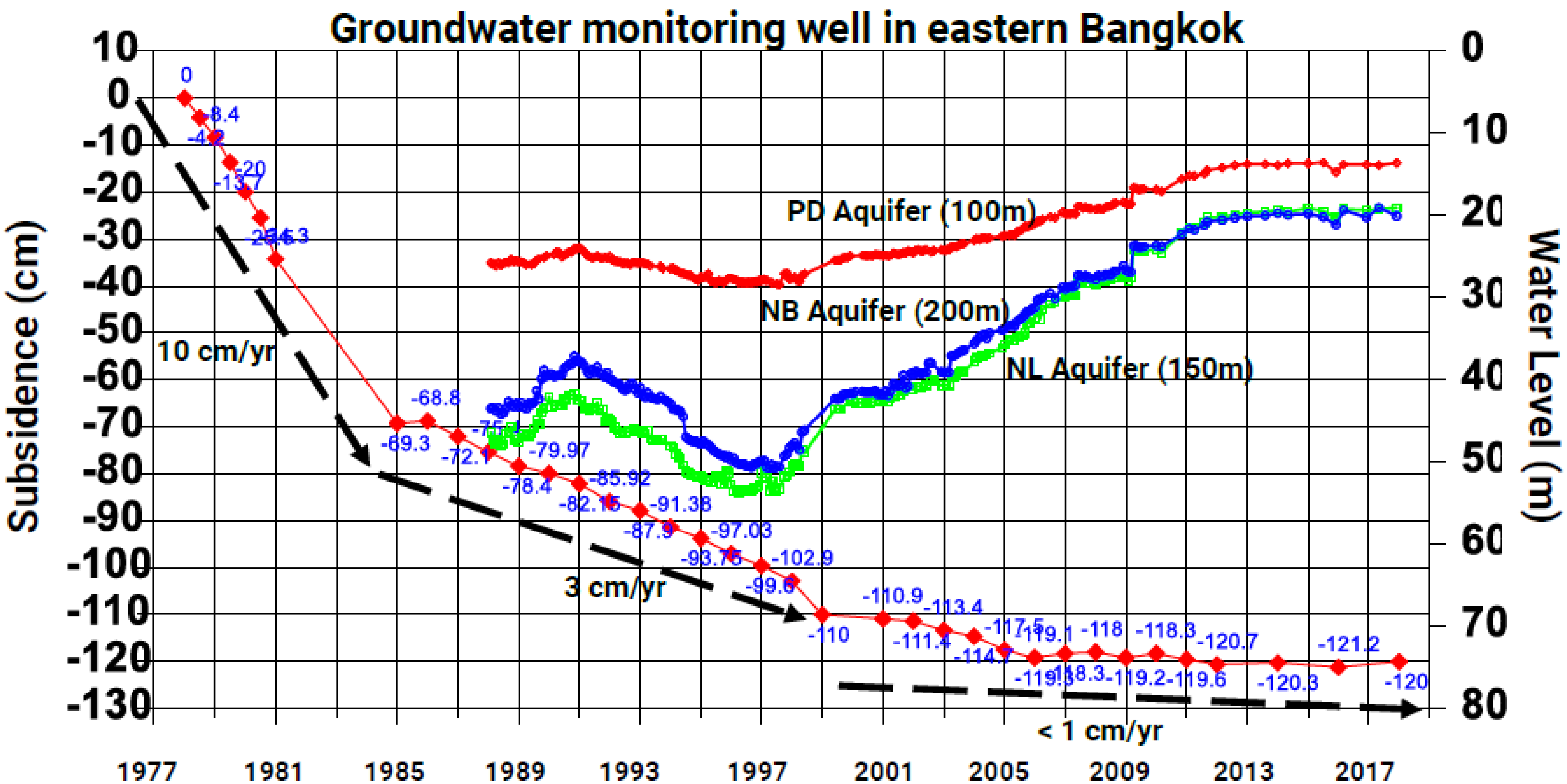


9 m since 1930s

San Francisco

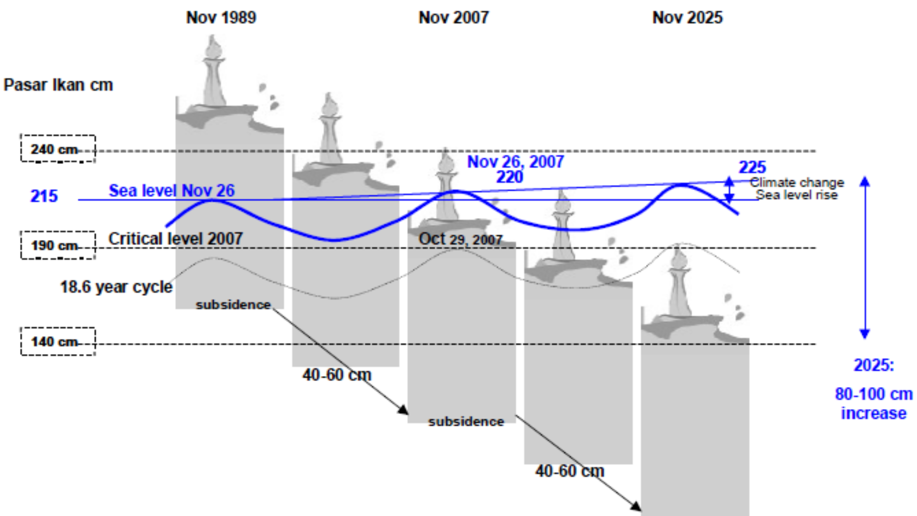
Los Angeles

Case 2: Bangkok



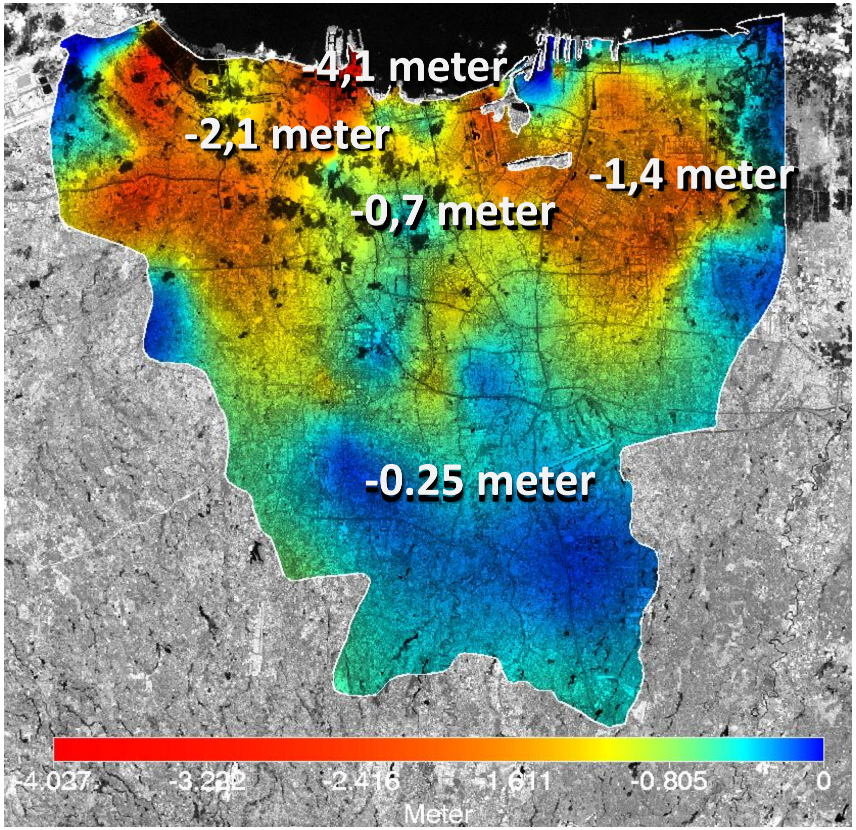
Courtesy: Chadaporn Busarakum

Case 3: Jakarta



Brinkman and Hartman, 2009

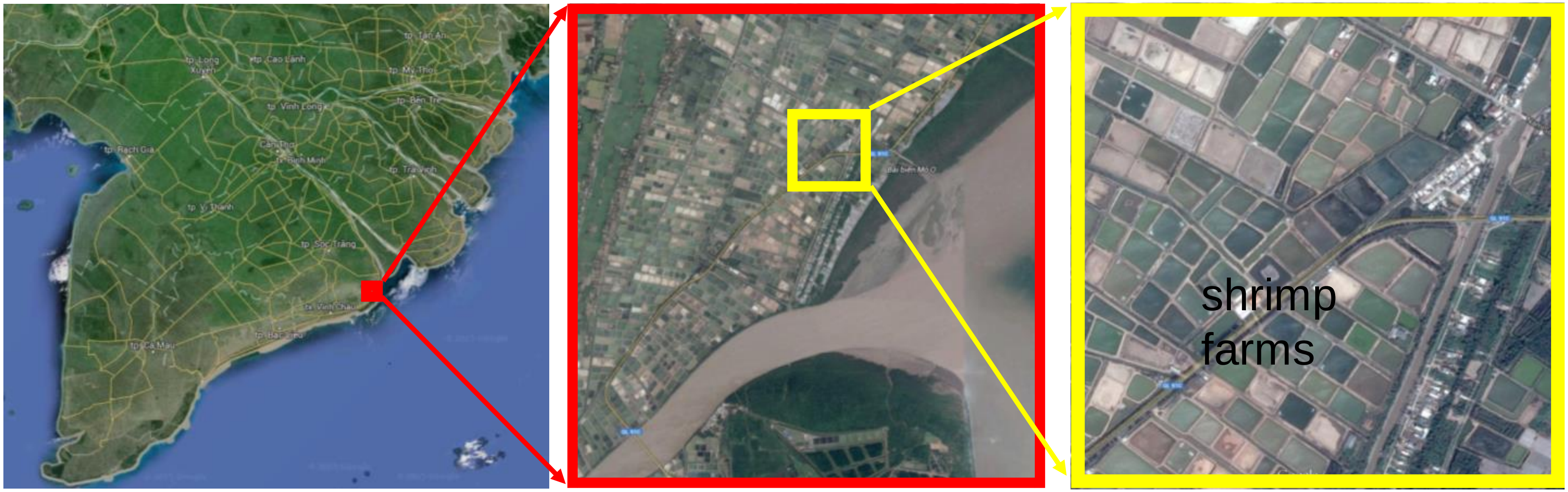
Cumulative subsidence map of Jakarta 1974-2010



Subsidence rates: up to <u>25 cm/year</u>

Case 4: Groundwater overexploitation in Mekong Delta

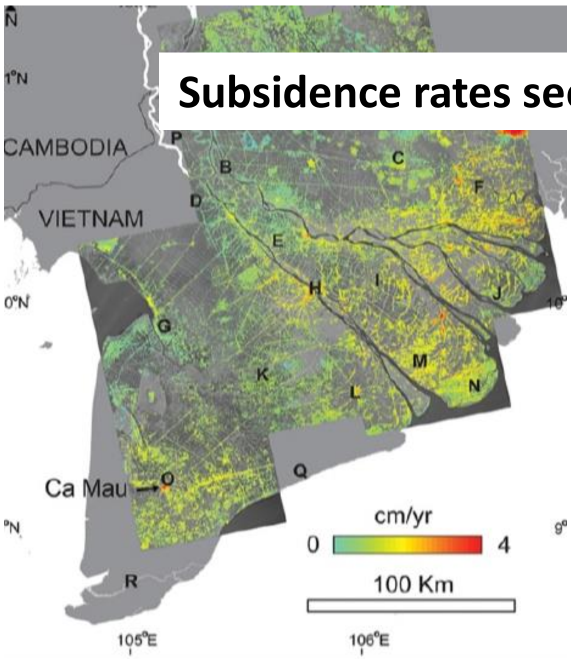
Aquaculture (e.g. shrimp farms) need an large quantity of fresh groundwater



The Mekong delta is sinking

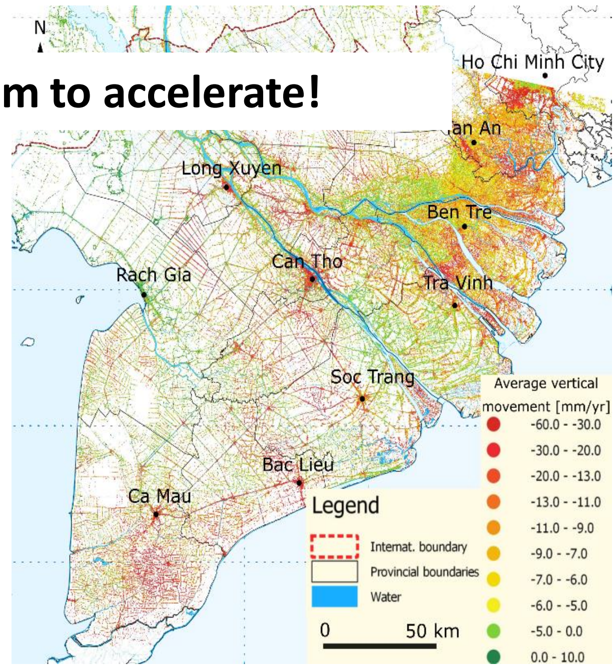
Estimated InSAR-derived subsidence rates (cm/yr)

Subsidence rates seem to accelerate!



2006-2010:
Up to 4 cm/yr

Erban et al., 2014. Environ. Res. Lett.

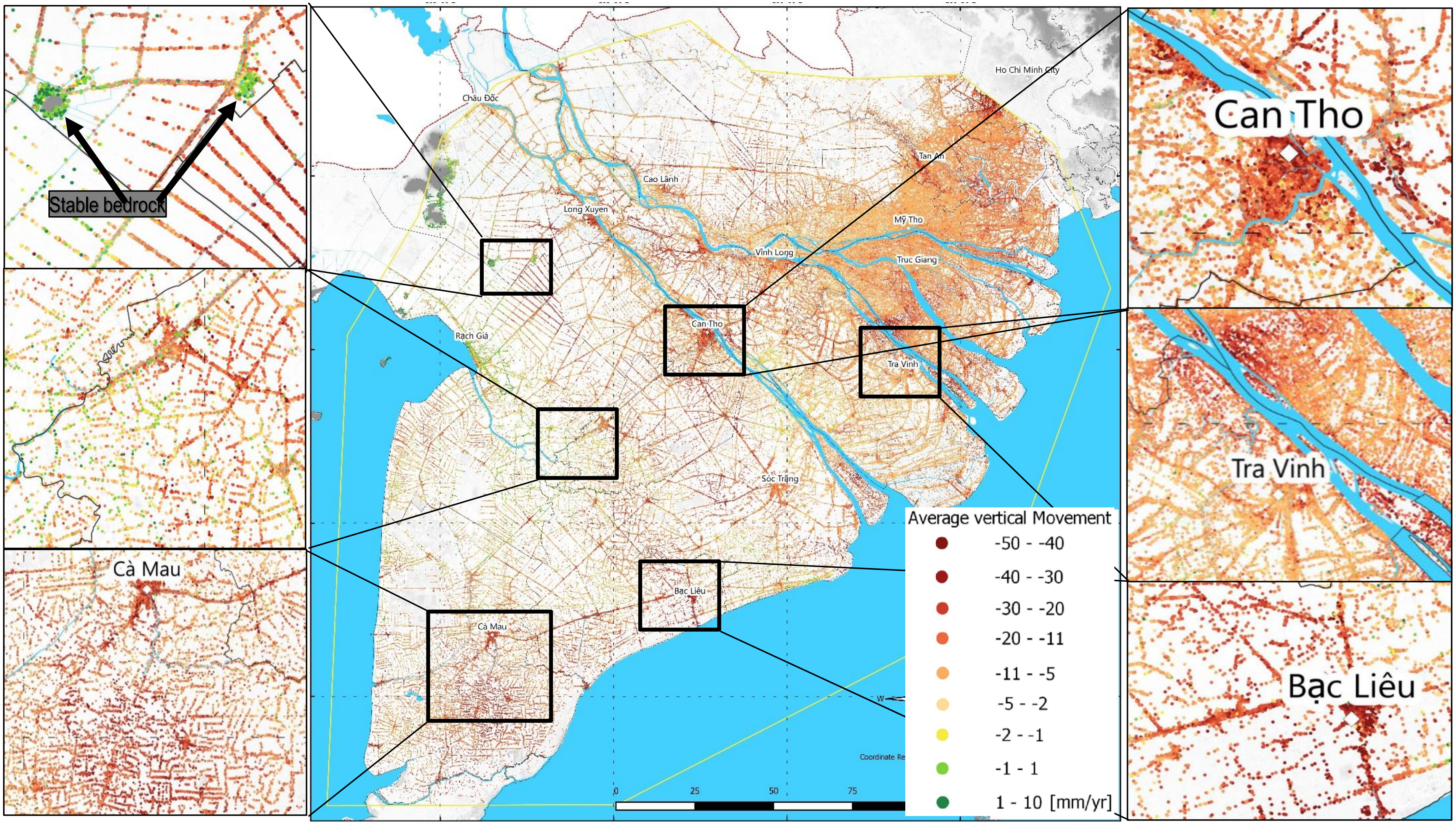


2014-2019:
Up to 6 cm/yr

EU Copernicus EMSN062

Evidence on the ground

Satelite measured subsidence rates (*2014-2019*): ~10-50 mm/yr

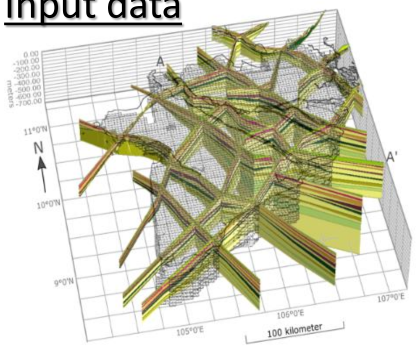


Copernicus ESMN-62 in cooperation with GIZ and BGR

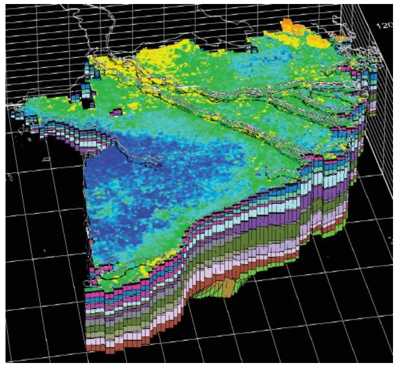
Hydraulic and hydrogeological data from DWRPIS and SIWRR

iMOD-WQ-SEAWAT-SUB-CR: 3D model groundwater salinity + subsidence

<u>Input data</u>

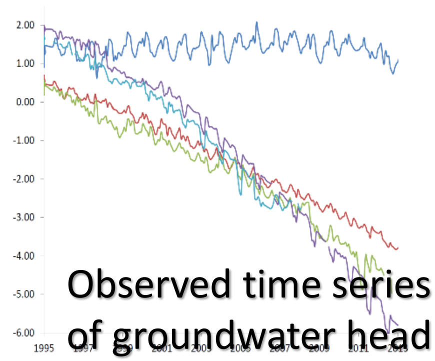


Geological borelogs and cross-sections

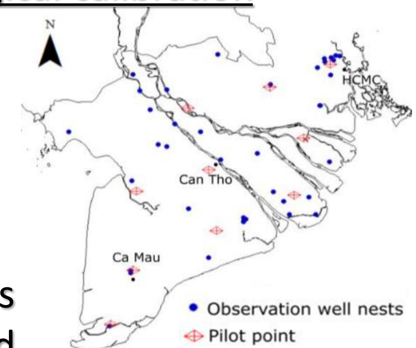


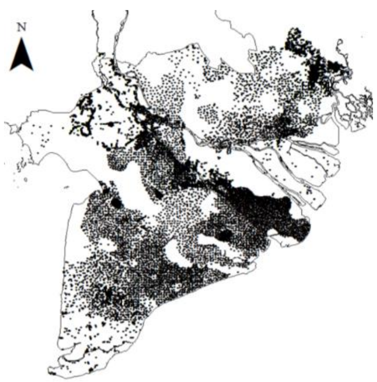
3D geology

<u>Hydrogeological calibration</u>

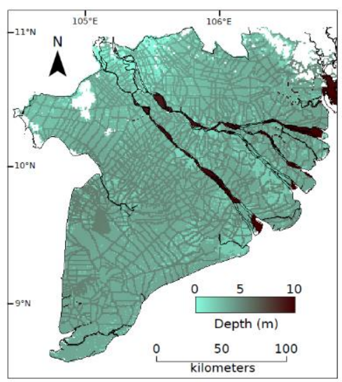


Observed time series of groundwater head



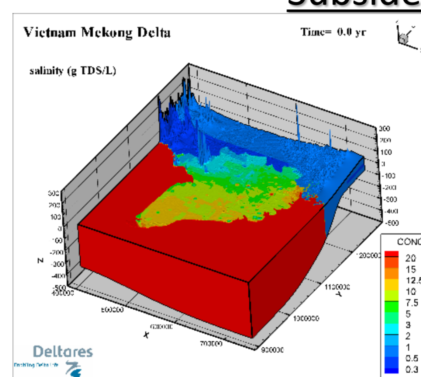


Location, depth & rate of groundwater extractions

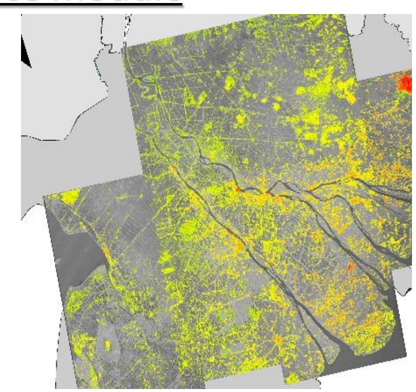


Surface water system

<u>Subsidence module</u>



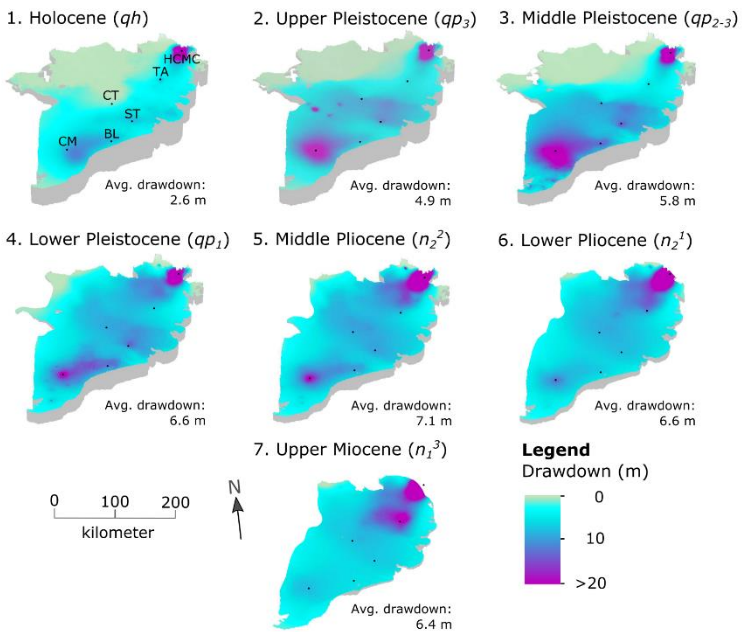
3D salinity

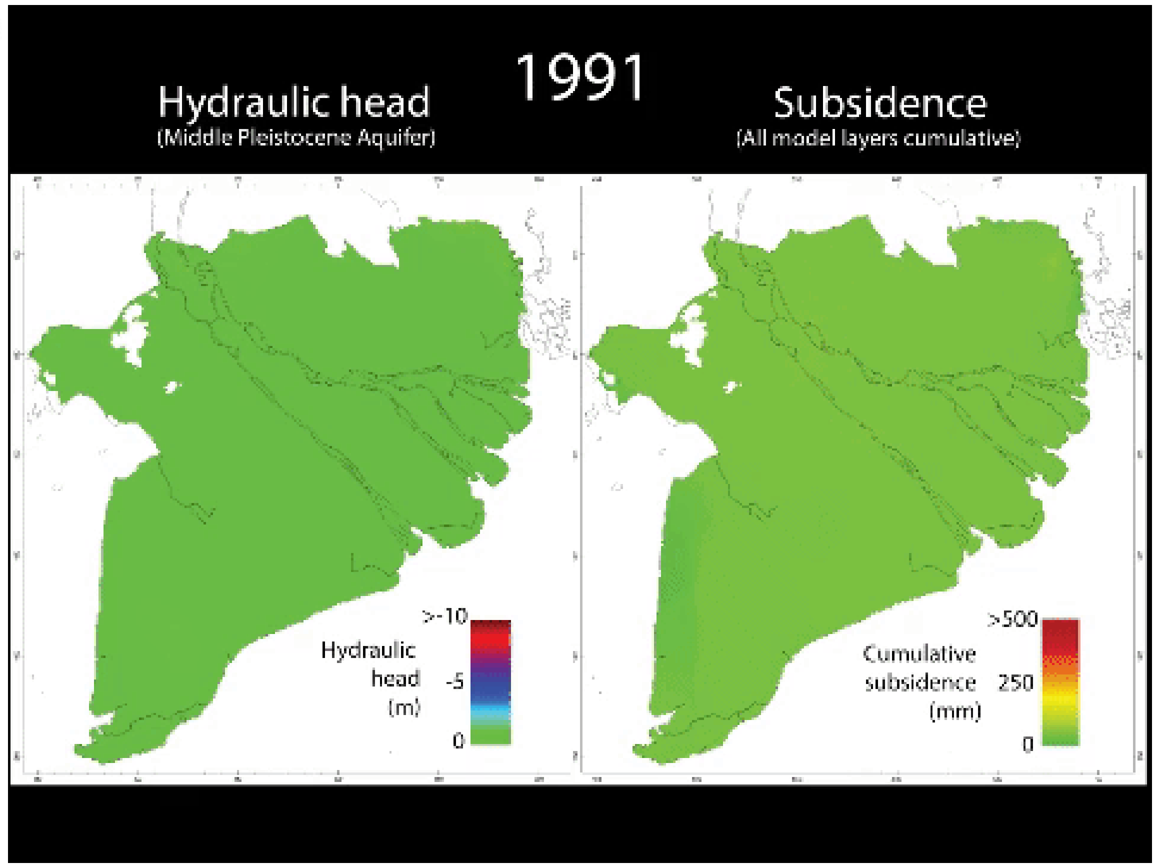


Validation: InSAR-derived subsidence (Erban et al., 2014)

Minderhoud et al., 2017 - Environmental Research Letters

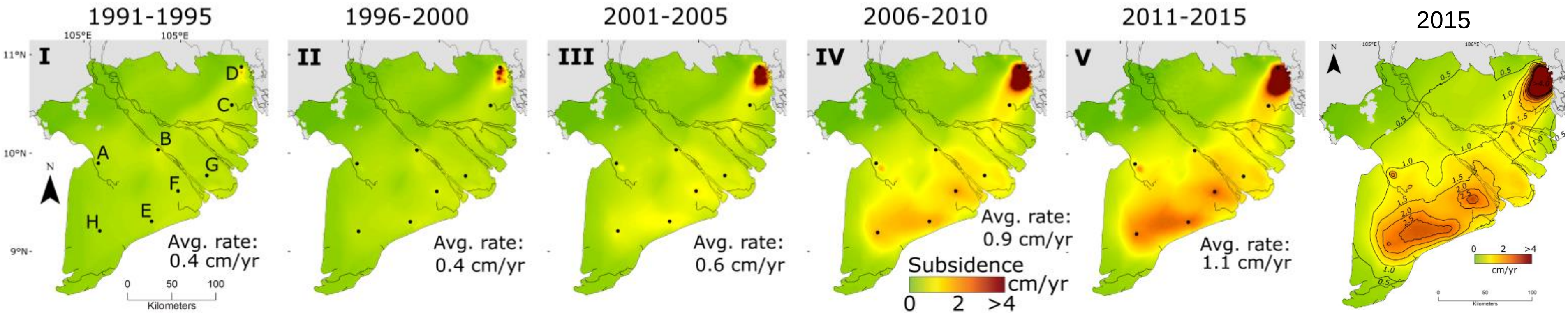
25 years of simulated groundwater extraction



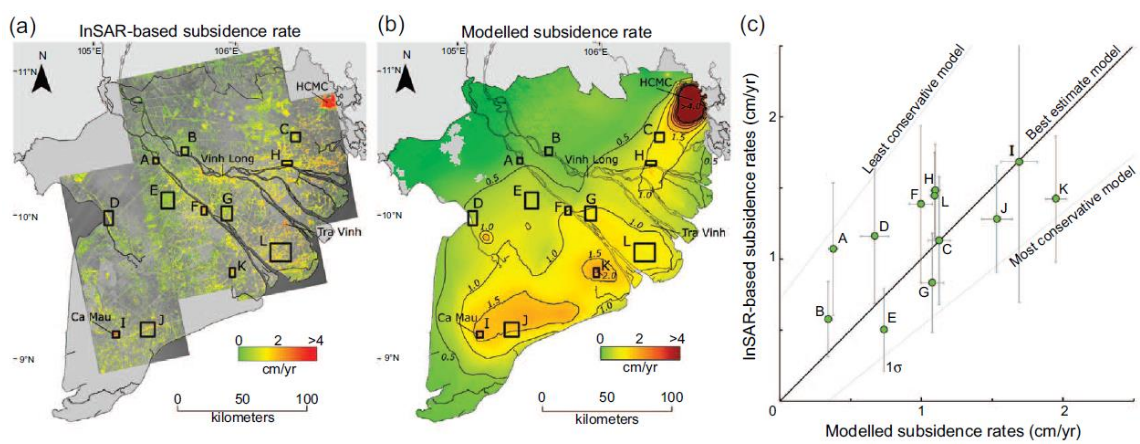


Groundwater extraction is much larger than groundwater recharge, and replenishment is very limited

Extraction-induced subsidence is accelerating!



Groundwater extraction-driven subsidence exceeds absolute sea-level rise by a magnitude!



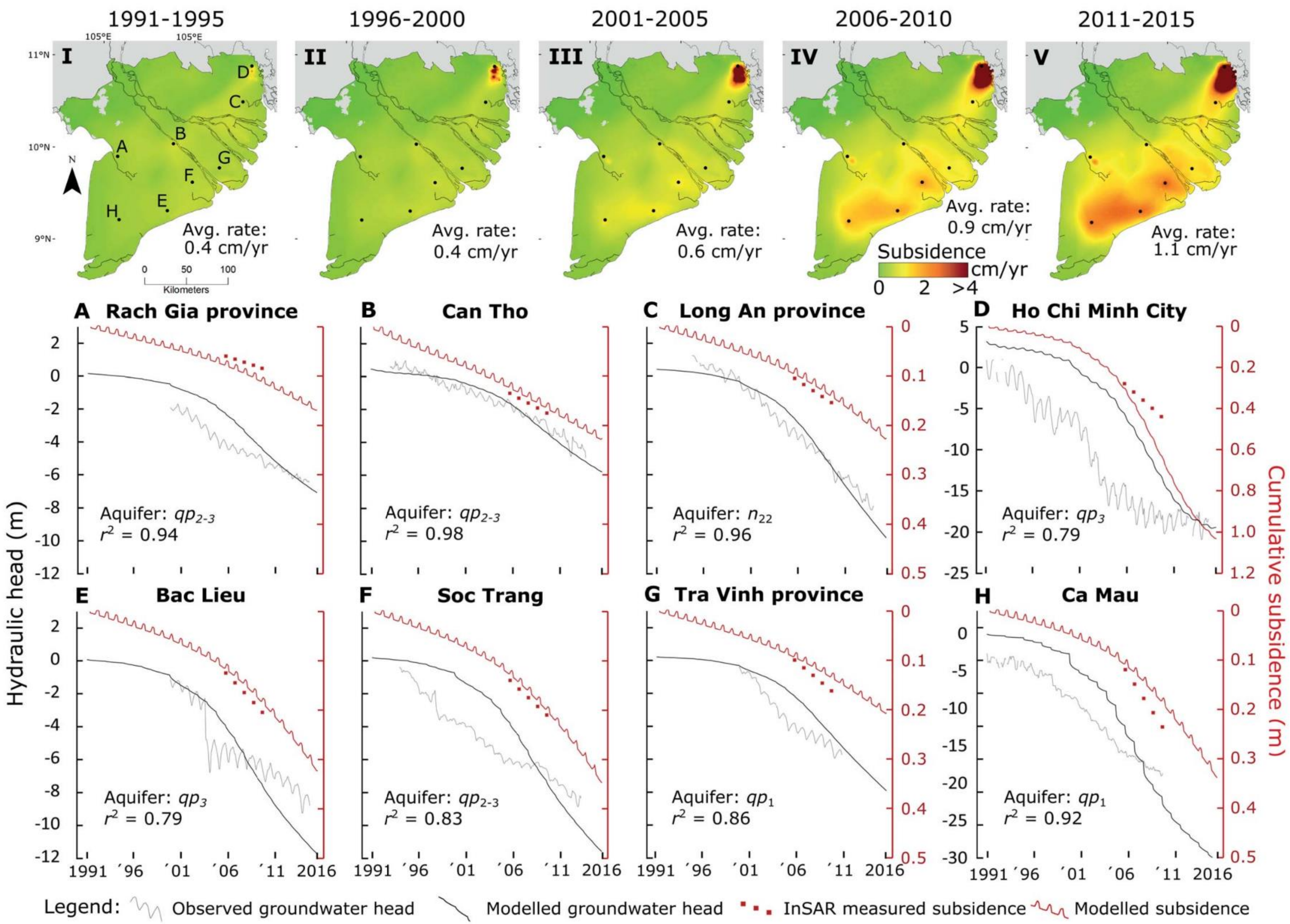
Most/least conservative model: 60%/160% of the best estimate model rates

Sources of uncertainties in modeling results:

- **Hydrogeology and geotechnical parameters**
- **Extraction data**
- **Geological schematization**
- **Layer discretization**

Minderhoud et al., 2017
Environmental Research Letters

Large groundwater extractions lead to subsidence in the Mekong delta (results Rise and Fall project)

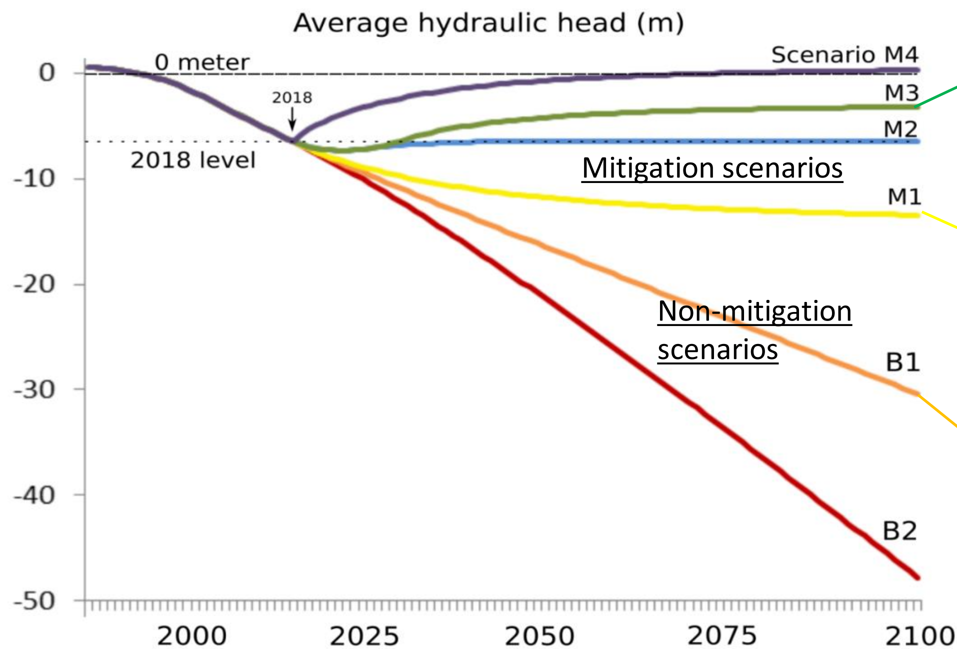


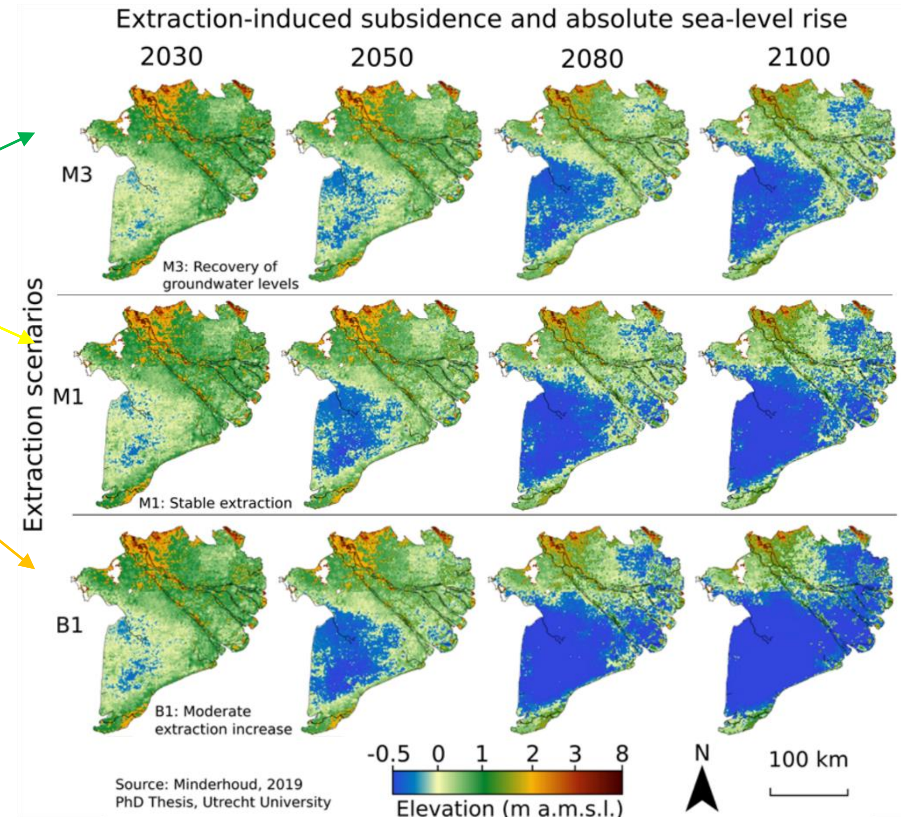
Minderhoud, P. S. J., Erkens, G., Van Hung, P., Vuong, B. T., Erban, L. E., Kooi, H., & Stouthamer, E. (2017). Impacts of 25 years of Groundwater extraction on subsidence in the Mekong delta, Vietnam. Environmental Research Letters, 12, 13. https://doi.org/10.1088/1748-9326/aa7146

The future of the Mekong delta?

The decisions of today, will determine tomorrow

Scenarios of future groundwater extraction pathways



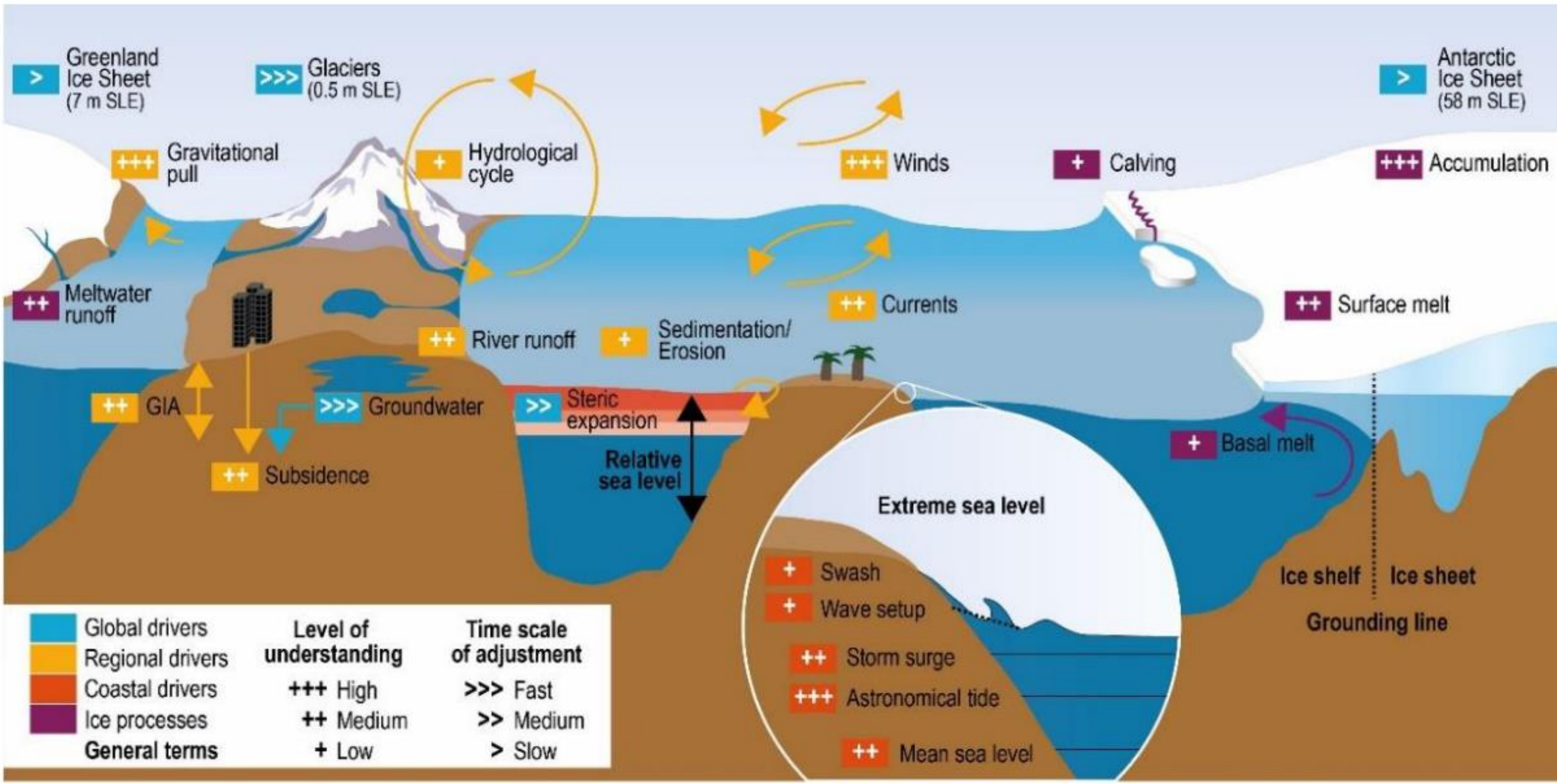


Minderhoud et al., in review

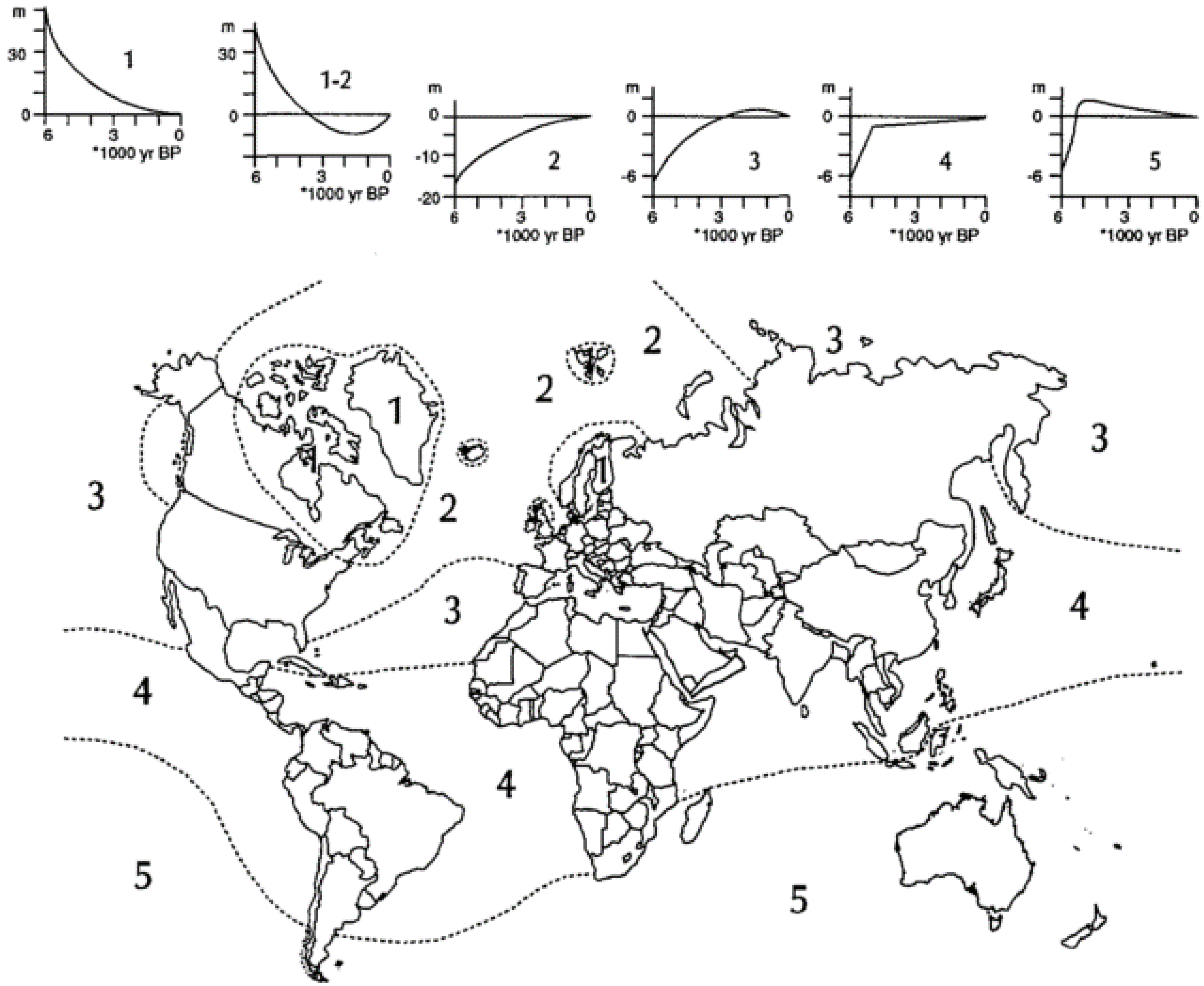
N.B. New InSAR measurements point to a potential underestimation of subsidence by the model

Stress 6: Mean Sea Level Rise

Illustration of climate and non-climate driven processes that influence sea level along coasts

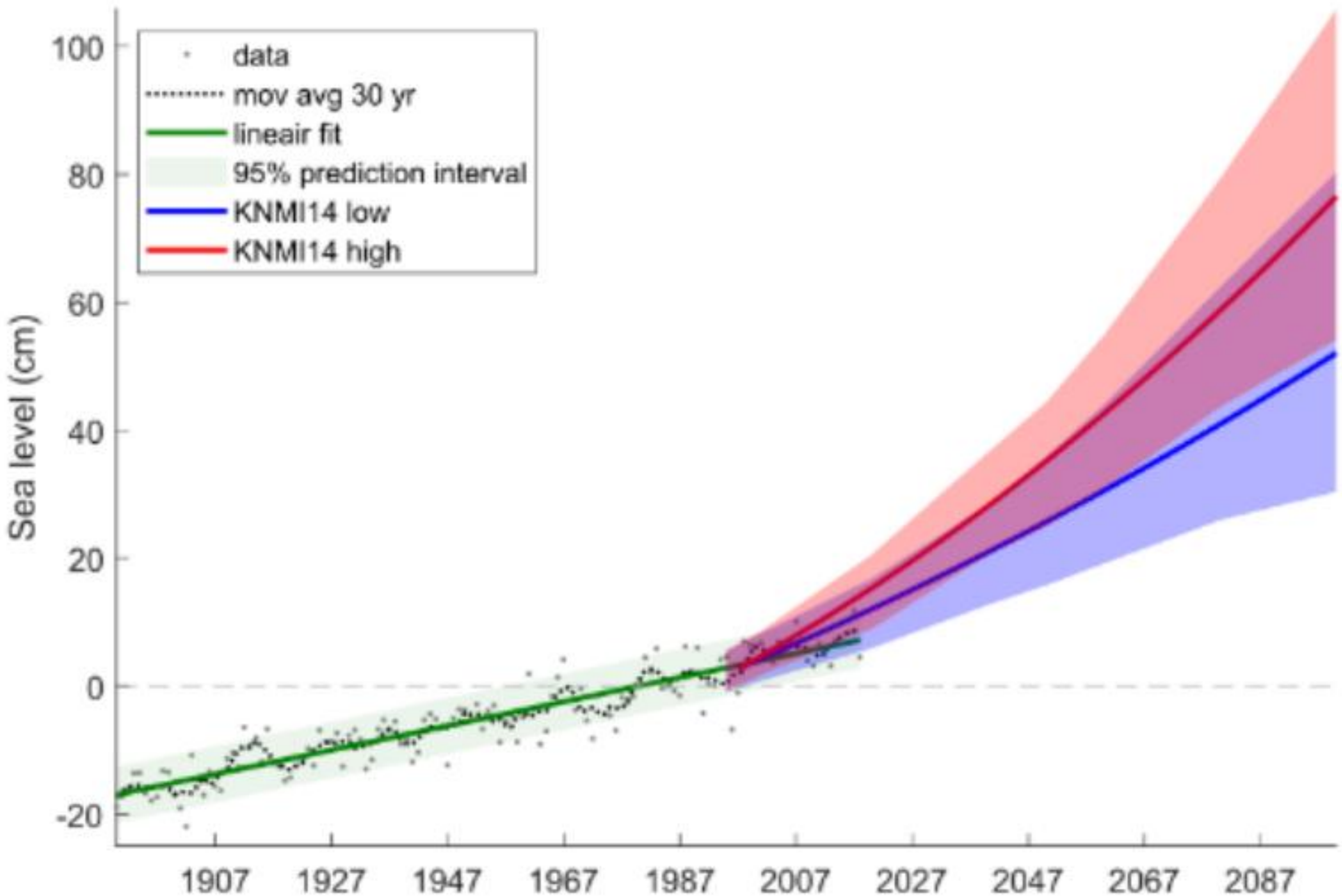


Regional distribution of Holocene Sea-level Changes



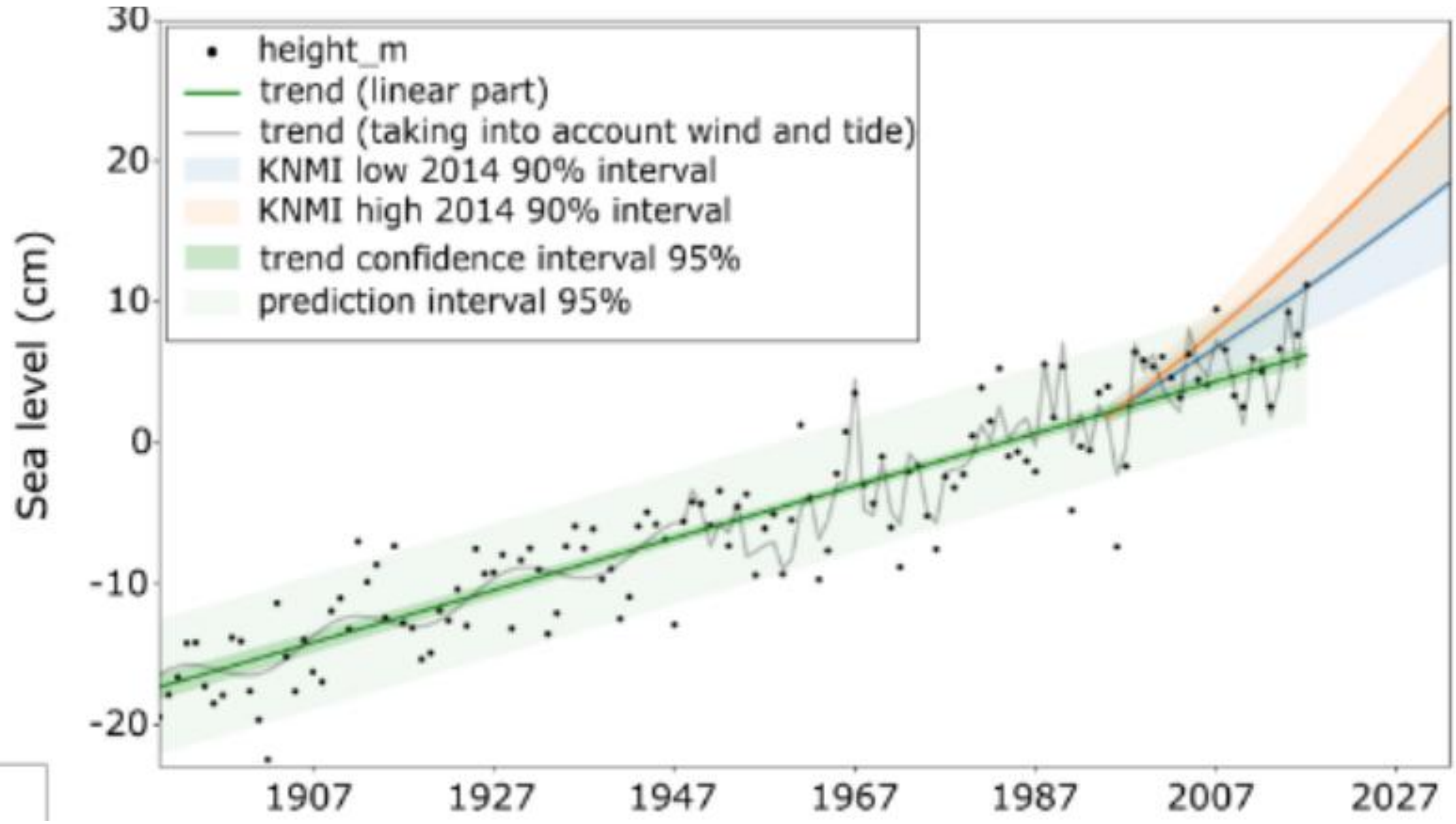
Source:
Pirazzoli, P.A. & Pluet, J., 1991. World Atlas of Holocene Sea-level Changes. Elsevier Oceanography Series, Vol. 58

KNMI sea level projections and historic observations in the Zeespiegelmonitor

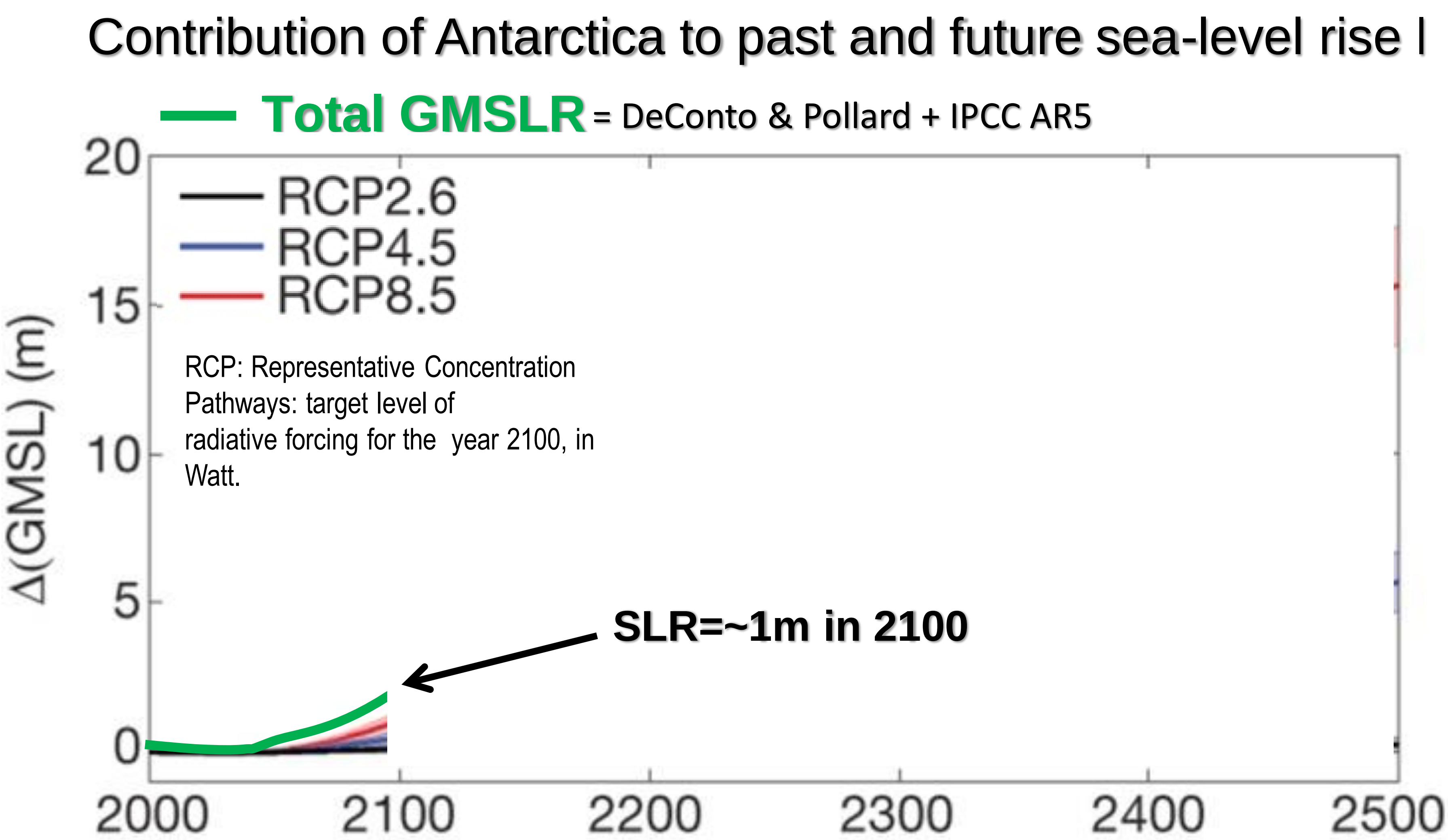


Hurk, B. van den, Geertsema, T., n.d. An assessment of present day and future sea level rise at the Dutch coast.

KNMI sea level projections and historic observations in the Zeespiegelmonitor



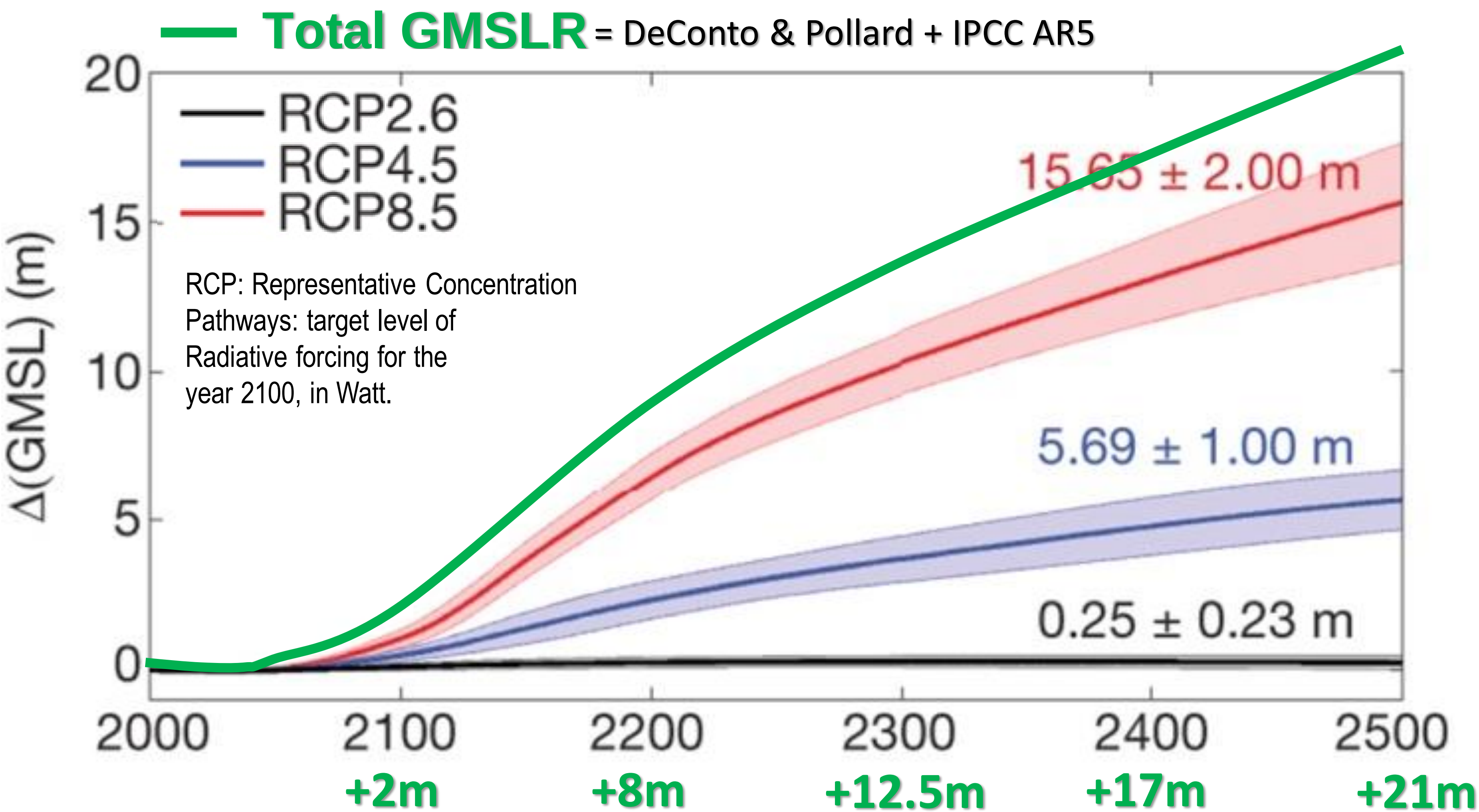
Stress: Global Mean Sea Level Rise (GMSL)



DeConto *and Pollard. 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591–597 (2016) doi:10.1038/nature17145*

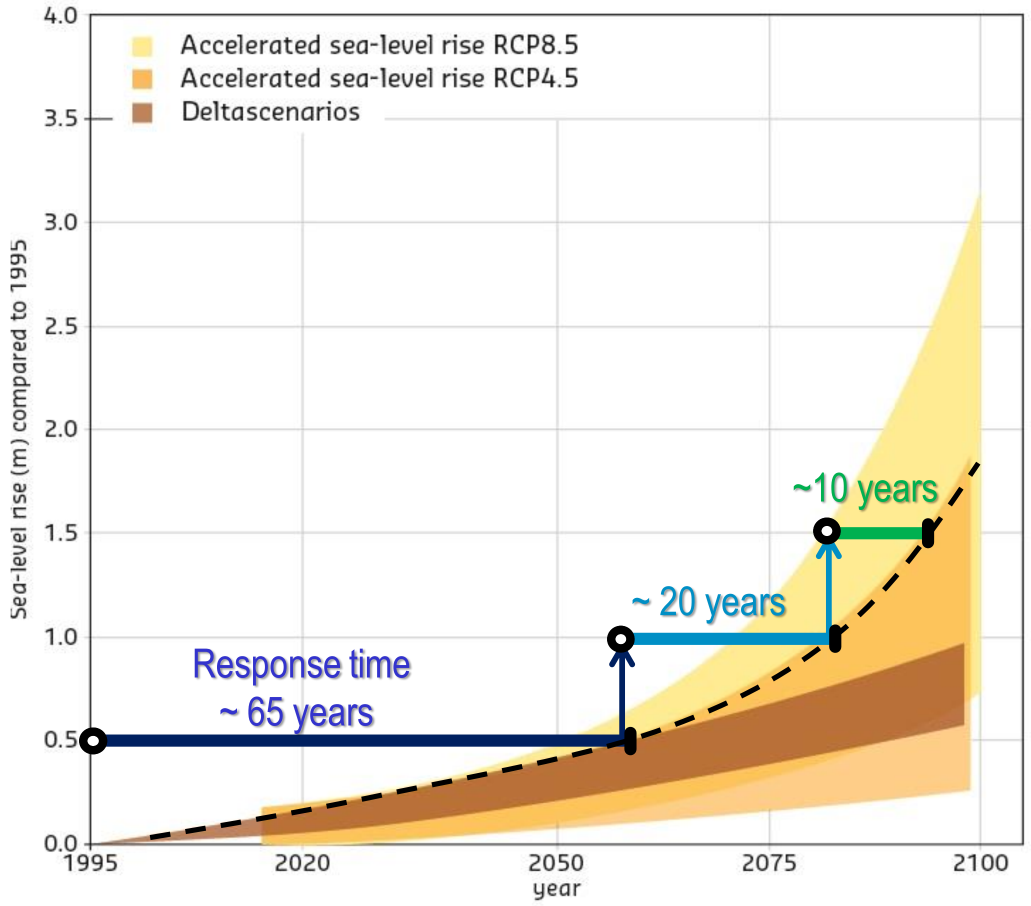
Stress: Global Mean Sea Level Rise (GMSL)

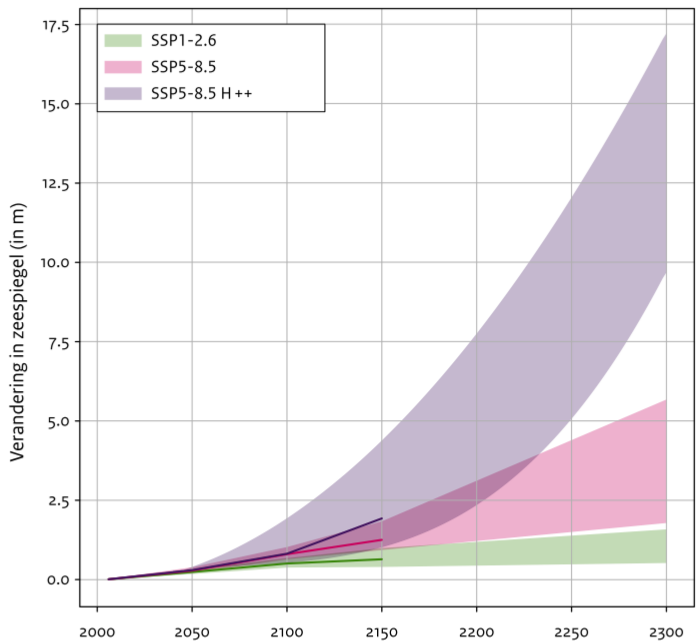
Contribution of Antarctica to past and future sea-level rise l



DeConto *and Pollard. 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591–597 (2016) doi:10.1038/nature17145*

Stress 6: Mean Sea Level Rise

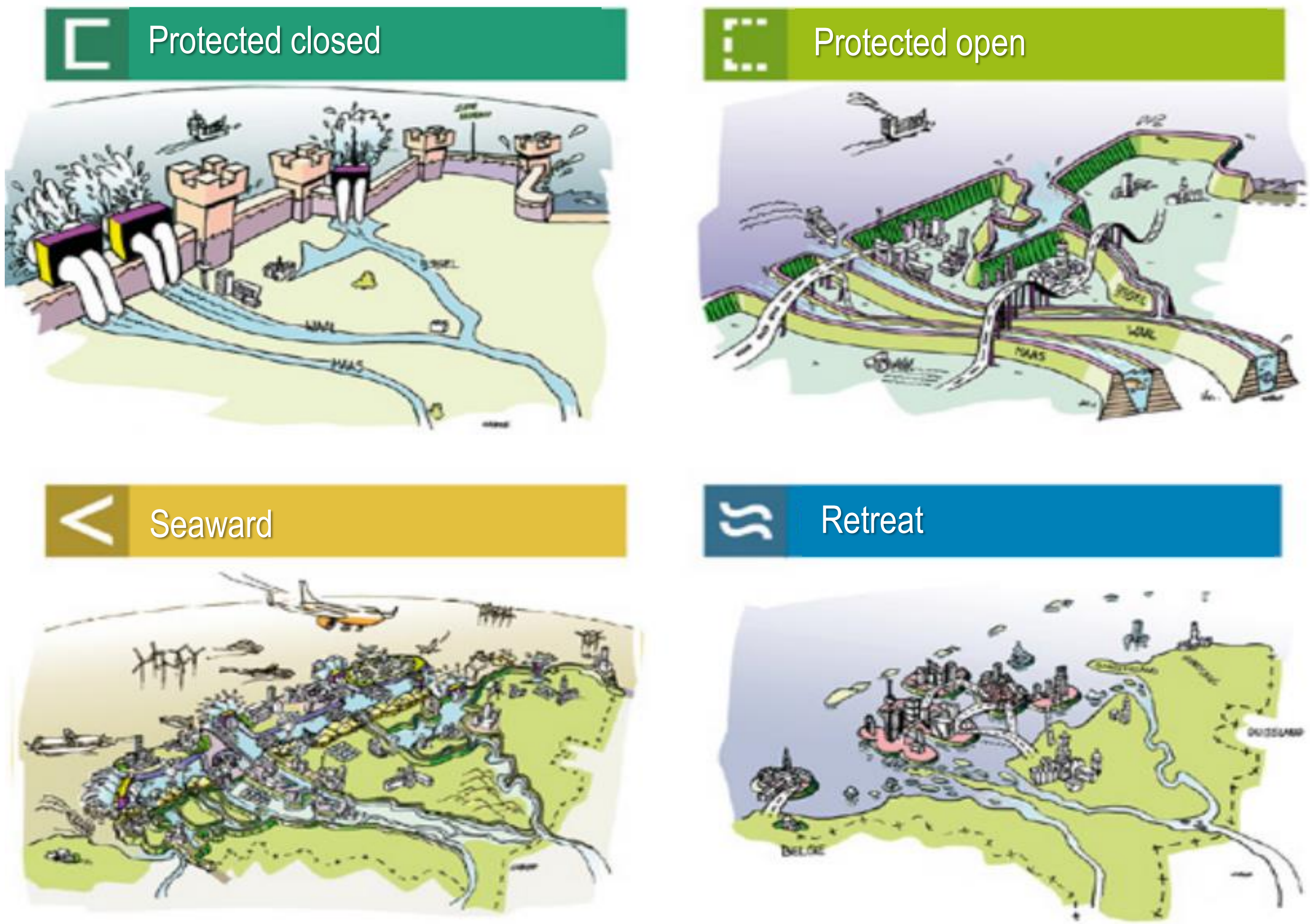




KNMI, 2021. KNMI Klimaatsignaal'21: hoe het klimaat in Nederland snel verandert.

Haasnoot et al., 2019. Strategieën voor adaptatie aan hoge en versnelde zeespiegelstijging. Een verkenning. 1–65.
Haasnoot et al., 2018. Mogelijke gevolgen van versnelde zeespiegelstijging voor het Deltaprogramma. Een verkenning, Deltares rapport 11202230-005-0002.
Deconto, R.M., Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591–597. https://doi.org/10.1038/nature17145

Netherlands Later Adaptive strategies



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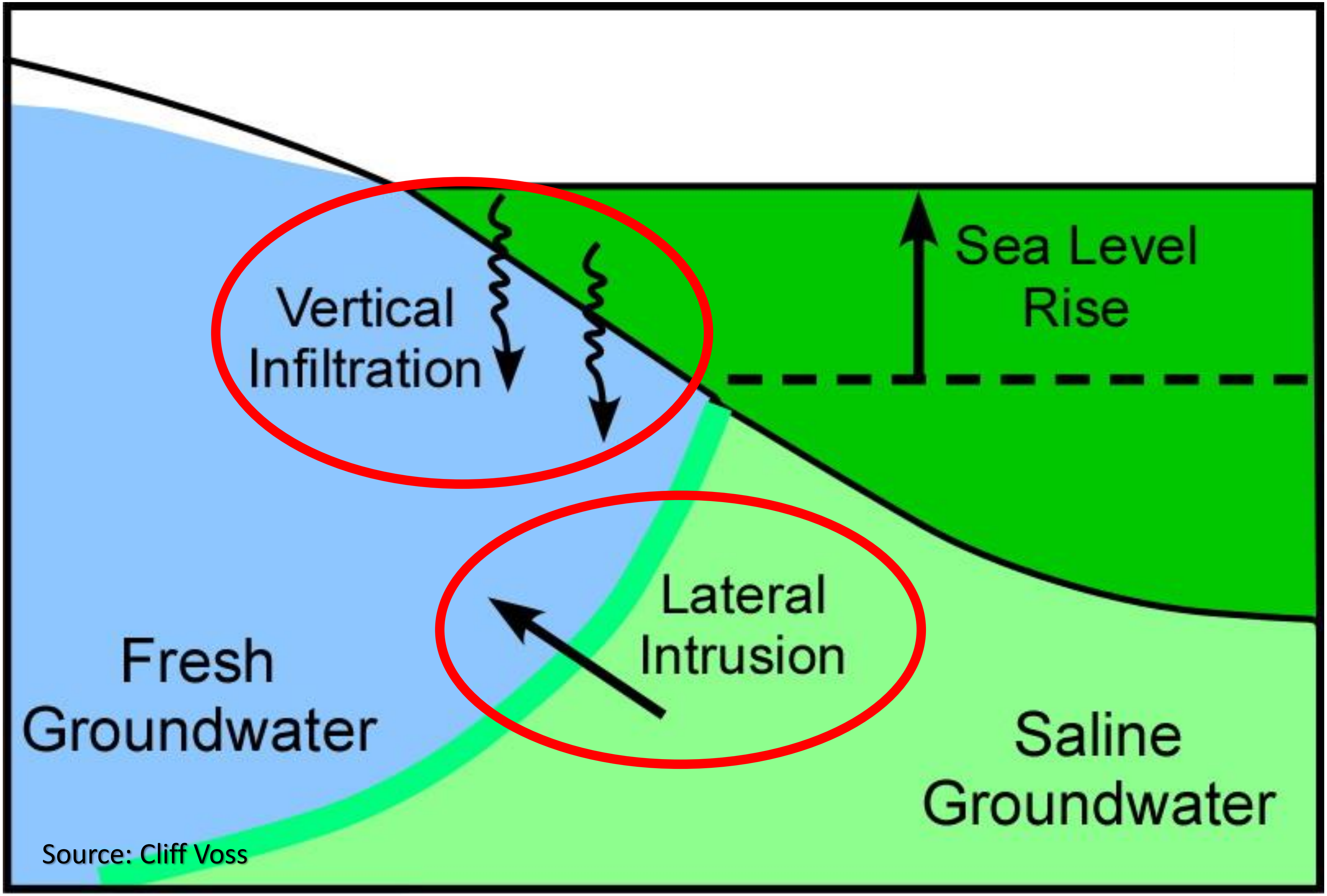
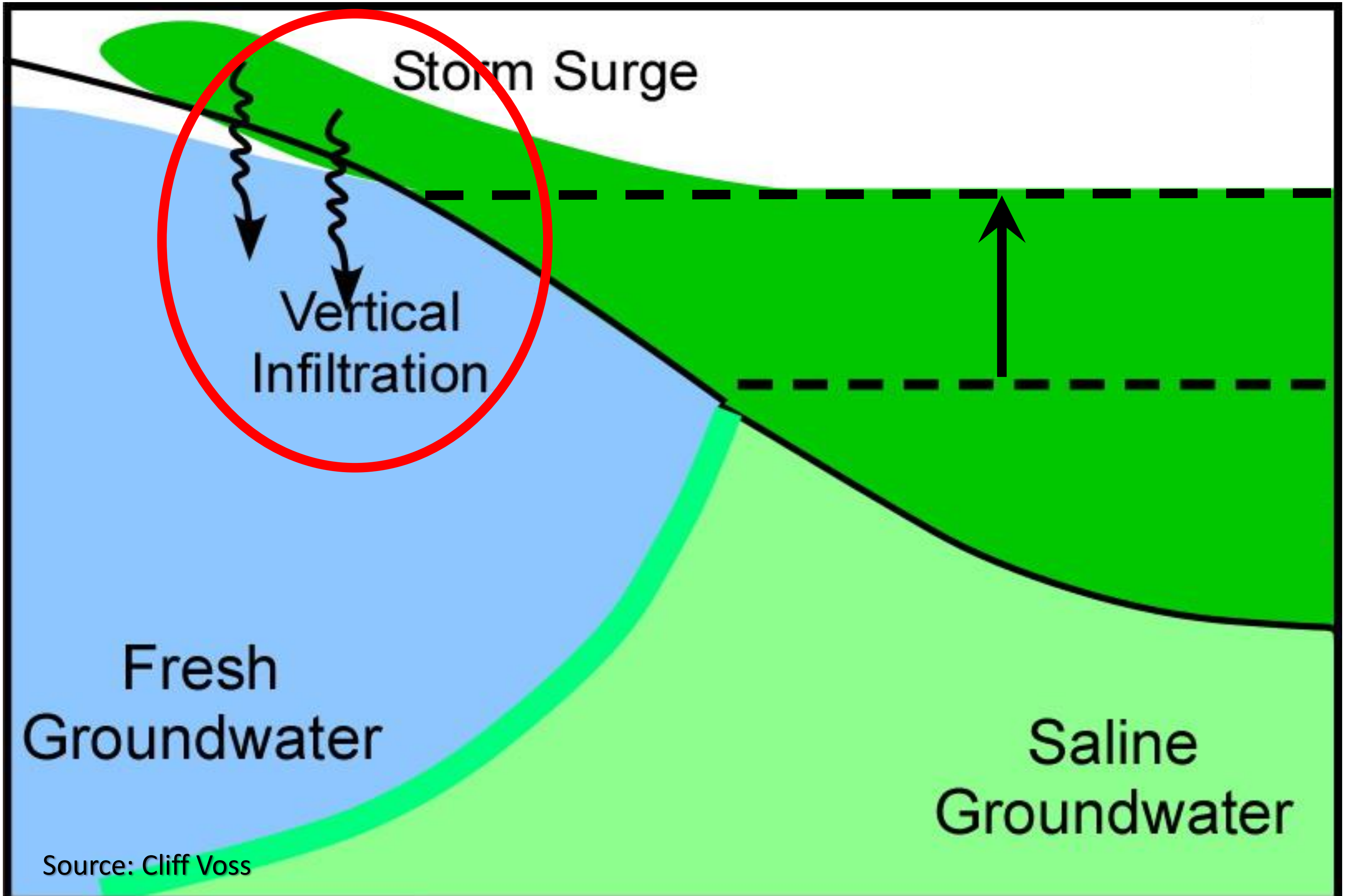
Modes of Salinization due to Sea-Level Rise

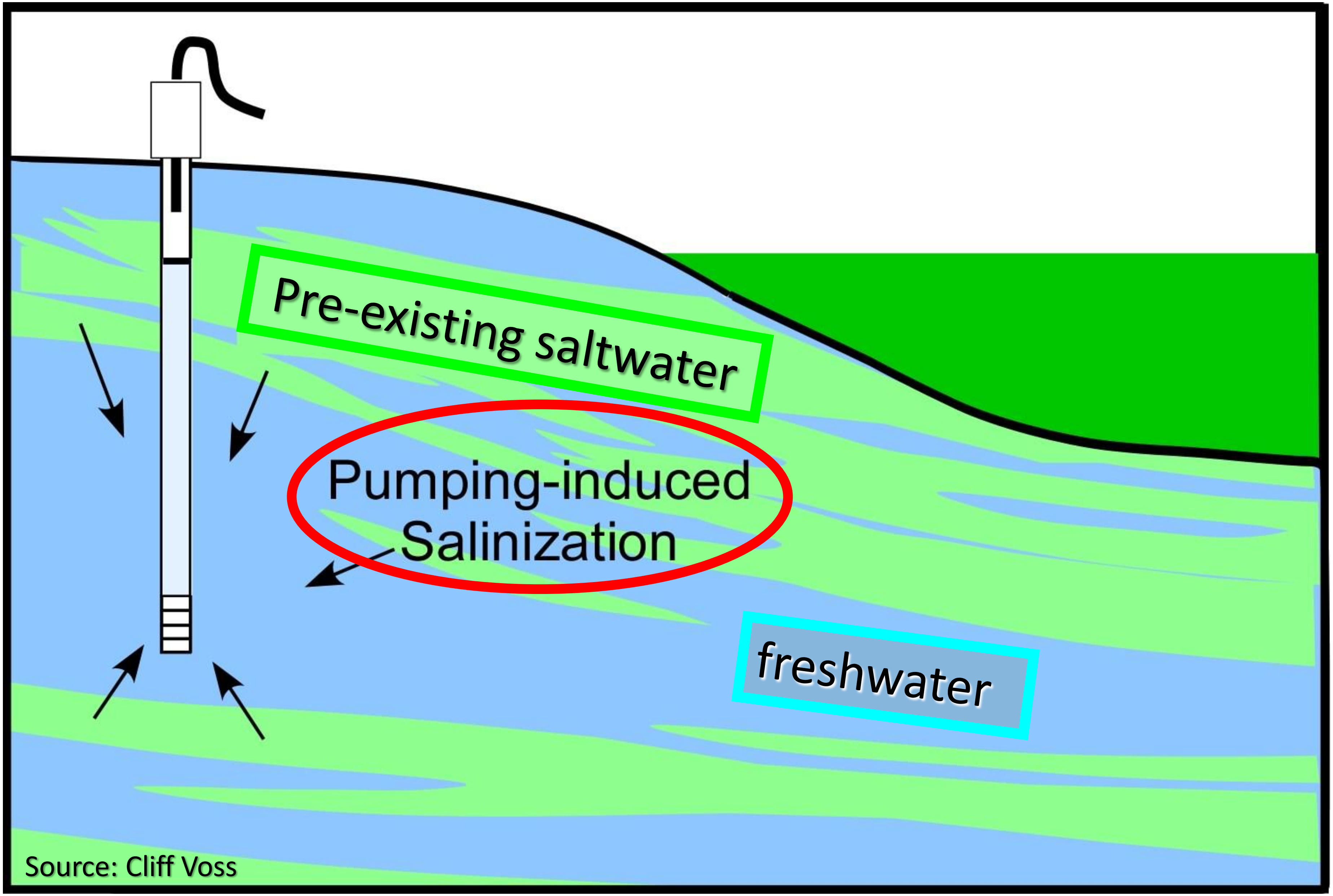


Source: Cliff Voss

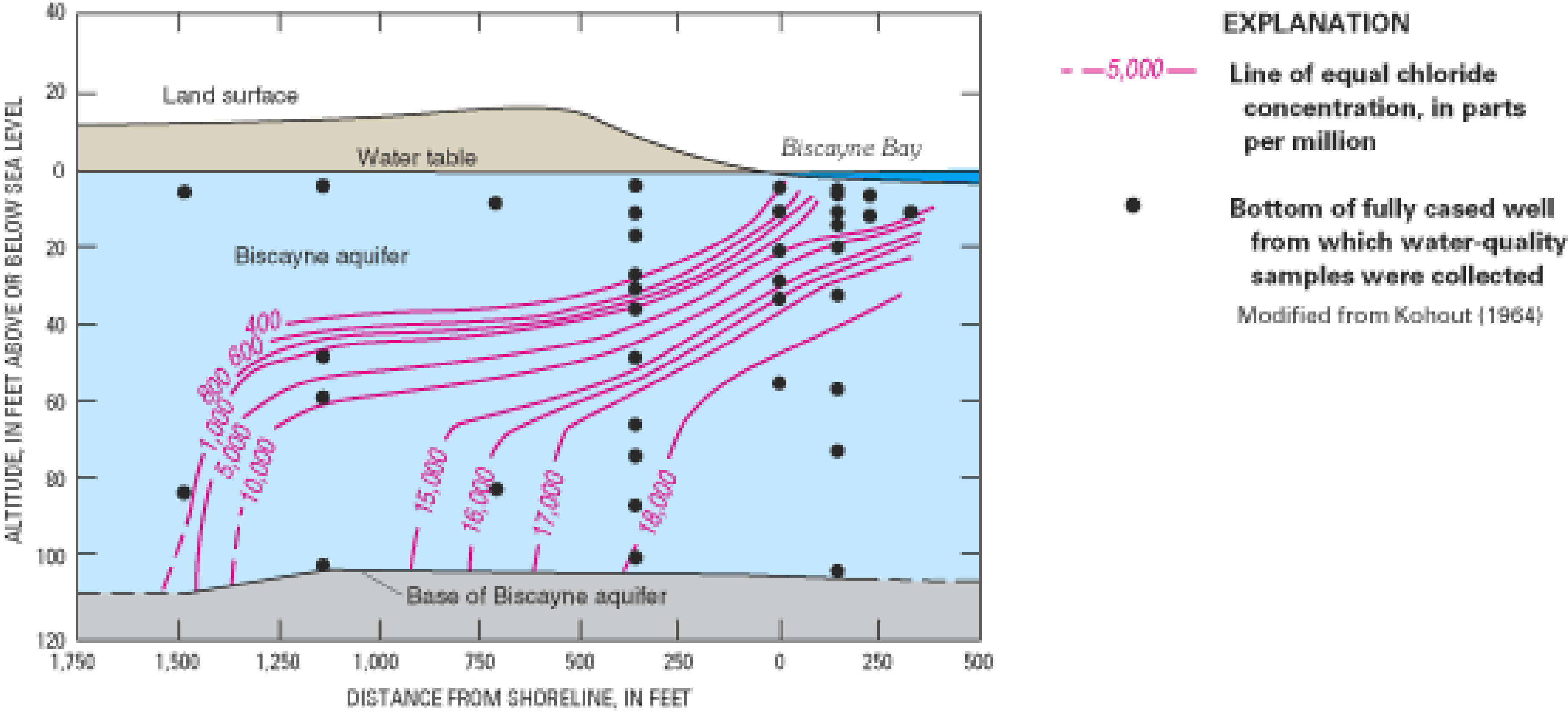
Modes of Salinization due to Sea-Level Rise



Salinization due to Pumping

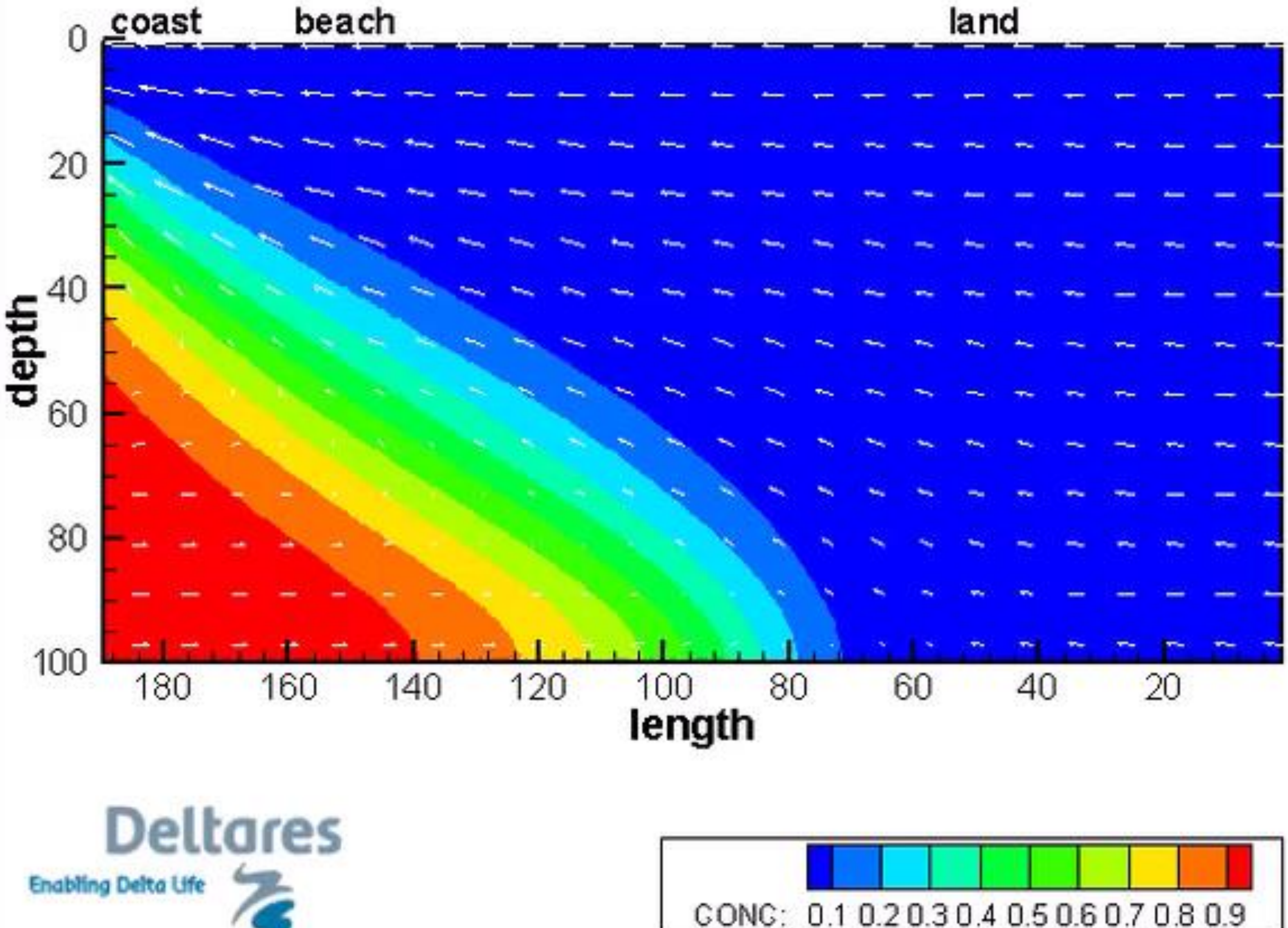


Biscayne aquifer, Florida USA: Henry's case



Impact of sea level rise on a coastal groundwater system:

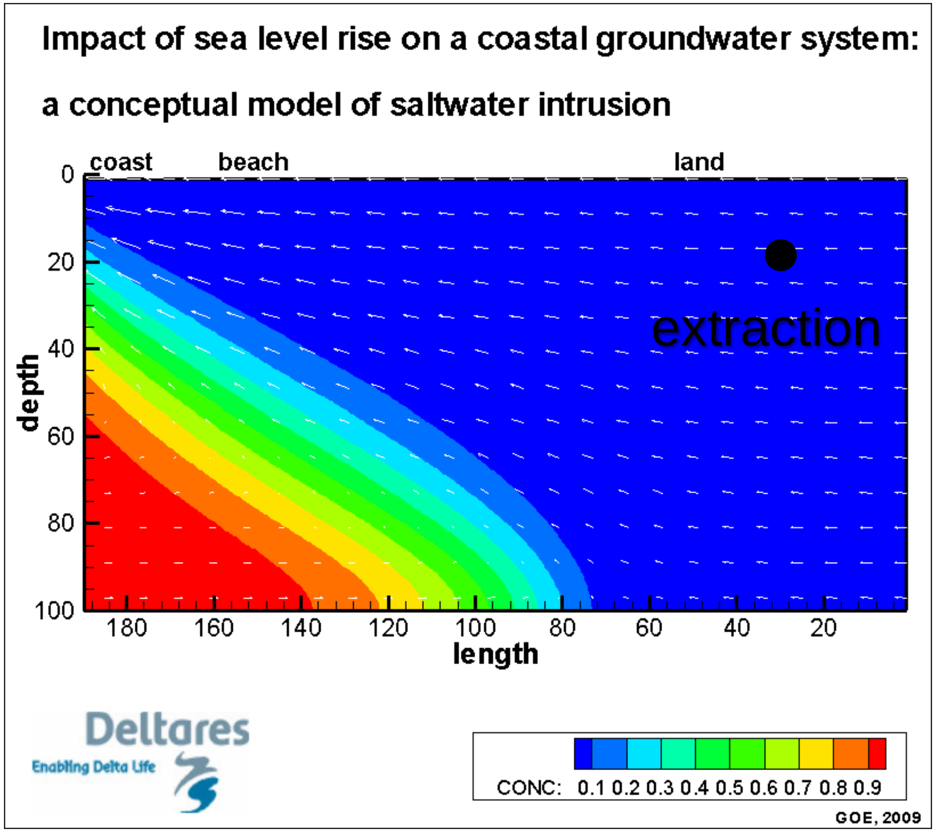
a conceptual model of saltwater intrusion

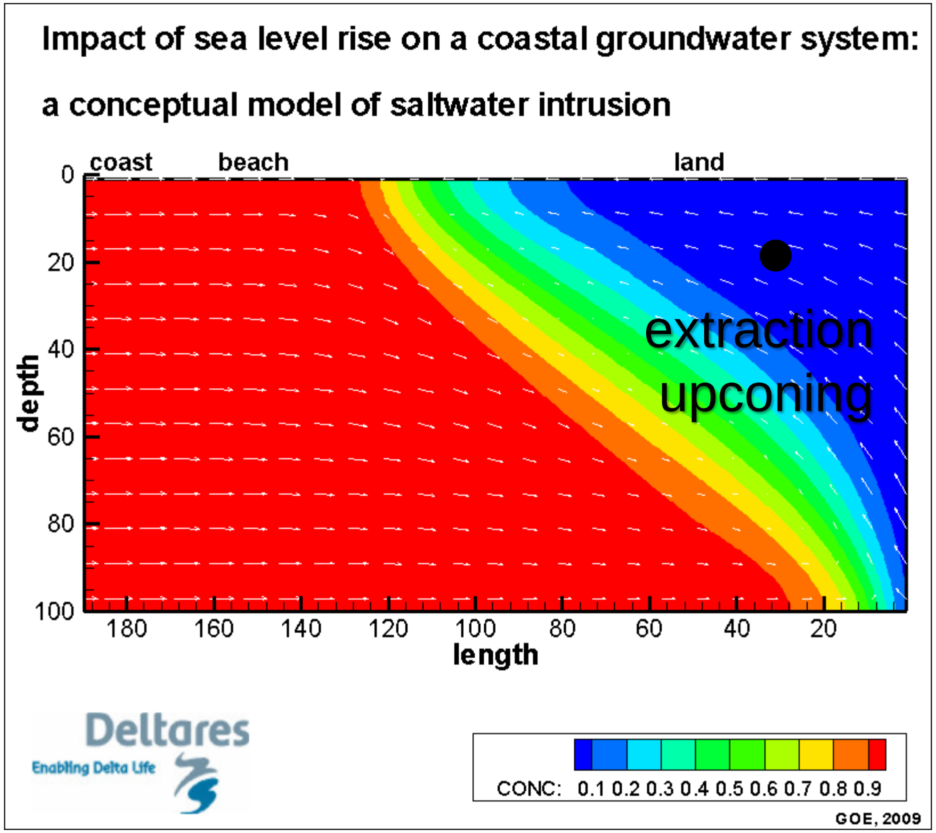


Deltares
Enabling Delta Life

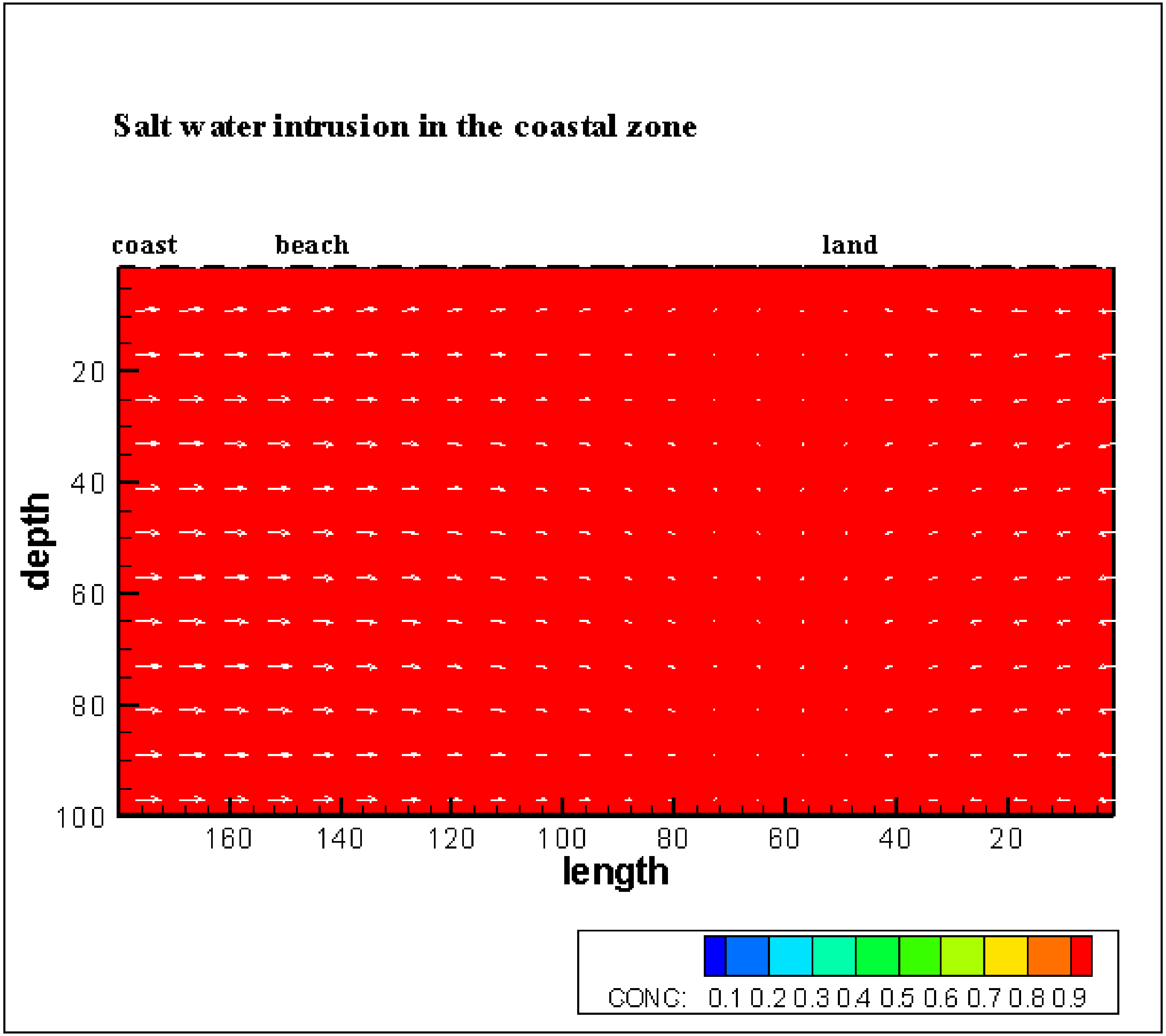
GOE, 2009

Sea level rise and salt water intrusion





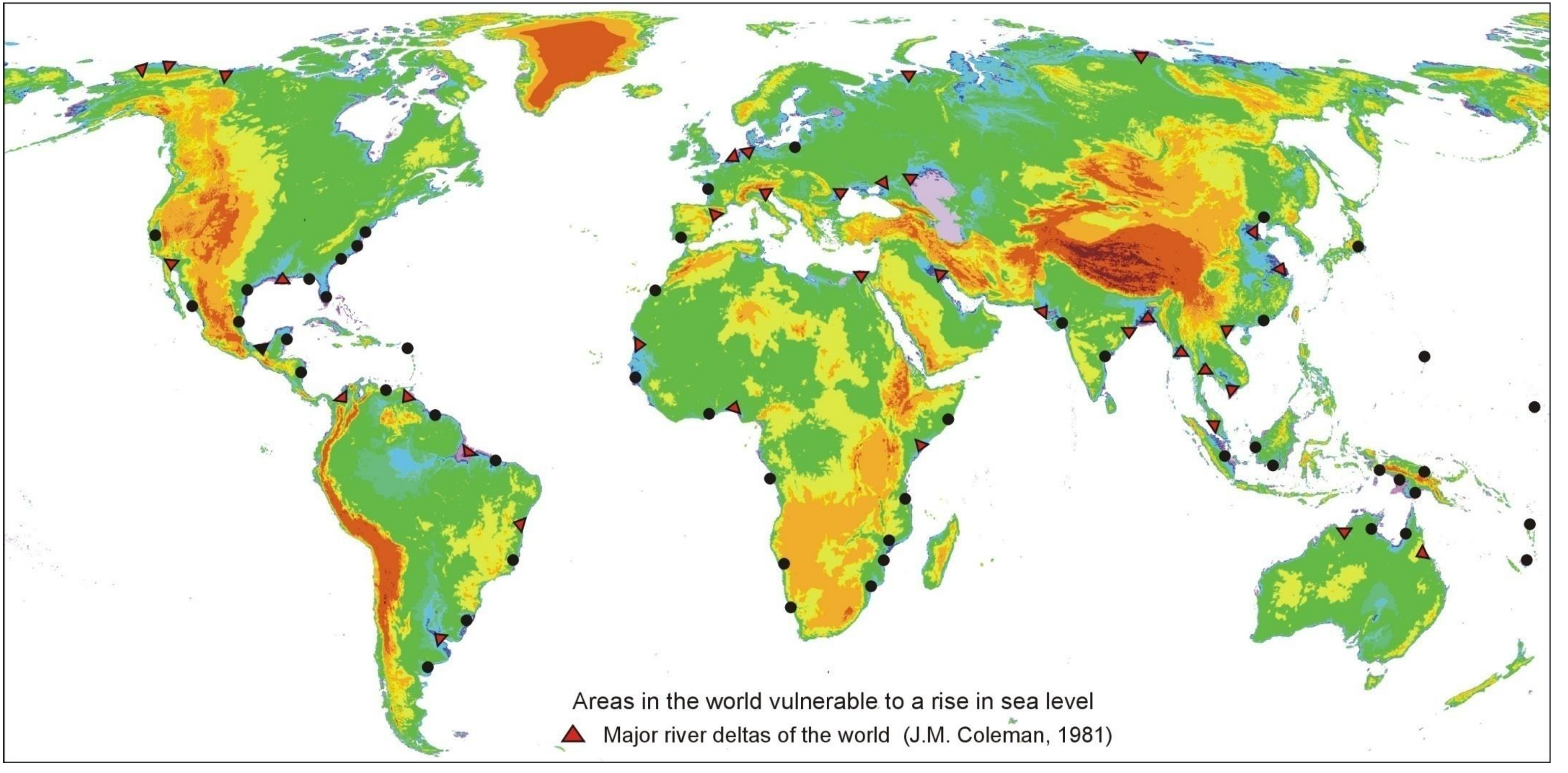
Salt water intrusion



Effects of sea level rise on groundwater resources in deltaic areas

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

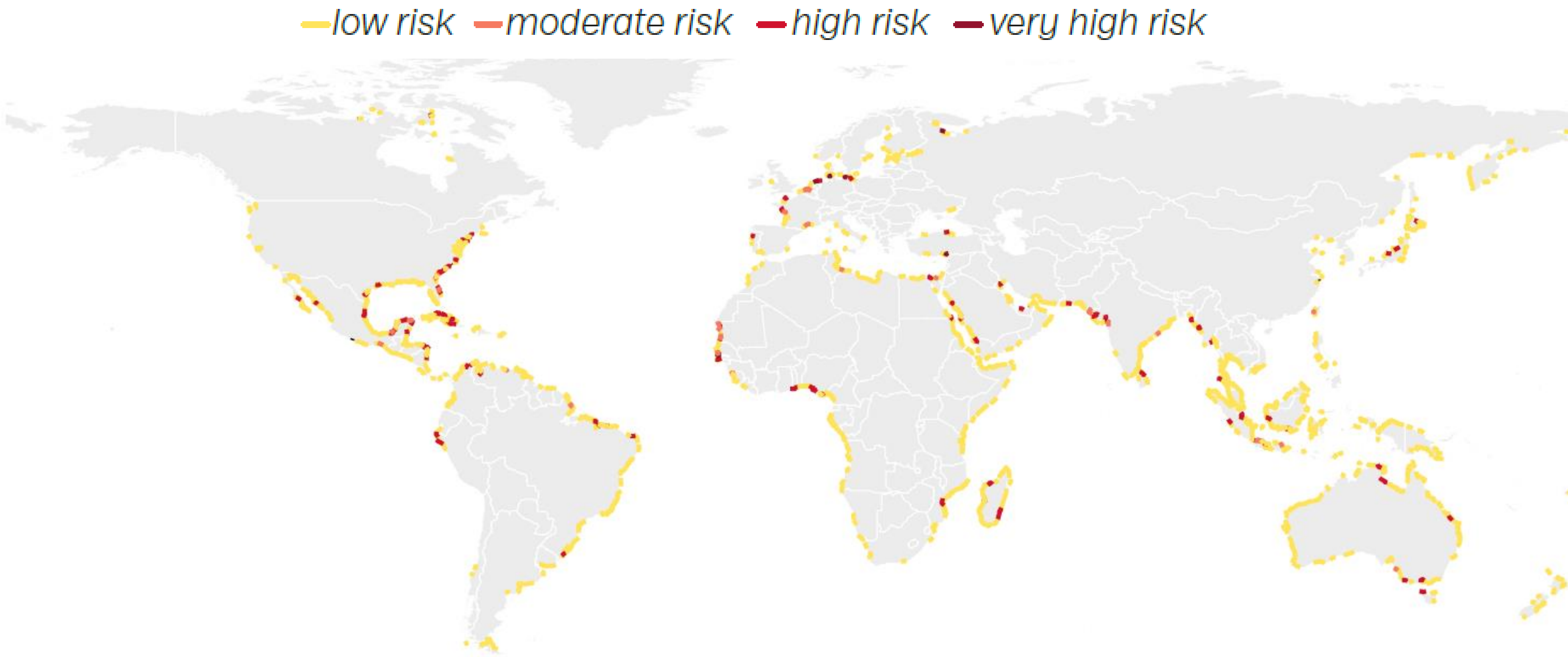
Effects of sea level rise on groundwater resources in deltaic areas



Digital Elevation Model (DEM)

Global groundwater salinisation vulnerability map

EXAMPLE - More than 35 million people could lose more than 10% of their fresh groundwater resources by 2100, compared to 2020, according to RCP 8.5 sea level rise scenario.

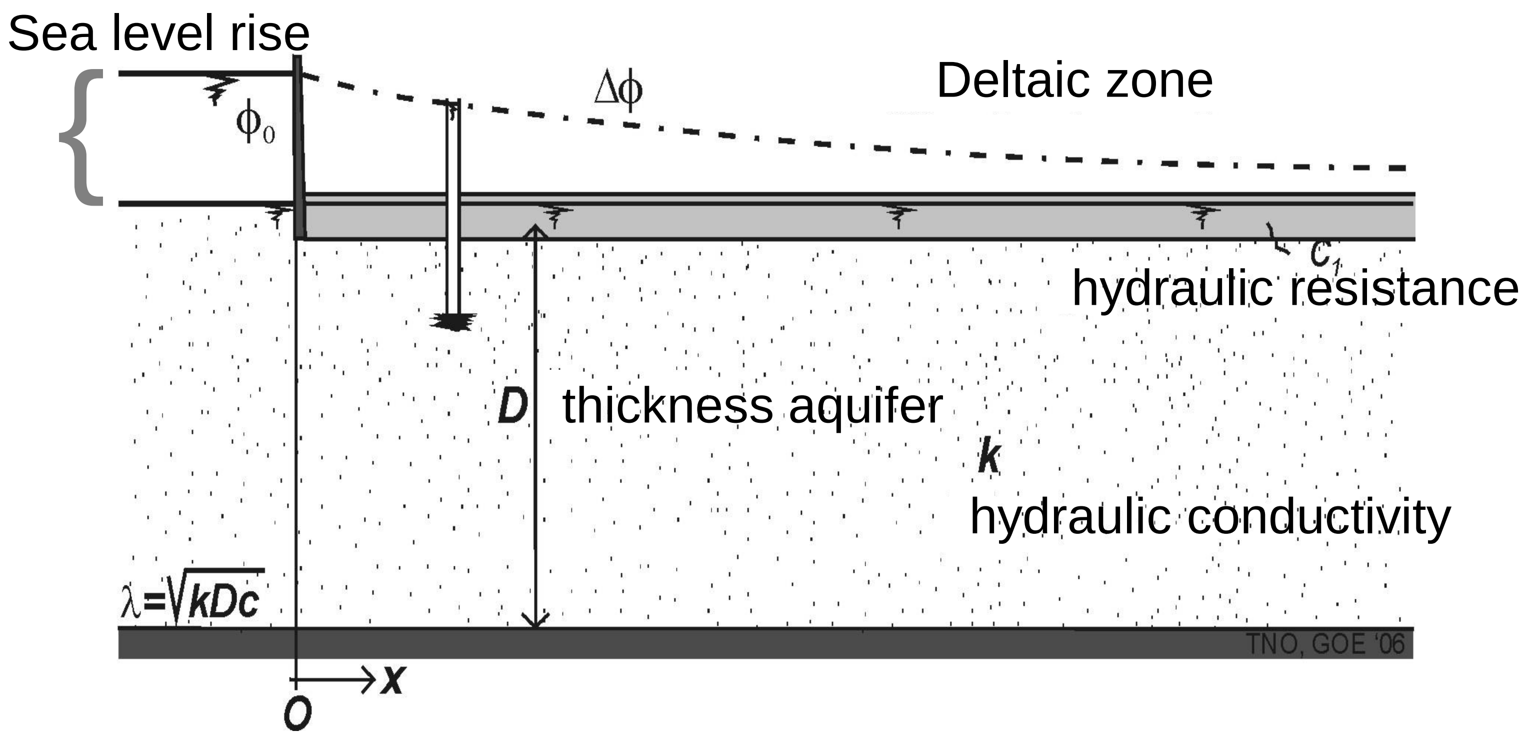


fresh groundwater will decrease due to sea-level rise compared to present conditions

Zamrsky et al. 2022, in reviews

Effect of sea level rise:

Analytical approach for zone of influence in deltaic areas



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

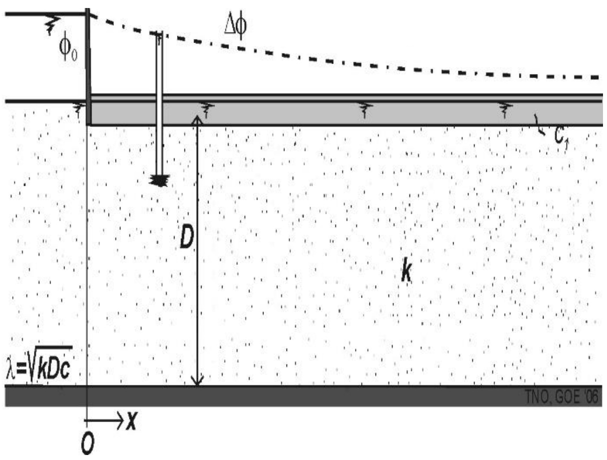
$$\lambda = \sqrt{kDc}$$

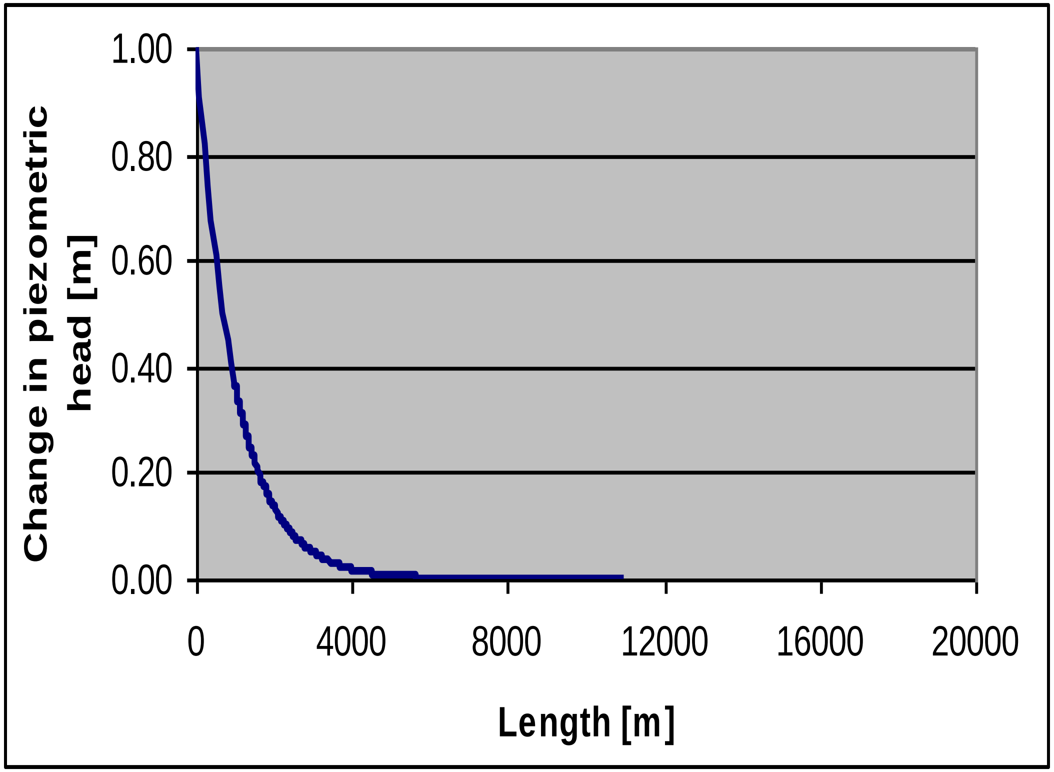
- Zone of influence is equal to sqrt(kDc)
- At x=3l, only 5% of sea level rise is detactable

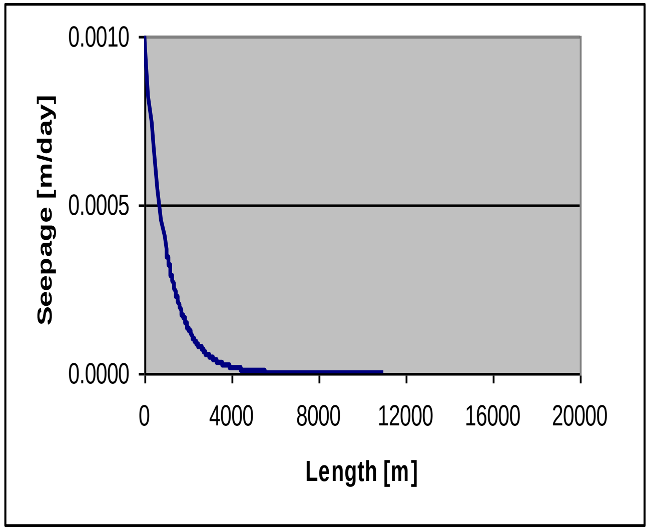
Effect of sea level rise:

Case 1 with Dutch subsoil parameters

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



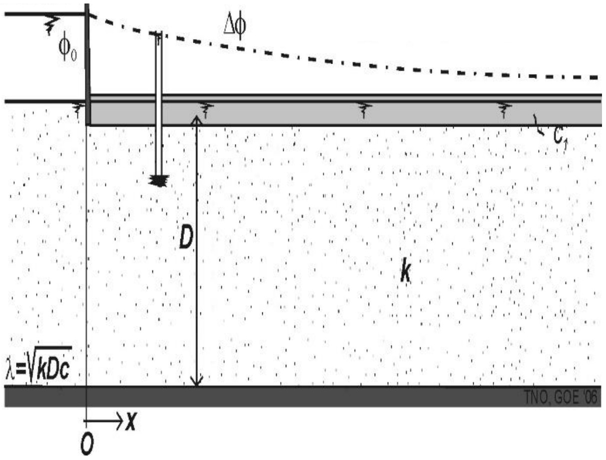


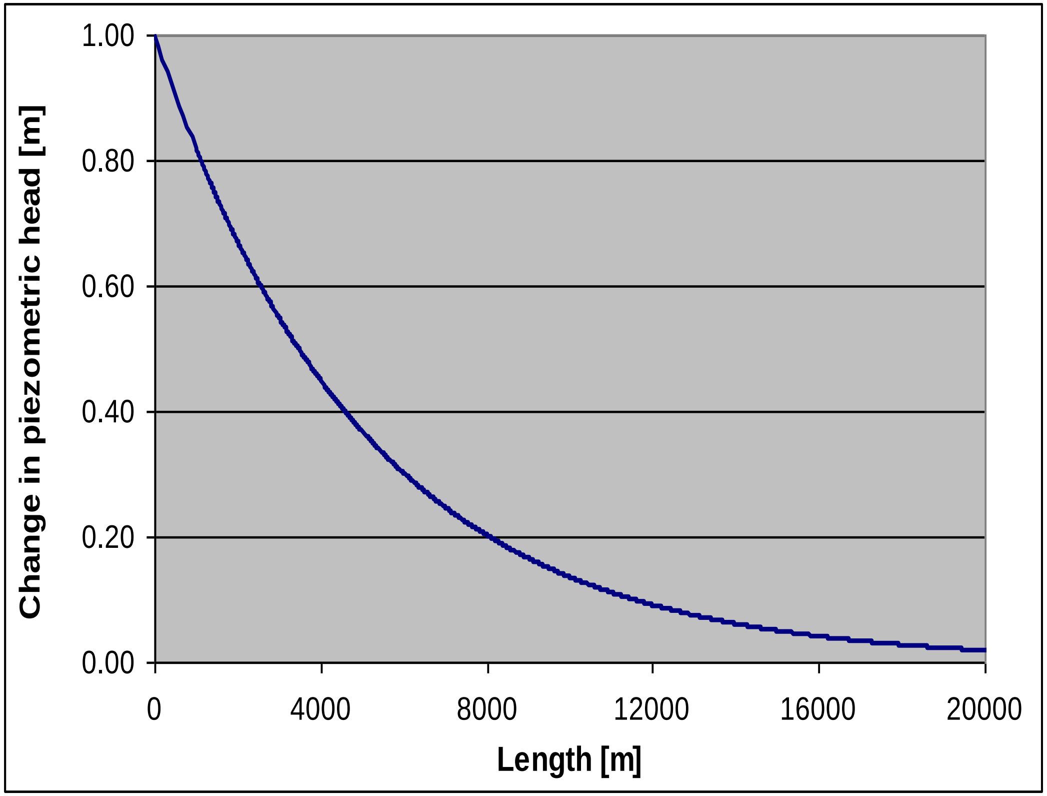


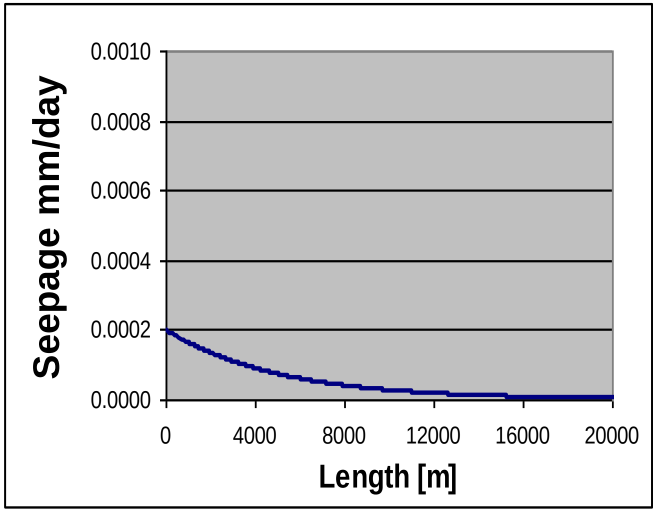
Effect of sea level rise:

Case 2 with Dutch subsoil parameters

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

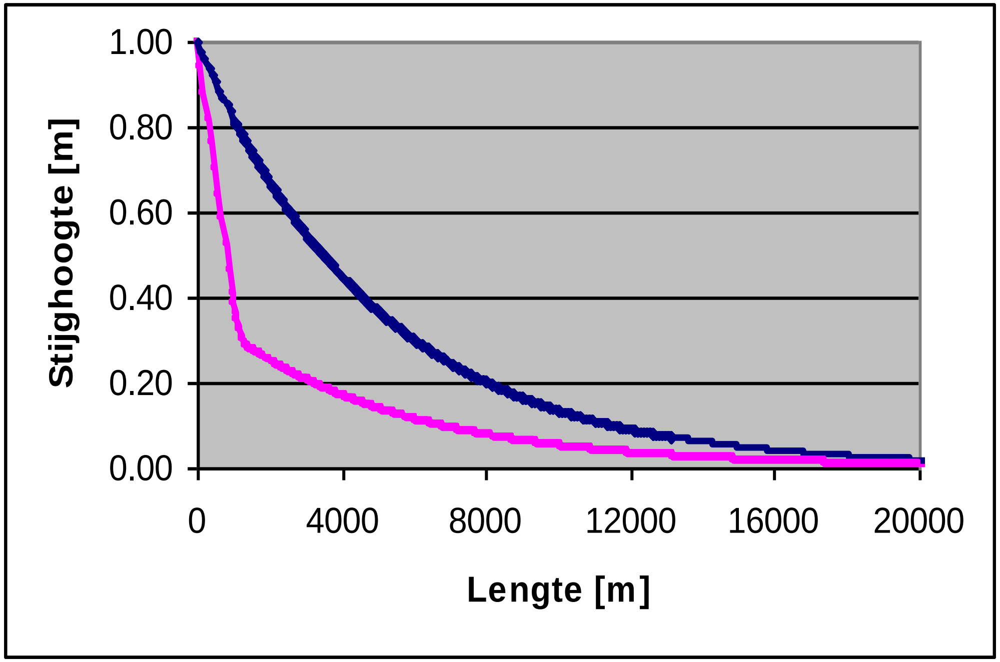


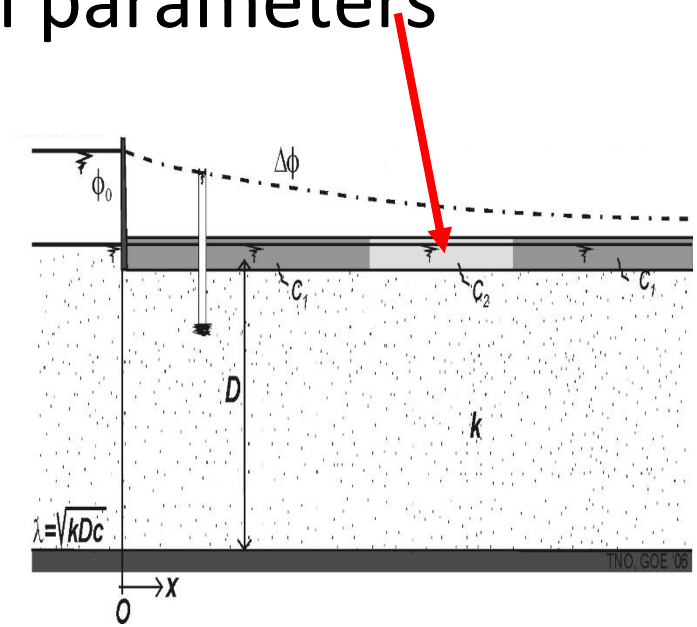


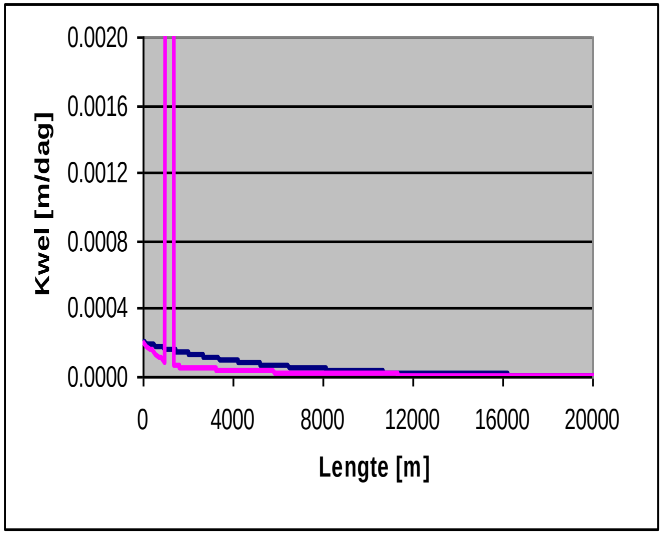


Case 3 with Dutch subsoil parameters

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

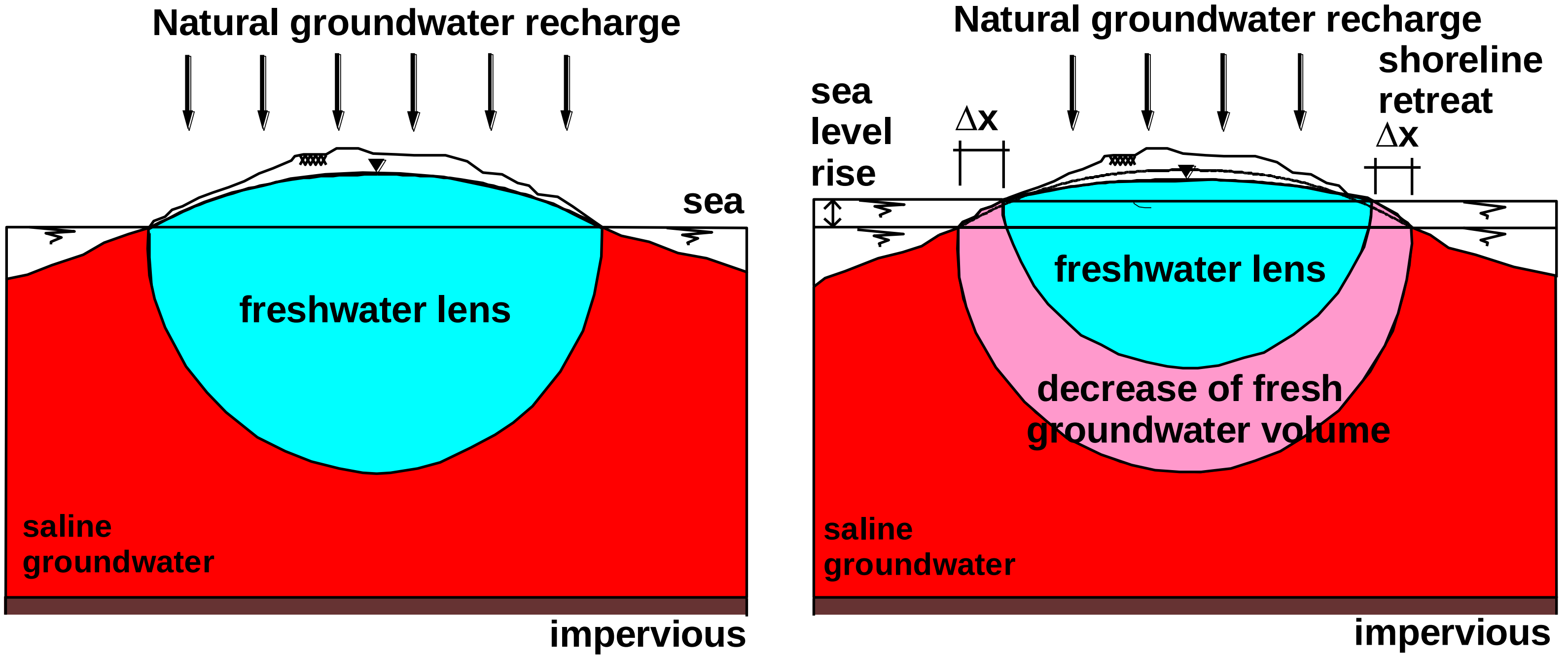






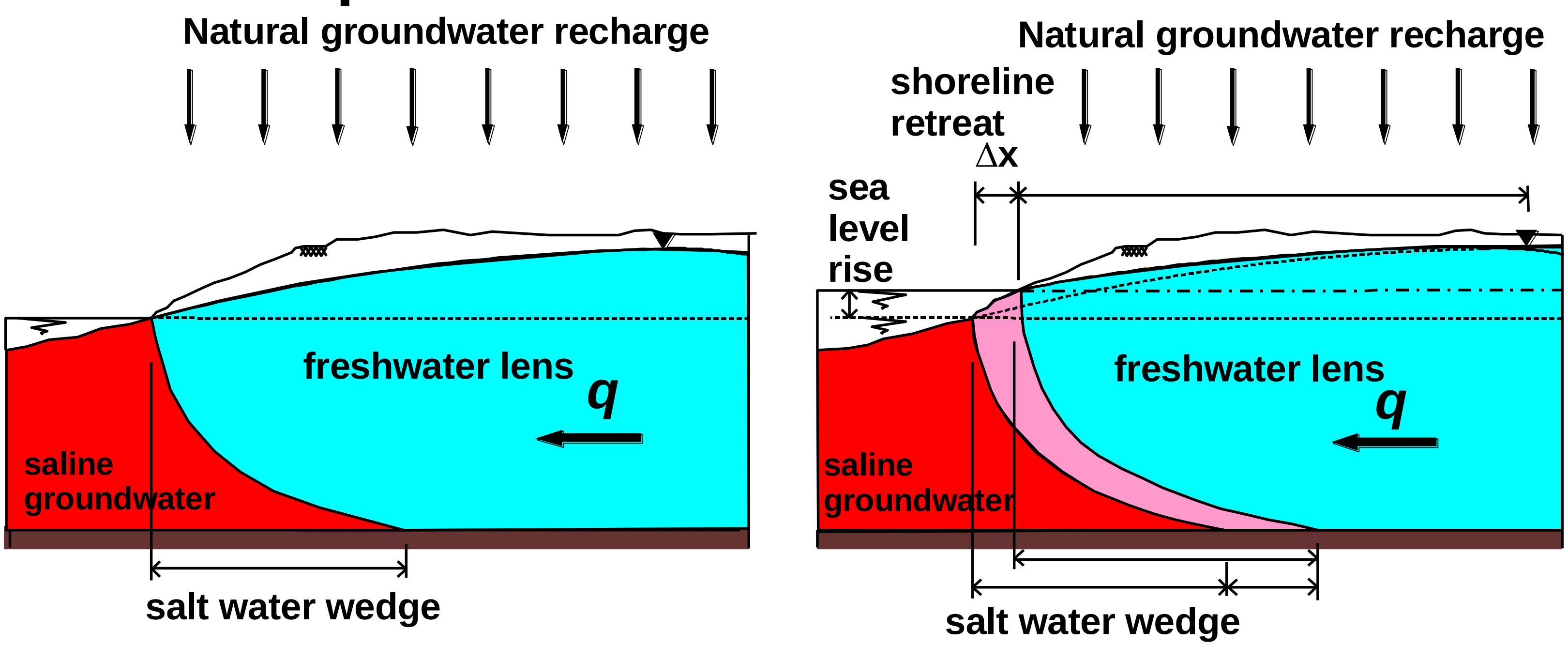
Effect of a relative sea level rise (1):

Deep aquifer



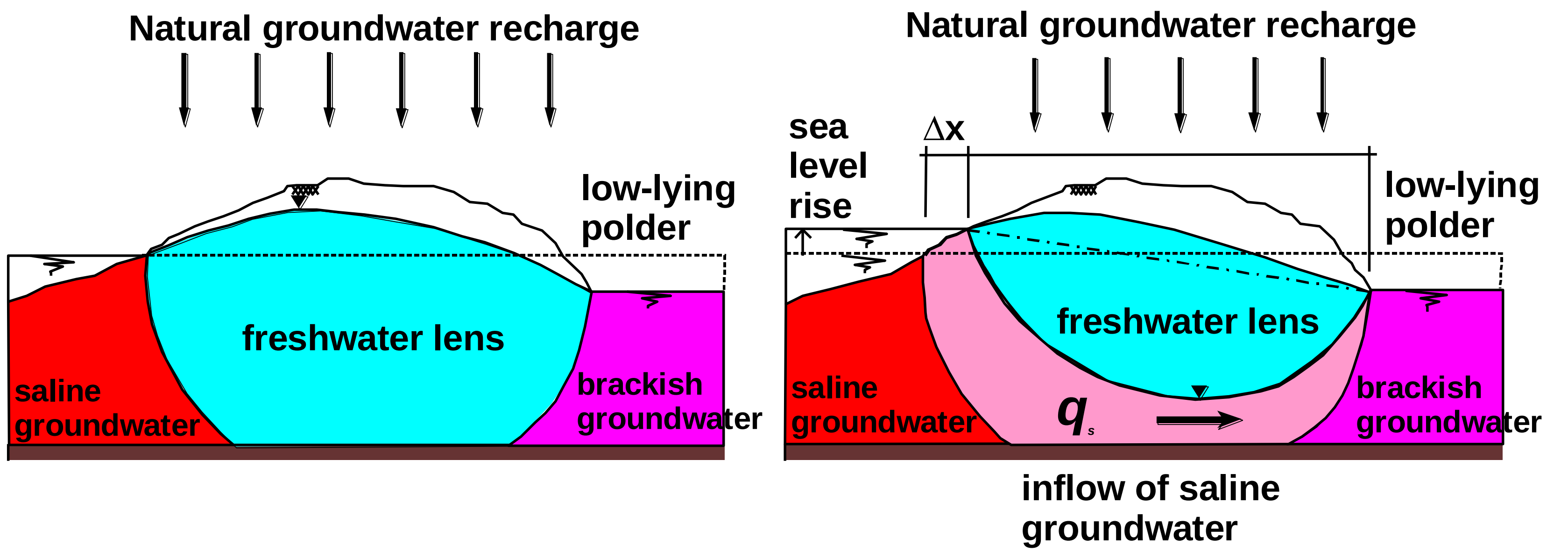
Effect of a relative sea level rise (2):

Shallow aquifer

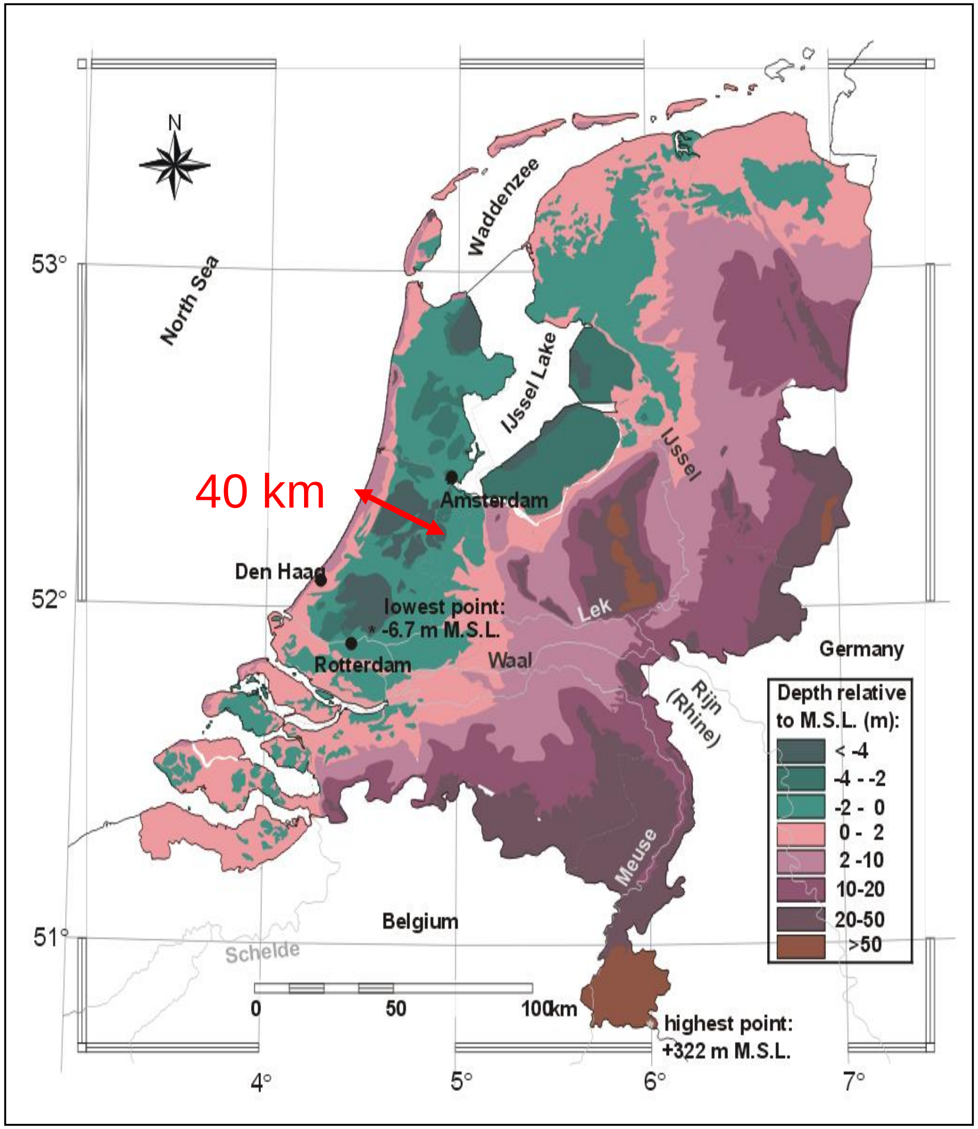


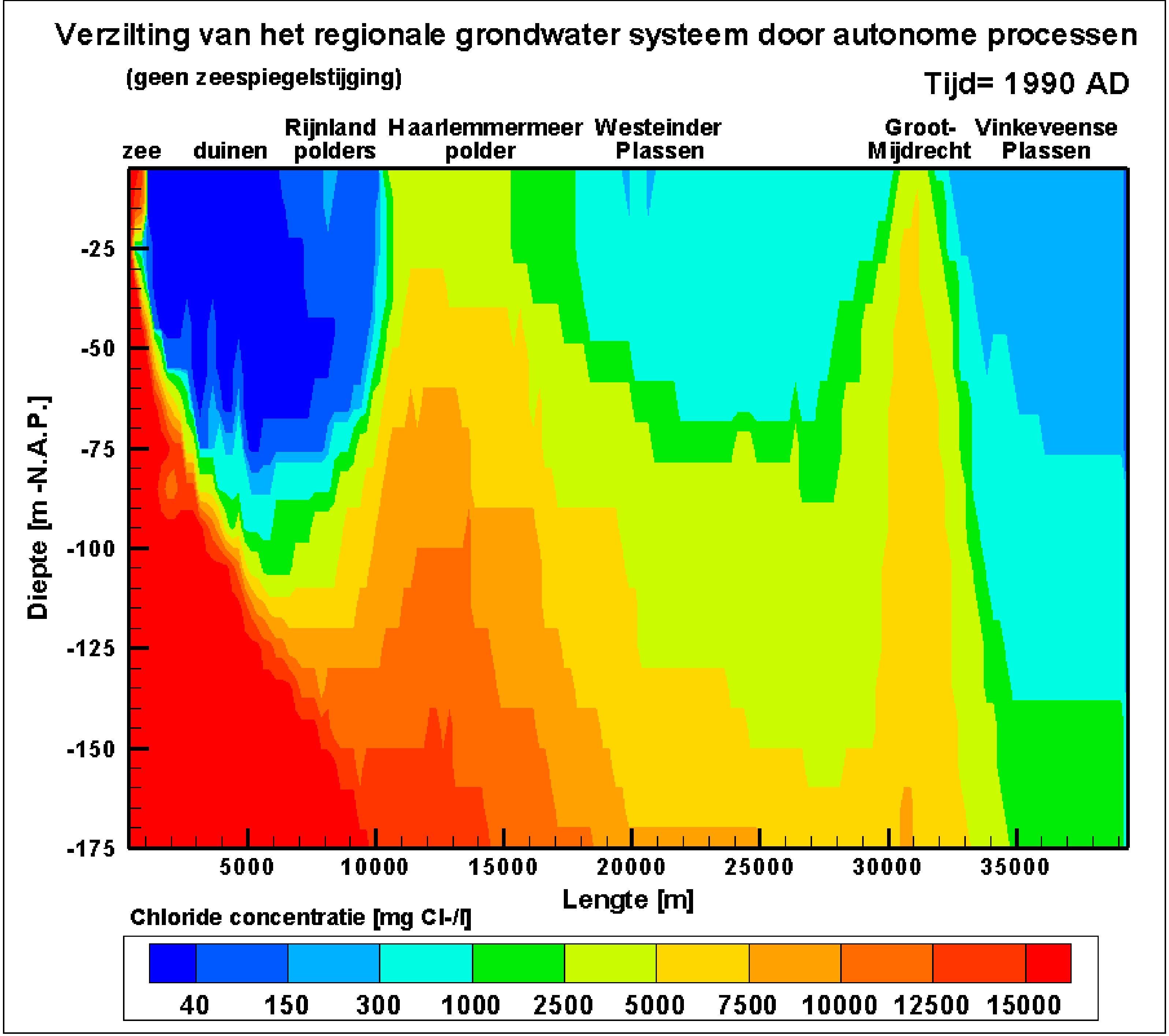
Effect of a relative sea level rise (3):

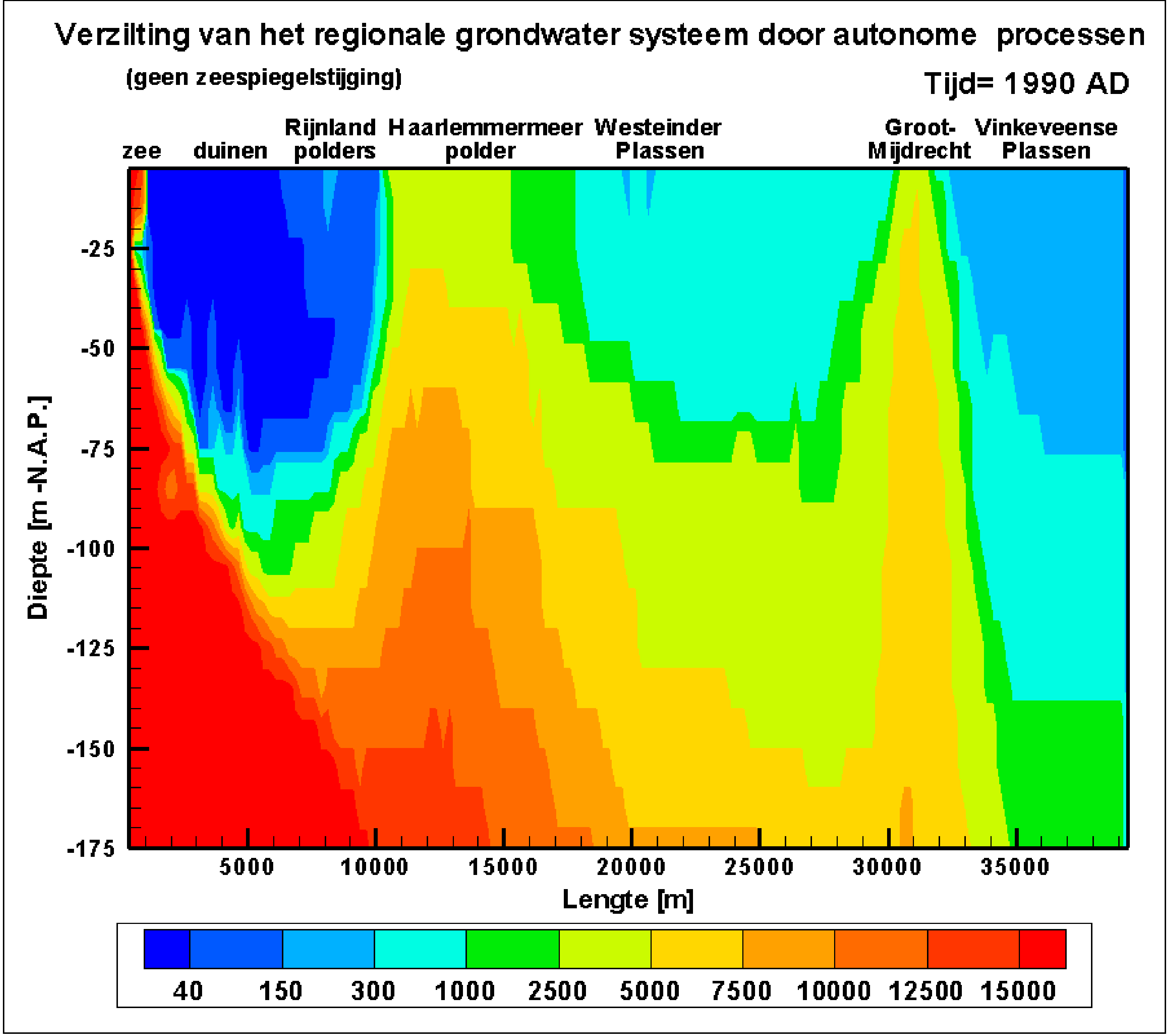
Shallow aquifer



Effect sea level rise on groundwater salinity in a 2D profile




Verzilting van het regionale grondwater systeem door autonome processen
(geen zeespiegelstijging)
Tijd= 1990 AD
zee
duinen
Rijnland polders
Haarlemmermeer polder
Westeinder Plassen
Groot-Mijdrecht
Vinkeveense Plassen
Diepte [m -N.A.P.]
-25
-50
-75
-100
-125
-150
-175
5000
10000
15000
20000
25000
30000
35000
Lengte [m]
Chloride concentratie [mg Cl-/l]
40
150
300
1000
2500
5000
7500
10000
12500
15000


Verzilting van het regionale grondwater systeem door autonome processen
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Tijd= 1990 AD
zee
duinen
Rijnland polders
Haarlemmermeer polder
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-25
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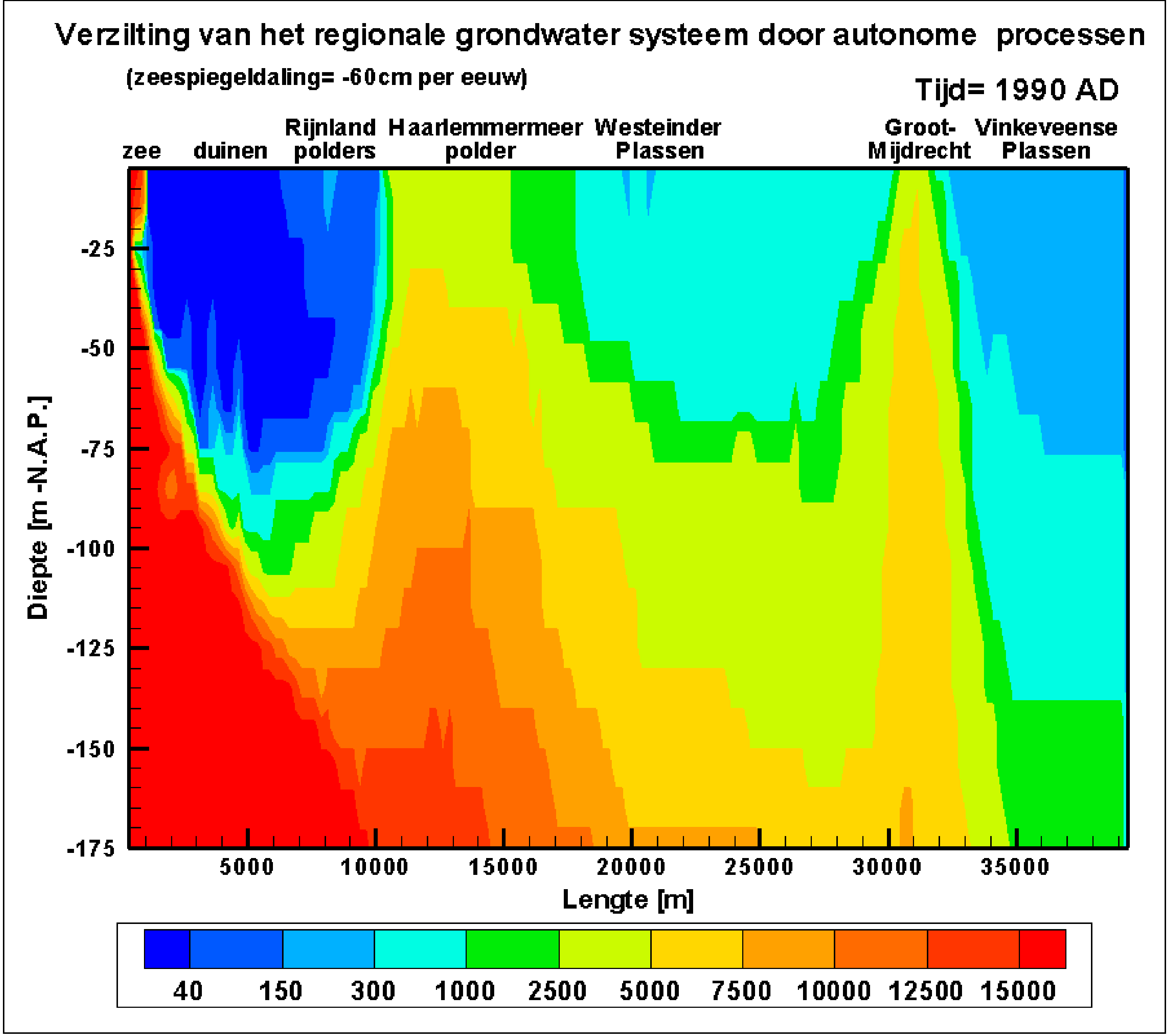
5000
10000
15000
20000
25000
30000
35000
Lengte [m]
40
150
300
1000
2500
5000
7500
10000
12500
15000



Verzilting van het regionale grondwater systeem door autonome processen
(zeespiegeldaling= -60cm per eeuw)
Tijd= 1990 AD
zee
duinen
Rijnland polders
Haarlemmermeer polder
Westeinder Plassen
Groot-Mijdrecht
Vinkeveense Plassen
Diepte [m -N.A.P.]
-25
-50
-75
-100
-125
-150
-175
5000
10000
15000
20000
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30000
35000
Lengte [m]
40
150
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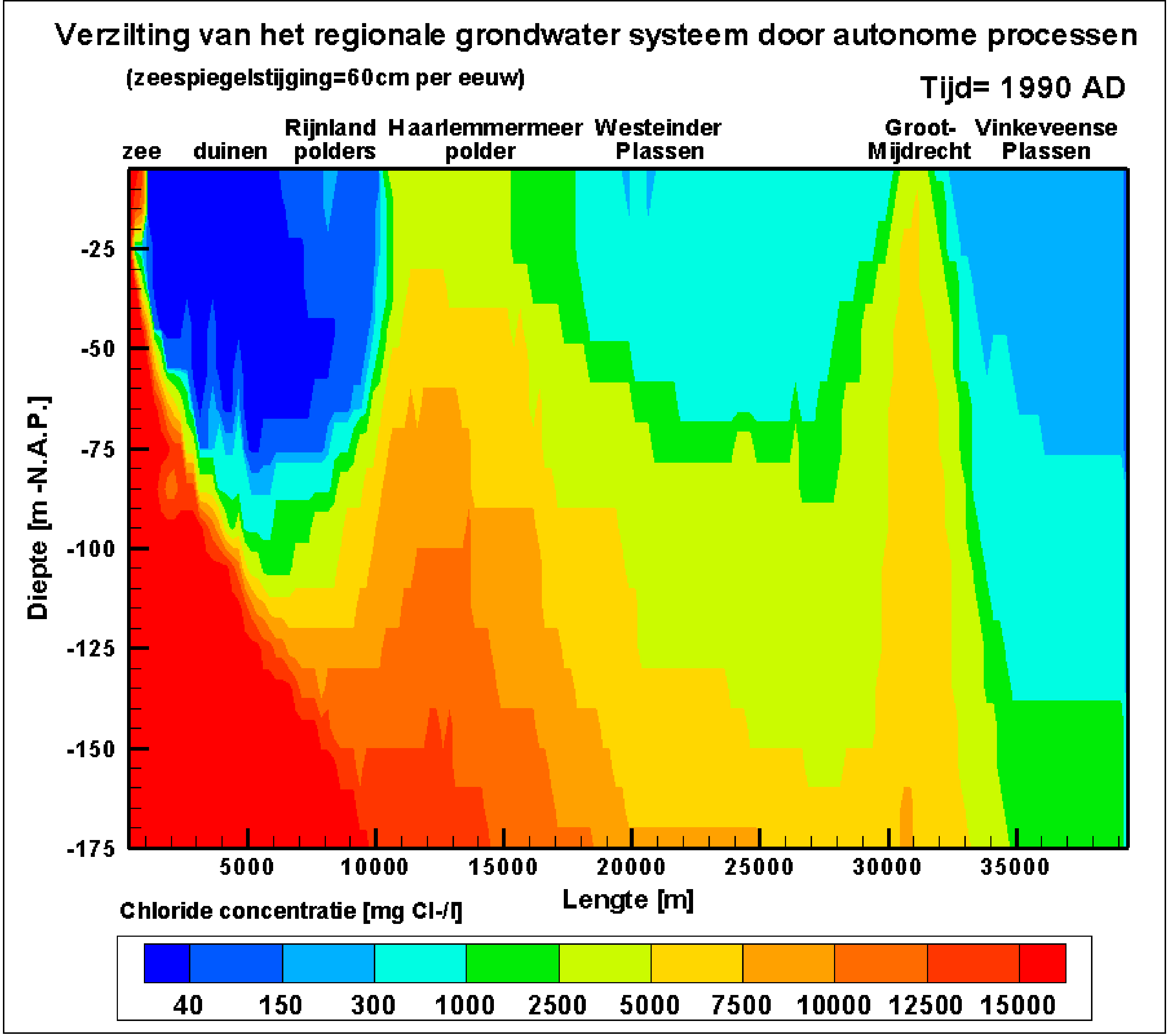
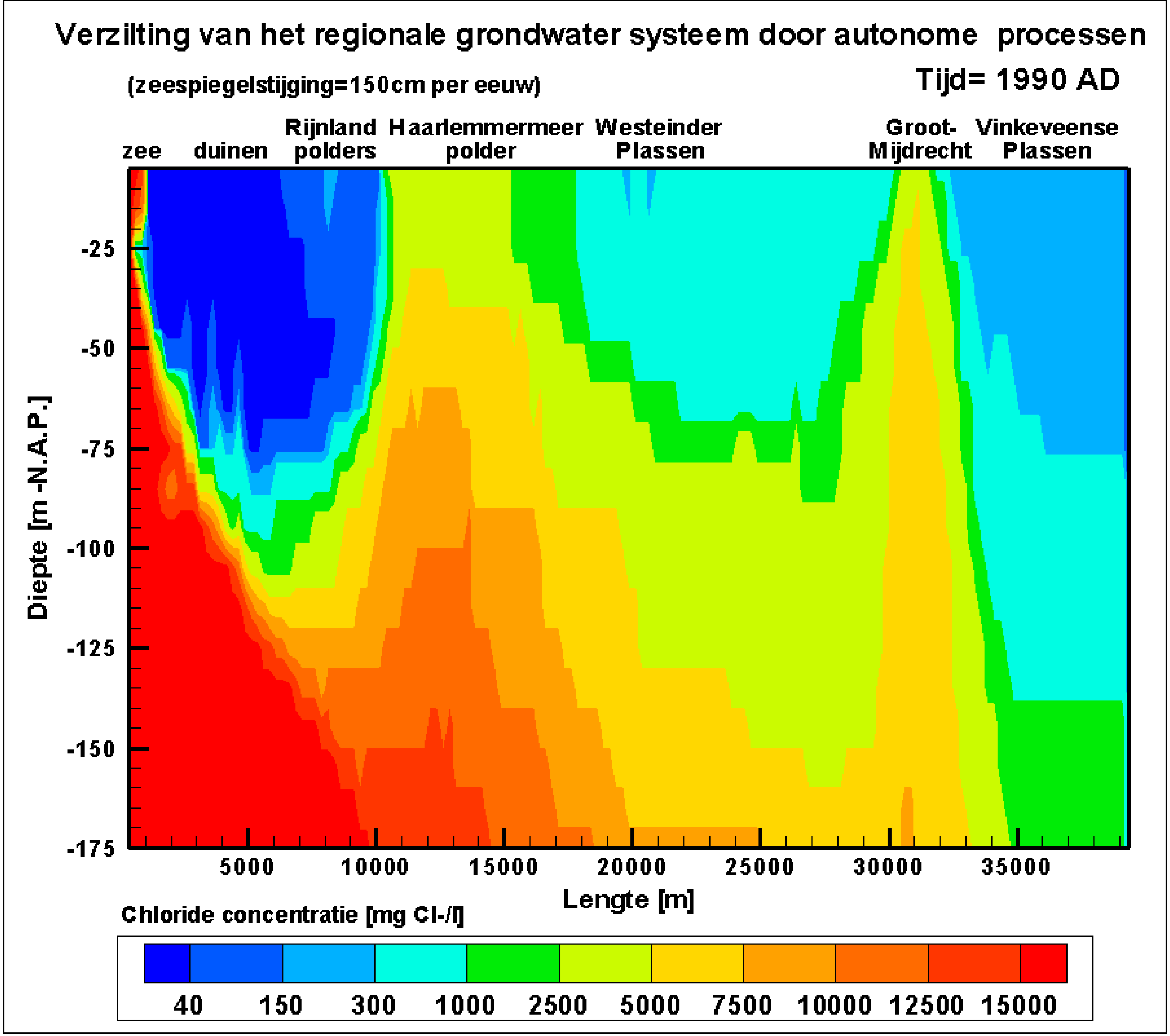
1000
2500
5000
7500
10000
12500
15000



Verzilting van het regionale grondwater systeem door autonome processen
(zeespiegelstijging=60cm per eeuw)
Tijd= 1990 AD
zee
duinen
Rijnland polders
Haarlemmermeer polder
Westeinder Plassen
Groot-Mijdrecht
Vinkeveense Plassen
-25
-50
-75
-100
-125
-150
-175
Diepte [m -N.A.P.]
5000
10000
15000
20000
25000
30000
35000
Lengte [m]
Chloride concentratie [mg Cl-/l]
40
150
300
1000
2500
5000
7500
10000
12500
15000



Verzilting van het regionale grondwater systeem door autonome processen
(zeespiegelstijging=150cm per eeuw)
Tijd= 1990 AD
zee
duinen
Rijnland polders
Haarlemmermeer polder
Westeinder Plassen
Groot-Mijdrecht
Vinkeveense Plassen
Diepte [m -N.A.P.]
-25
-50
-75
-100
-125
-150
-175
5000
10000
15000
20000
25000
30000
35000
Lengte [m]
Chloride concentratie [mg Cl-/l]
40
150
300
1000
2500
5000
7500
10000
12500
15000

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)

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

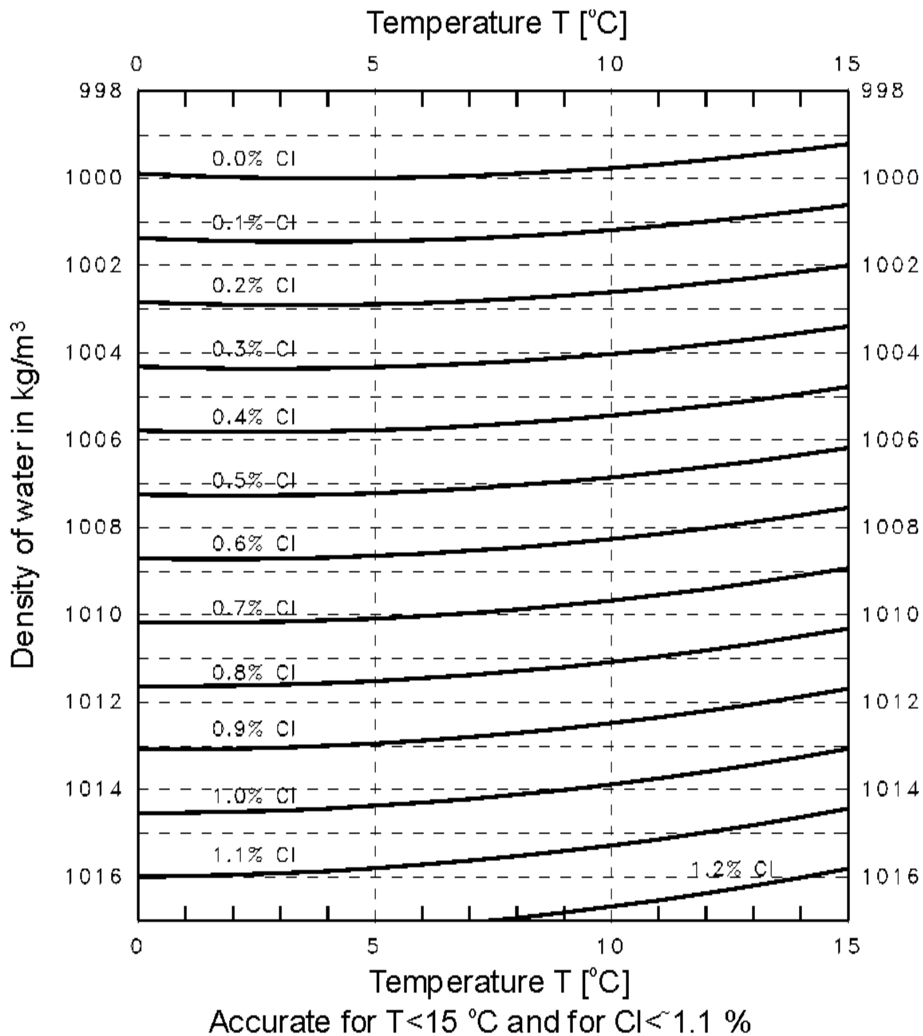
Equation of state (SEAWAT)

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

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

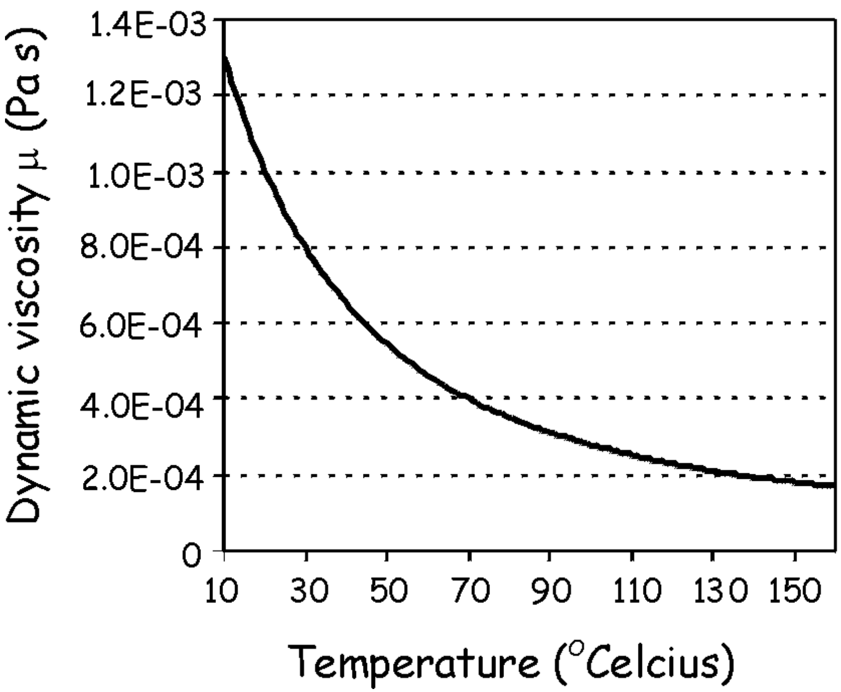


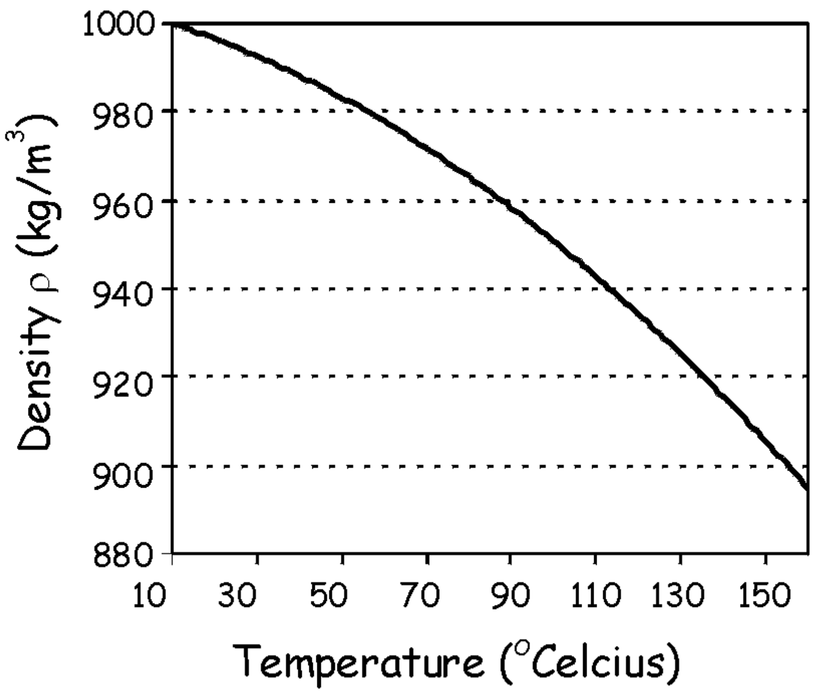
$$\rho_{(S,T)} = 1000 + 0.8054S - 0.0065(T - 4 + 0.2214S)^2$$

Knudsen (1902)

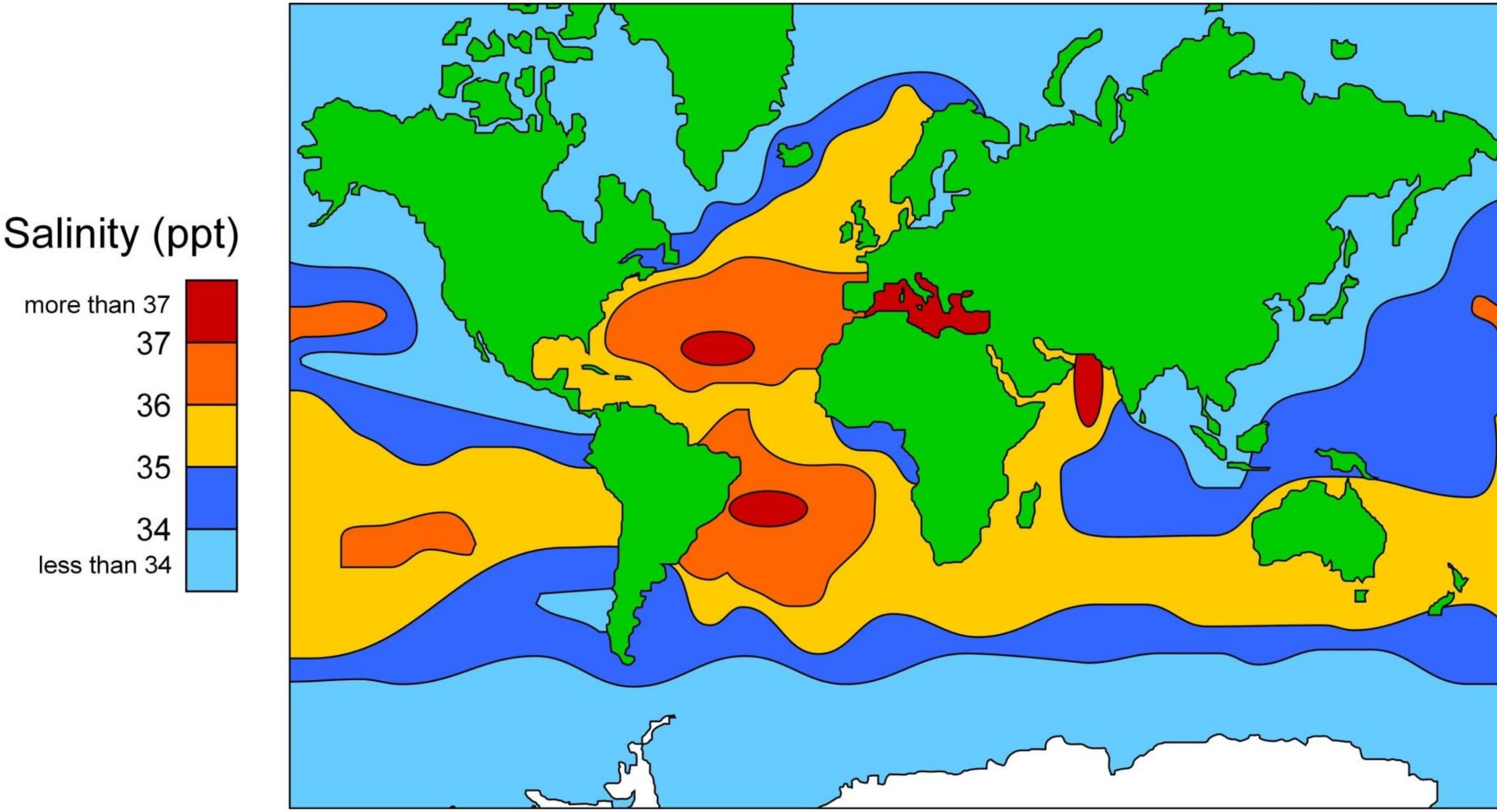
Density and viscosity depend on temperature

(10^oC-160 ^oC)

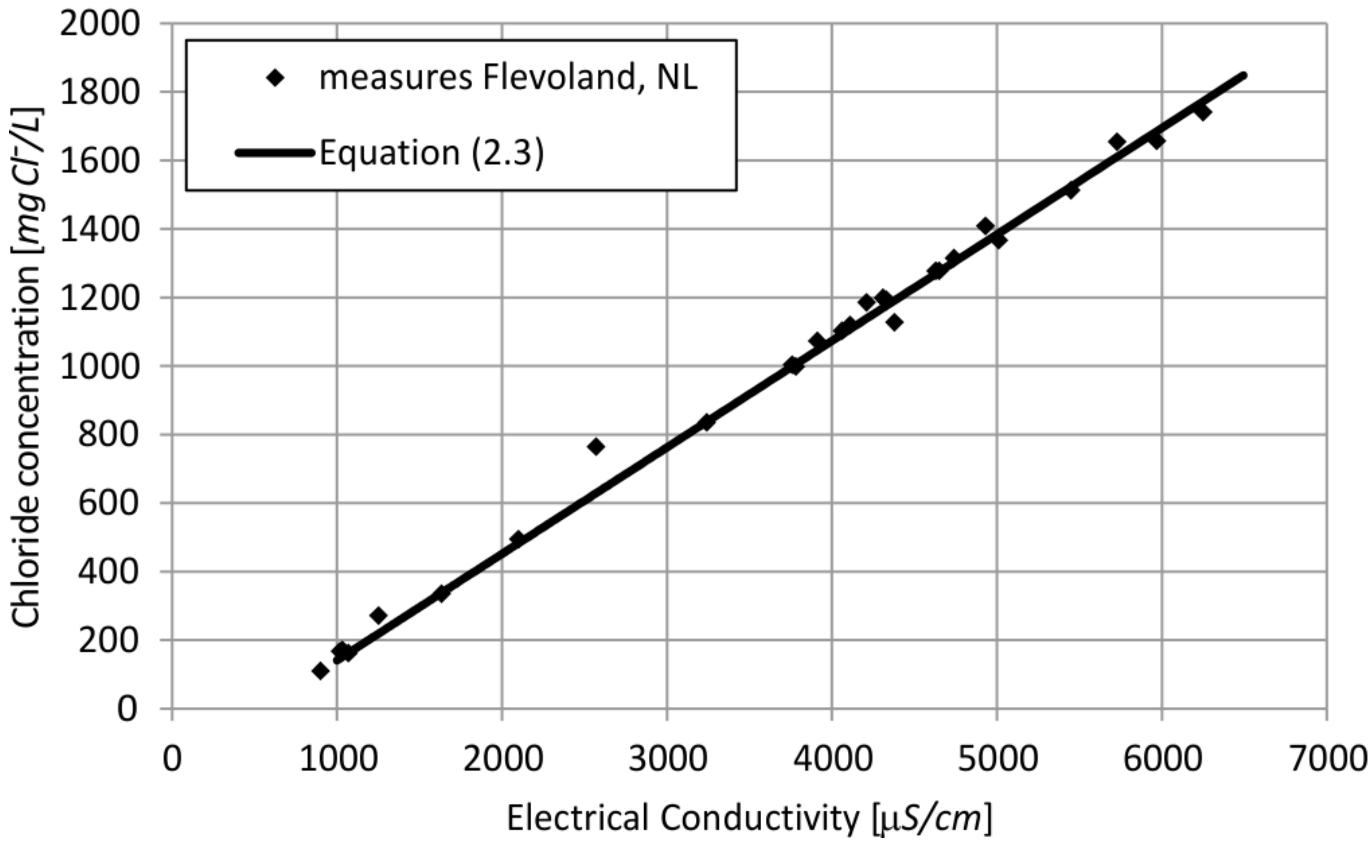




Salinity in ocean waters



Close relation between chloride concentration and Electrical Conductivity



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

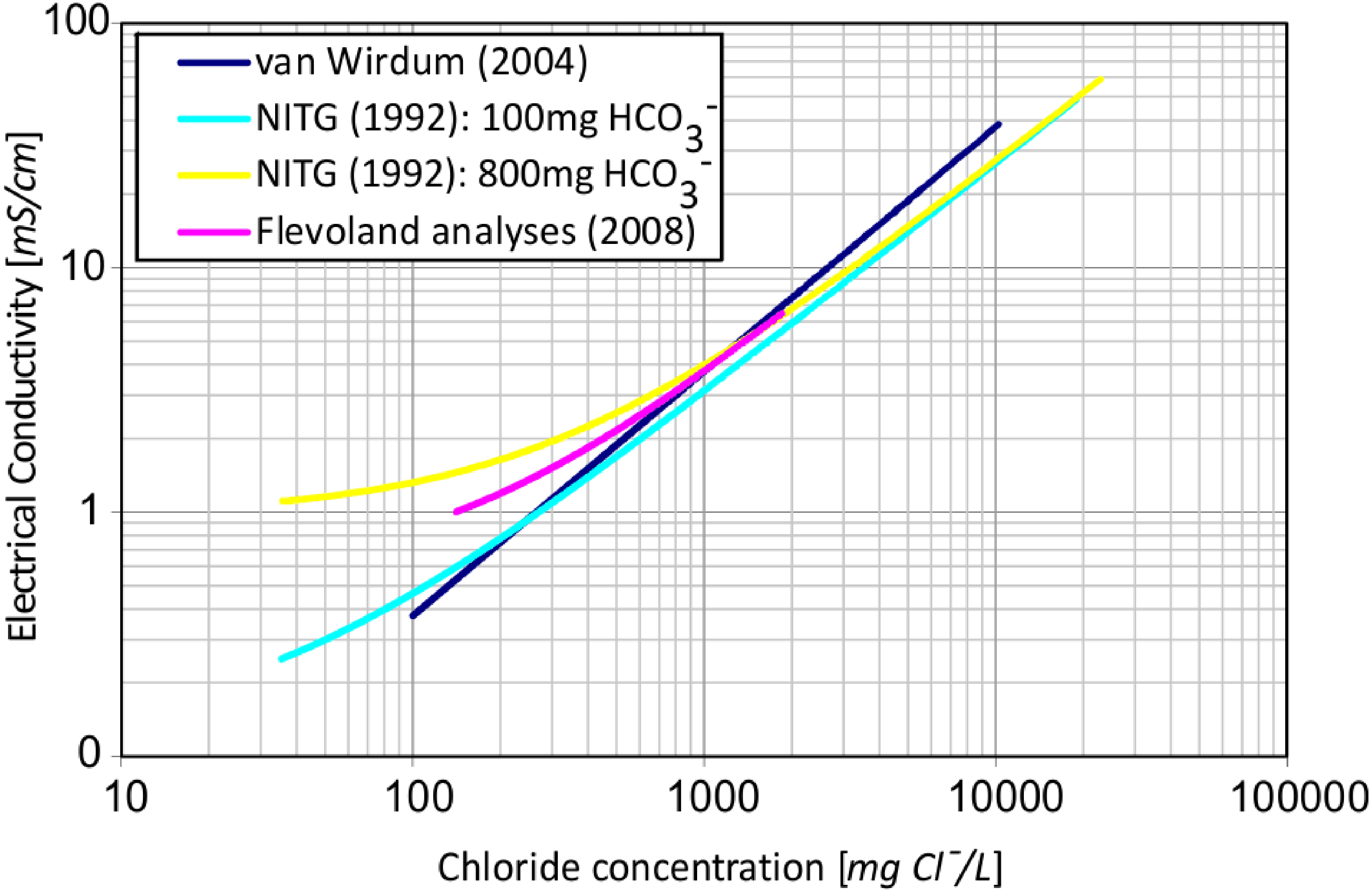
Close relation between chloride concentration and Electrical Conductivity

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

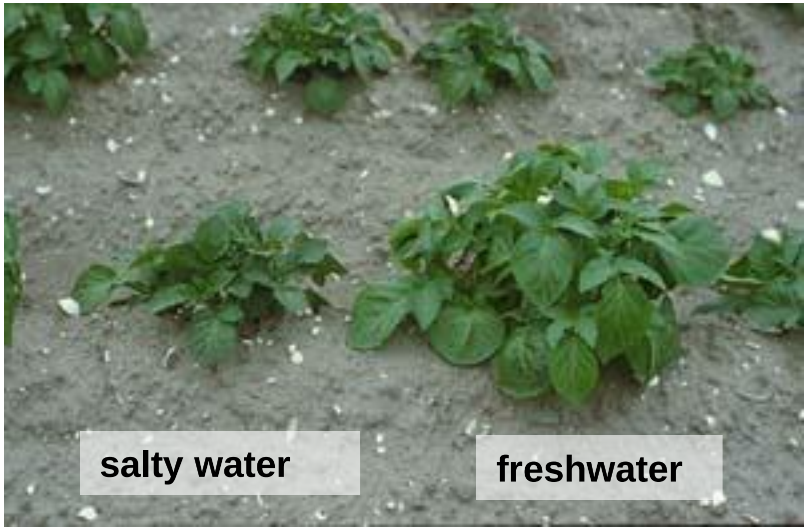
ocean water:
~19000 *mg Cl-/L* or ~34555 *mg TDS/L*
~5 *S/m* or ~48 *mS/cm*

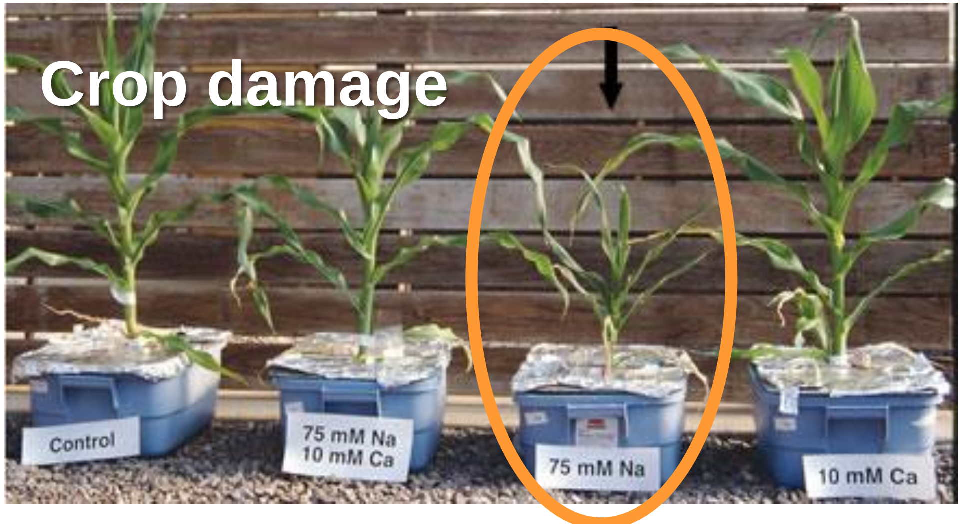
the ratio Cl^- over TDS equal to ~0.554, under stable normal seawater environments

EC versus Chloride



Salt in water is a problem





Saline groundwater 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

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

-drinking water:

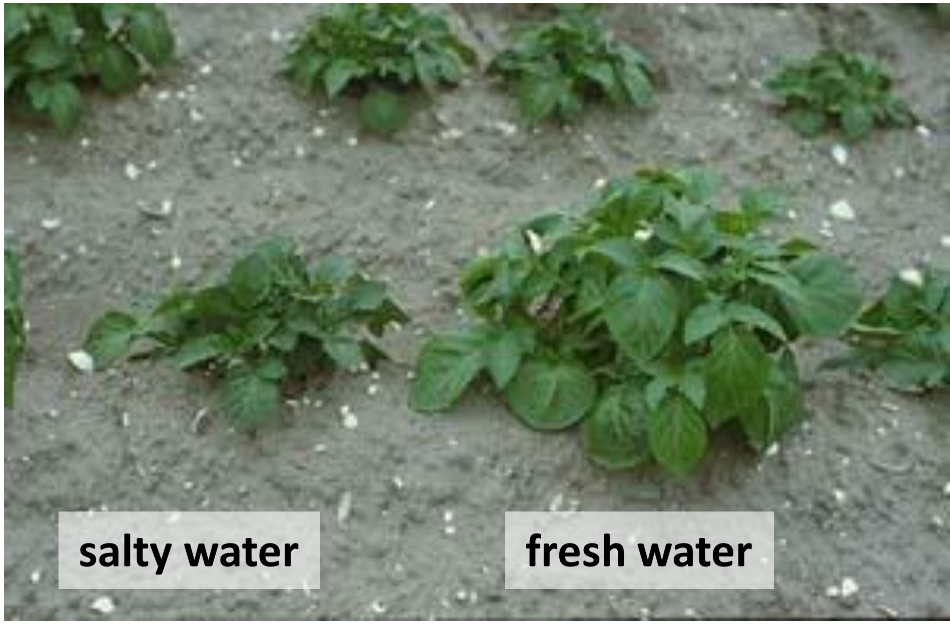
- taste (100-300 mg Cl^-/l)
- long term health effect
- norm: EC& WHO=150 mg Cl^-/l (live stock=1500 mg Cl^-/l)

-industry:

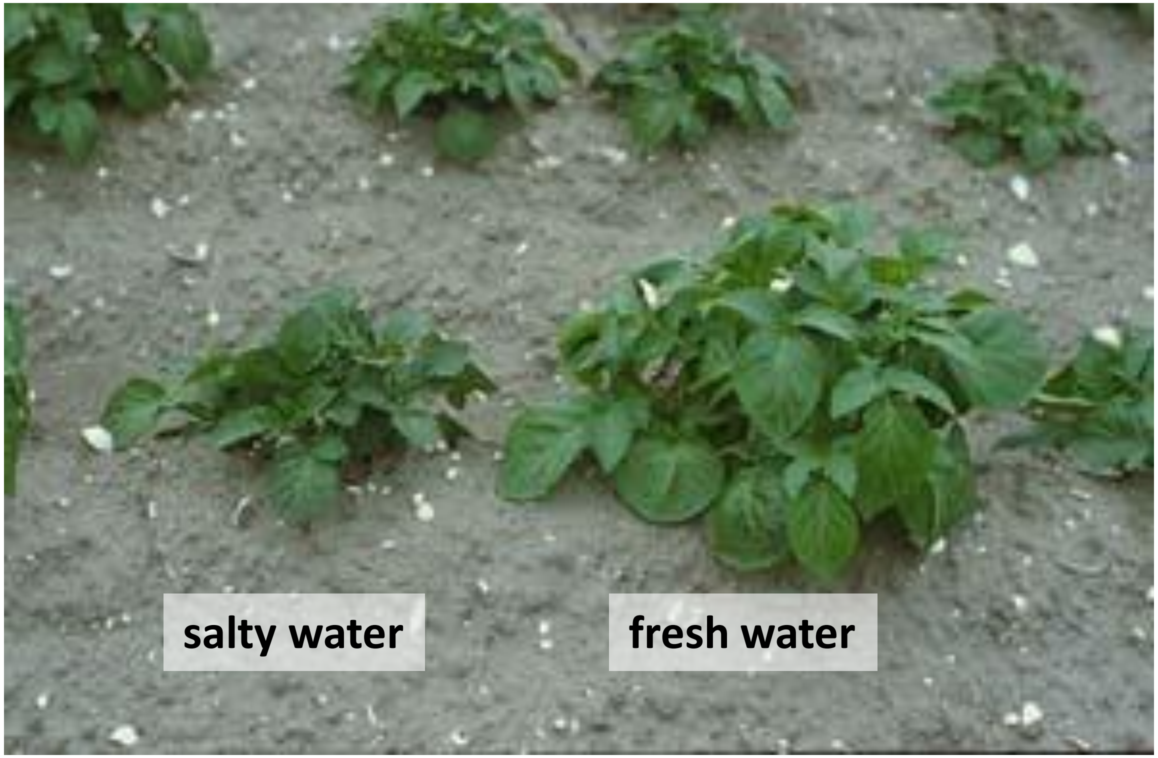
- corrosion pipes
- preparation food

-irrigation/agriculture:

- production crops
- salt damage

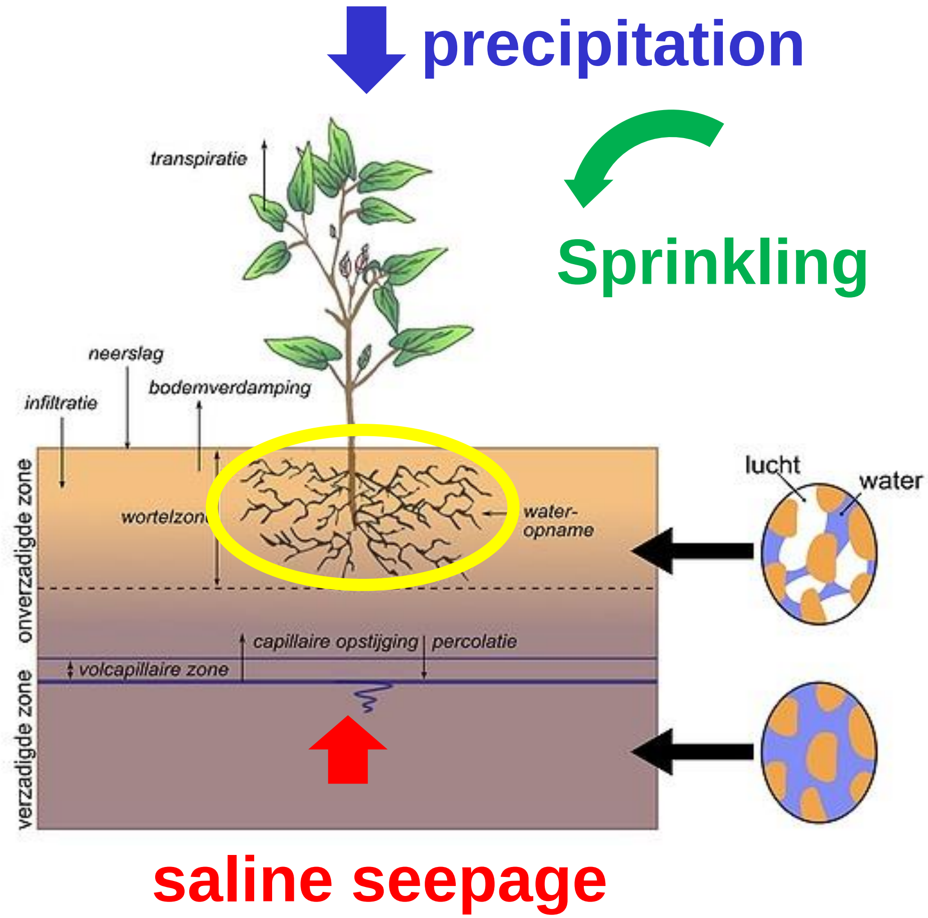


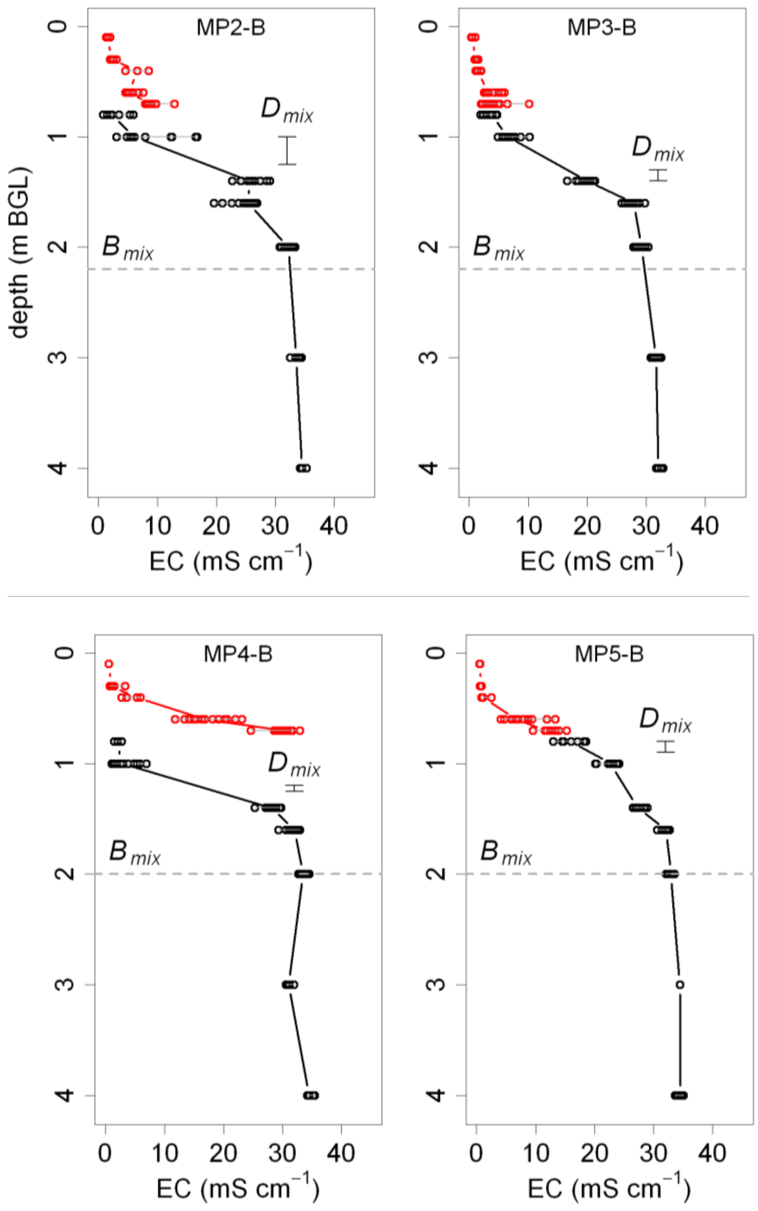
Effects salinisation: salt damage



Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

Salt-resistant crops





Salt damage to crops

Important parameters:

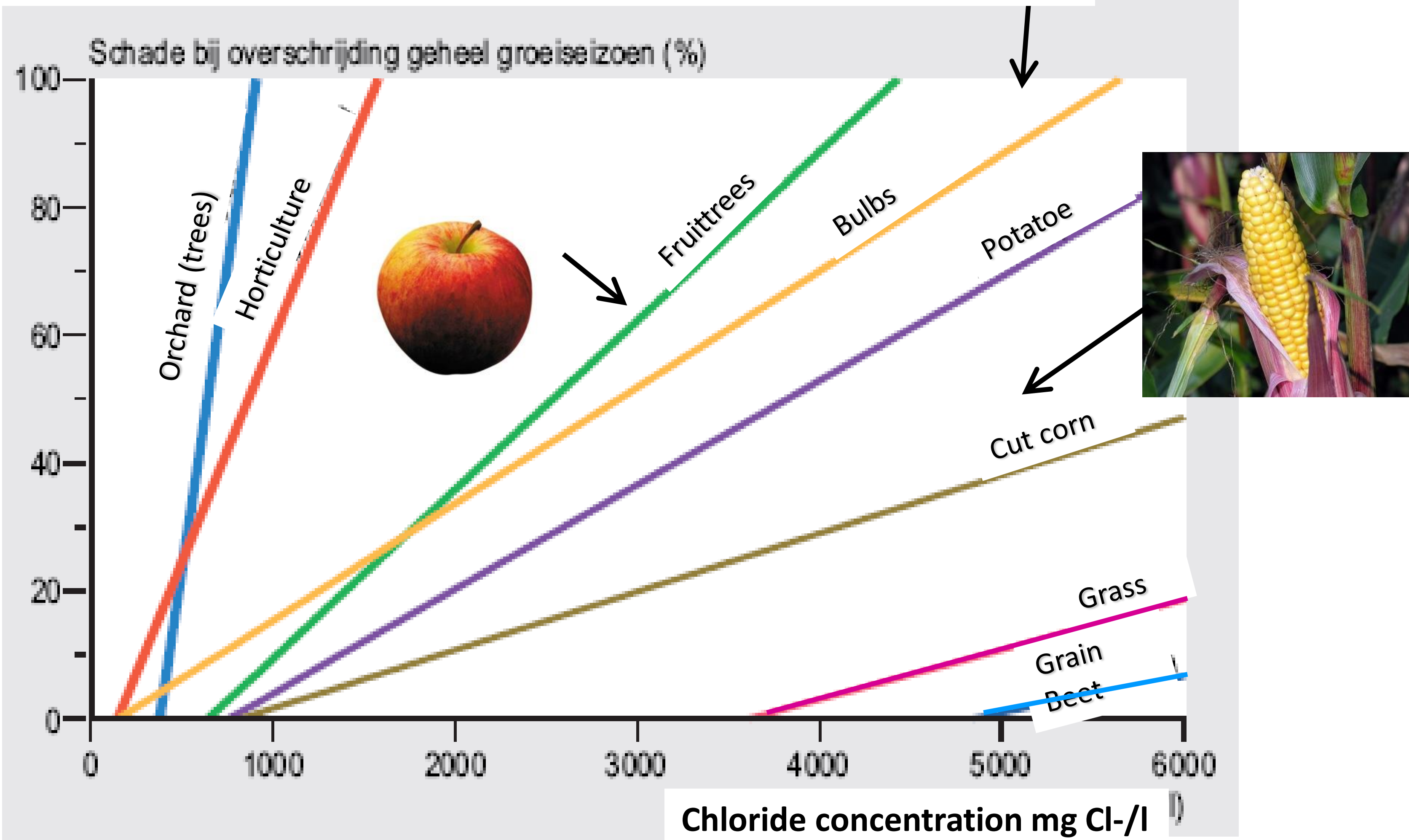
- Chloride concentration in the root zone
- land use
- sensitivity crops

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

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

Question:

Demand fresh water per capita per day?:

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


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

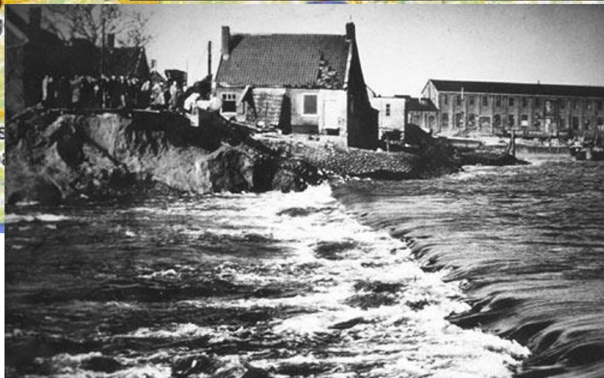
10 litres of water
for 1 sheet of A4-paper

Groundwater salinization in the Netherlands

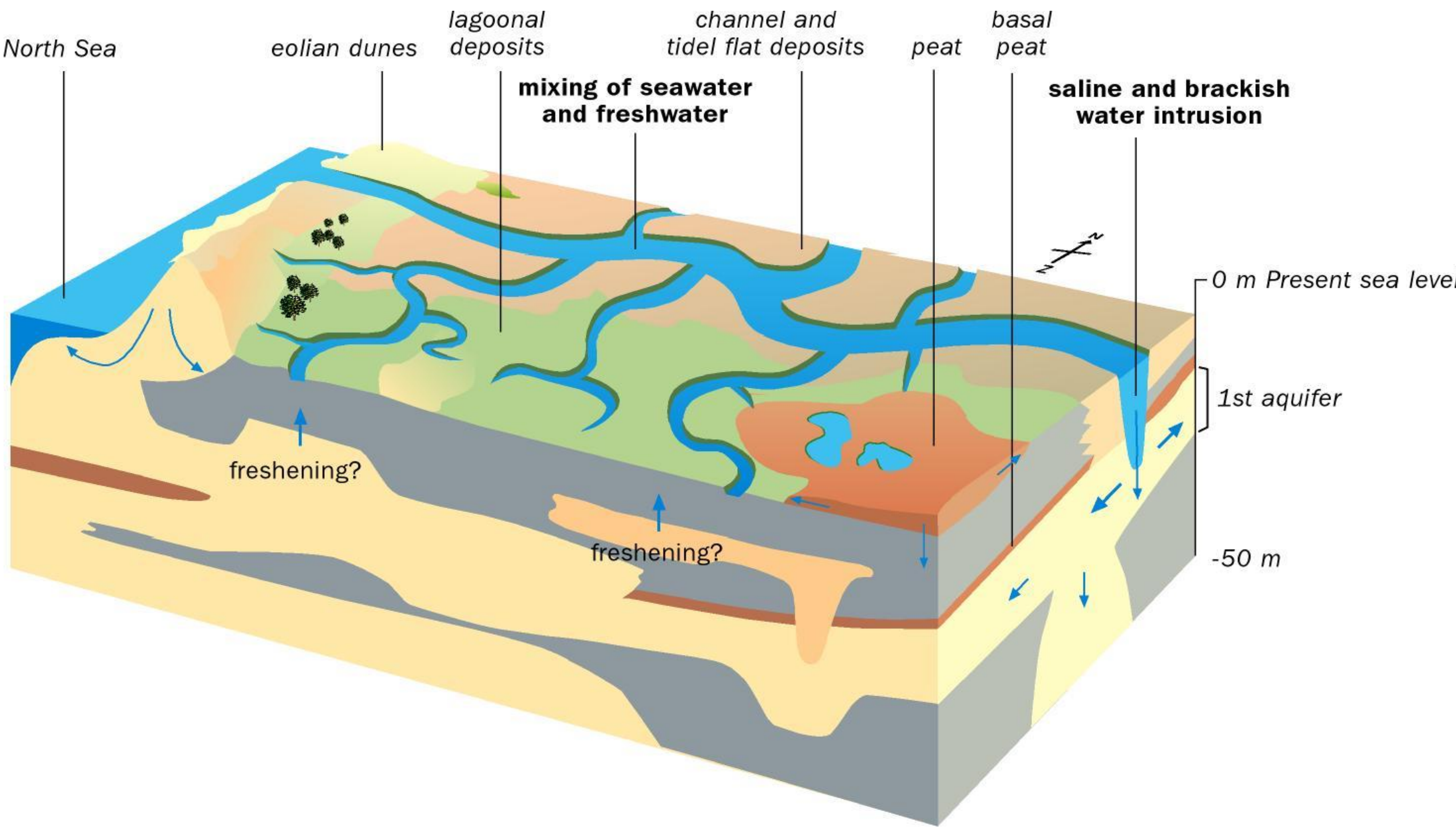
The Netherlands: low-lying lands

http://flood.firetree.net

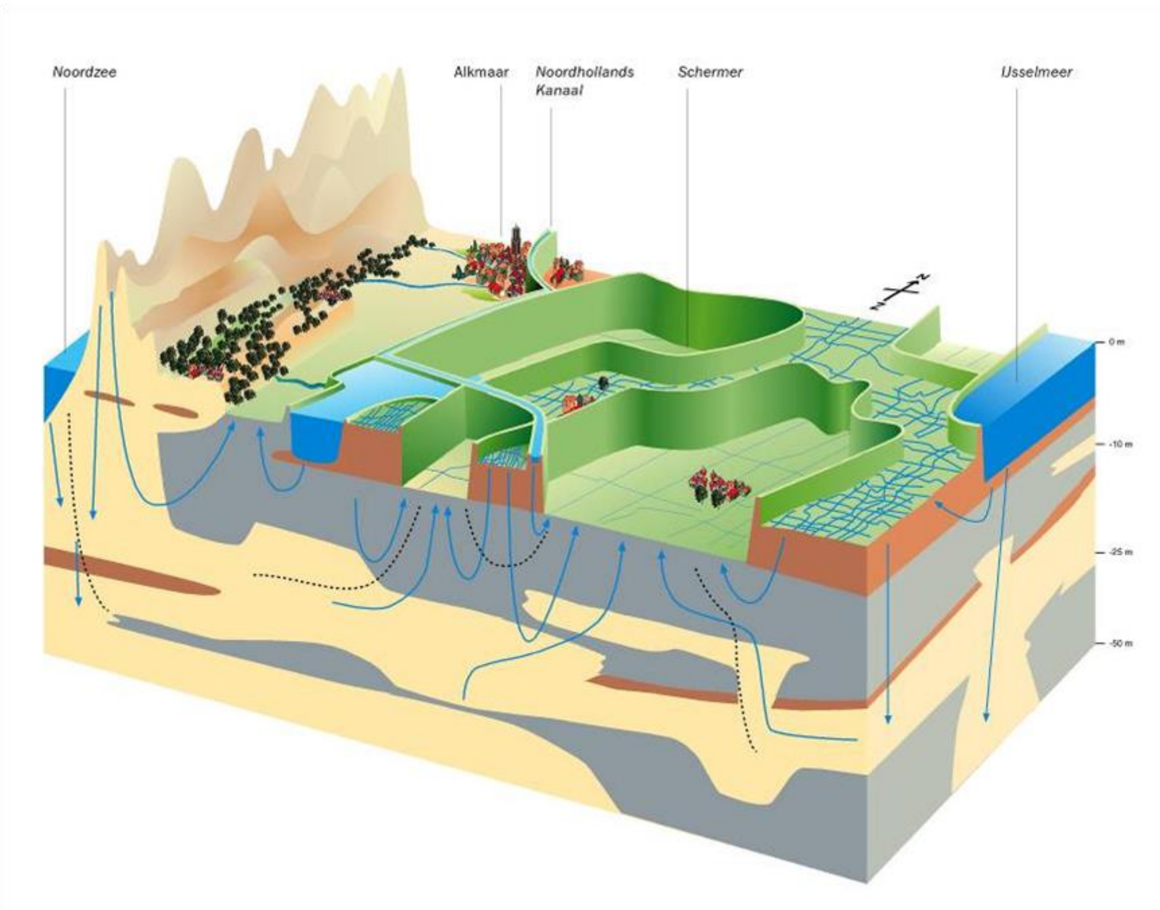
~50km



The Netherlands in the past, before human influences (~4000 BC)



The current coastal groundwater system in the Netherlands



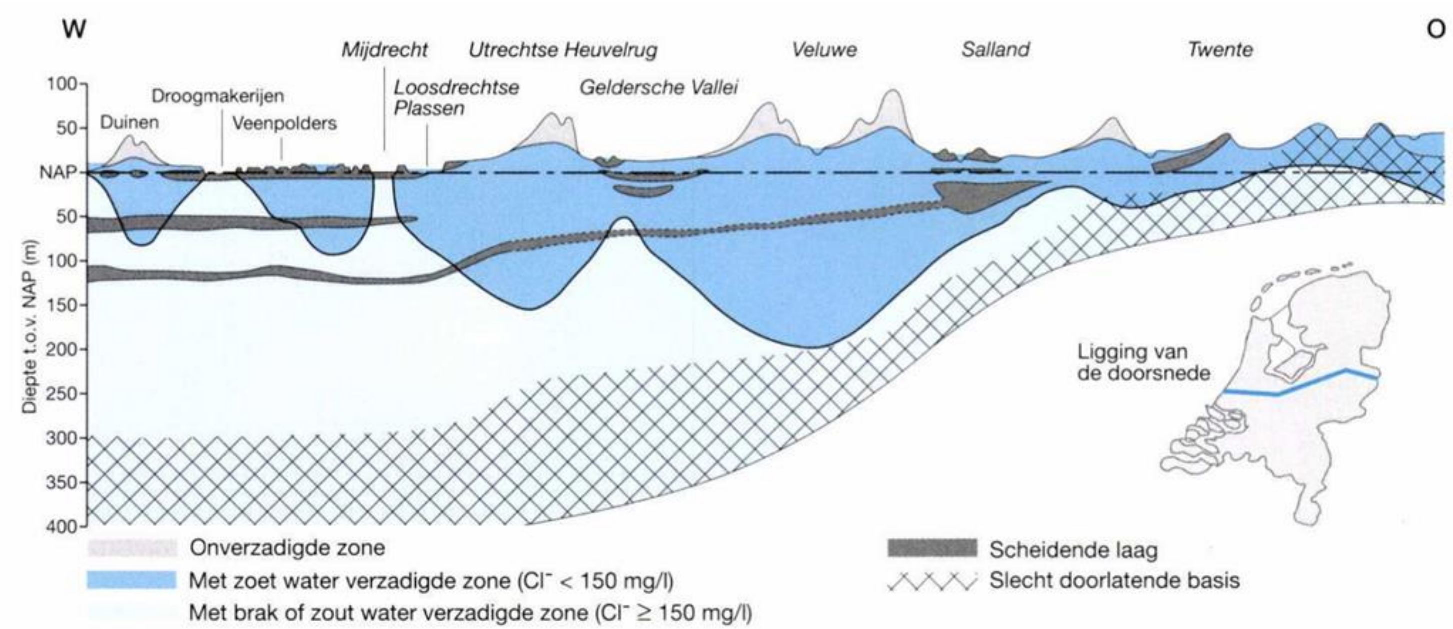
Level reductions in the past have caused groundwater flows inland

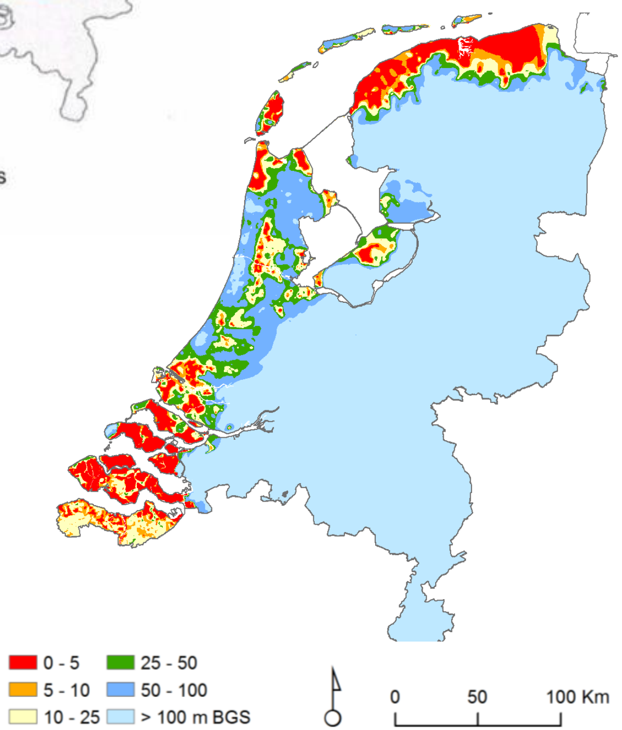
History (palaeohydrogeology) important: groundwater flow is a slow process

The past still influences the distribution of fresh-brackish-salt groundwater

Fresh-salt distribution can vary greatly over a short distance

Saline groundwater in the Netherlands

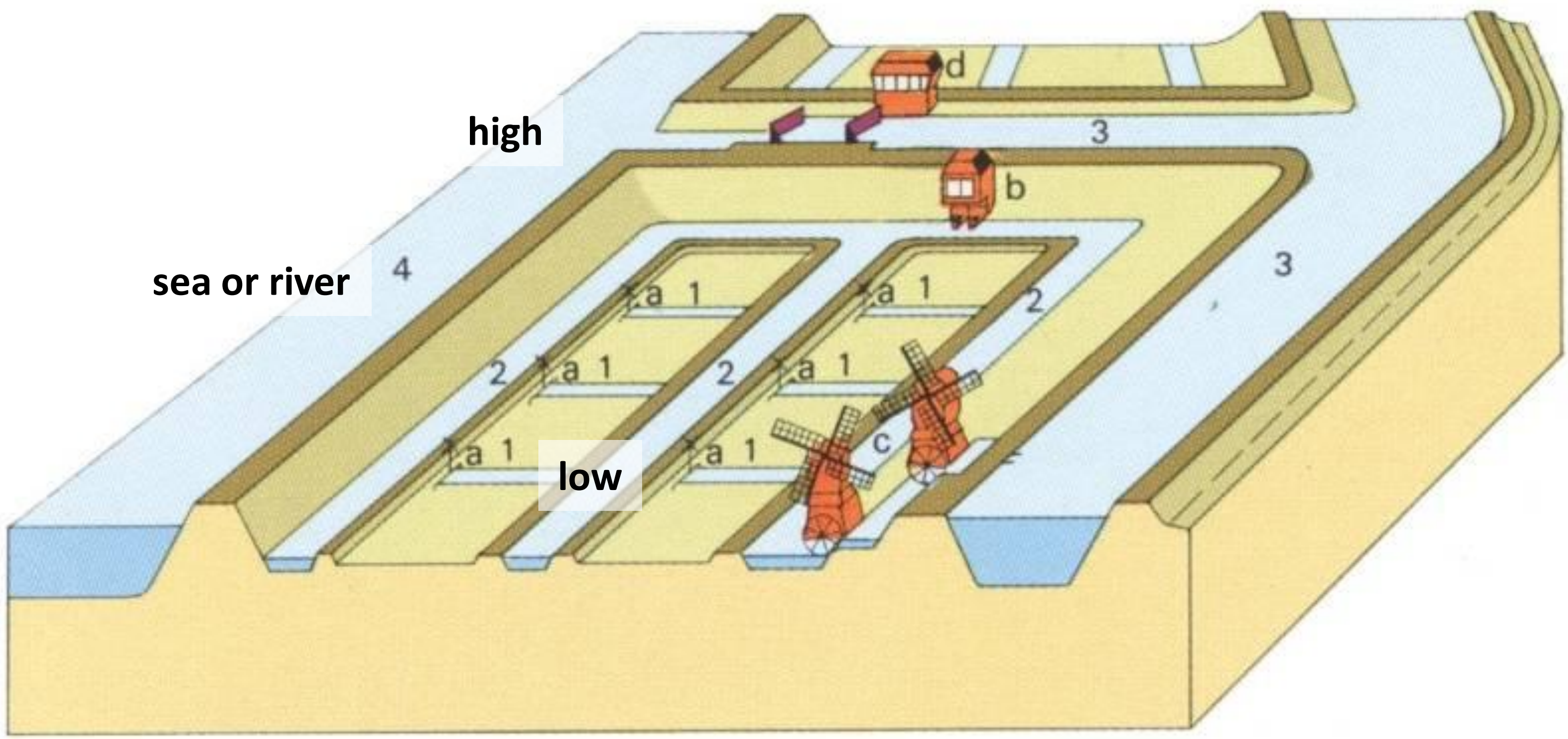




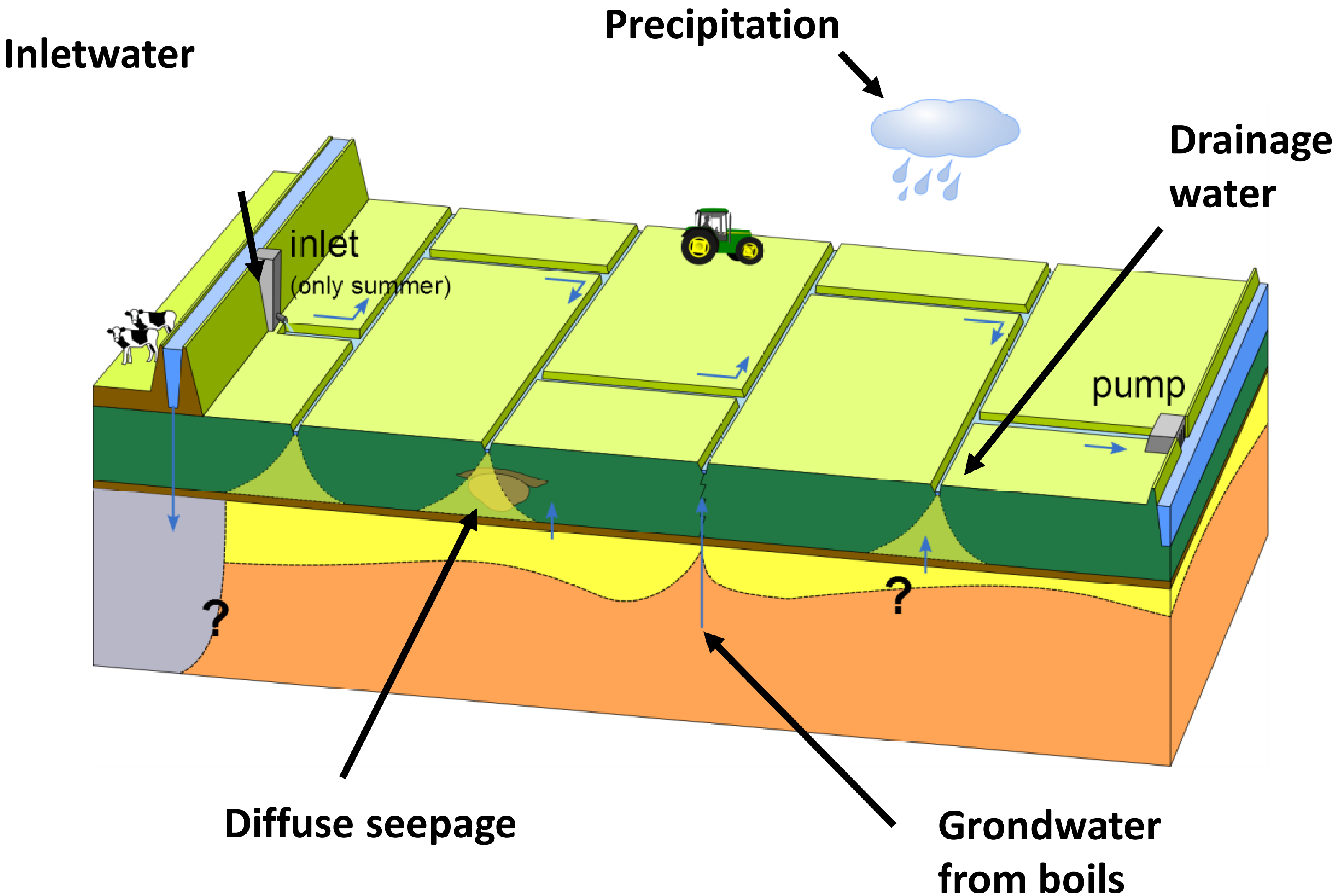
The polder system

A polder is:

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

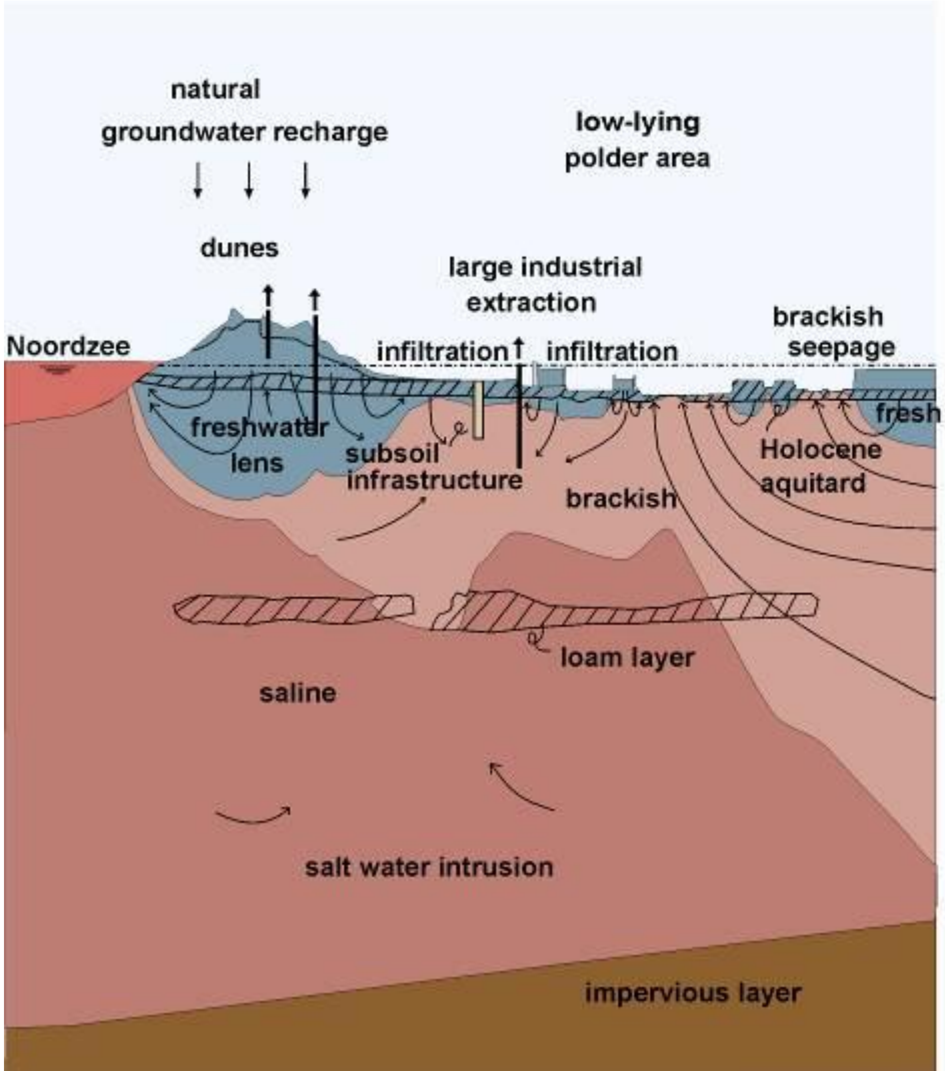


Polder system: a schematic overview of water flows

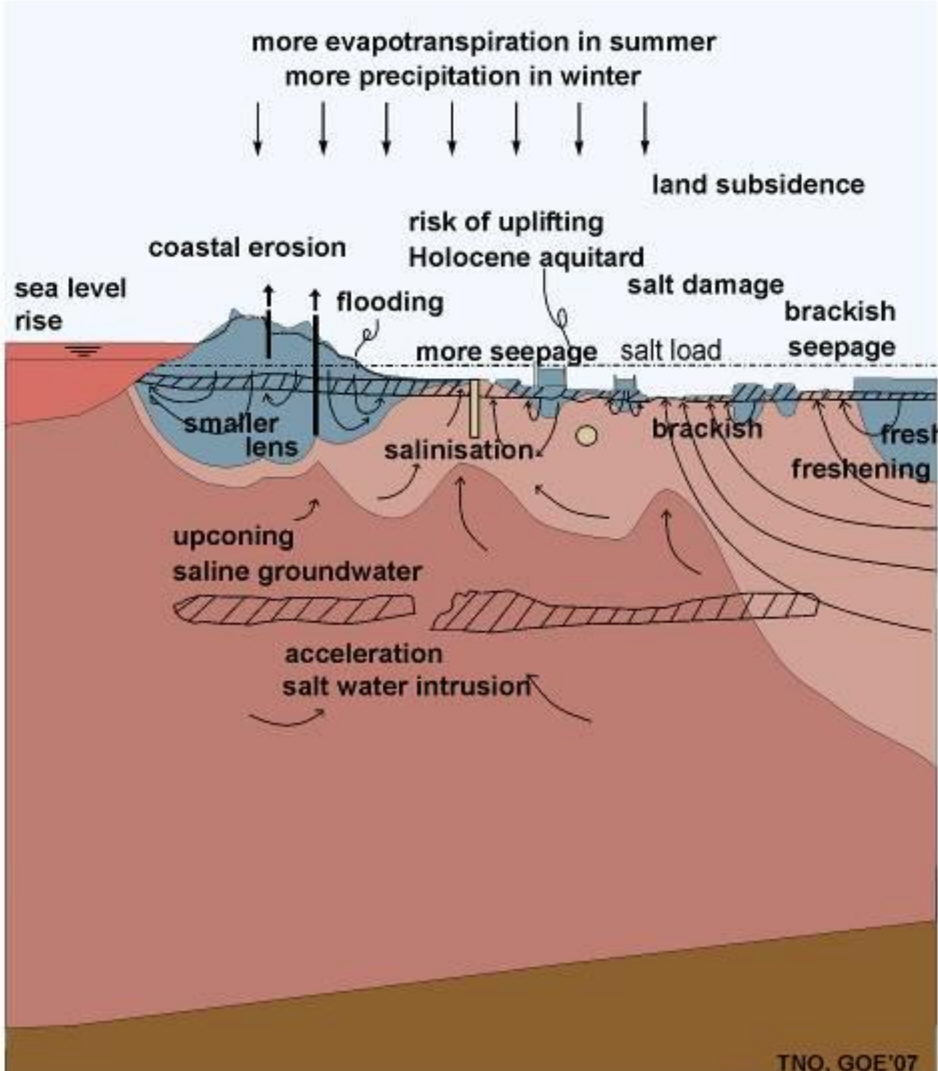


The Dutch groundwater system under stress

Present processes

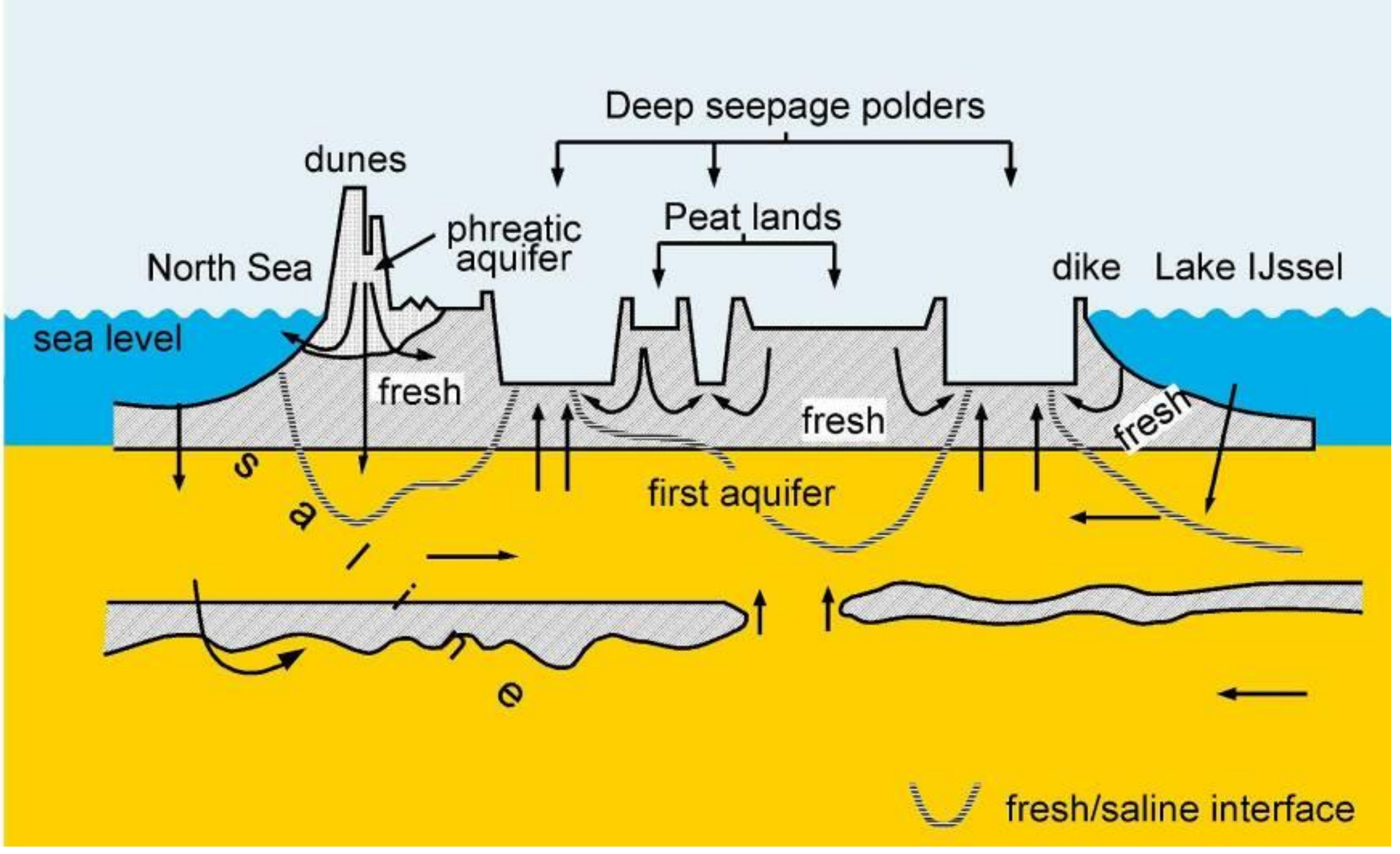


Future changes



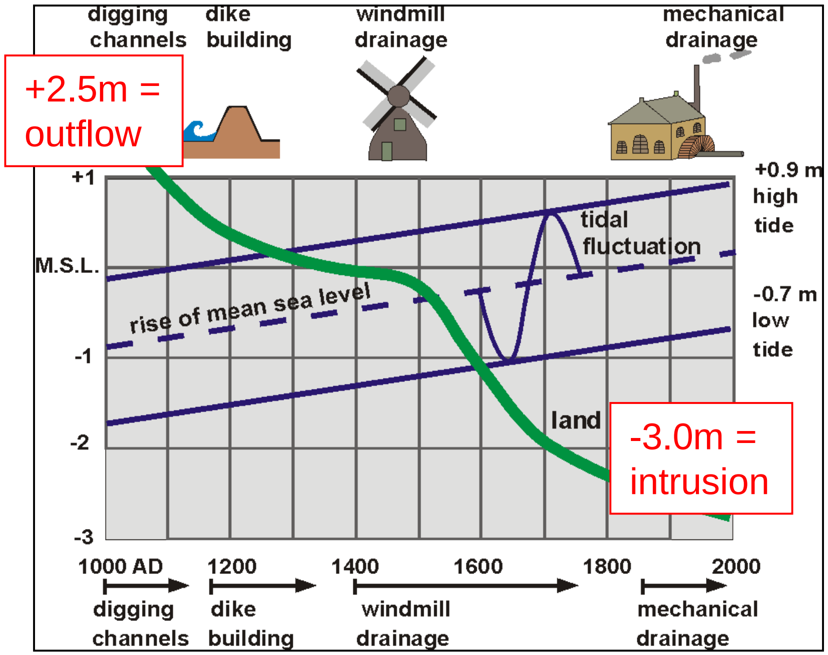
Saline seepage leads to:

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

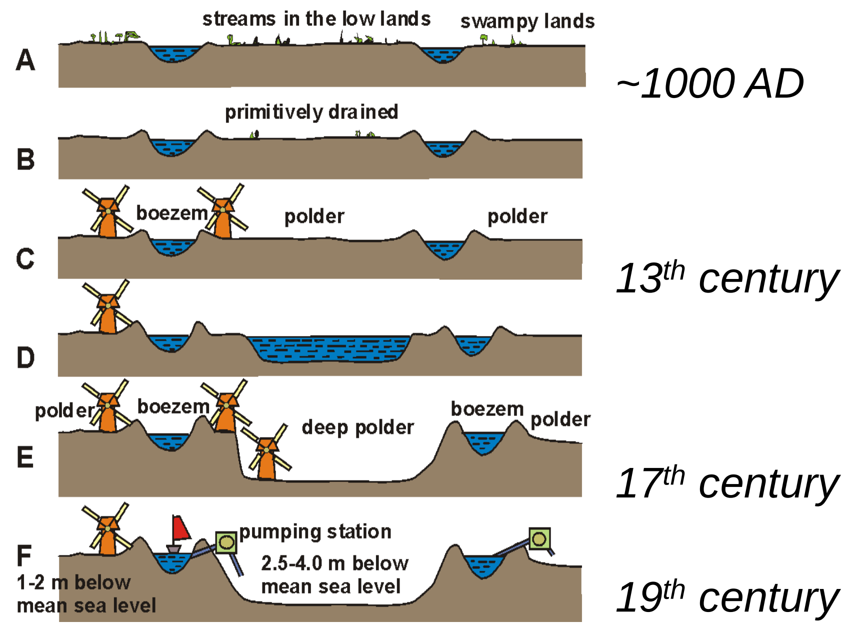


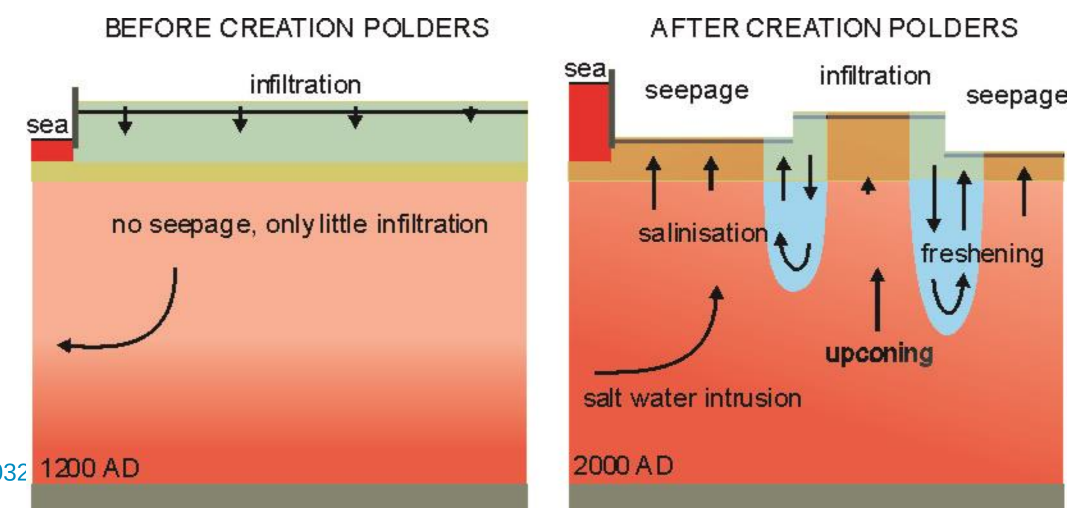
From fresh water outflow to salt water inflow

Historical subsidence of the ground surface in Holland



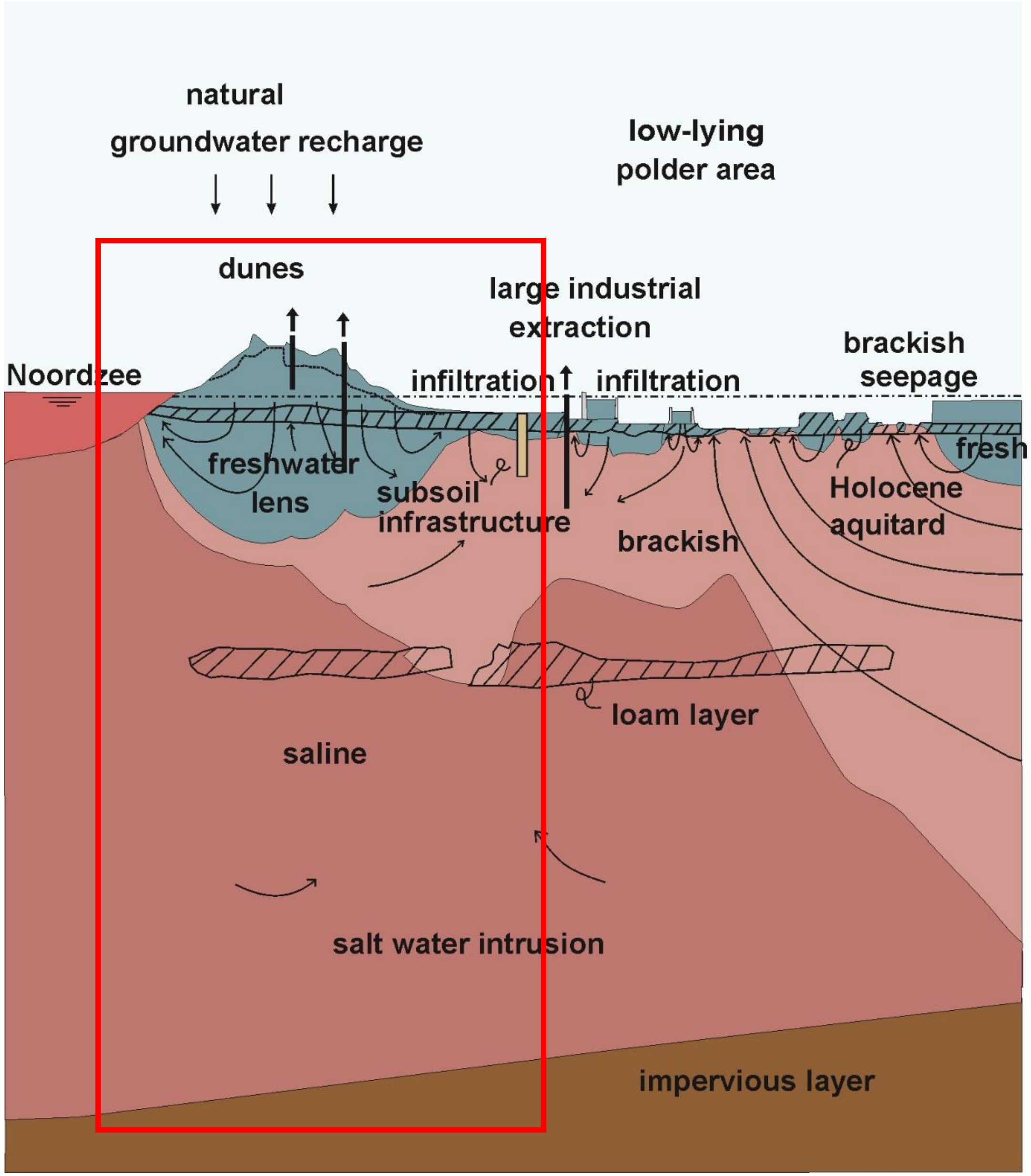
Ground surface





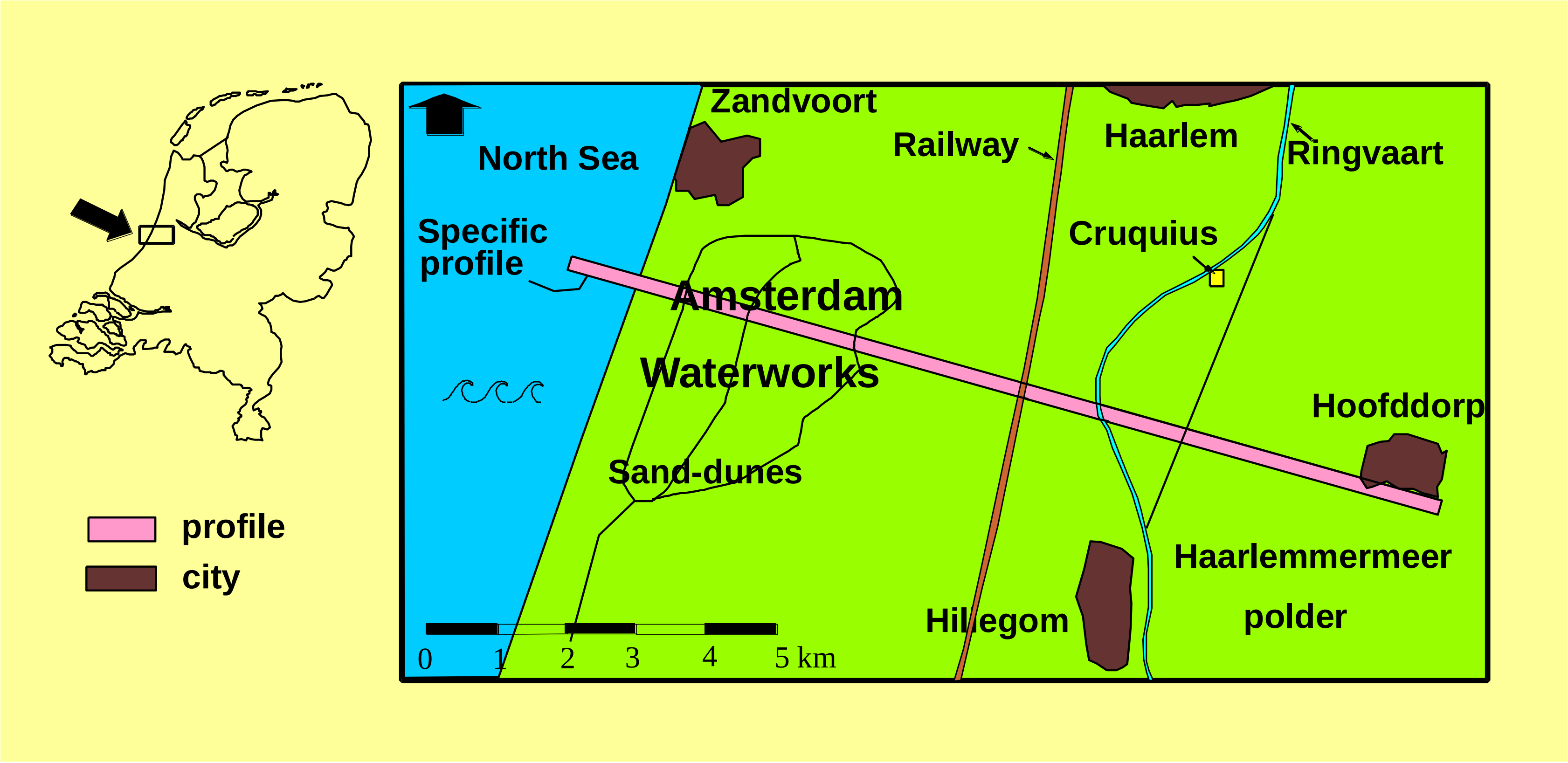
My first density dependent groundwater flow and solute transport model in 1990!

Saltwater intrusion in the Netherlands

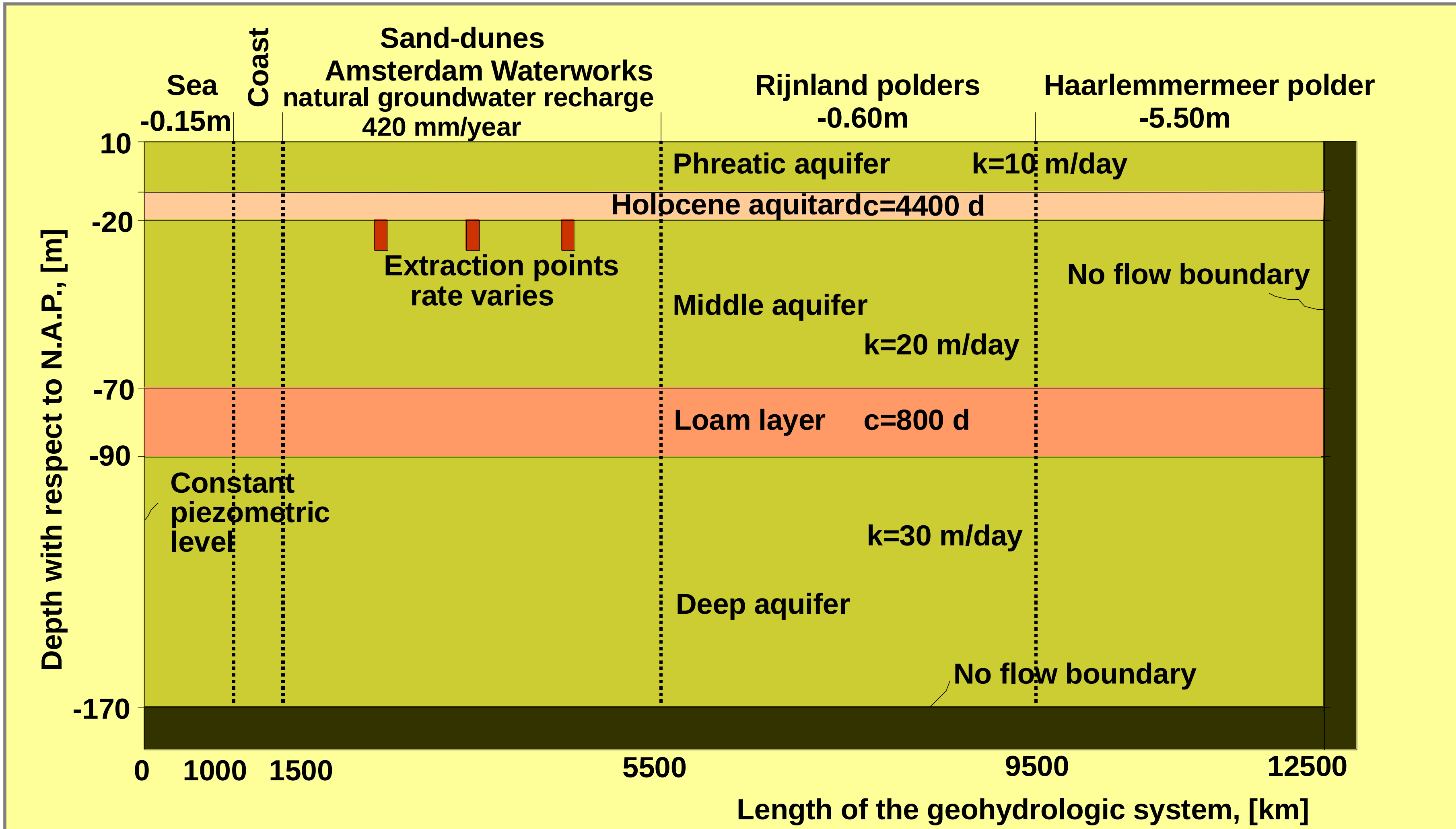


Saltwater intrusion in the Dutch coastal zone

Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder

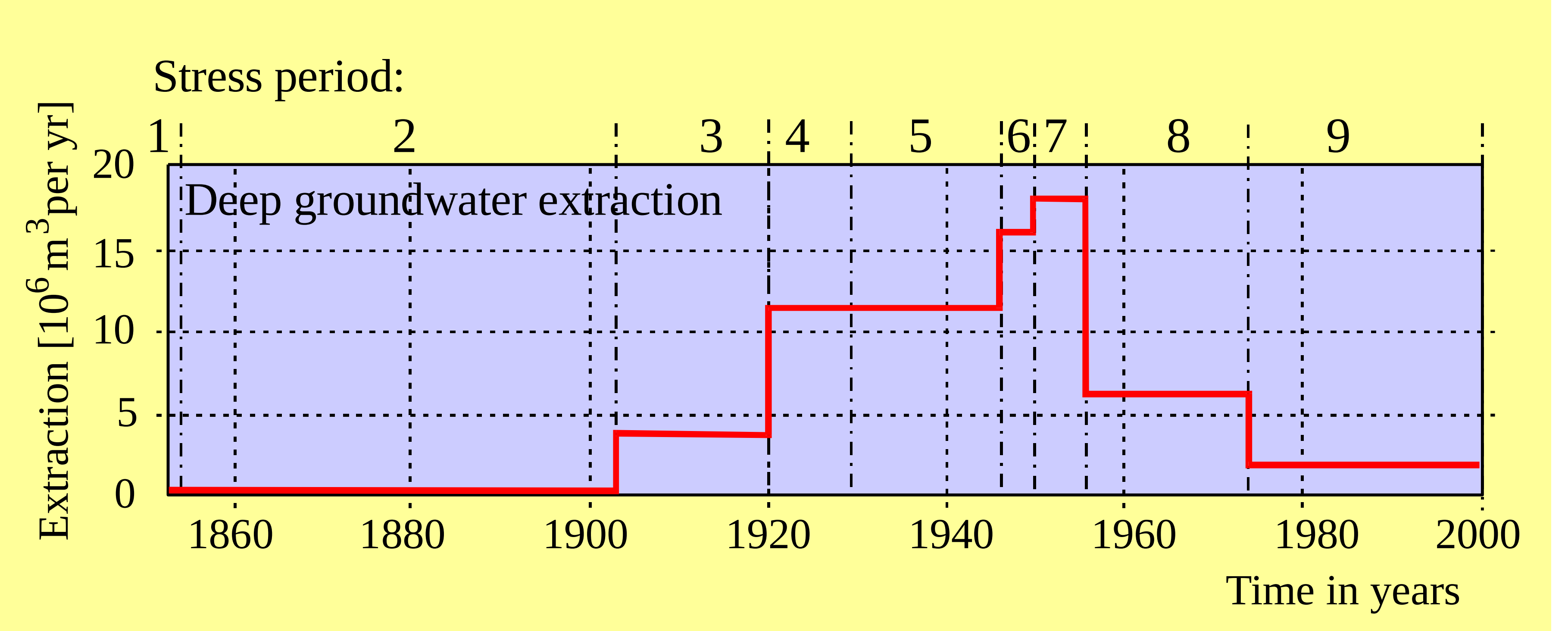


Geometry, subsoil parameters, boundary conditions

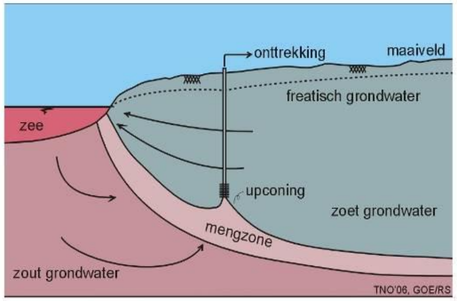


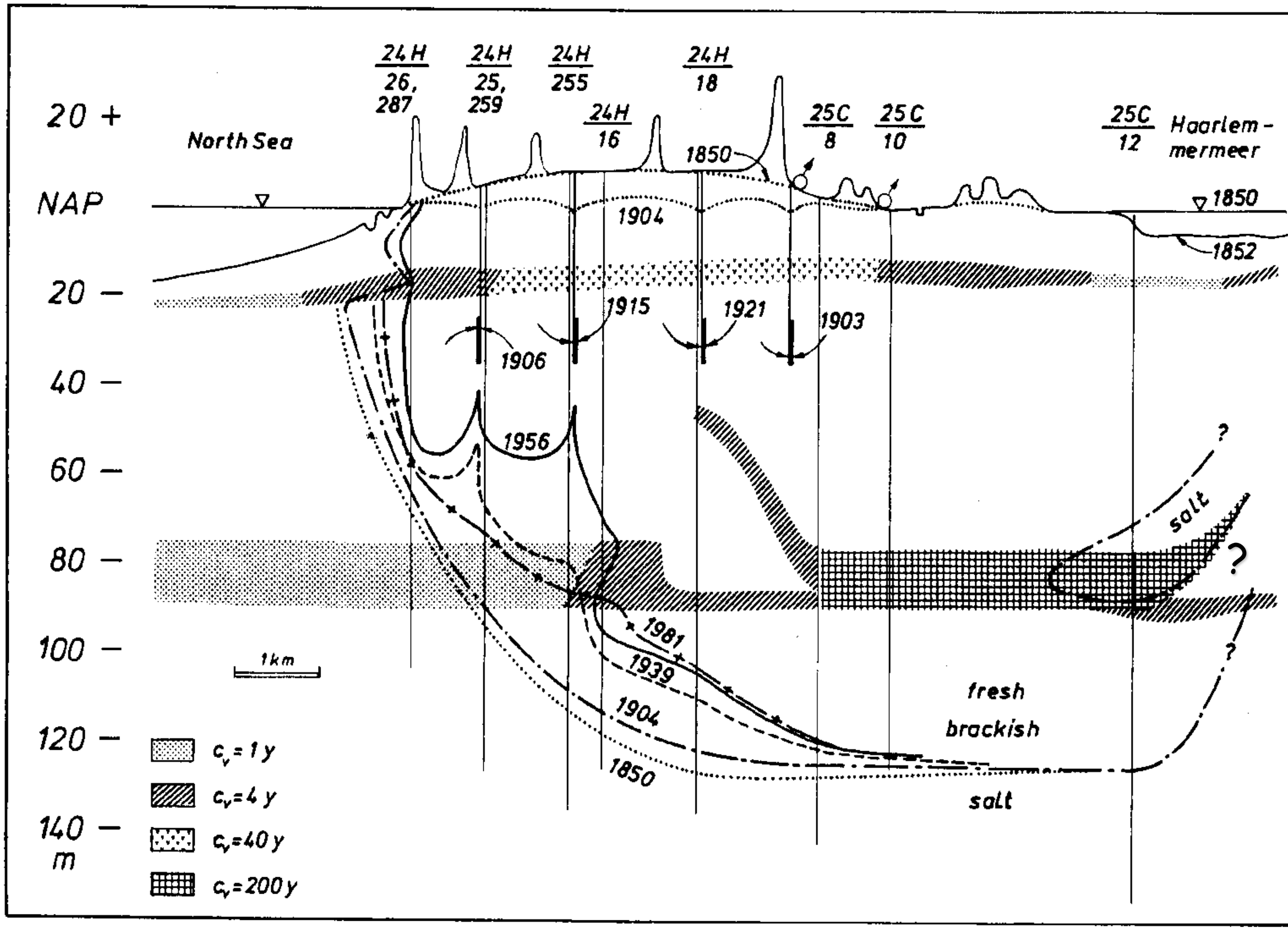
Saltwater intrusion in the Dutch coastal zone

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



Upconing of brackish-saline groundwater





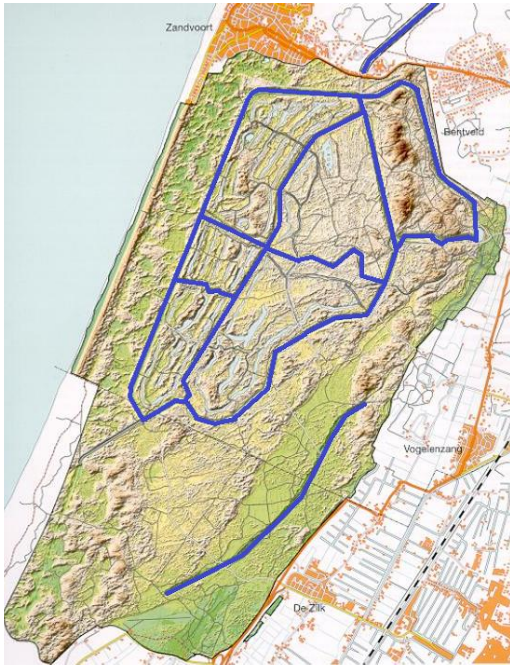
Stuyfzand, 1993

Since 1957 in the Netherlands: large-scale Managed Aquifer Recharge for drinking water

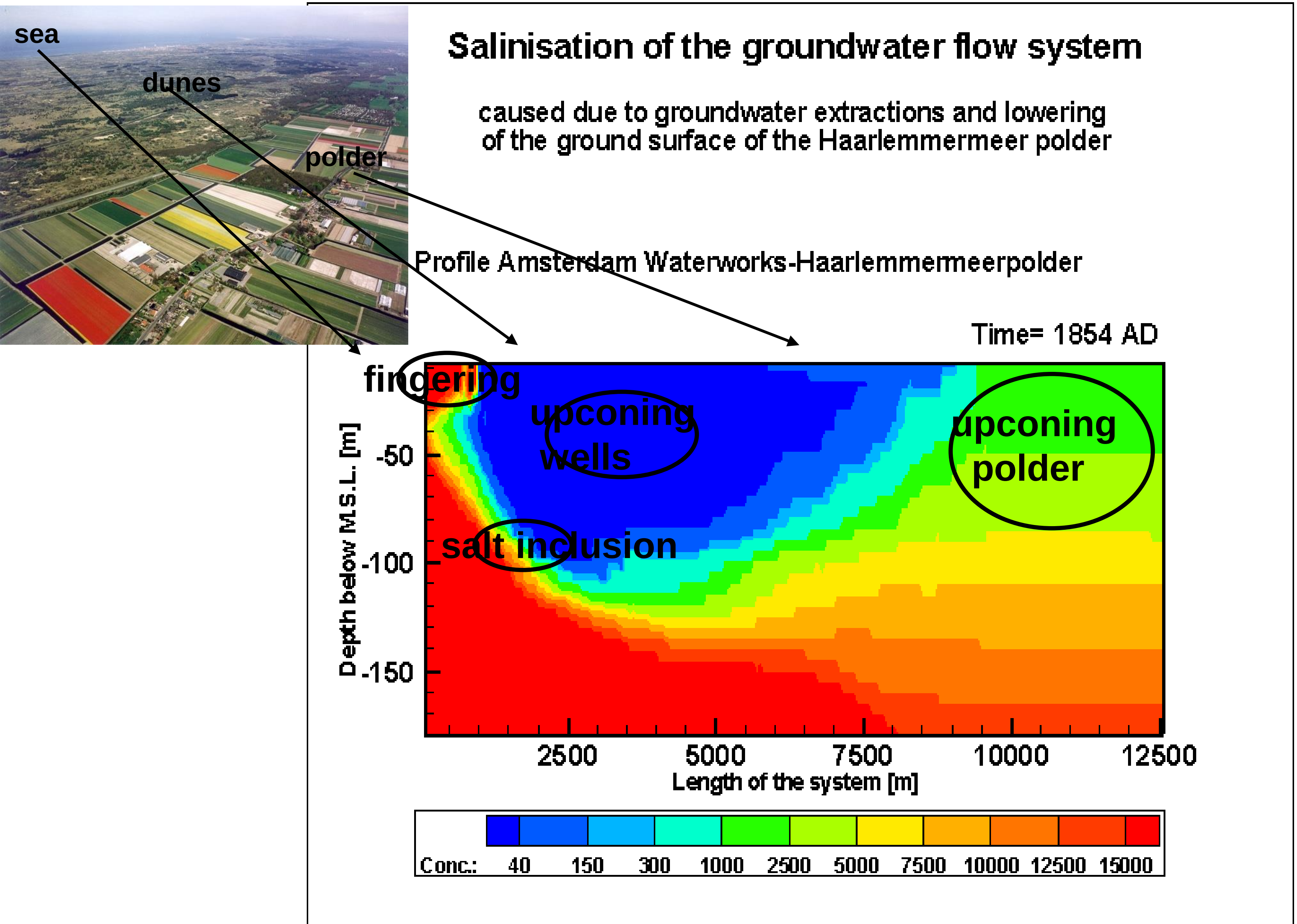
Dune water supply for Amsterdam:

- Artificial infiltration of river water from Rhine River started in 1957
- 40 km of abstraction canals
- 9 km of drains
- 40 recharge ponds (86 ha)
- 65 Mm^3/year
- 60% Amsterdam water supply

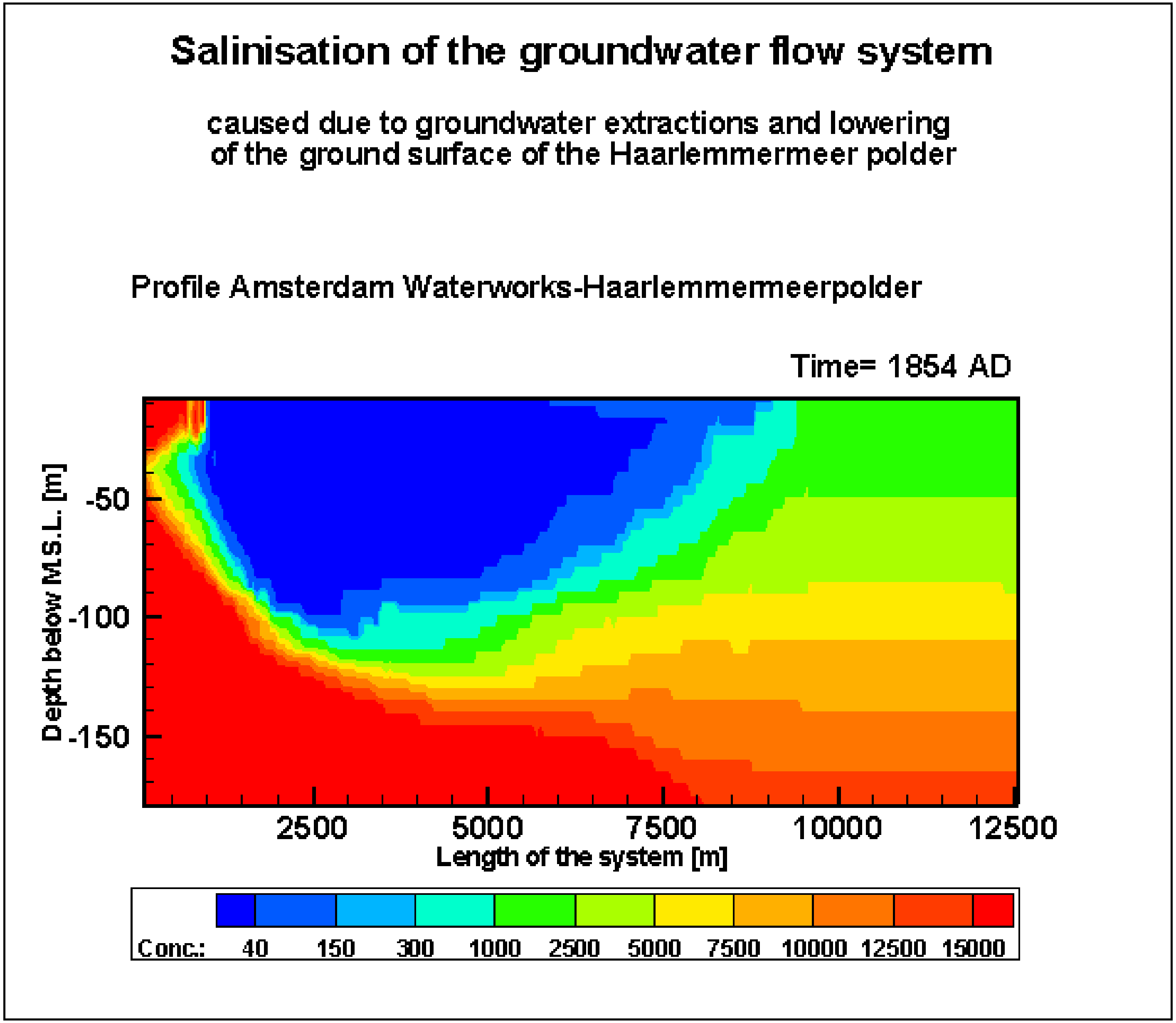
- Groundwater is a very reliable source for water supply, but is likely not renewable and should be used sustainable.
- Extractions must be managed and monitored systematically.
- We apply conjunctive use of surface as well as groundwater. Feasible tested technologies include river bank infiltration, gallery, and infiltration basin.



Saltwater intrusion in the Dutch coastal zone



Saltwater intrusion in the Dutch coastal zone



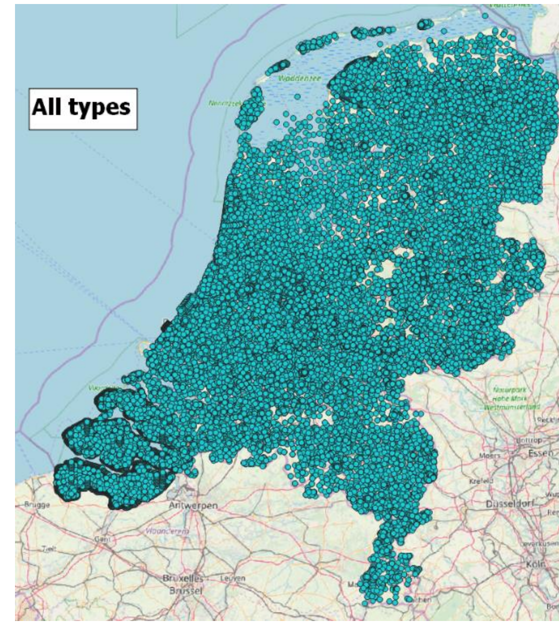
Palaeo hydrogeological modelling

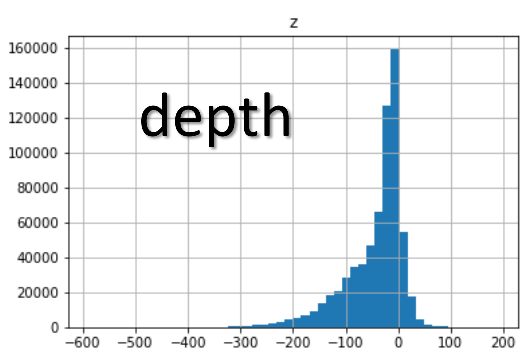
Palaeo-modeling salt water intrusion during the Holocene: an application to the Netherlands

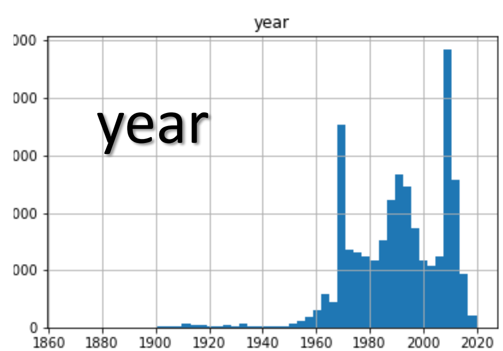
Delsman, J.R., Hu-a-ng, K.R.M., Vos, P.C., De Louw, P.G.B., Oude Essink, G.H.P., Stuyfzand, P.J.,Bierkens, M.F.P., 2014. Paleo-modeling of coastal saltwater intrusion during the Holocene: An application to the Netherlands. Hydrol. Earth Syst. Sci. 18, 3891–3905. https://doi.org/10.5194/hess-18-3891-2014

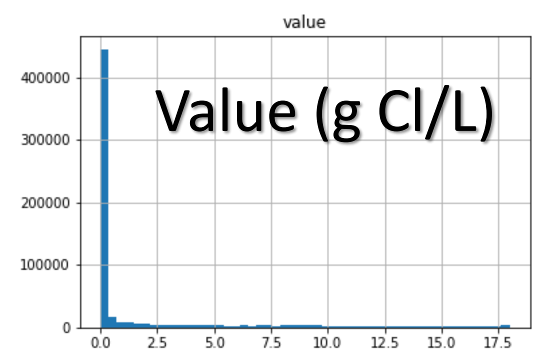
From measurements to 3D salinity distribution

- 2.7M measurement locations:
  - Chemical analyses, geophysisical measurements (Borelogs, VES, ECPTs, Airborne EM)
  - Varying quality, heavily biased to fresh, shallow
- 3D indicator kriging
- ‘Soft data’ to guide interpolation (sea, deep)
- Transparent and reproducible workflow

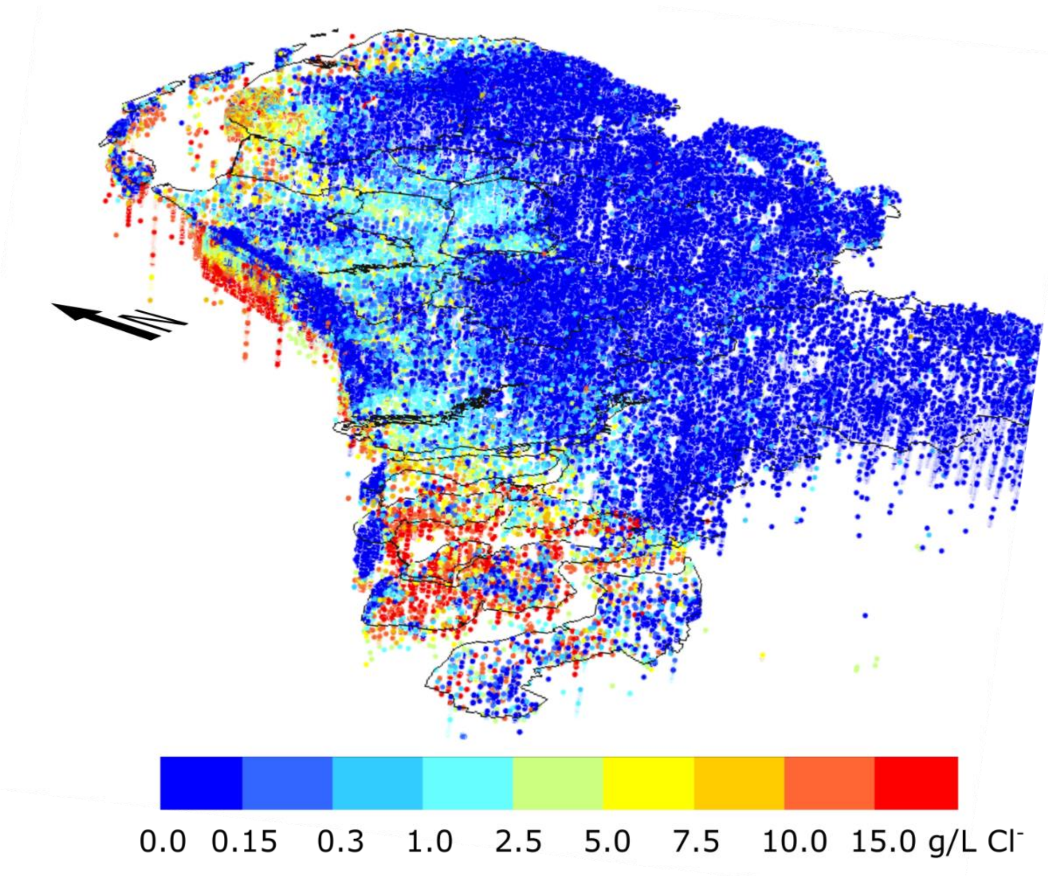


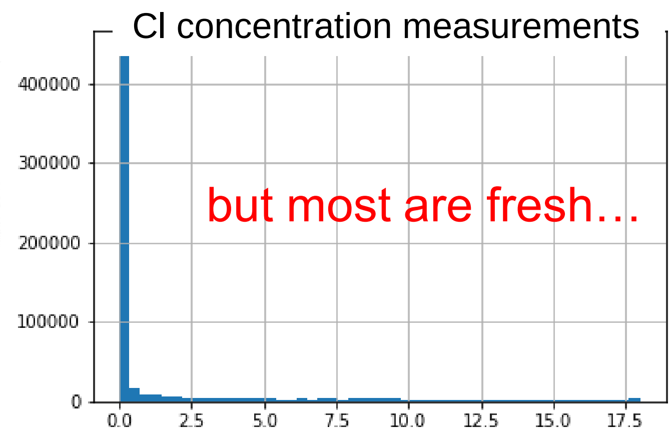


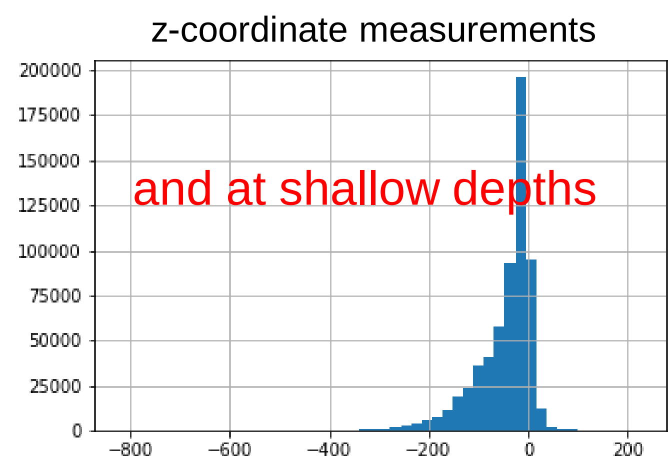


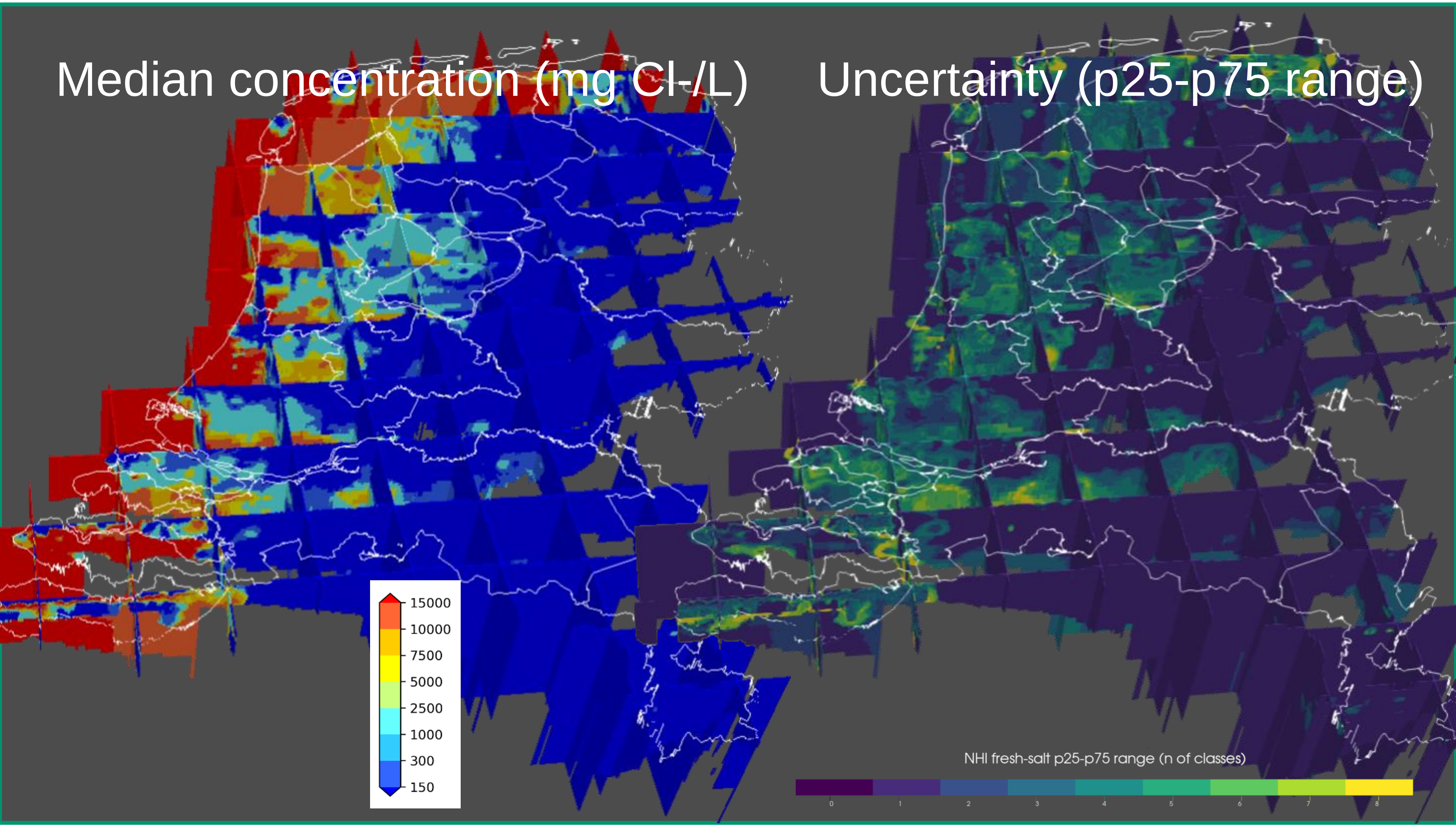


Current groundwater salinity distribution

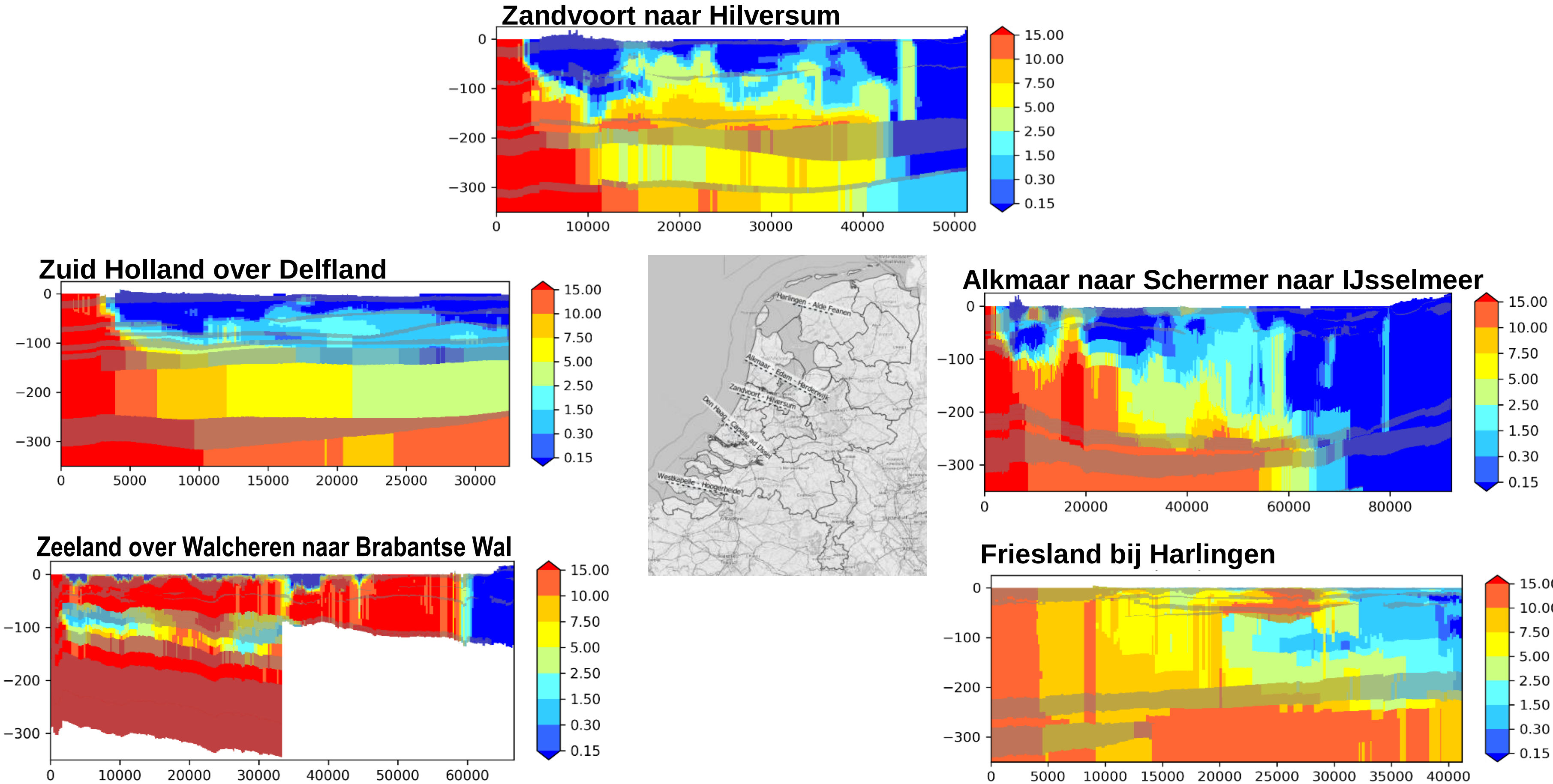


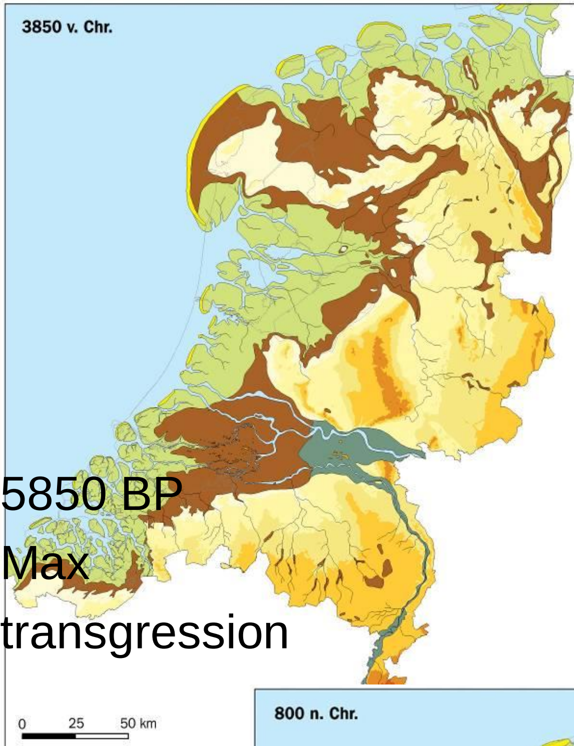


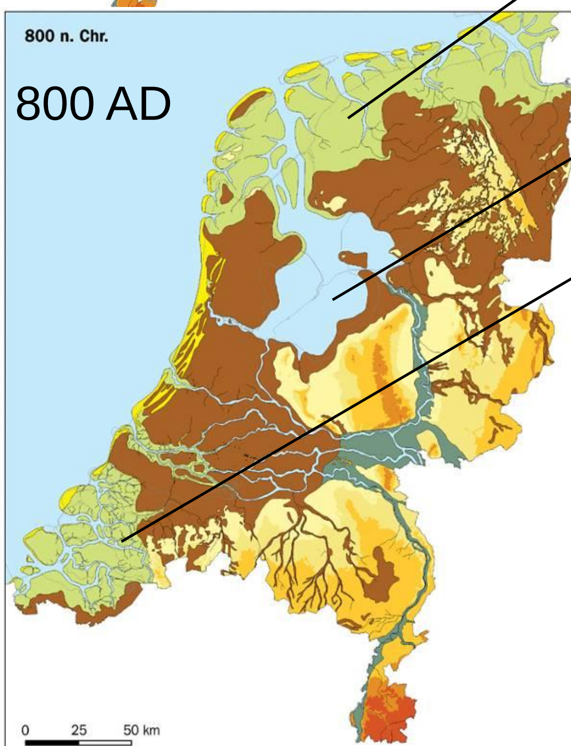


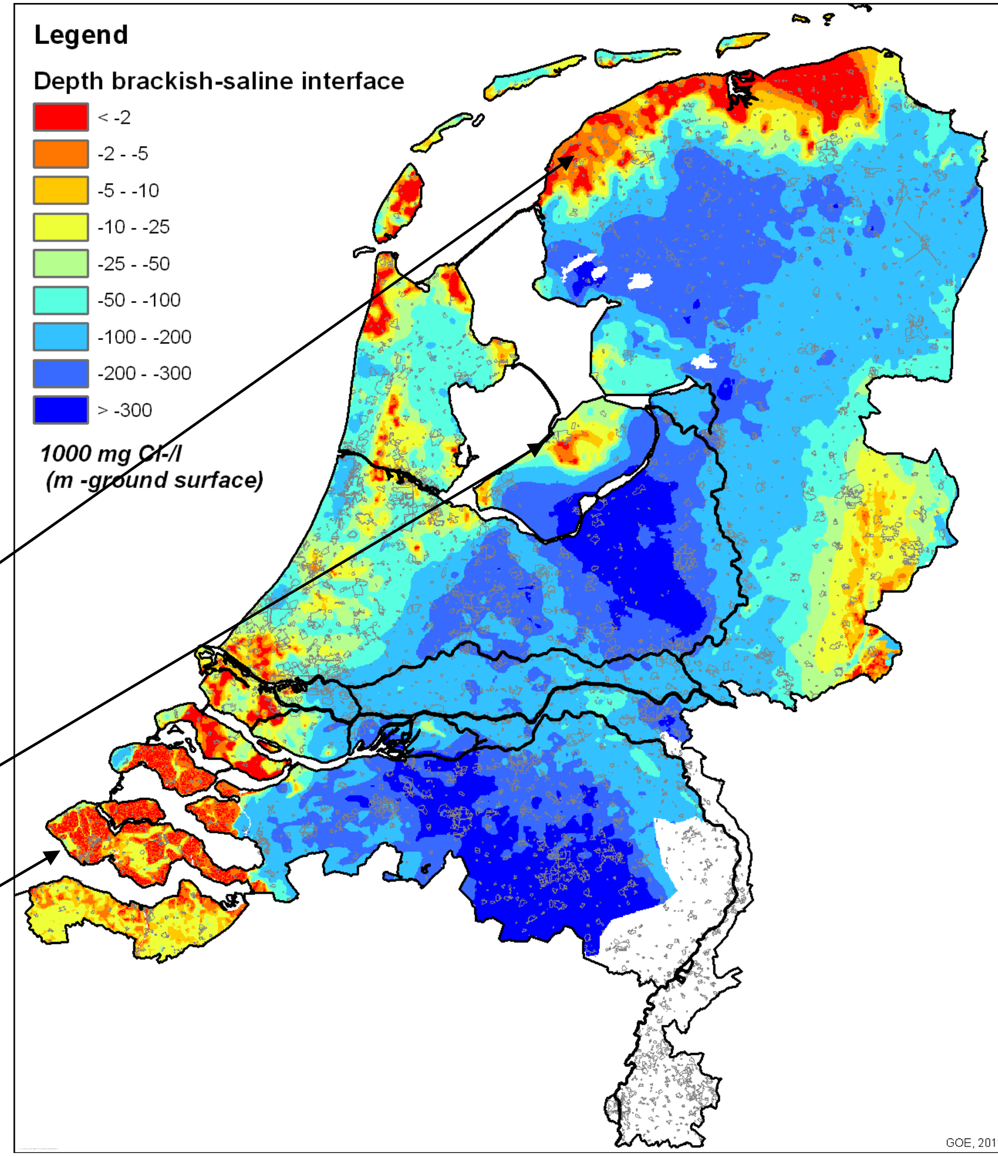

Median concentration (mg Cl-/L)
Uncertainty (p25-p75 range)
15000
10000
7500
5000
2500
1000
300
150
NHI fresh-salt p25-p75 range (n of classes)

2D present-day groundwater salinity (mg Cl/L), from NHI fresh-salt









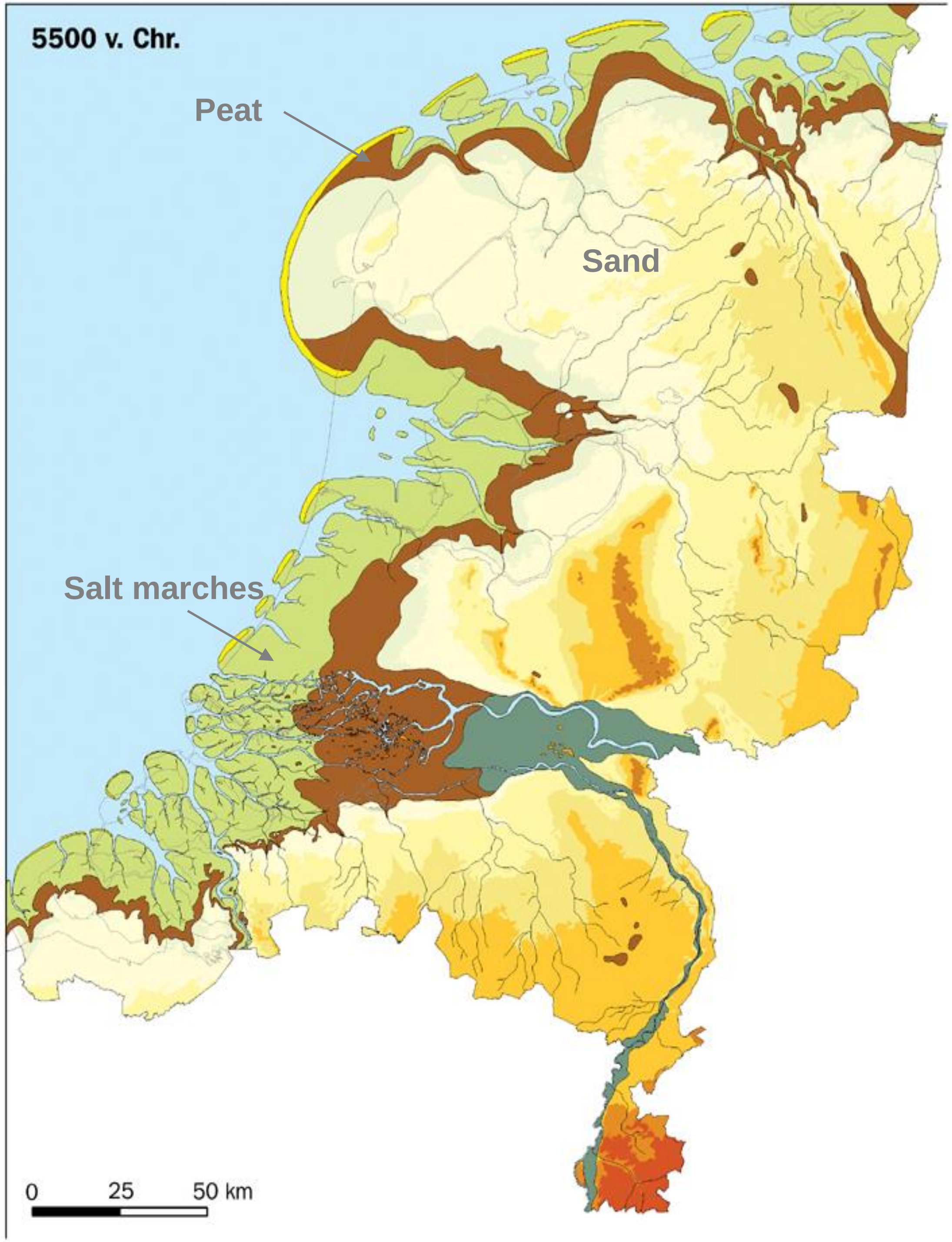
Based on:

- Analyses
- VES
- Borehole measurement

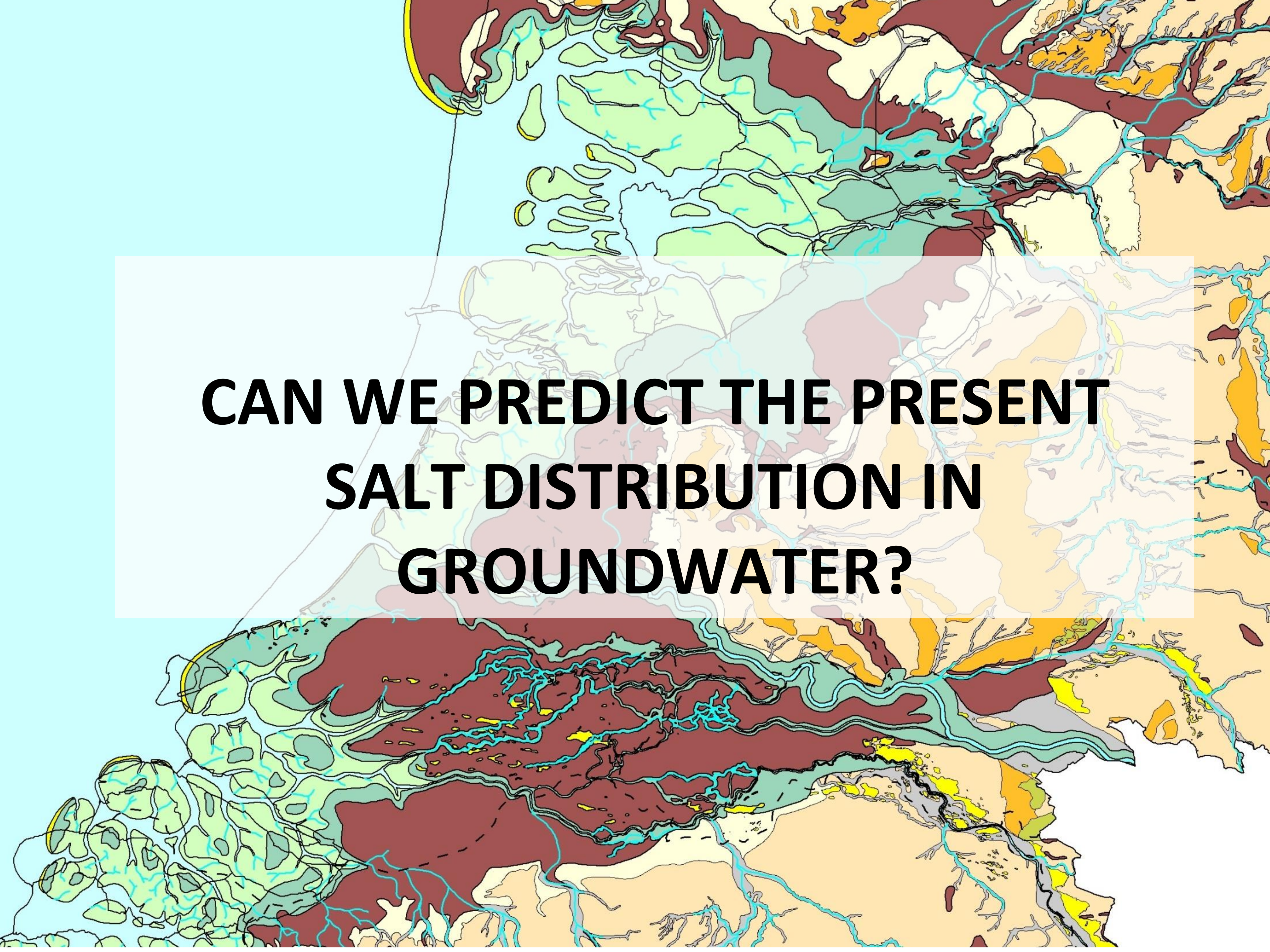
The Holocene transgressions

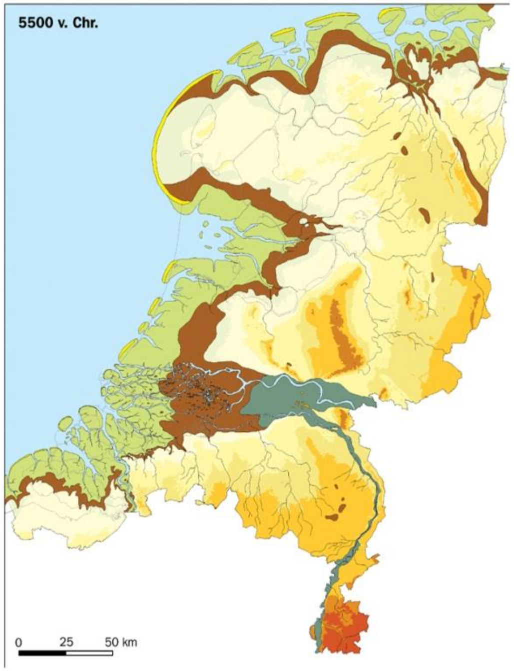
Major impact on present regional brackish groundwater systems

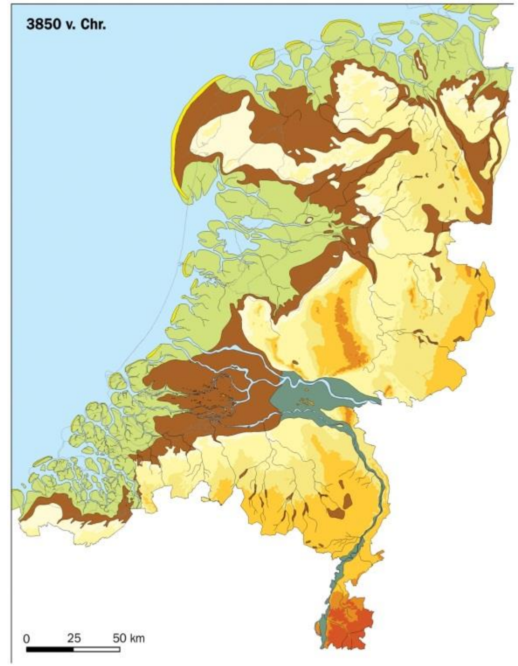
7500 BP

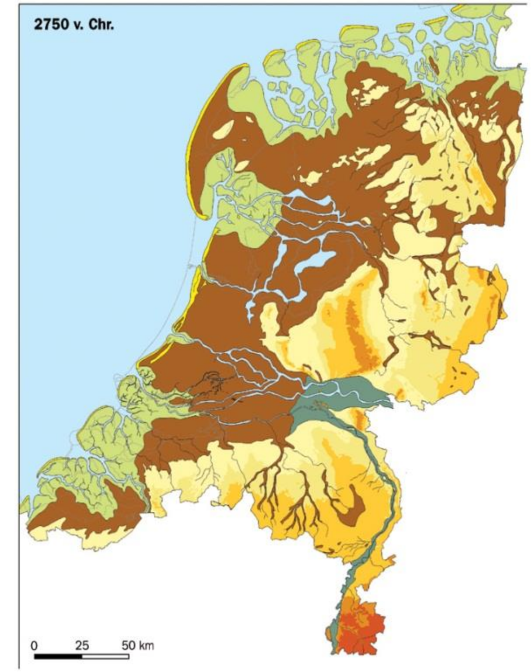


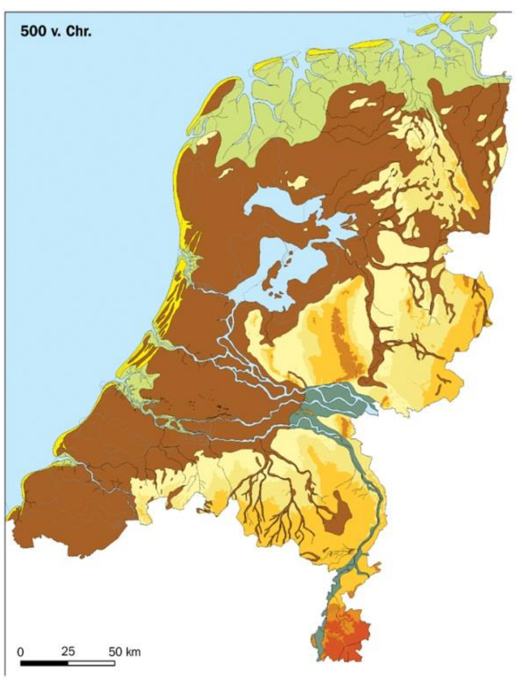
CAN WE PREDICT THE PRESENT SALT DISTRIBUTION IN GROUNDWATER?

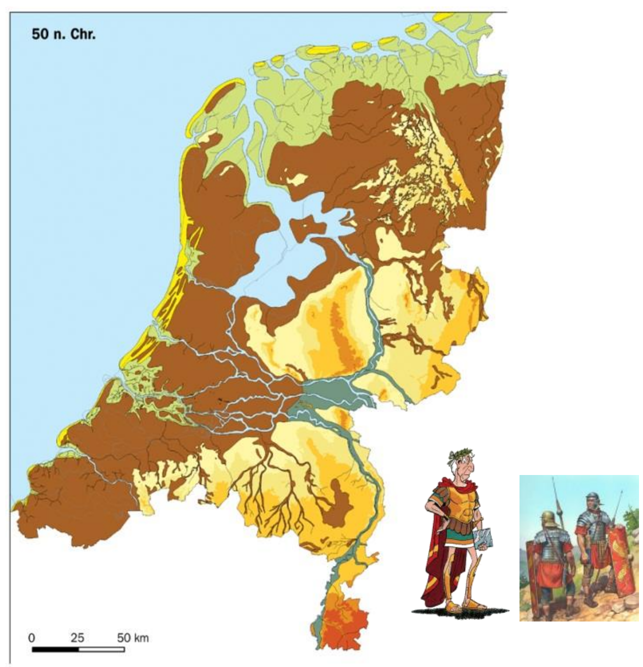


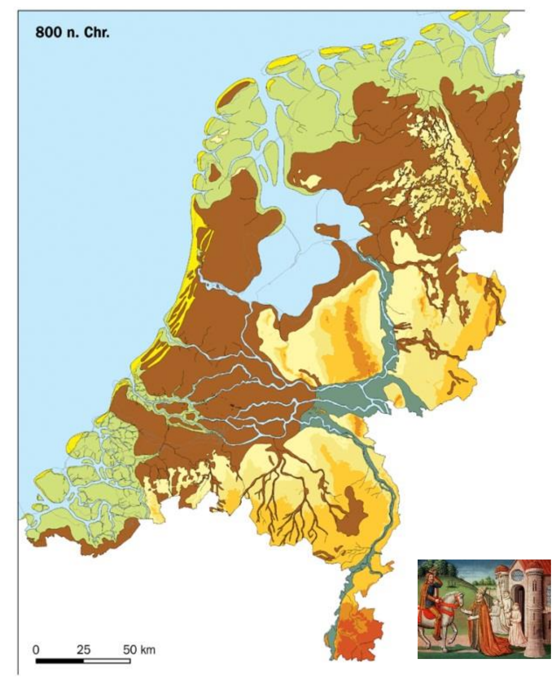

5500 v. Chr.
0 25 50 km


3850 v. Chr.
0 25 50 km


2750 v. Chr.
0 25 50 km

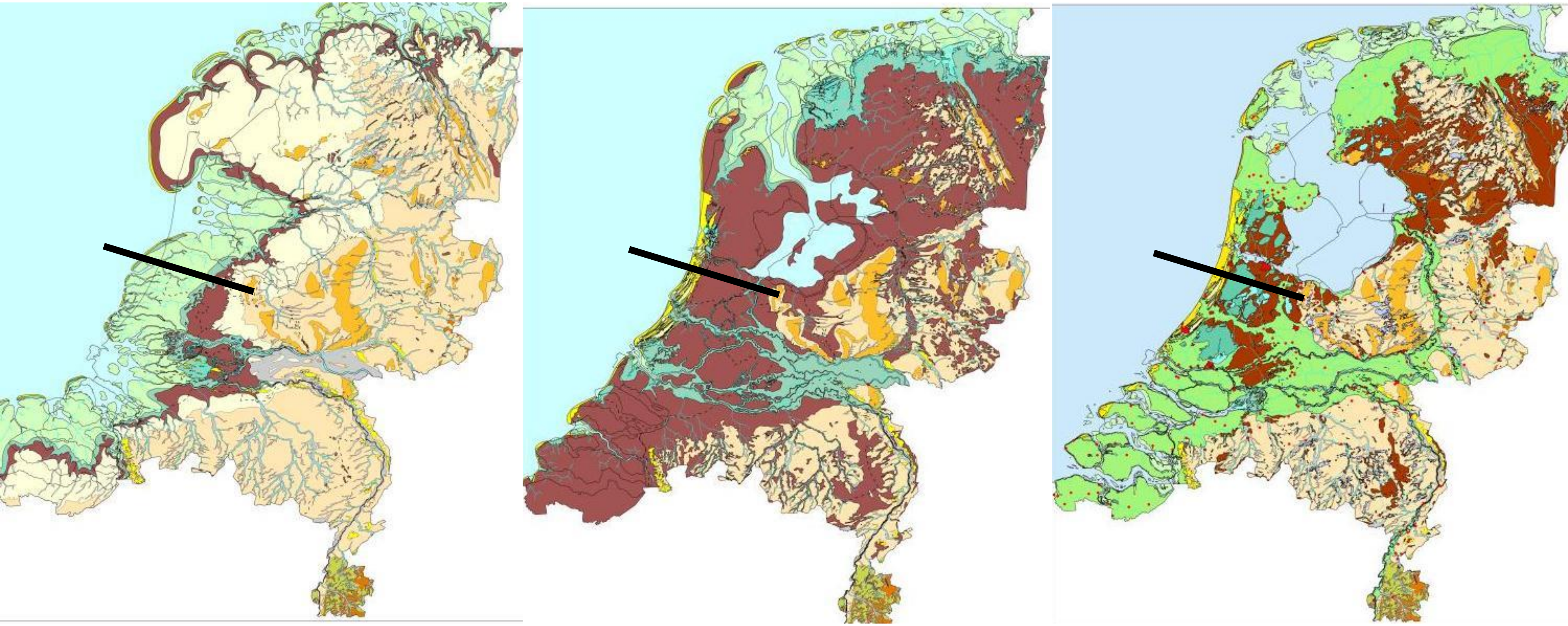

500 v. Chr.
0 25 50 km


50 n. Chr.
0 25 50 km


800 n. Chr.
0 25 50 km

Palaeogeographical development

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



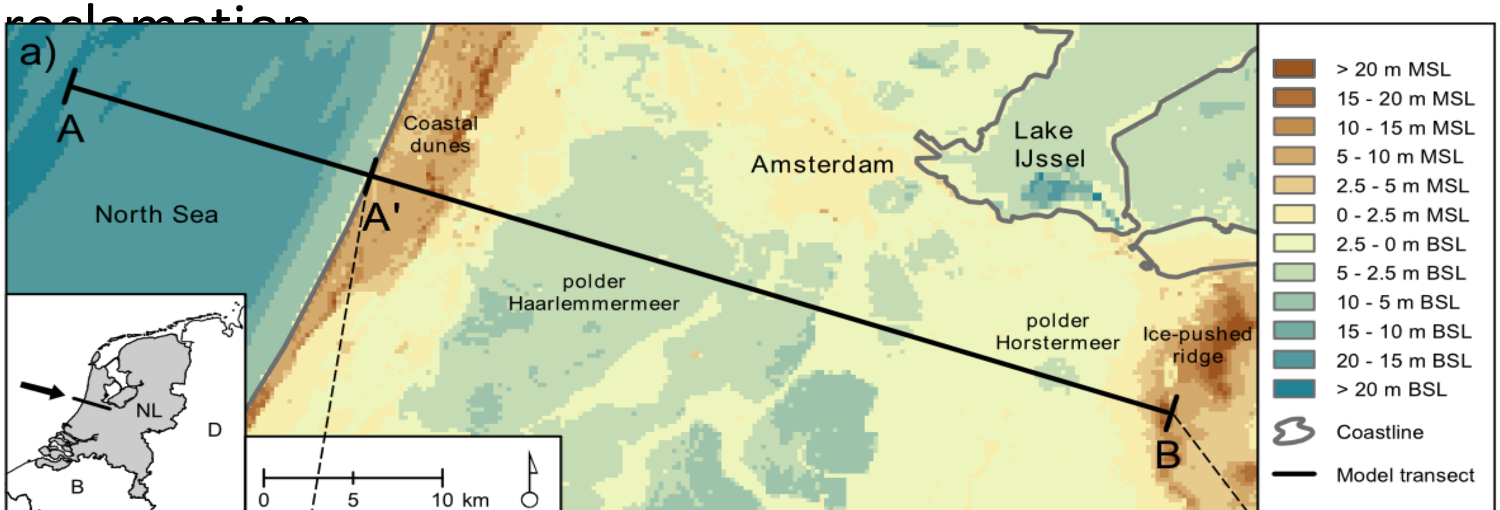
Maximal transgression **Peat development** **Reclaimed land, polder**

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

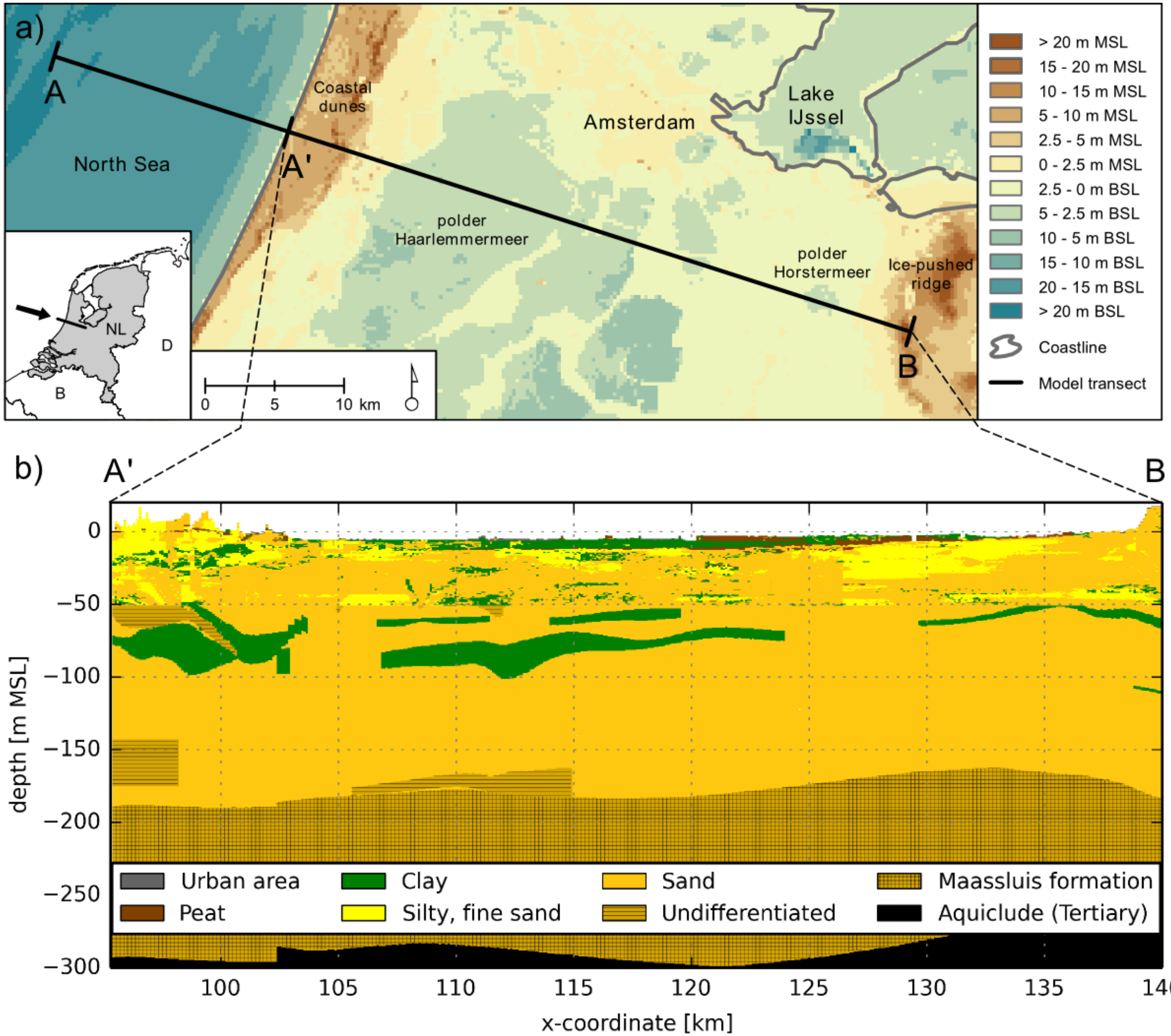
Atlas NL in het Holoceen (Vos et al, 2011)

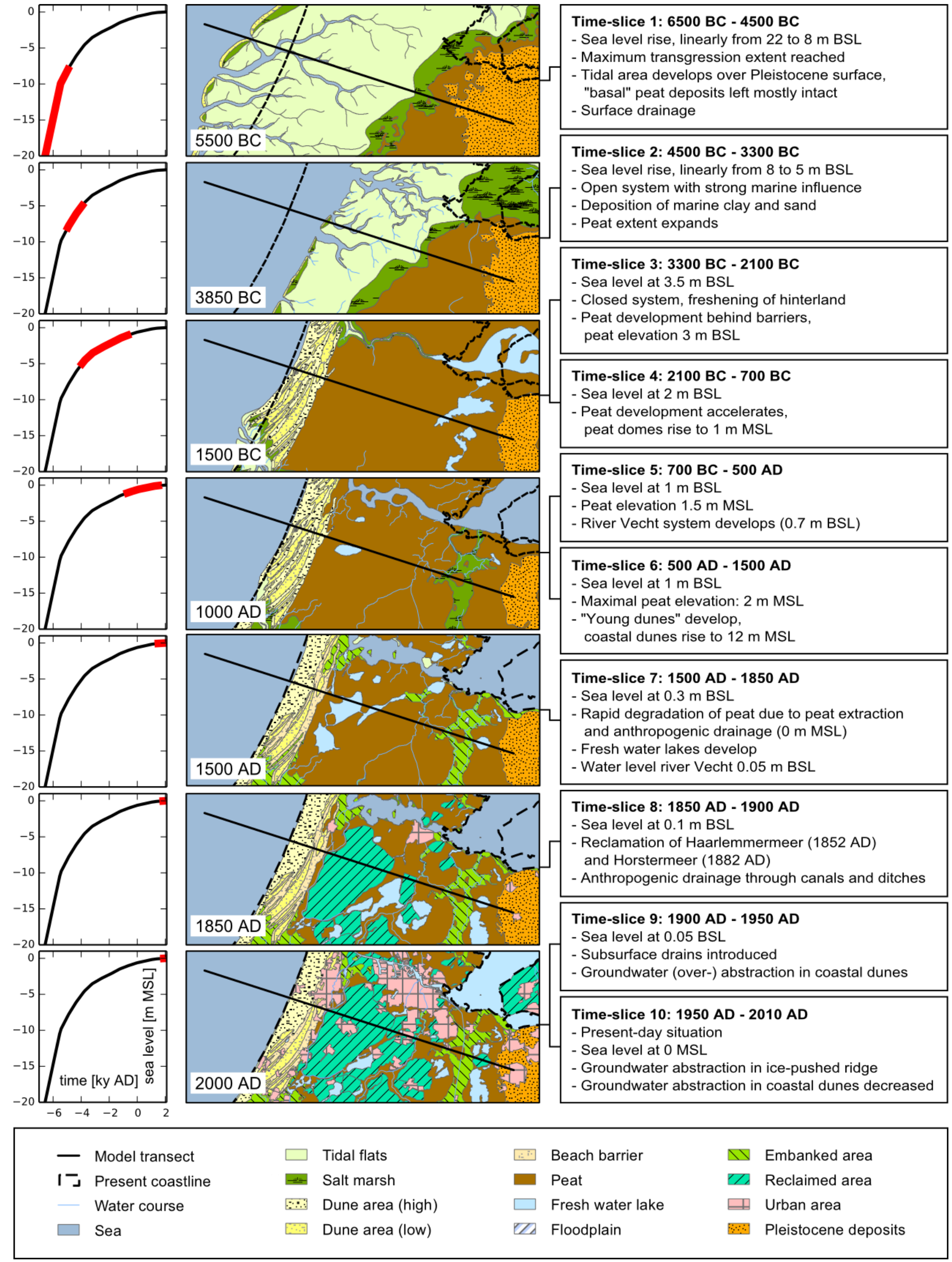
Occurrence of salt under the polder Haarlemmermeer

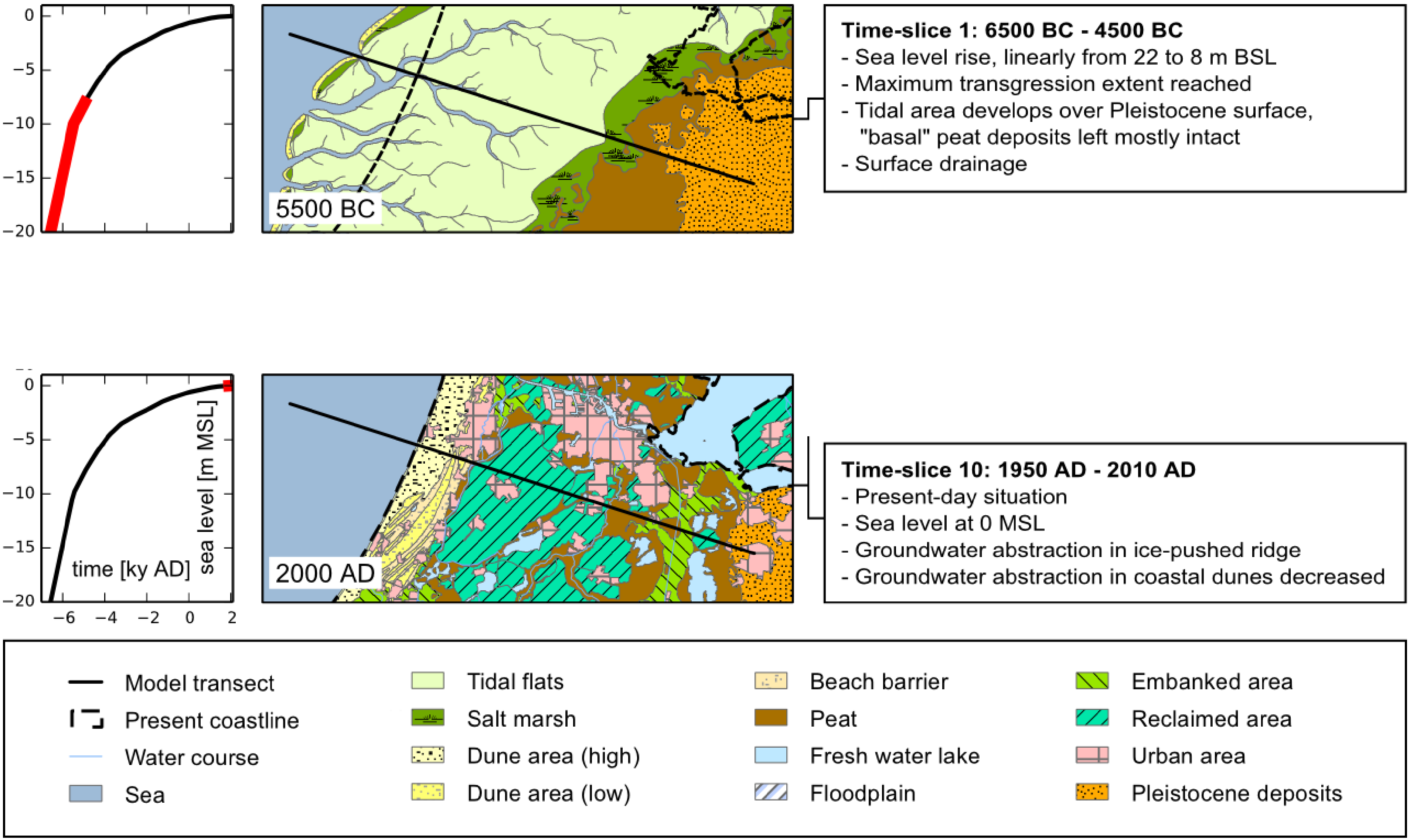
- Model profile Zandvoort - Hoofddorp – Hilversum
- Palaeogeographical development (Vos et al, 2011)
- 6500 BC - 2010 AD
- marine transgression
- Peat development, peat degradation, drainage, reclamation



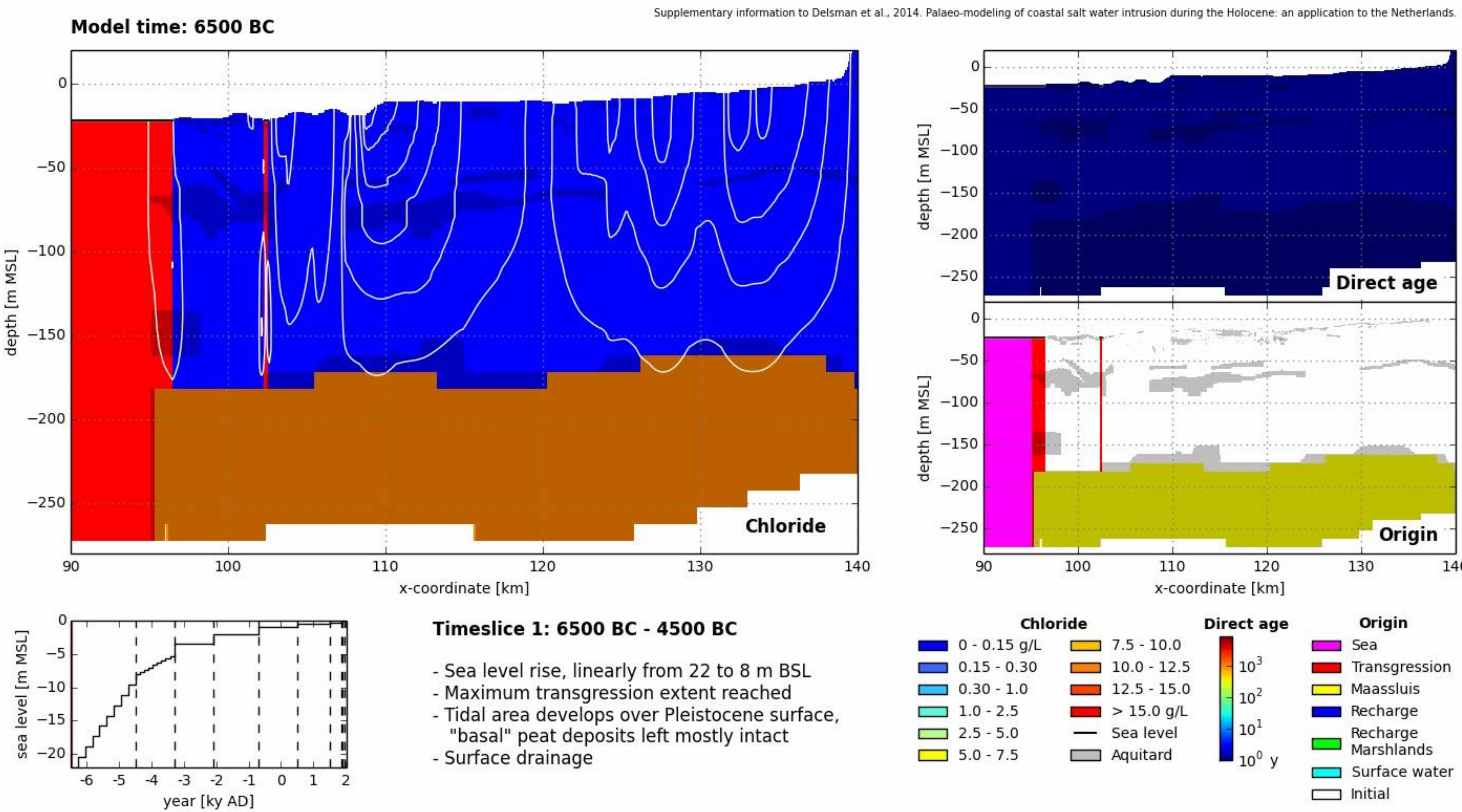
Delsman et al., HESS, 2013


a)
A
A'
B
Coastal dunes
North Sea
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)


sea level [m MSL]
time [ky AD]
5500 BC
3850 BC
1500 BC
1000 AD
1500 AD
1850 AD
2000 AD
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

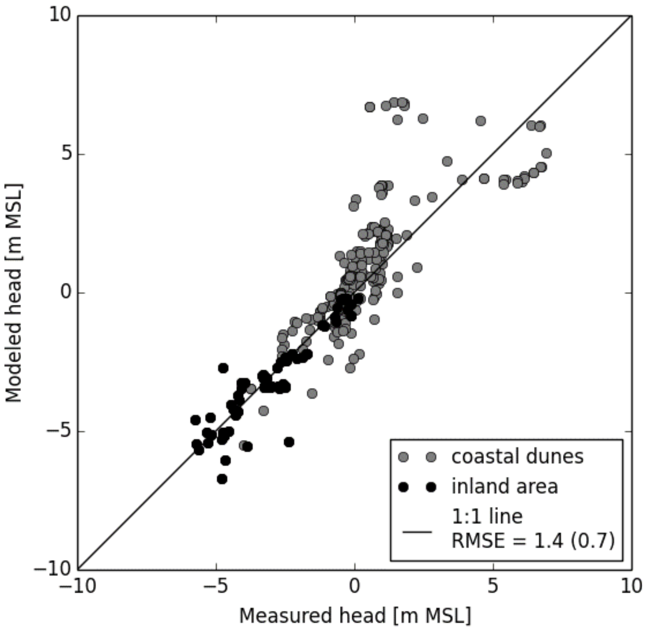

5500 BC
Time-slice 1: 6500 BC - 4500 BC
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage
2000 AD
Time-slice 10: 1950 AD - 2010 AD
- Present-day situation
- Sea level at 0 MSL
- Groundwater abstraction in ice-pushed ridge
- Groundwater abstraction in coastal dunes decreased
time [ky AD]
sea level [m MSL]
0
−5
−10
−15
−20
−6
−4
−2
0
2
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

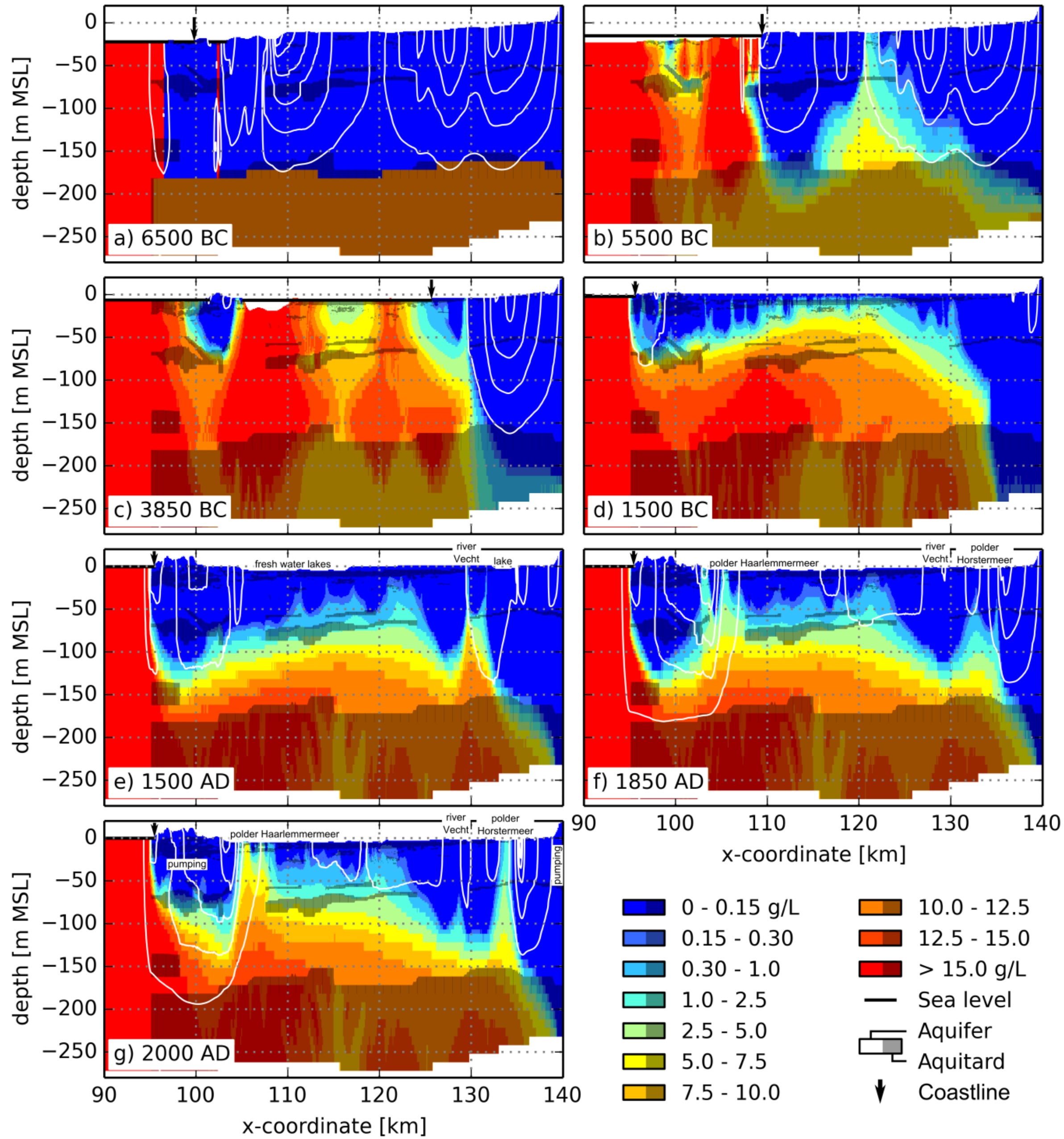
Development saline groundwater



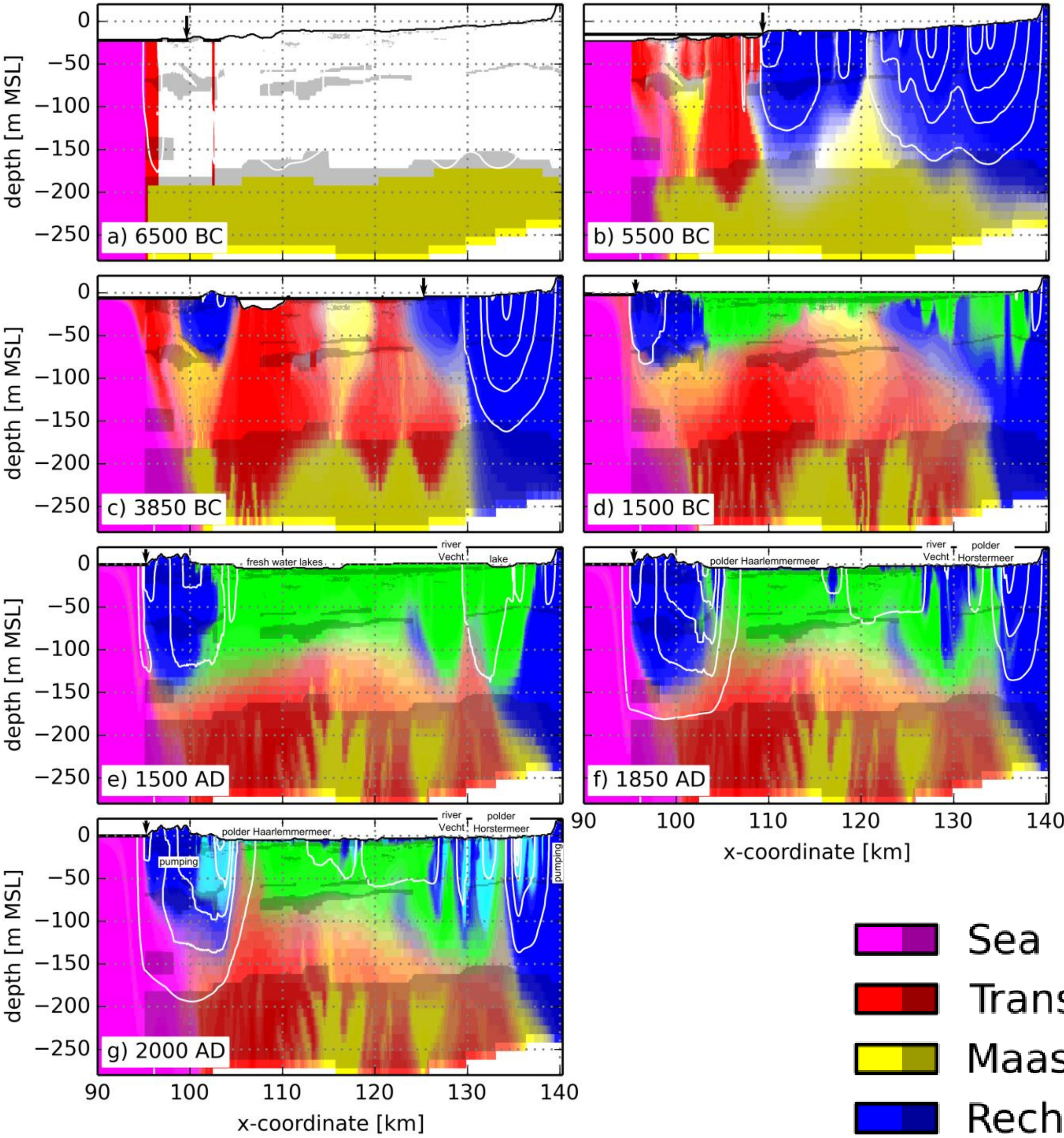
Delsman et al., HESSD, 2013

Model versus measurements

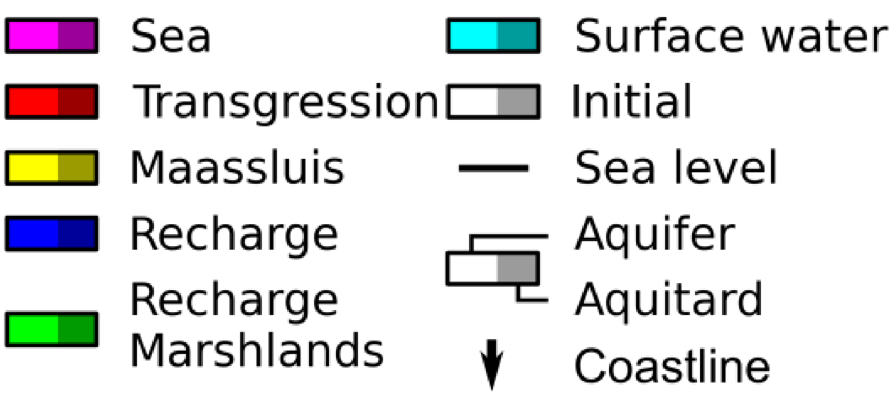




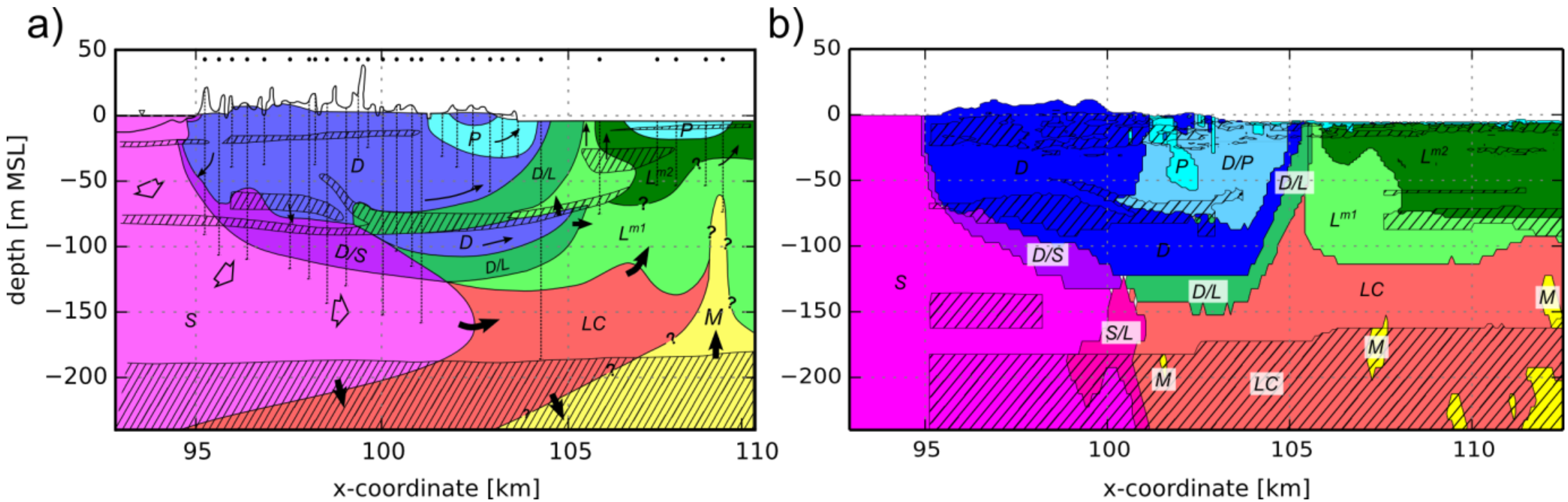
Origin

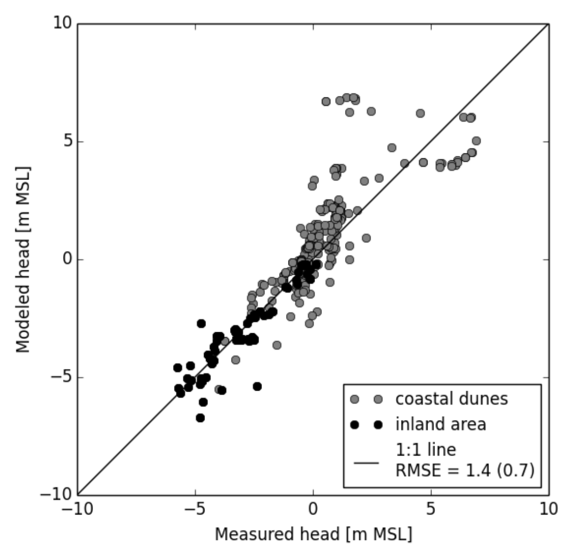


a) 6500 BC
b) 5500 BC
c) 3850 BC
d) 1500 BC
e) 1500 AD
f) 1850 AD
g) 2000 AD
depth [m MSL]
x-coordinate [km]
fresh water lakes
river Vecht
lake
polder Haarlemmermeer
polder Horstermeer
pumping

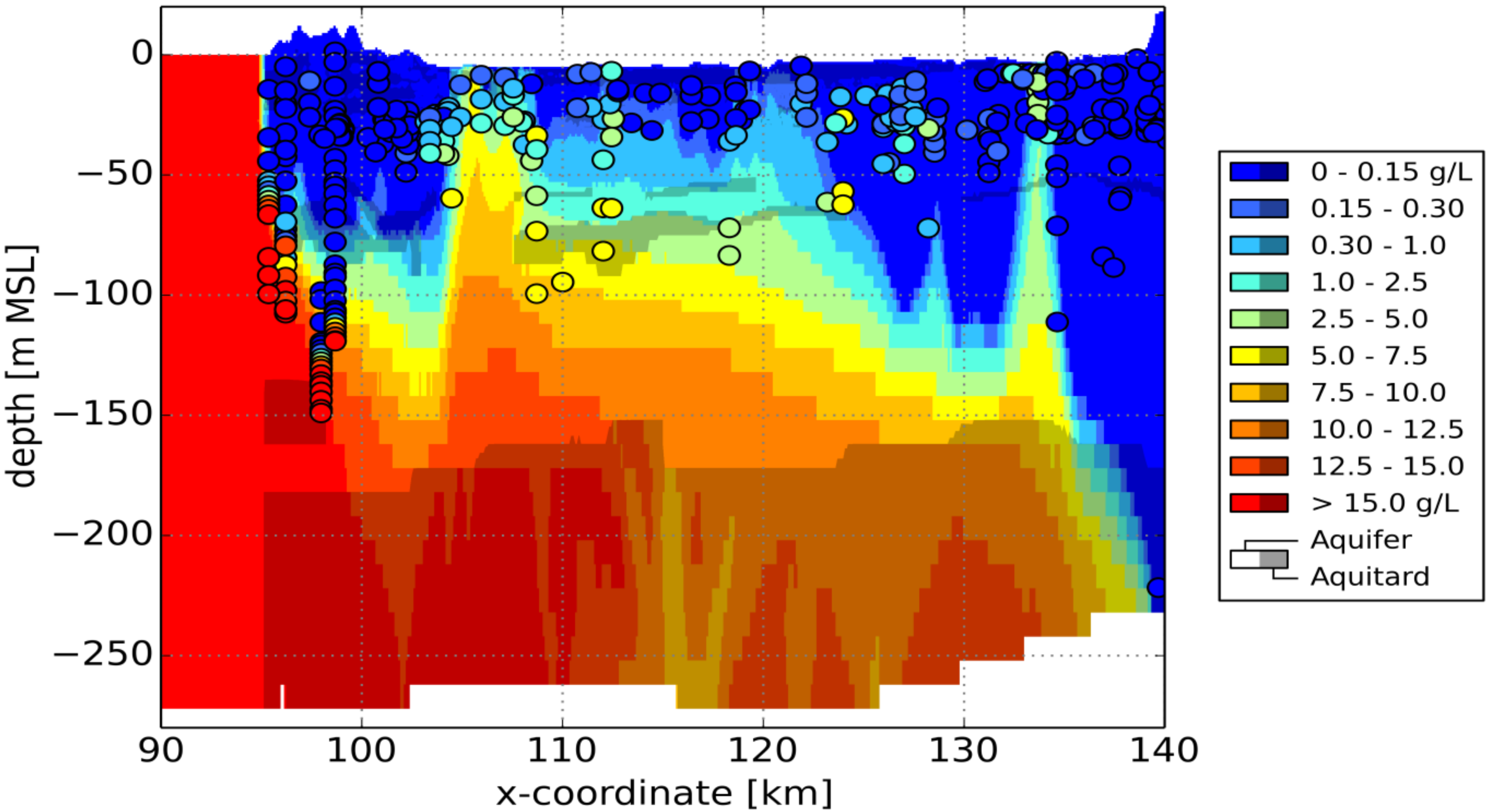


Sea
Transgression
Maassluis
Recharge
Recharge Marshlands
Surface water
Initial
Sea level
Aquifer
Aquitard
Coastline

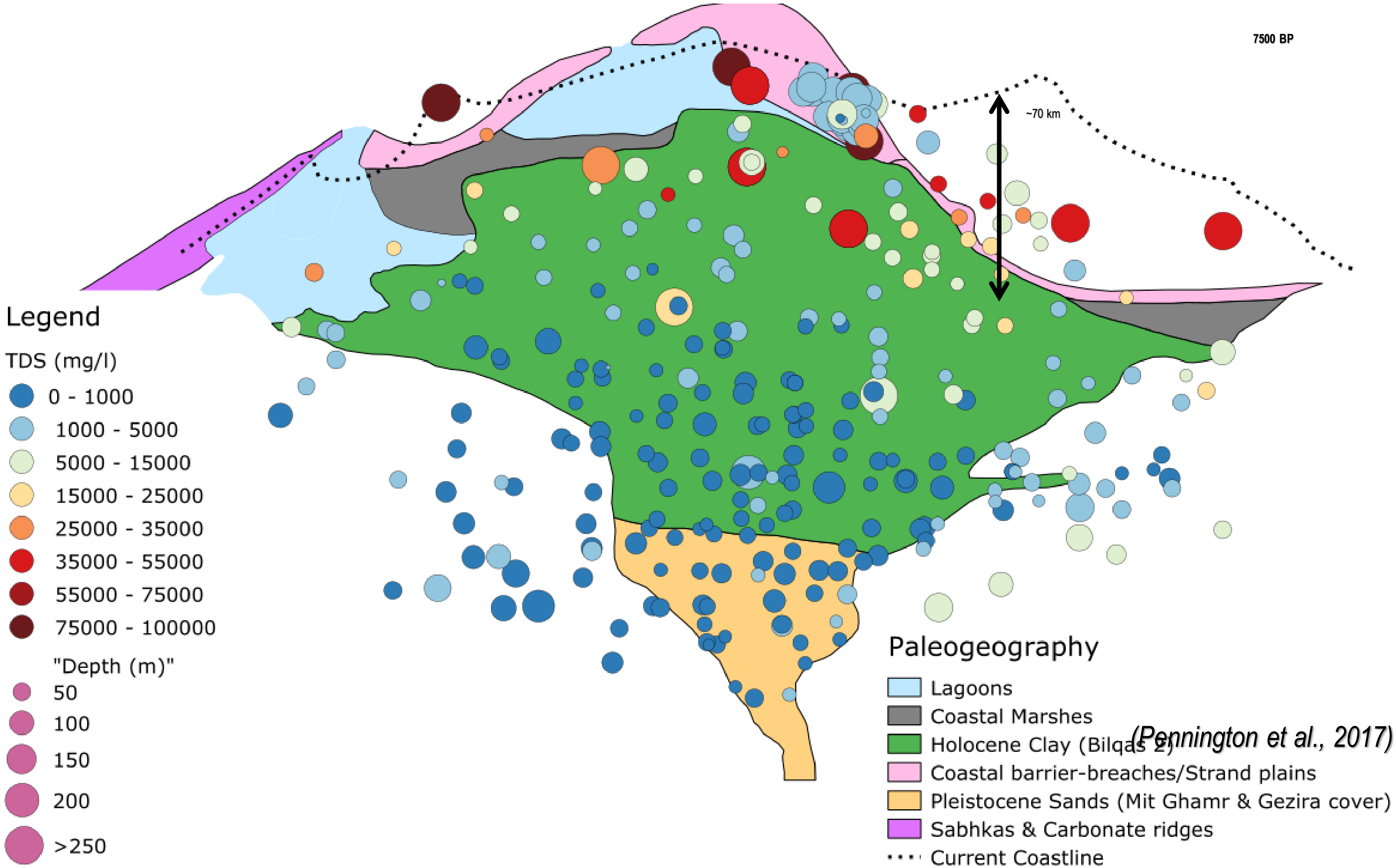

a)
b)
depth [m MSL]
x-coordinate [km]
50
0
−50
−100
−150
−200
95
100
105
110
P
D
D/L
D/S
S
LC
M
L^{m1}
L^{m2}
D/P
S/L


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)

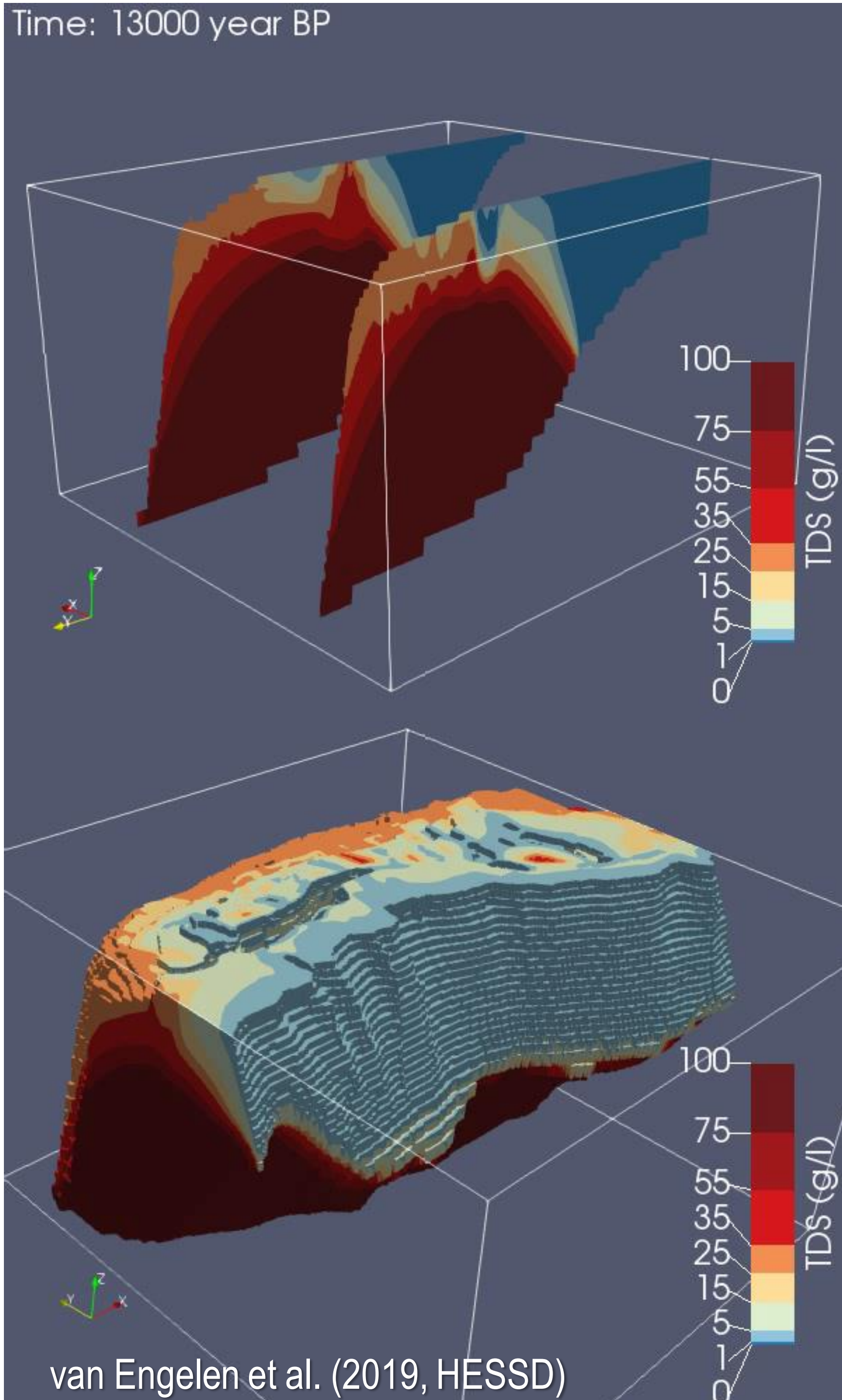
Model versus measurements



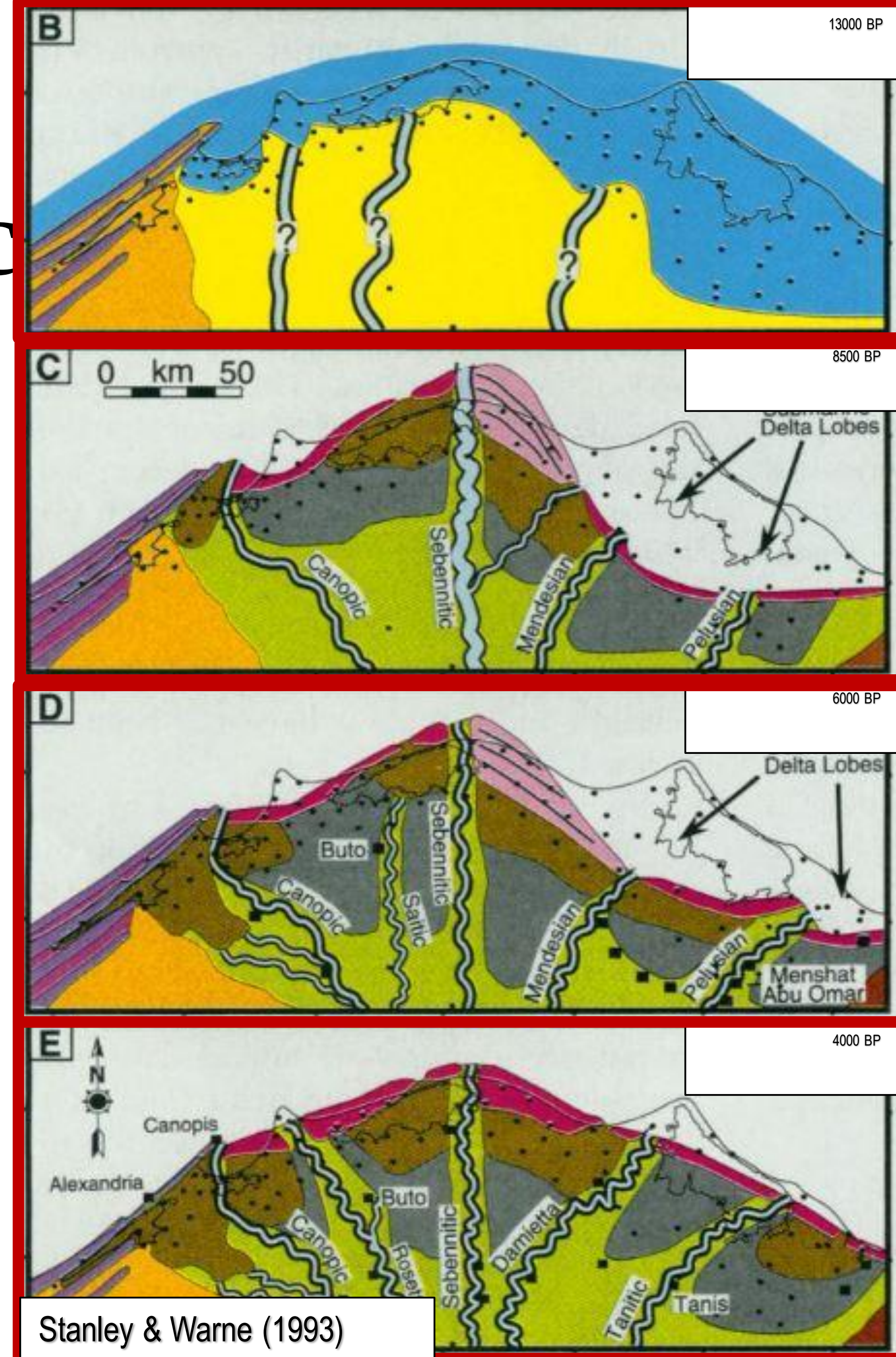
Paleohydrogeology Nile Delta: a data-poor delta



Van Engelen, J., Verkaik, J., King, J., Nofal, E.R., Bierkens, M.F.P.P., Oude Essink, G.H.P., 2019. A three-dimensional palaeo-reconstruction of the groundwater salinity distribution in the Nile Delta Aquifer. Hydrol. Earth Syst. Sci. 23, 5175–5198.



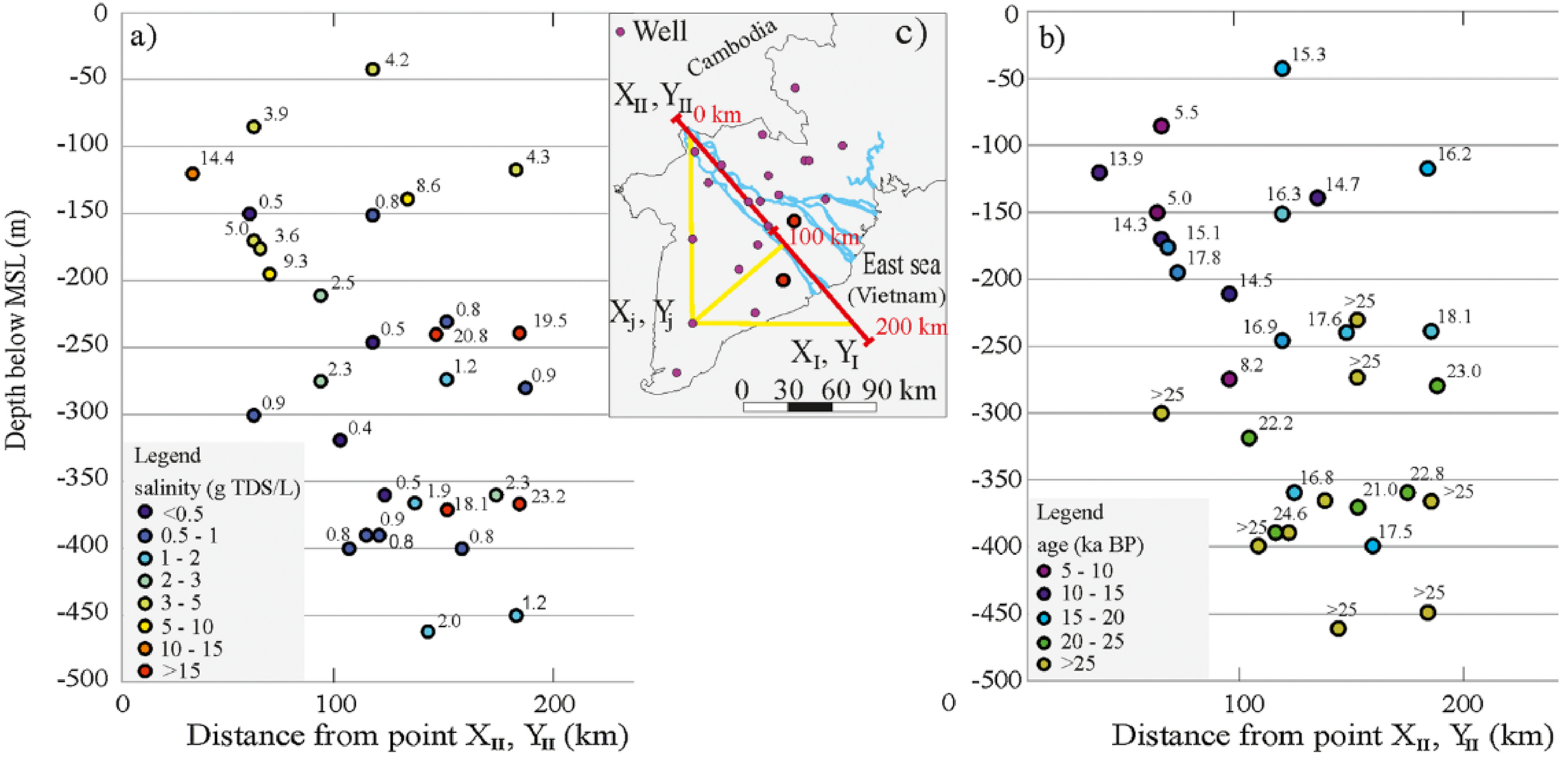
van Engelen et al. (2019, HESSD)



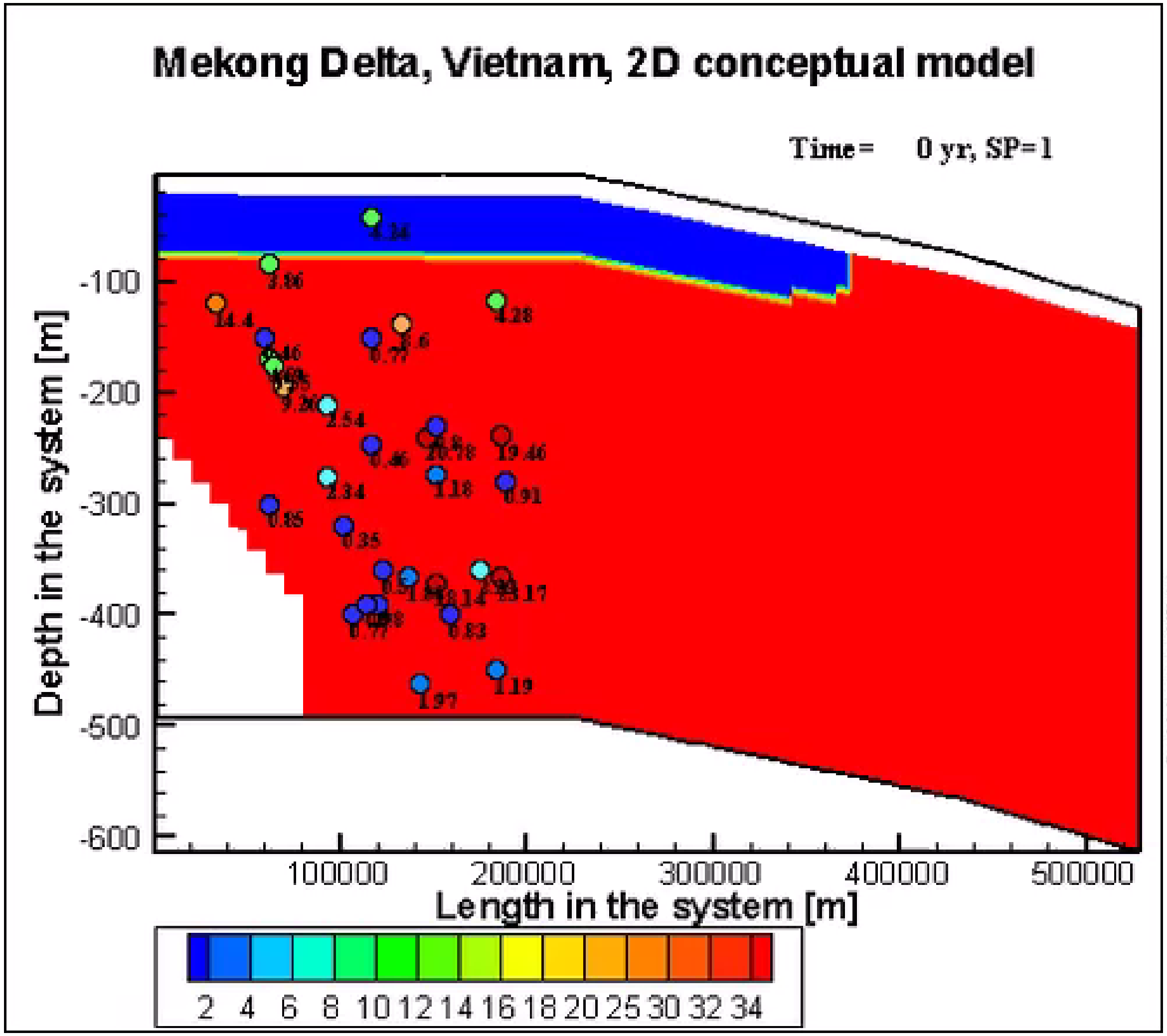
Stanley & Warne (1993)

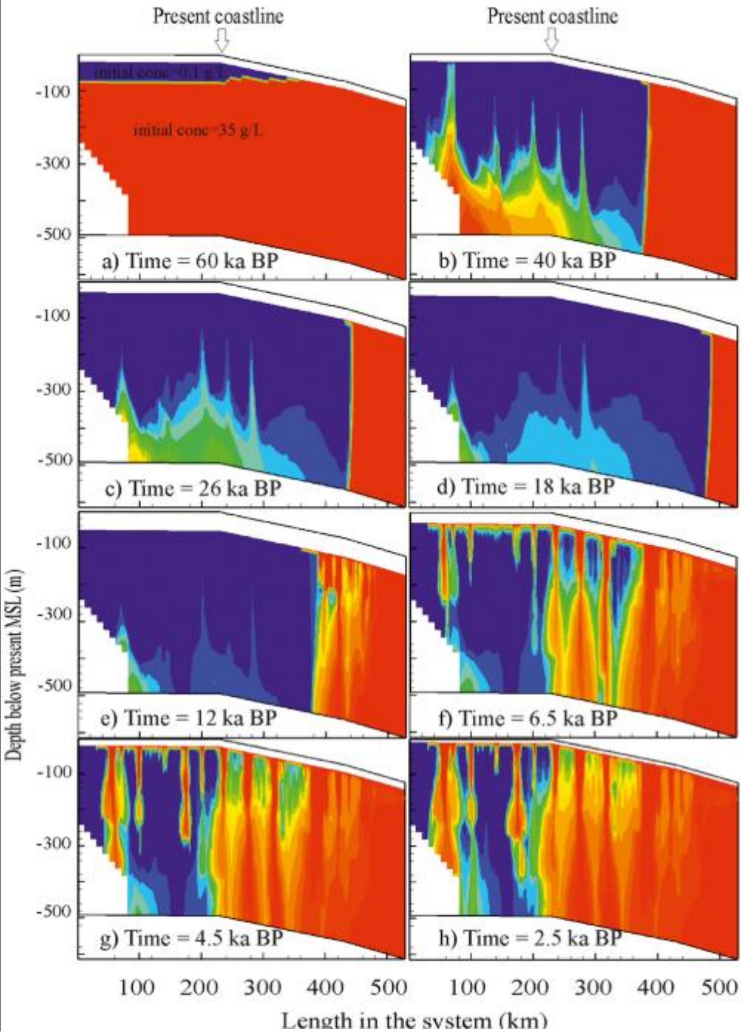
Paleo reconstruction groundwater salinity: Mekong delta

Observed groundwater salinity **Observed groundwater age**

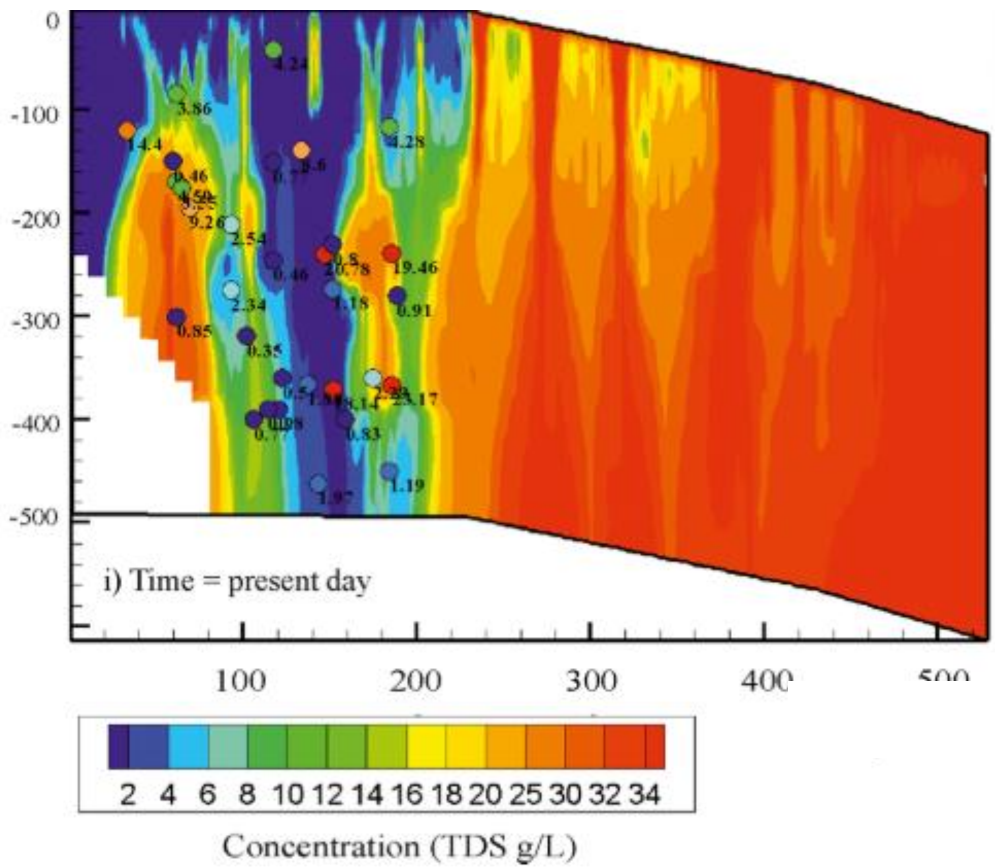


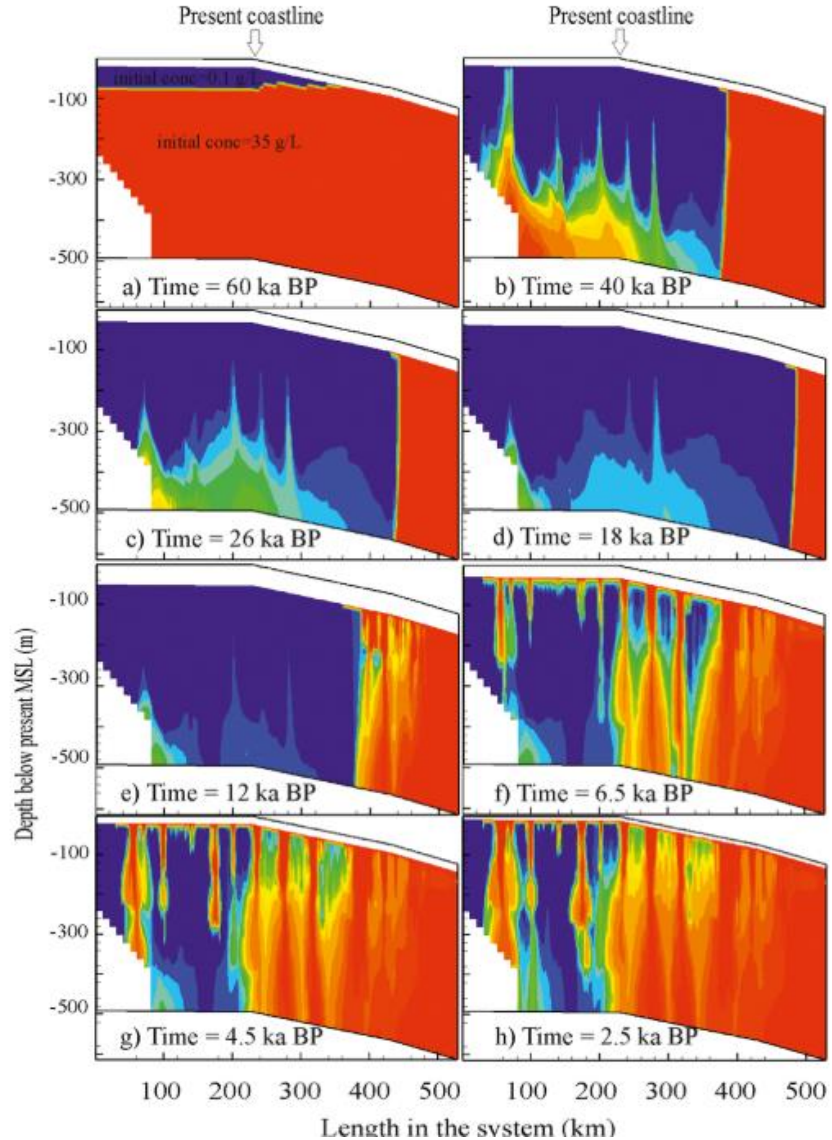
Modelling groundwater salinity Mekong delta over 60kyr



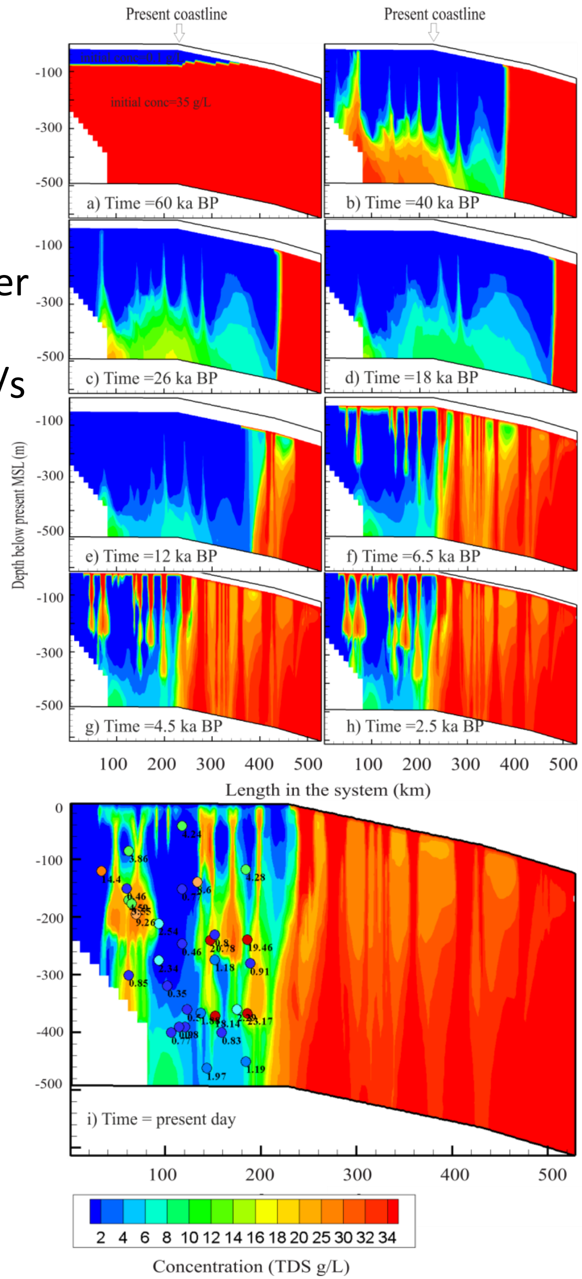


Modelling groundwater salinity Mekong delta over 60kyr





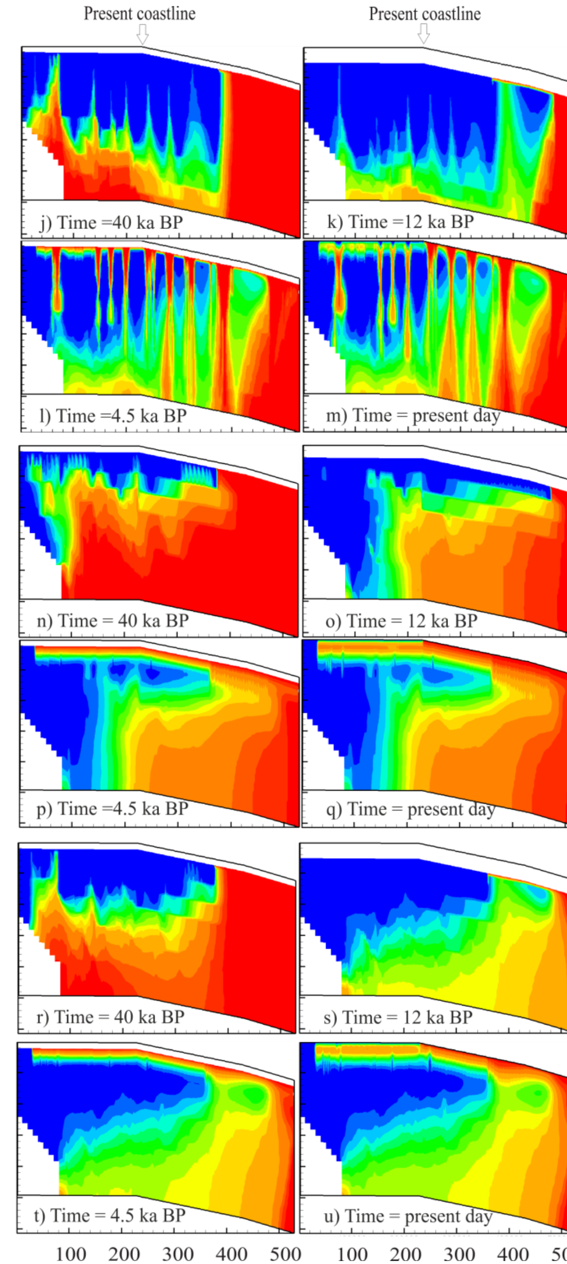
reference case
"geology i"
more disconnected strata and thinner aquitards
with $K_h = 10^{-7}$ m/s



"geology ii"
more connected thicker aquitards
with $K_h = 10^{-7}$ m/s

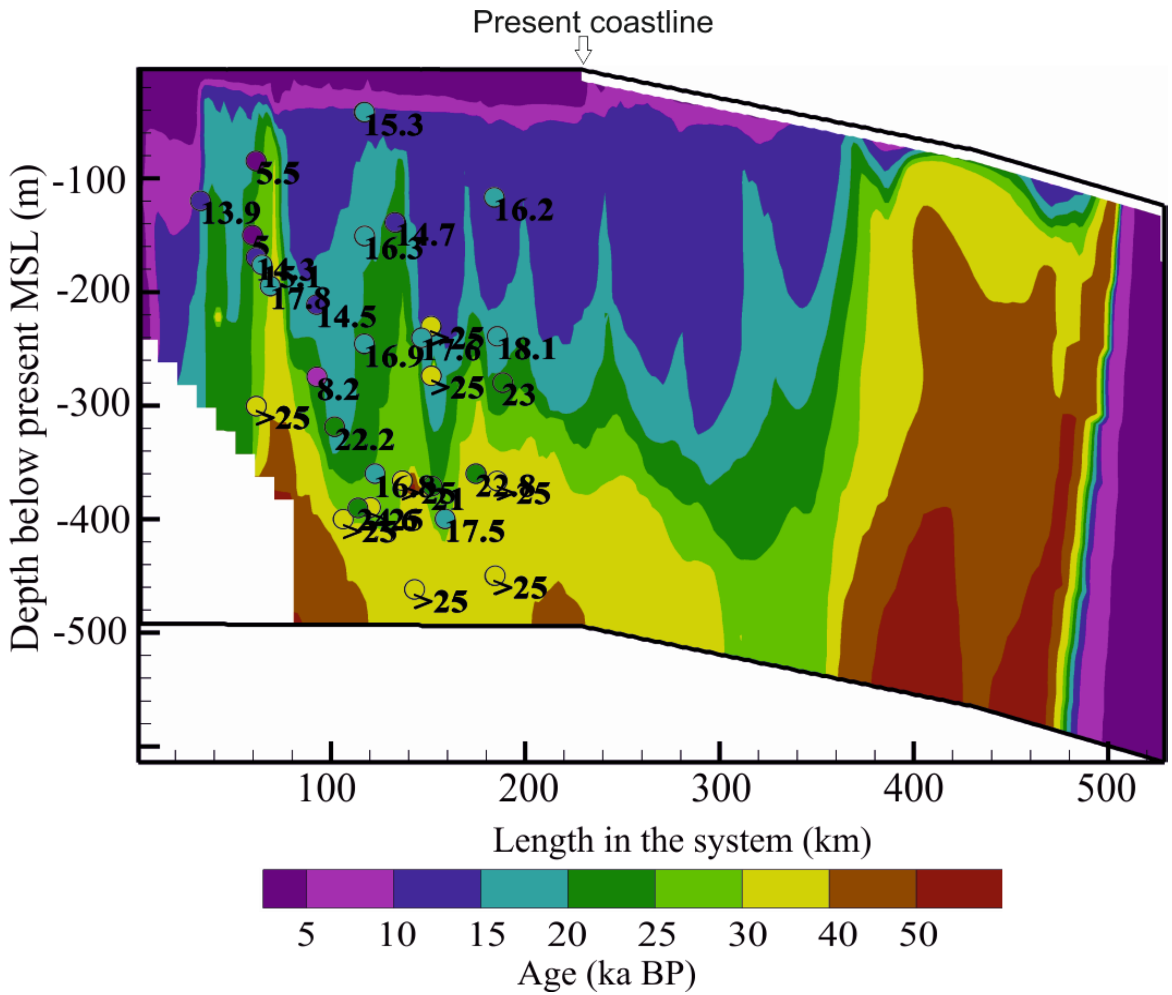
"geology iii"
more disconnected strata and thinner aquitards
with $K_h = 10^{-10}$ m/s

"geology iii"
more disconnected strata and thinner aquitards
with $K_h = 10^{-8}$ m/s



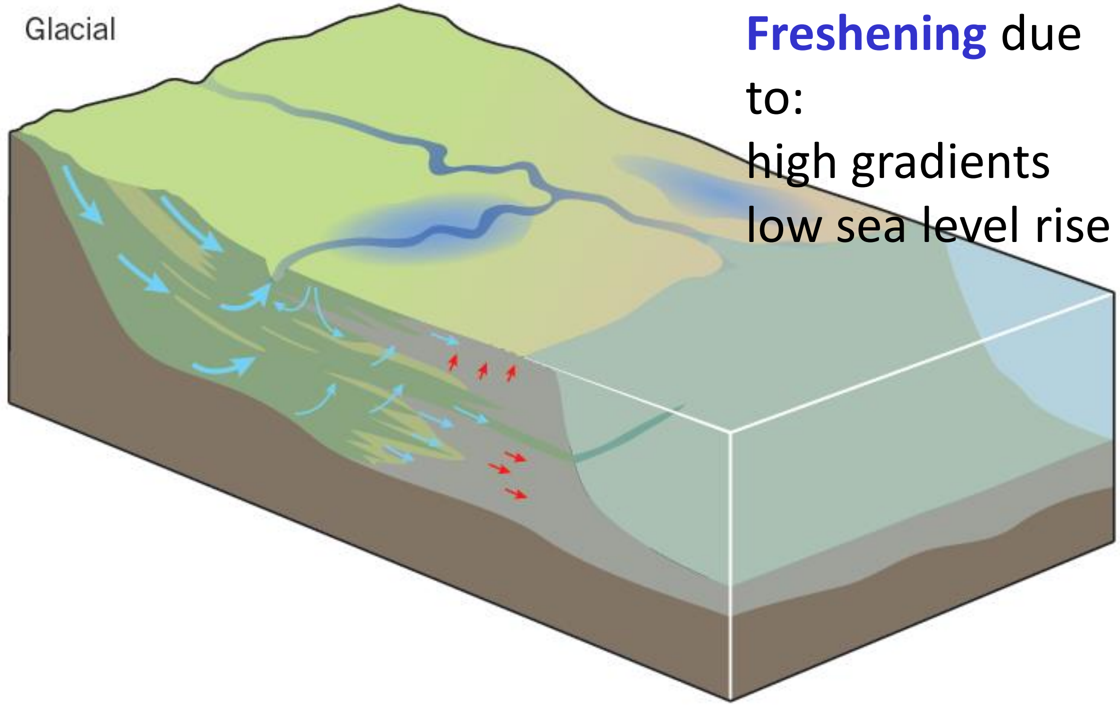
Results of ref case, modelled and observed age

Modeled GW age distribution reference case at present day

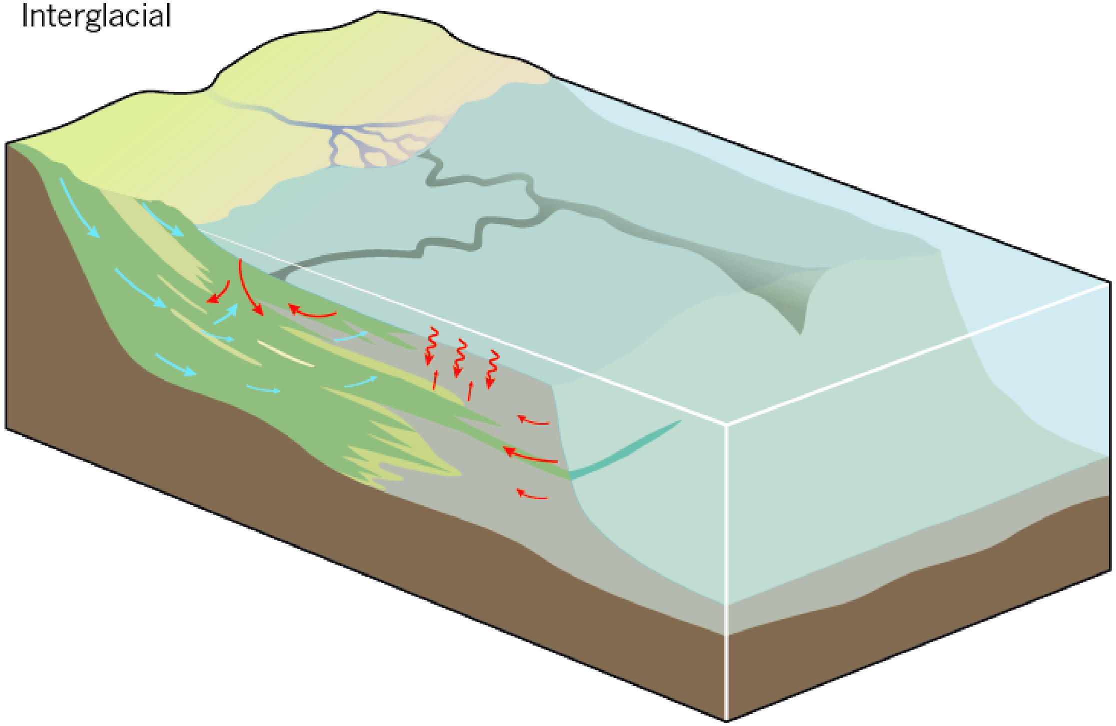


- Most fresh groundwater in the Vietnamese Mekong Delta was recharged 60-12 kyr ago
- Presently, groundwater is hardly being recharged due to high resistance top layer

Genesis and preservation



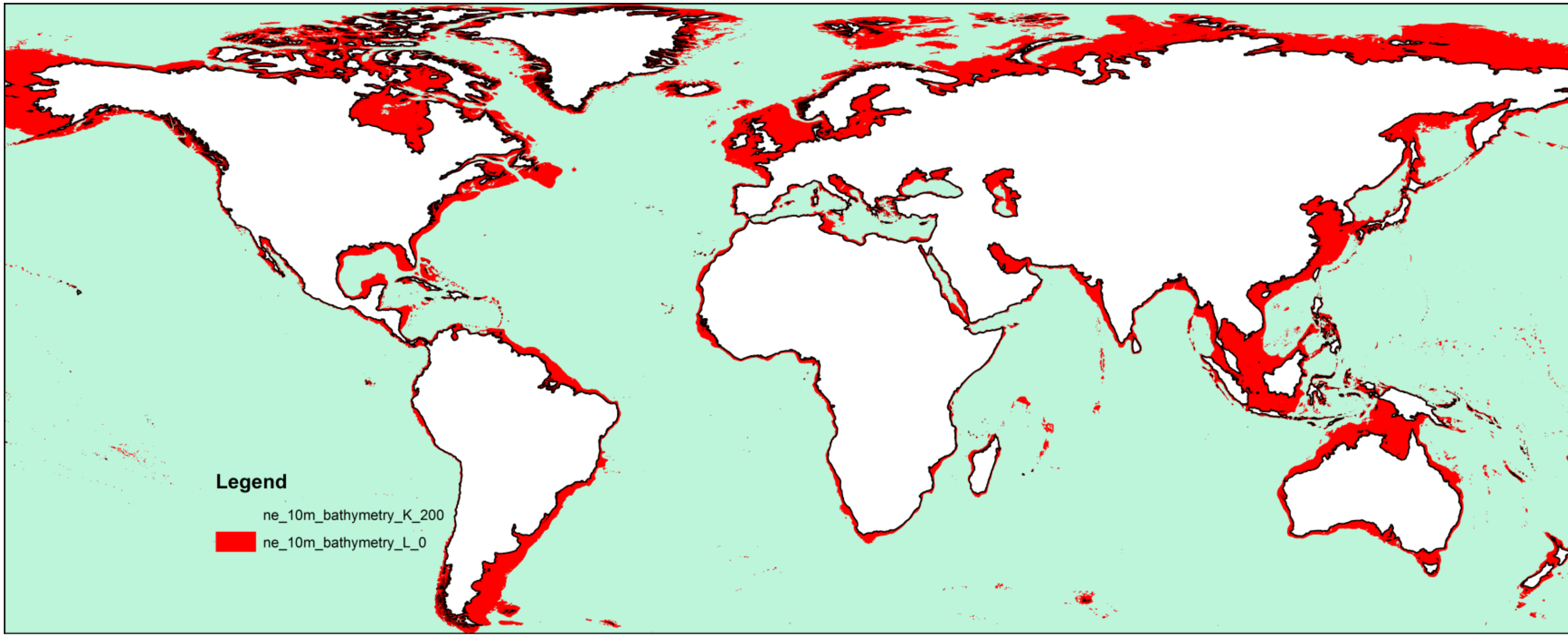
Freshening due to:
high gradients
low sea level rise

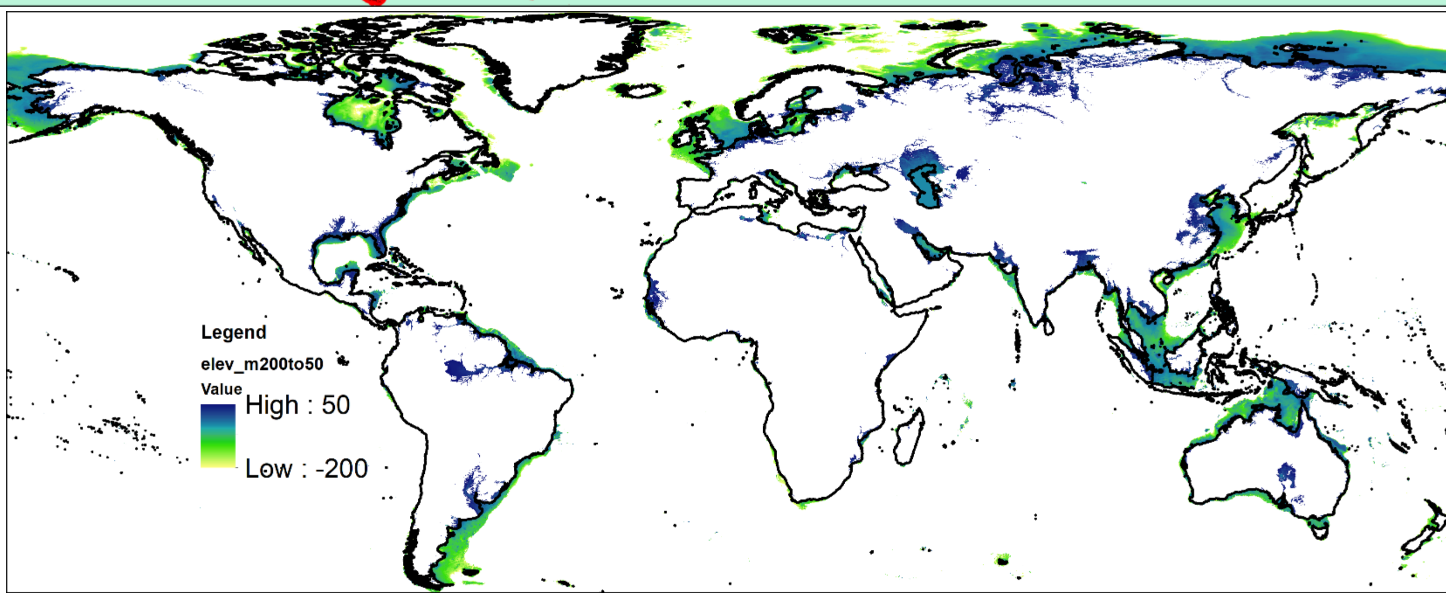


Salinisation due to:
marine transgression and vertical inflow of saline surface water

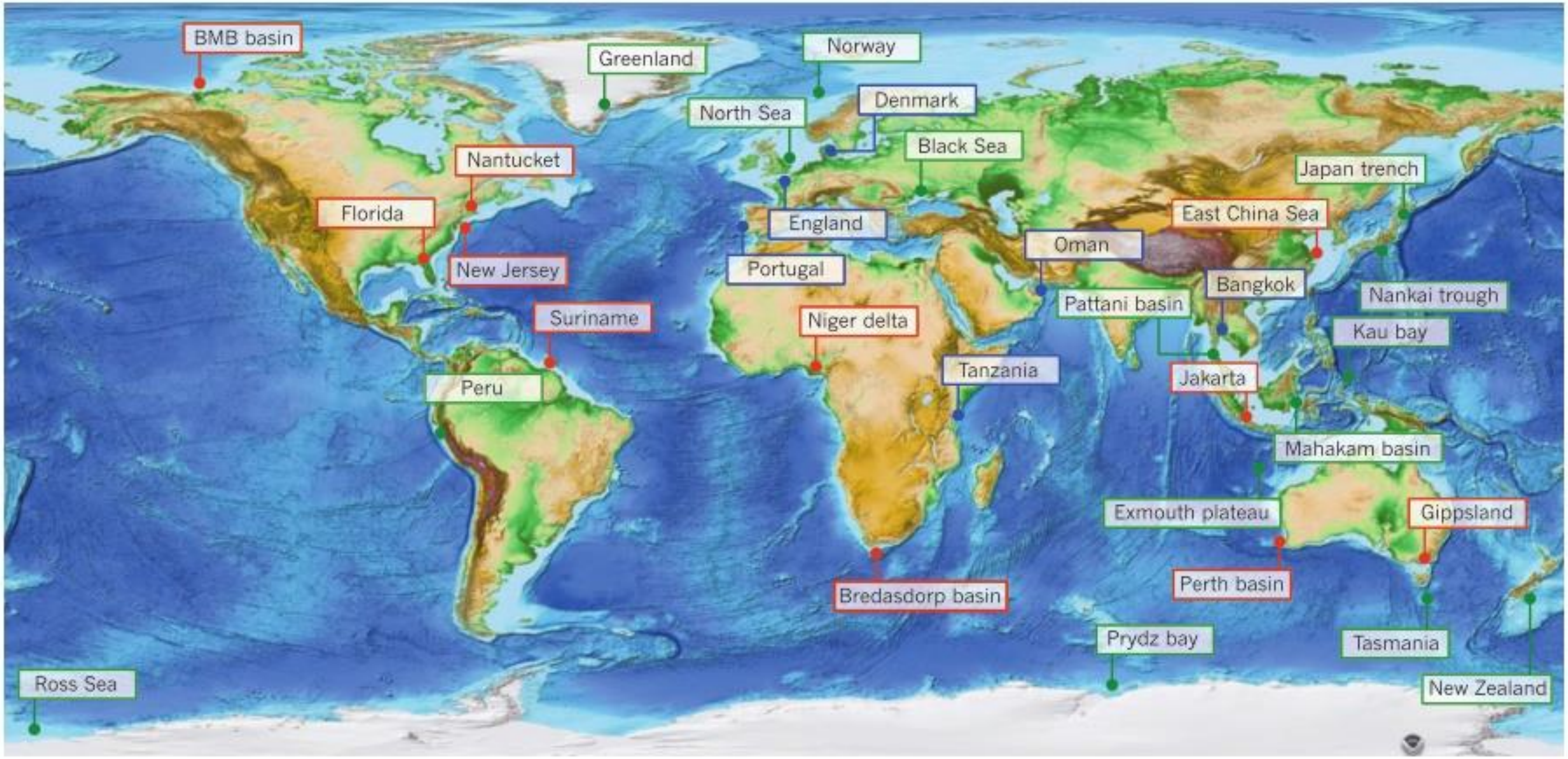
Source: Post et al, Nature, 2013

Possible locations of offshore (submarine) groundwater





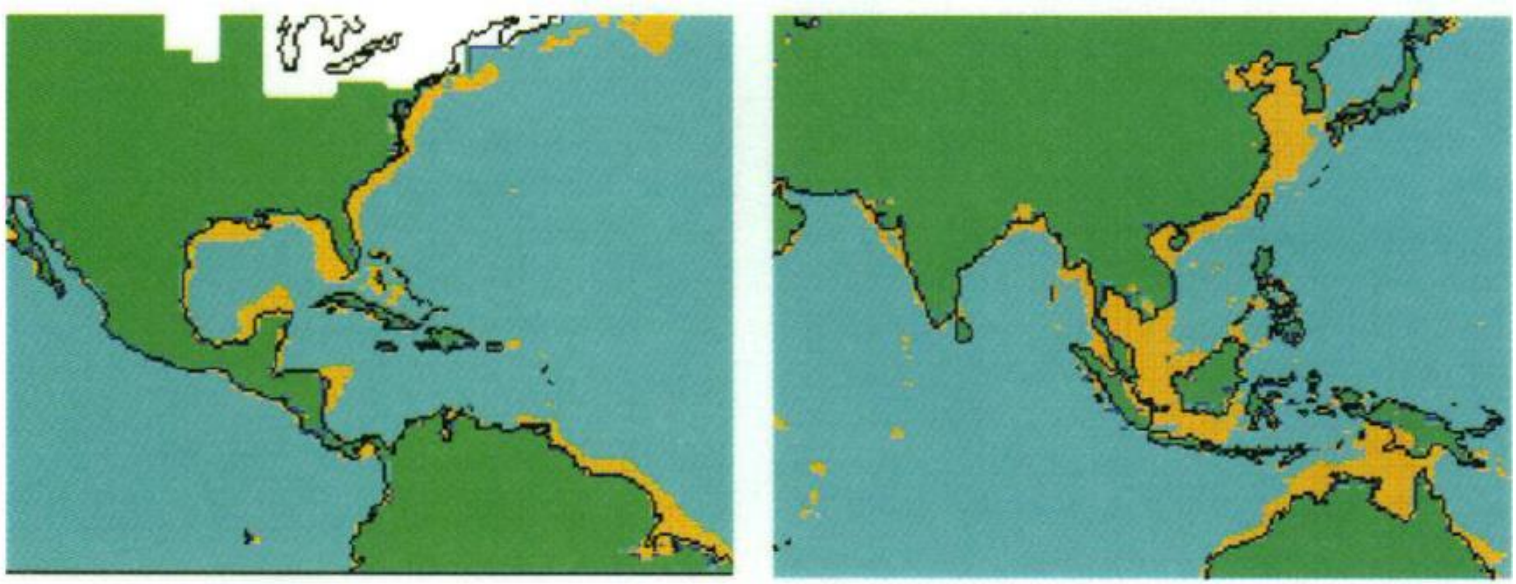
World map of topography and bathymetry showing known occurrences of fresh and brackish offshore groundwater



Post et al., Nature, 2013

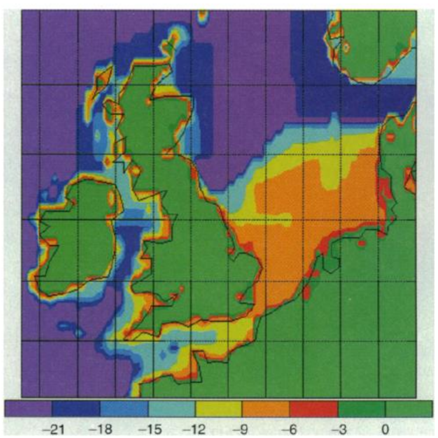
Coastal zone cases around the world

Occurrence related to dynamic sea-levels and coastlines

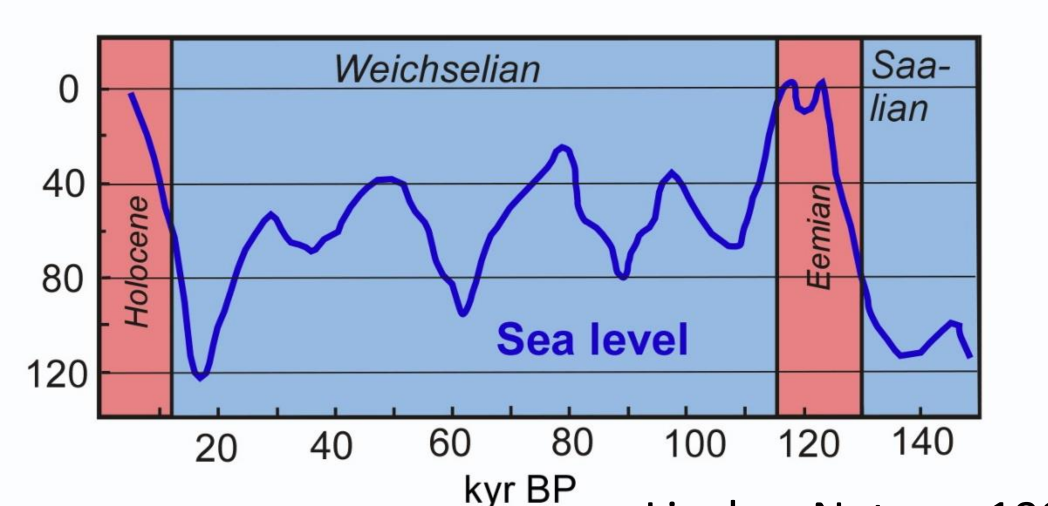


Exposed continental shelves

Peltier, *Science*, 1994

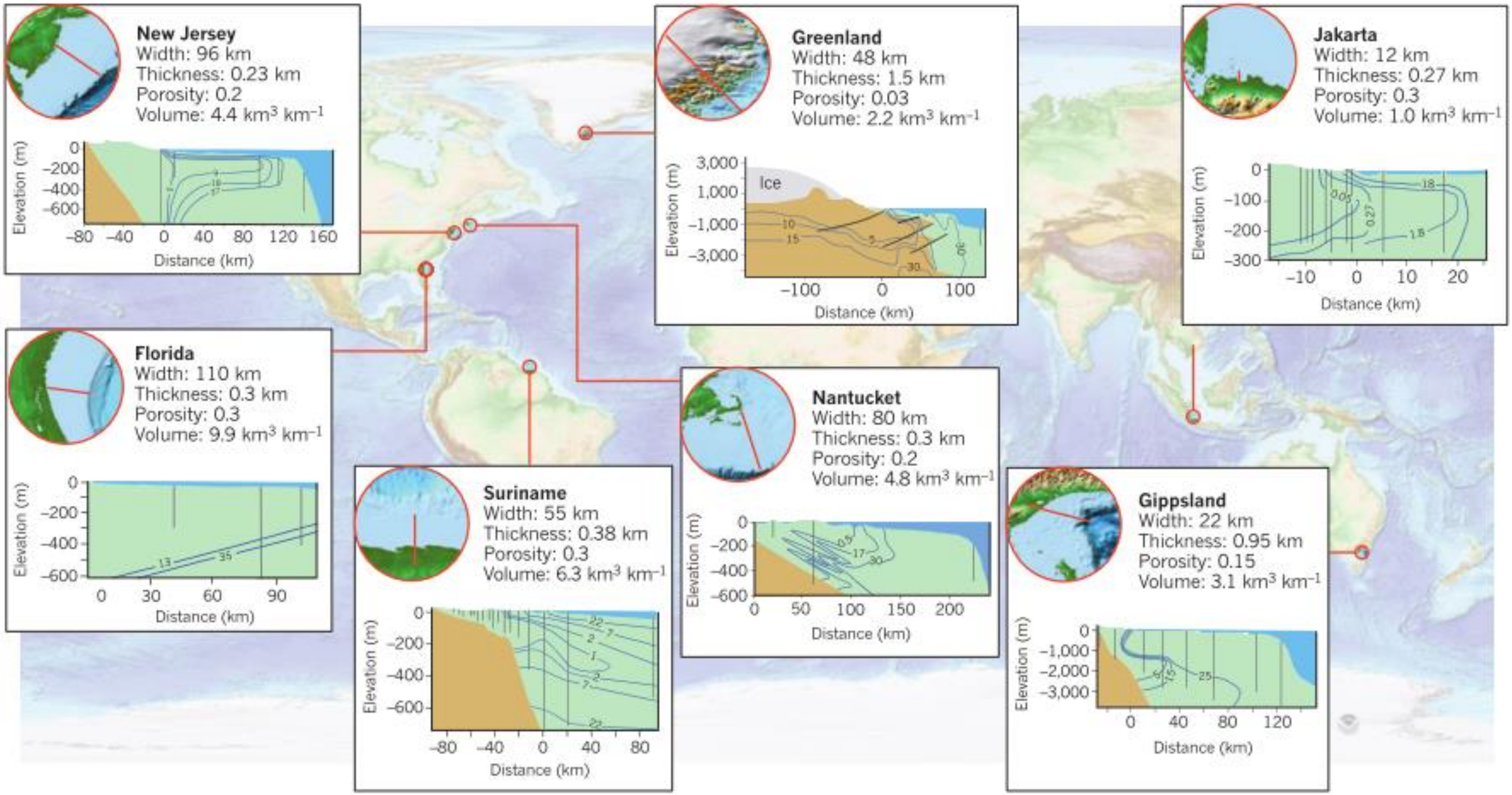


Inundated (kyr BP)



Linsley, Nature, 1996

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



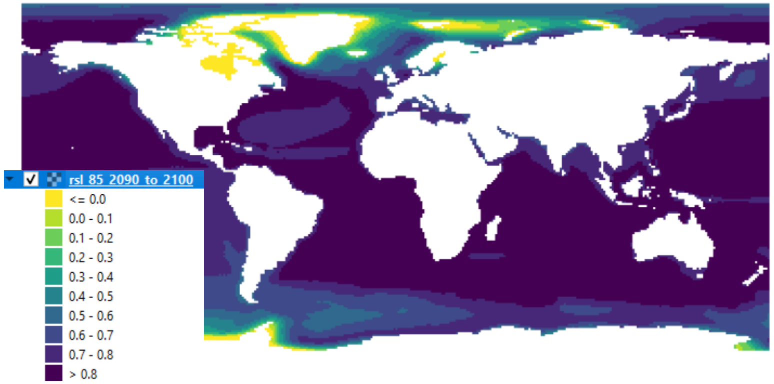
Work Daniel Zamsky: Data sources and general approach

1. Global data (DEM, hydrogeology, groundwater recharge)
2. Modelling 2D profiles in unconsolidated sediment media (including paleo-reconstruction)
3. SLR based on IPCC-SROCC (2019) report, regional SLR for RCPs 2.5, 4.5, 8.5, up to 2100 (global till 2300)

TABLE 1 | Global datasets collected and used as input.

Dataset name	Description	Resolution	References
GEBCO 2014[1,2]	Global topography and bathymetry	30″	Weatherall et al., 2015
ATE[2]	Unconsolidated groundwater system thickness estimation (unconsolidated sediments only)	Vector	Zamrsky et al., 2018
P[2], ET[2]	Long term average annual precipitation and evapotranspiration	30″	NTSG, 2019
GLHYMPS[2]	Bottom aquifer hydraulic conductivity	30″	Gleeson et al., 2014
GLHYMPS 2.0 (GUM)[2]	Upper aquifer hydraulic conductivity	30″	Huscroft et al., 2018
Soilgrids[2]	Soil layer thickness	30″	Hengl et al., 2014
Soil hydraulic properties[2]	Global soil hydraulic conductivity	30″	Montzka et al., 2017
COSCAT[1,2]	Segmentation of the shelf and basins	Vector	Meybeck et al., 2006
MARCAT[1]	Segmentation of the shelf and basins, typology	Vector	Laruelle et al., 2013
WTD[2]	Water table depth (relative to sea level)	30″	Fan et al., 2017
Ocean floor age[1]	Age of oceanic bottom	2′	Müller et al., 2008
Delta dispersion[1]	Dispersion system classification	Vector	Walsh and Nittrouer, 2009
Delta location	Location of 40 largest deltas worldwide	Vector	Tessler et al., 2015
LGM[1]	Last glacial maximum global extent	Vector	Ehlers and Gibbard (2004)
Tectonic plate boundaries[1]	Indicates passive/active margins	Vector	Coffin et al., n.d.
GLIM[1]	Global lithology classification	Vector	Hartmann and Moosdorf, 2012
Seafloor sediment type	Seafloor lithology classification	6′	Dutkiewicz et al., 2015

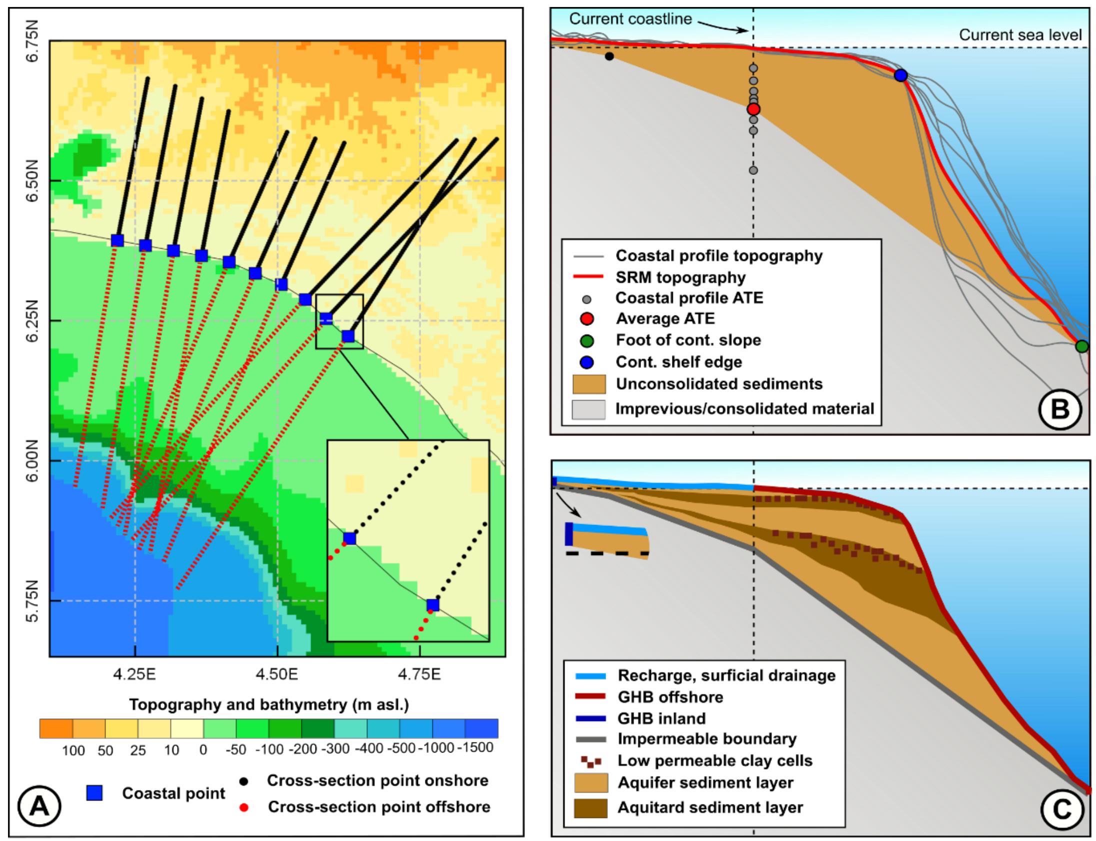
[1] *Used for estimating the global geological heterogeneity,* [2] *used as input for SEAWAT models, implemented using SEAWAT (Langevin et al., 2008).*



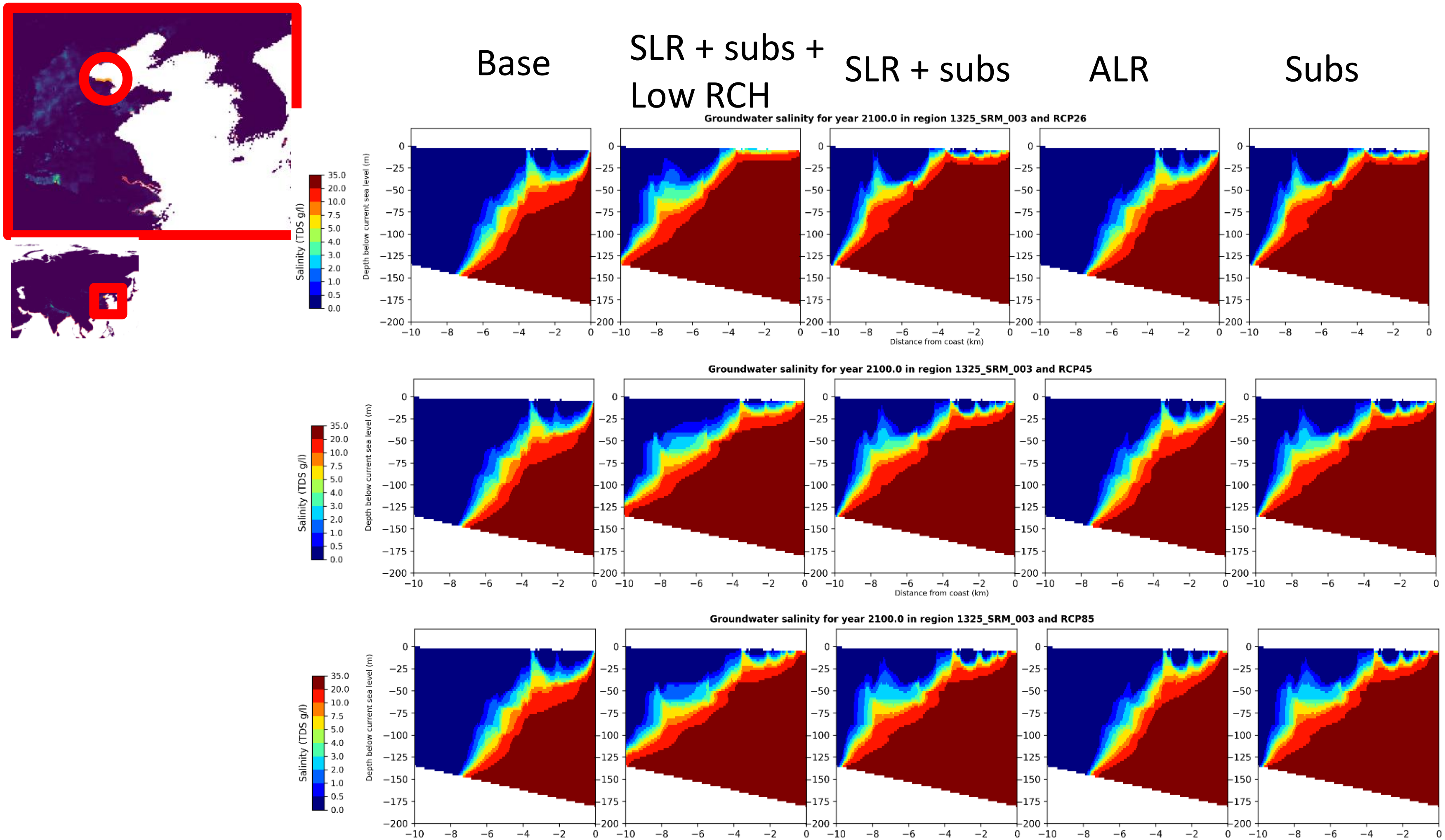
Zamrsky, D., Oude Essink, G.H.P., Sutanudjaja, E.H., Van Beek, L.P.H., Bierkens, M.F.P., 2022. Offshore fresh groundwater in coastal unconsolidated sediment systems as a potential fresh water source in the 21st century. Environ. Res. Lett. 17, 1–22. https://doi.org/https://doi.org/10.1088/1748-9326/ac4073

Modelling setup

1. Average representative profile aggregated over a larger coastal region (hundreds of km)
2. Several geological scenario conditions to cover uncertainties (Zamrsky et al. 2018, 2020)
3. Results as change in fresh groundwater volume compared to 2000AD



Example results



Estimated volumes of offshore fresh groundwater volumes

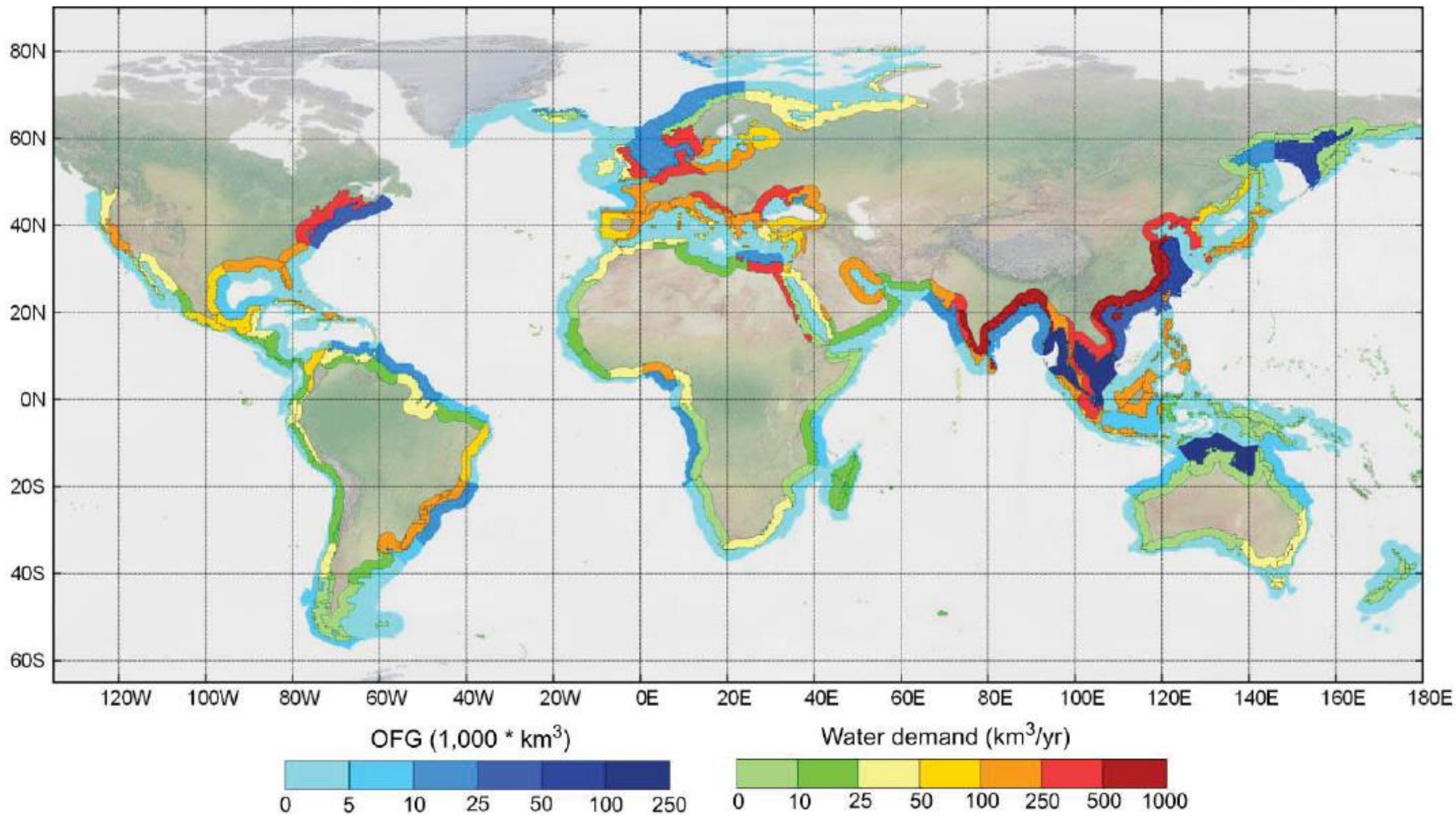
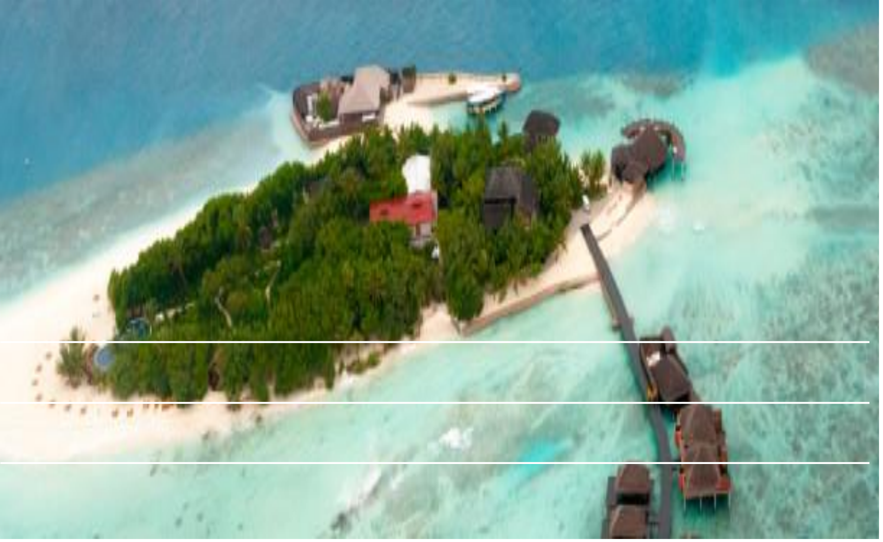


Figure 1 Estimated regional OFG volumes (in 1,000 km^3) plotted with regional coastal current water demand (km^3/yr) based on the global hydrological and water resources model PCR-GLOBWB (30). Note that gross water demand is plotted, which includes losses and return flows. South-east and East Asia stands out as regions where OFG could provide an additional source of fresh water and therefore has most potential for OFG exploration.



Deltares
Enabling Delta Life

Universiteit Utrecht

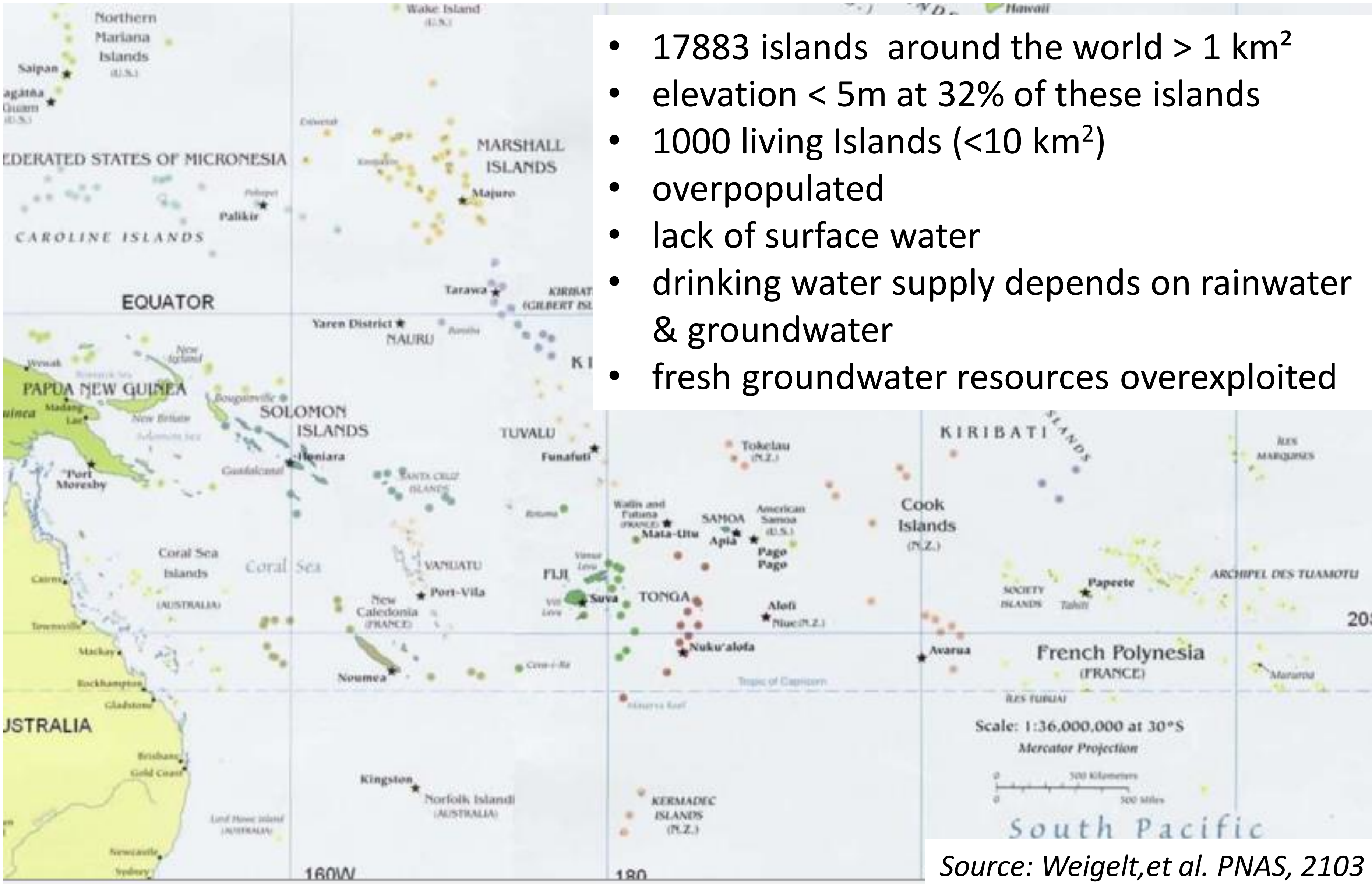
Fresh groundwater resources in SIDS under climate and global stresses







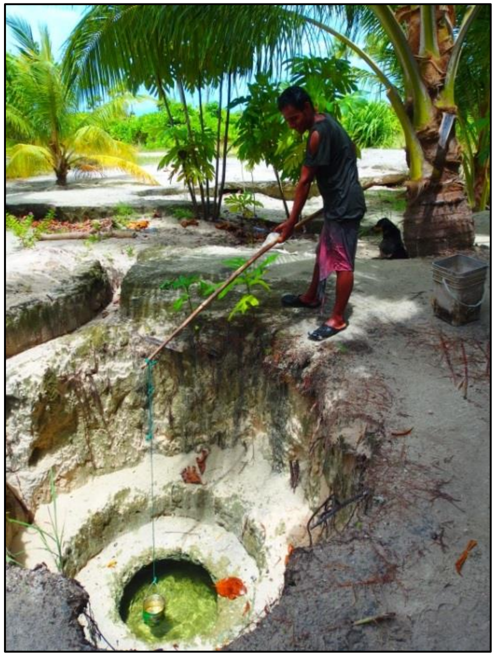

Facts SIDS: small island developing states in Pacific



- 17883 islands around the world > 1 km²
- elevation < 5m at 32% of these islands
- 1000 living Islands (<10 km^2)
- overpopulated
- lack of surface water
- drinking water supply depends on rainwater & groundwater
- fresh groundwater resources overexploited

Source: Weigelt,et al. PNAS, 2103

Water resources at SIDS



Headlines: SIDS / Water Resources / Climate Change

Before we drown
we may die of thirst

Obama declares disaster as Marshall Islands suffers worst-ever drought

Running Dry: Almost a year after the drought, Palau is still trying to overcome water challenges

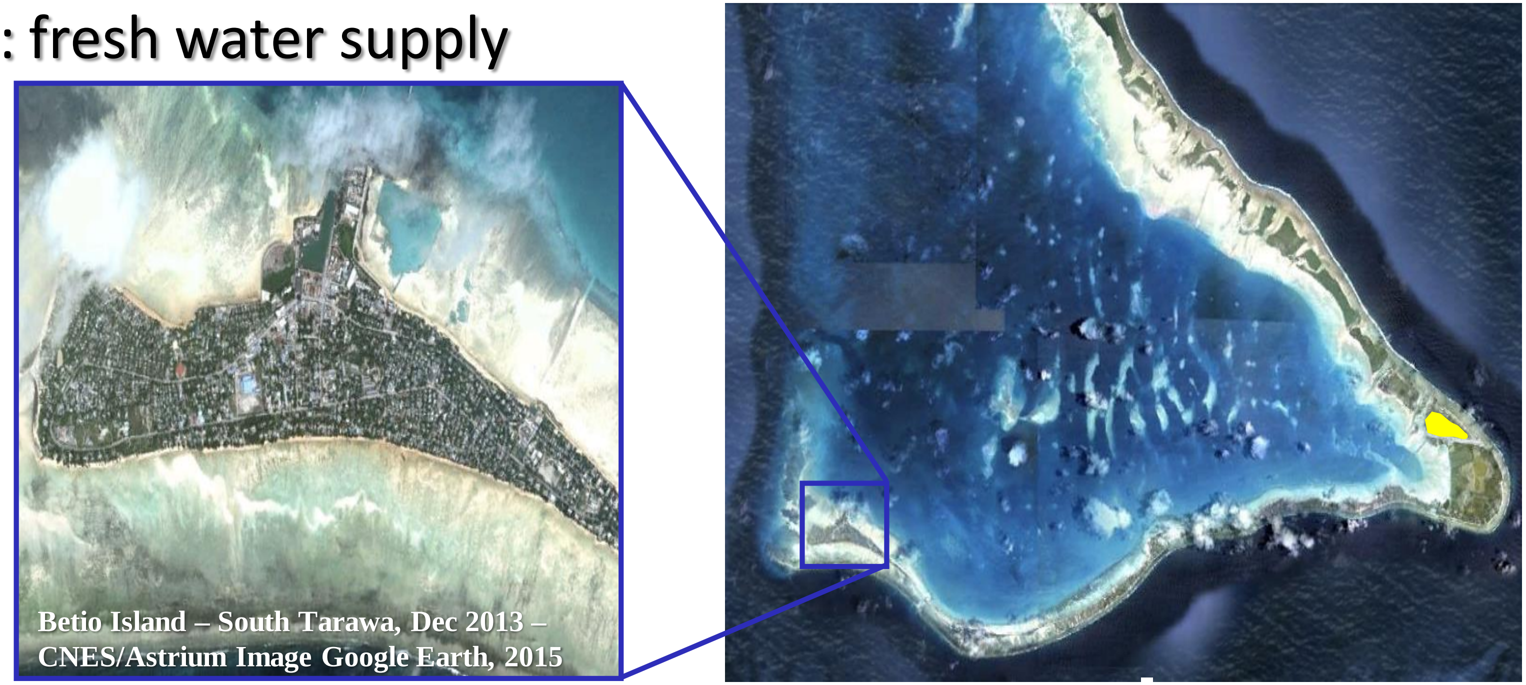
Winston the strongest, first Category 5 cyclone to hit Fiji

1907 (Vanuatu) (most likely 1905-1906)

'Emau – we are having a very long drought here and in much need of rain to water the ground…The Emau people have no water either to drink or cook food with, and are boating over from Efate. The coconut trees are ceasing to bear, and some of them are dying….' The New Hebrides Magazine January 1907 and August 1908.

Case Kiribati: fresh water supply

Case Kiribati: fresh water supply



Betio Island – South Tarawa, Dec 2013 – CNES/Astrium Image Google Earth, 2015

Today

38 litres per person per day

~per capita share of the sustainable yield of Bonriki and Buota potable groundwater reserves

~50%

Supply system losses

Current estimates of leakages and losses in transmission

~2 x

More people

Potential population increase at current growth rates

>5%

Climate impact

Potential climate change impact on sustainable yield over 20 year period

2035

<9 litres per person per day

assuming 3.47% growth, 5% reduction in sustainable yield, and no changes to current system losses

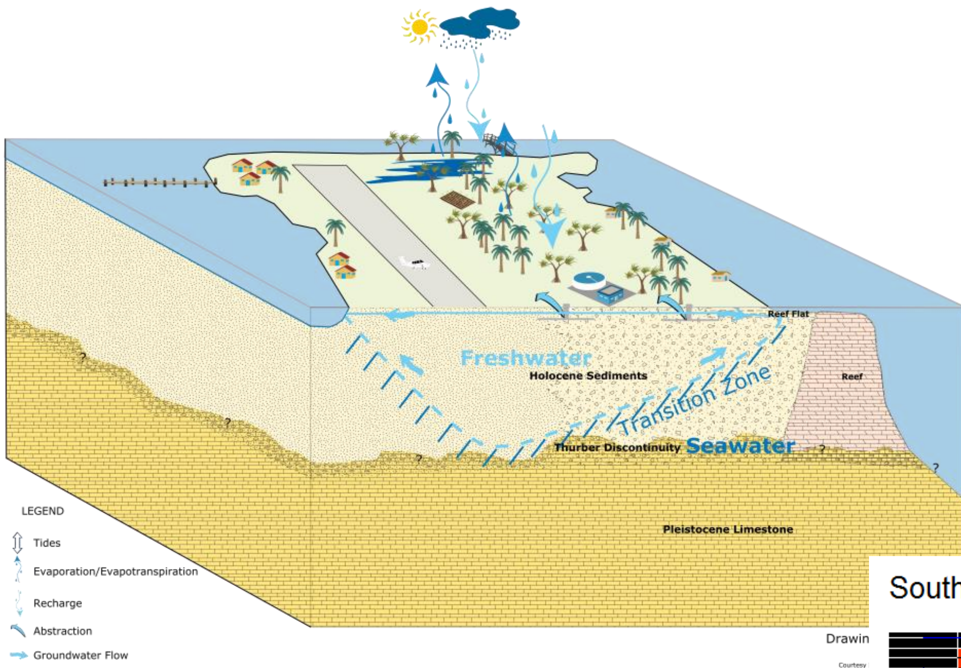
Source: Hebblethwaite, D. (2015)

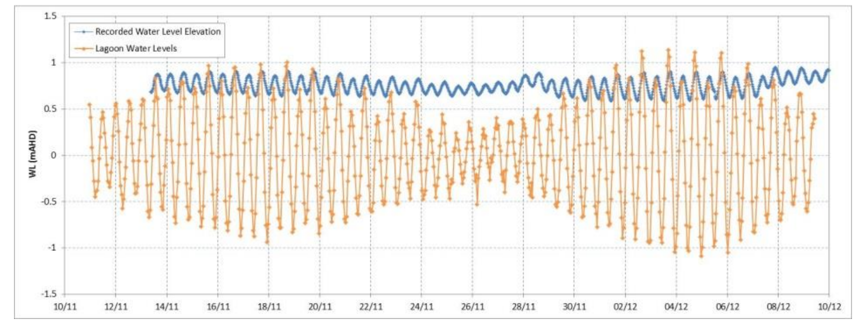
The challenge

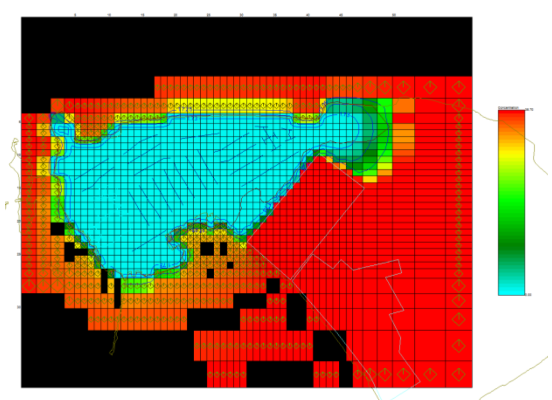
“Before we drown we may die of thirst” (Weiss, 2015)

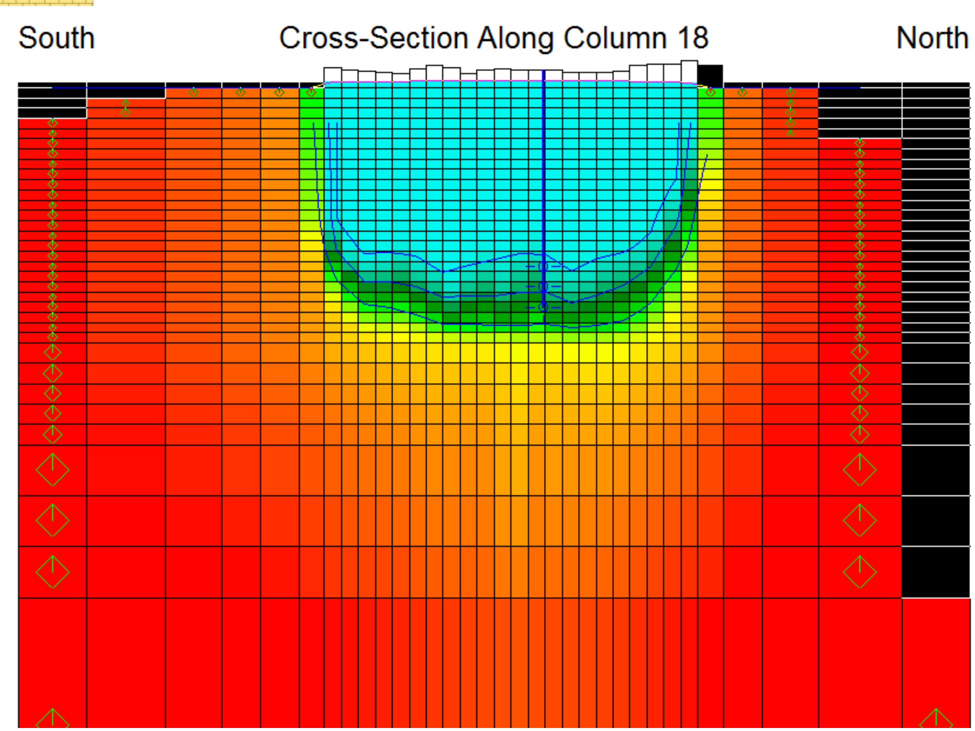
Anote Tong President of Kiribati

Case Kiribati: Conceptual and numerical modelling tools

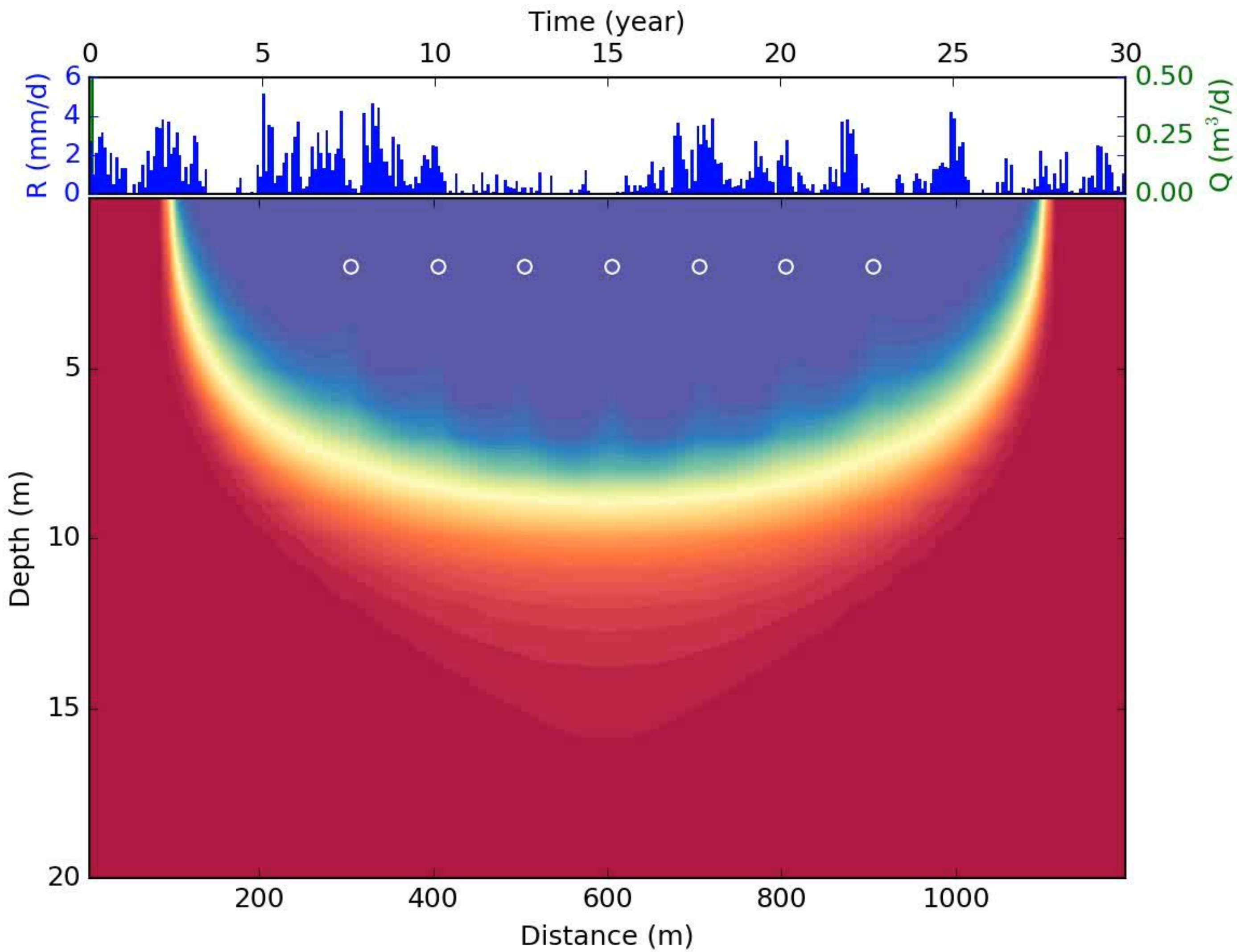




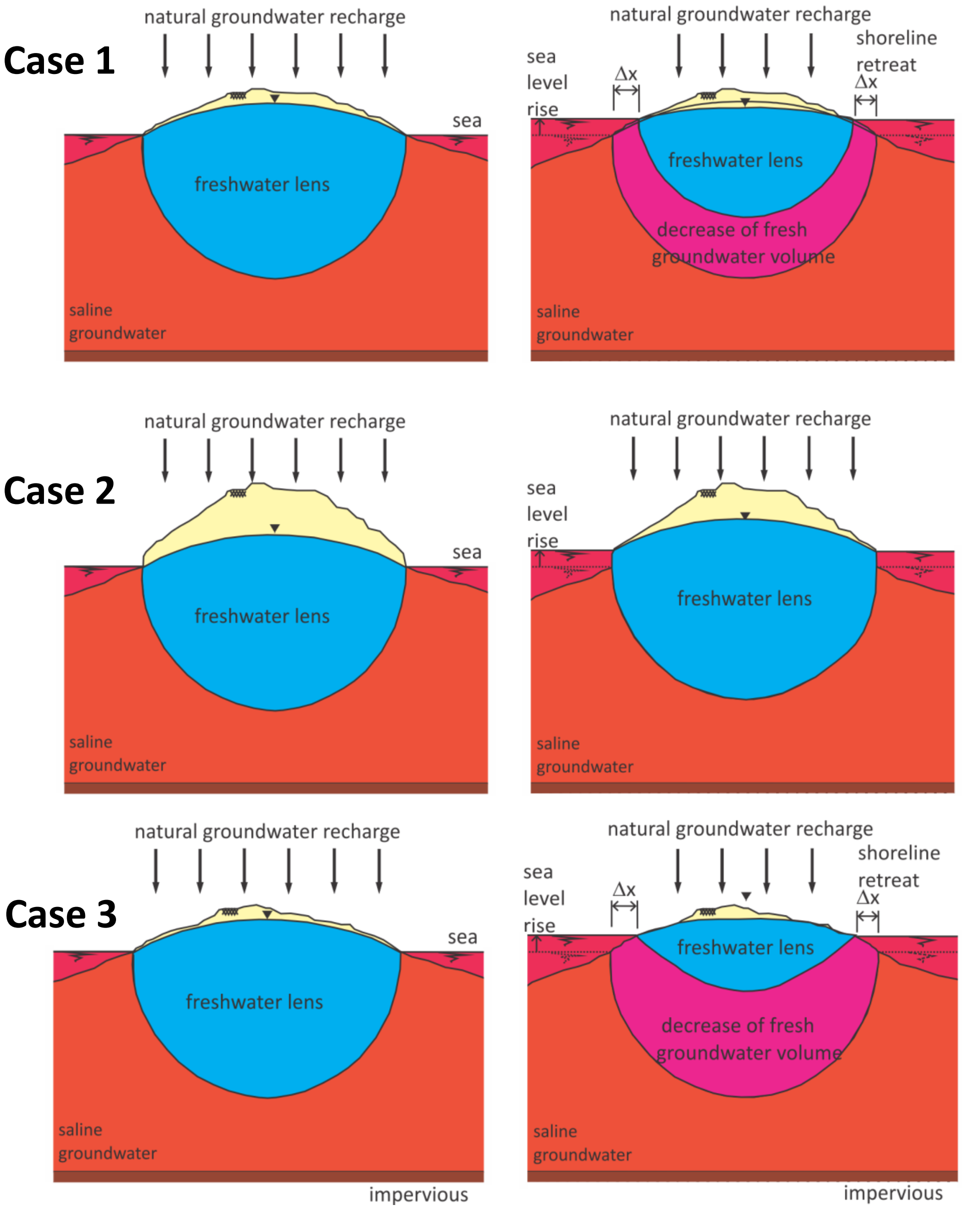




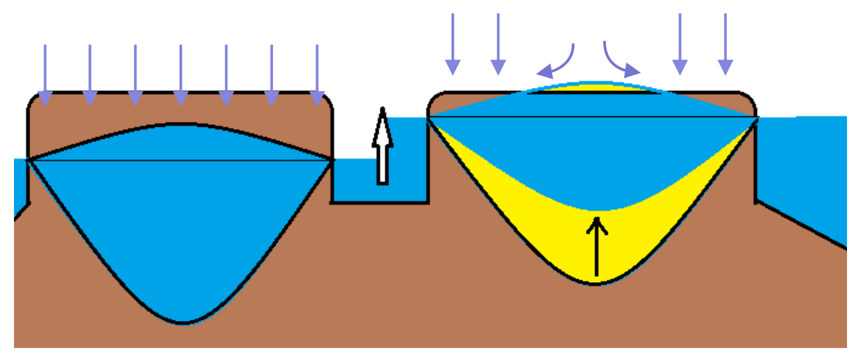
Case Kiribati: Numerical modelling tools



Stresses to fresh groundwater lenses



- erosion reduces fresh groundwater volumes
- volume reduction is linear to erosion width island



Case Kiribati: Understanding the groundwater system






Mapping the salinity distribution

Airborne EM surveys:
much cheaper, faster, 3D, AND
as equal accurate as
conventional geophysical methods

TNO innovation for life

BGR

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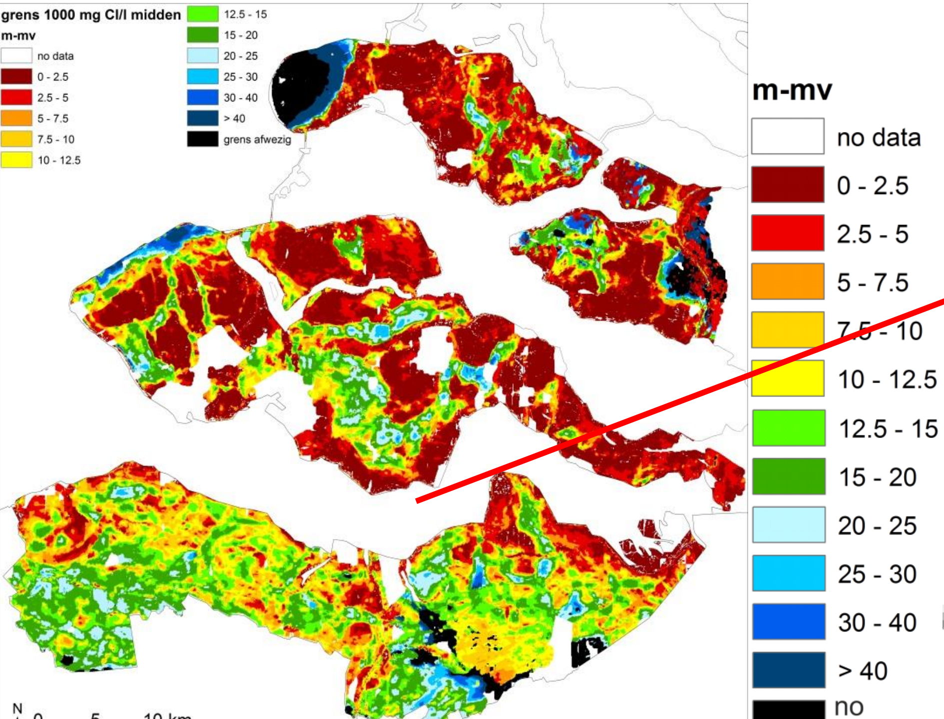
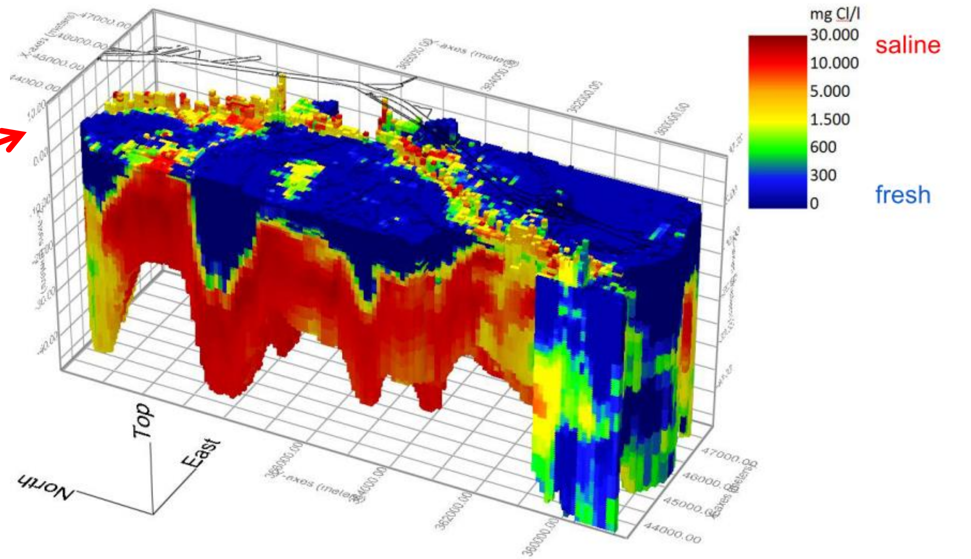


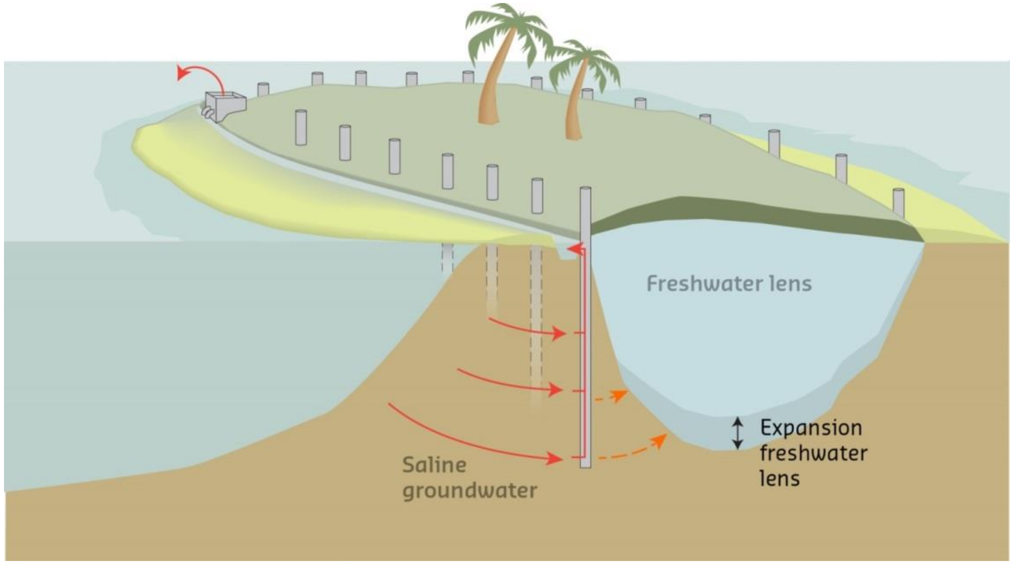
FRESHEM Zeeland



FRESHEM pilot Canal zone, visualization in iMOD

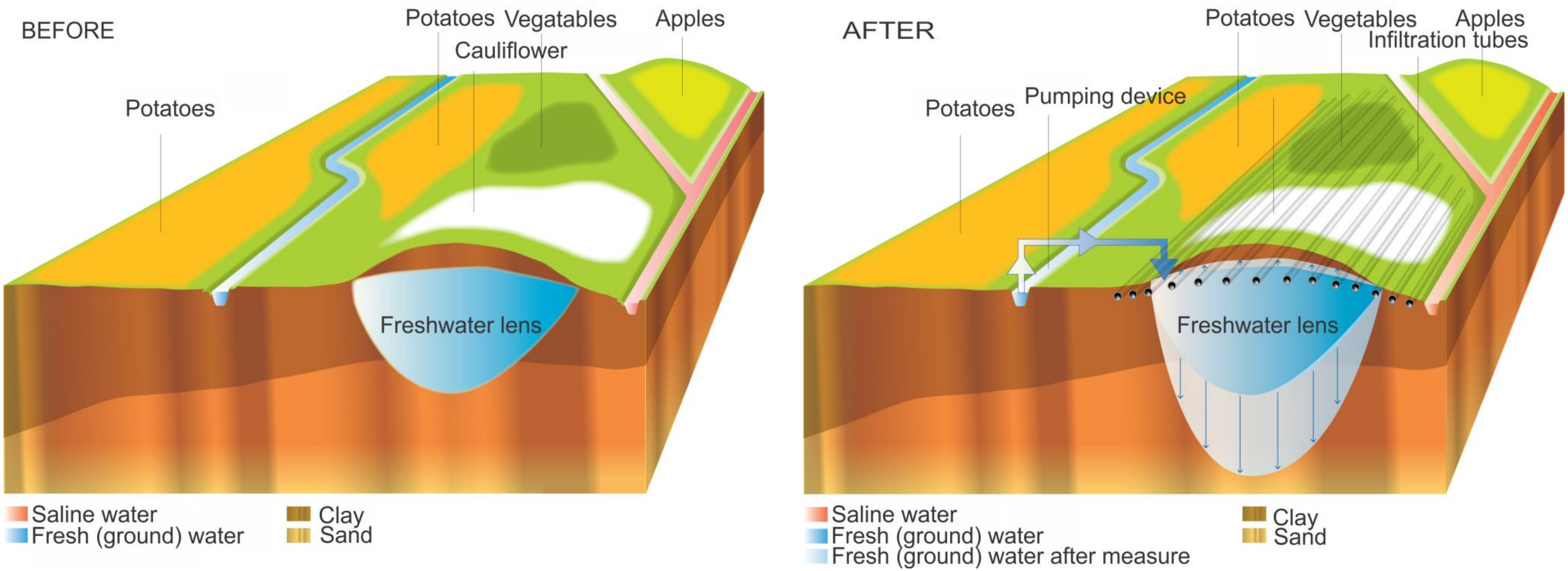
Seepage systems

Tested seepage system for Protecting fresh groundwater resources on small oceanic islands from sea-level rise: SEEPCAT



ASR / MAR

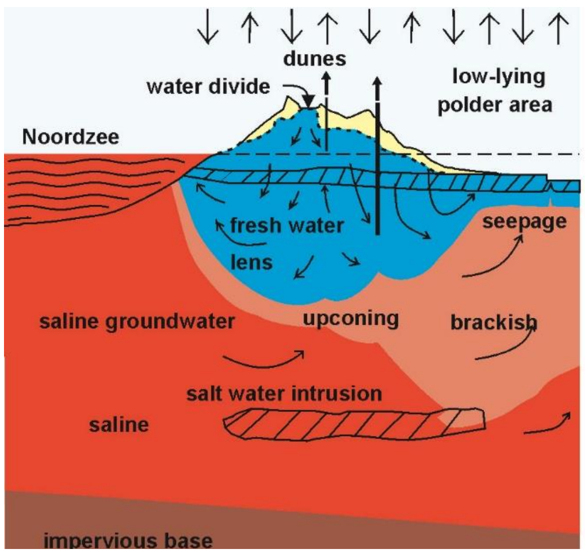
Aquifer Storage and Recovery / Managed Aquifer Recharge

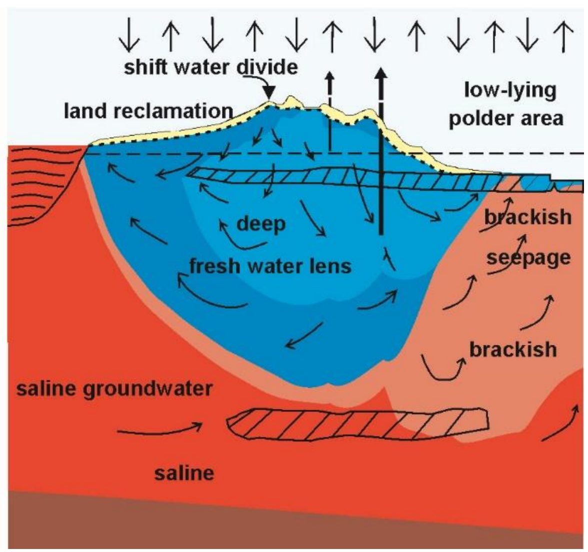


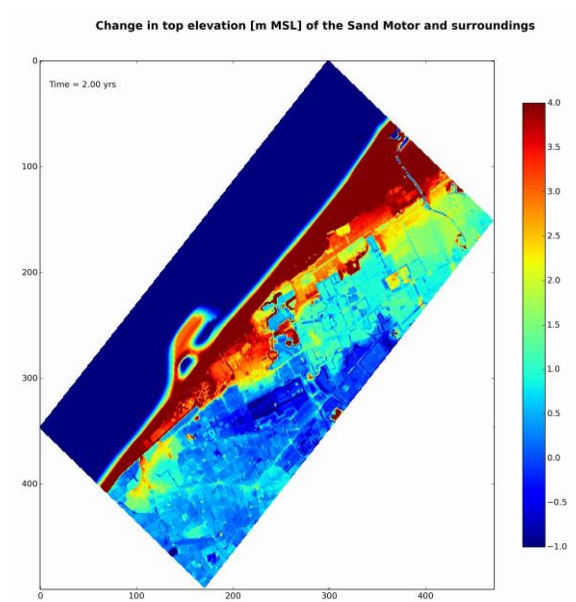
Deltares Enabling Delta Life · KWR · Acacia Water Solutions in Groundwater · HZ University of Applied Sciences · Alterra Wageningen UR · GO-FRESH · imaGeau instrumentation du sous-sol · Fugro

Increase strategic freshwater reservoirs in the coastal zone

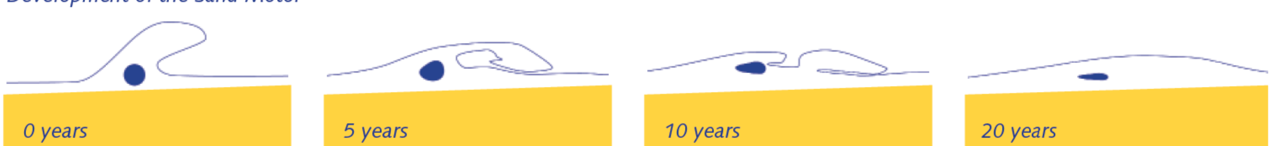
200m width sand suppletion at the Dutch Coast will on the long run to a built-up of ~1000 million m3 fresh groundwater







Development of the Sand Motor



Salt resistant crops on salinized soils

Meijer FOR SURE

20220325_GEO4-4425

Deltares Enabling Delta Life

Global Quick Scan of the Vulnerability of Groundwater systems to Tsunamis*

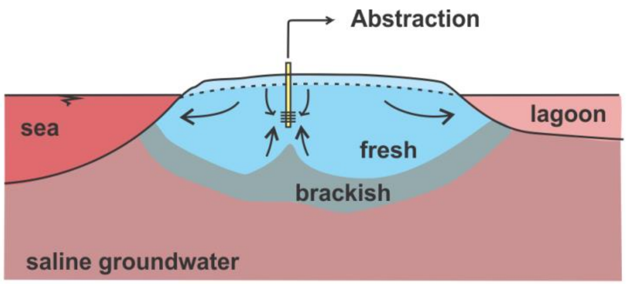
**or other flooding events*

Daniel Zamrsky[1,2], Marta Faneca Sànchez[1], **Gu Oude Essink**[1,3]
Subsurface and Groundwater Systems
Deltares, The Netherlands
freshsalt.deltares.nl

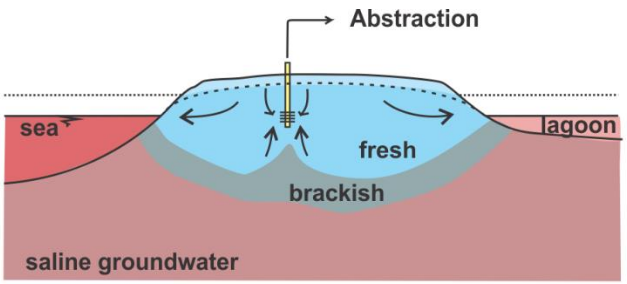
[2] WAGENINGEN UR
For quality of life

[3] Universiteit Utrecht

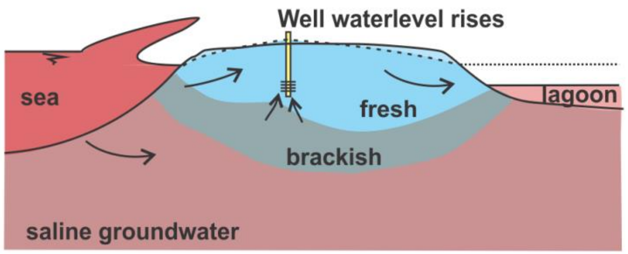
1. *Sense of Urgency*
2. *Approach*
   -vulnerability Tsunami index map
   -modelling salt groundwater
3. *Preliminary results*



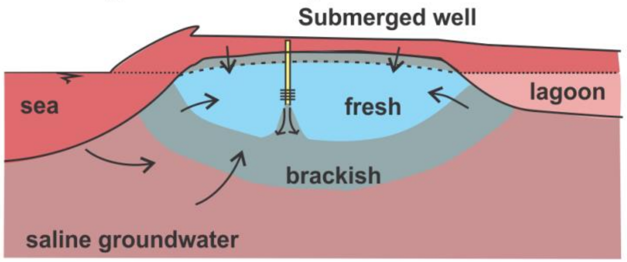
1. Before Tsunami



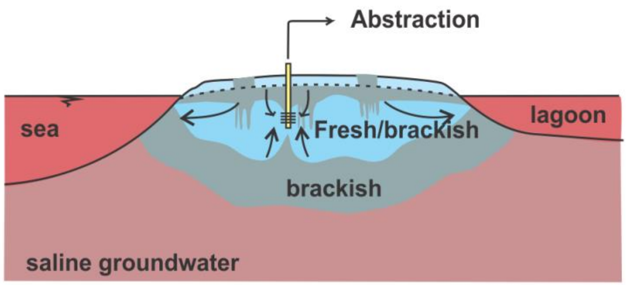
2. Just before Tsunami:
Lowering of sea- and lagoonwater level



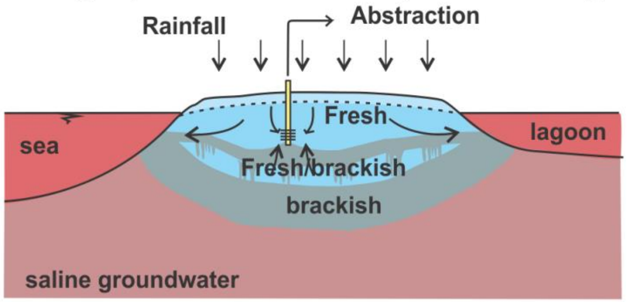
3. Just before Tsunami:
Subsurface pressure wave precedes surface wave



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

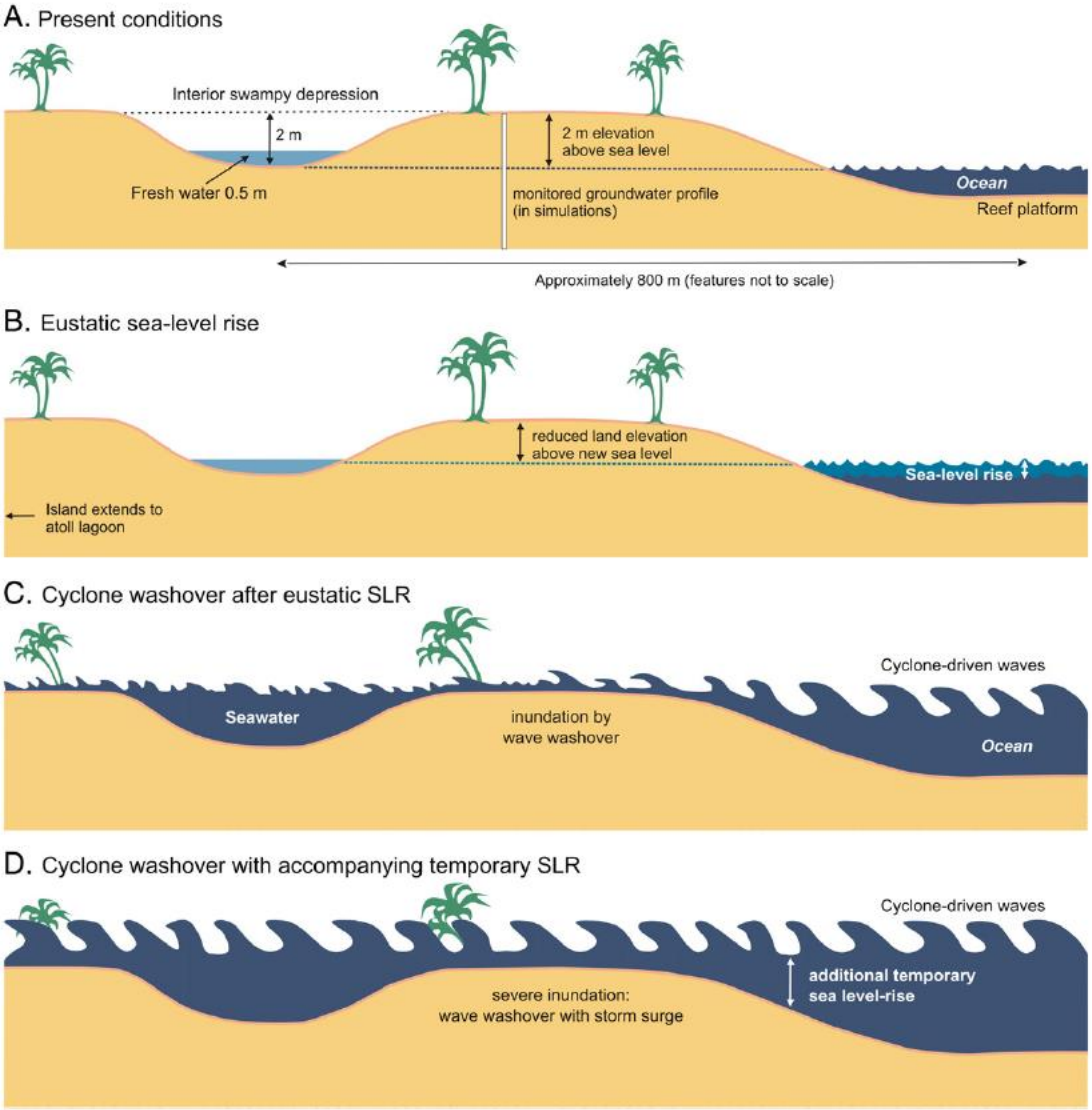


5. After Tsunami
Freshwater mixed with brackish water



6. After Tsunami
Recharge by rainfall replaces brackish water

The fate of freshwater lenses on atoll

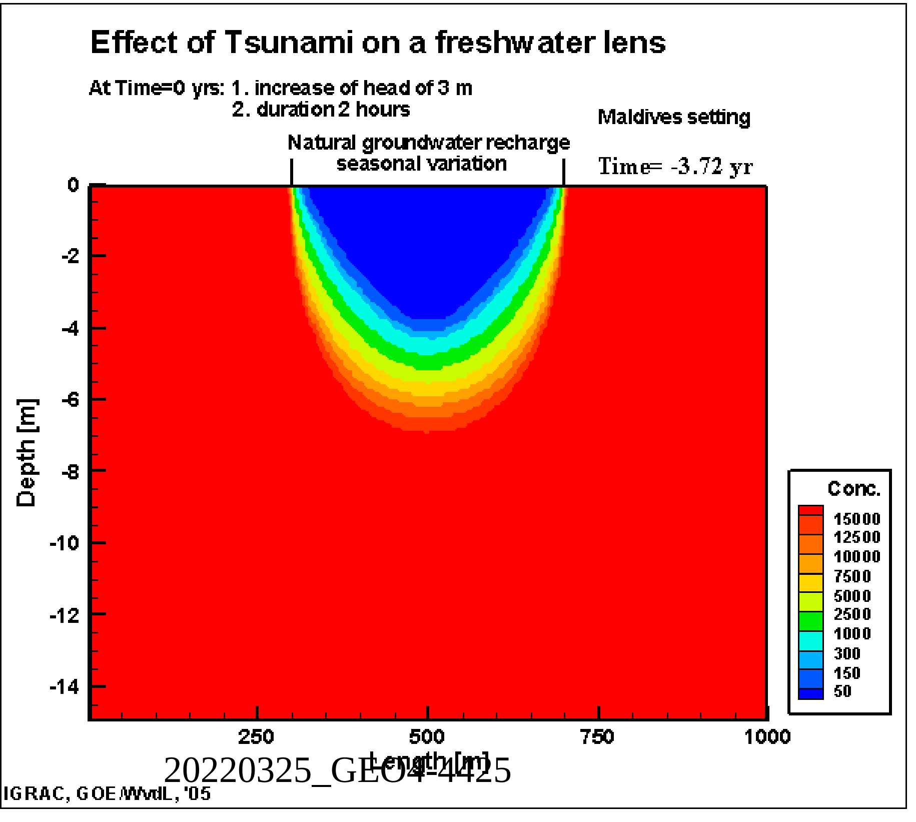


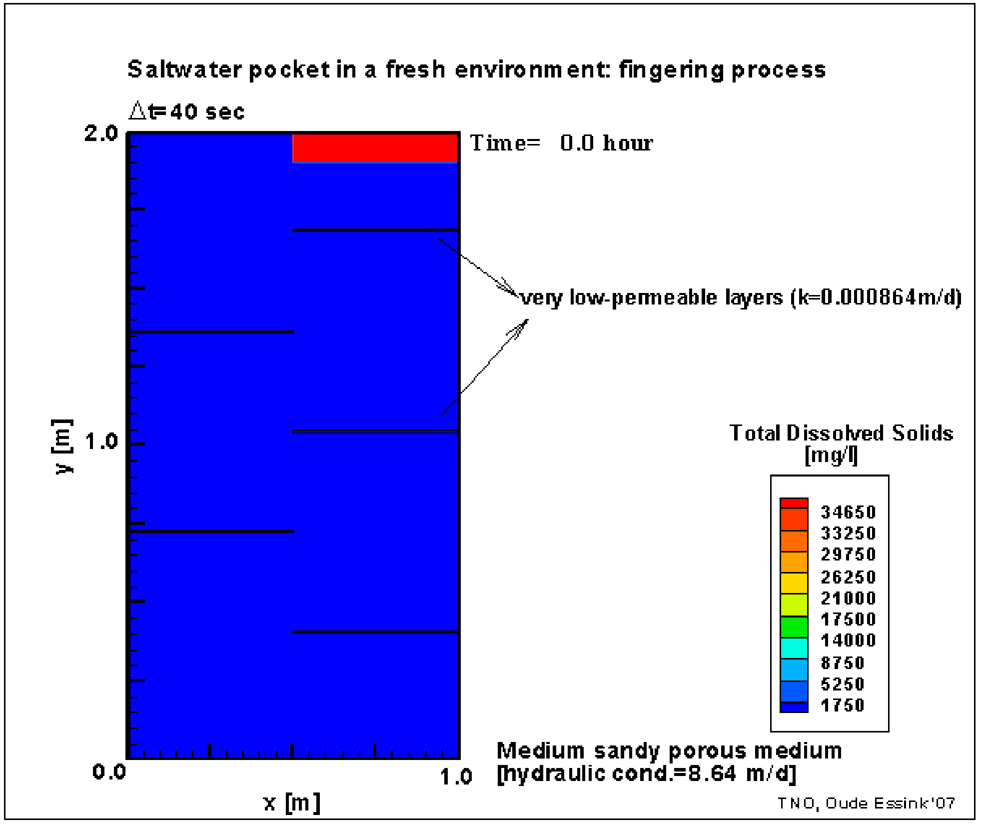
Chui, T.F.M., Terry, J.P., 2015. Groundwater salinisation on atoll islands after storm-surge flooding: modelling the influence of central topographic depressions. Water Environ. J. 29, 430–438. https://doi.org/10.1111/wej.12116

Salinisation processes of fresh groundwater reserves

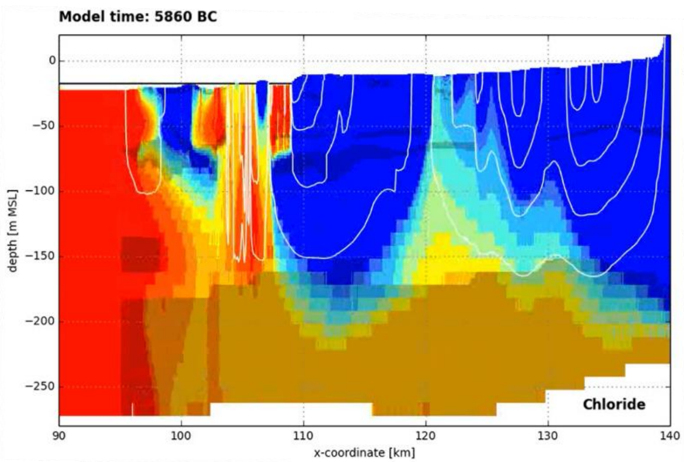
Impression of relevant salinisation processes in coastal aquifers:

- Contamination freshwater lens after sea water flooding
- Saline fingering processes in the subsoil

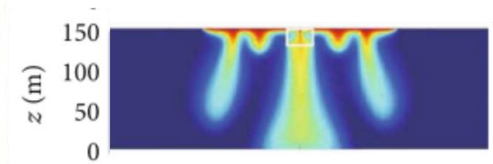




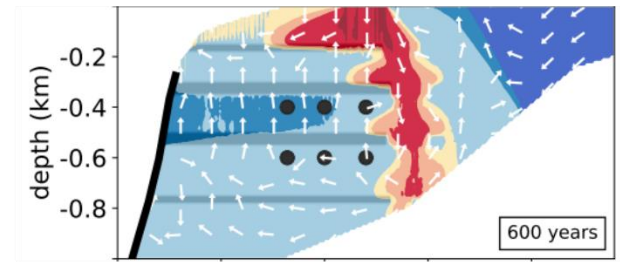
Examples salinity processes in vertical direction



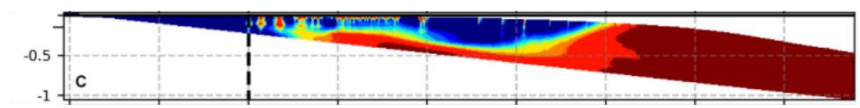
Delsman et al., 2014



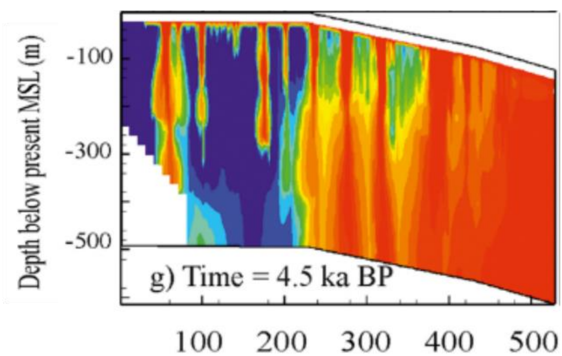
Yan et al., 2019



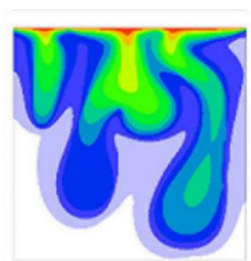
Van Engelen et al., 2018

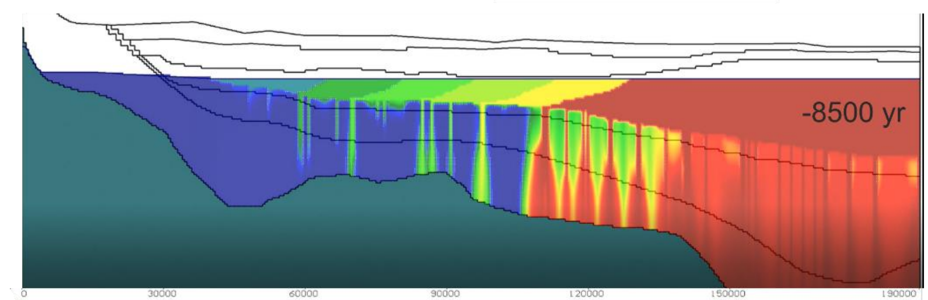


Zamrsky et al., 2020



Pham et al., 2019

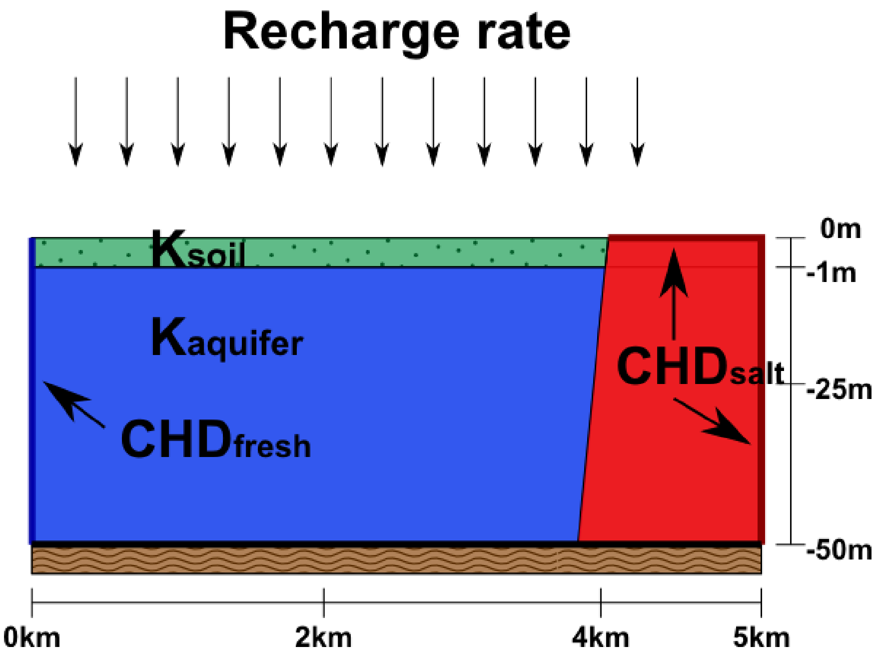

Xie et al., 2011

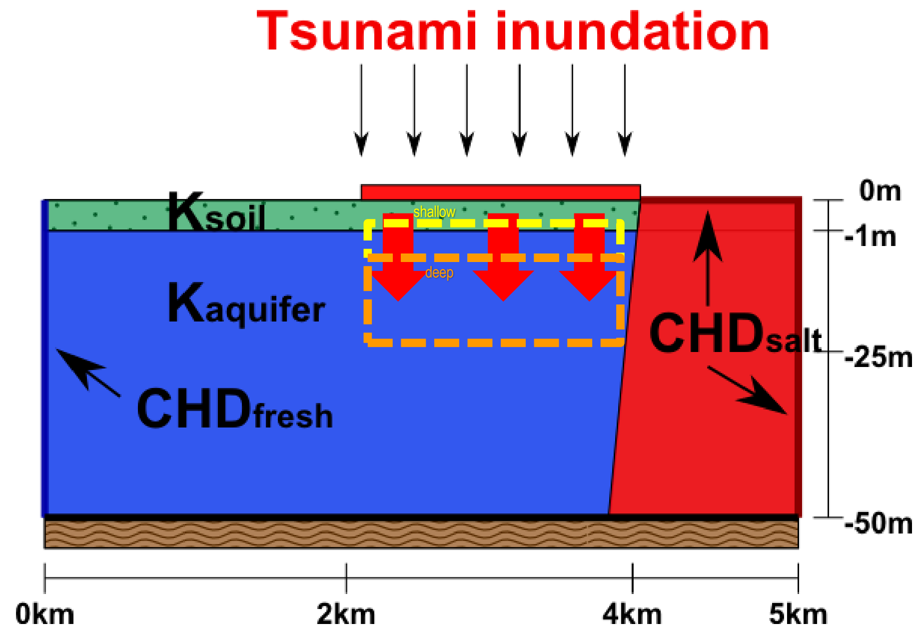


Larsen et al., 2017

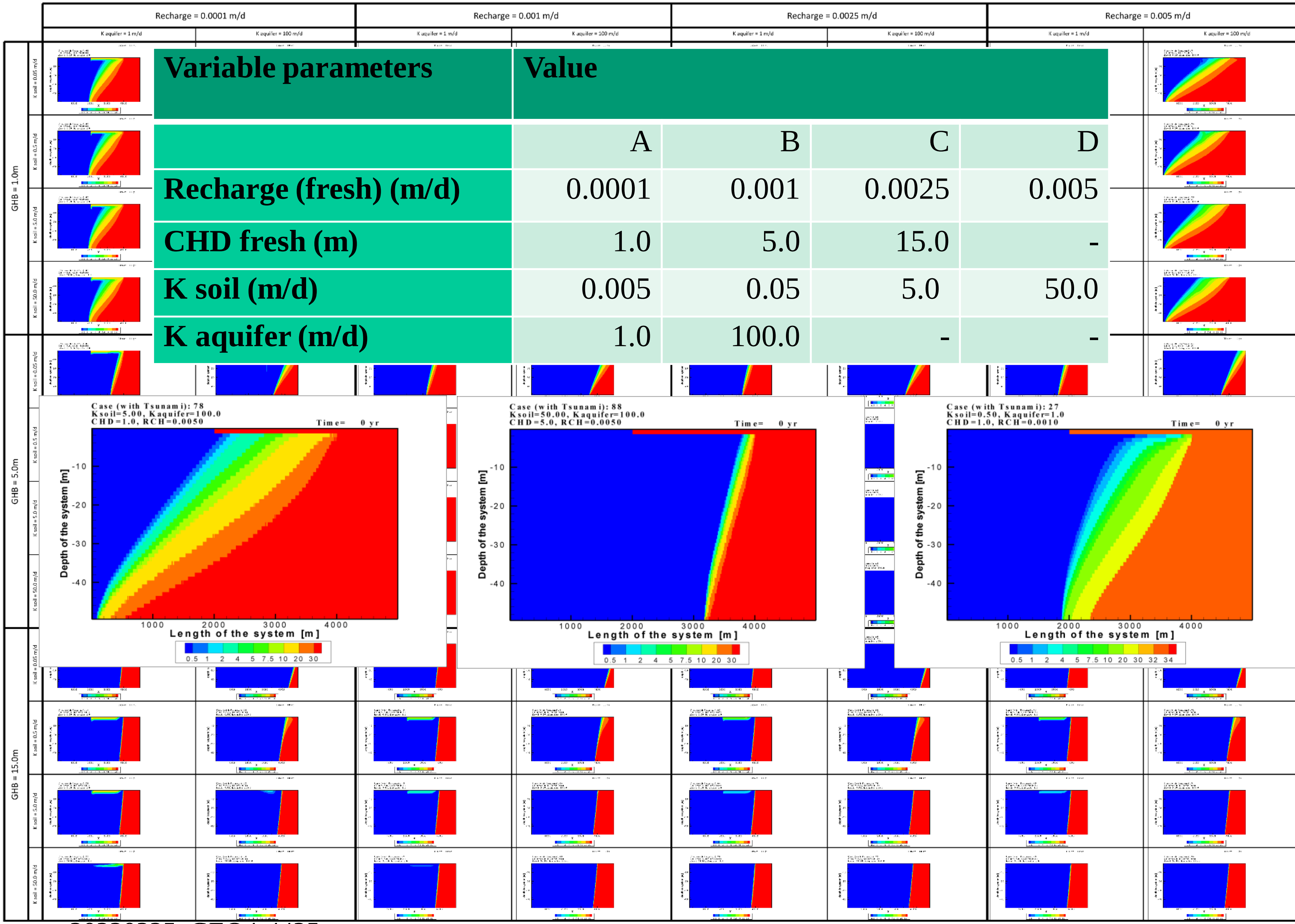
Concept 2D modelling variable-density groundwater flow and coupled salt transport

Normal system



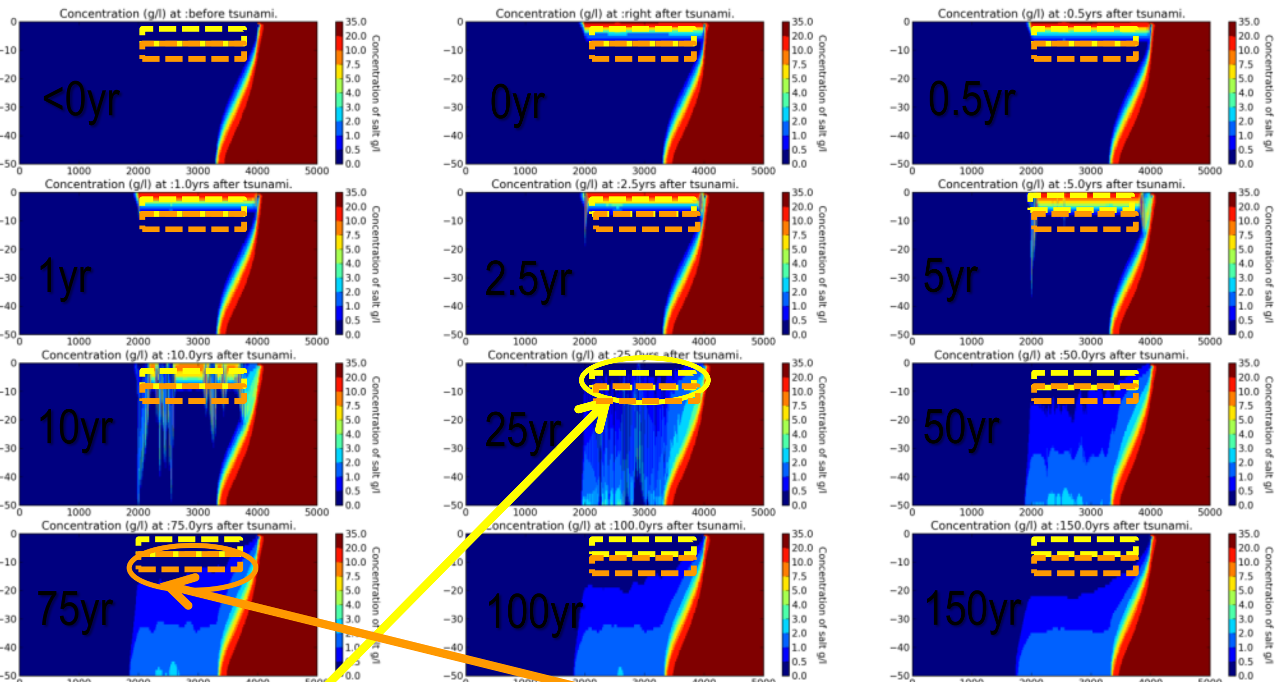


- Focus on coastal *deep* and *shallow* fresh groundwater resources
- How long does it takes before the groundwater system is fresh again, available for groundwater extractions?

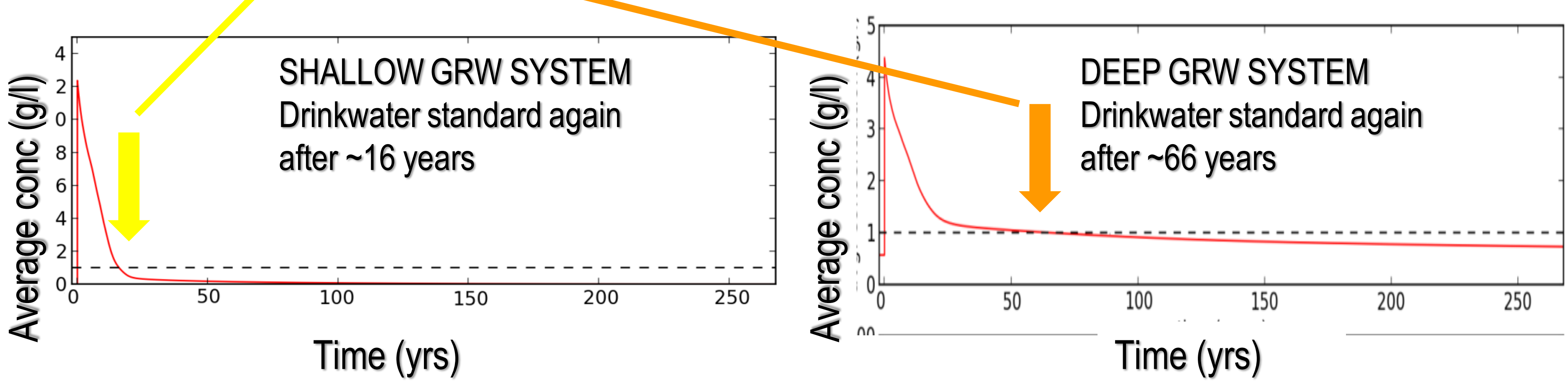


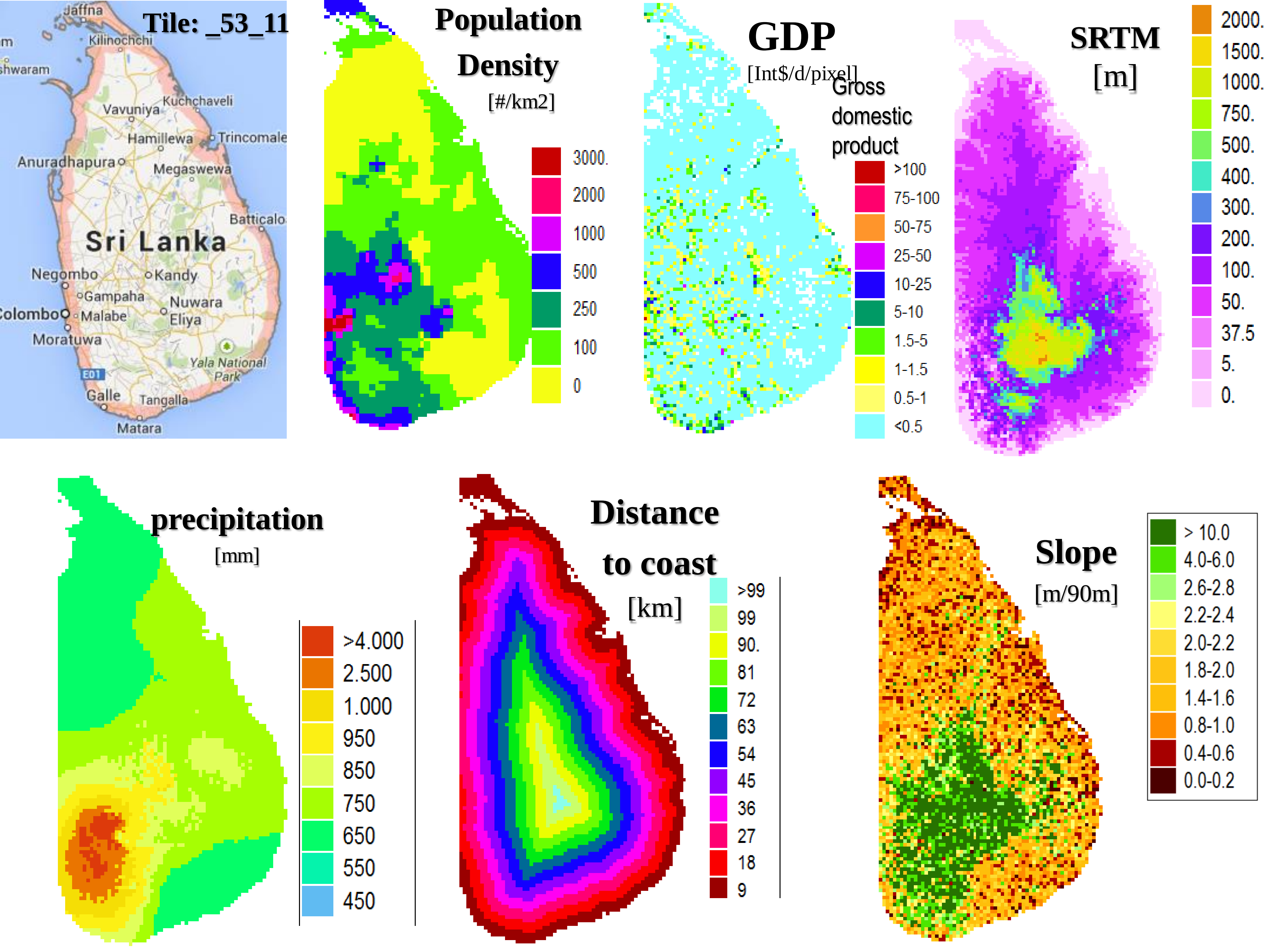
Variable parameters	Value			
	A	B	C	D
Recharge (fresh) (m/d)	0.0001	0.001	0.0025	0.005
CHD fresh (m)	1.0	5.0	15.0	-
K soil (m/d)	0.005	0.05	5.0	50.0
K aquifer (m/d)	1.0	100.0	-	-

Results of one case

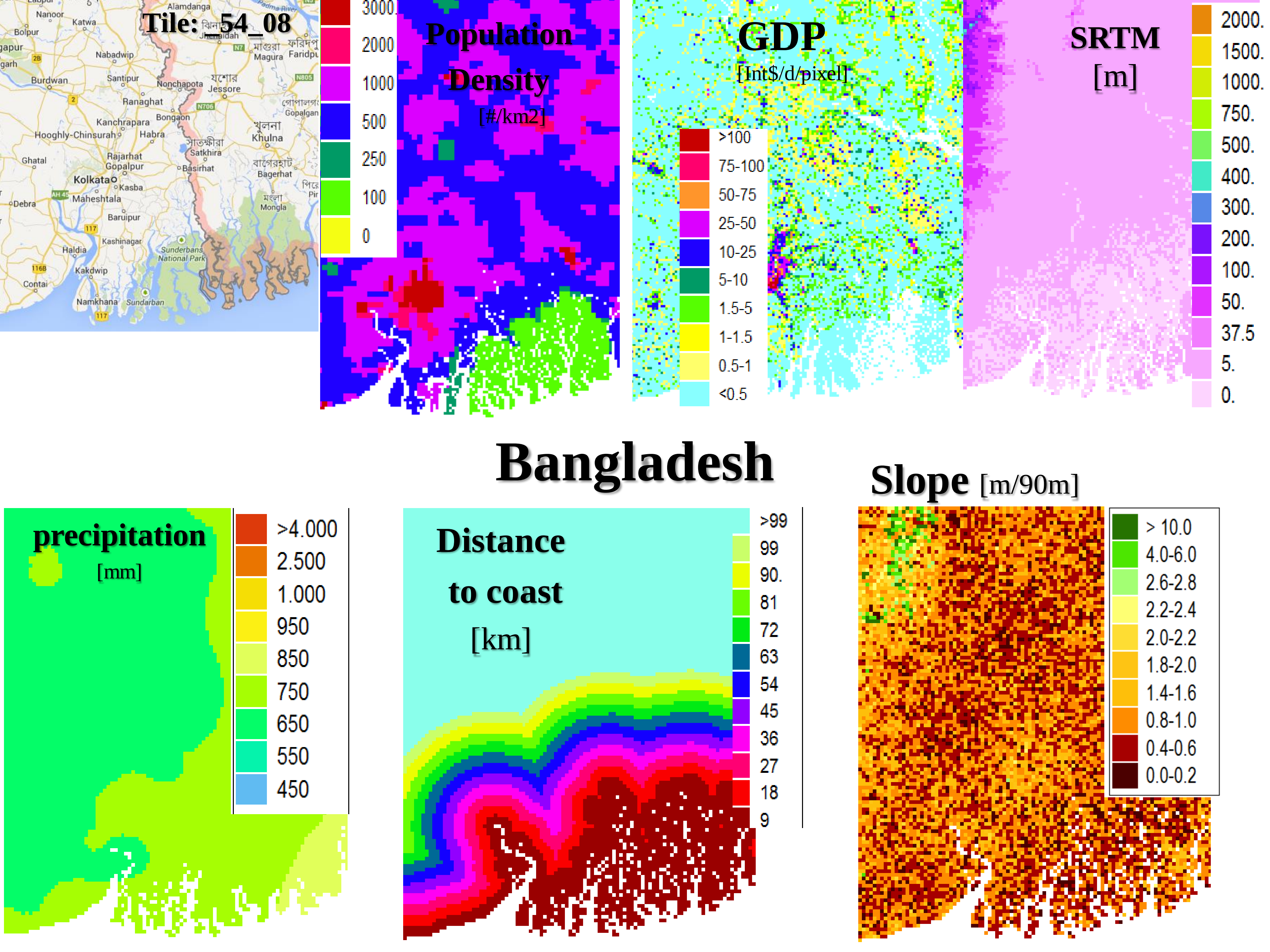


Salt water fingers intrude the groundwater system the coming tens of years





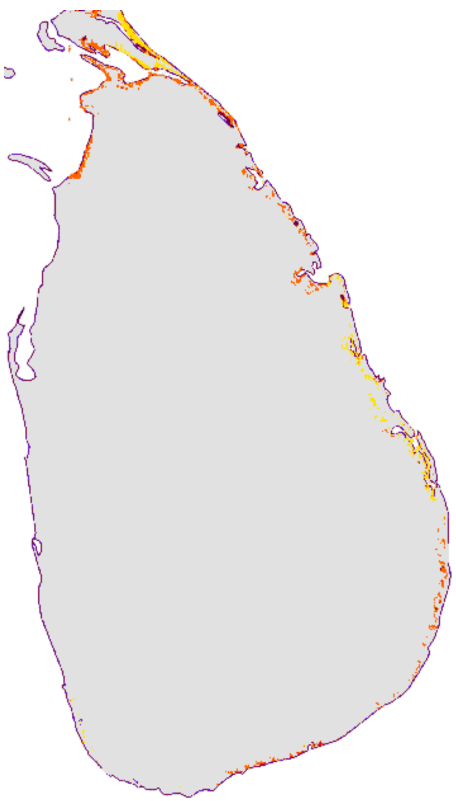
Tile: _53_11
Jaffna
Kilinochchi
Vavuniya
Kuchchaveli
Hamillewa
Trincomalee
Anuradhapura
Megaswewa
Batticaloa
Sri Lanka
Negombo
Kandy
Gampaha
Nuwara Eliya
Colombo
Malabe
Moratuwa
Yala National Park
E01
Galle
Tangalla
Matara
Population Density
[#/km2]
3000.
2000
1000
500
250
100
0
GDP
[Int$/d/pixel]
Gross domestic product
>100
75-100
50-75
25-50
10-25
5-10
1.5-5
1-1.5
0.5-1
<0.5
SRTM
[m]
2000.
1500.
1000.
750.
500.
400.
300.
200.
100.
50.
37.5
5.
0.
precipitation
[mm]
>4.000
2.500
1.000
950
850
750
650
550
450
Distance to coast
[km]
>99
99
90.
81
72
63
54
45
36
27
18
9
Slope
[m/90m]
> 10.0
4.0-6.0
2.6-2.8
2.2-2.4
2.0-2.2
1.8-2.0
1.4-1.6
0.8-1.0
0.4-0.6
0.0-0.2


Tile: 54_08
Kolkata
Khulna
Jessore
Satkhira
Bagerhat
Mongla
Sundarbans National Park
Population Density
[#/km2]
3000
2000
1000
500
250
100
0
GDP
[Int$/d/pixel]
>100
75-100
50-75
25-50
10-25
5-10
1.5-5
1-1.5
0.5-1
<0.5
SRTM
[m]
2000.
1500.
1000.
750.
500.
400.
300.
200.
100.
50.
37.5
5.
0.
Bangladesh
Slope [m/90m]
> 10.0
4.0-6.0
2.6-2.8
2.2-2.4
2.0-2.2
1.8-2.0
1.4-1.6
0.8-1.0
0.4-0.6
0.0-0.2
precipitation
[mm]
>4.000
2.500
1.000
950
850
750
650
550
450
Distance
to coast
[km]
>99
99
90.
81
72
63
54
45
36
27
18
9

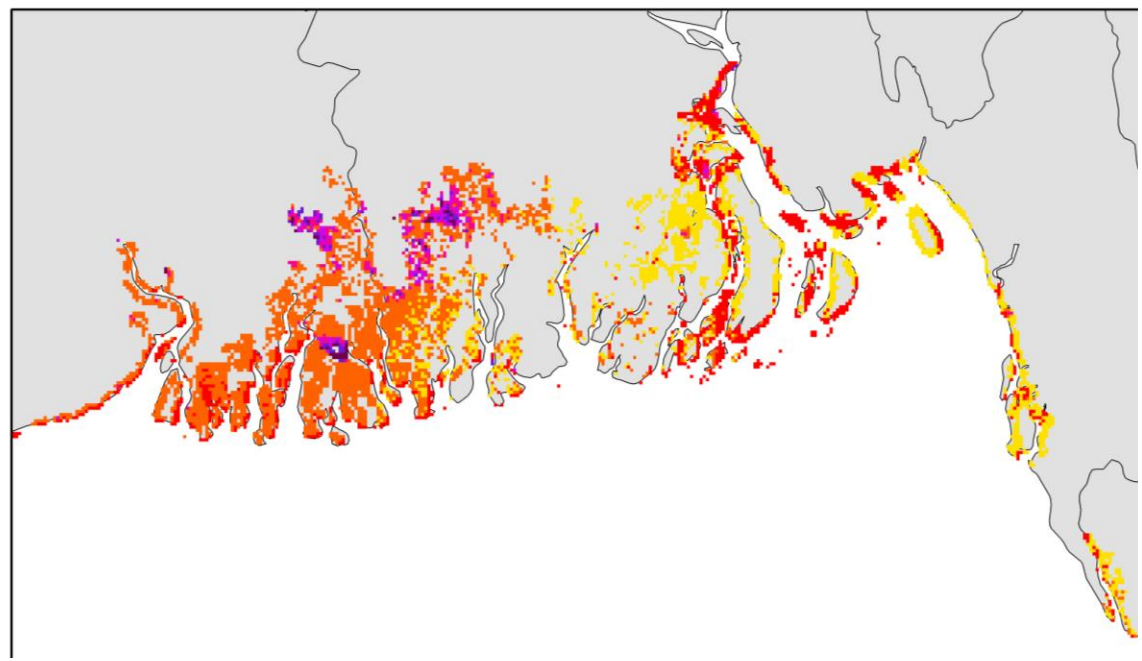
Mapping the results

Legend

- system stays saline >50yrs
- < - 5
- 5 - 10
- 10 - 12,5
- 12,5 - 15
- 15 - 17,5
- 17,5 - 20
- >20



Time (yrs) before the shallow coastal groundwater system is fresh enough again for drinking water extraction

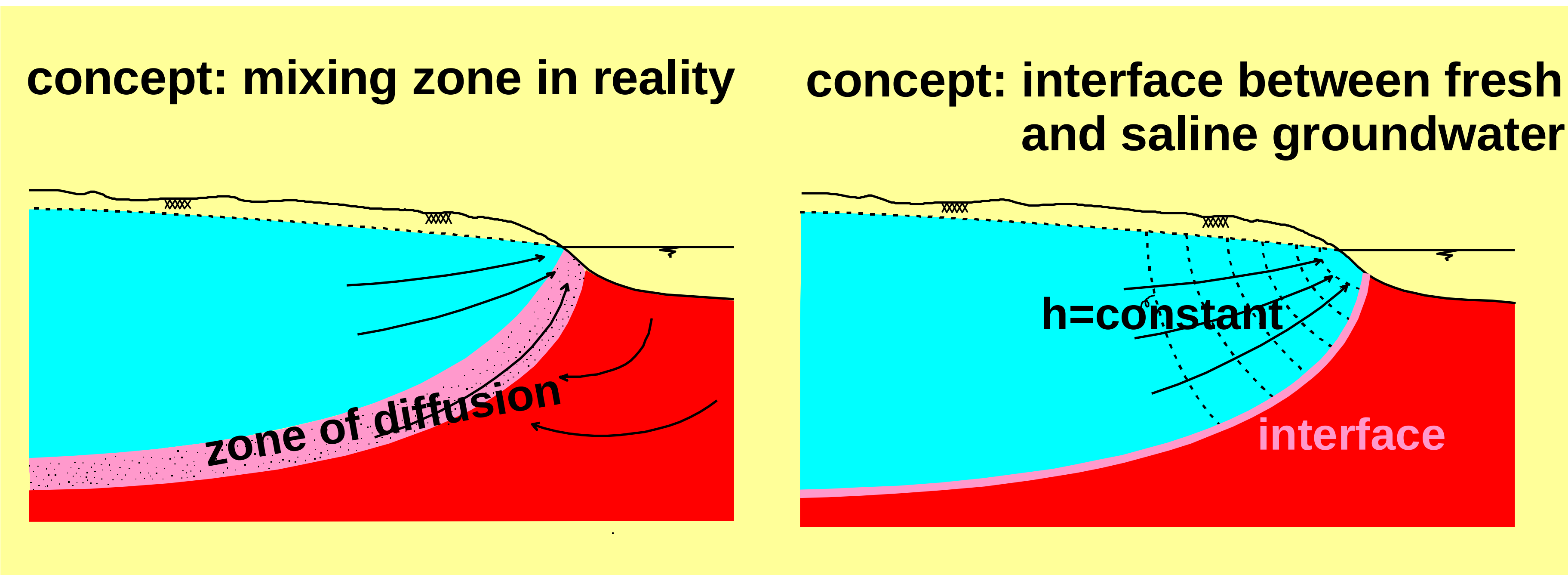


- Shallow groundwater system
- GDP<1 US$/day/capita

Sharp interface between fresh and saline groundwater

Badon Ghyben-Herzberg principle

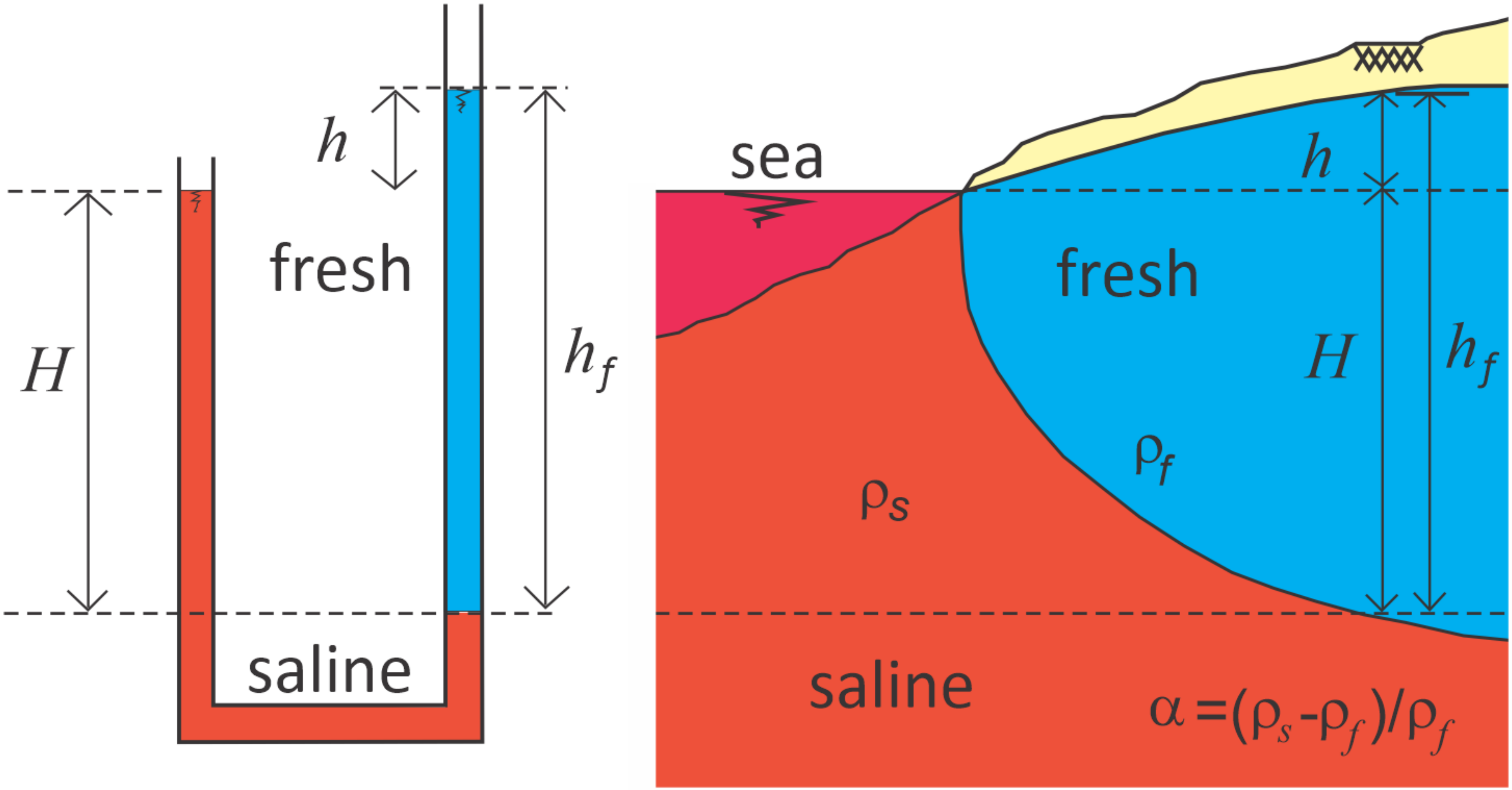
Difference between reality and Badon Ghyben-Herzberg approximation

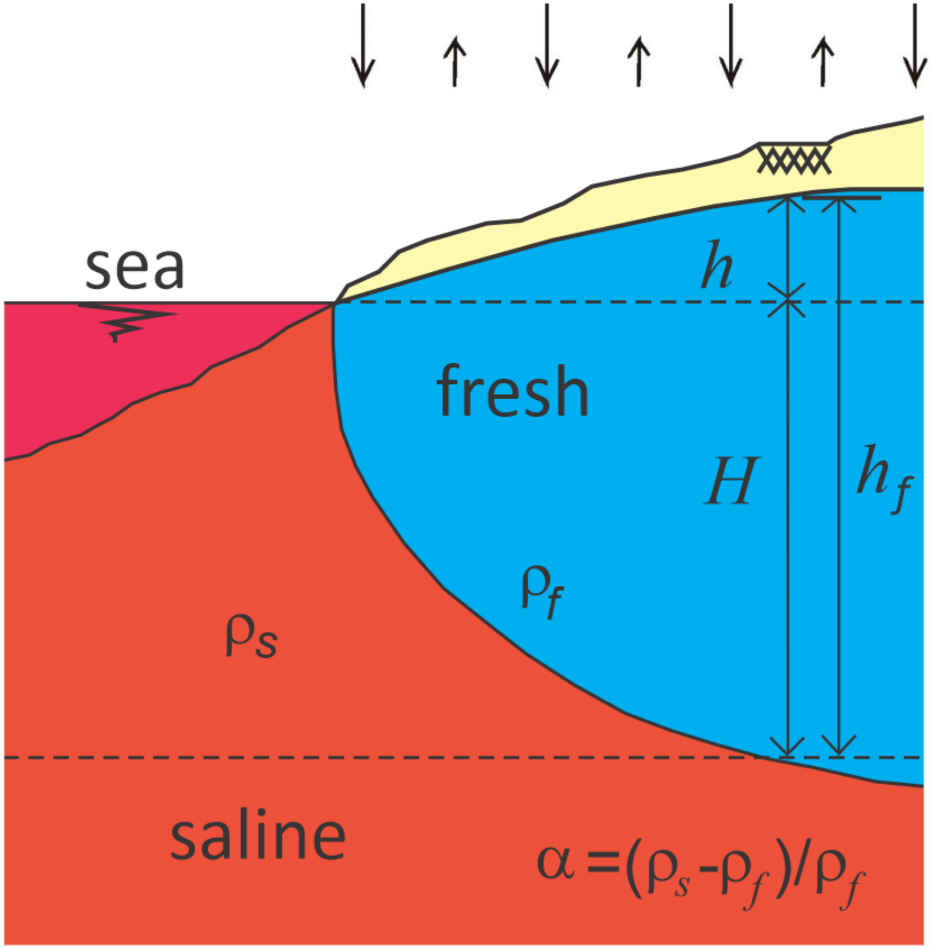


Badon Ghijben-Herzberg principle

The principle suggests an interface between fresh and saline groundwater

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



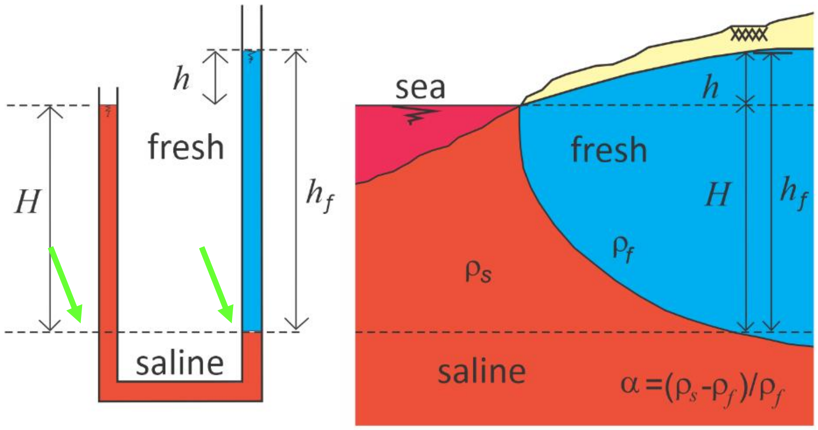

sea
h
fresh
H
h_f
ρ_f
ρ_s
saline
$\alpha = (\rho_s - \rho_f)/\rho_f$

pressure saline groundwater=pressure fresh groundwater

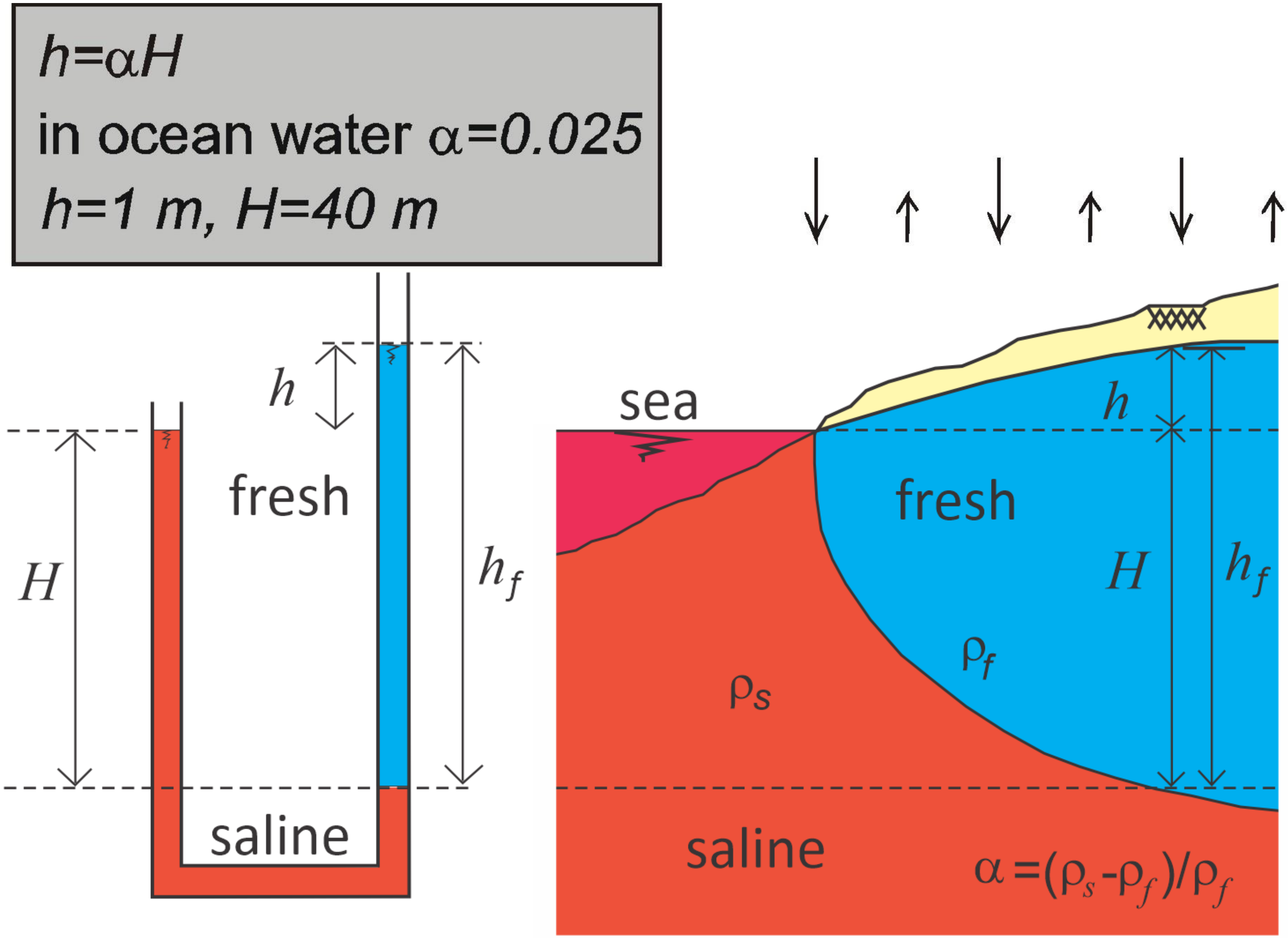
$$\rho_s H g = \rho_f (H + h) g$$

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

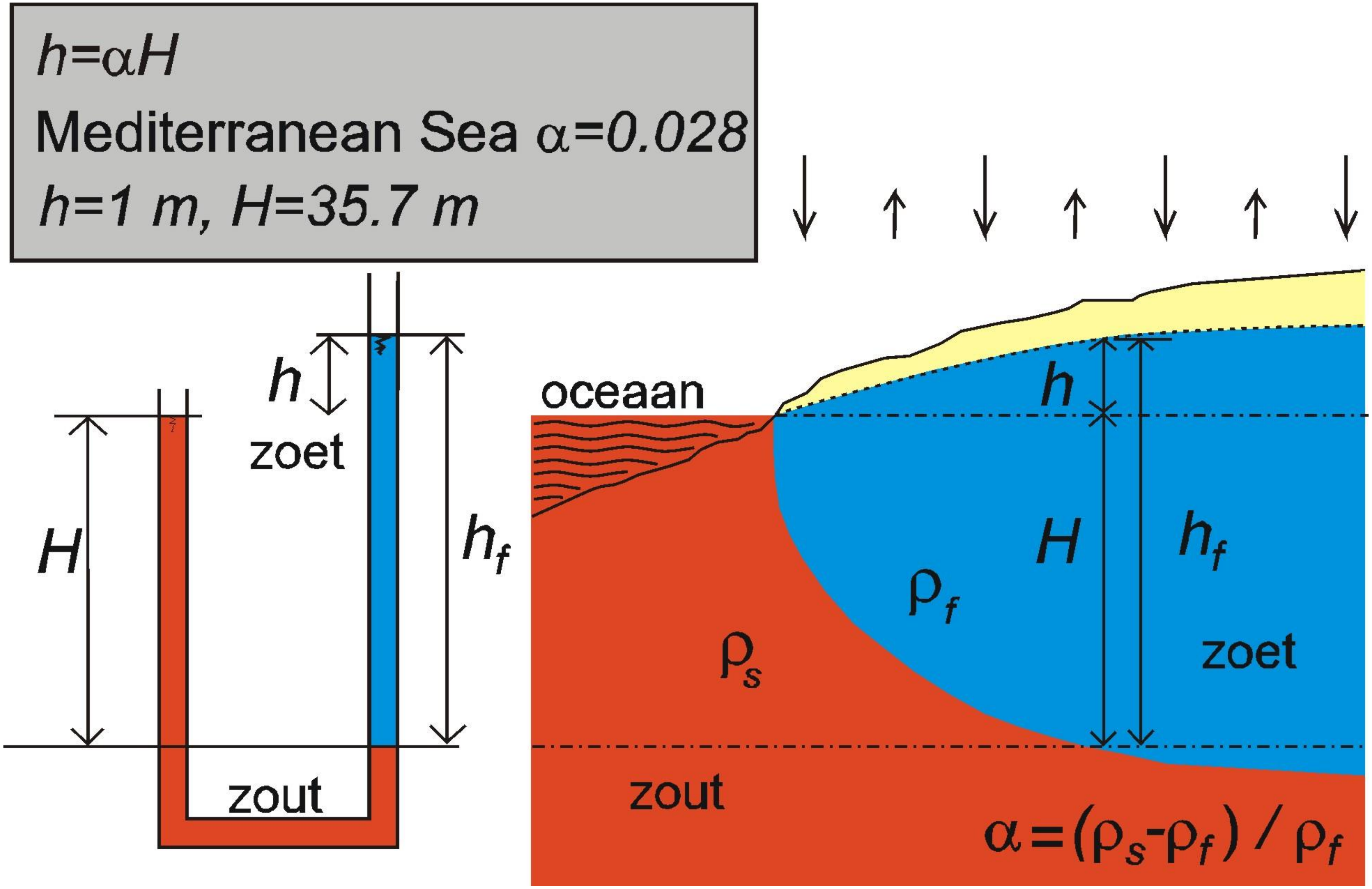
$$h = \alpha H$$



$$h = \alpha H \qquad h = \frac{\rho_s - \rho_f}{\rho_f} H \qquad h = \frac{1025 - 1000}{1000} H$$



$$h = \alpha H \qquad h = \frac{\rho_s - \rho_f}{\rho_f} H \qquad h = \frac{1028 - 1000}{1000} H$$



Badon Ghyben-Herzberg principle

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

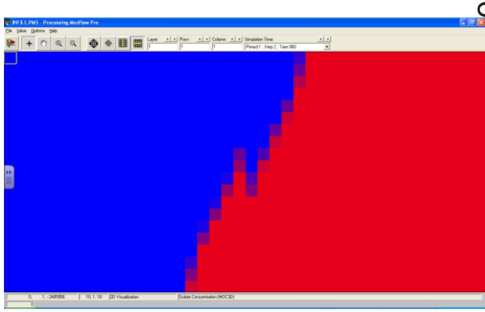
- interface is a simple approximation
- dispersion zone <10m
- relative simple geometries

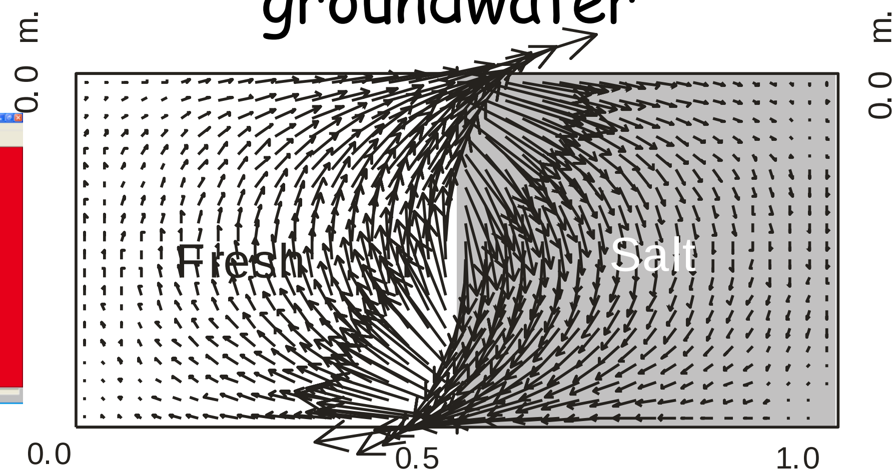
Badon Ghyben-Herzberg principle

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

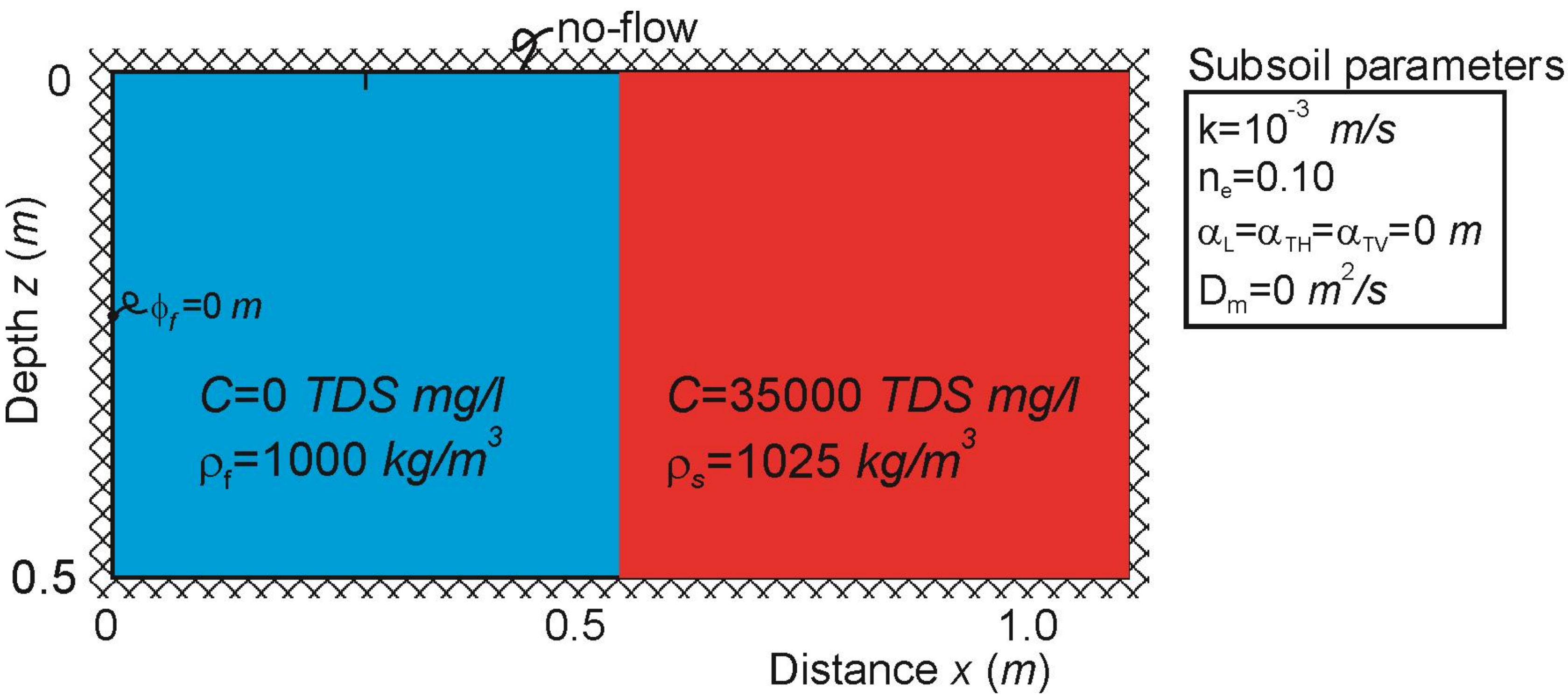
Case 1: Vertical interface between fresh and saline groundwater



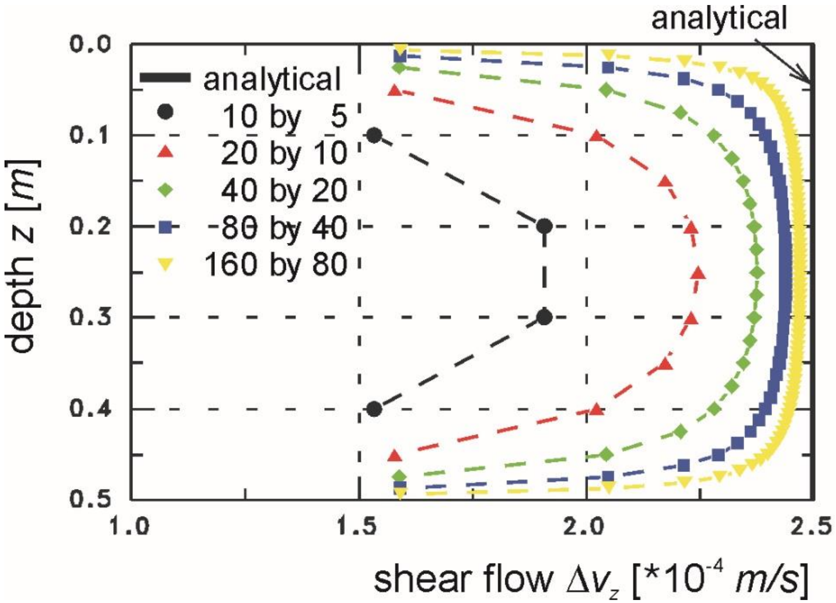


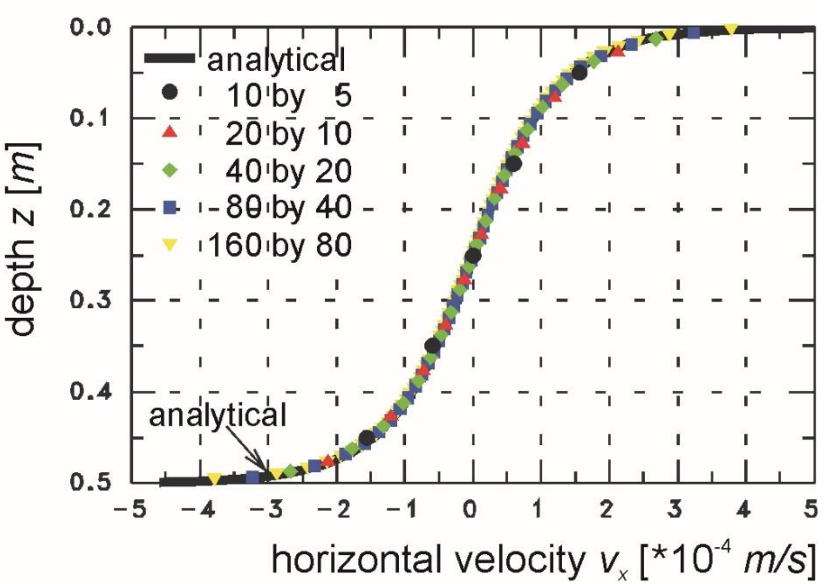
Parameters			
Layers	20	K_{hor}	$1\ 10^{-3}$ m/s
Rows	1	T	$2.5\ 10^{-5}$ m/s
Columns	40	Anisotropy K_{hor}/K_{ver}	1
Δx	0.025 m	n_e	0.1
Δy	1 m	α_L	0 m
Δz	0.025 m	α_T	0 m
Stress periods	15		
Initial concentration	0 and 35000 mg/l		
bouyancy	0.025		

Vertical interface



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

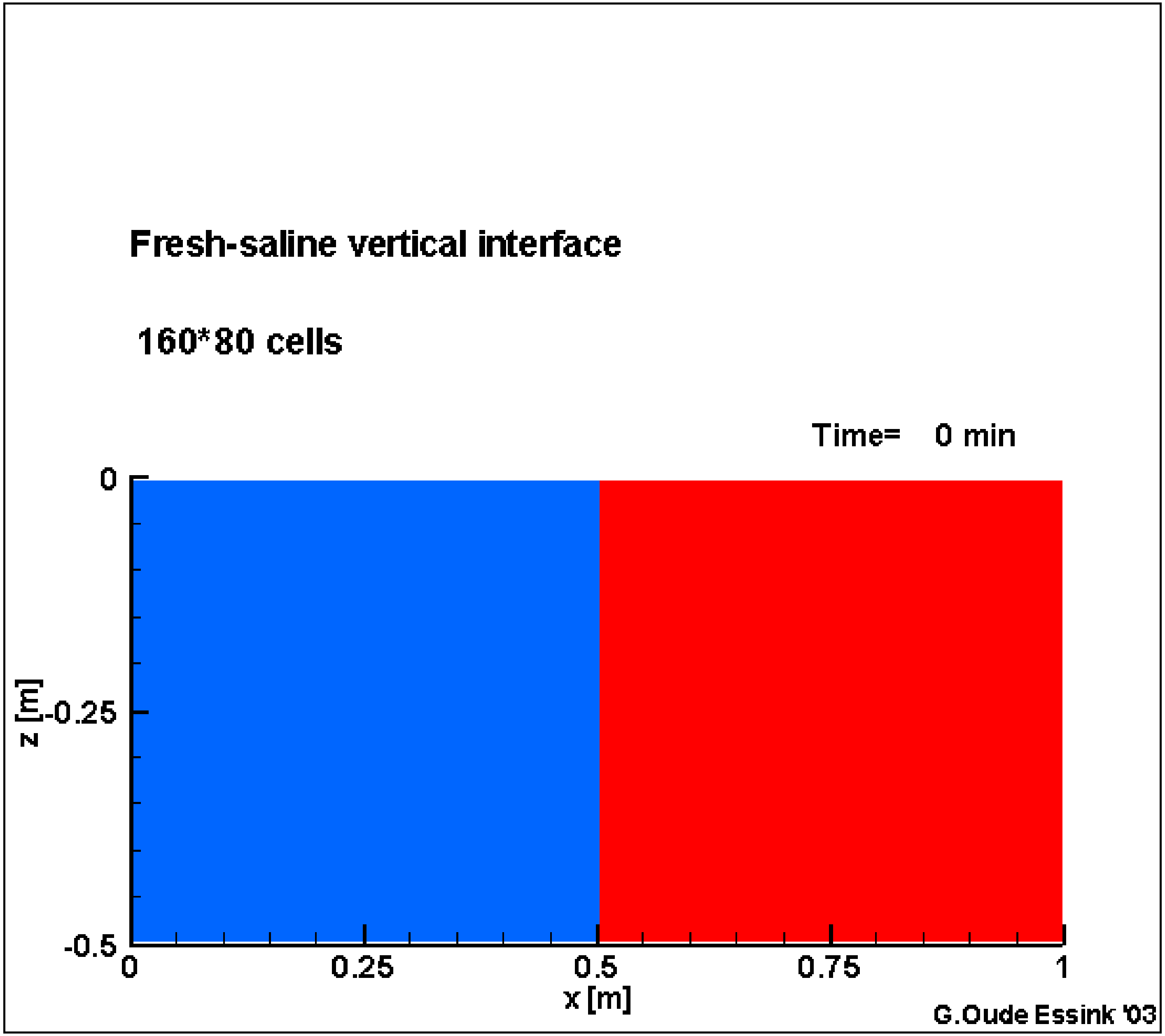




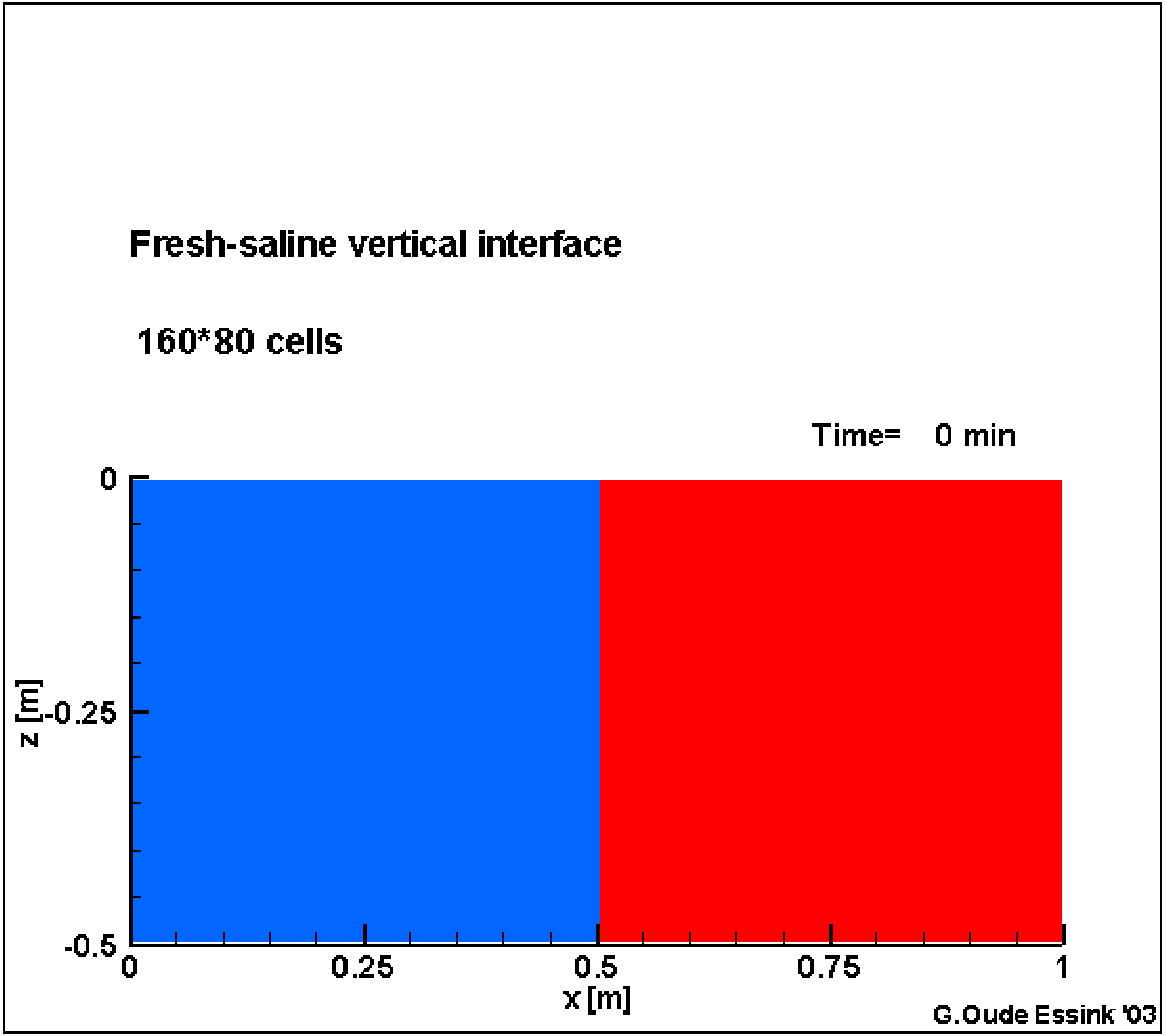
$$\Delta v_z = \frac{k}{n_e}\left(\frac{\rho_s - \rho_f}{\rho_f}\right)$$

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

Vertical interface



Vertical interface



The effect of numerical solvers on the salt transport

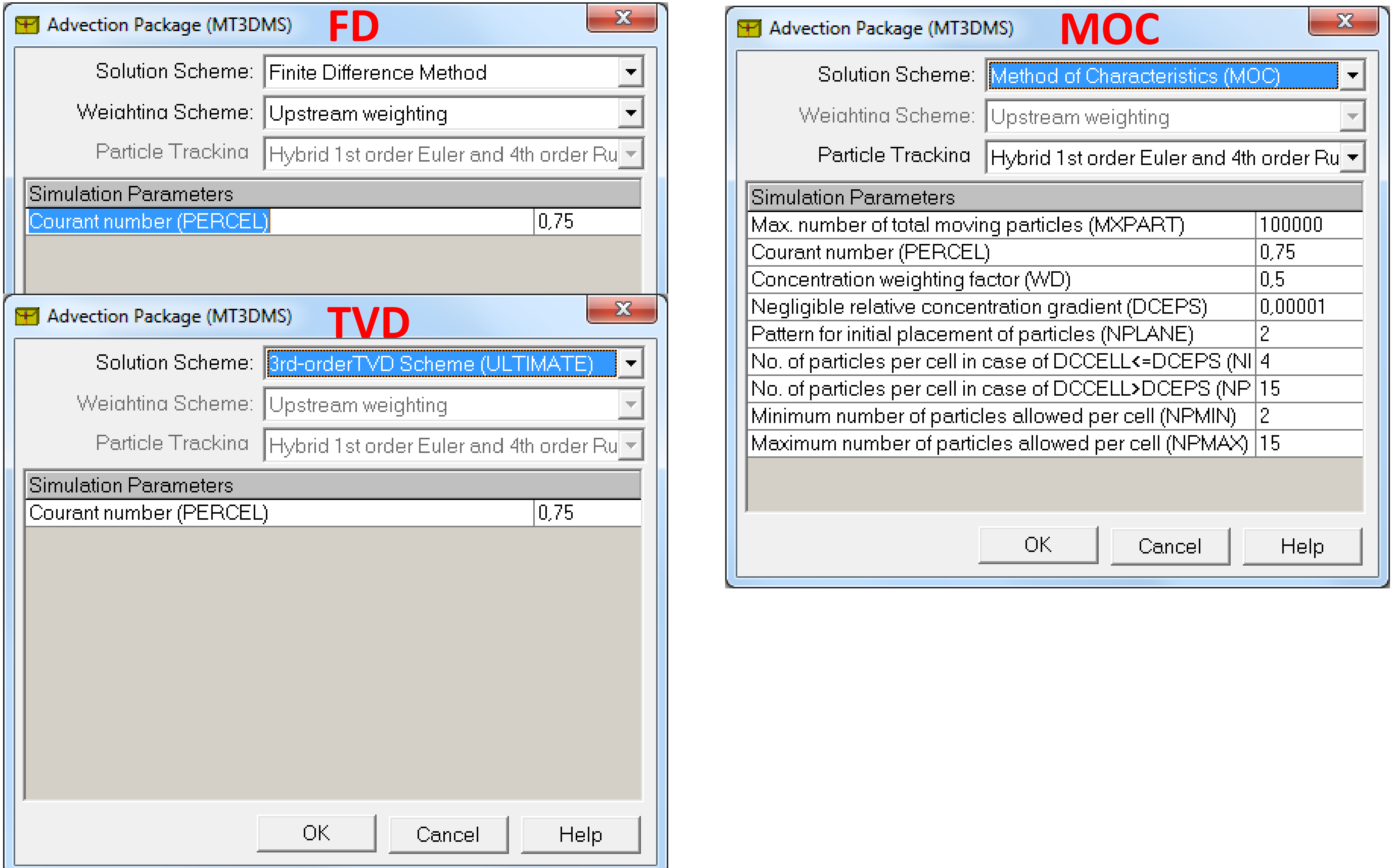
Examples

Check for the meaning of parameters:

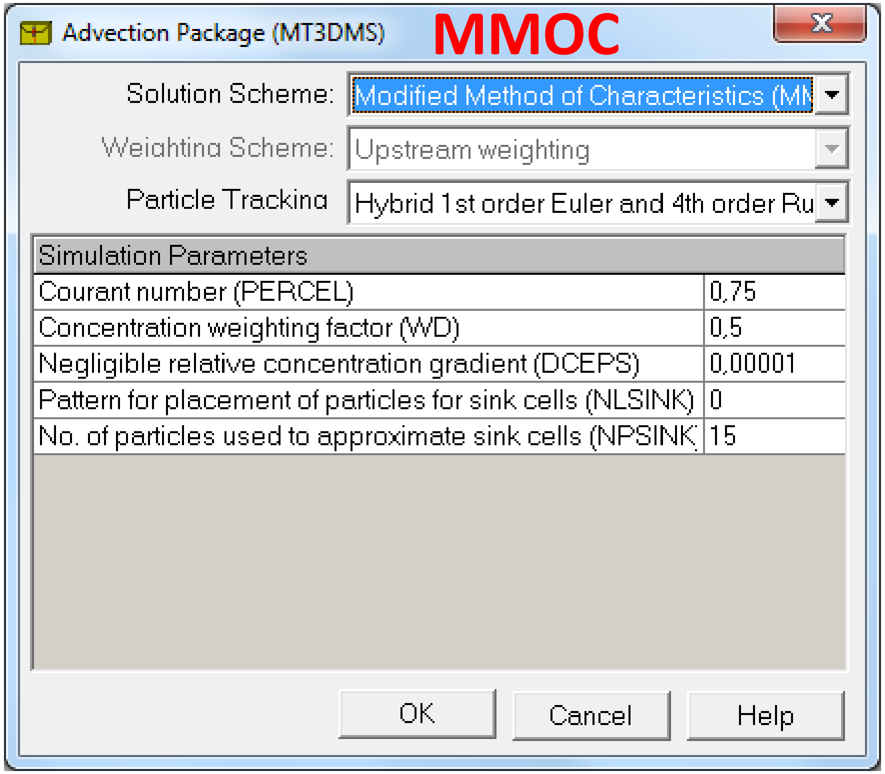
Zheng, C., Wang, P.P., 1999. MT3DMS: A modular three-dimensional multispeces transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems. Technical report, Waterways Experiment Station, US Army Corps of Engineers, Strategic Environmental Research and Development Program - Contract Report SERDP-99-1.

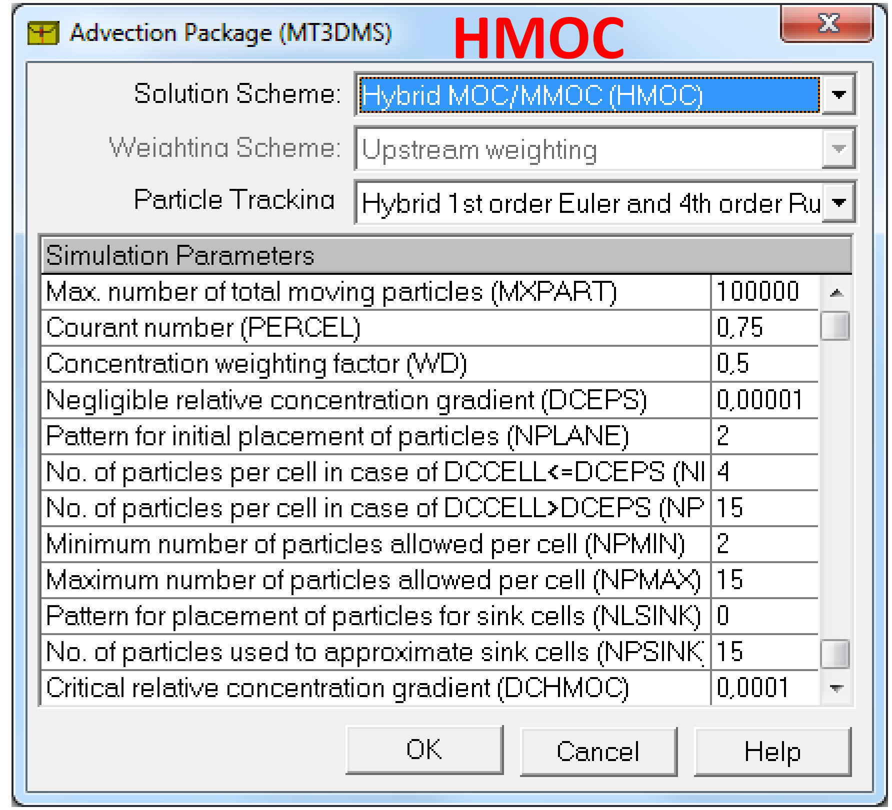
https://hydro.geo.ua.edu/mt3d/mt3dmanual.pdf

Default parameters solvers



Default parameters solvers

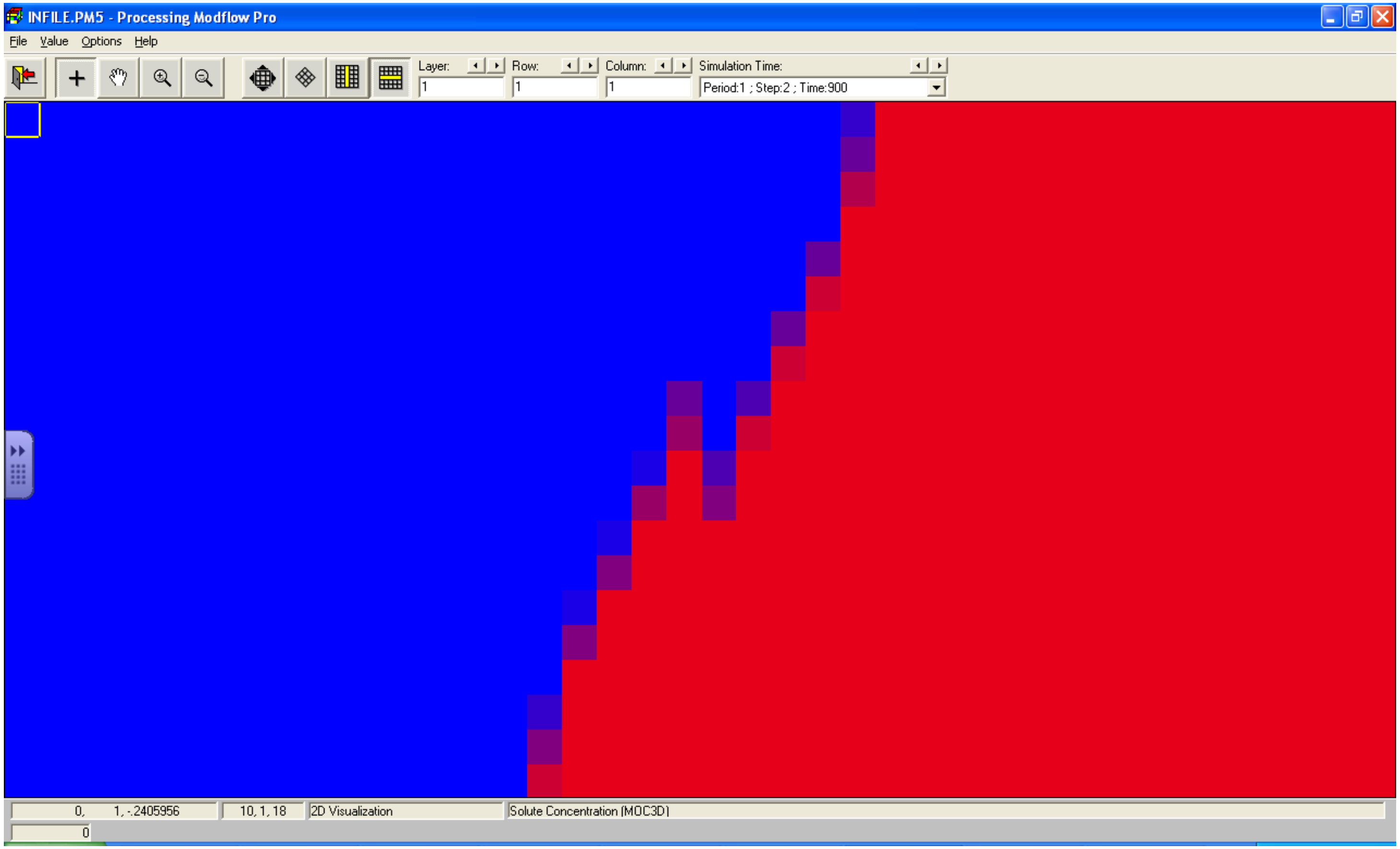




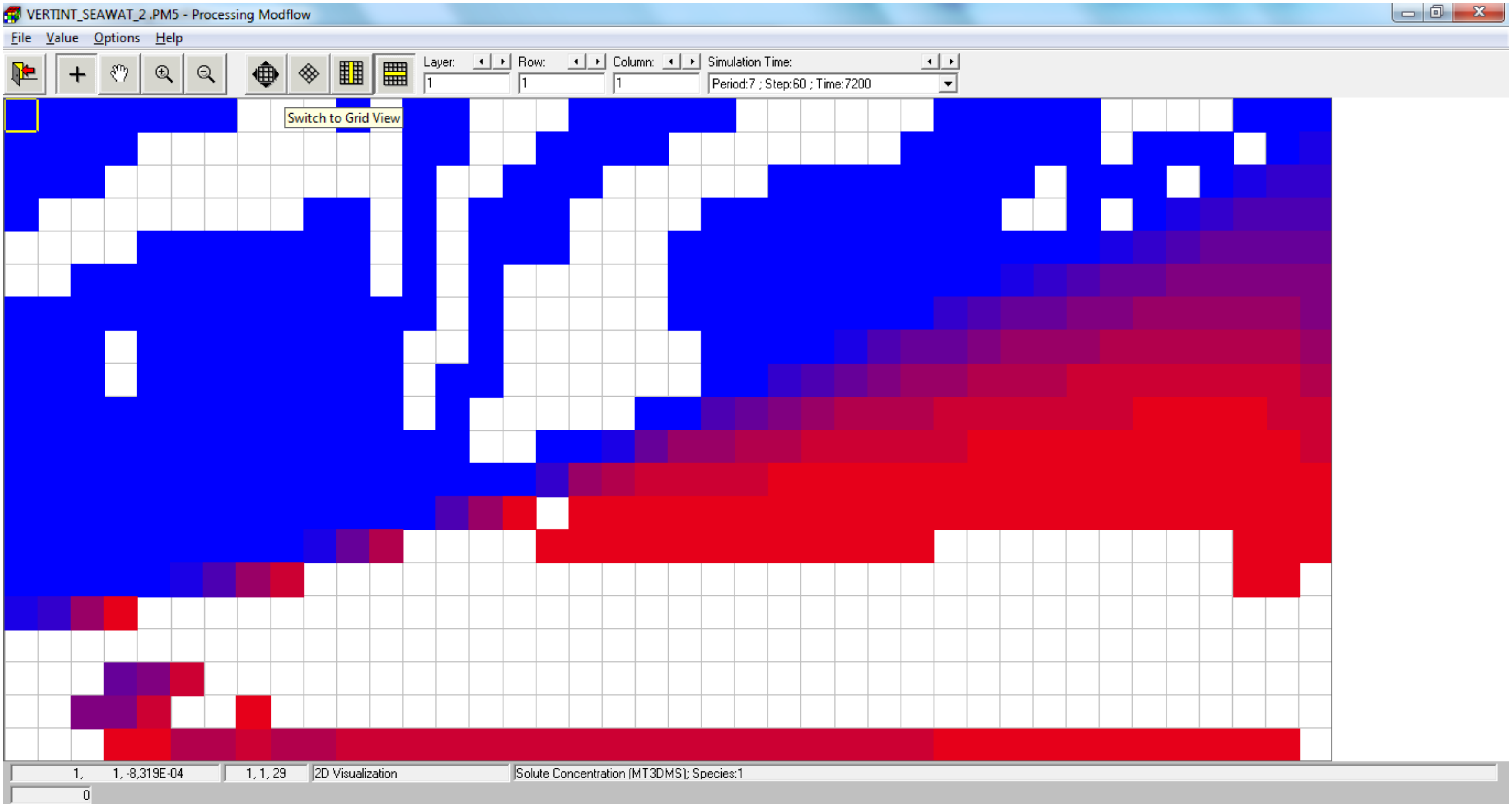
More information:

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

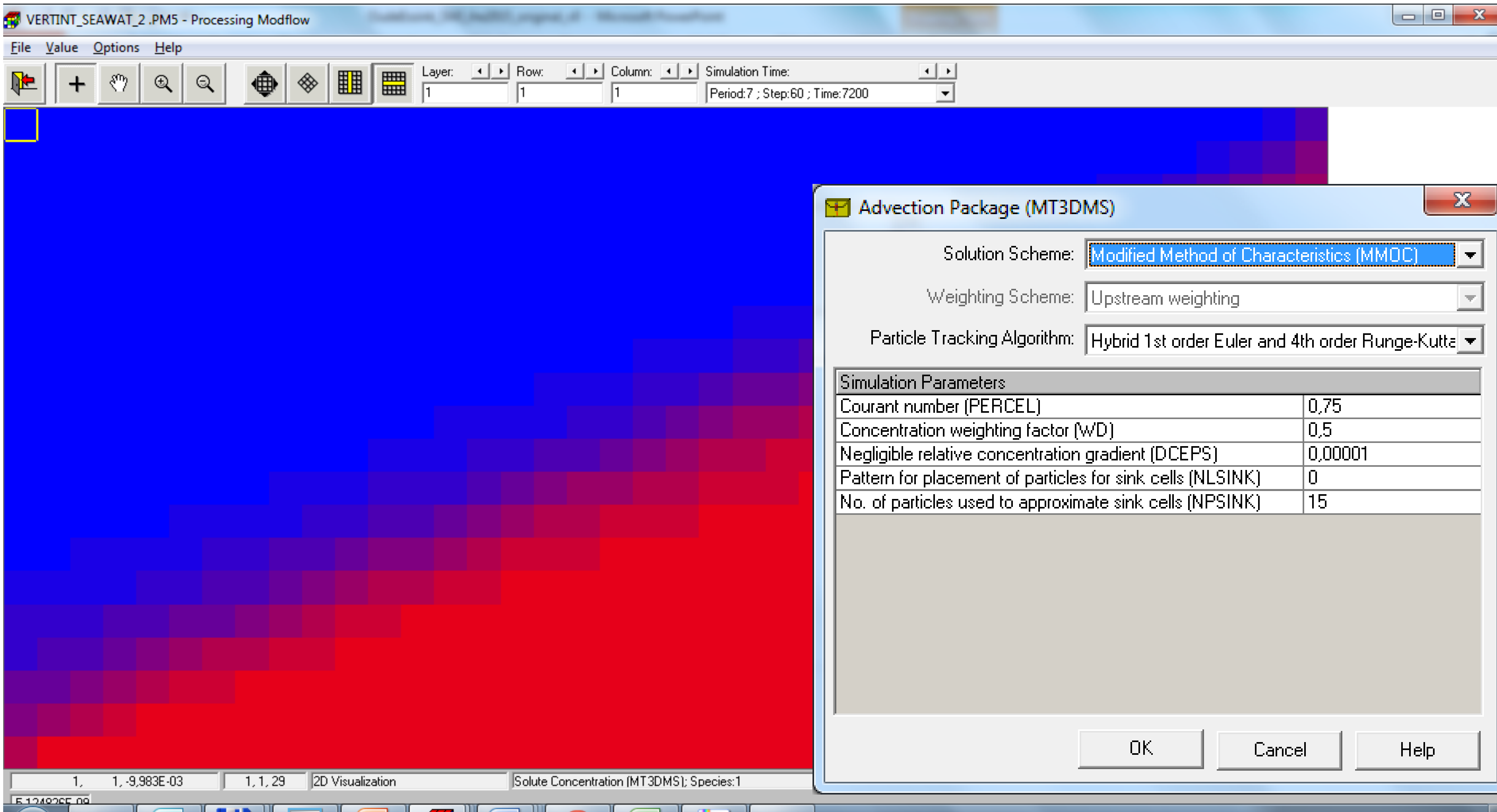
1 particle per cell, MOCDENS3D



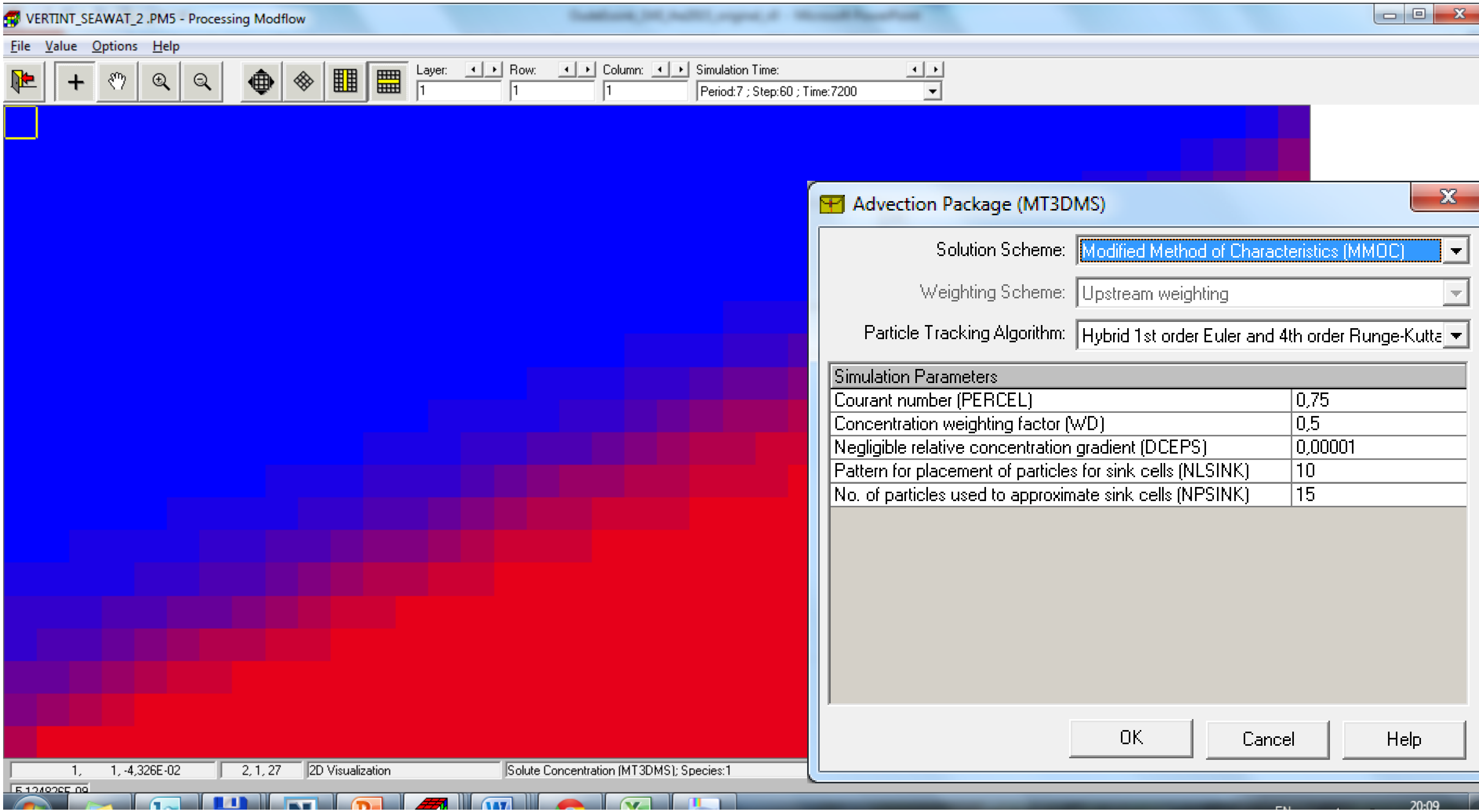
ULTIMATE


VERTINT_SEAWAT_2.PM5 - Processing Modflow
File Value Options Help
Layer: 1
Row: 1
Column: 1
Simulation Time:
Period:7 ; Step:60 ; Time:7200
Switch to Grid View
1, 1, -8,319E-04
1, 1, 29
2D Visualization
Solute Concentration (MT3DMS); Species:1
0

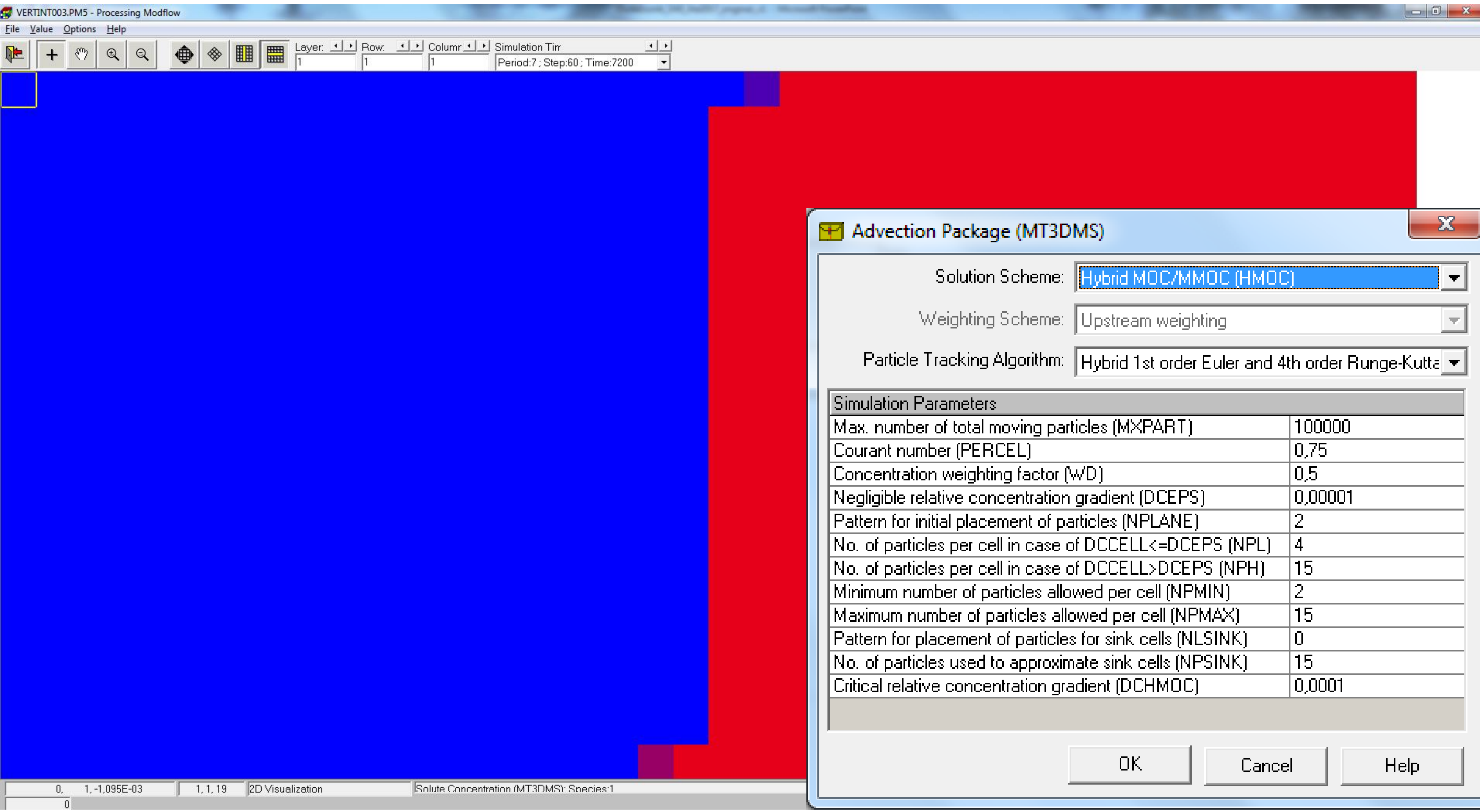
MMOC, NPLANE=0



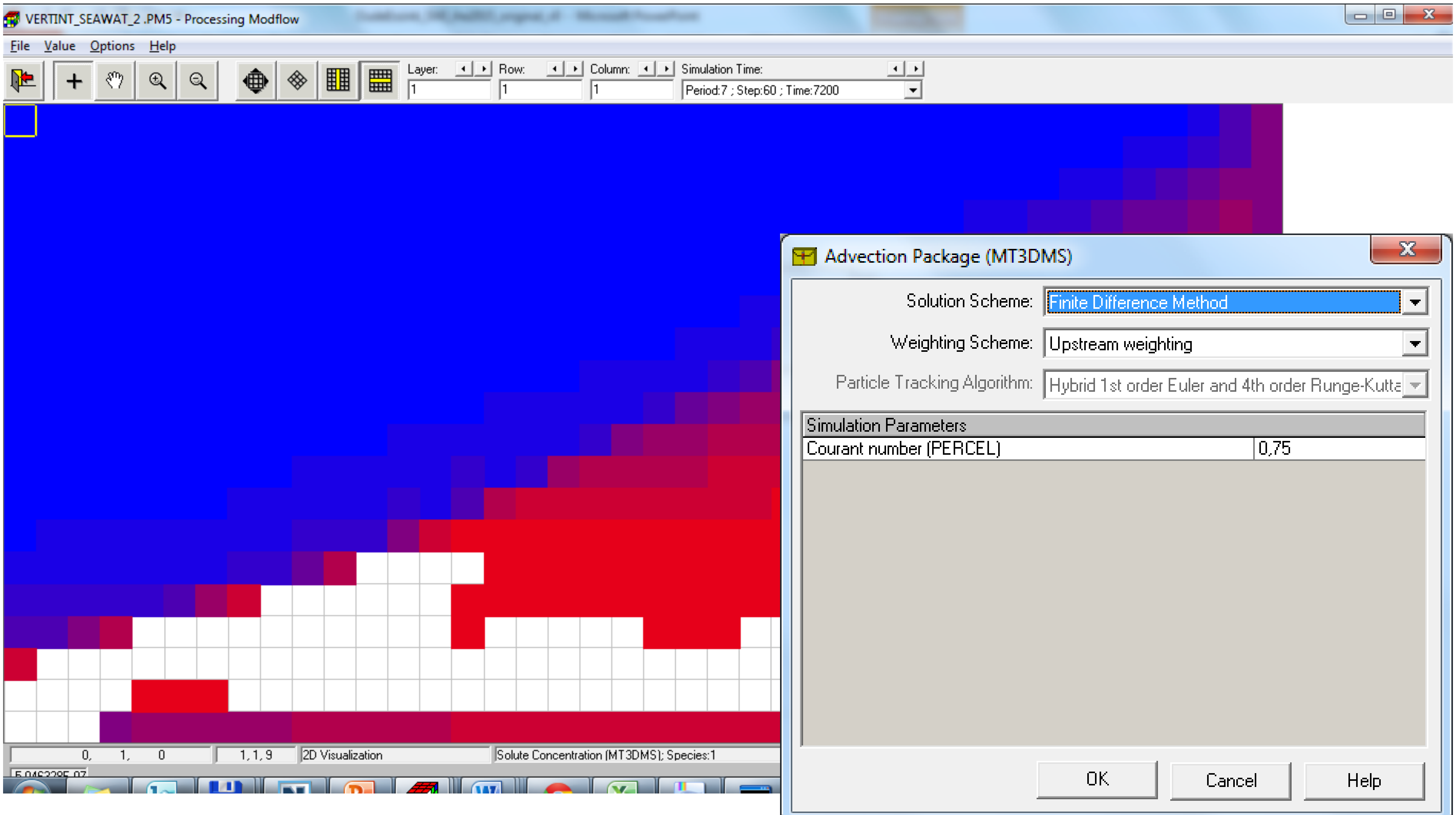
MMOC, NPLANE=10



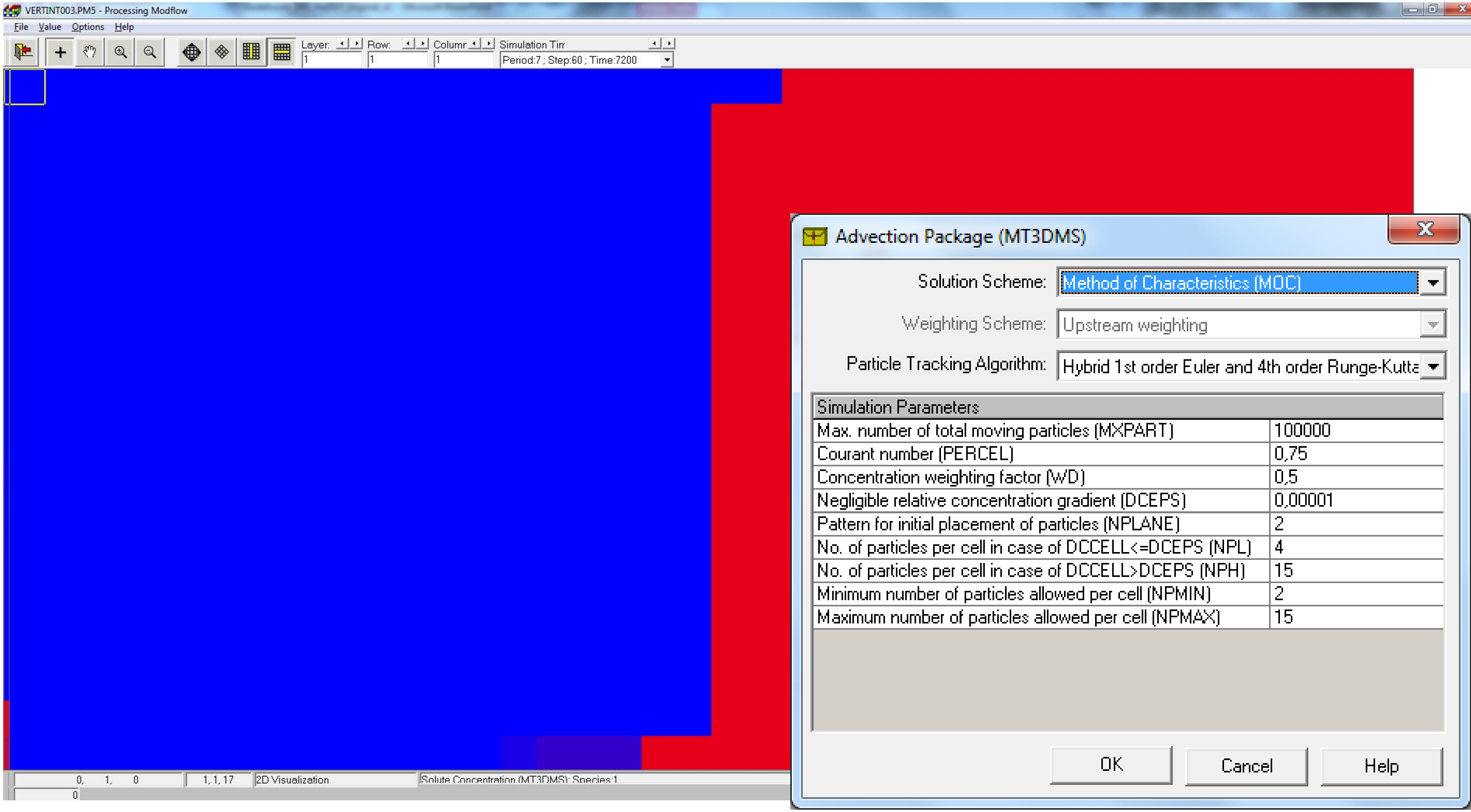
HMOC


VERTINT003.PM5 - Processing Modflow
File Value Options Help
Layer: Row: Column Simulation Tim
Period:7 ; Step:60 ; Time:7200
2D Visualization
Solute Concentration (MT3DMS): Species:1
Advection Package (MT3DMS)
Solution Scheme: Hybrid MOC/MMOC (HMOC)
Weighting Scheme: Upstream weighting
Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta
Simulation Parameters
Max. number of total moving particles (MXPART) 100000
Courant number (PERCEL) 0,75
Concentration weighting factor (WD) 0,5
Negligible relative concentration gradient (DCEPS) 0,00001
Pattern for initial placement of particles (NPLANE) 2
No. of particles per cell in case of DCCELL<=DCEPS (NPL) 4
No. of particles per cell in case of DCCELL>DCEPS (NPH) 15
Minimum number of particles allowed per cell (NPMIN) 2
Maximum number of particles allowed per cell (NPMAX) 15
Pattern for placement of particles for sink cells (NLSINK) 0
No. of particles used to approximate sink cells (NPSINK) 15
Critical relative concentration gradient (DCHMOC) 0,0001
OK
Cancel
Help

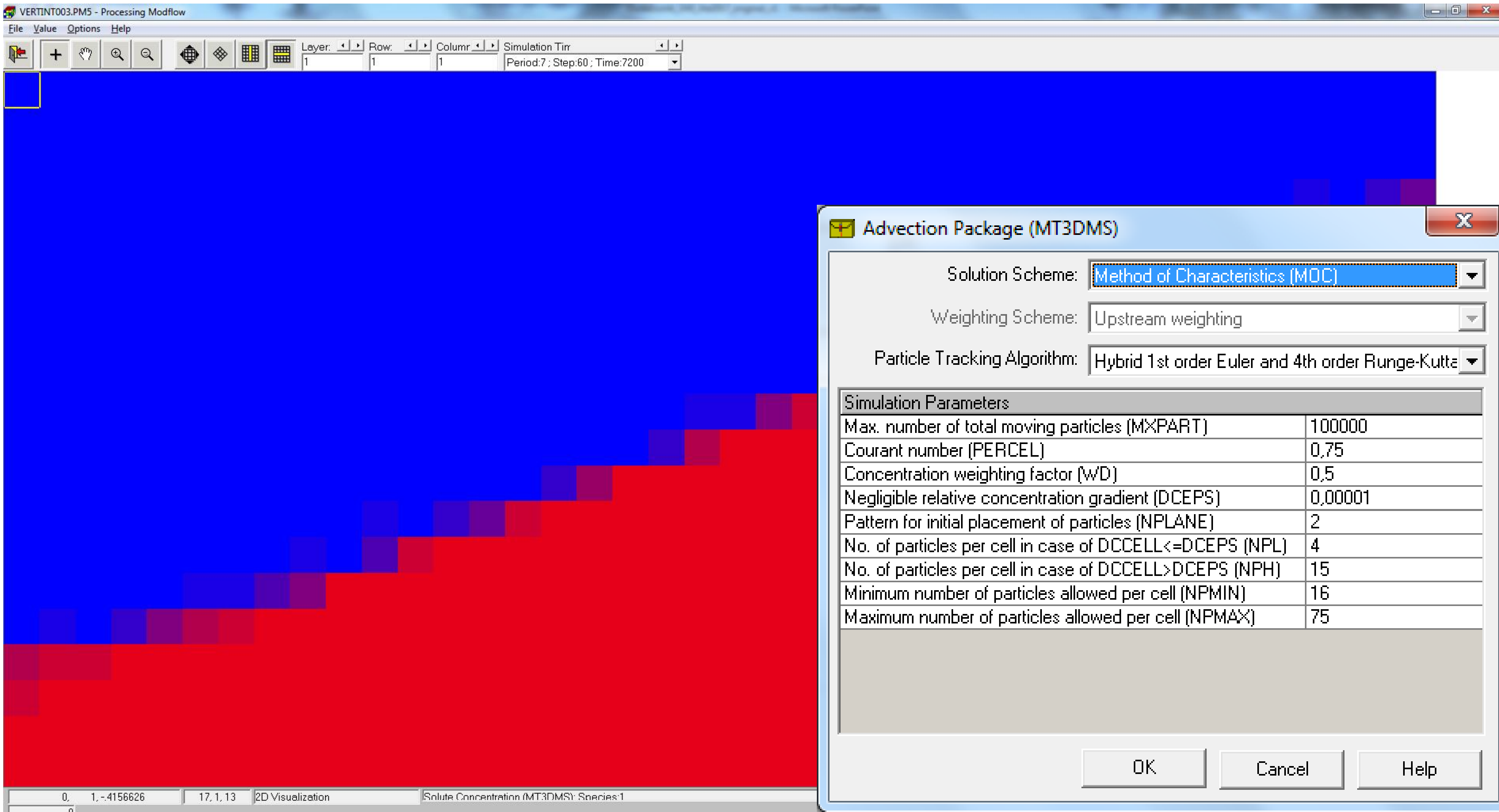
Finite Difference Method



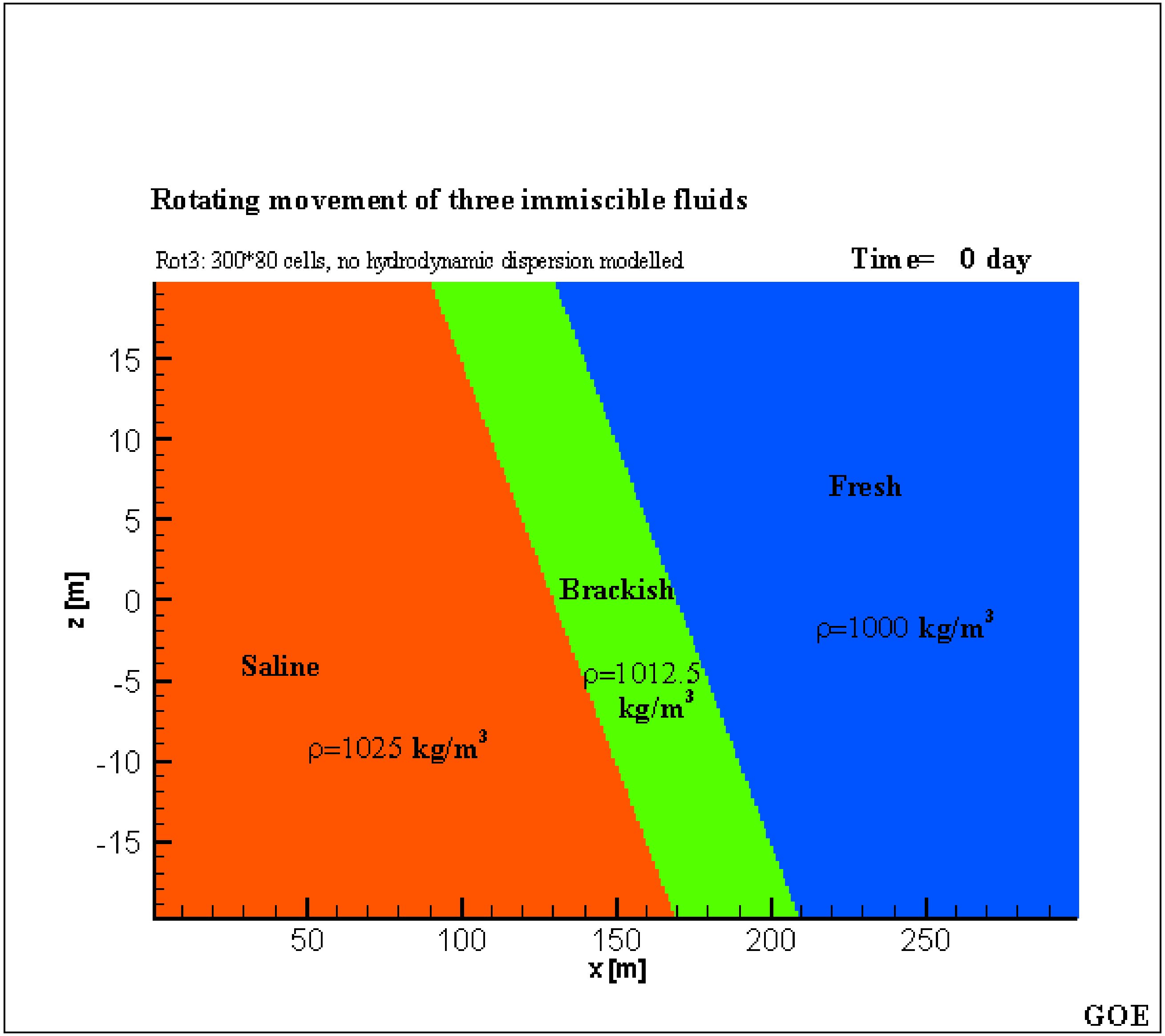
MOC


VERTINT003.PM5 - Processing Modflow
File
Value
Options
Help
Layer:
Row:
Columr
Simulation Tir
Period:7 ; Step:60 ; Time:7200
Advection Package (MT3DMS)
Solution Scheme:
Method of Characteristics (MOC)
Weighting Scheme:
Upstream weighting
Particle Tracking Algorithm:
Hybrid 1st order Euler and 4th order Runge-Kutta
Simulation Parameters
Max. number of total moving particles (MXPART)
100000
Courant number (PERCEL)
0,75
Concentration weighting factor (WD)
0,5
Negligible relative concentration gradient (DCEPS)
0,00001
Pattern for initial placement of particles (NPLANE)
2
No. of particles per cell in case of DCCELL<=DCEPS (NPL)
4
No. of particles per cell in case of DCCELL>DCEPS (NPH)
15
Minimum number of particles allowed per cell (NPMIN)
2
Maximum number of particles allowed per cell (NPMAX)
15
OK
Cancel
Help
2D Visualization
Solute Concentration (MT3DMS): Species:1

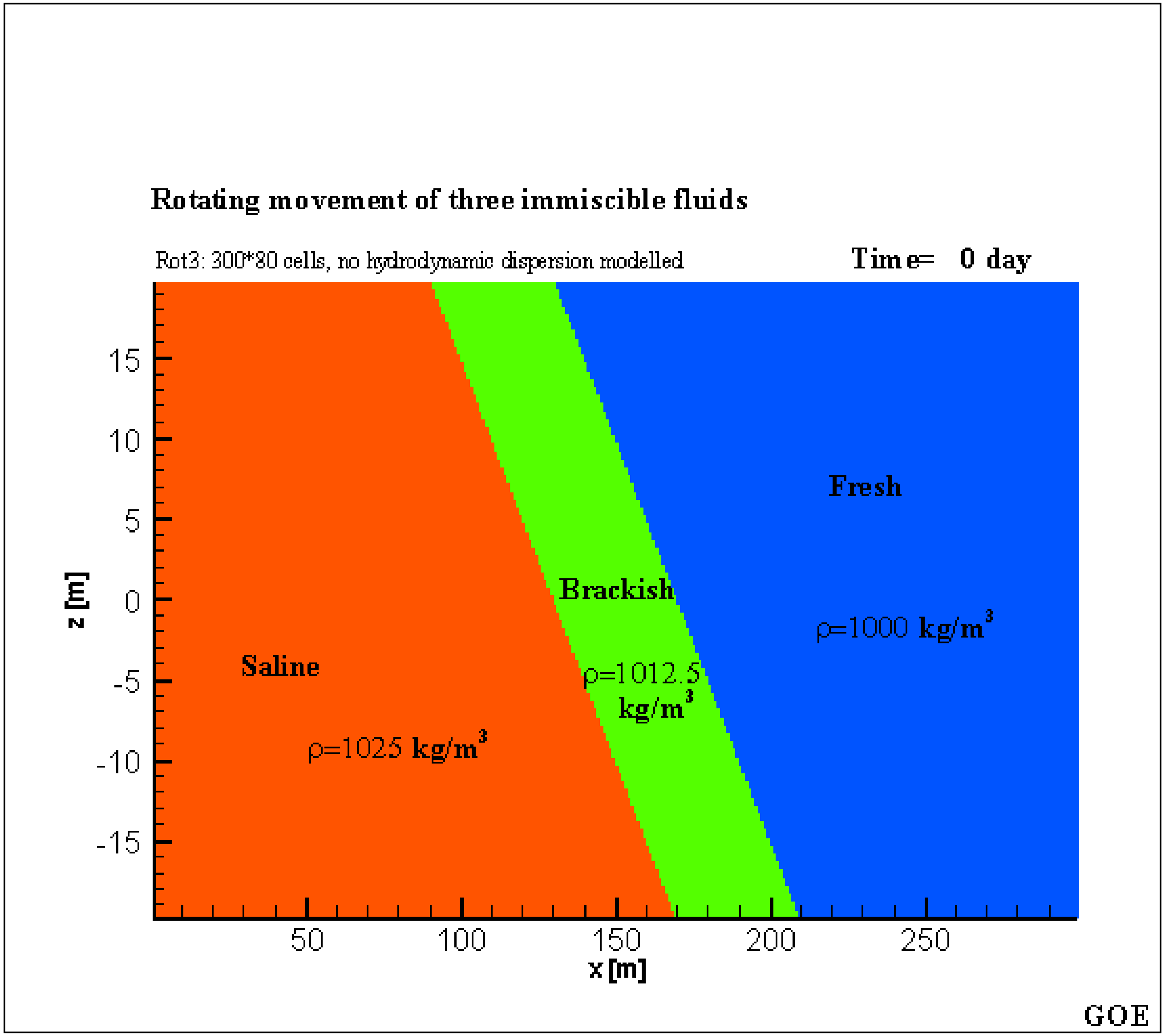
MOC


VERTINT003.PM5 - Processing Modflow
File Value Options Help
Layer: 1
Row: 1
Column 1
Simulation Tim
Period:7 ; Step:60 ; Time:7200
Advection Package (MT3DMS)
Solution Scheme: Method of Characteristics (MOC)
Weighting Scheme: Upstream weighting
Particle Tracking Algorithm: Hybrid 1st order Euler and 4th order Runge-Kutta
Simulation Parameters
Max. number of total moving particles (MXPART) 100000
Courant number (PERCEL) 0,75
Concentration weighting factor (WD) 0,5
Negligible relative concentration gradient (DCEPS) 0,00001
Pattern for initial placement of particles (NPLANE) 2
No. of particles per cell in case of DCCELL<=DCEPS (NPL) 4
No. of particles per cell in case of DCCELL>DCEPS (NPH) 15
Minimum number of particles allowed per cell (NPMIN) 16
Maximum number of particles allowed per cell (NPMAX) 75
OK
Cancel
Help
0, 1, -.4156626
17, 1, 13
2D Visualization
Solute Concentration (MT3DMS): Species 1

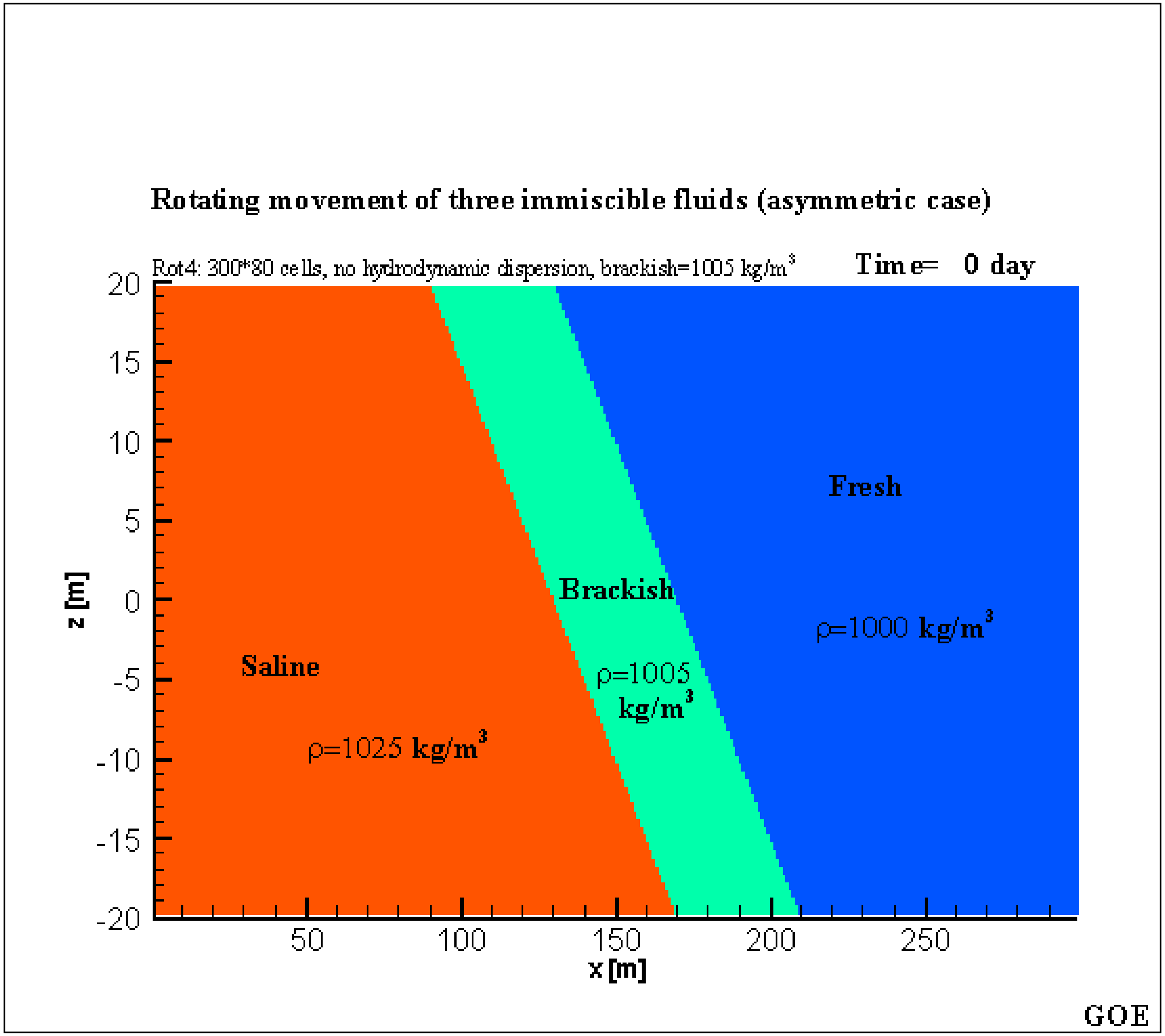
Rotating immiscible interfaces



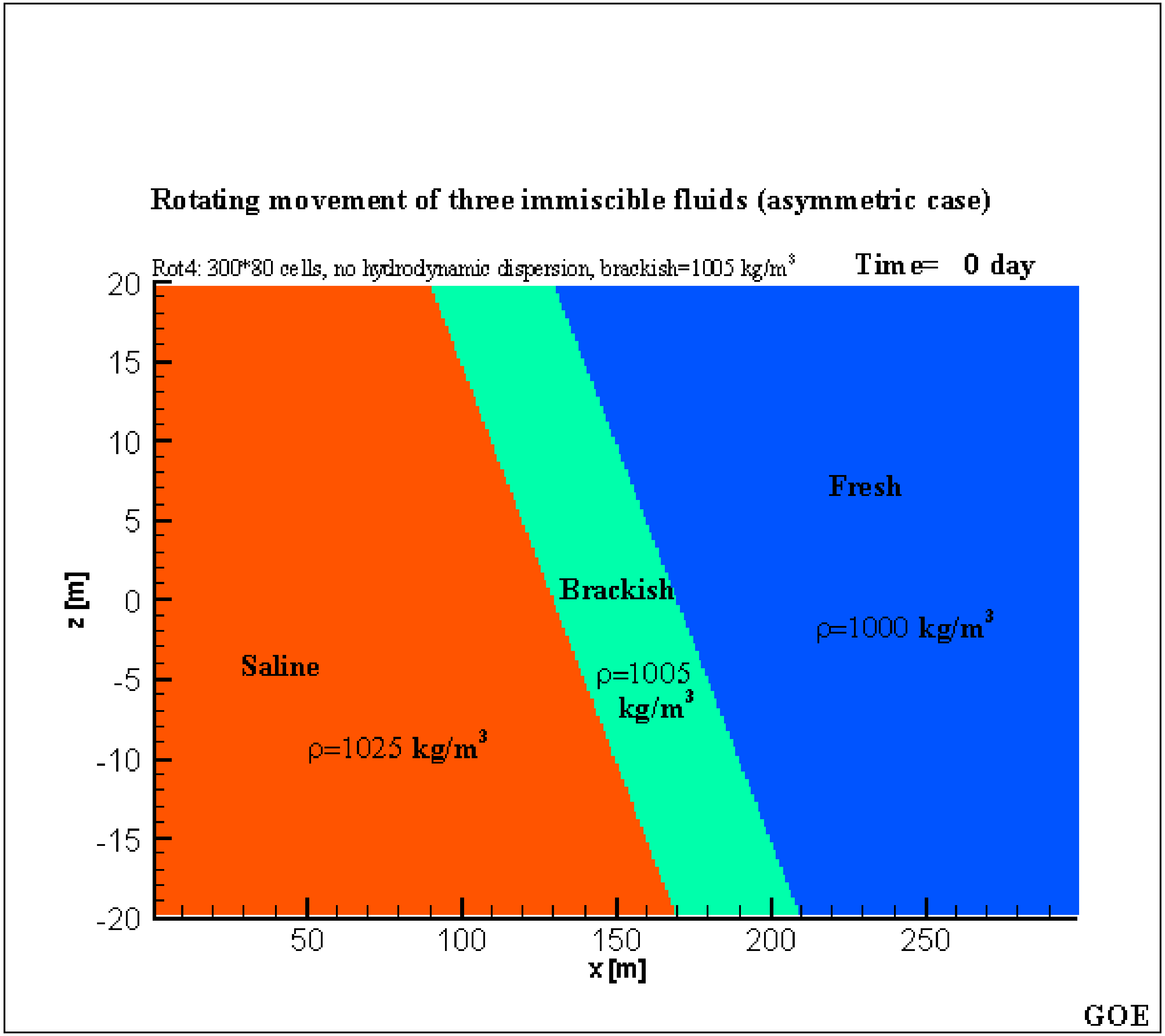
Rotating immiscible interfaces



Rotating immiscible interfaces (asymmetric)

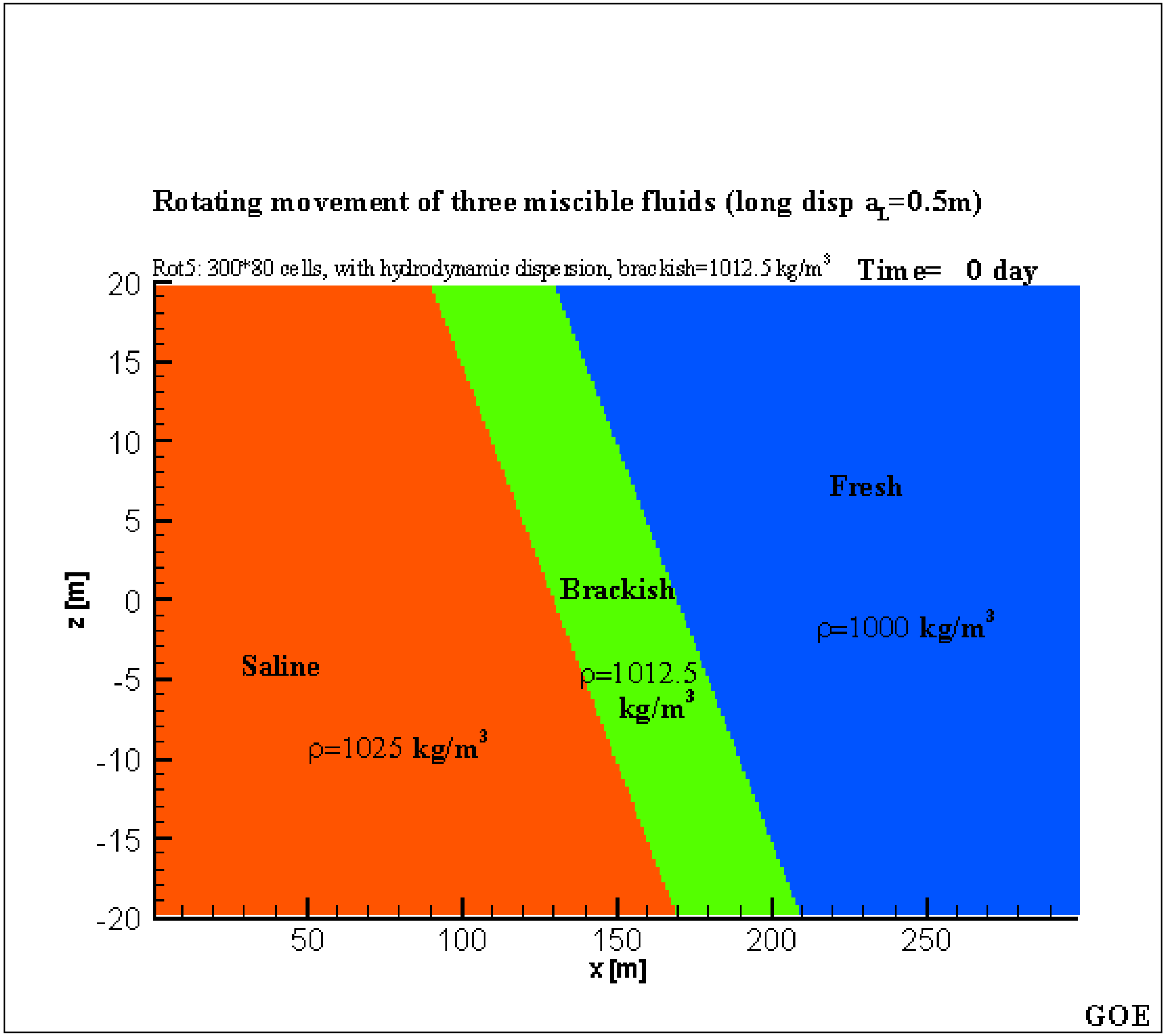


Rotating immiscible interfaces (asymmetric)

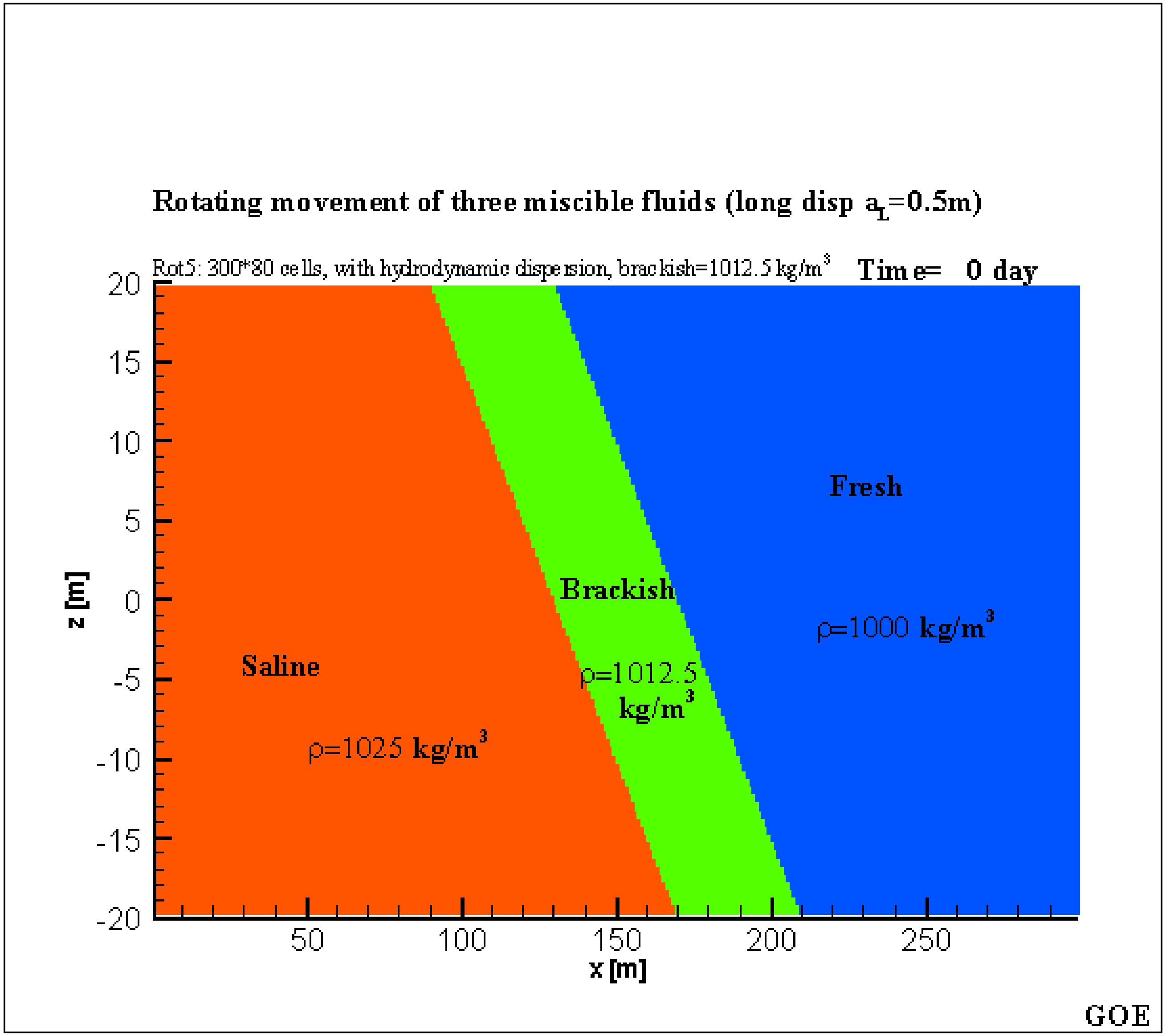


Bakker, M., Oude Essink, G.H.P. & Langevin, C. 2004. The rotating movement of three immiscible fluids, J. of Hydrology 287, 270-278

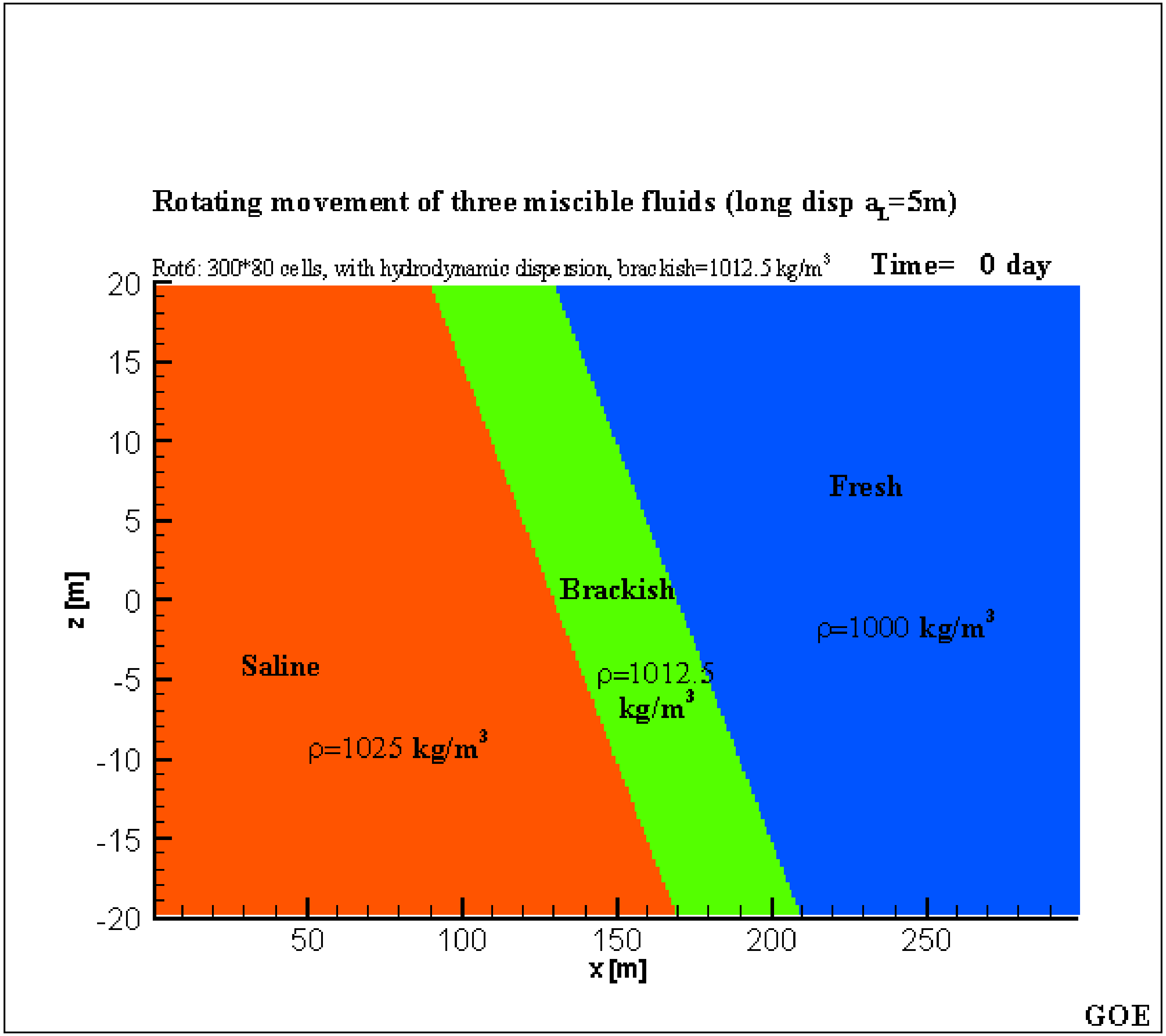
Rotating interfaces with dispersion α_L=0.5m



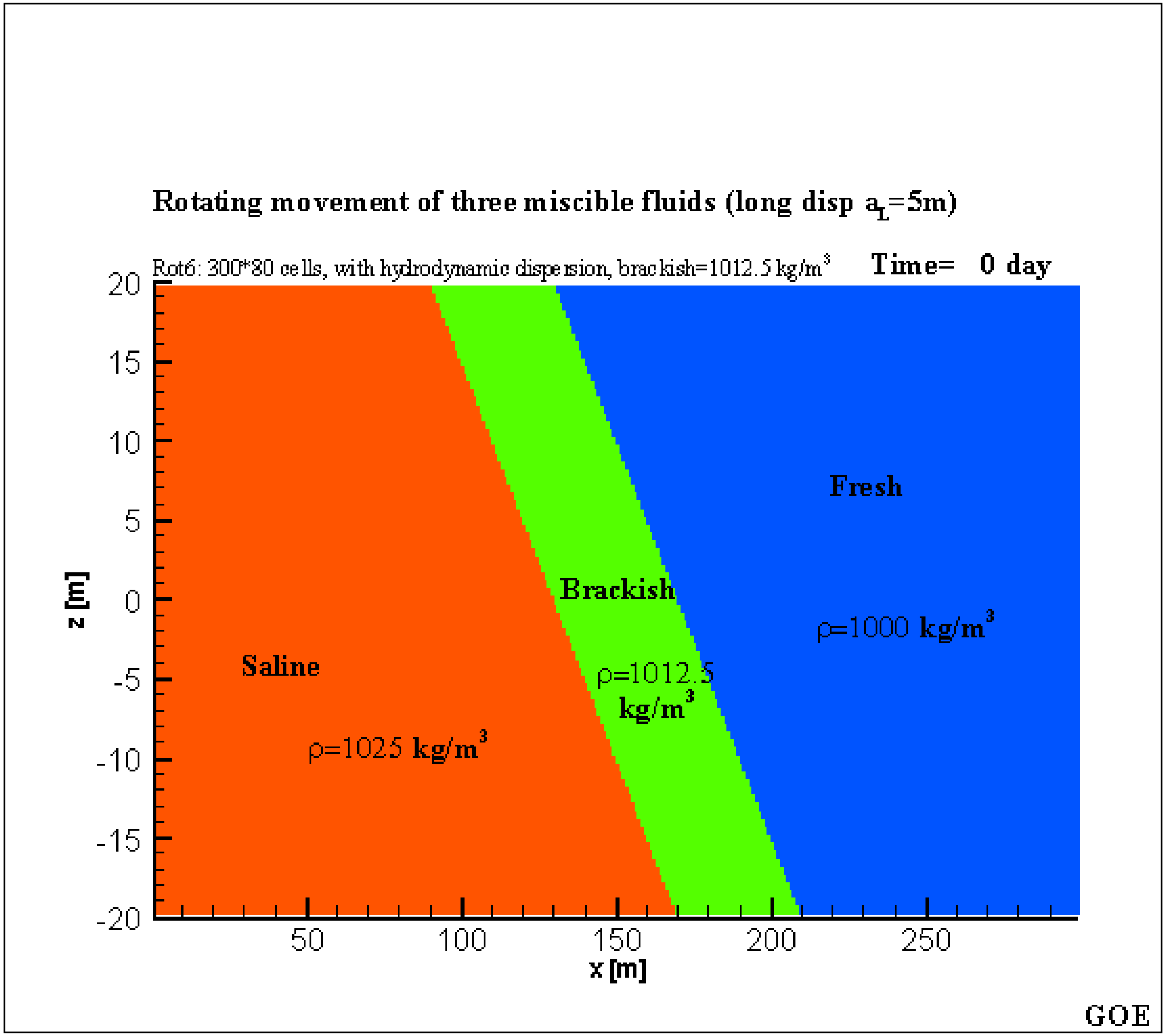
Rotating interfaces with dispersion α_L=0.5m



Rotating interfaces with dispersion α_L=5m



Rotating interfaces with dispersion α_L=5m



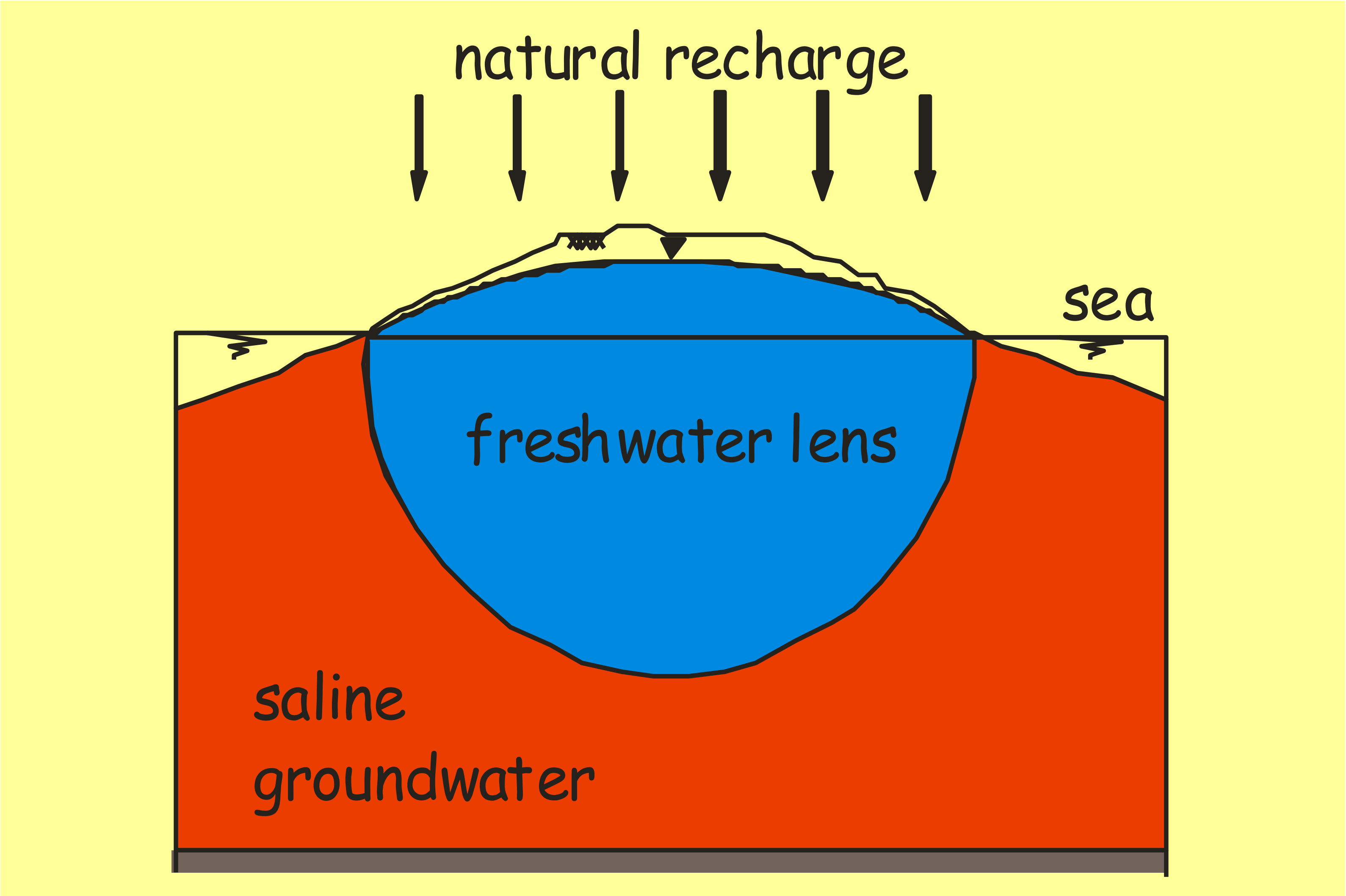
Rotating immiscible interfaces

Conclusion:

To check the variable-density component of your code,

this immiscible interface benchmark can be used.

Evolution of a freshwater lens



Question:

How long does it take before the volume of a freshwater lens in a sand-dune area with width of 4km is filled?:

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

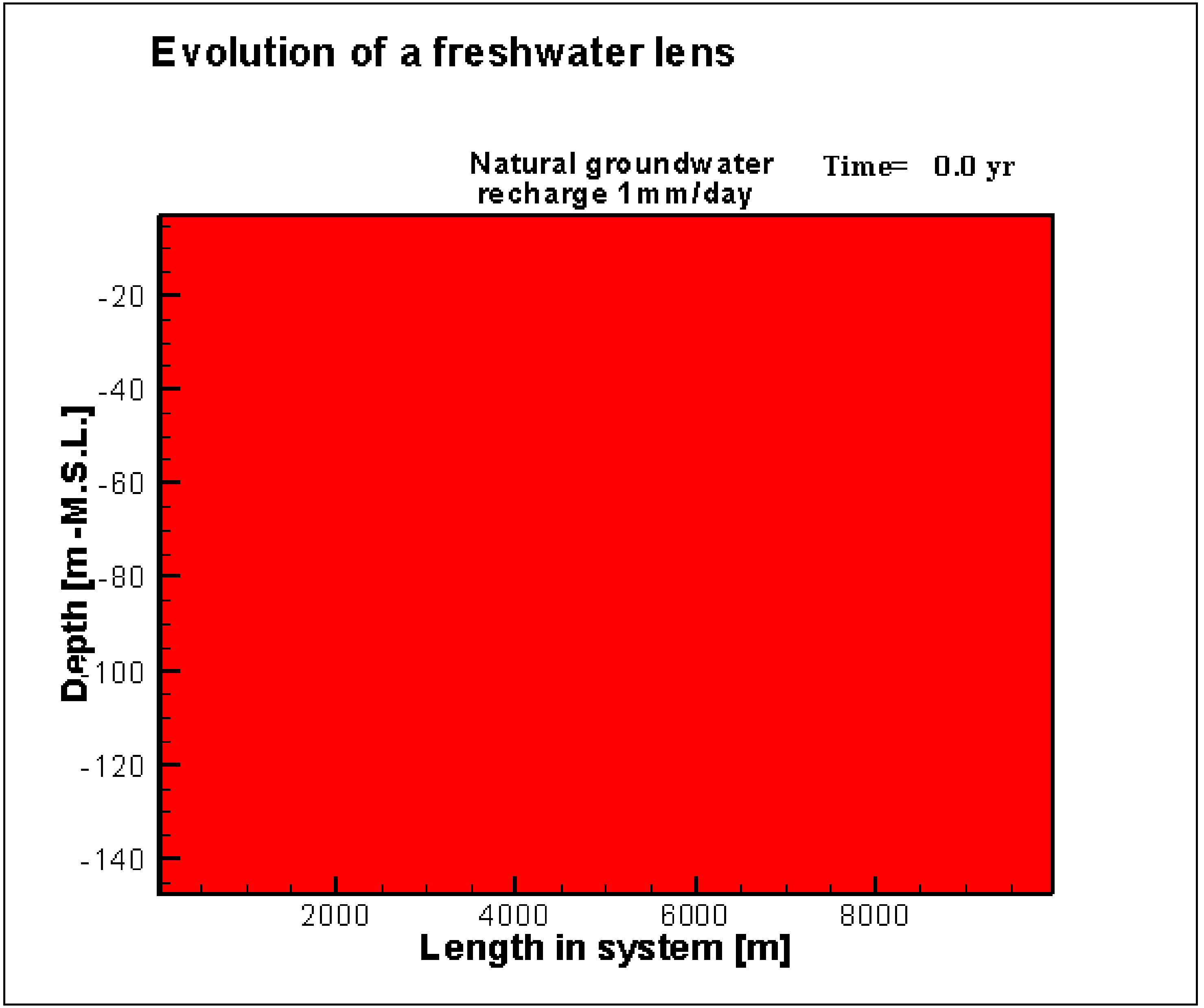
T = specific time scale

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

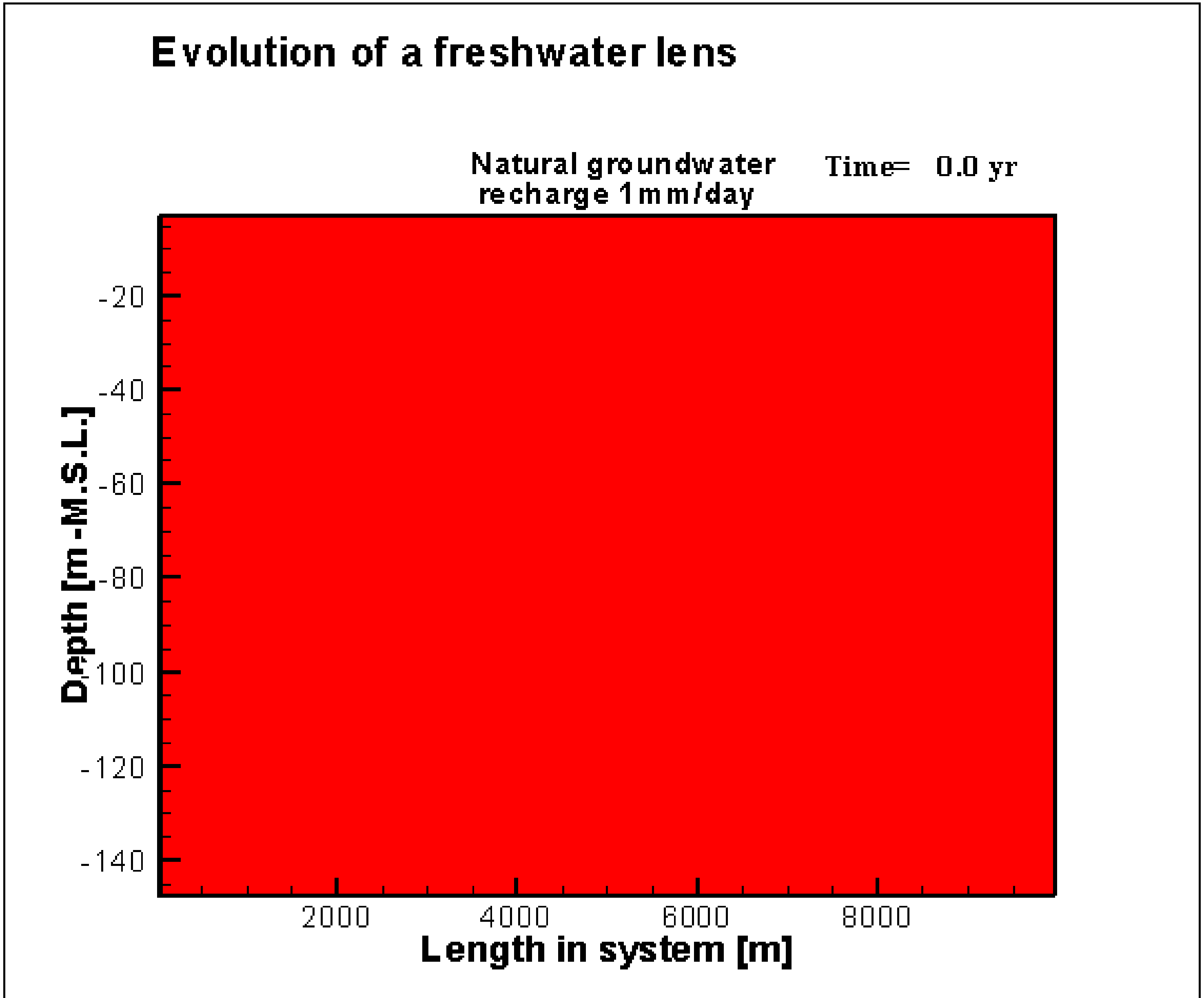
In the Netherlands: **T** = 75-200 jaar,

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

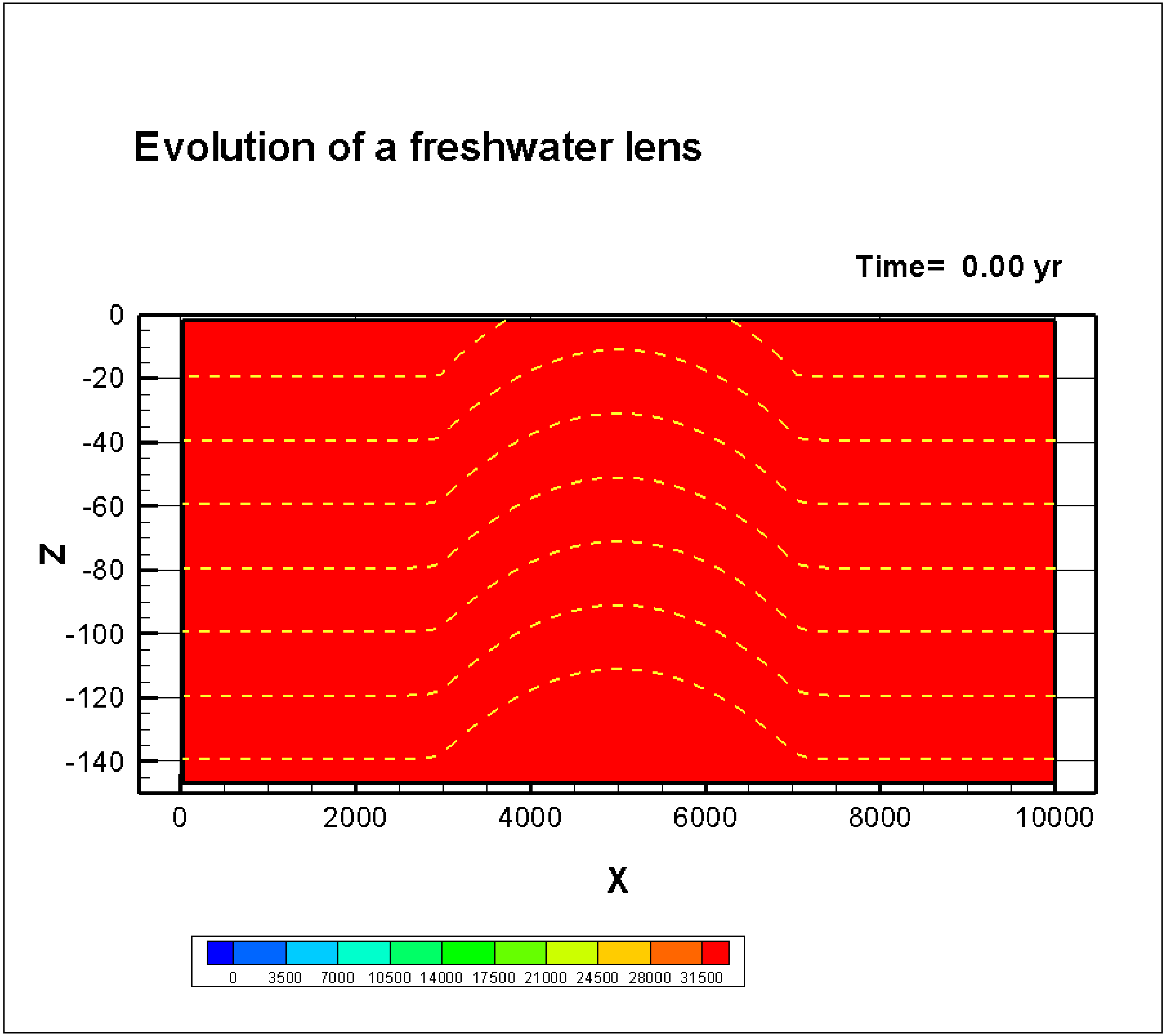
Concept: evolution freshwater lens (not Griend!)



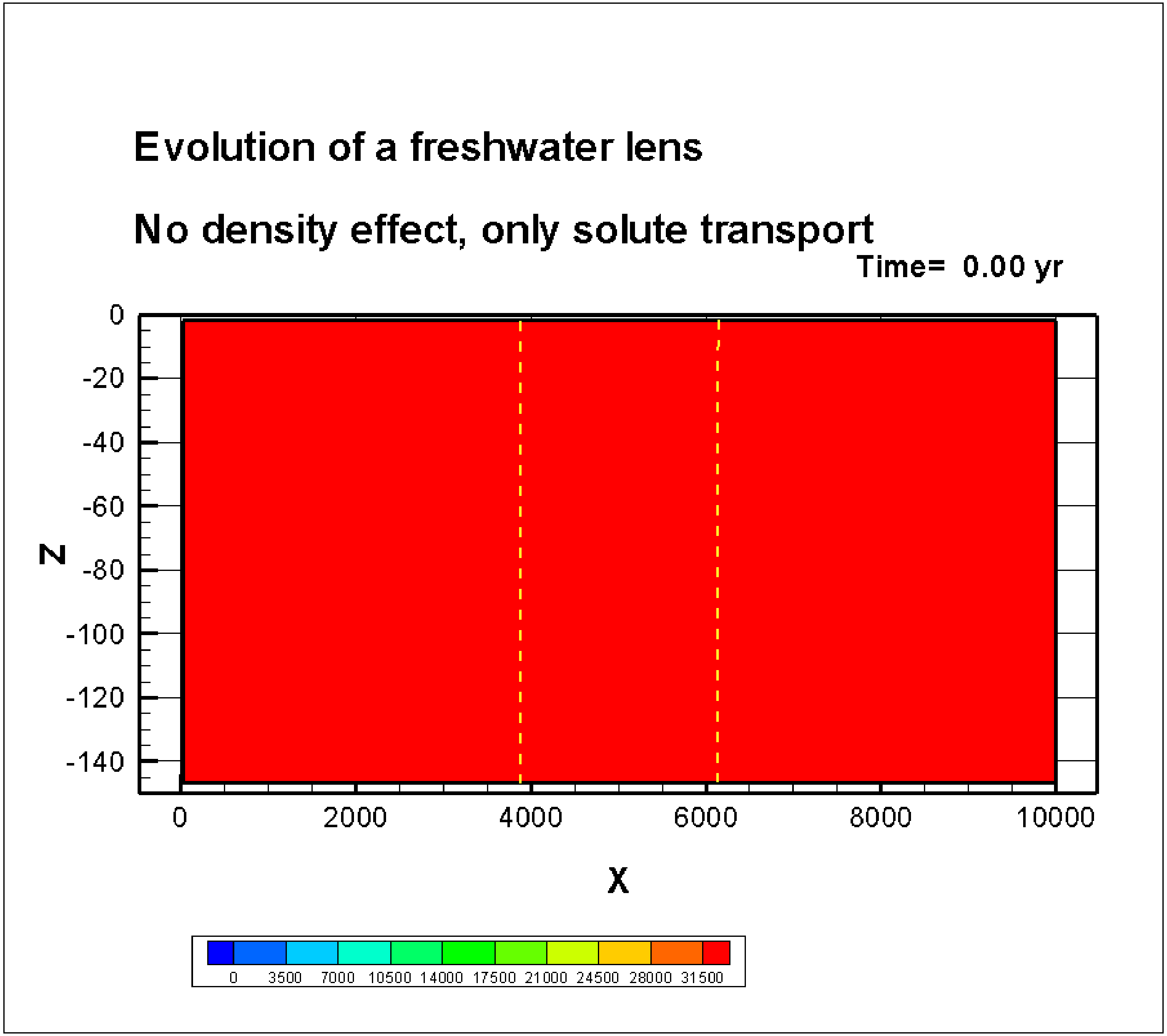
Concept: evolution freshwater lens (not Griend!)



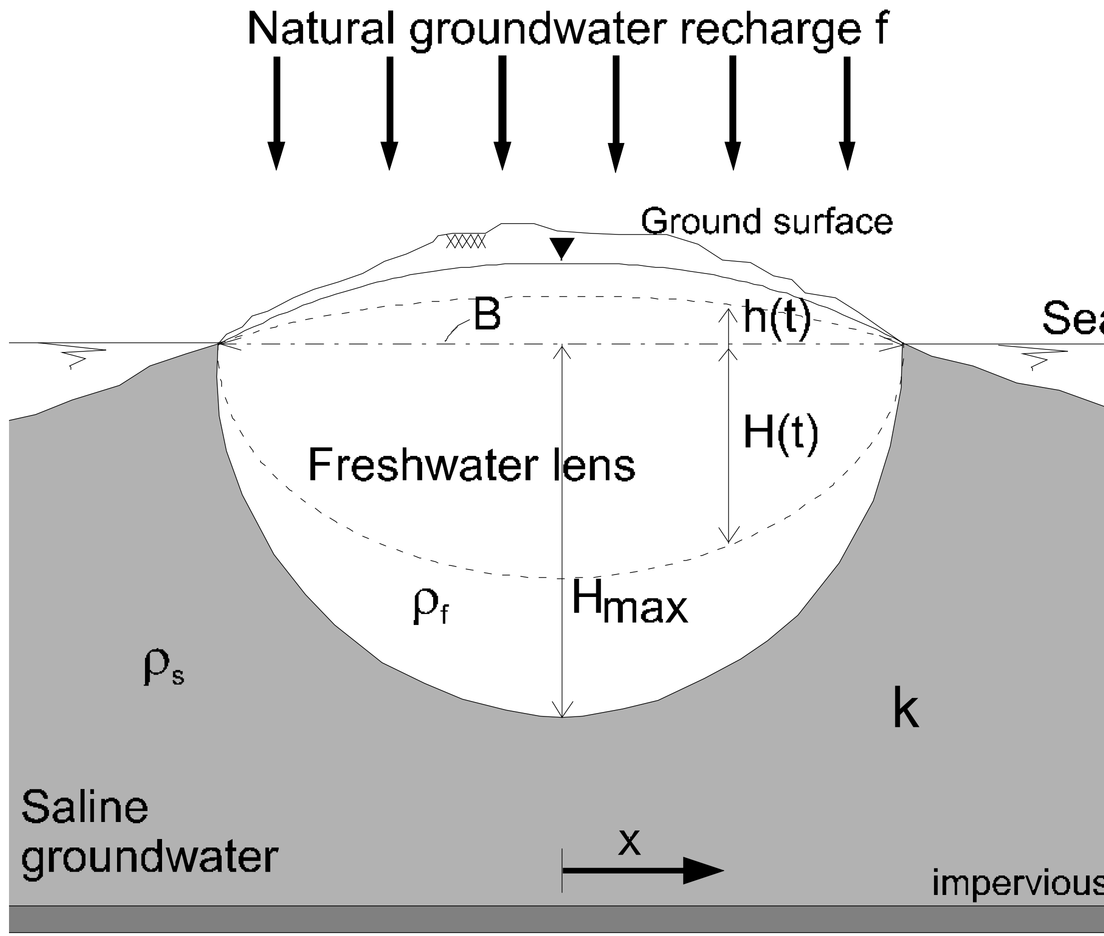
Evolution freshwater lens



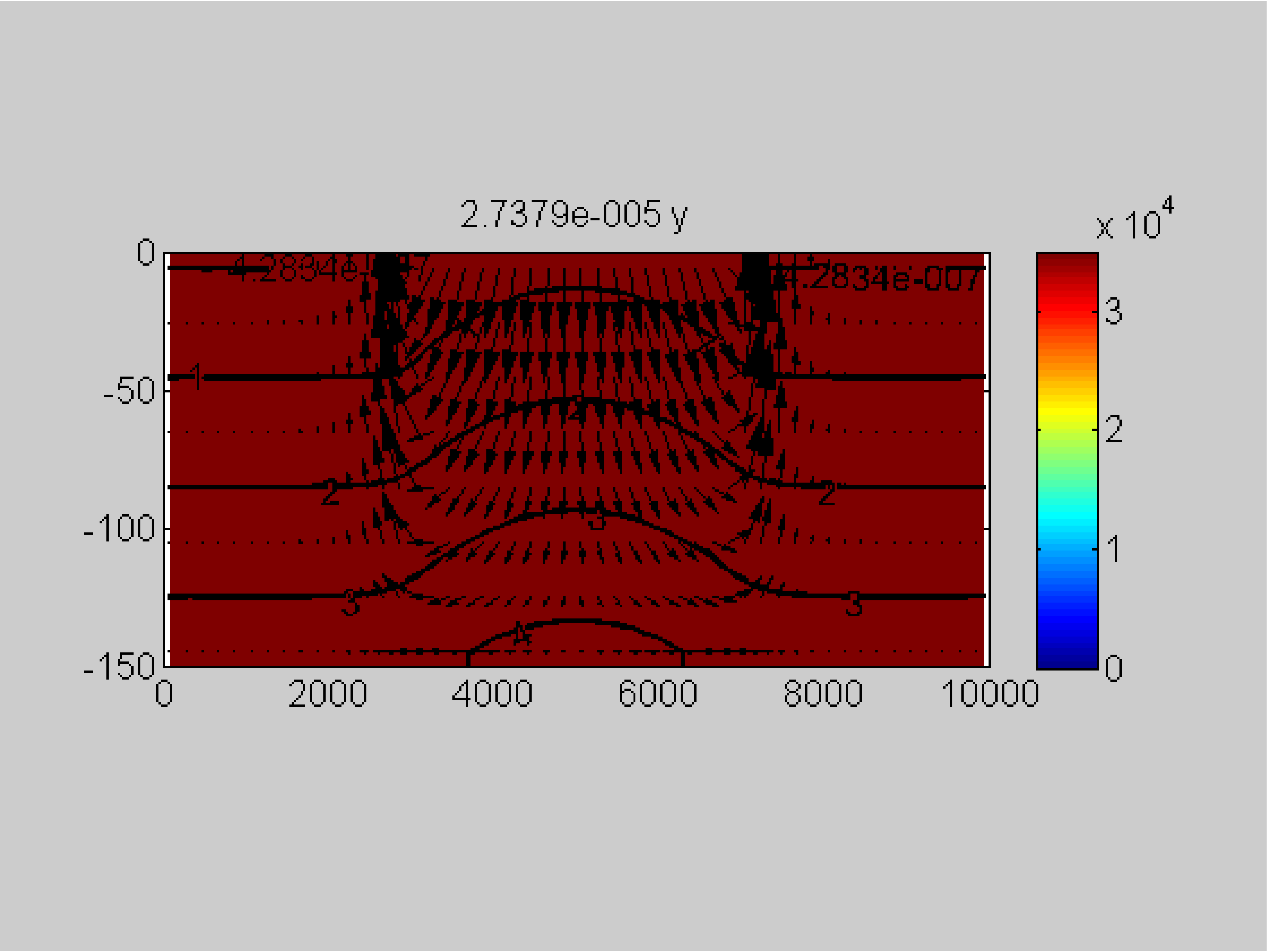
Evolution freshwater lens: no density effects



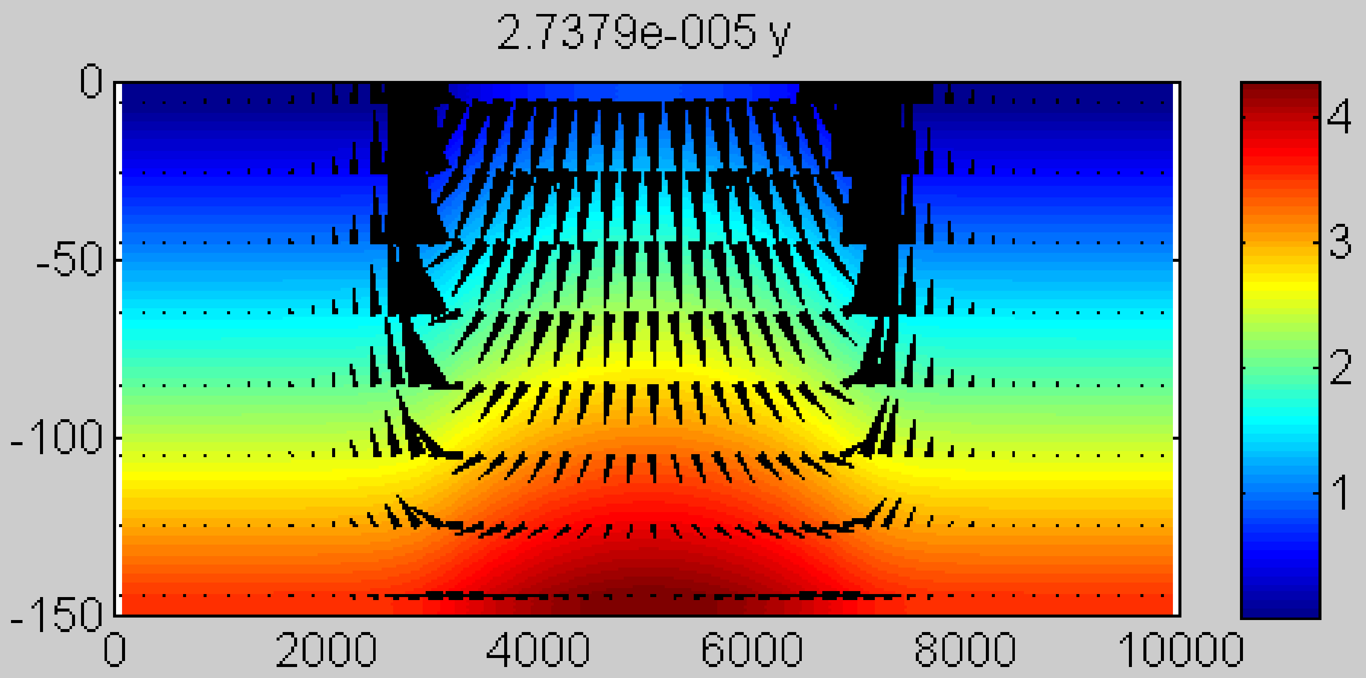
Case 2: Development of a freshwater lens



Evolution lens



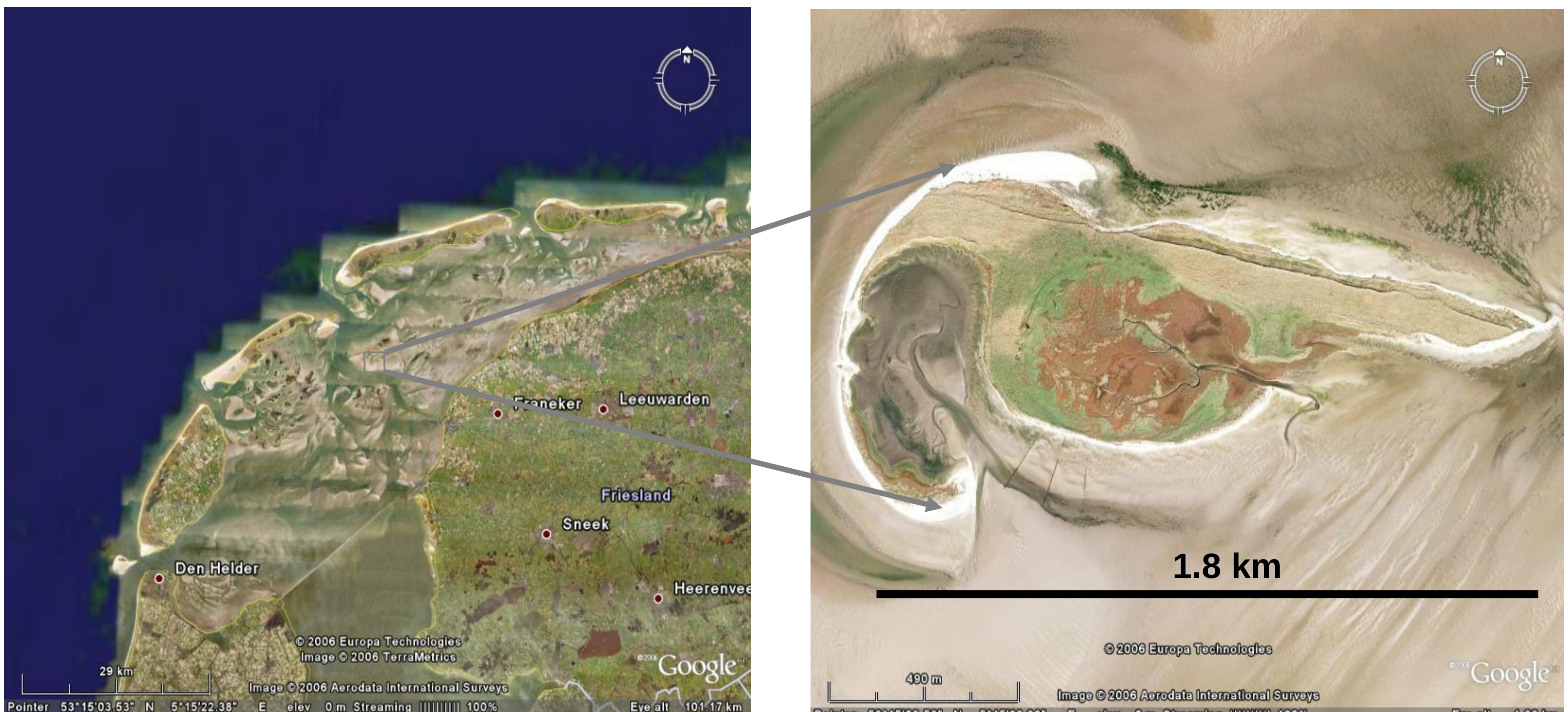
Evolution freshwater head



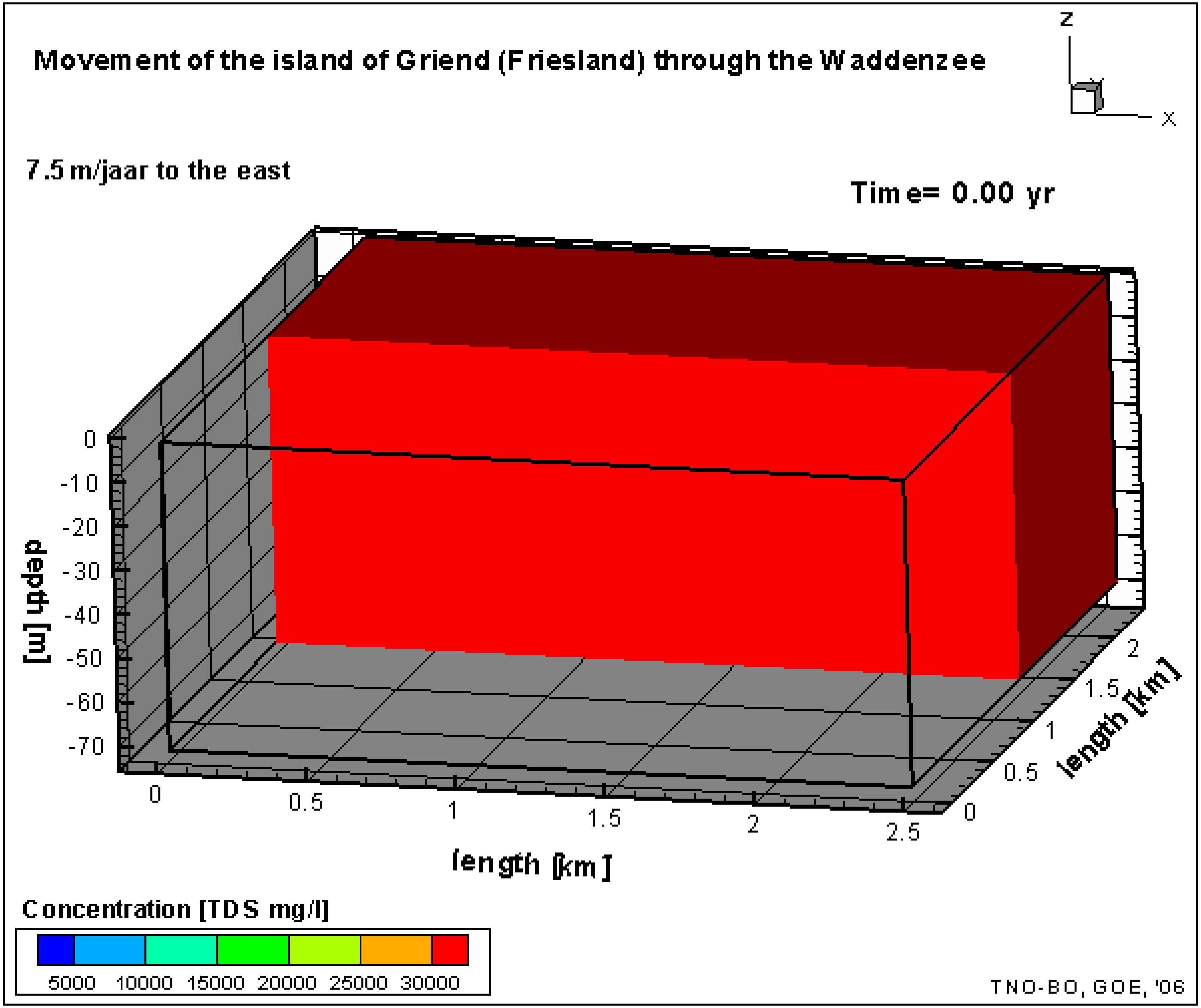
The island of Griend

Issues:

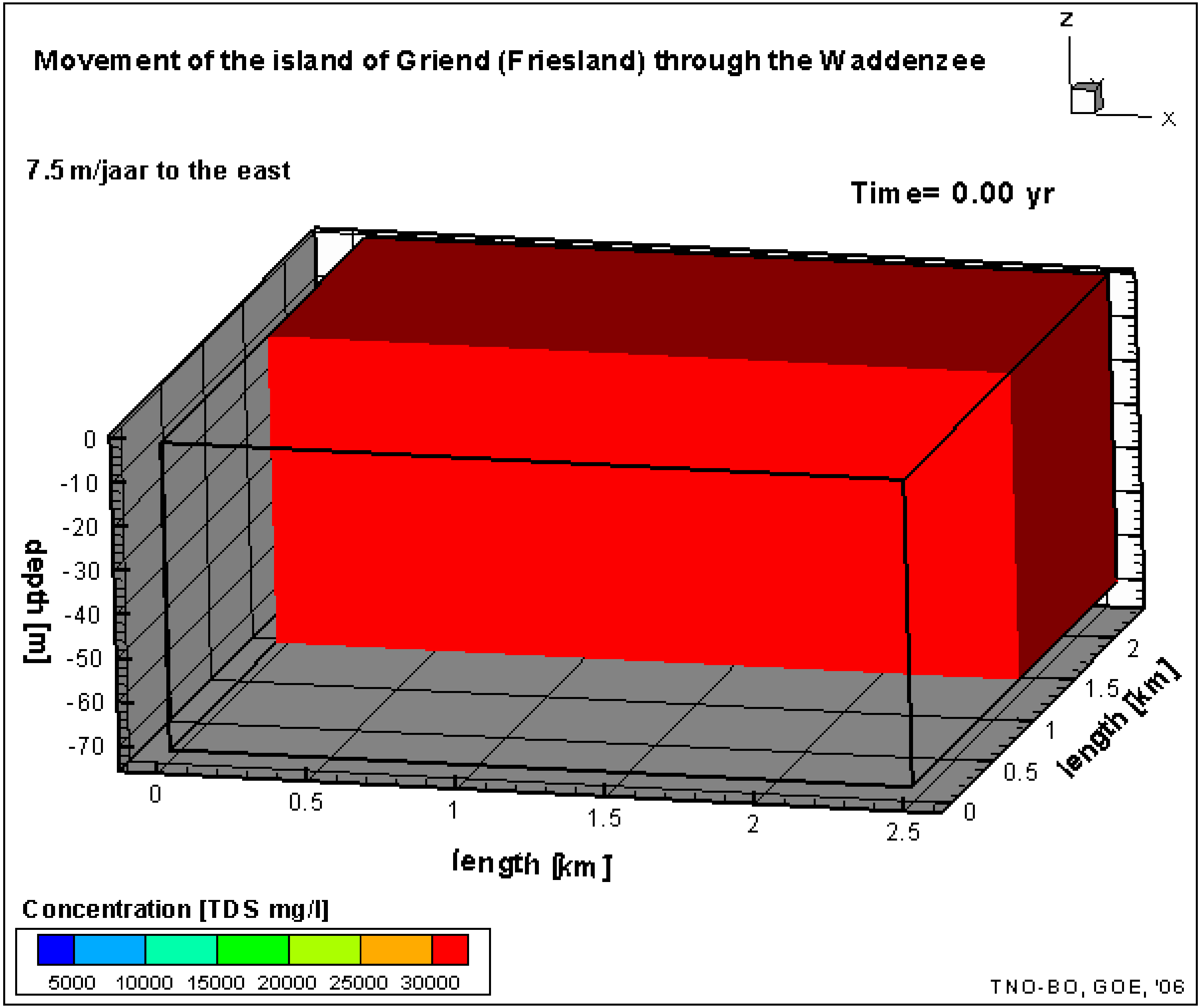
1. Small island moves ~7.5m per year to the east
2. Effect on the volume of the freshwater lens:
   - Can a lens be developed?
   - What is the thickness of the lens?



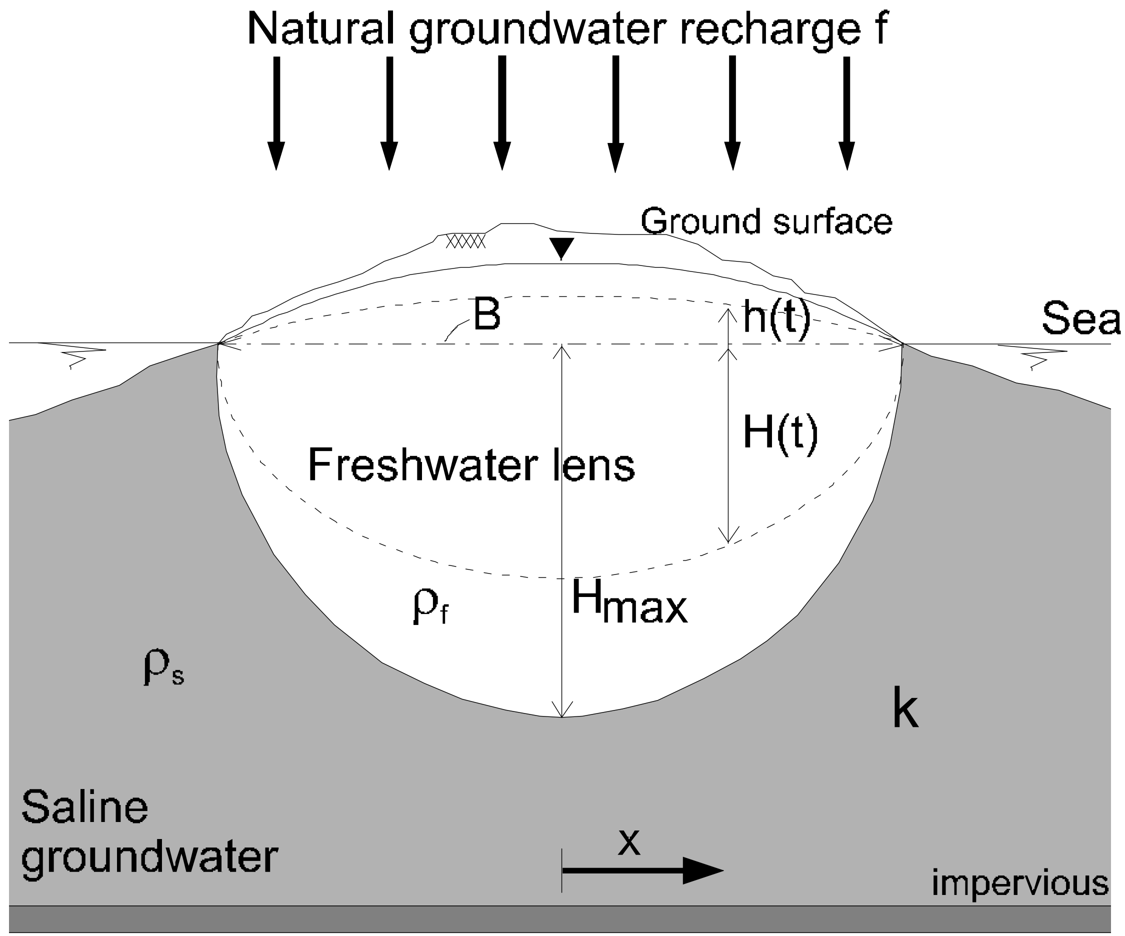
Movement of De Griend and creation of the lens



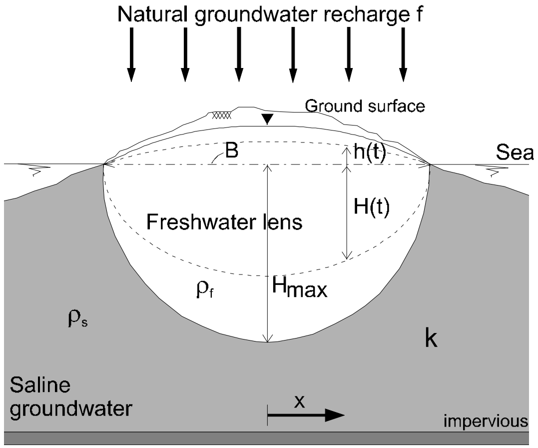
Movement of De Griend and creation of the lens



Case 2: Development of a freshwater lens



Case 2: Development of a freshwater lens



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

On the benchmark Freshwater lens, exercise 4

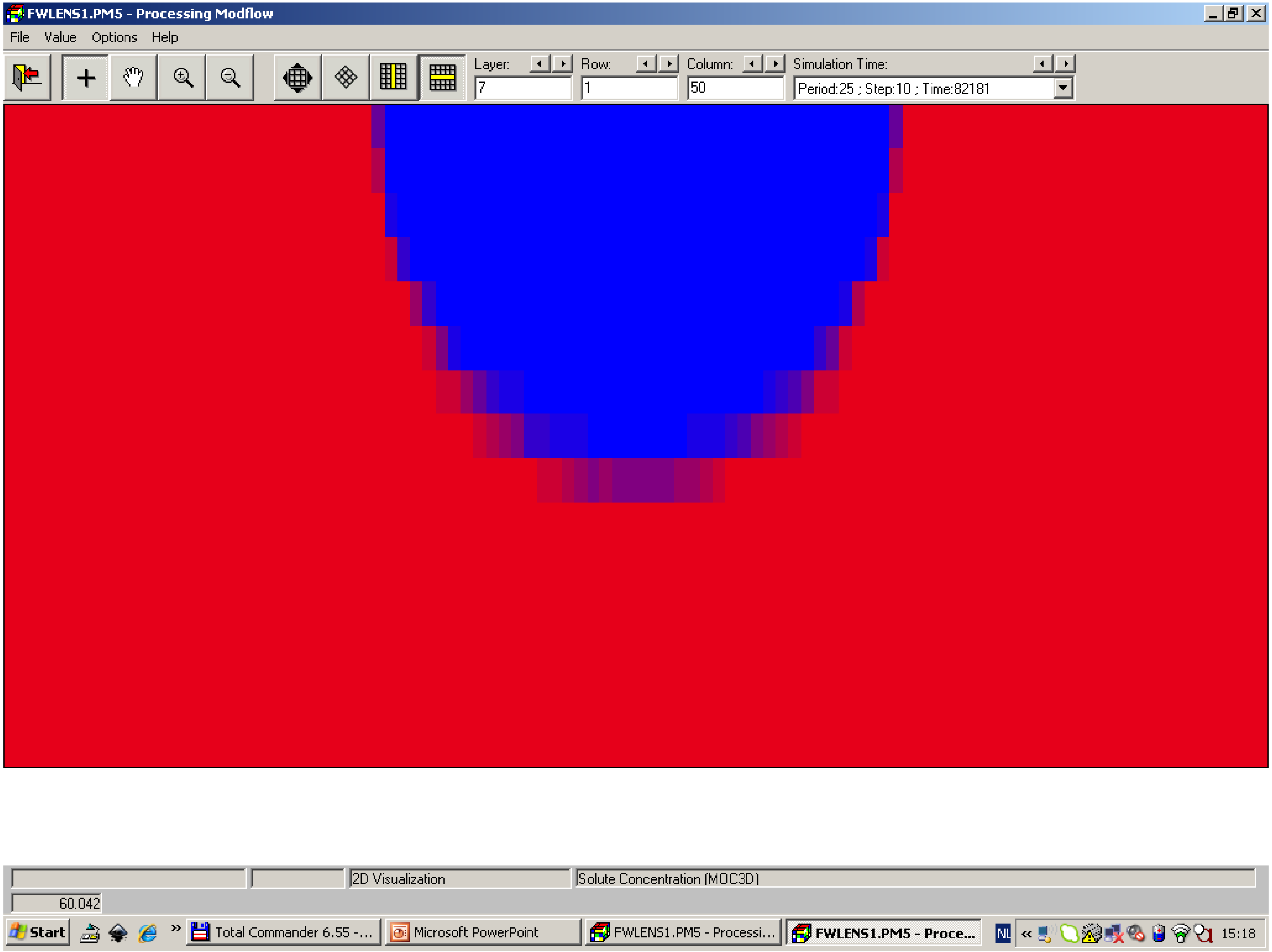
How much groundwater (approximately, in m3/day/m') can be extracted without serious upconing of saline and brackish groundwater (serious means a TDS-concentration>300 mg/l. Make only a coarse and quick calculation. Try to supply 100.000 people with drinking water on an island with a length L of 10 km?

- Length B lens=4000m,Recharge=0.001m/d
- Flux in: 4m^2/day, or 4 m^3/day per stretched meter

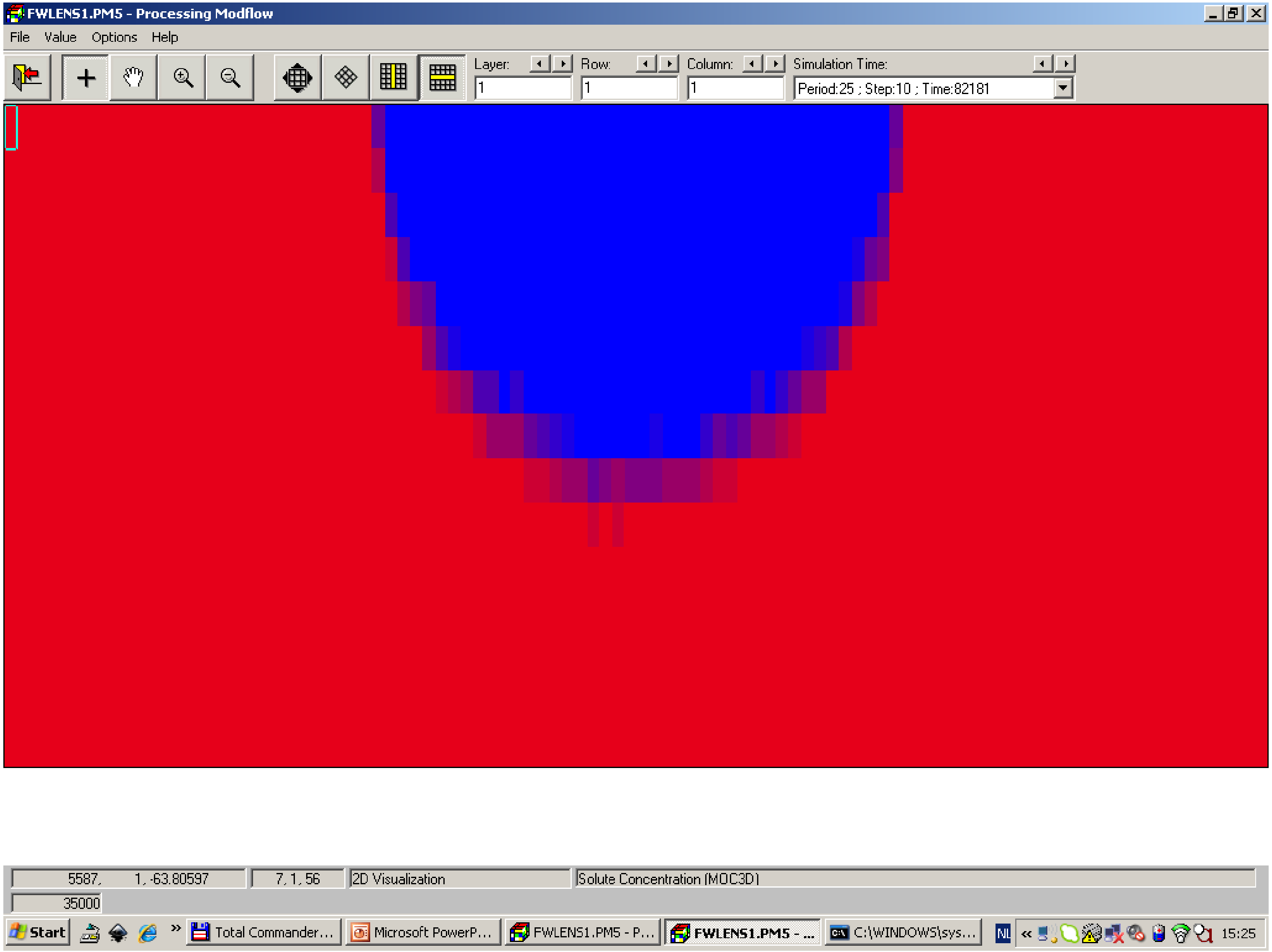
- 100.000 people with say 100 l/day is 10.000 m^3/day
- Length L =10km=10000m

- So the rate of fresh groundwater you want to extract from this 1m wide cross-section is 10.000 m^3/day/10000m= 1 m^2/day
- You have to extract in total -1 m2/day out of this 2D cross-section (of 1m stretched)

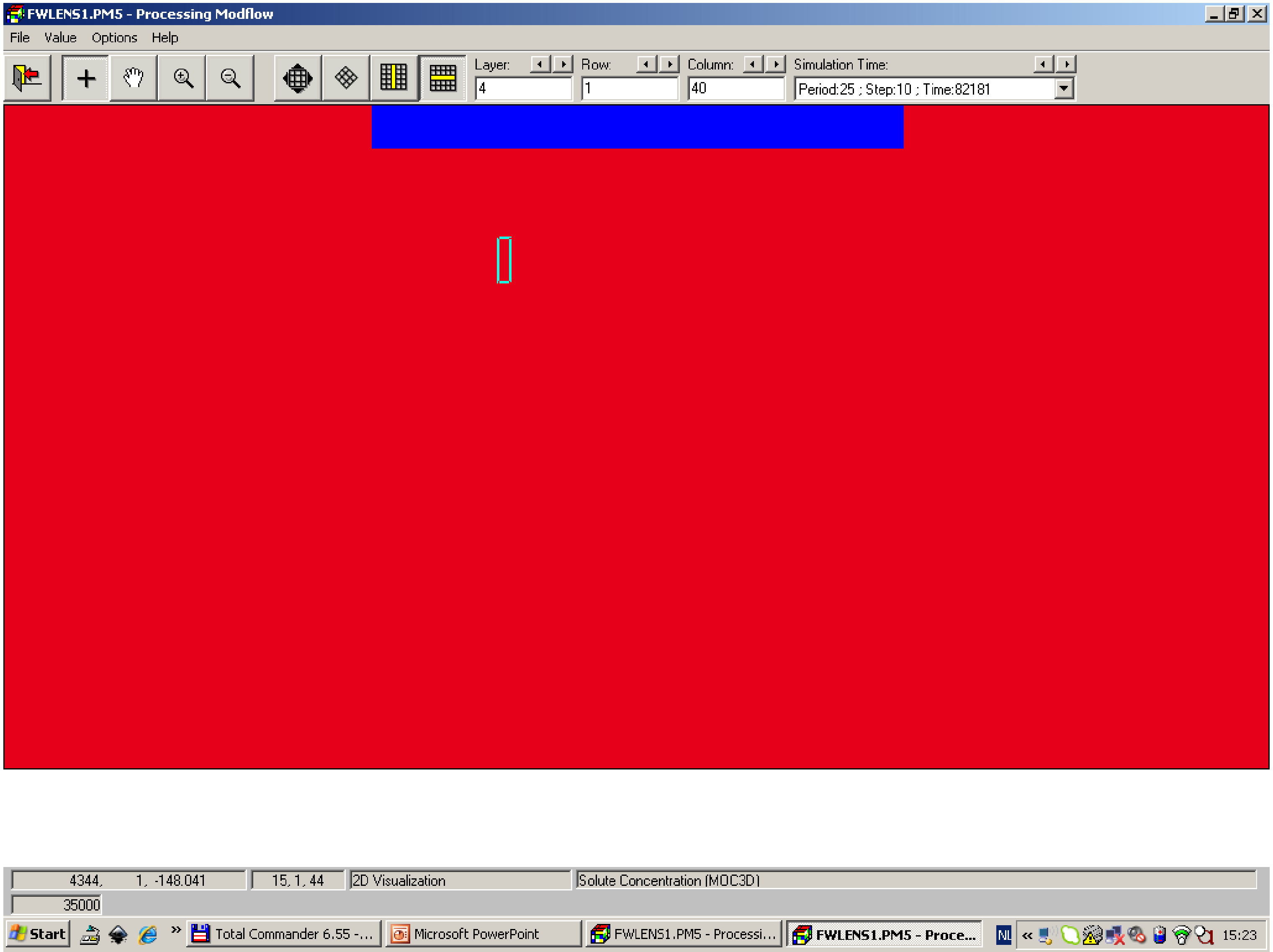
MOCDENS3D, no disp, 16part



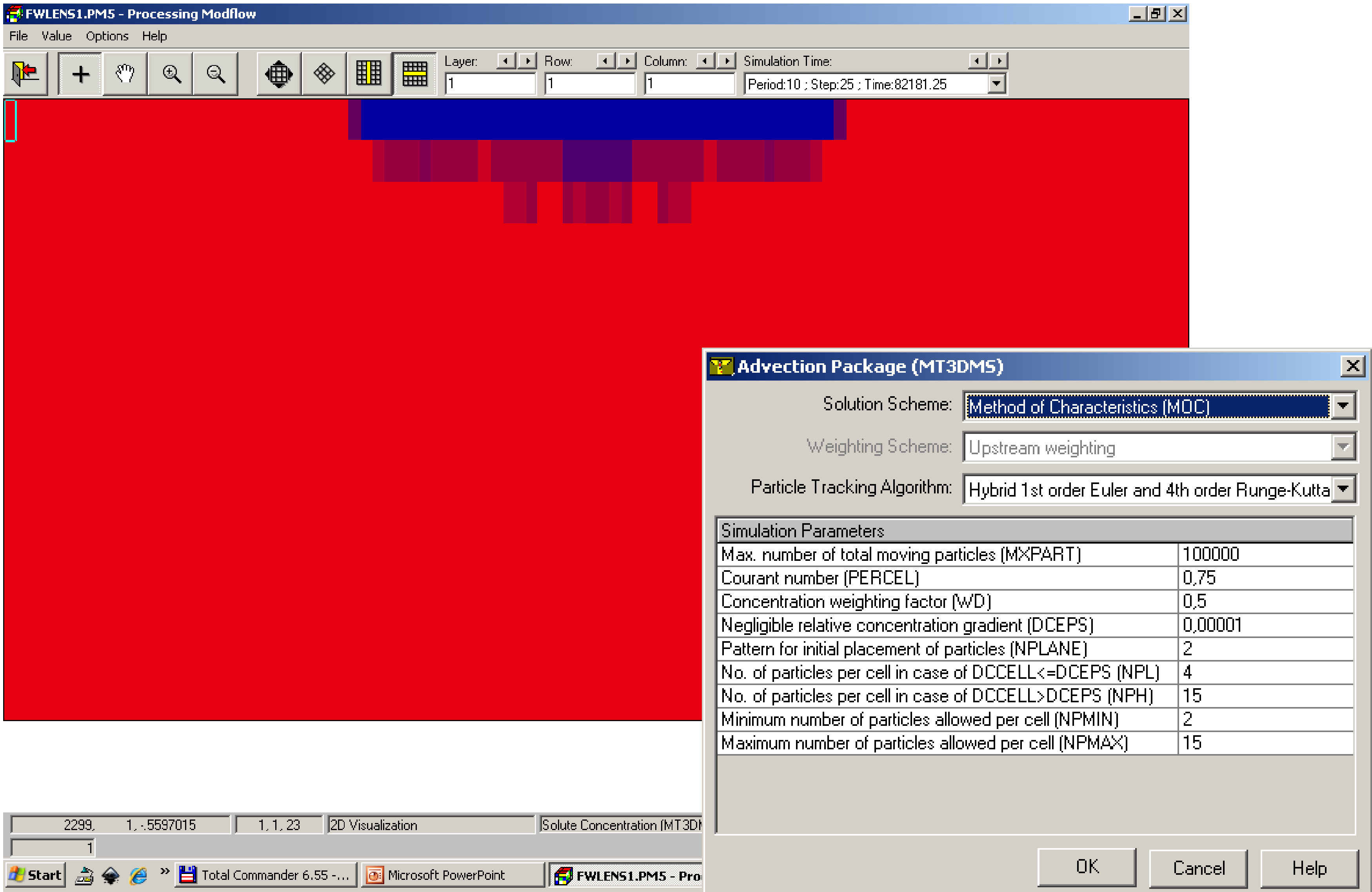
MOCDENS3D, no disp, 4part



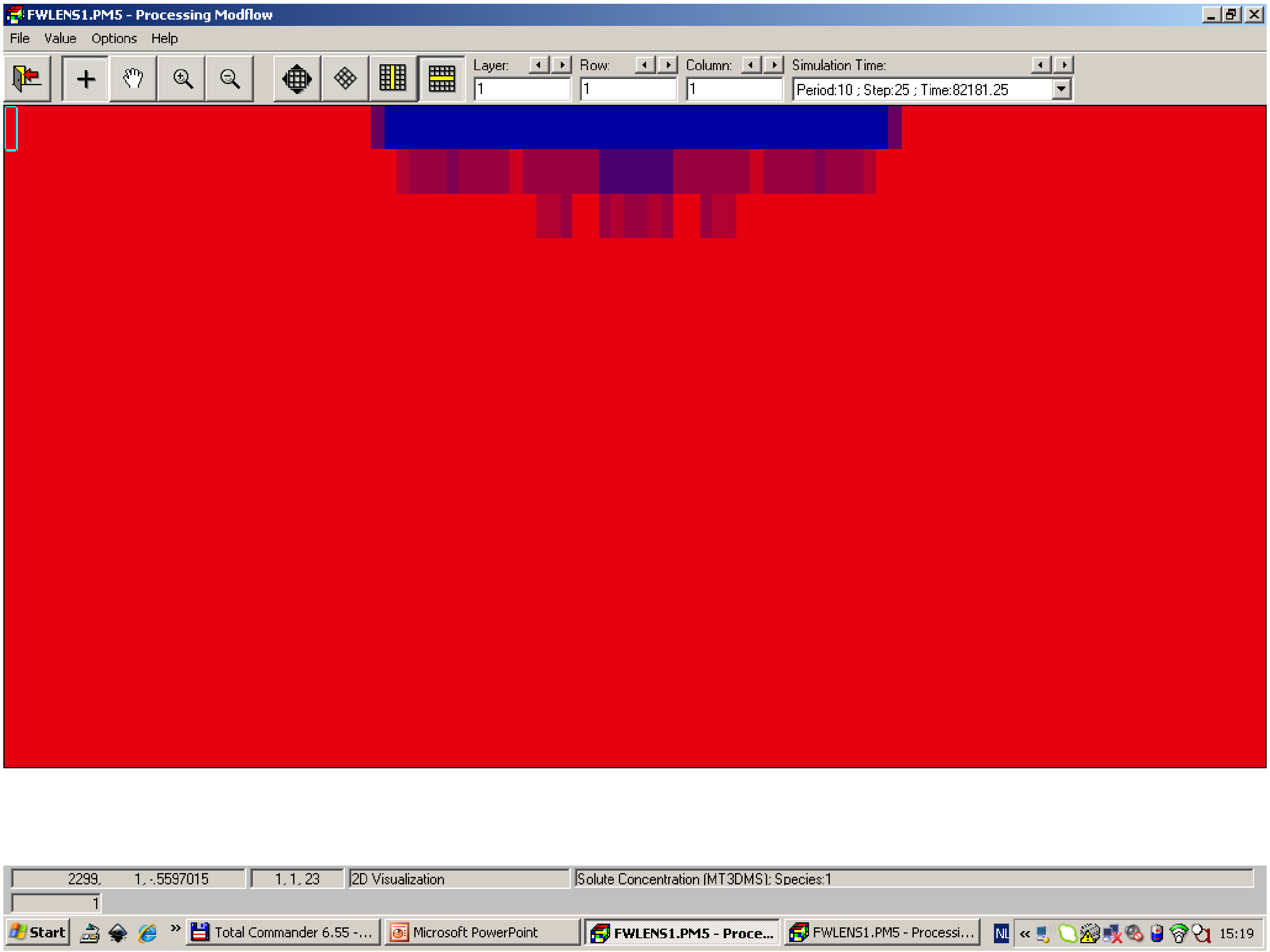
MOCDENS3D, no disp, 1part



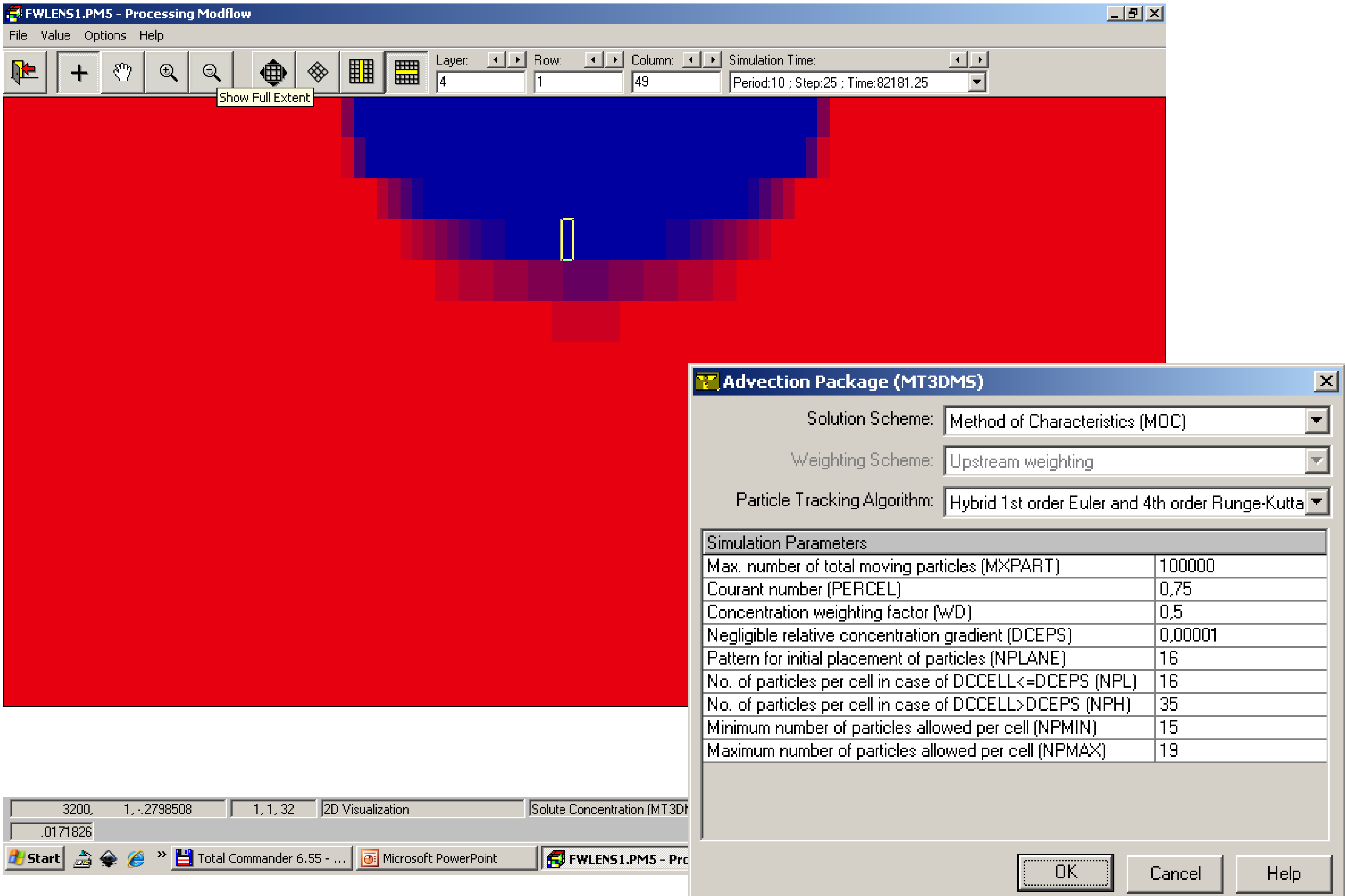
SEAWAT, MOC, NPLANE=2



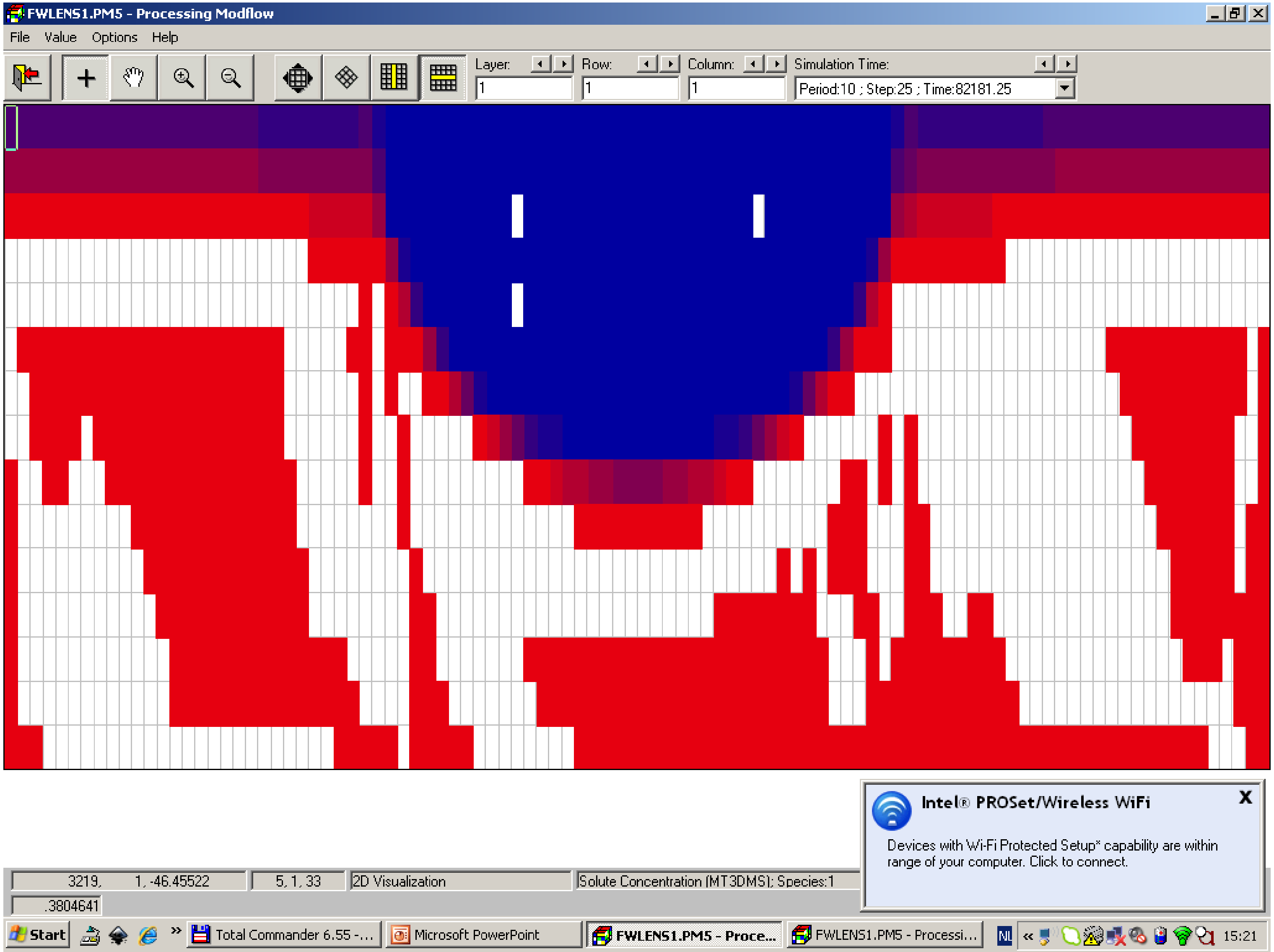
SEAWAT, MOC, 4.NPLANE=16



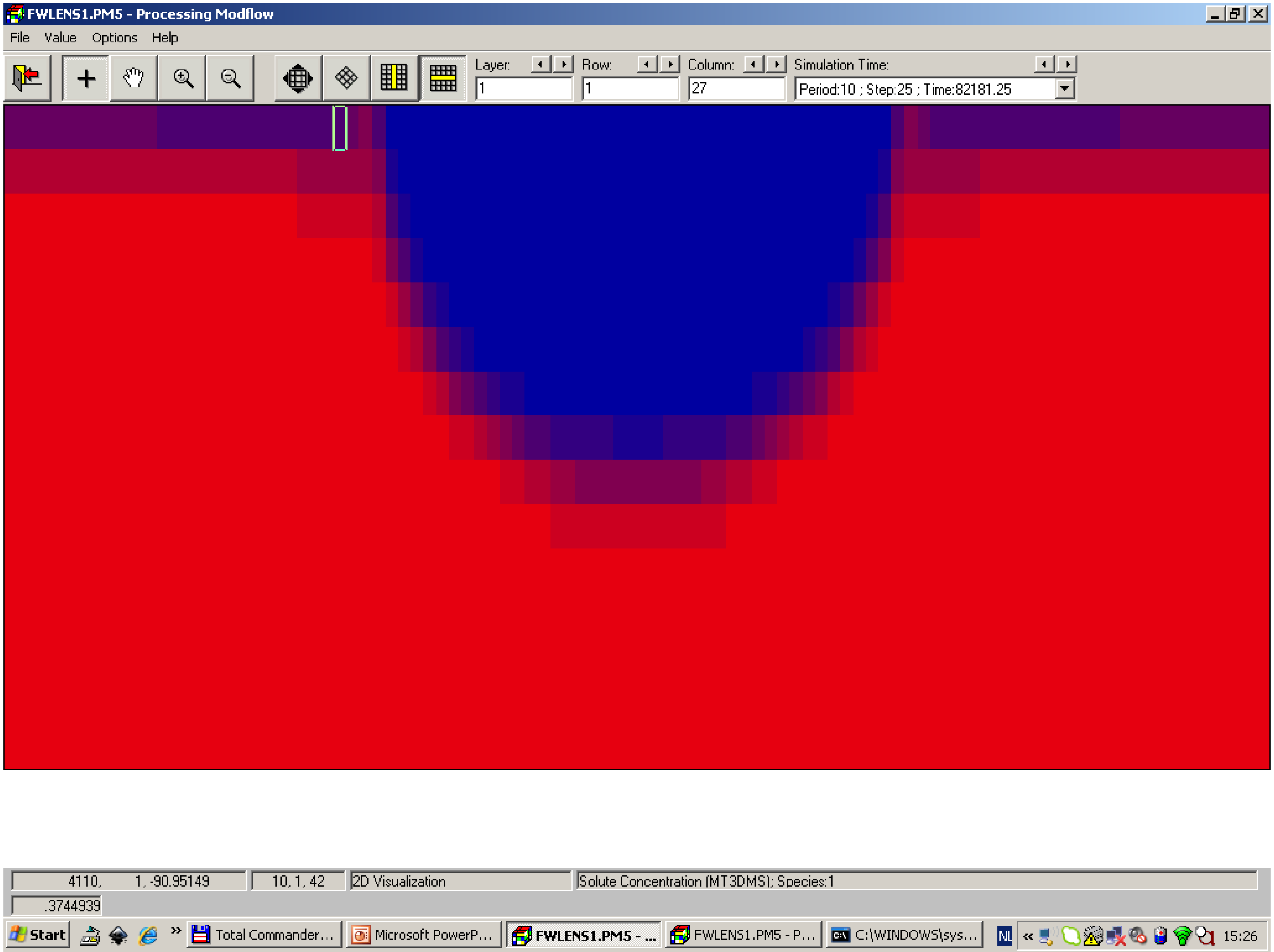
SEAWAT, MOC, 20sec, NPLANE=16, etc.



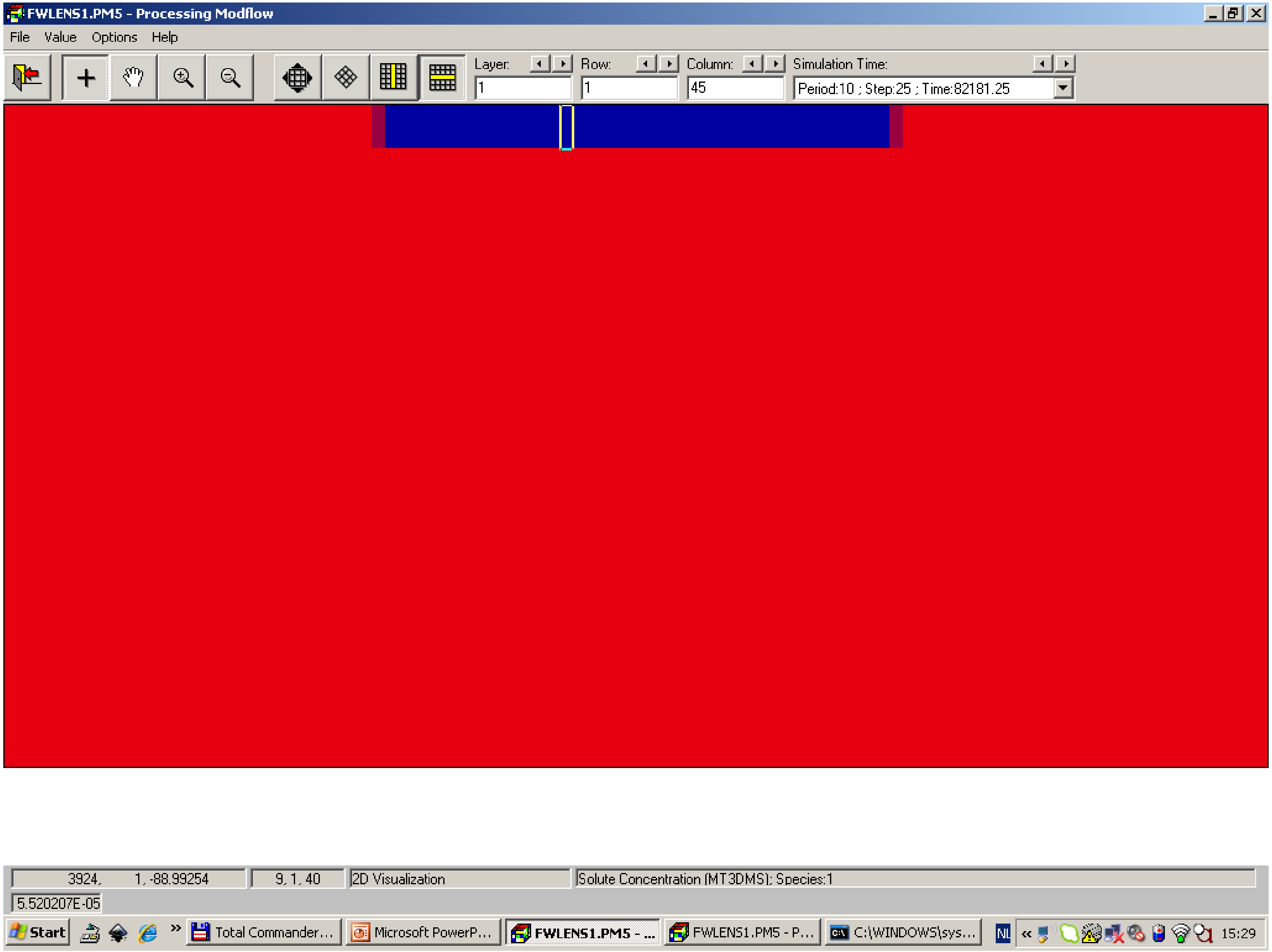
SEAWAT, ULTIMATE, 16.56sec



SEAWAT, MMOC, 8.5sec



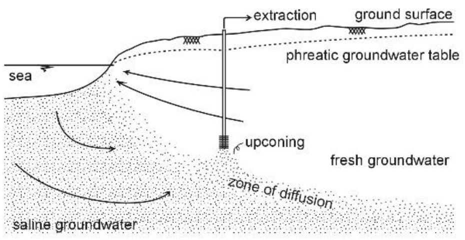
SEAWAT, HMOC, 6.8sec

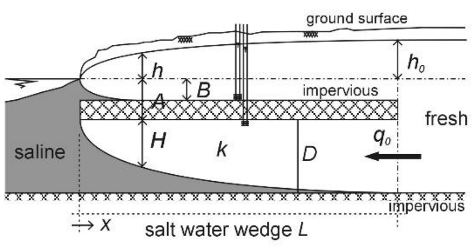


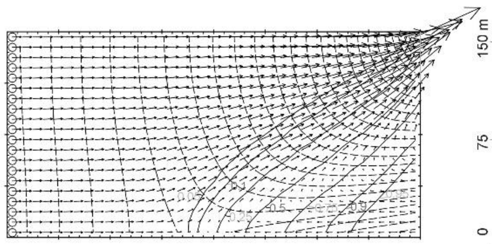
Analytical solutions

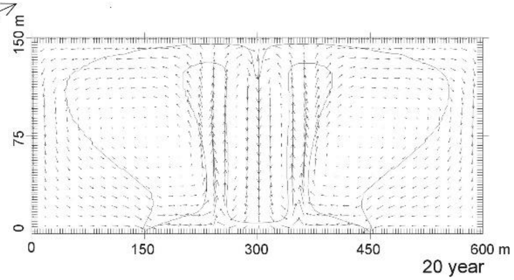
Analytical solutions

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



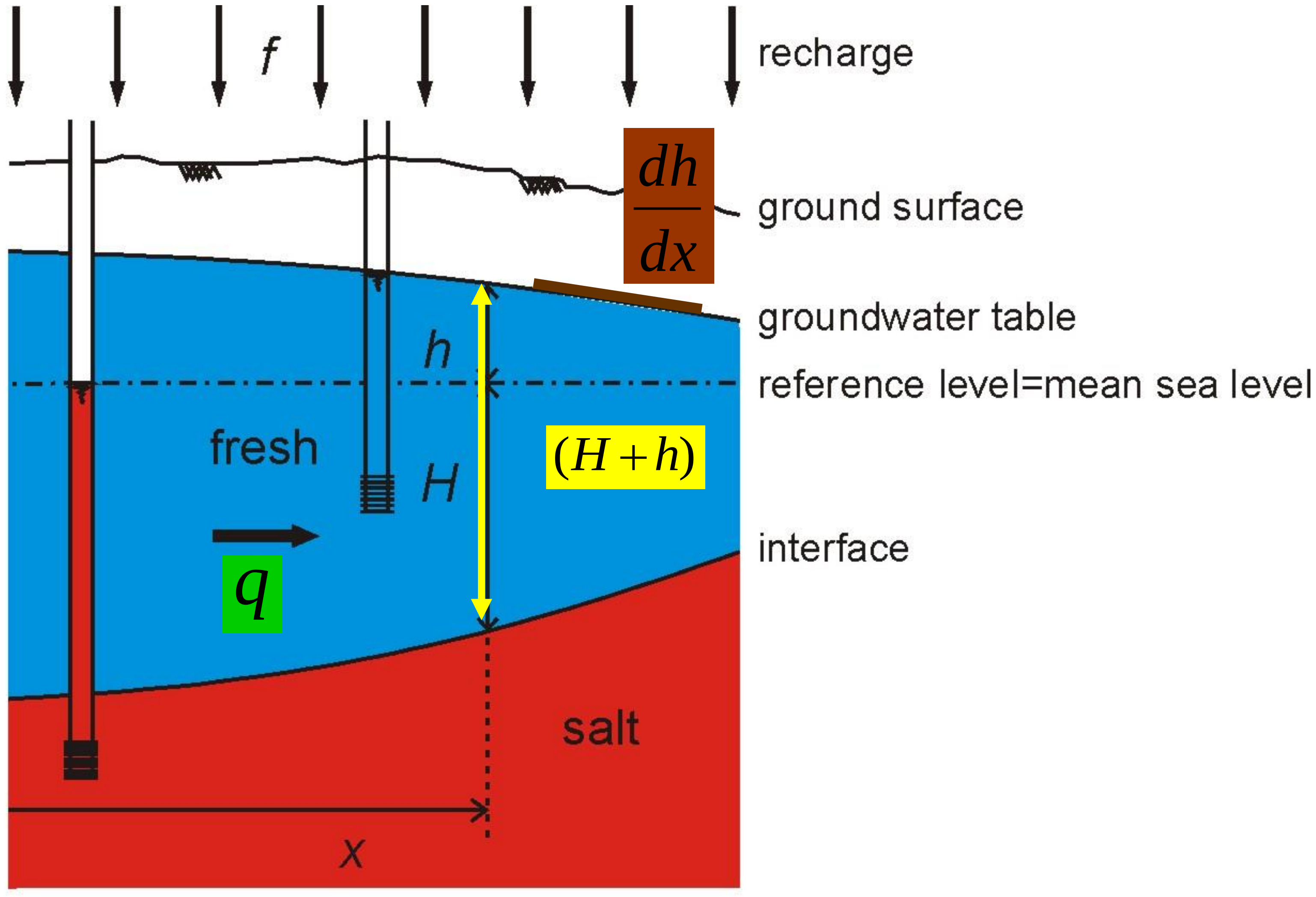






http://public.deltares.nl/display/FRESHSALT/Download

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)

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

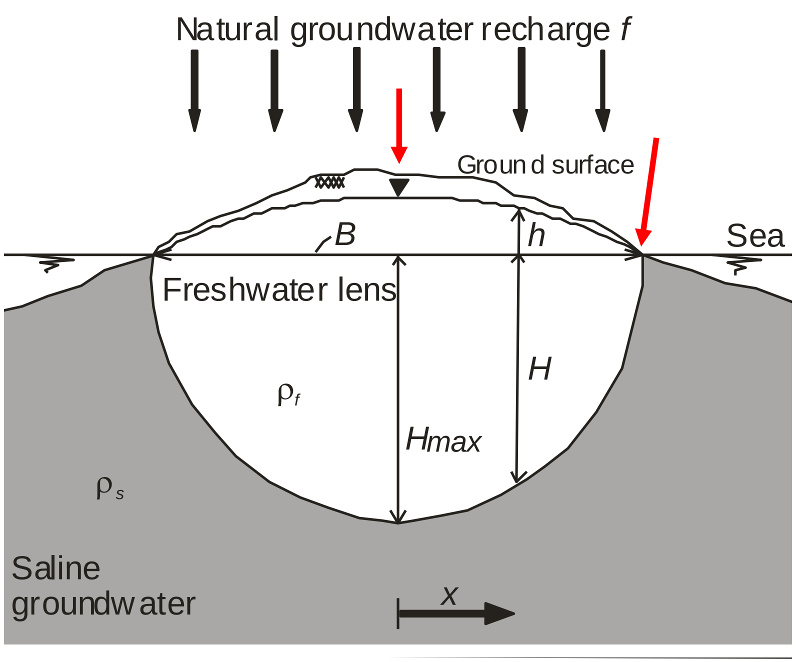
$$h = \alpha H$$

$$q = fx + C1$$

Example 1: Elongated island

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

$$q = fx + C1$$

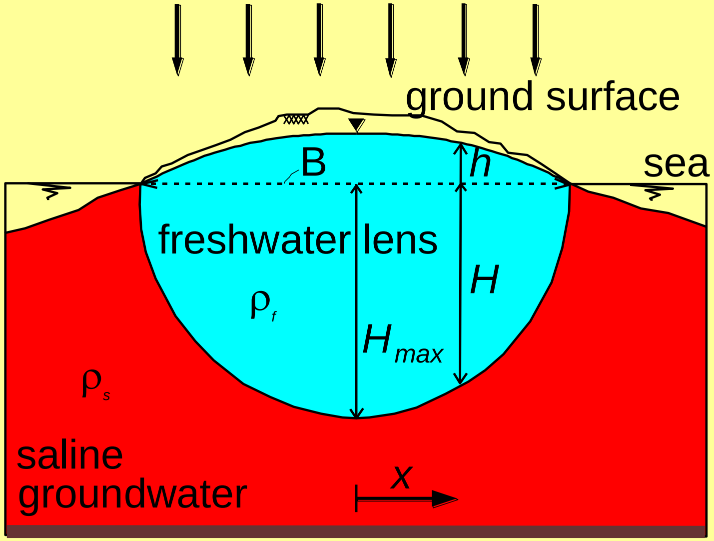


Boundary conditions

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

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

Example of analytical solutions (I)



Depth of fresh-saline interface H

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

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

Maximal thickness lens

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

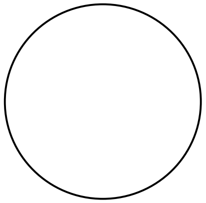
Volume lens

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

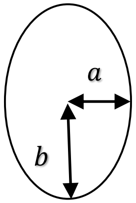
Characteristic time $\mathrm{T} = \dfrac{\text{volume of water in lens}}{\text{inflow of water}} = \dfrac{\pi n_e B}{8}\sqrt{\dfrac{(1+\alpha)}{kf\alpha}}$

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

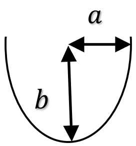
- Surface of a circle is: πr^2



- Surface of an ellips is: πab



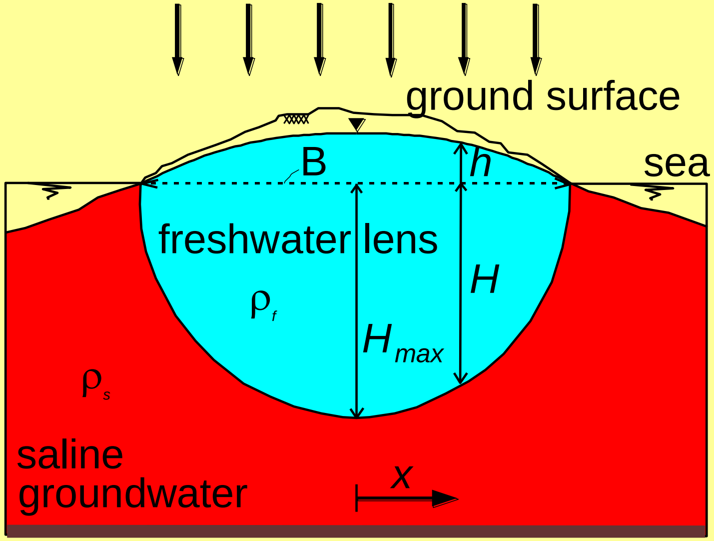
- Surface bottom lens: $\frac{1}{2}\pi ab$



- a=1/2B
- b=H_{max}

- Surface= ¼ πH_{max}B times n_e times *(1+α)* for the phreatic part

Example of analytical solutions (I)



Depth of fresh-saline interface H

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

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

$$n_e = 0.35$$

Maximal thickness lens

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

Volume lens (wrong in lectures notes)

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

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

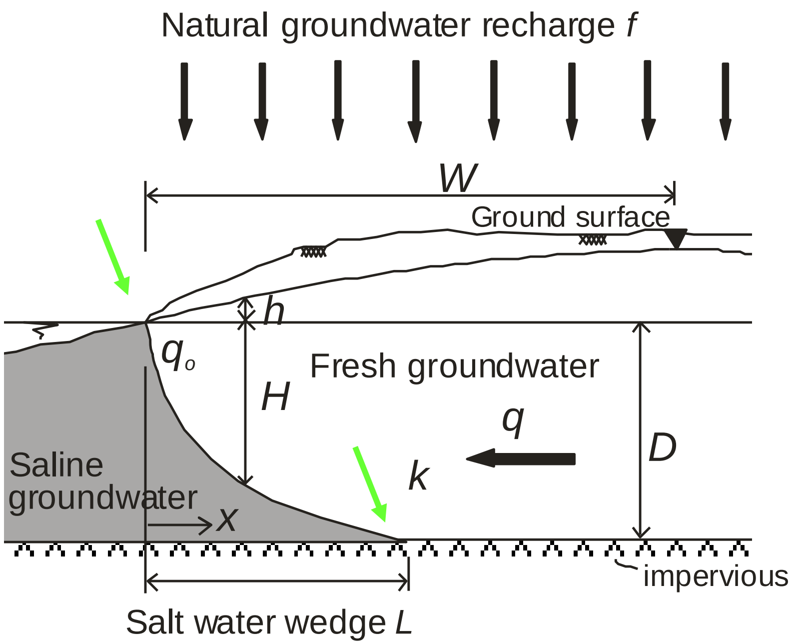
Lecture notes p. 32

W=4000m
f=1mm/d=0.001m/d
Q_recharge=$4m^3$/d per meter'=$4m^2$/d

50%=$2m^2$/d

Example 2: salt water wedge

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



Boundary conditions

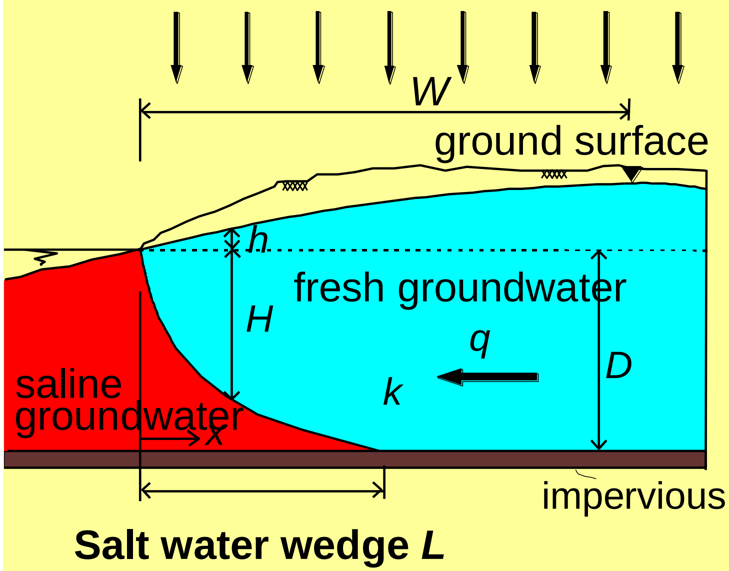
$$x = 0 : q = q_0 \rightarrow q_0 = -fW \rightarrow C1 = q_0$$

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

Length of salt water wedge

$$x = L : H = D$$

Example of analytical solutions (II)



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

$$q_0 = -fW$$

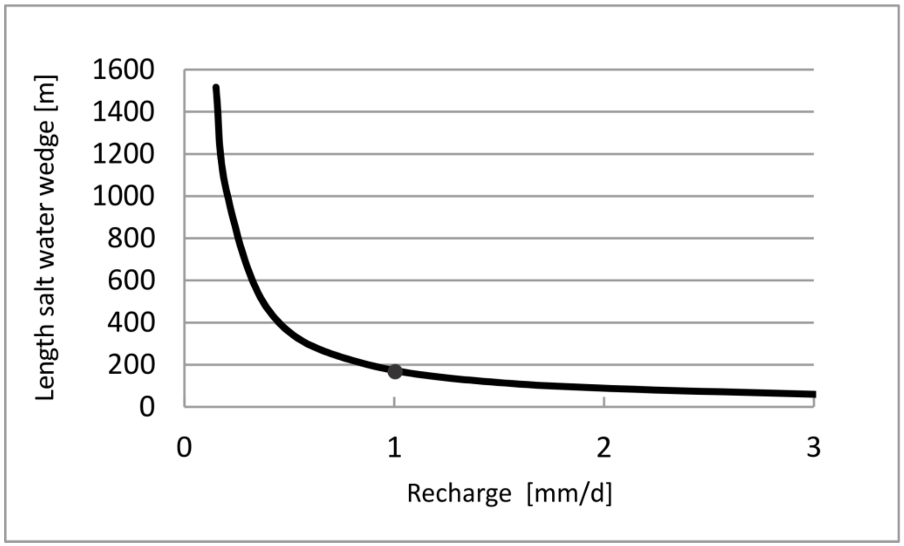
$$h = \alpha H$$

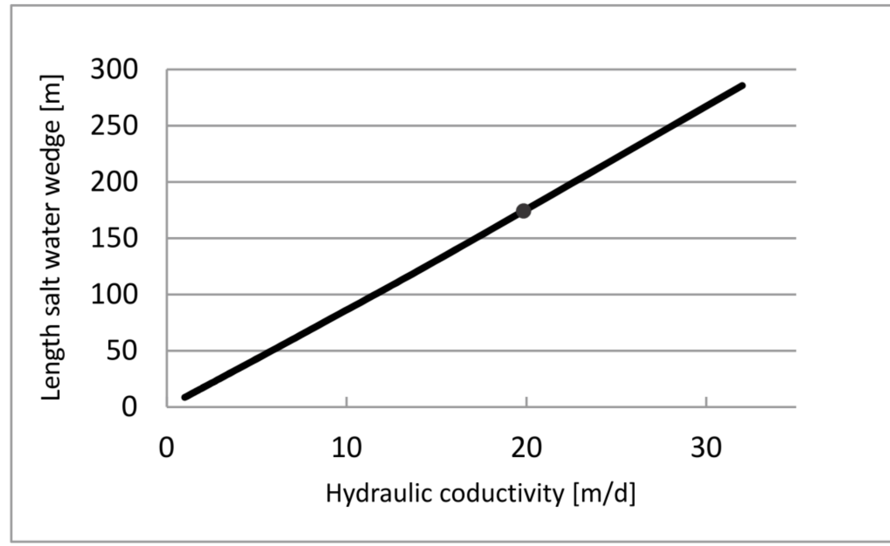
Example:

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

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

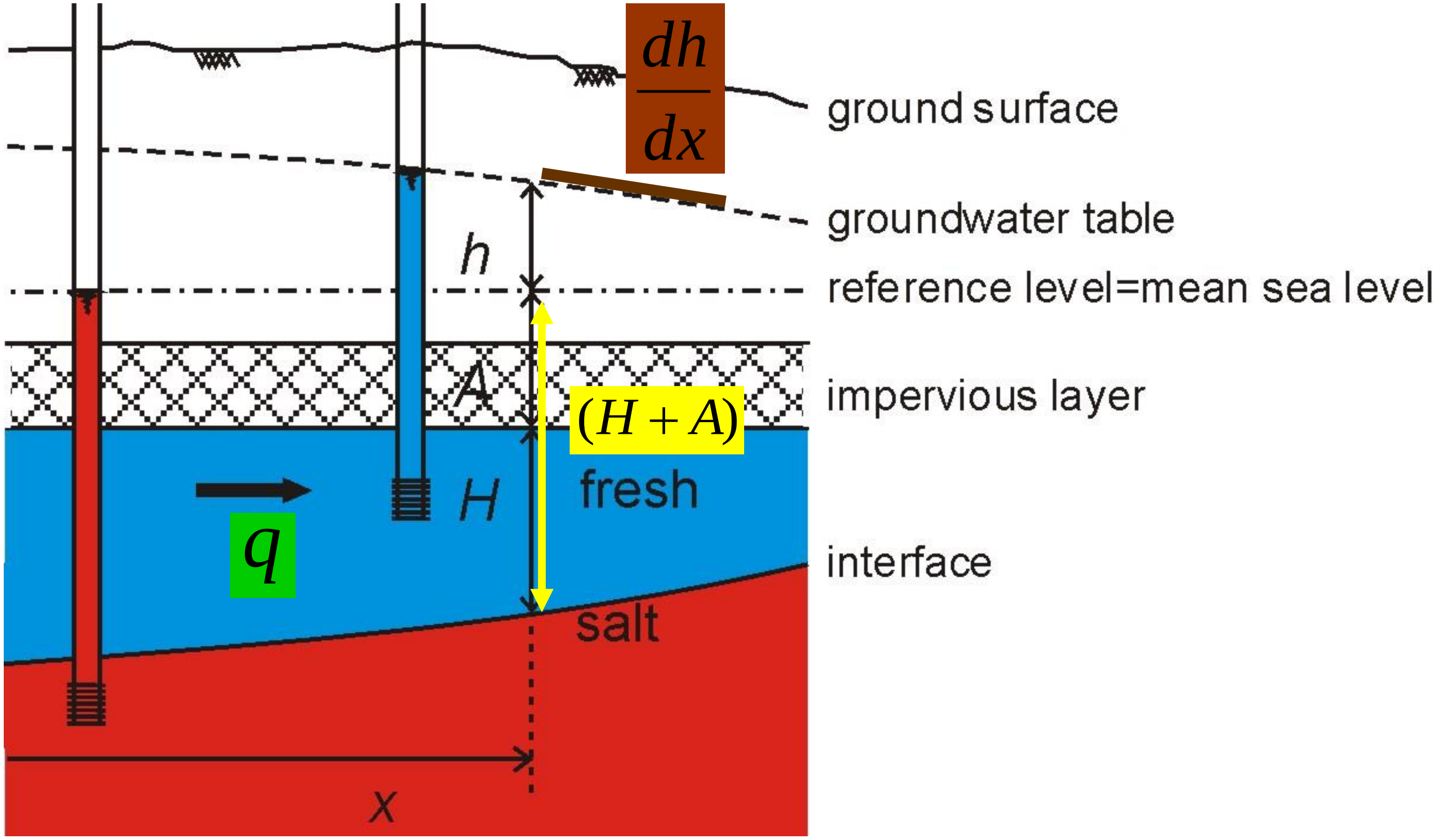
Length of the salt water wedge as a function of a. recharge and b. hydraulic conductivity





the dots resample with the example mentioned above

Confined aquifer (1D situation)



Confined aquifer (1D situation)

(I) Darcy

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

(II) Continuity

$$q = q_o$$

(III) BGH

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

Confined aquifer (1D situation)

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

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

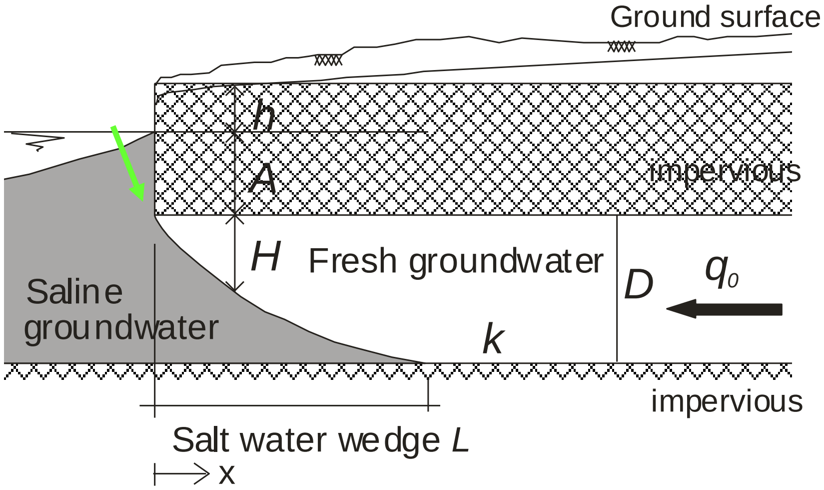
integration gives

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

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

Example 3: salt water wedge confined aquifer

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



Boundary condition

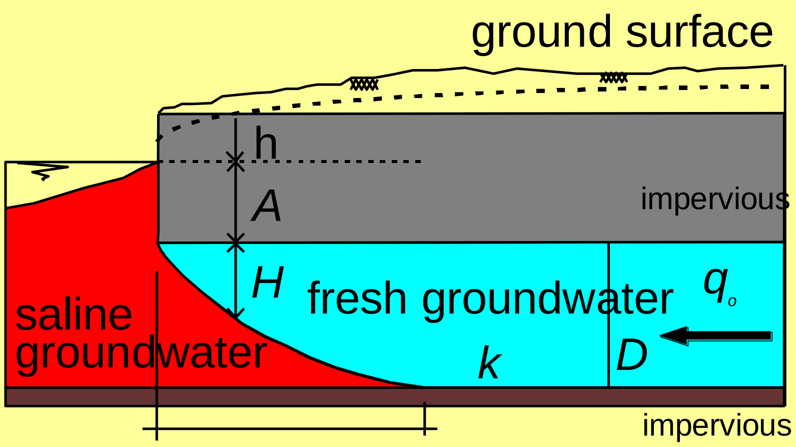
$$x = 0 : H = 0 \rightarrow C = 0$$

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

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

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

Example of analytical solutions (III)



Length of salt water wedge

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

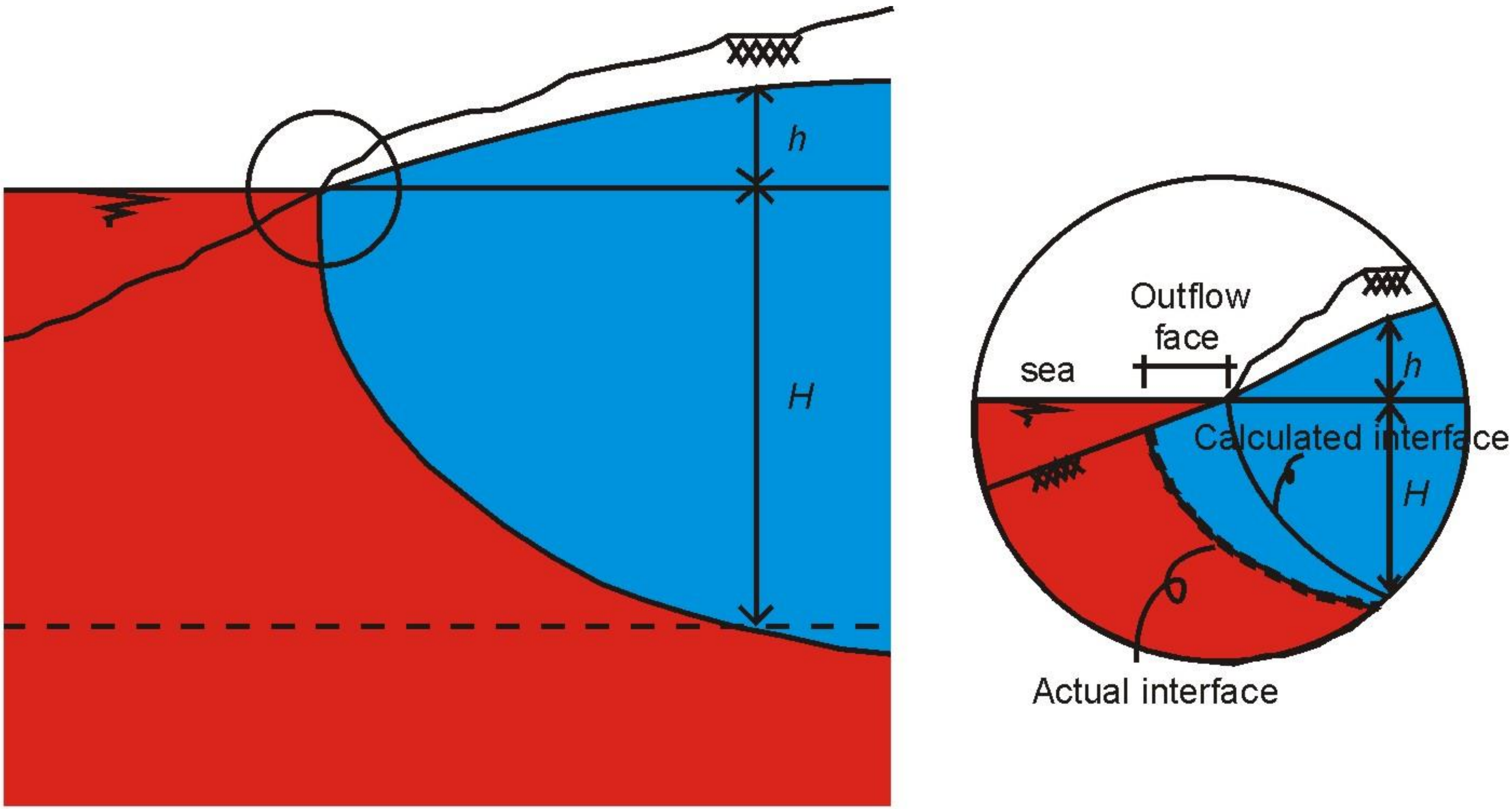
$$L = -\frac{kD^2\alpha}{2q_0}$$

Example:

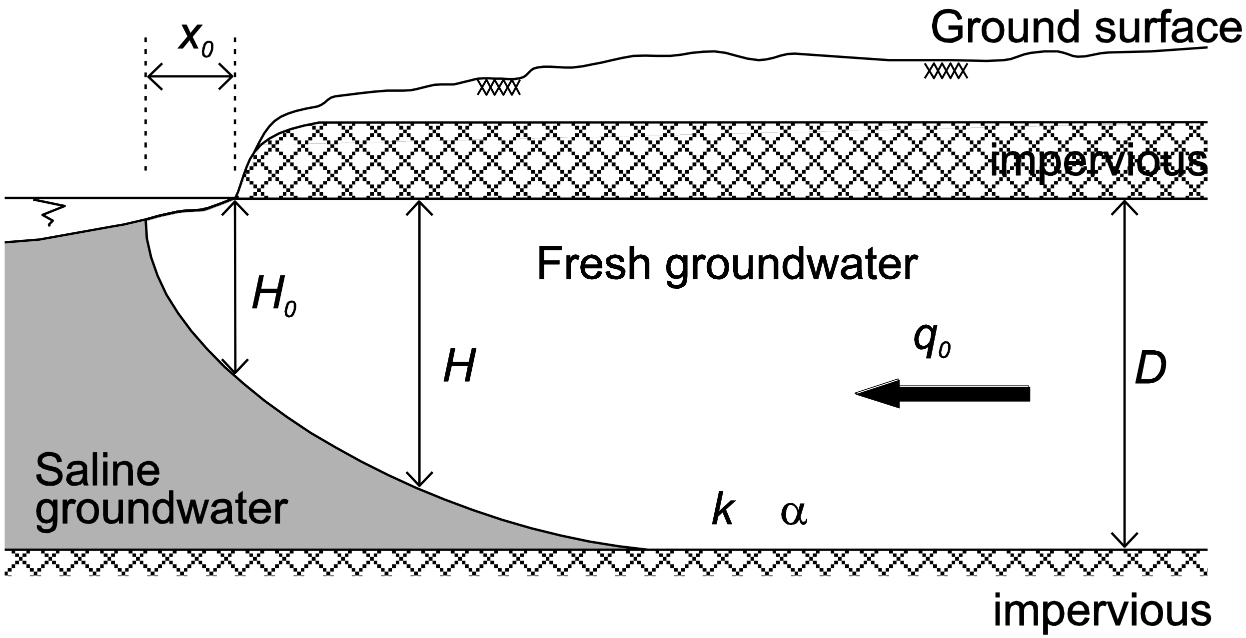
$$W = 2000\text{m},\ f = 0.001\text{m/day},\ \alpha = 0.025,\ k = 25\text{m/day},\ D = 40\text{m}$$

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

Outflow face (Submarine Groundwater Discharge)



Outflow face (Submarine Groundwater Discharge)

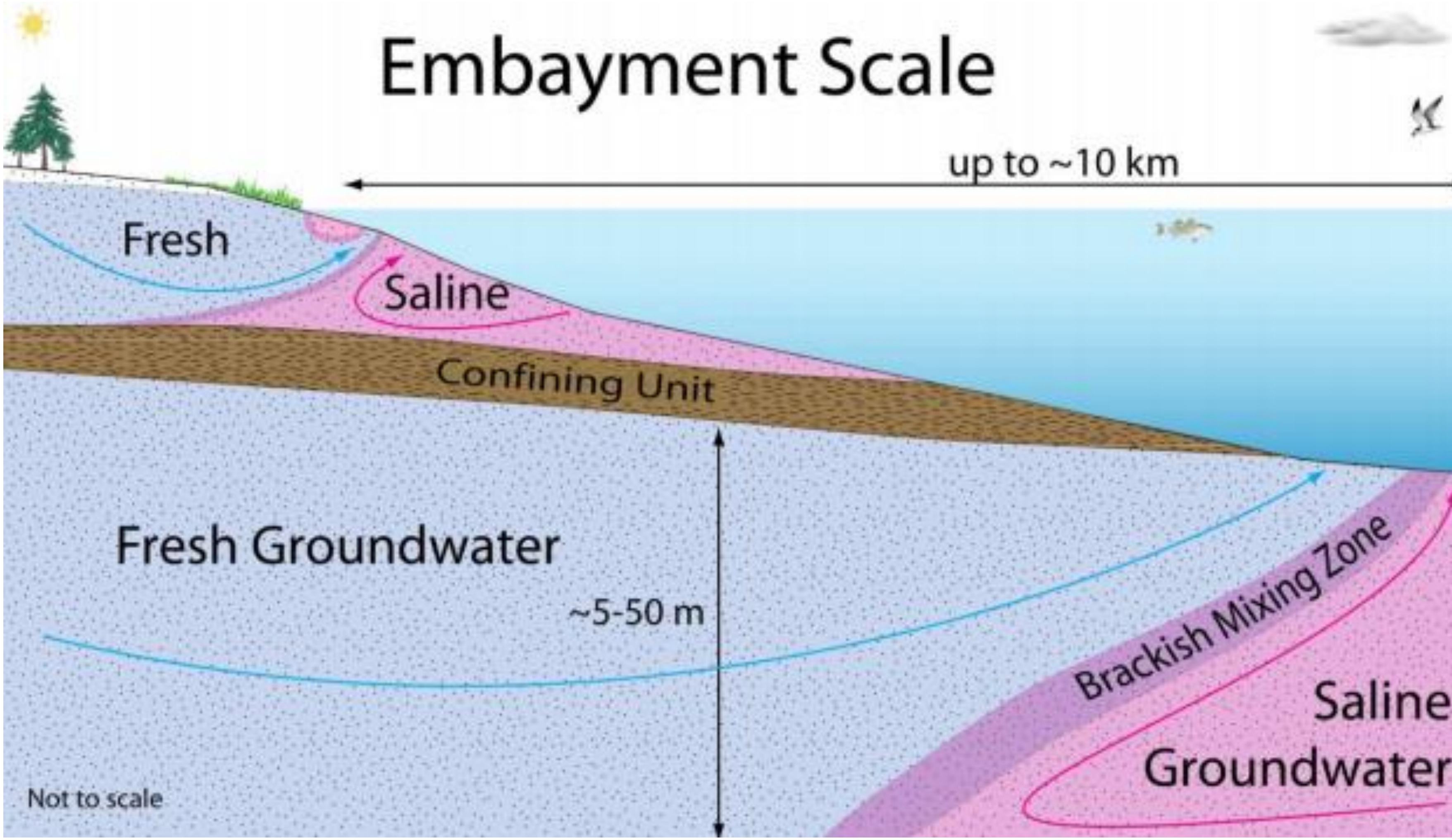


$$x_0 = \frac{q_0}{2k\alpha} \qquad H_0 = \frac{q_0}{k\alpha}$$ Glover (1959)

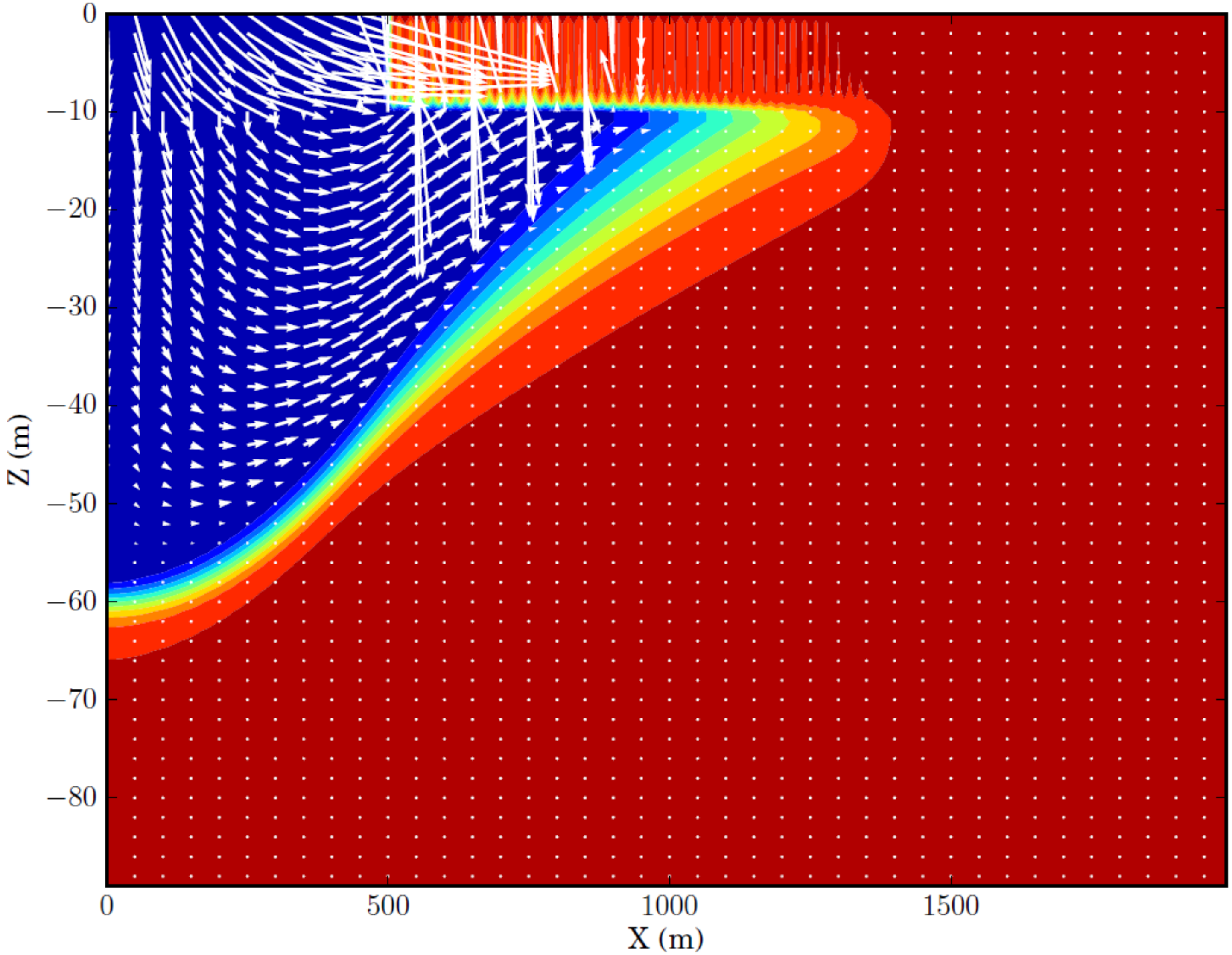
Example:
x_0= f*L/(2ka) = 0.001m/d*20000m/(2*20*0.025) = 20m (only!)

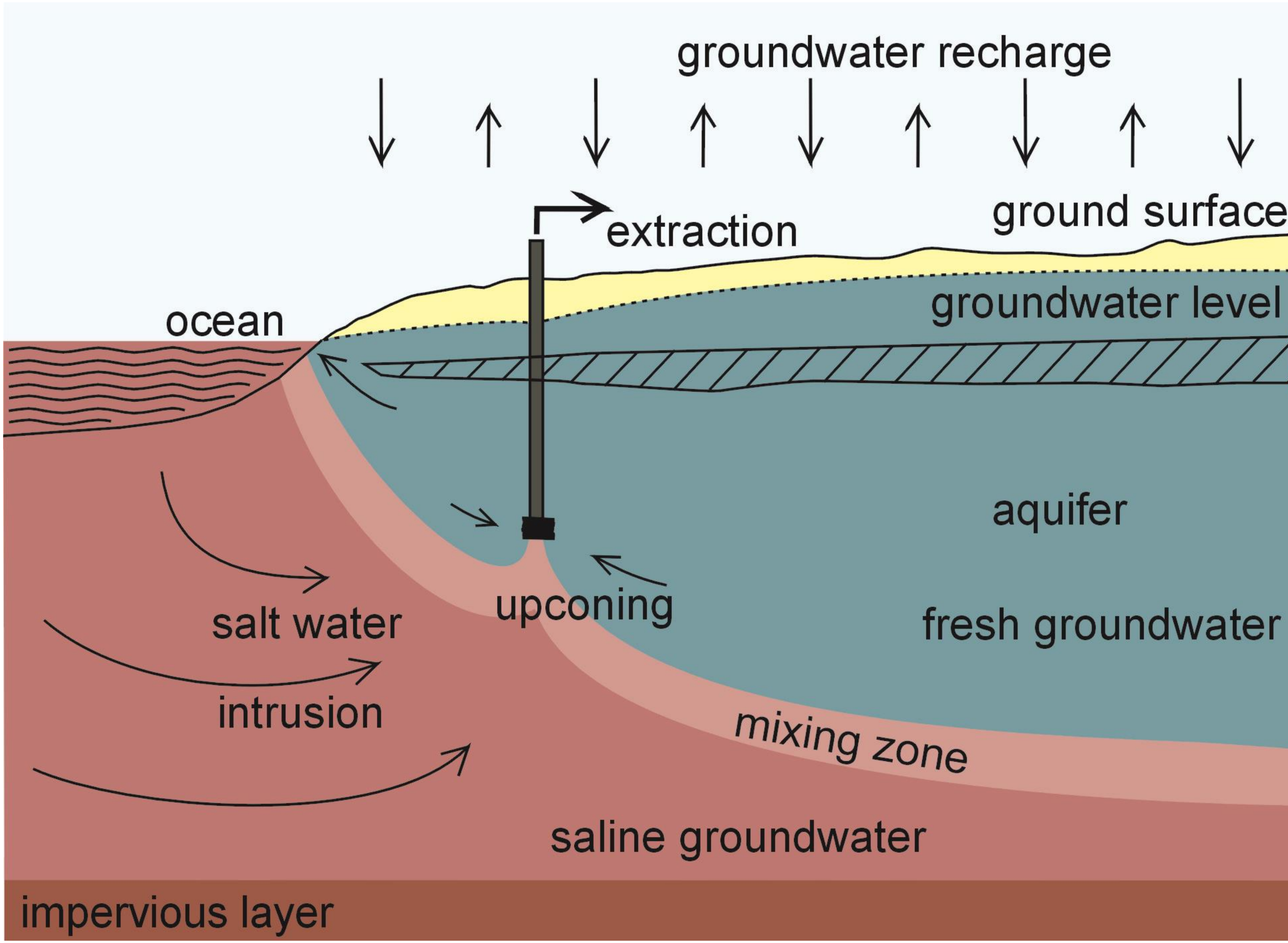
Note: no resistance layer offshore

Outflow face (Submarine Groundwater Discharge)

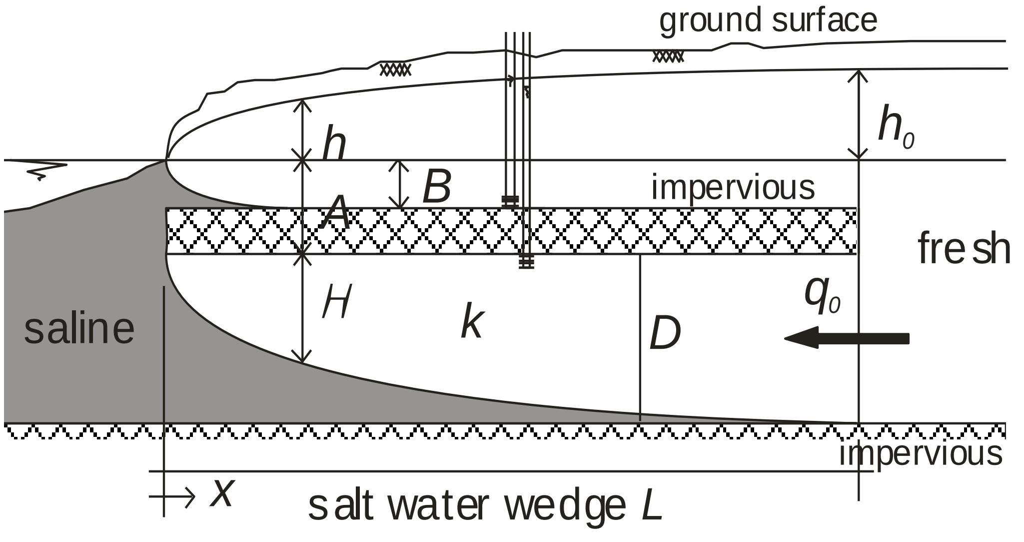


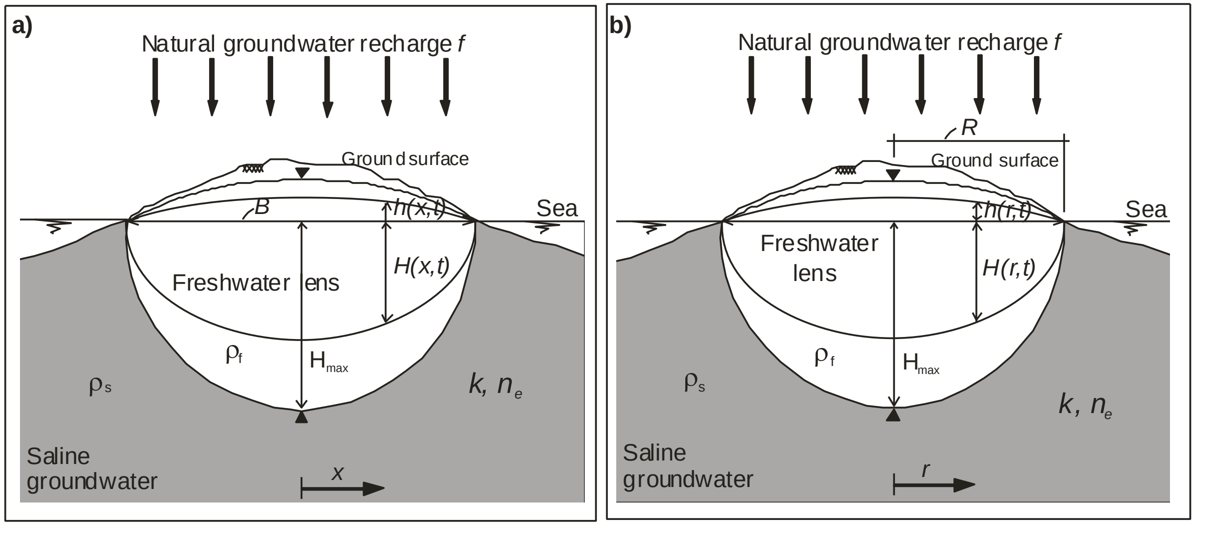
Outflow face (Submarine Groundwater Discharge)




groundwater recharge
extraction
ground surface
groundwater level
ocean
aquifer
upconing
salt water
intrusion
fresh groundwater
mixing zone
saline groundwater
impervious layer

See the lectures for more cases

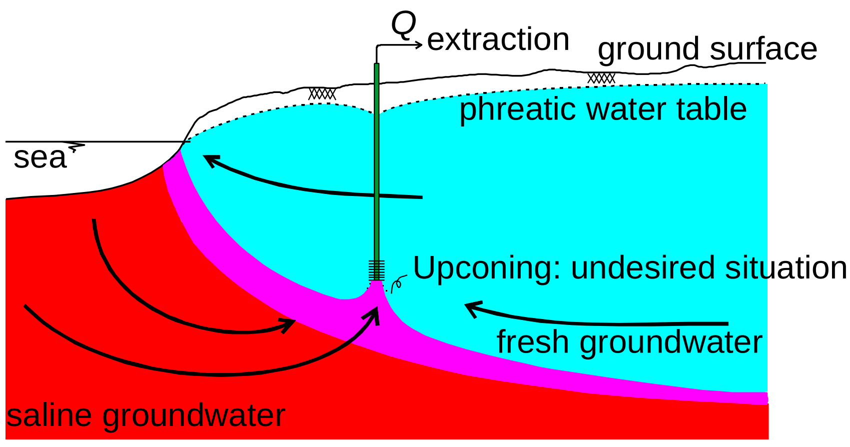




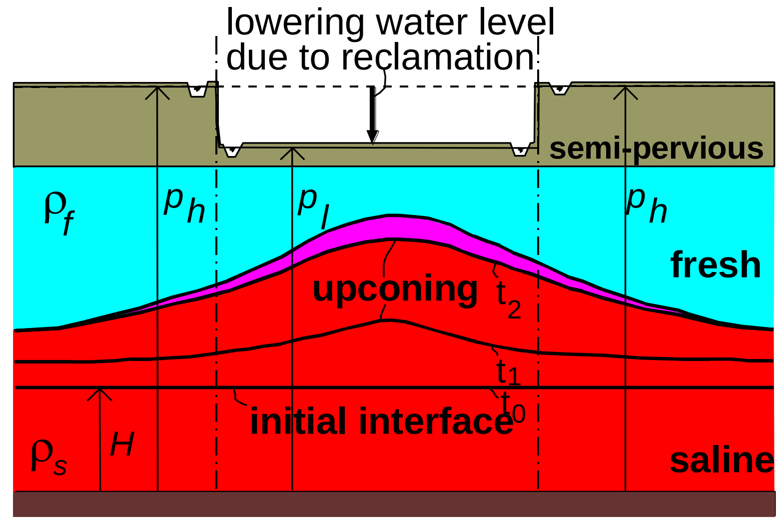
Upconing processes

Upconing of saline groundwater

Under an extraction well



Under a low-lying polder area

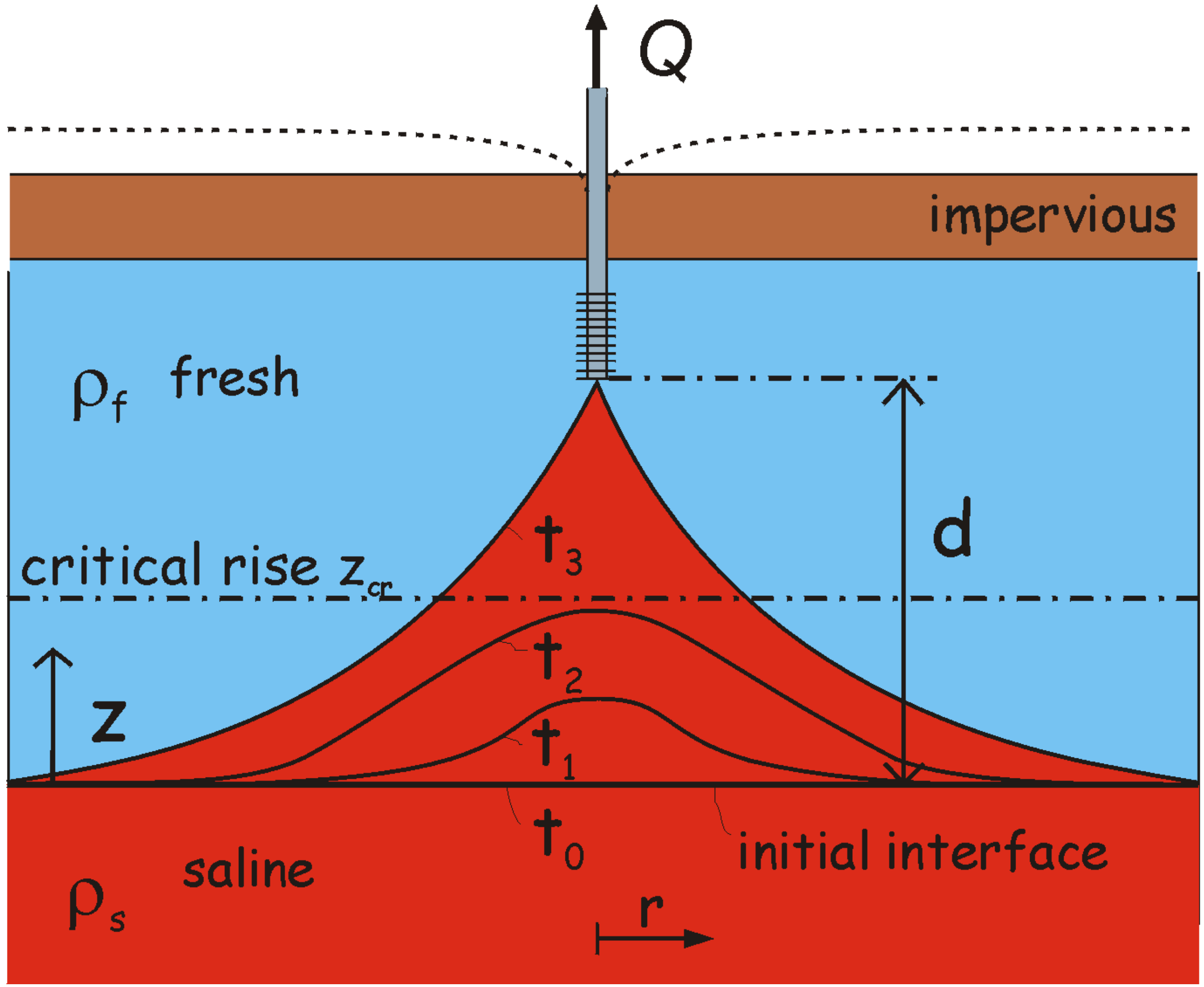


- movement of saline groundwater to extraction wells
- increase in salinity (>150-200 mg Cl-/l)
- lowering of the piezometric head (leads to land subsidence: e.g. Los Angeles: 9 m in the 1930's)

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

Examples of analytical solutions (IV)

Upconing of saline groundwater under an extraction well



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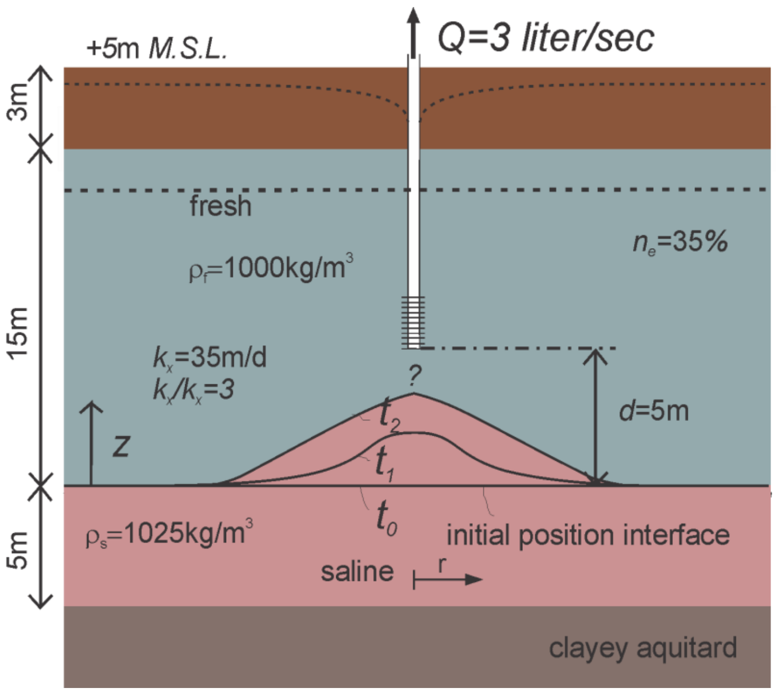
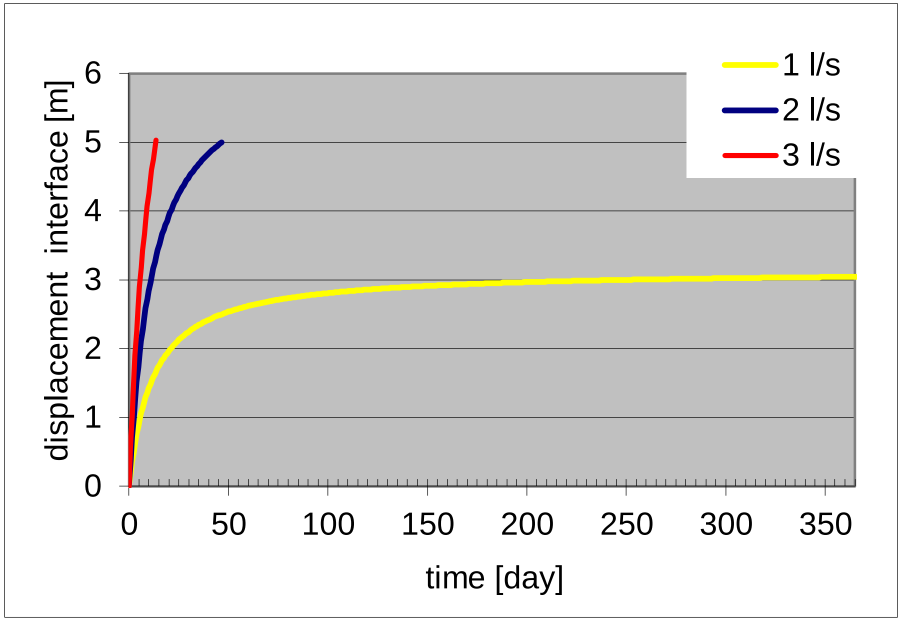
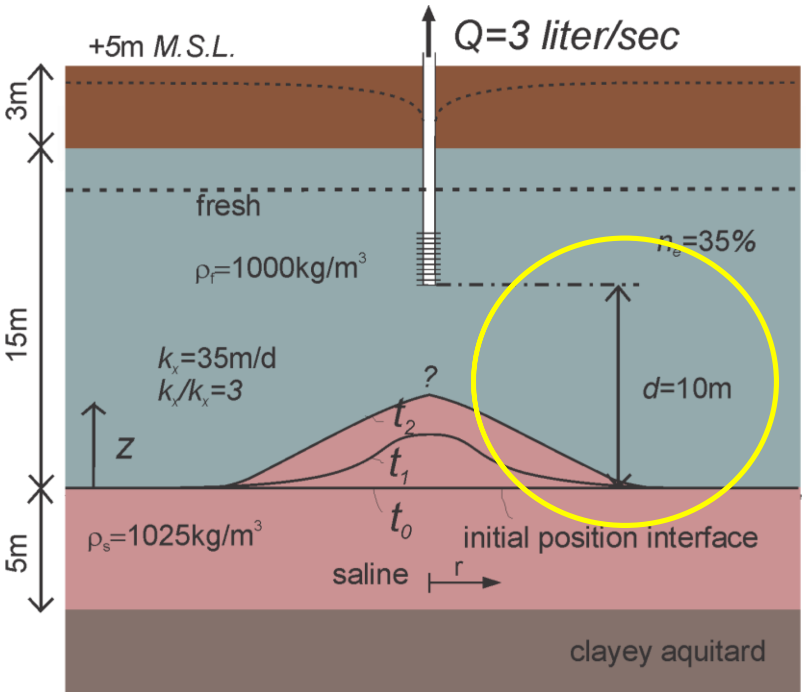
Situation Jurong Island: pilot extraction well

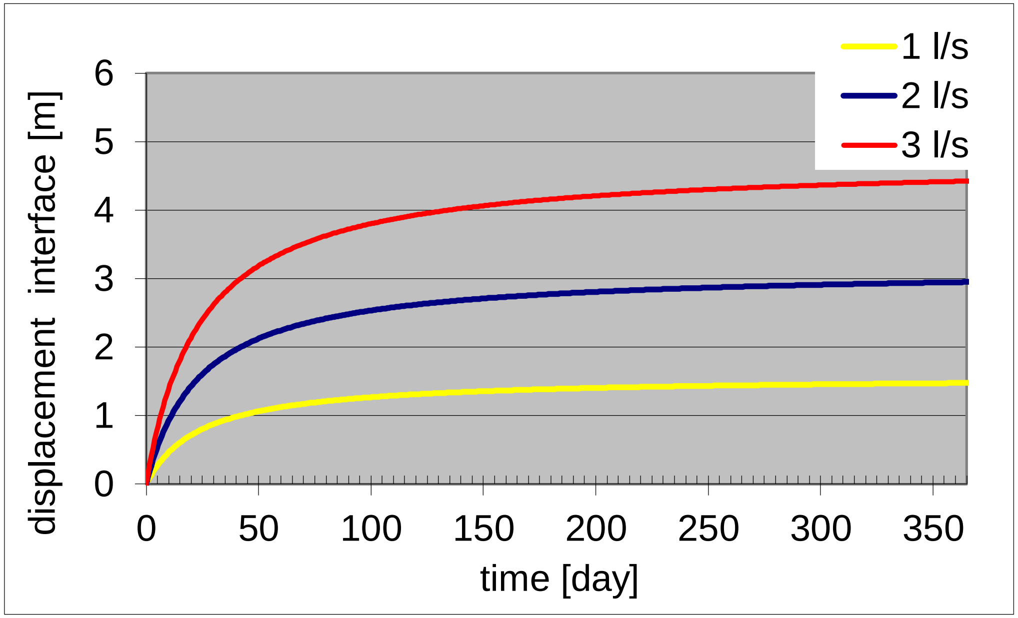




- Distance between well screen and initial interface: 5m
- Rapid upconing of interface, depending on extraction rate
- No saline groundwater in extraction well with scenario 1 l/s
- Good set-up for testing system

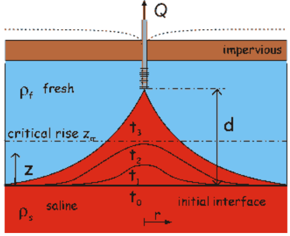
Situation Jurong Island: pilot extraction well: d=10m!





- **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

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

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

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

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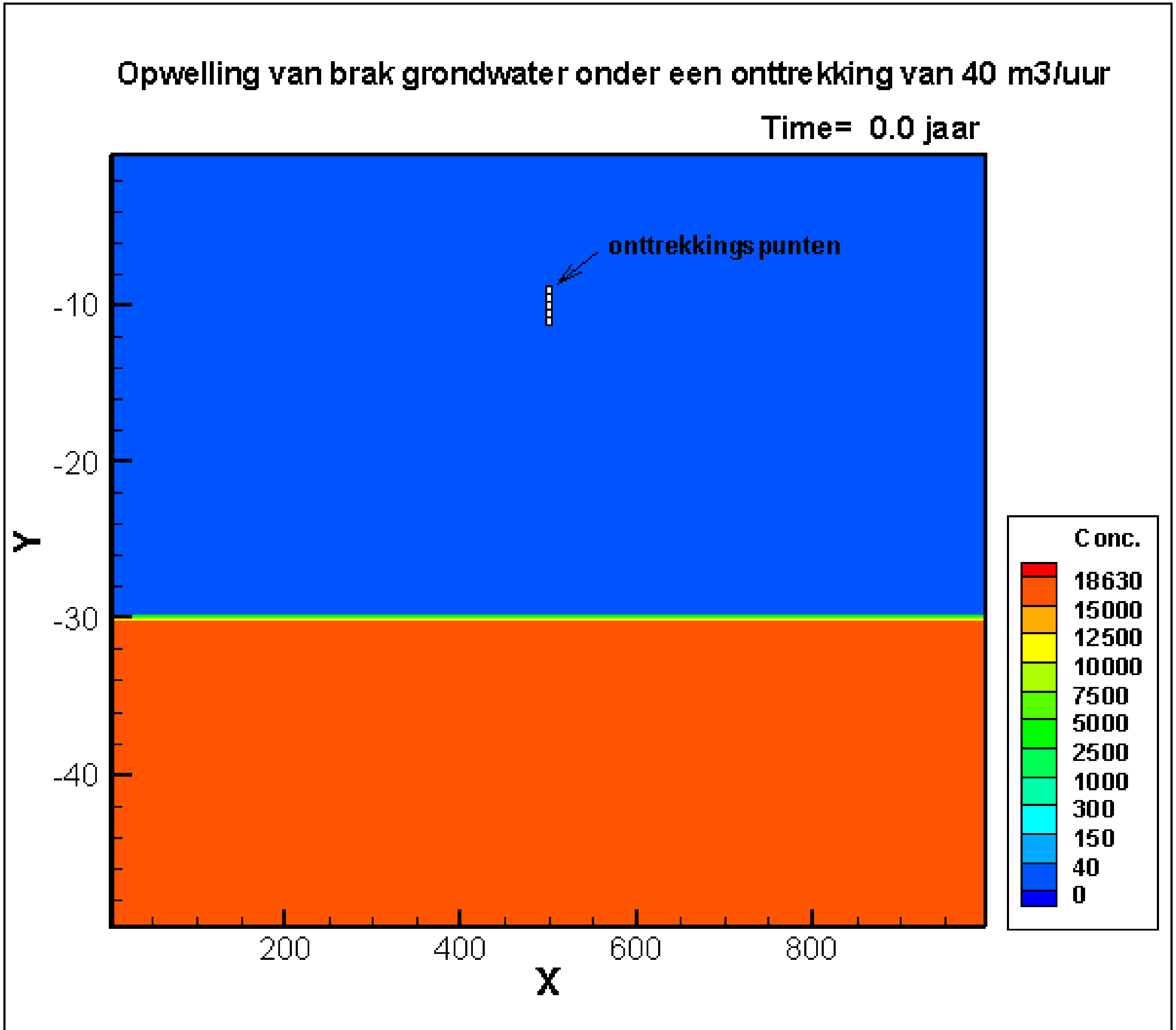
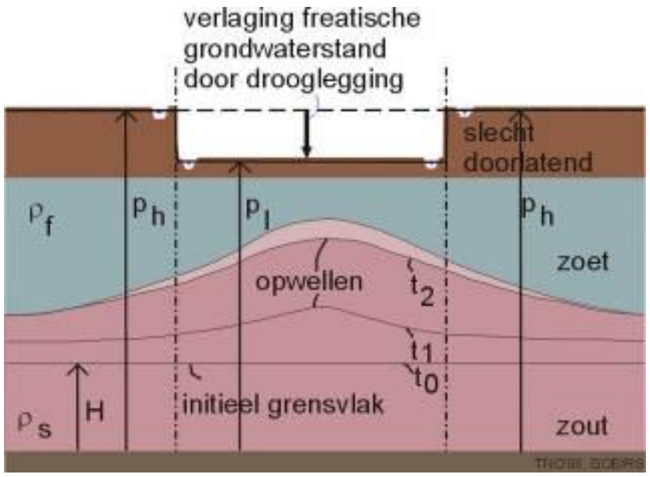
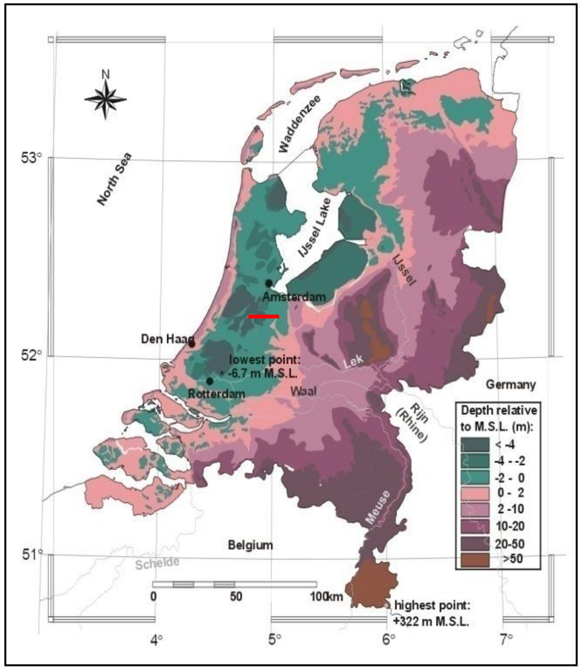
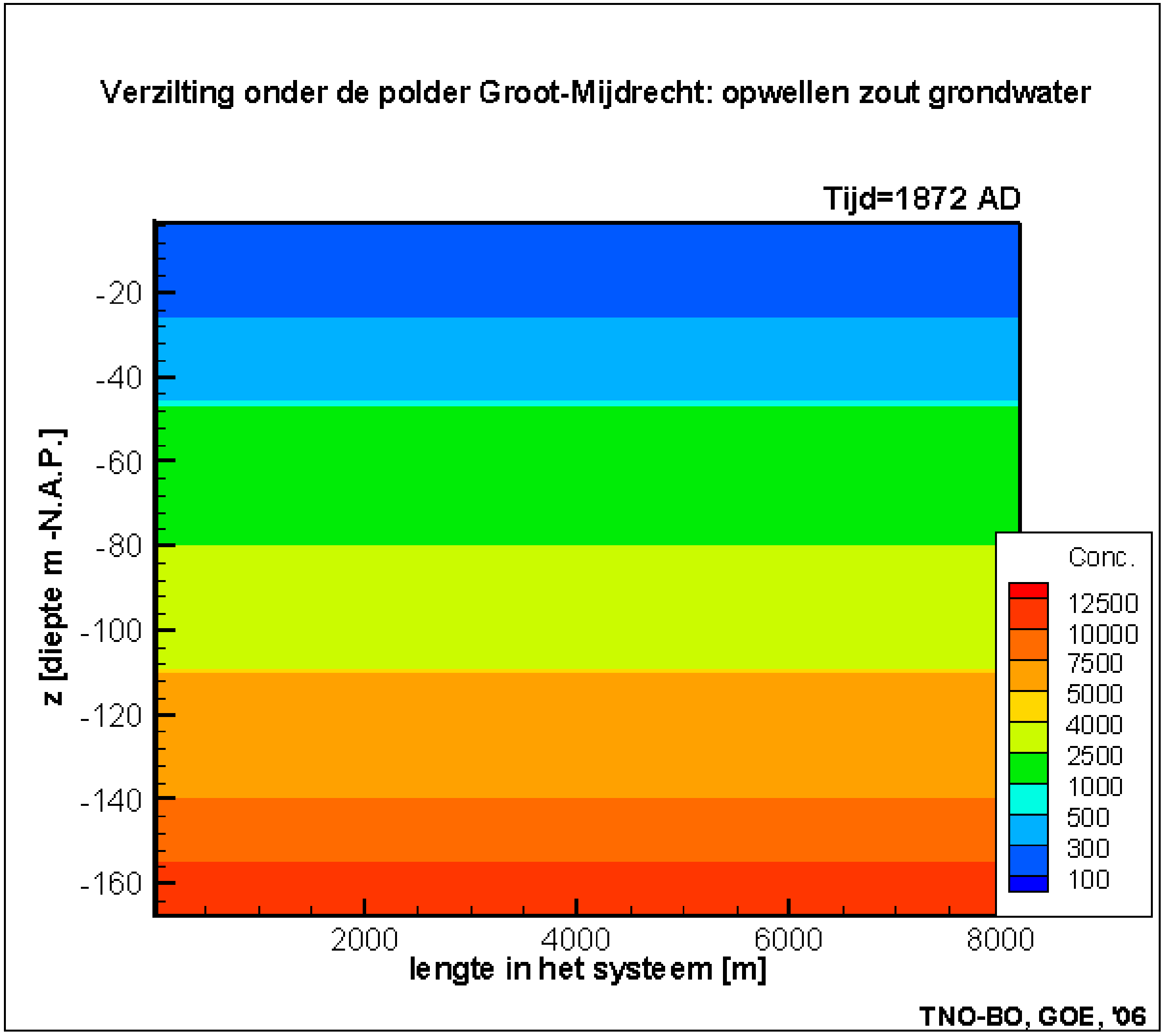
Upconing of salt under an extraction



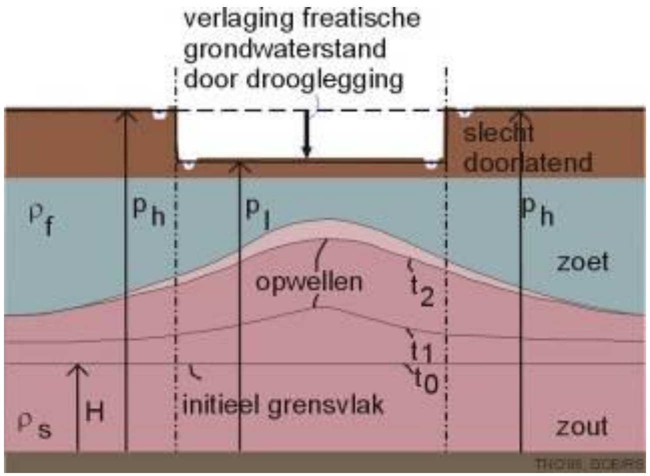
Upconing under a low-lying polder (Groot-Mijdrecht)

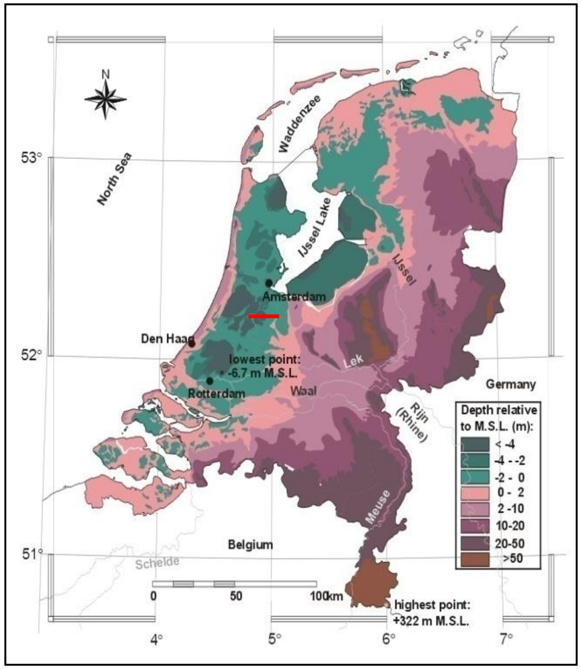


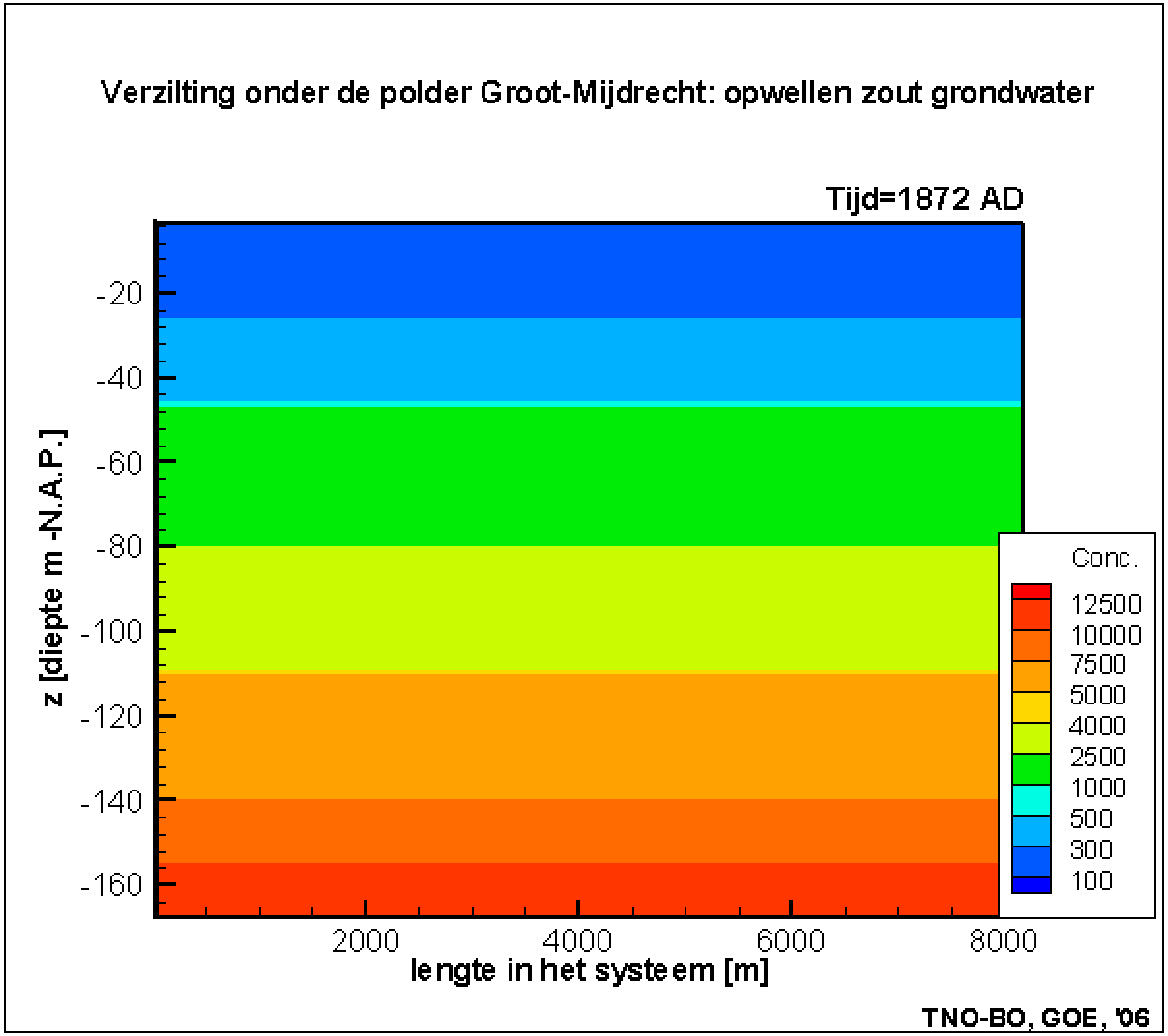




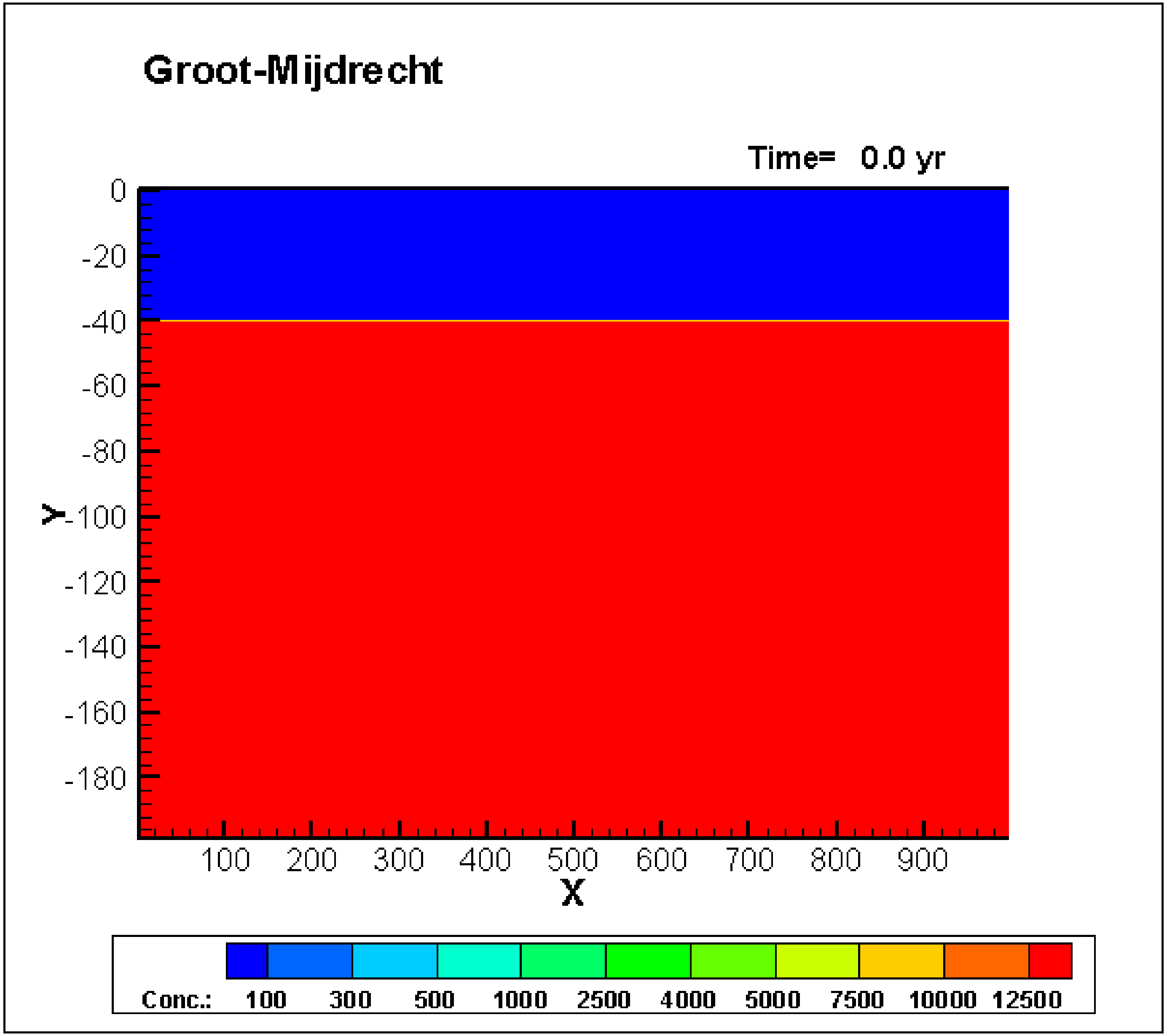
Upconing under a low-lying polder (Groot-Mijdrecht)



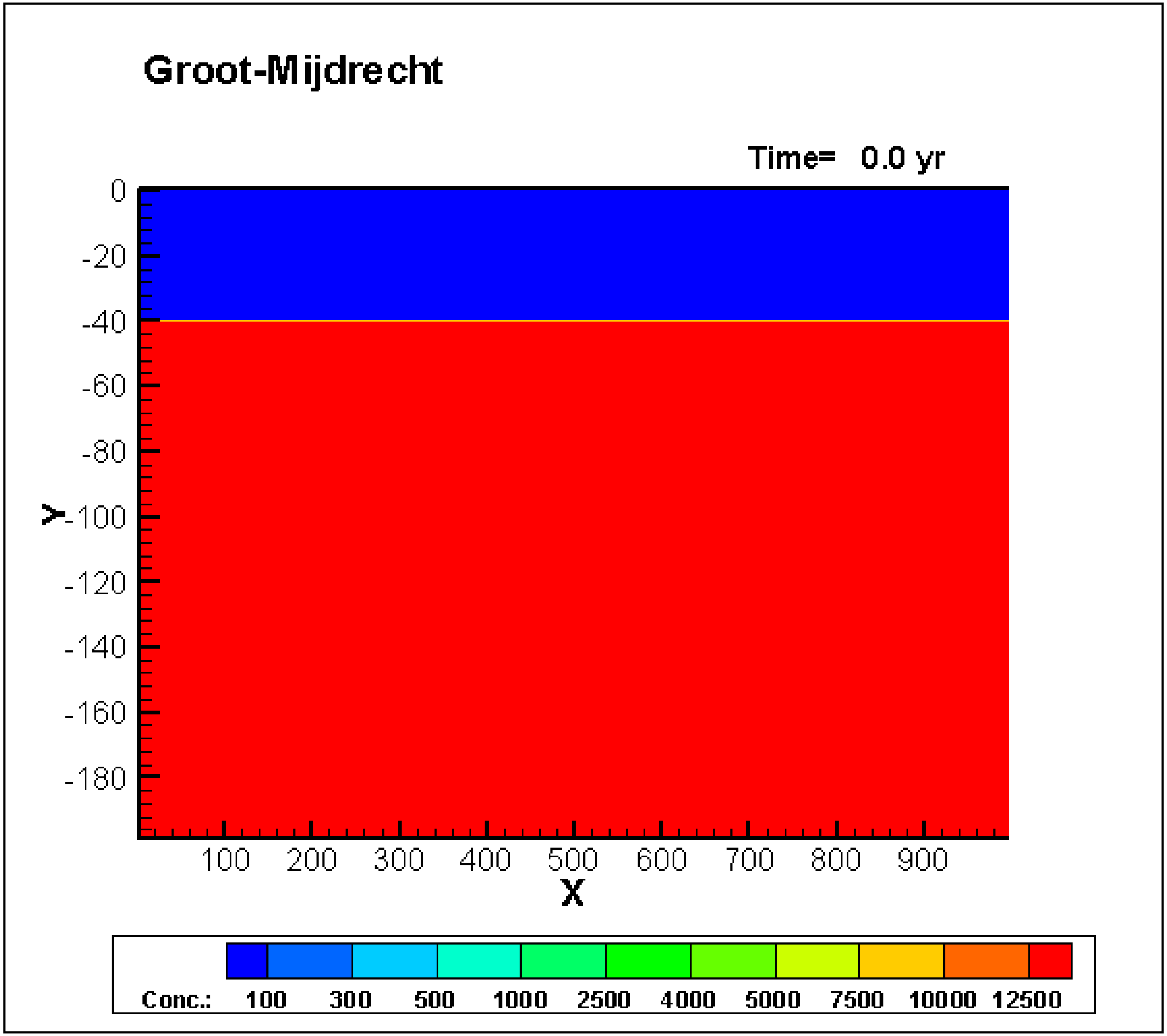




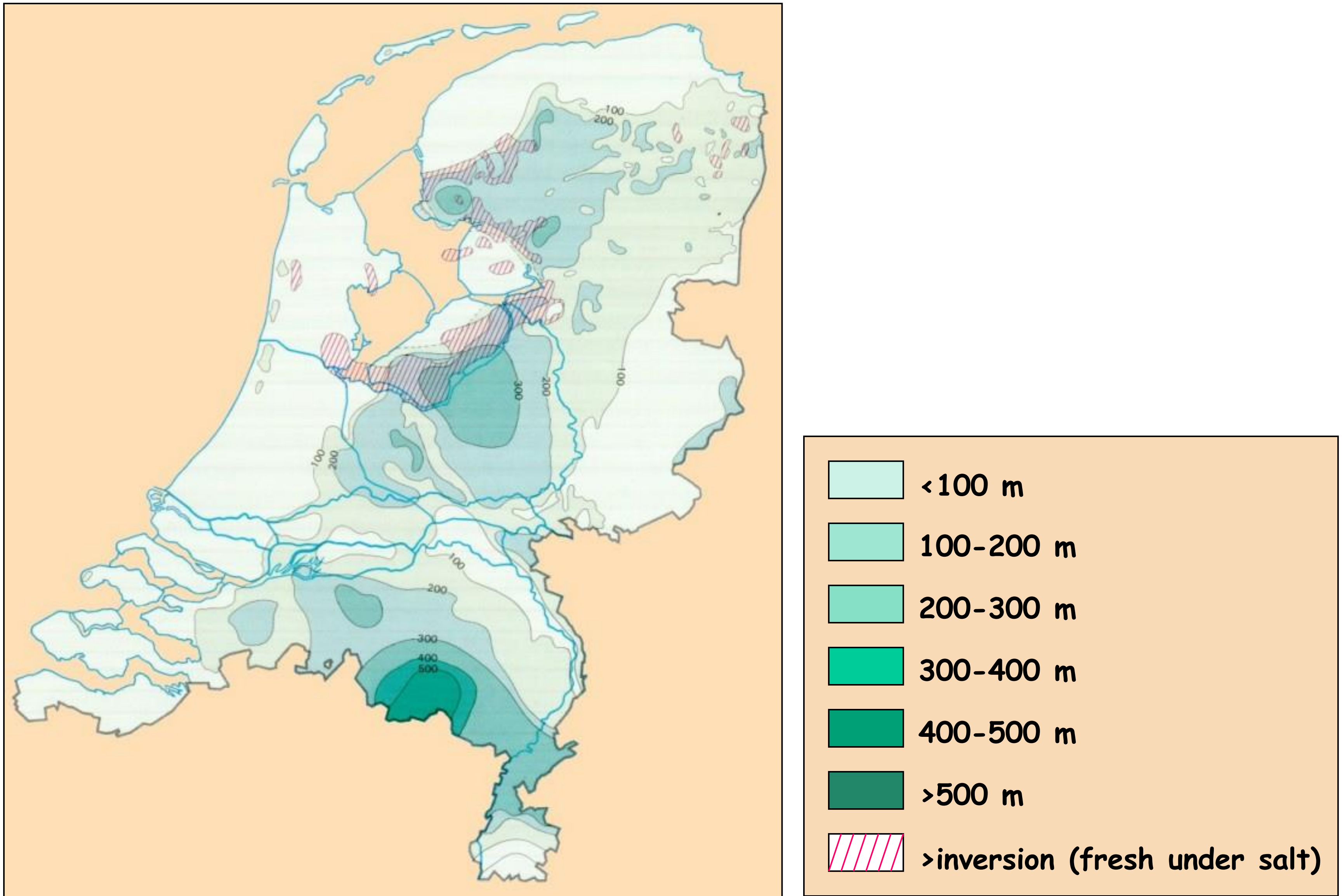
Upconing under a low-lying polder (Groot-Mijdrecht)



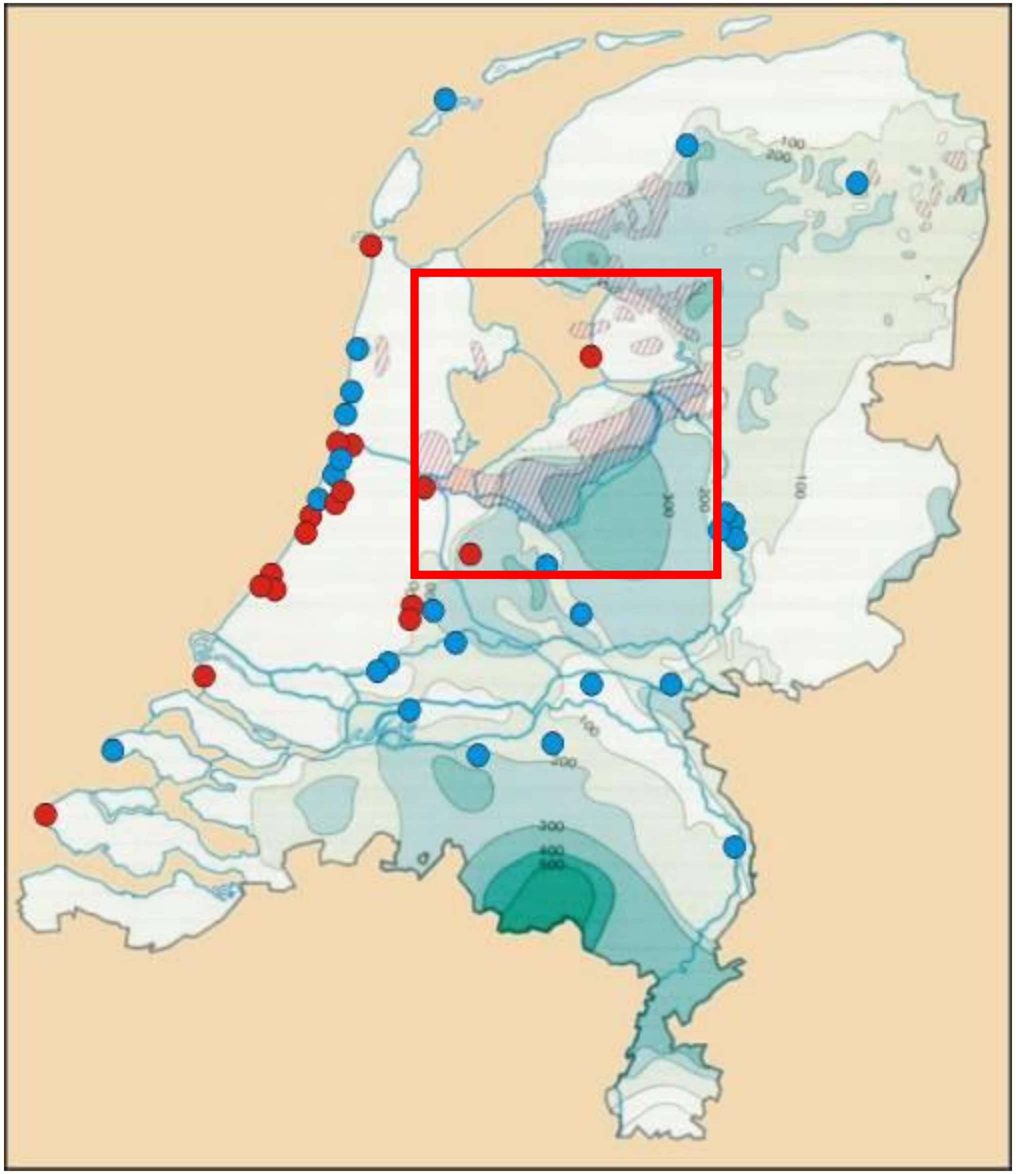
Upconing under a low-lying polder (Groot-Mijdrecht)



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



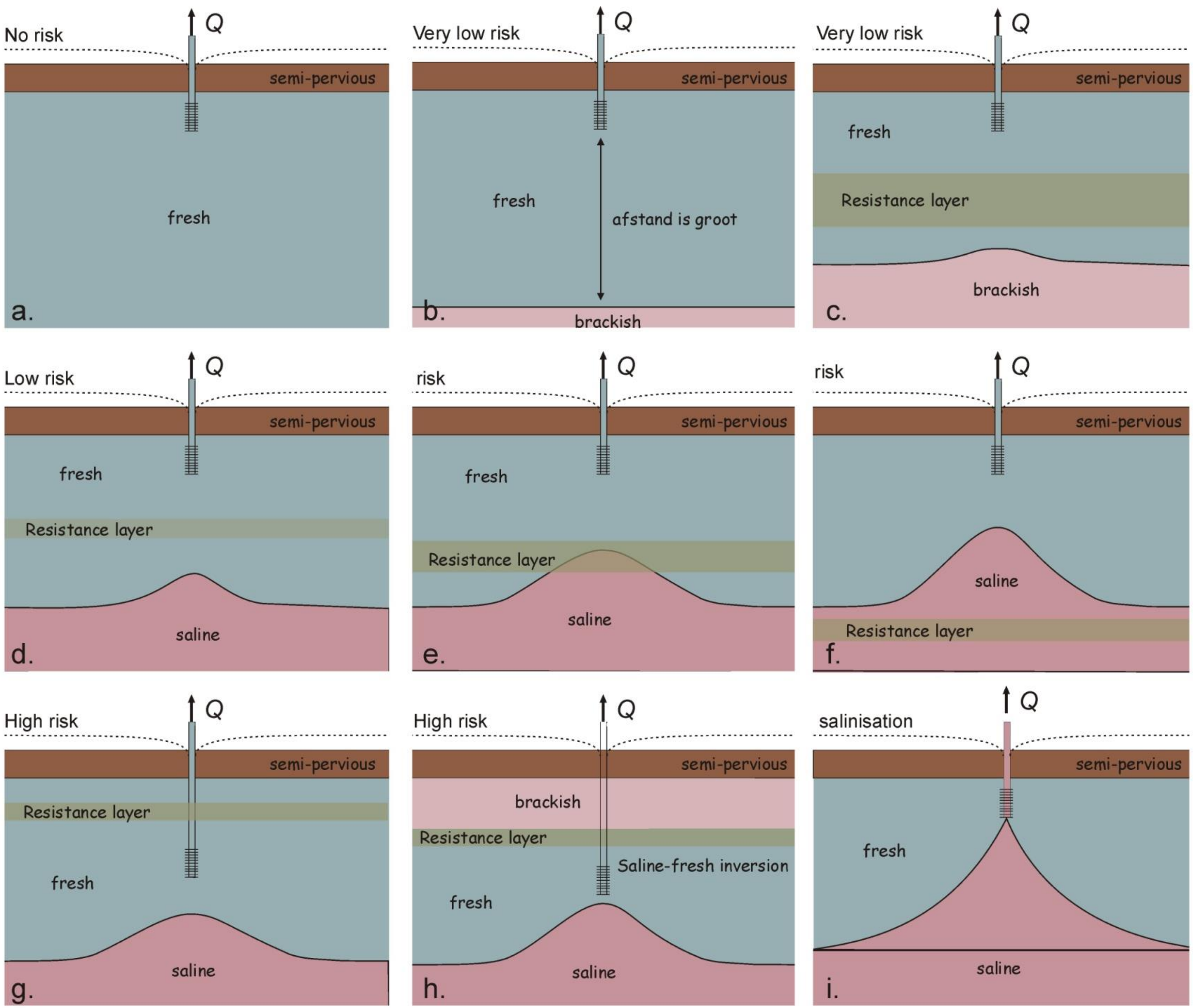
Availability of fresh groundwater



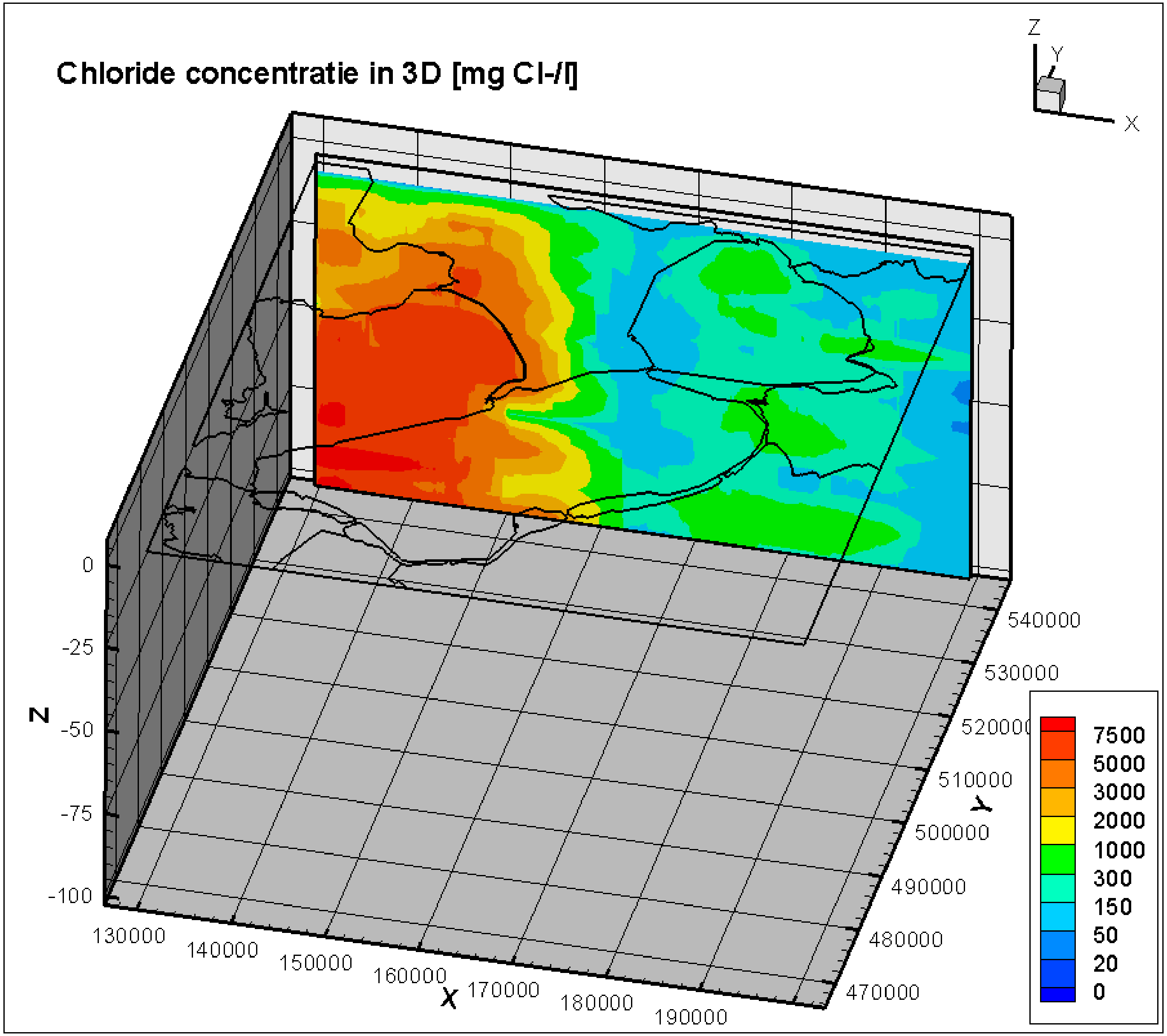
- <100 m
- 100-200 m
- 200-300 m
- 300-400 m
- 400-500 m
- >500 m
- >inversion (salt above fresh)

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

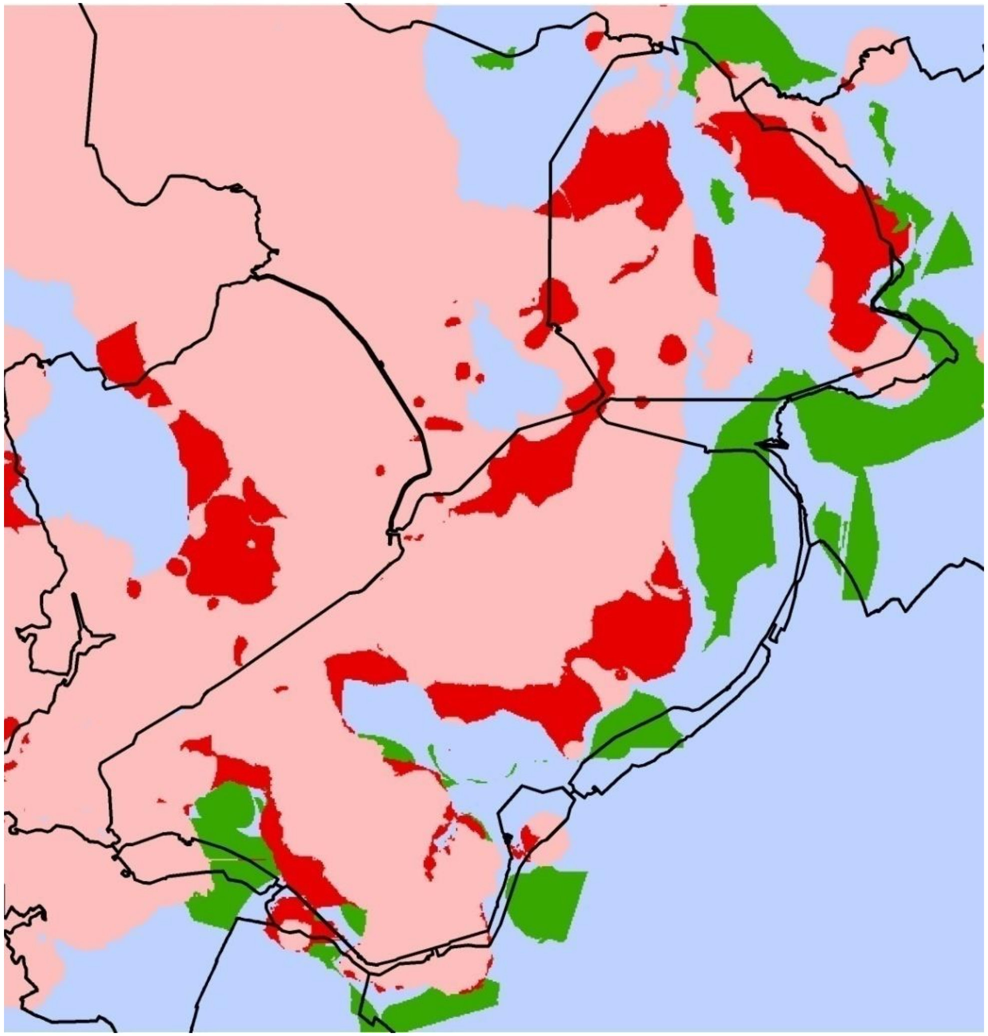
Different risks of upconing saline groundwater



Animation 3D Chloride concentration

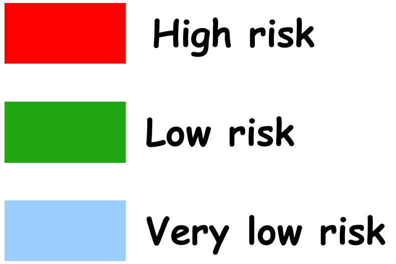


Upconing in Flevoland



Risk depends on:

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



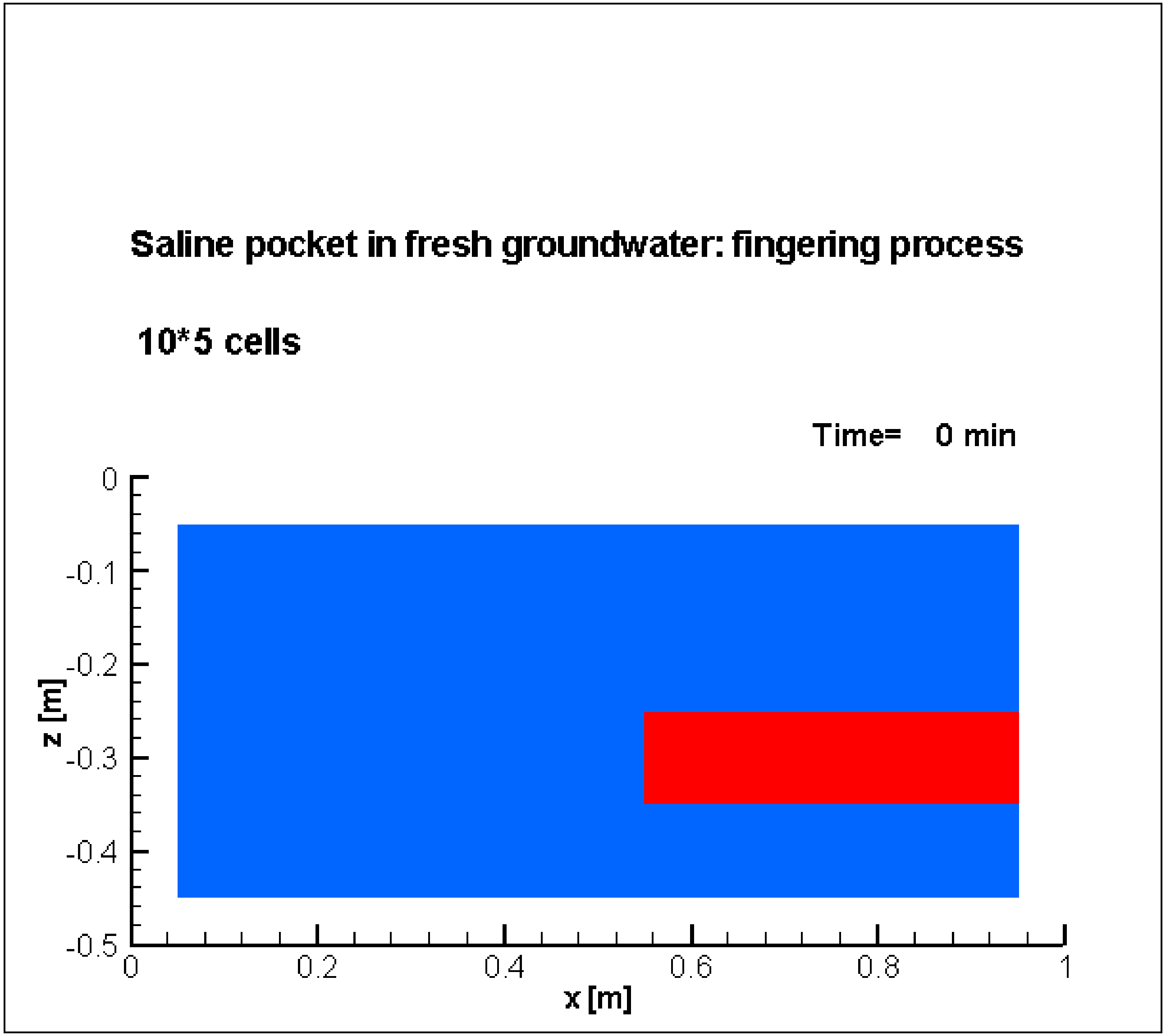
Salt water pocket in a fresh environment

Grid convergence

Time step

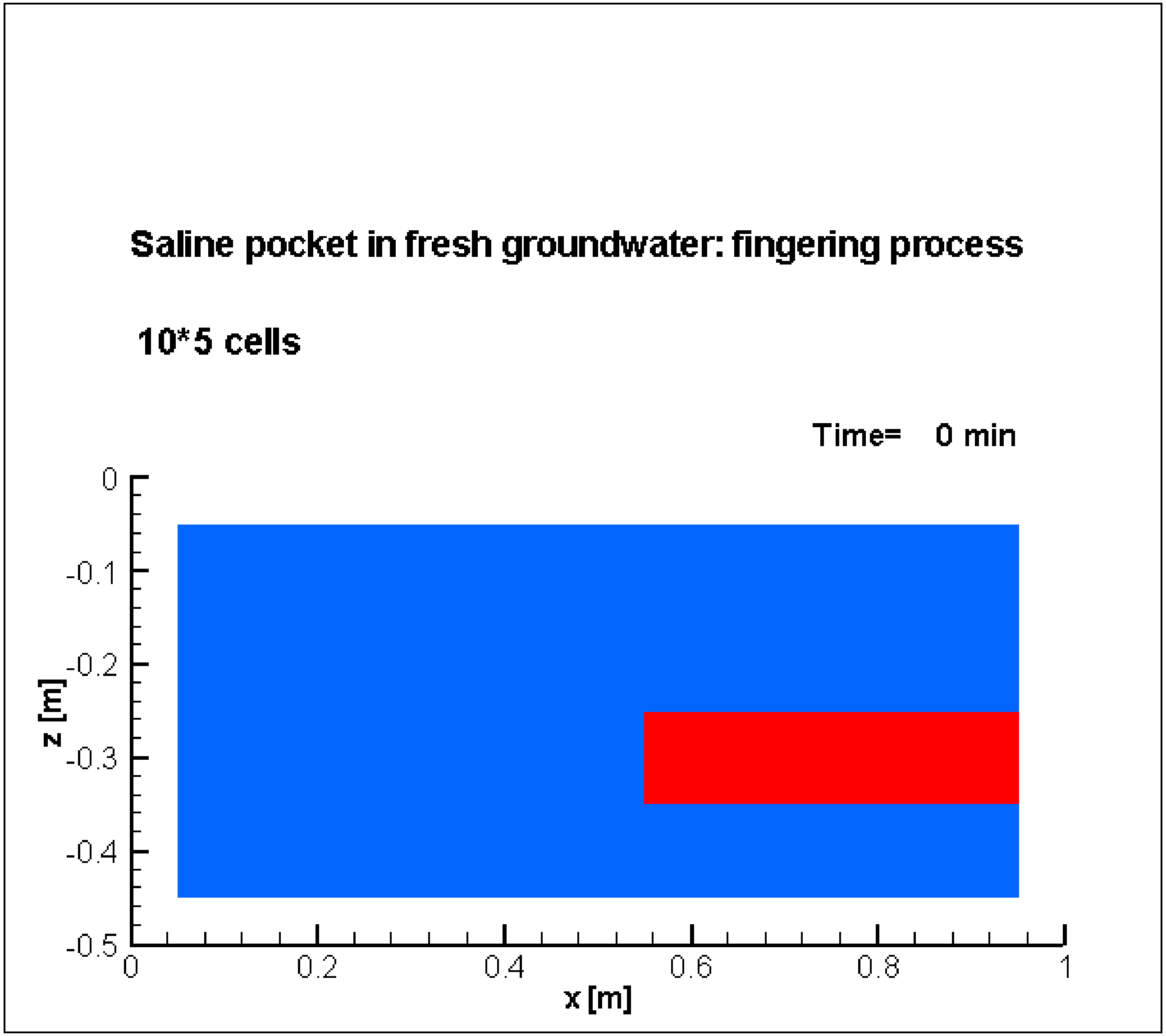
Salt water pocket in a fresh environment (I)

Effect of discretisation on a ‘salt lake problem’



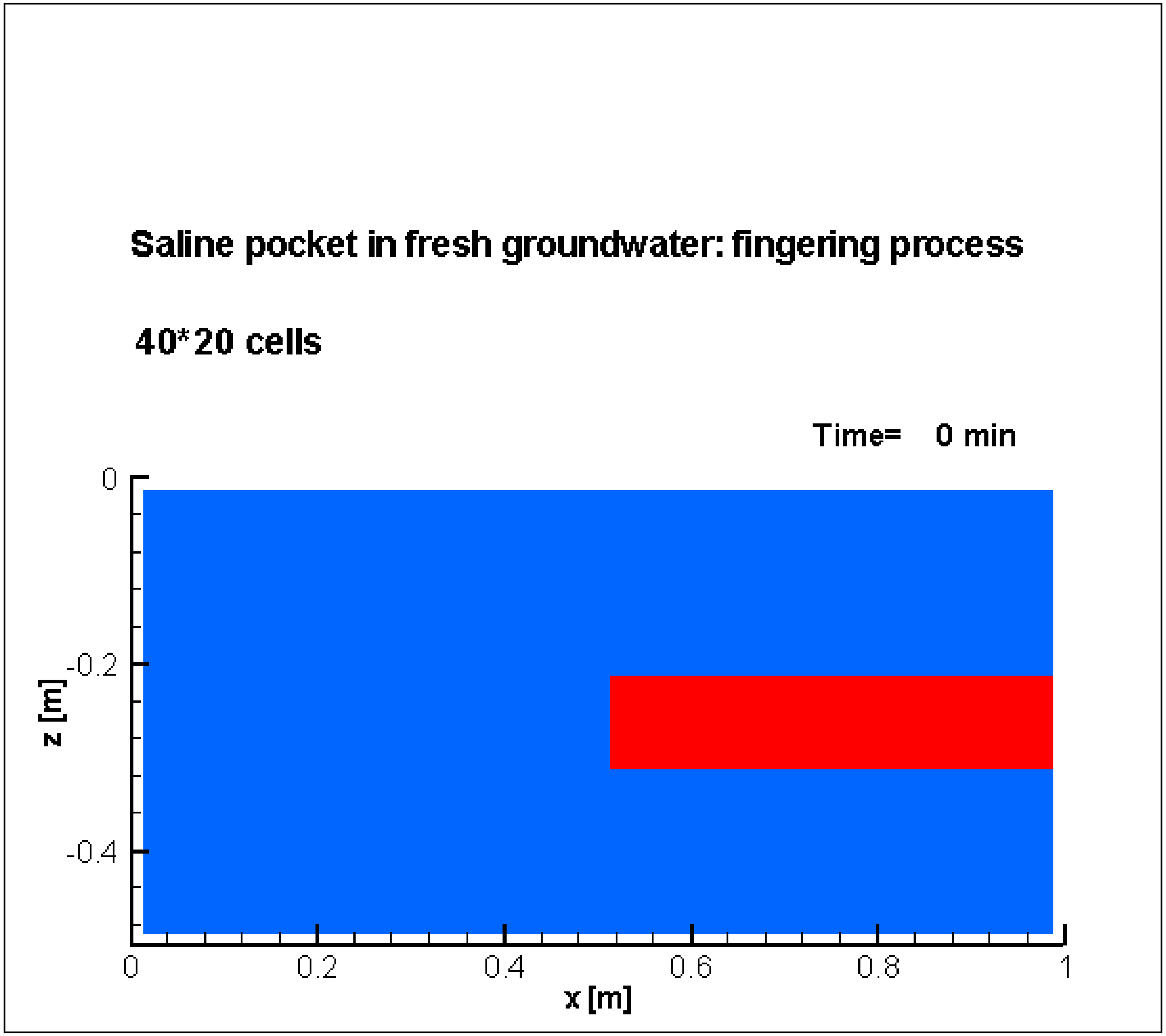
Salt water pocket in a fresh environment (I)

Effect of discretisation on a ‘salt lake problem’



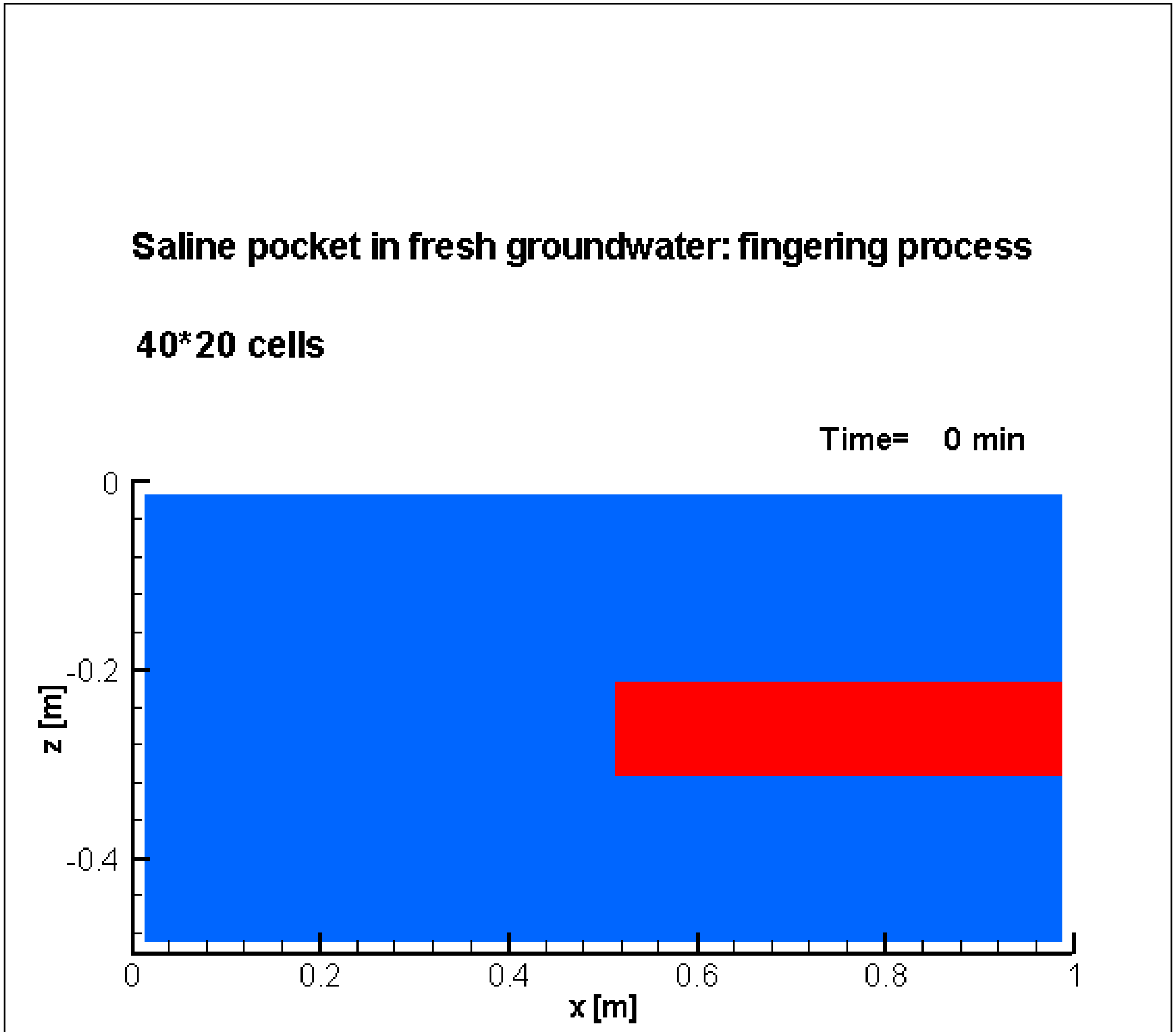
Salt water pocket in a fresh environment (II)

Effect of discretisation



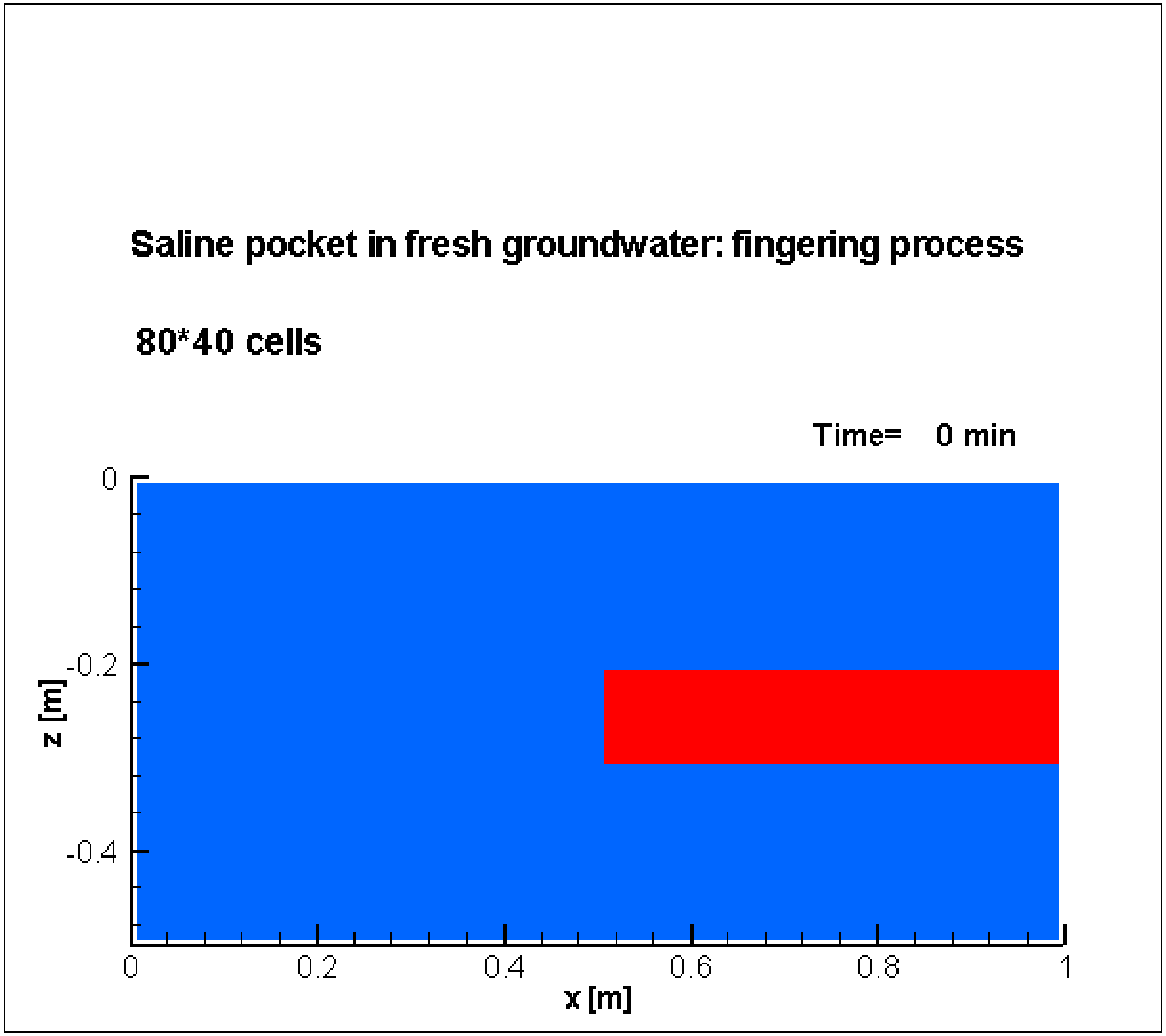
Salt water pocket in a fresh environment (II)

Effect of discretisation



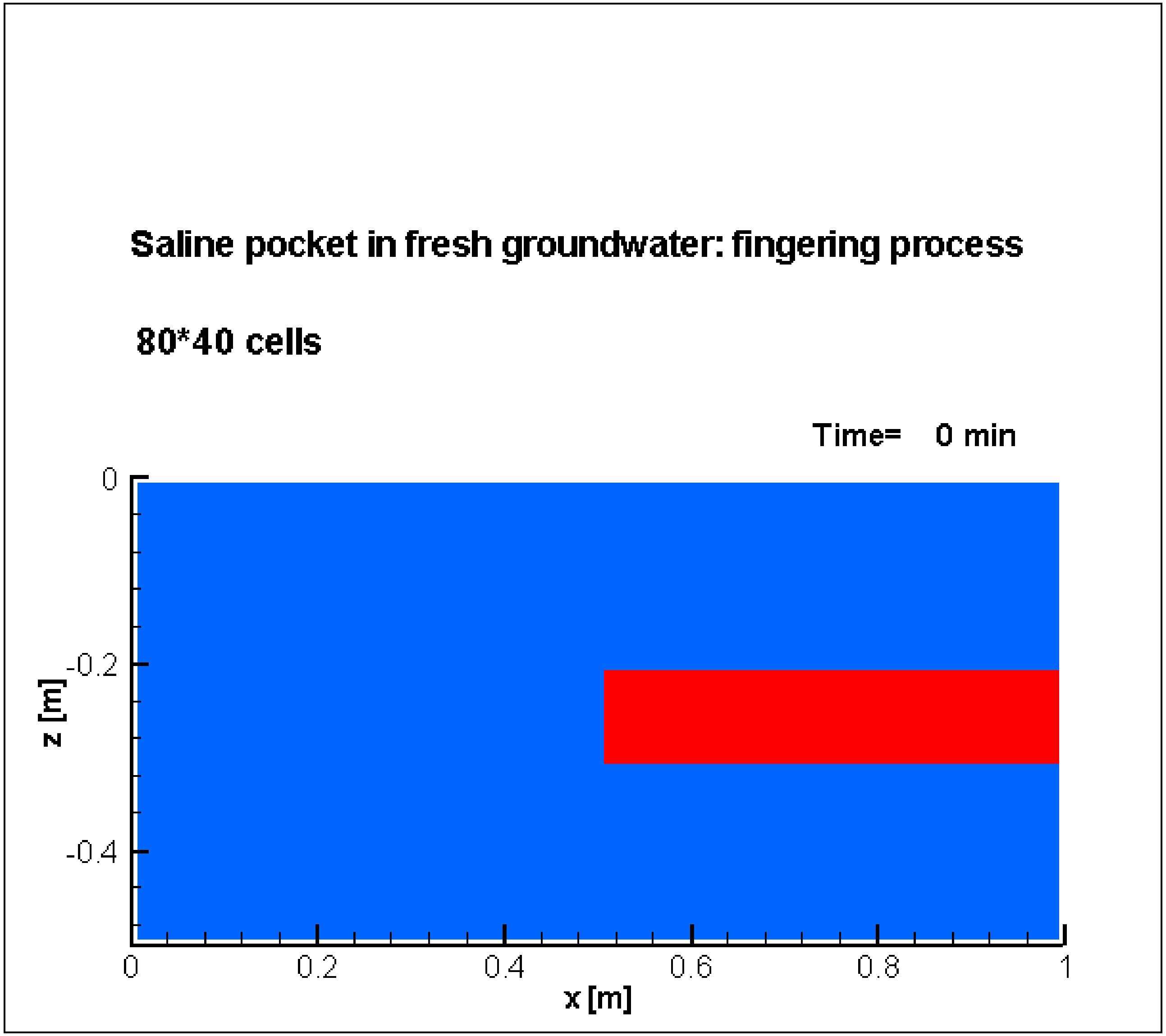
Salt water pocket in a fresh environment (III)

Effect of discretisation



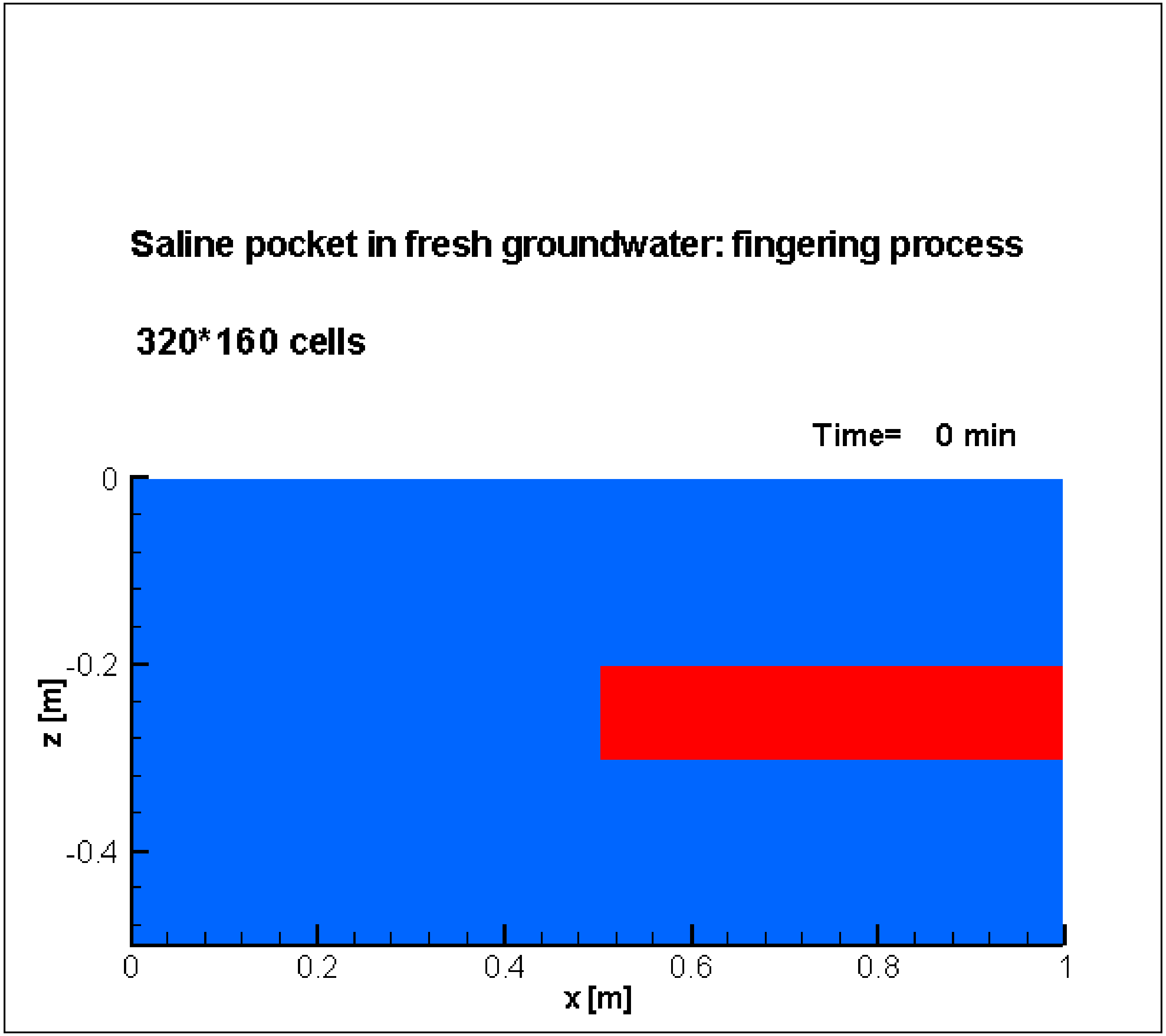
Salt water pocket in a fresh environment (III)

Effect of discretisation



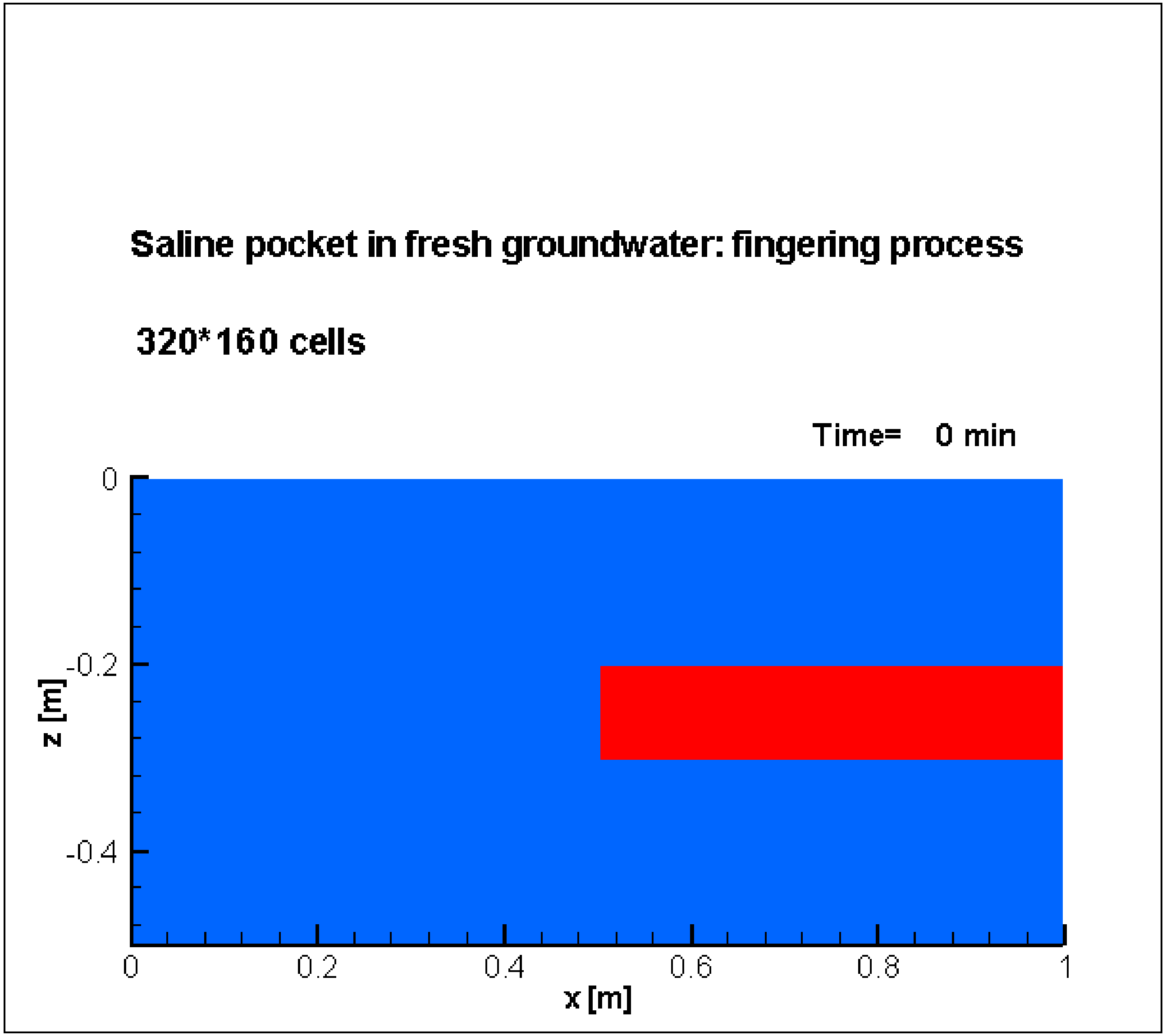
Salt water pocket in a fresh environment (IV)

Effect of discretisation



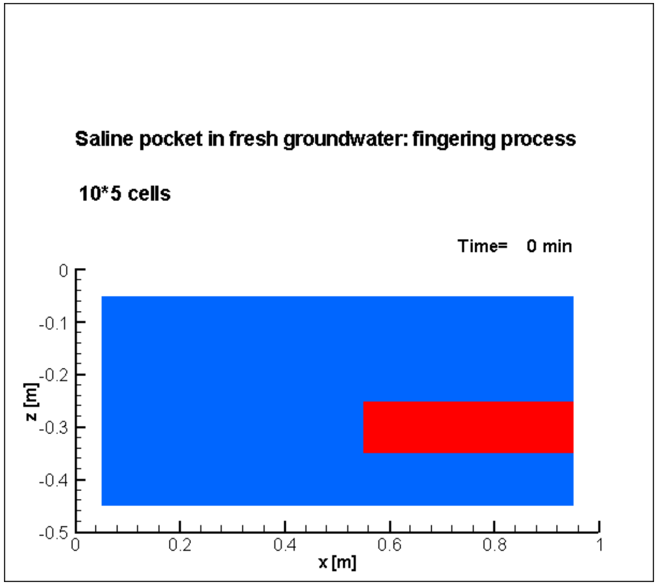
Salt water pocket in a fresh environment (IV)

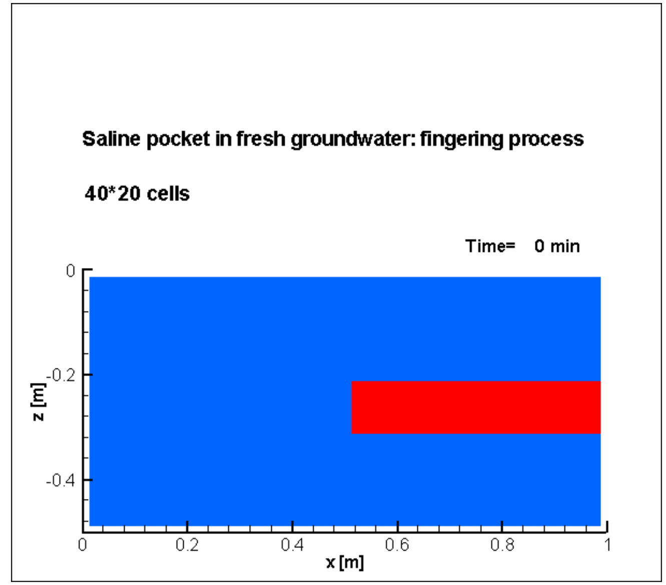
Effect of discretisation

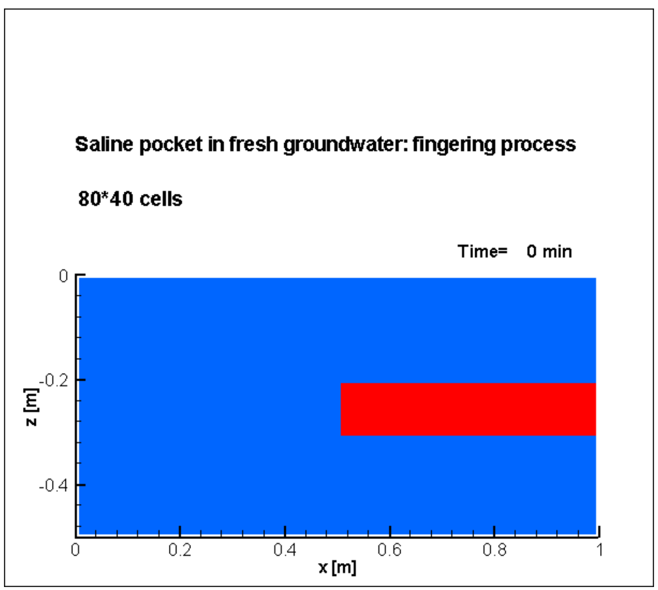


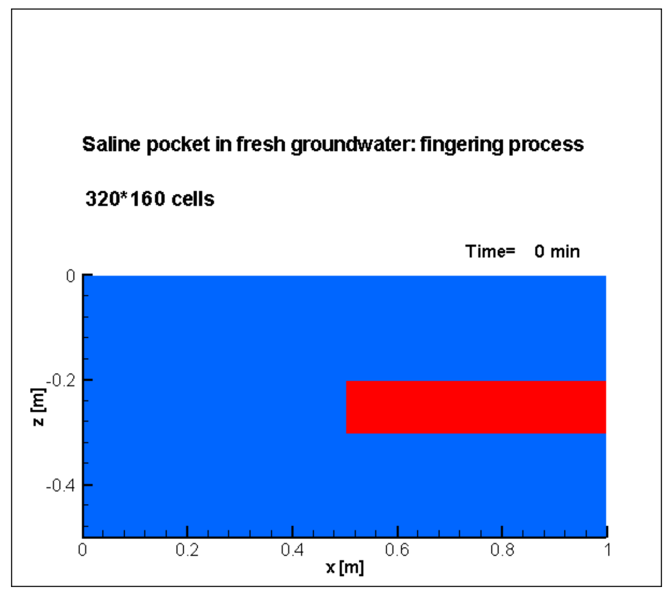
Salt water pocket in a fresh environment (V)

Effect of discretisation

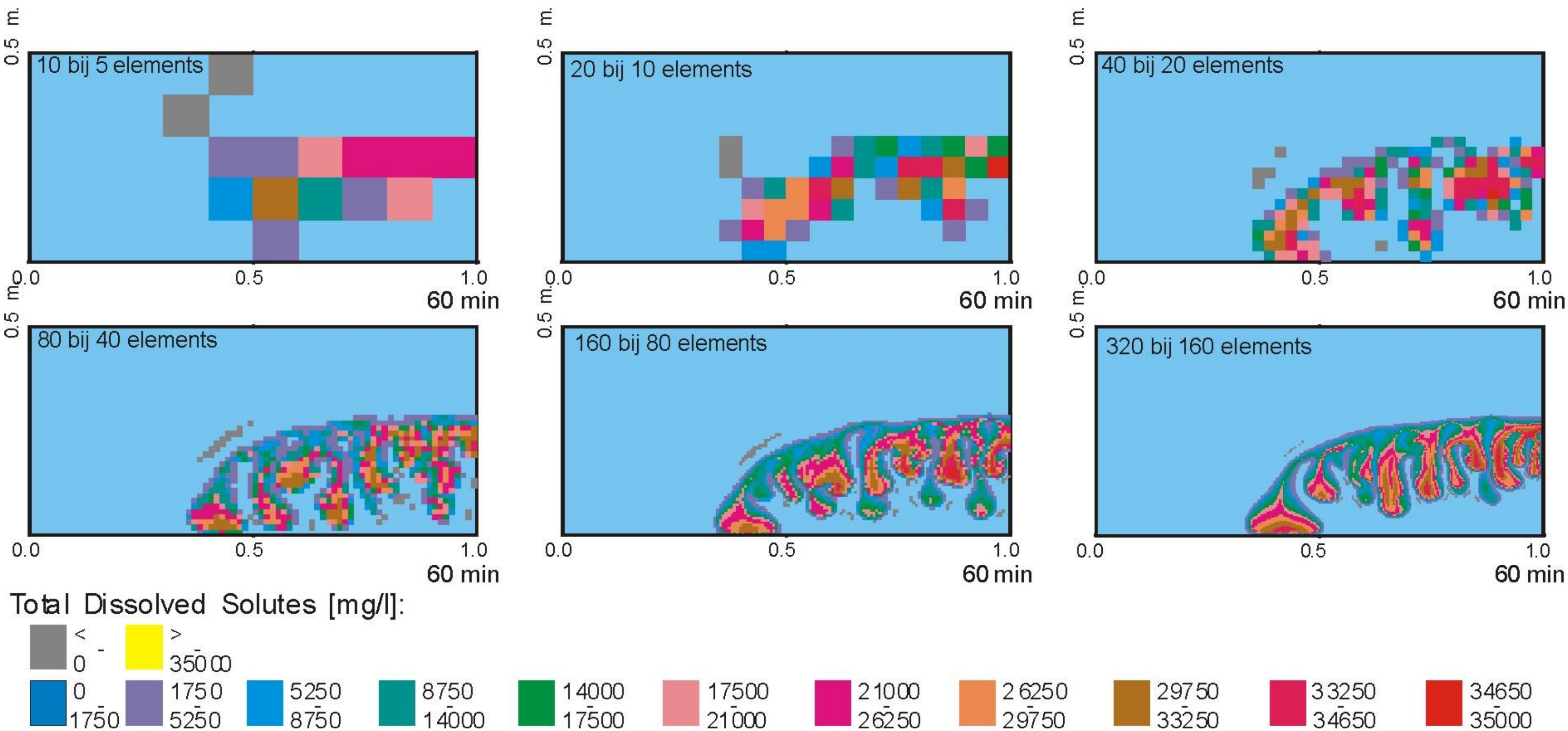






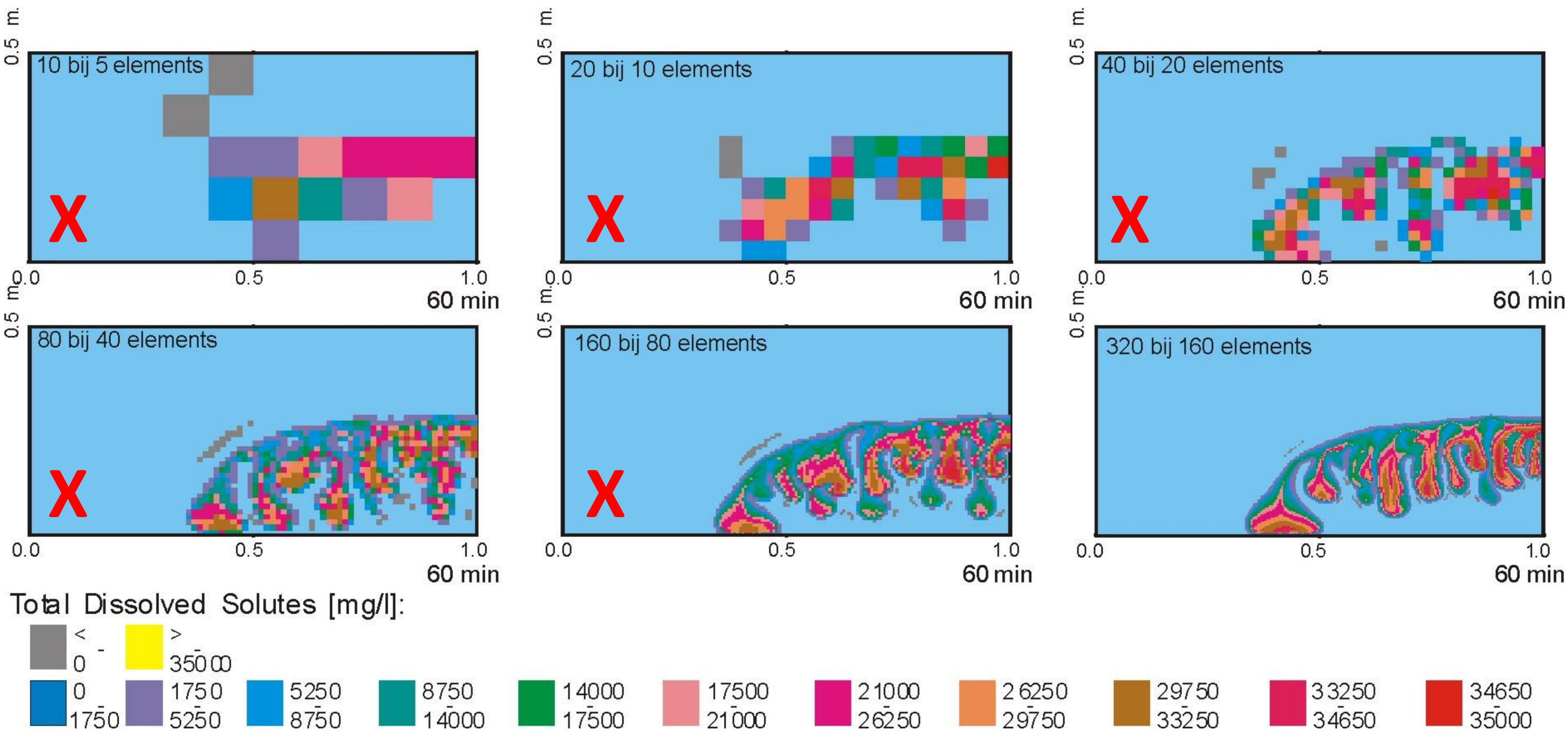


Effect of size model cell on physical process



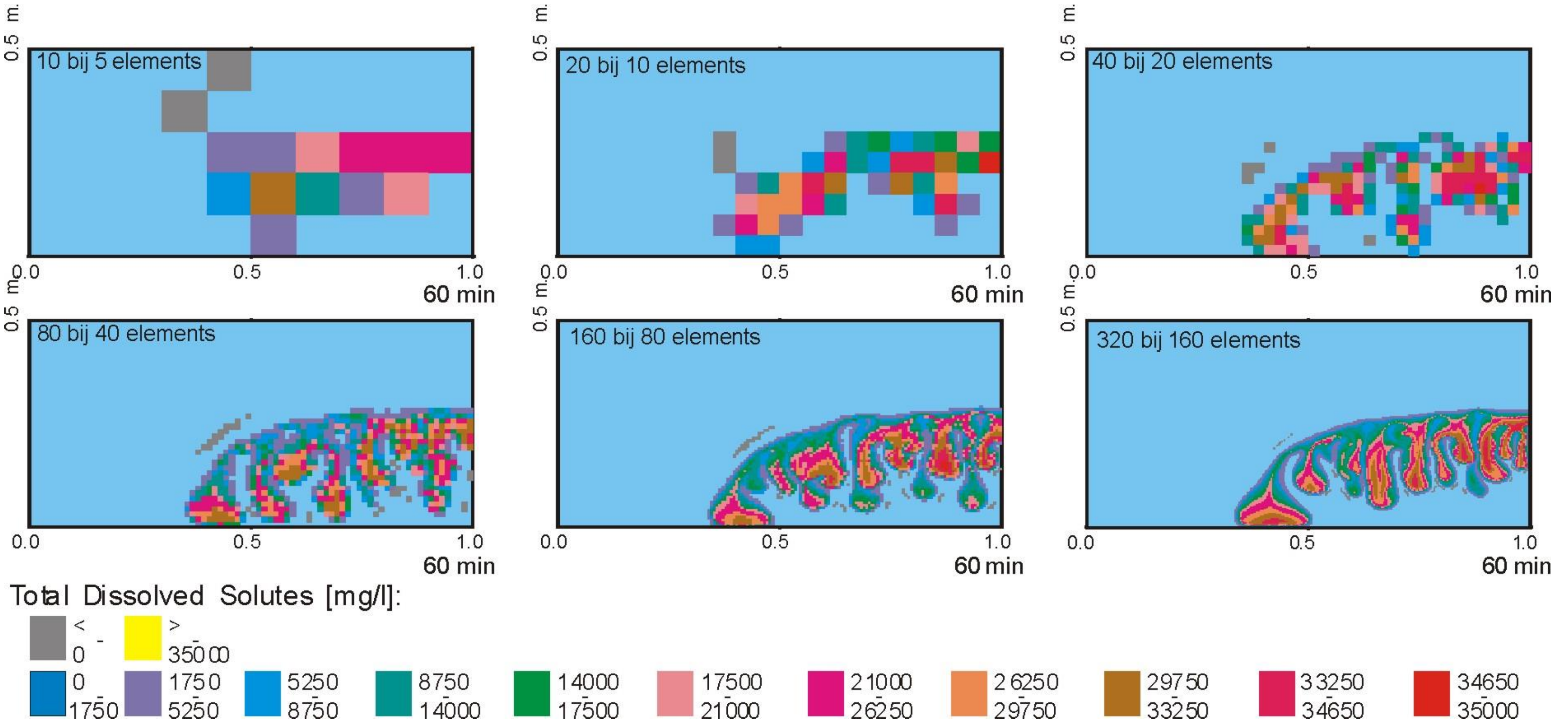
Size of cell has a large effect on modelling result!

Effect of size model cell on physical process



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

Effect of size model cell on physical process



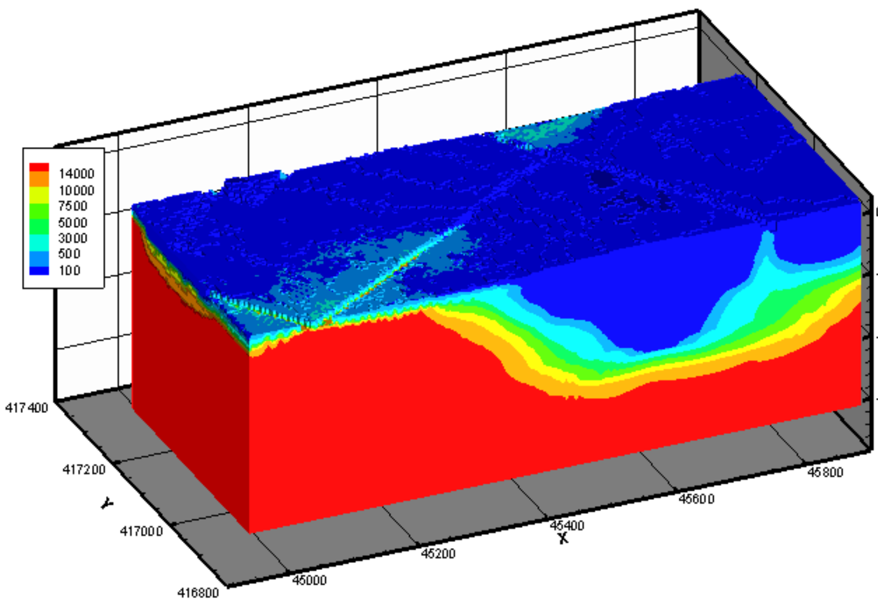
BUT: all models are GOOD for predicting the moment of touching the base!

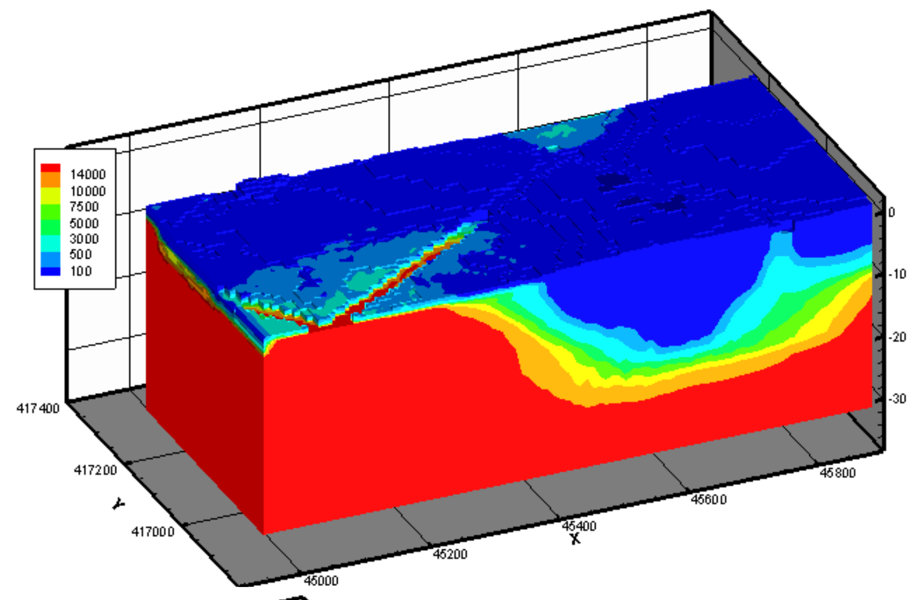
Salt water pocket in a fresh environment (VI)

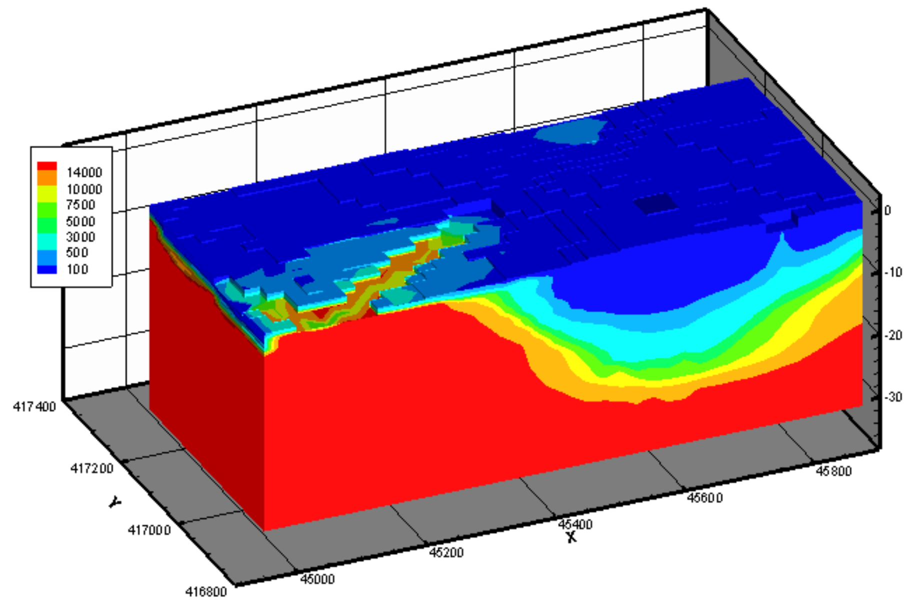
Conclusion:

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

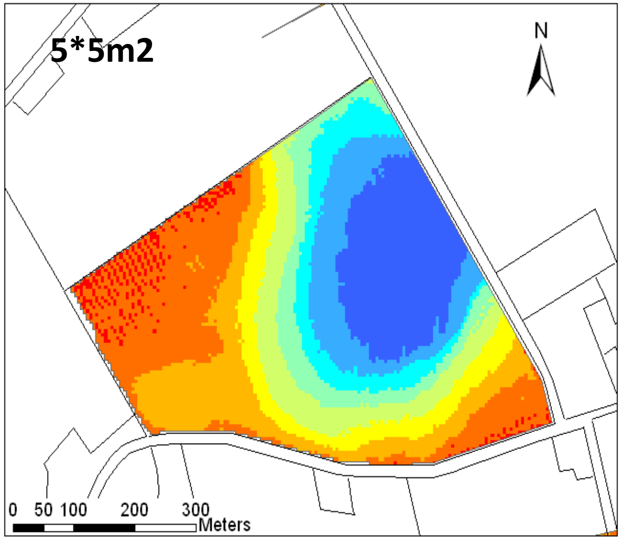
Different model scales: 5, 10, 25m2



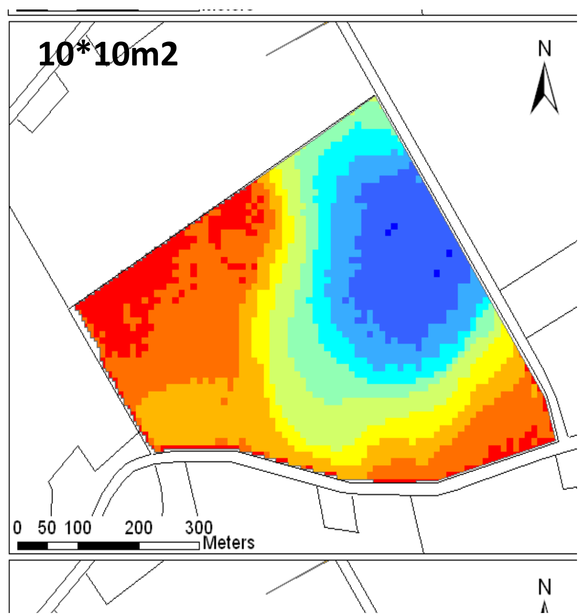


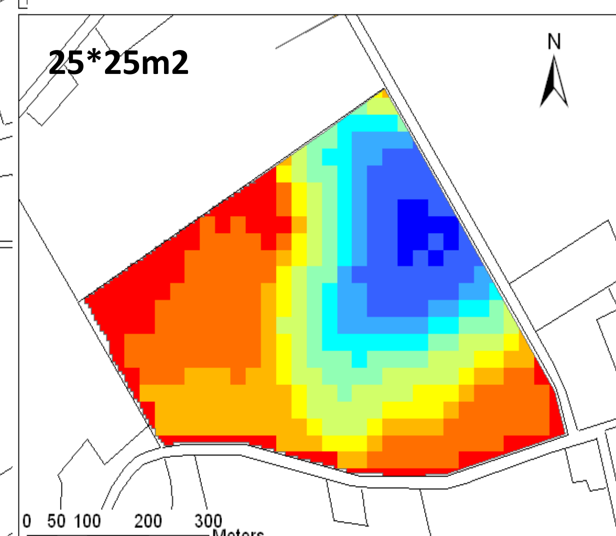


Different model scales

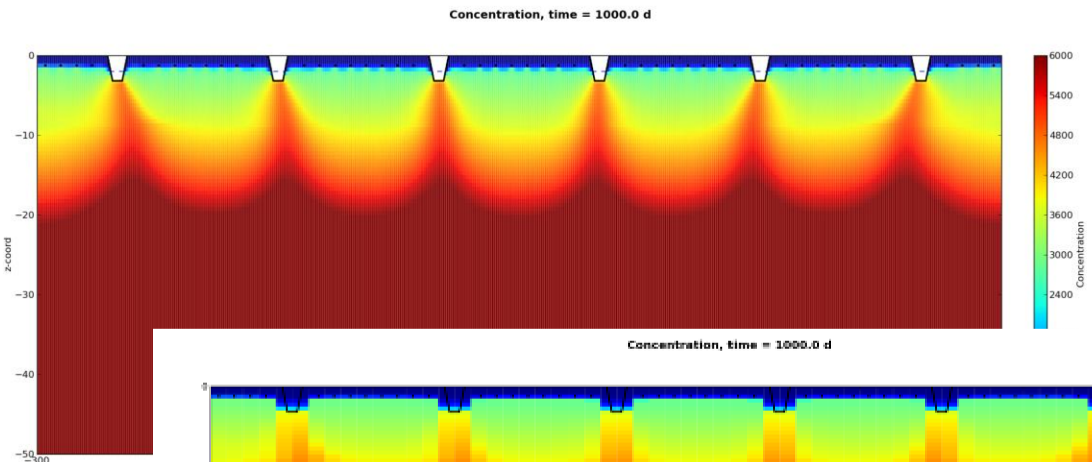


Which one is good enough?

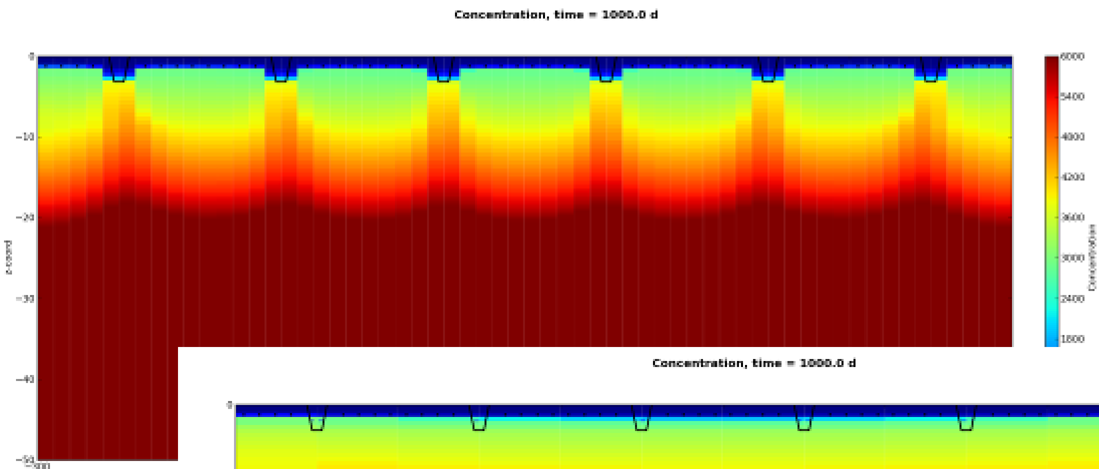




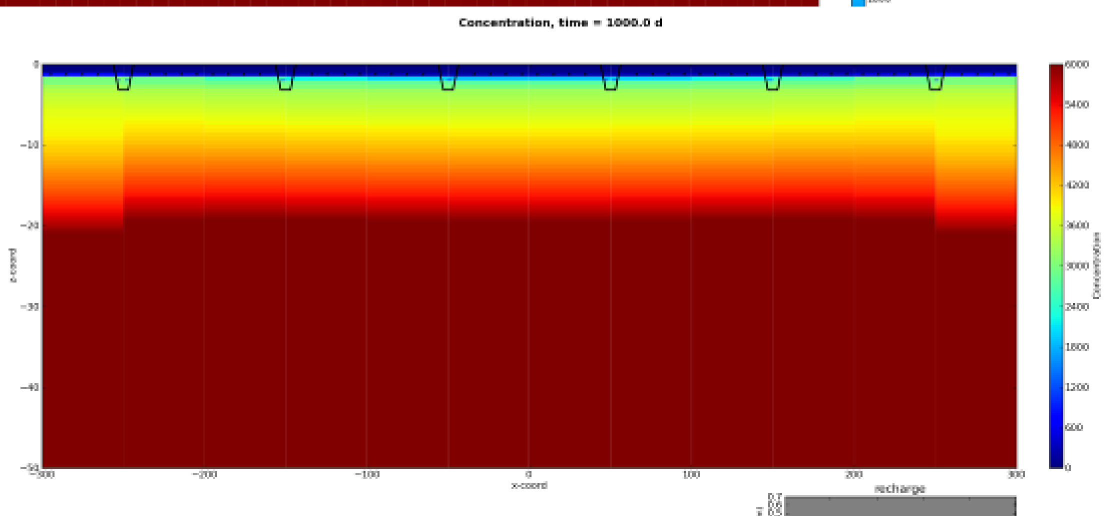
Upscaling issues: upconing under ditch



Cell size: 0.5m
Salt load: 3000 kg/d



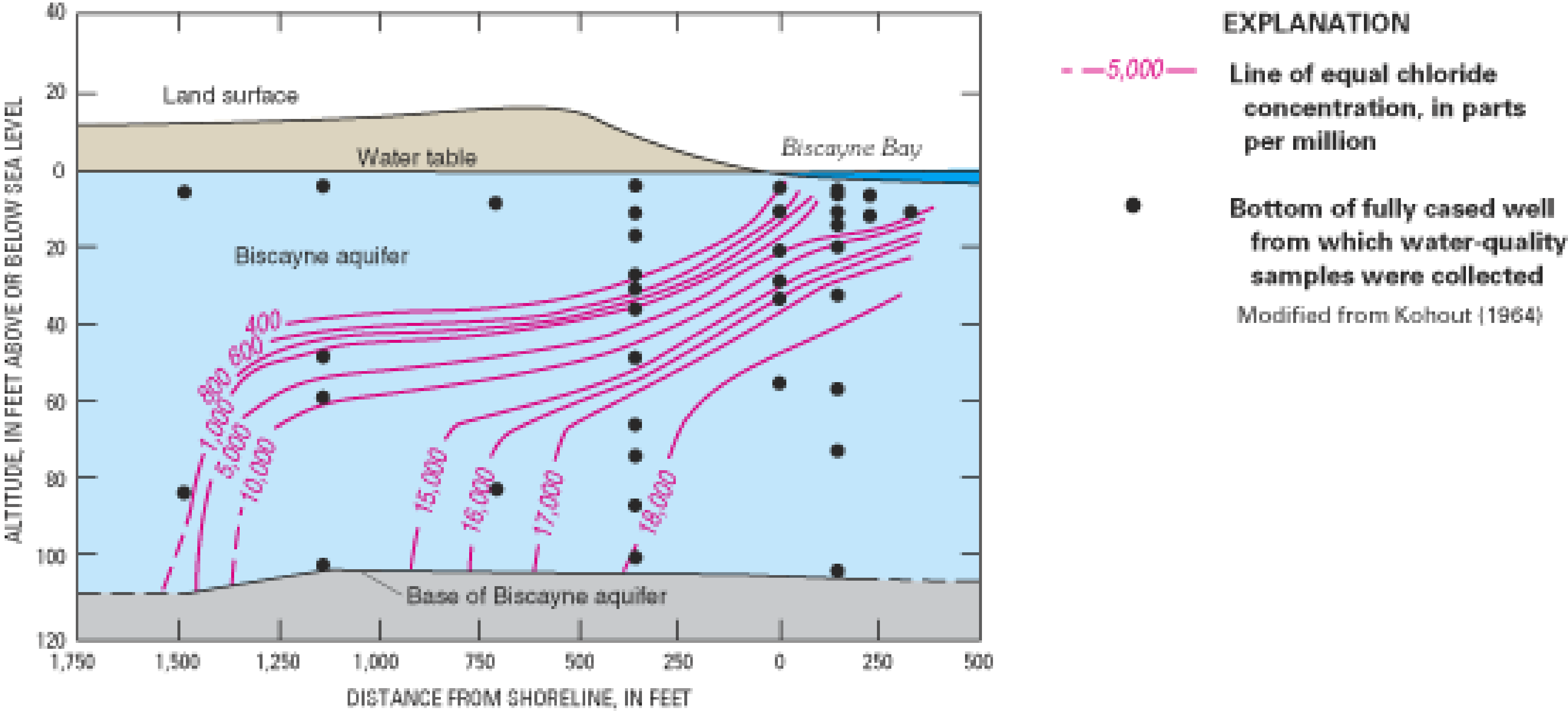
Cell size: 10m
Salt load: 1750 kg/d



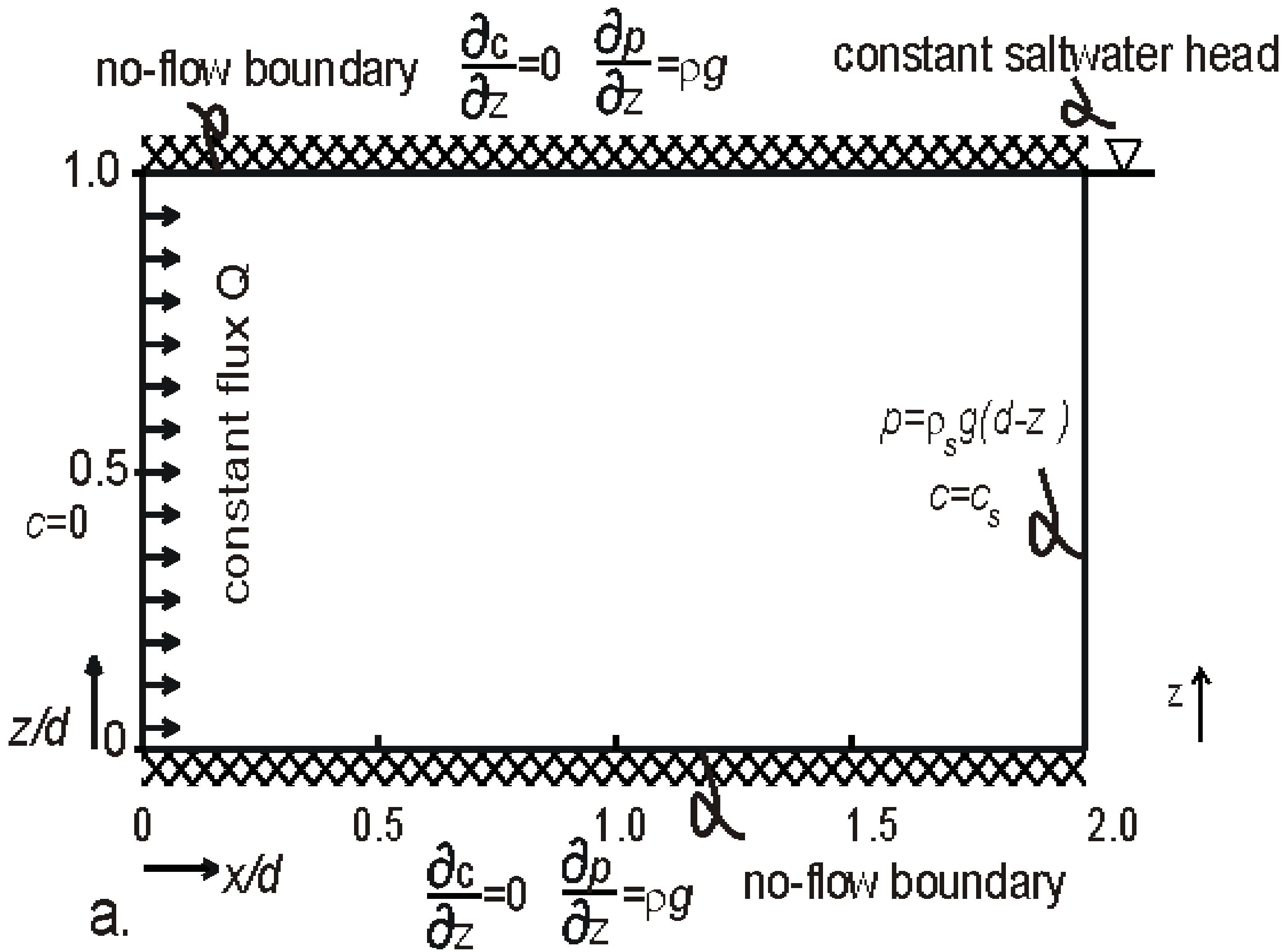
Cel size: 50m
Salt load: 2000 kg/d

a_L=0.01m

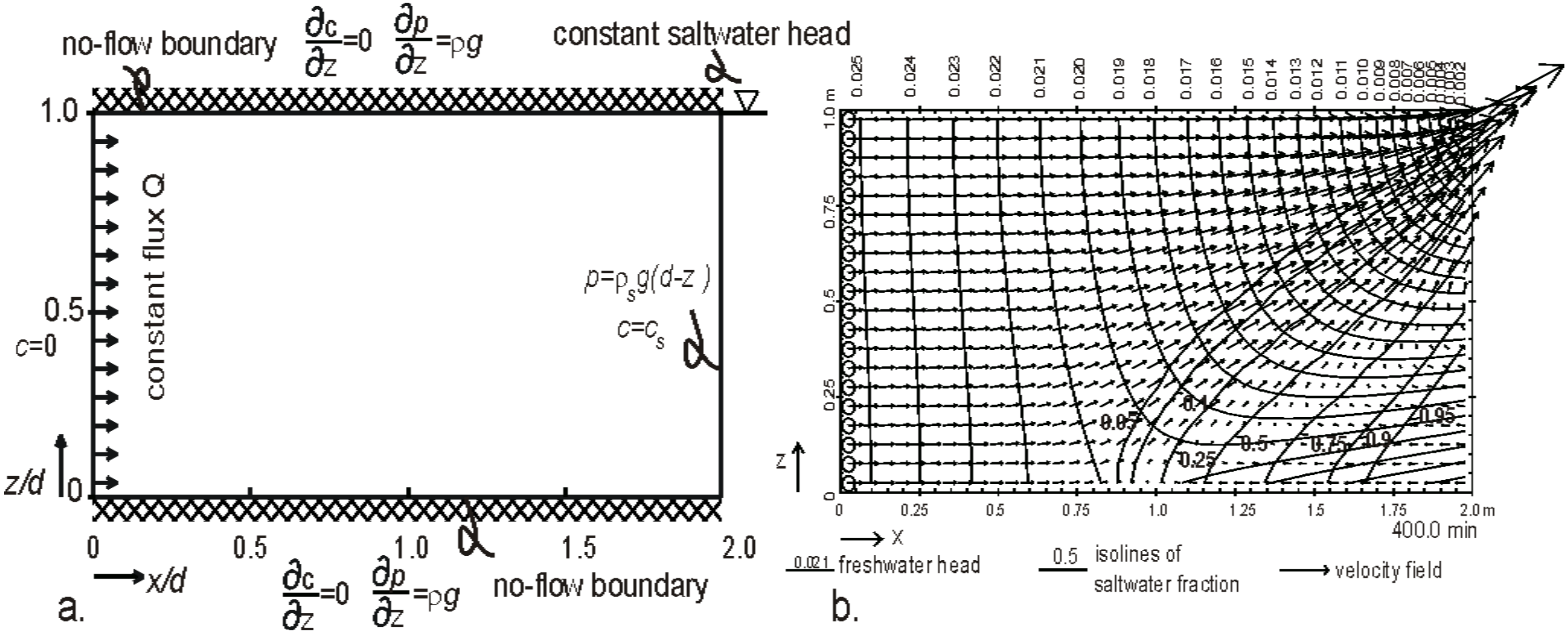
Biscayne aquifer, Florida USA: Henry's case



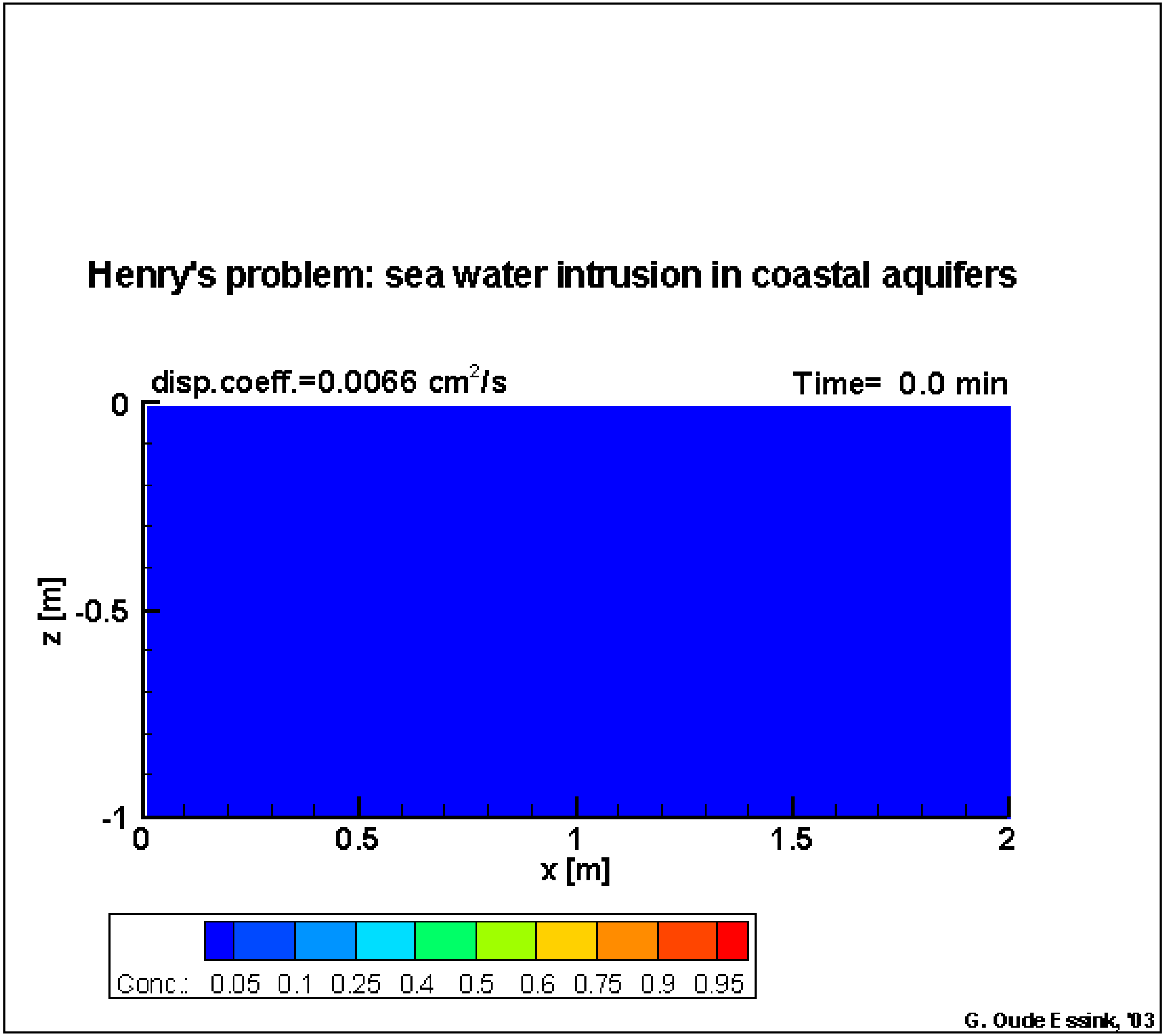
Henry's problem (1964)



Henry's problem



Henry's problem

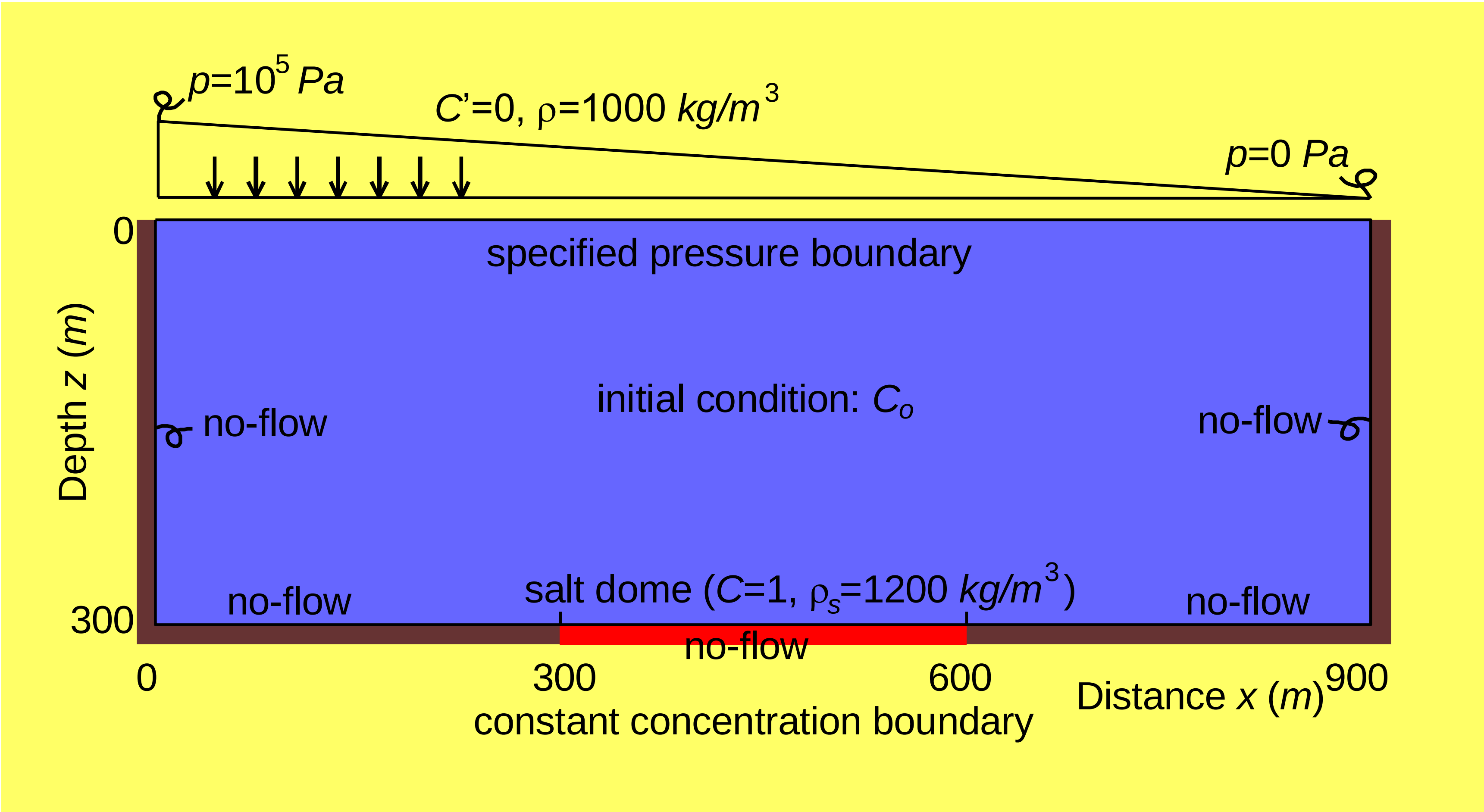


Henry's problem

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

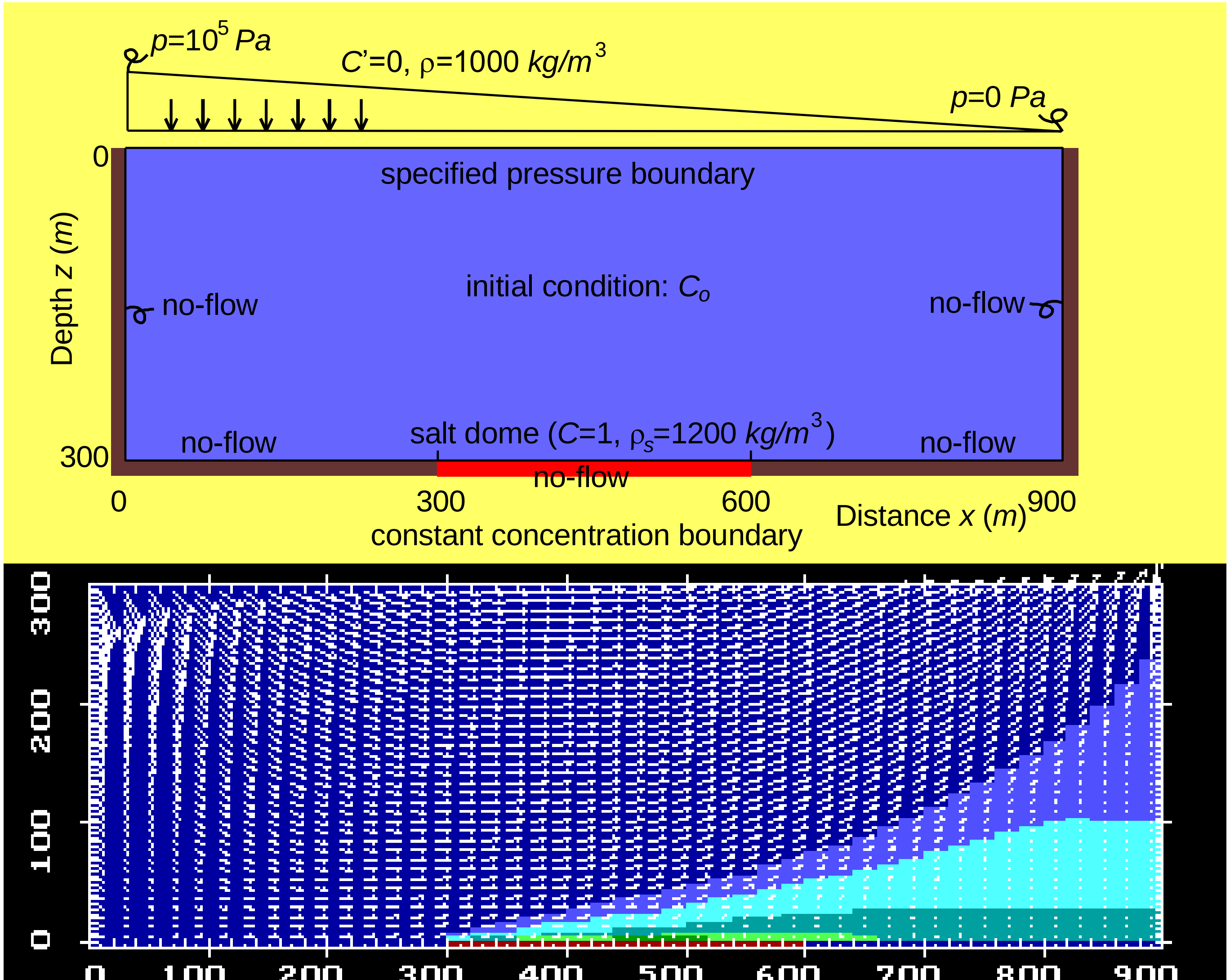
Hydrocoin:

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



Hydrocoin:

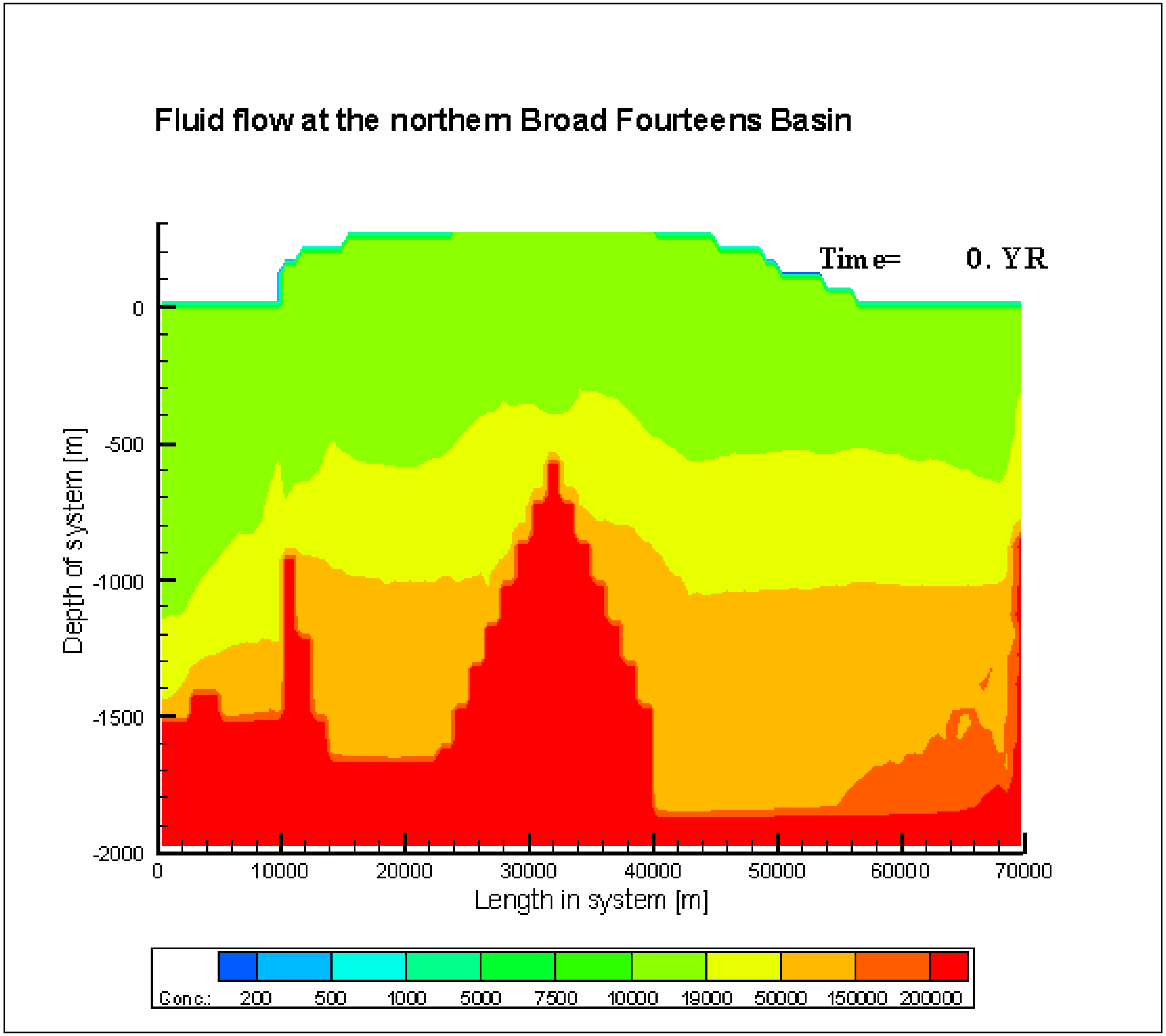
groundwater movement near salt domes



Salt fraction:

Broad 14 Basin, North Sea

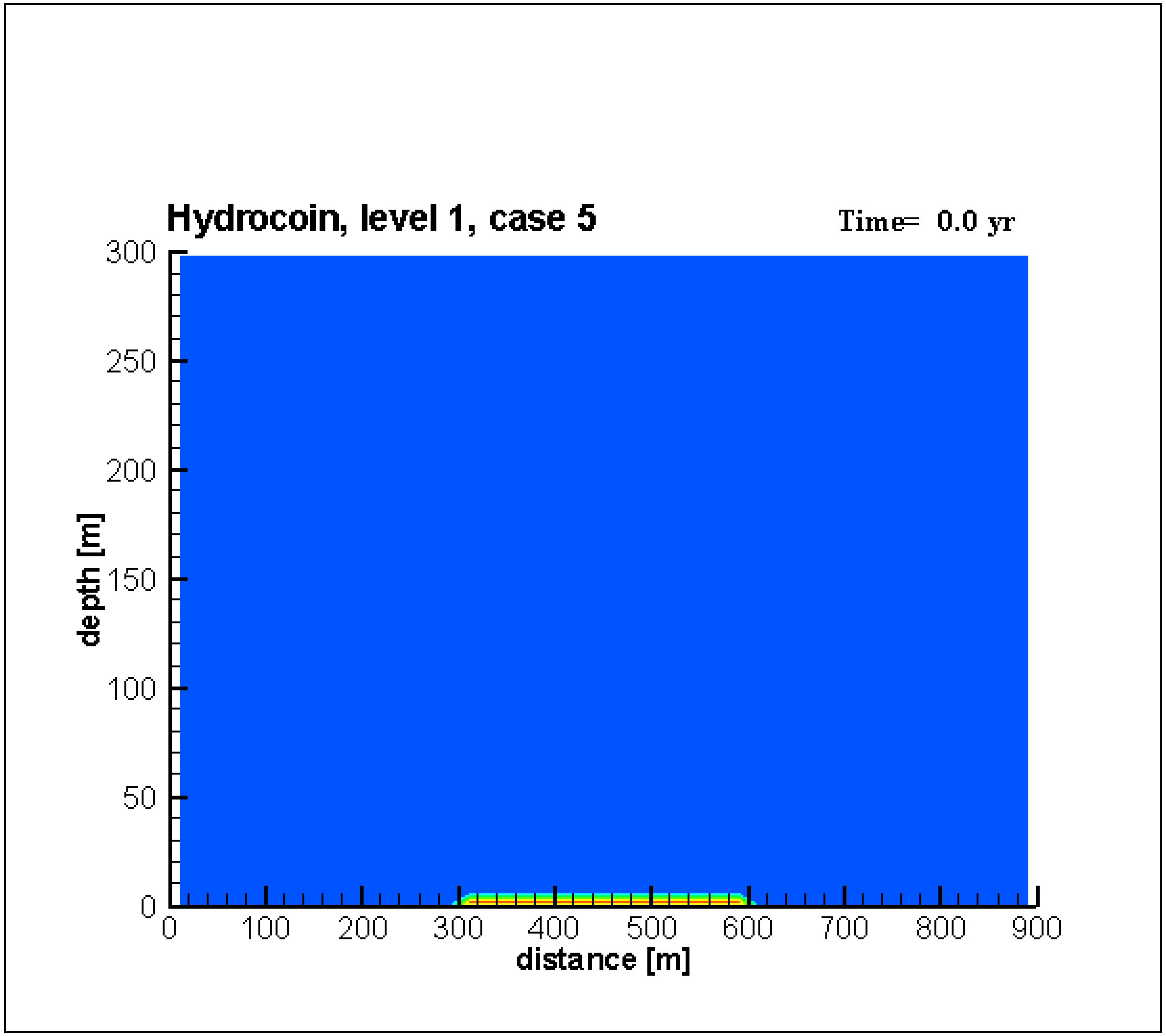
Geofluids'03, with L. Bouw



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

Hydrocoin: effect of boundary condition (I)

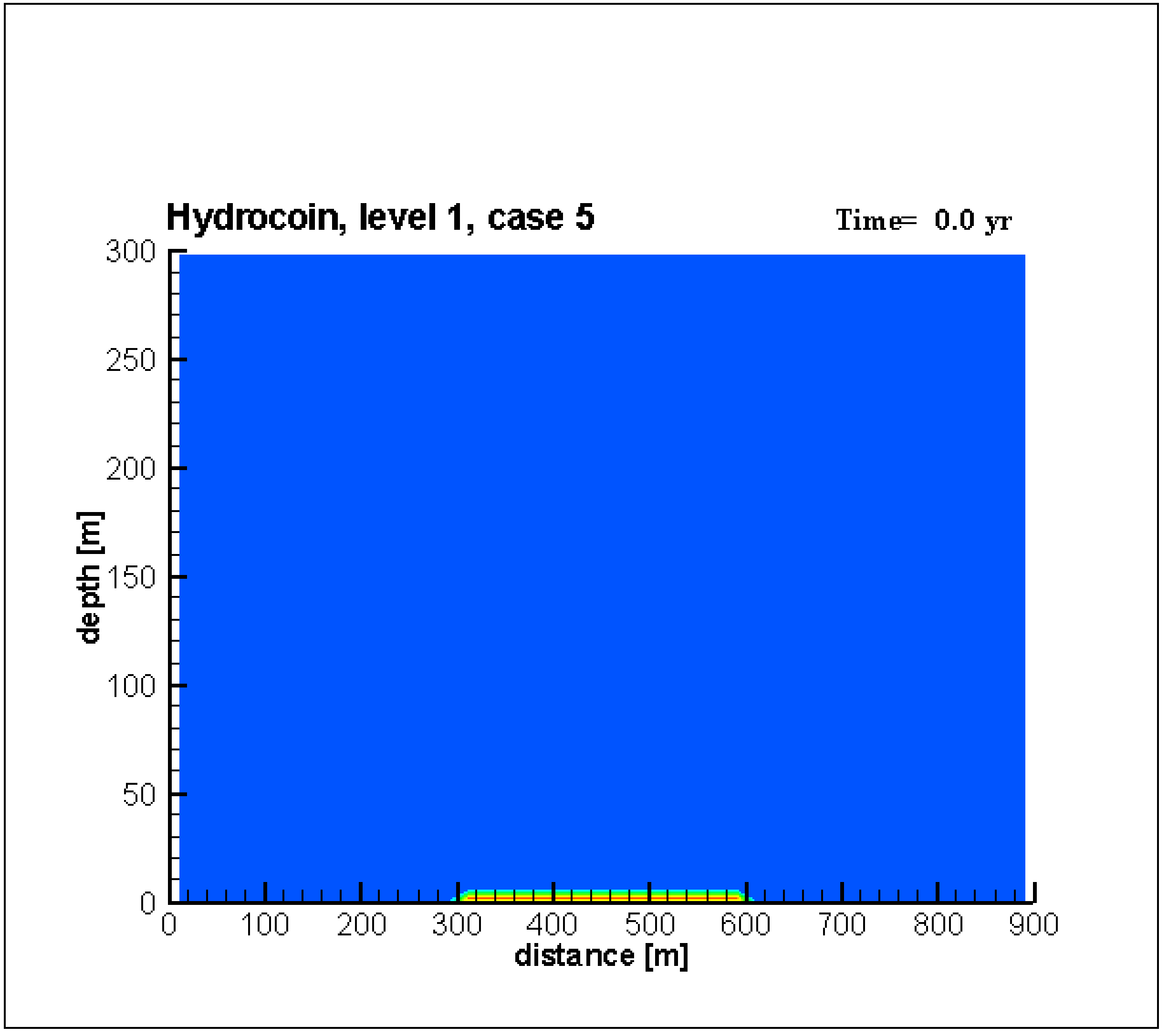
supply of brine through advection and hydrodynamic dispersion



recirculation type

Hydrocoin: effect of boundary condition (I)

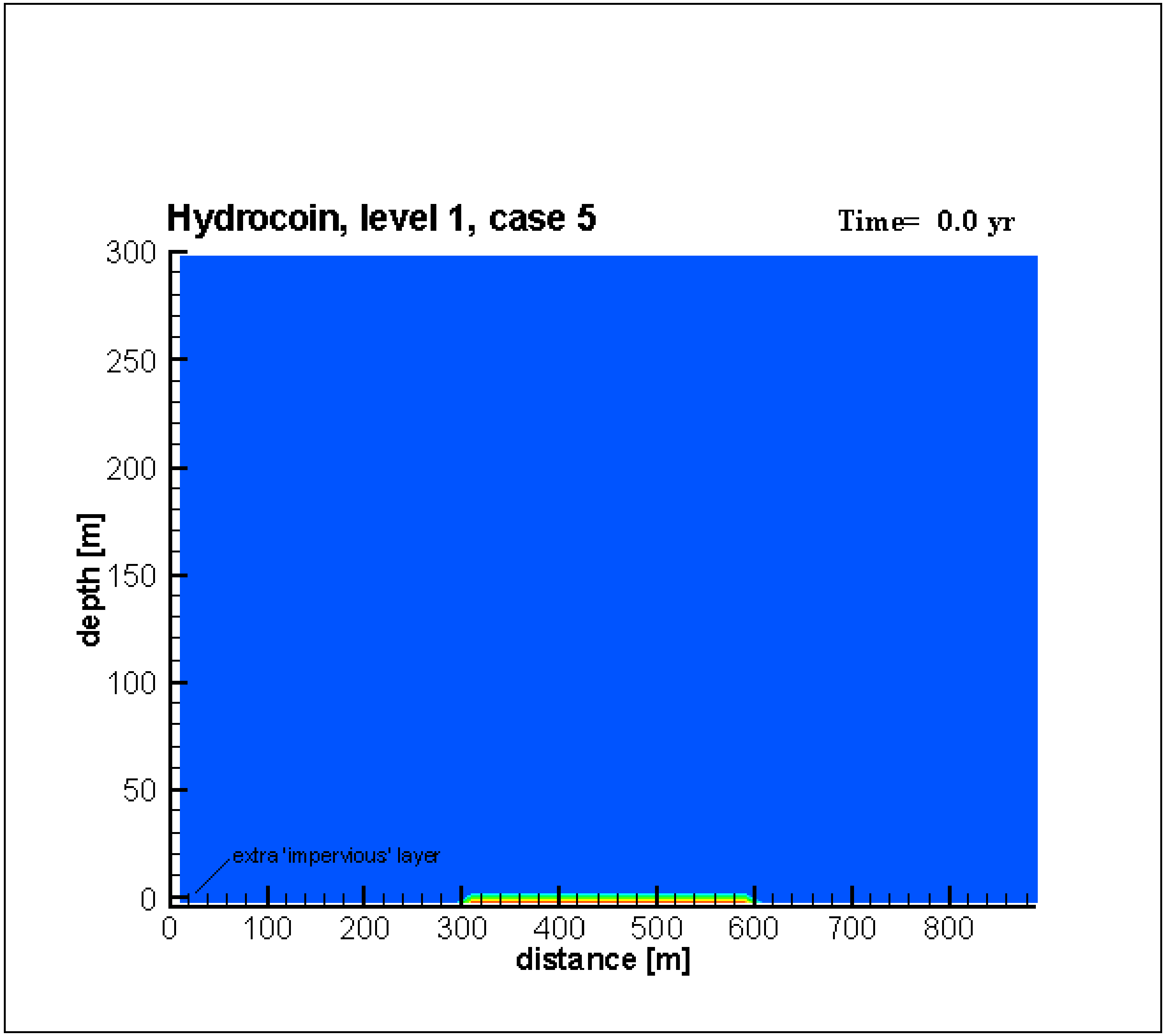
supply of brine through advection and hydrodynamic dispersion



recirculation type

Hydrocoin: effect of boundary condition (II)

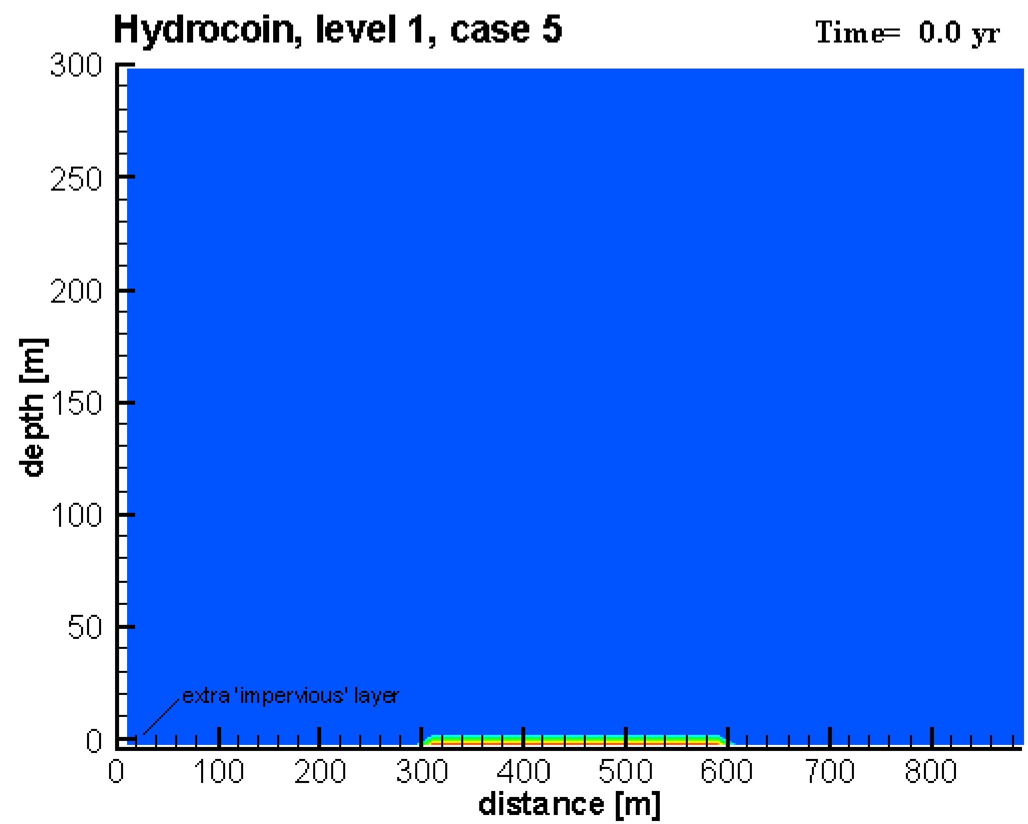
supply of brine through only hydrodynamic dispersion



swept-forward type

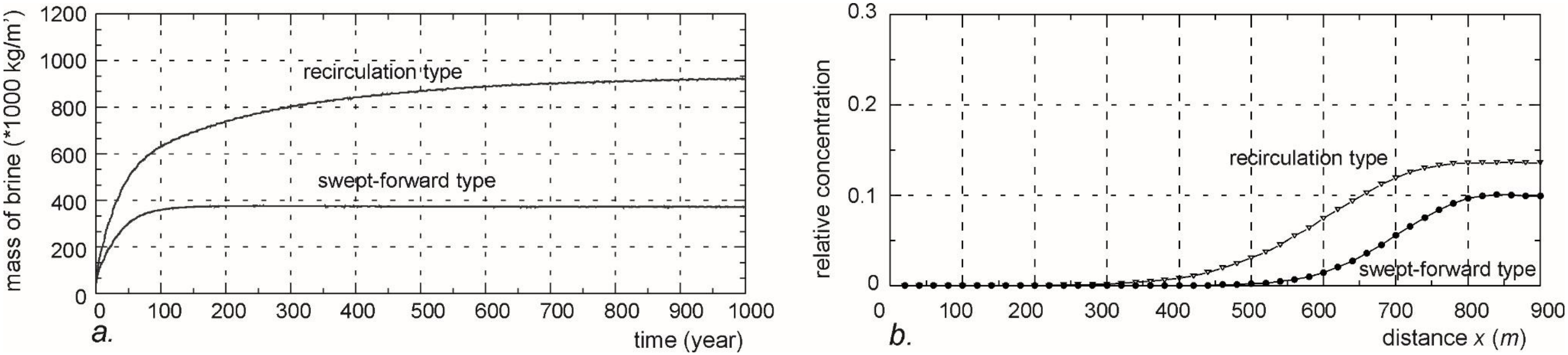
Hydrocoin: effect of boundary condition (II)

supply of brine through only hydrodynamic dispersion



swept-forward type

Hydrocoin: difference recirculation vs swept forward

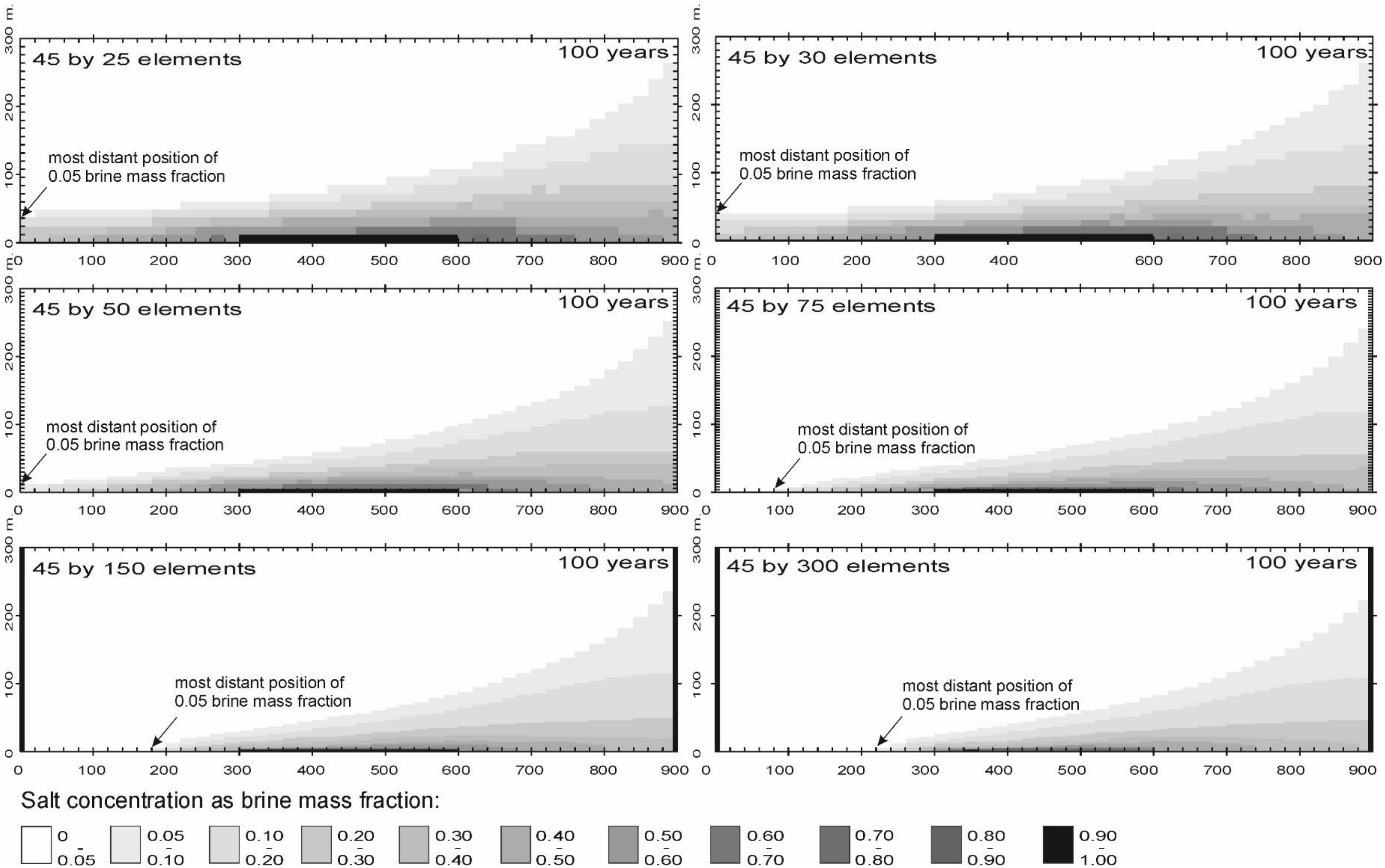


total mass of brine

brine conc at depth=200m

Lecture notes, p. 86-91

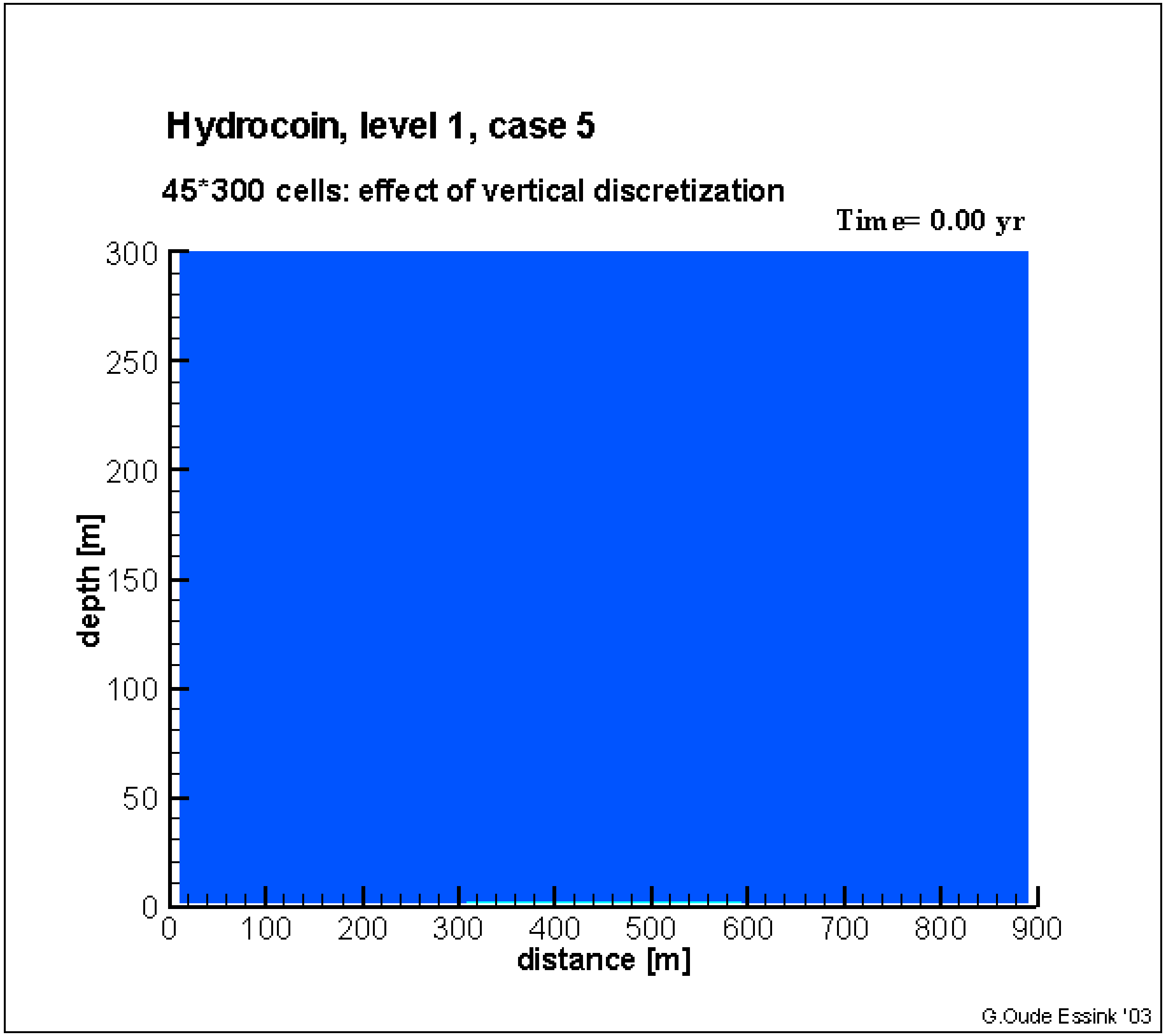
Hydrocoin: effect of vertical grid size



Recirculation type

Hydrocoin: effect of vertical discretization (III)

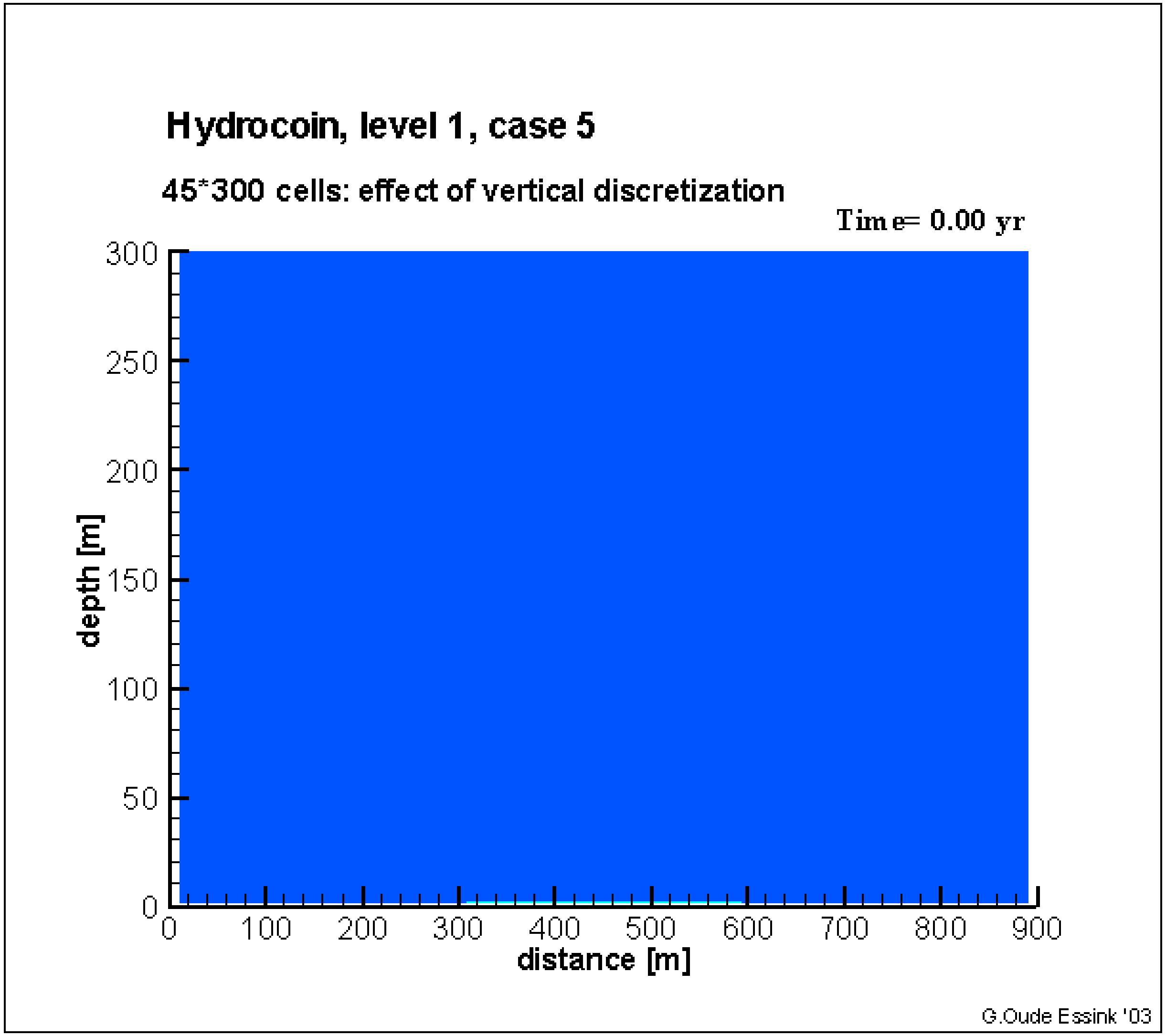
more vertical cells give better solution



like the swept-forward type

Hydrocoin: effect of vertical discretization (III)

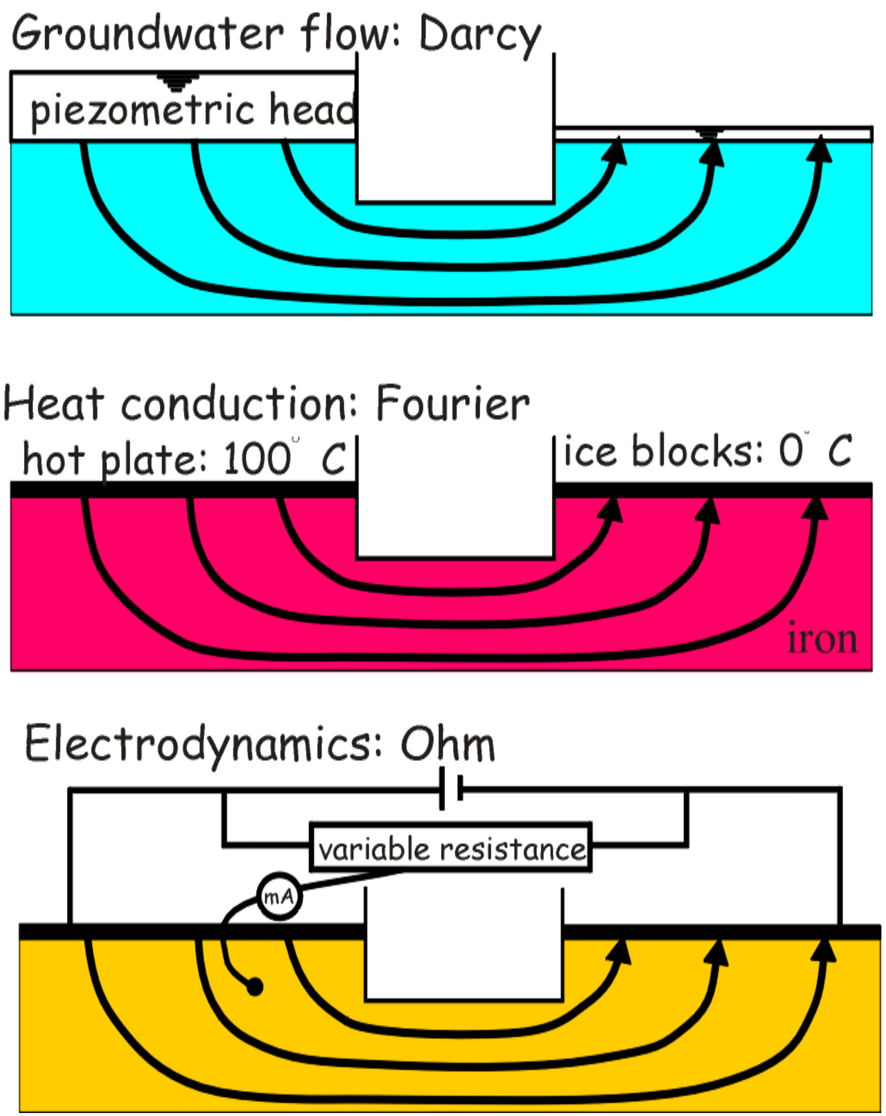
more vertical cells give better solution



like the swept-forward type

Analogy physical processes

Heat transport (analogy with solute transport)



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

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

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

Conduction and convection of heat

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

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

thermal conductivity [Joule/(m s ^{o}C)]

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

continuity equation

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

specific heat capacity [Joule/(kg ^{o}C)]

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

Analogy solute and heat transport

Solute: advection-dispersion equation

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

Heat: convection-conduction equation

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

Analogy heat and solute transport

Heat transport

Convection-conduction equation

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

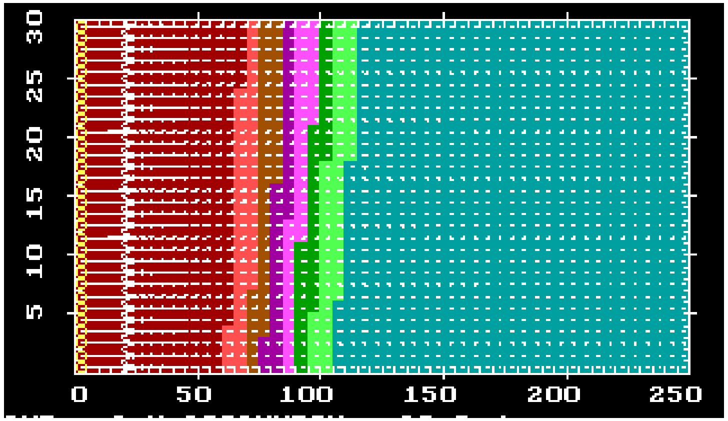
Equation of state: relation density & temperature

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

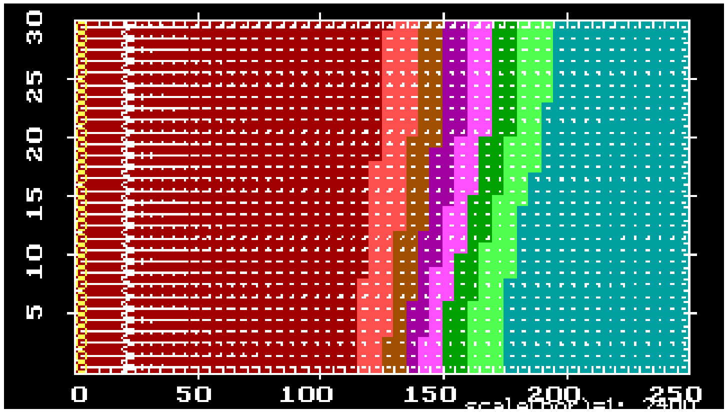
Analogy between solute and heat transport

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

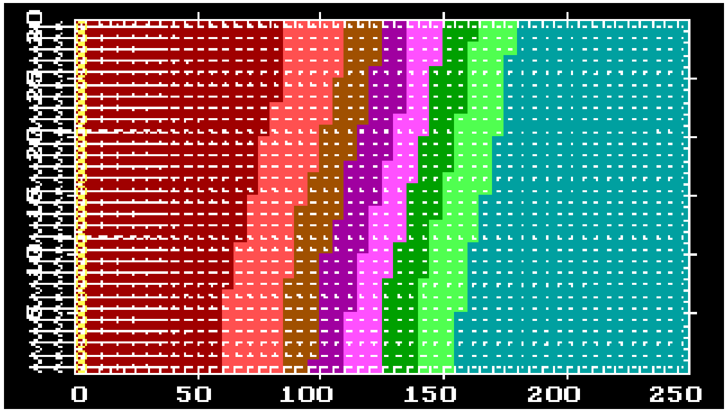
Energy storage in geothermal reservoirs



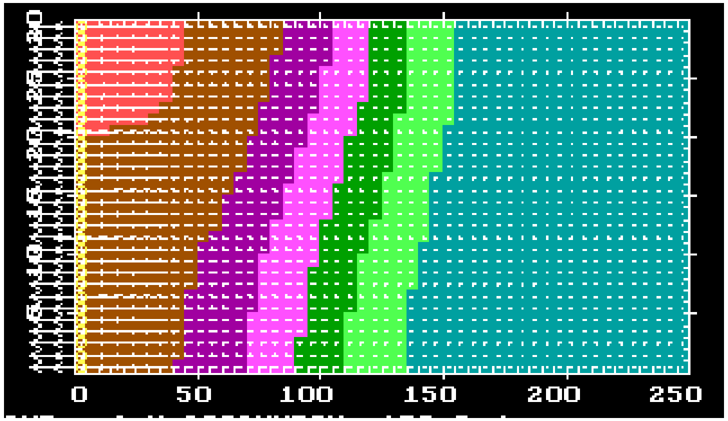
t=30 days



t=90 days

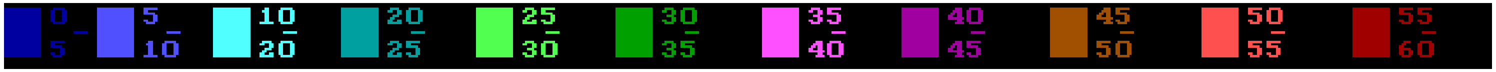


t=150 days



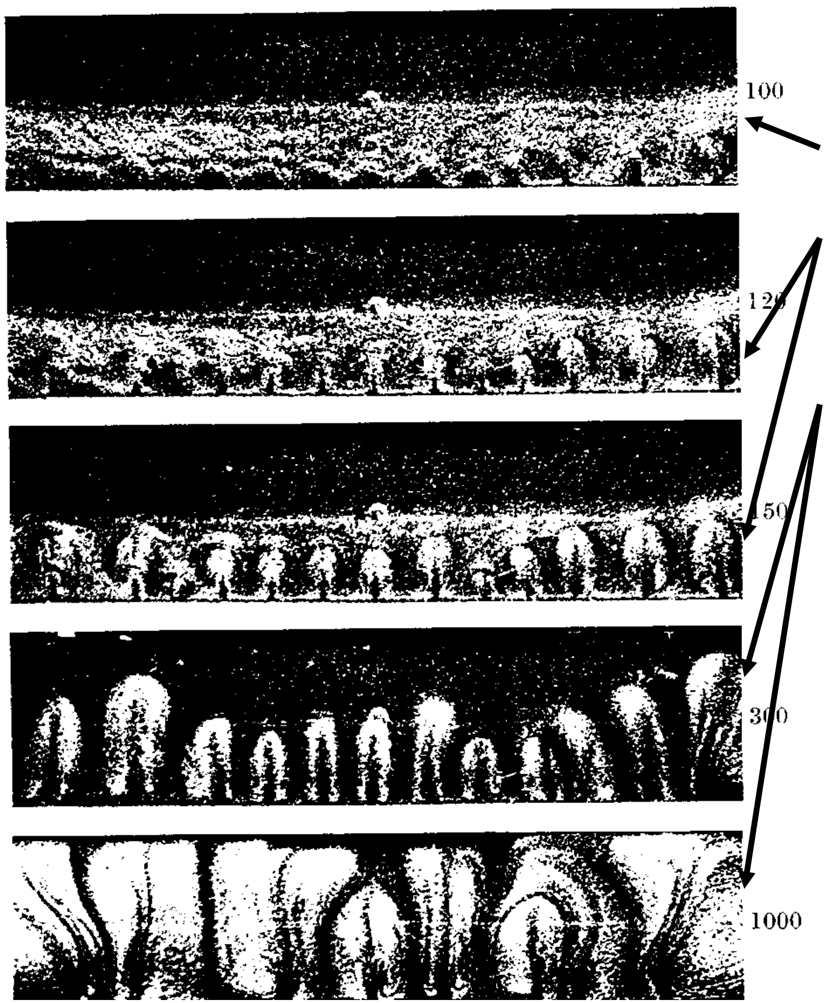
t=210 days

Temperature (degrees Celcius):



Elder problem (I)

It is originally a heat transport problem



Phases:

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

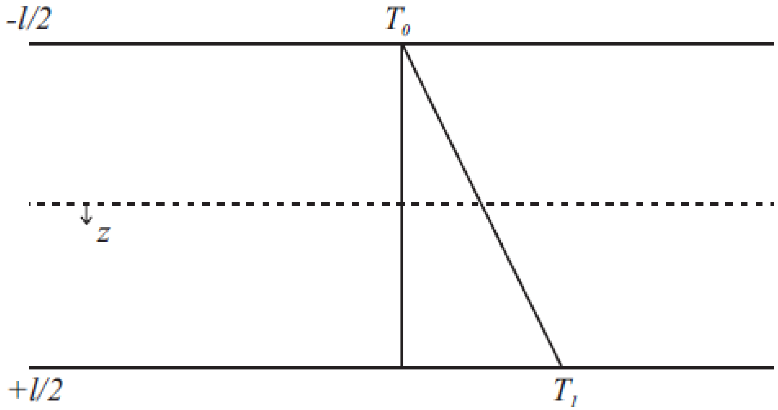
Convection of heat occurs when:

Rayleigh number > $4\pi^2$

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

Stability criteria

$$Ra = \frac{\rho_0 \alpha_f g \kappa (T_1 - T_0) l}{\mu \kappa_e} > 4\pi^2$$



Darcy equations:

$$q_x = -\frac{\kappa}{\mu}\frac{\partial p}{\partial x}$$

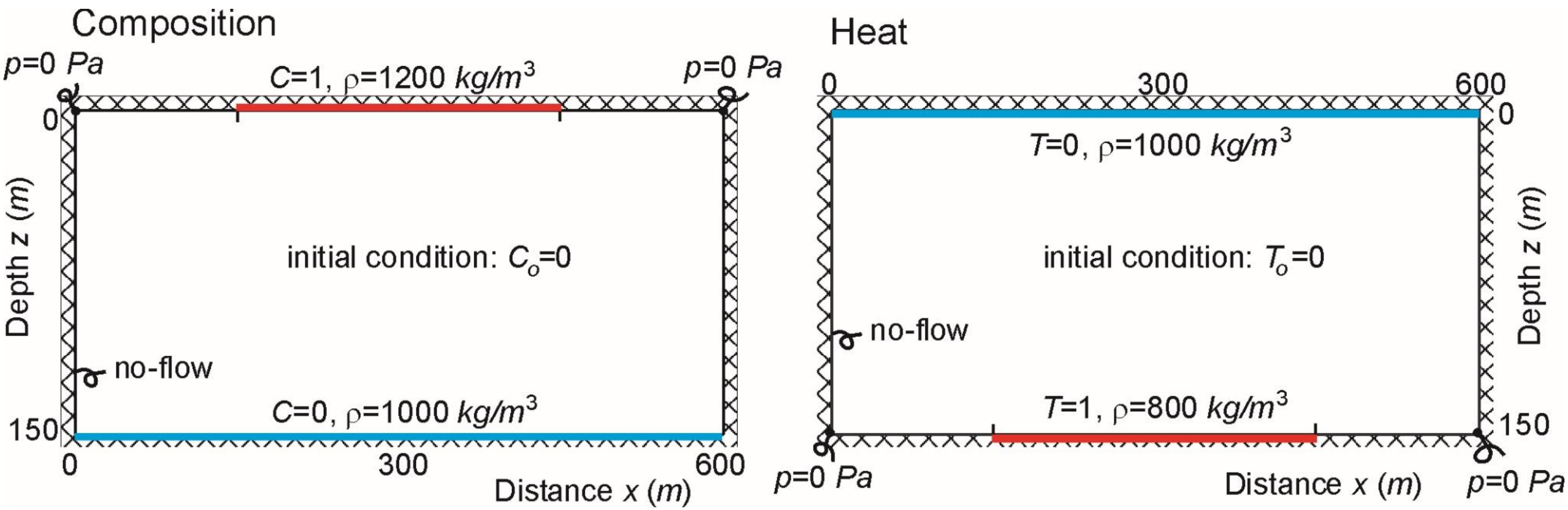
$$q_z = -\frac{\kappa}{\mu}\left(\frac{\partial p}{\partial z} - \rho g\right)$$

$$\rho = \rho_0 \left[1 - \alpha_f \left(T - T'\right)\right]$$

$$\frac{\lambda_e}{\rho c_f} = \kappa_e \text{ (=thermal diffusivity } M\ L^{-2}\text{)}$$

Elder problem (II)

Anology composition and heat



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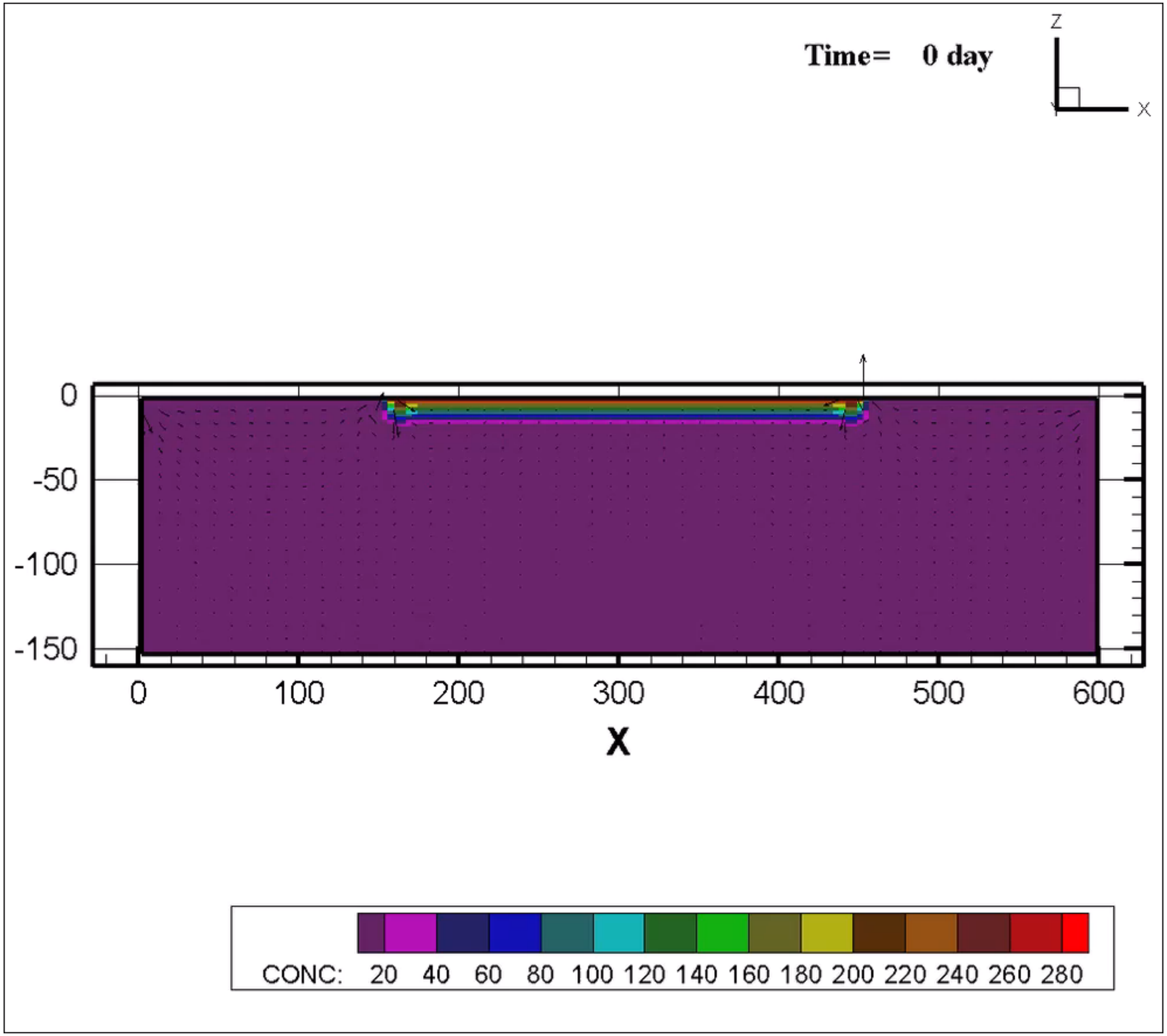
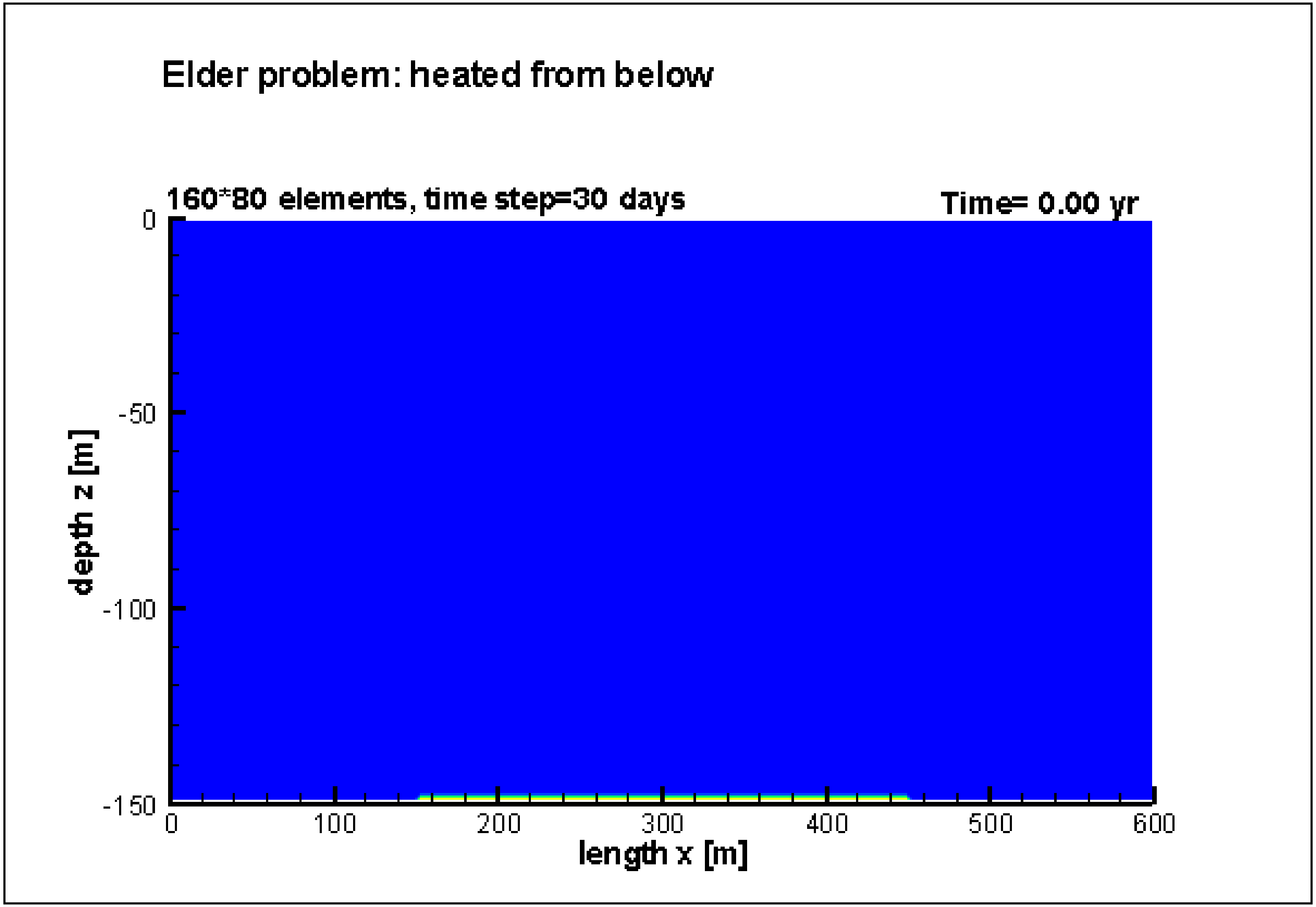
Case Elder, salt-fresh



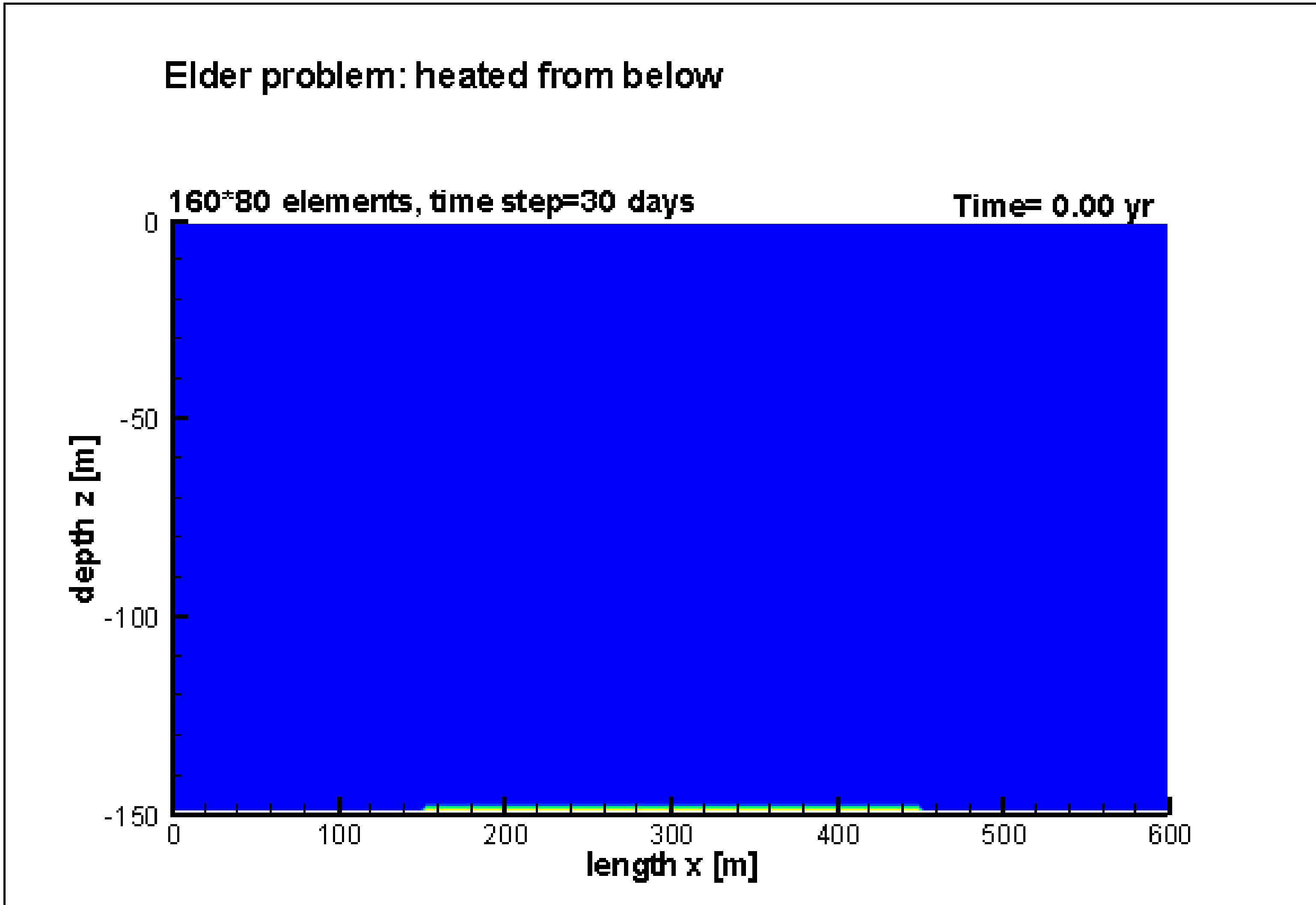
Elder problem (III)

Development of convection cells (Rayleigh number=400)

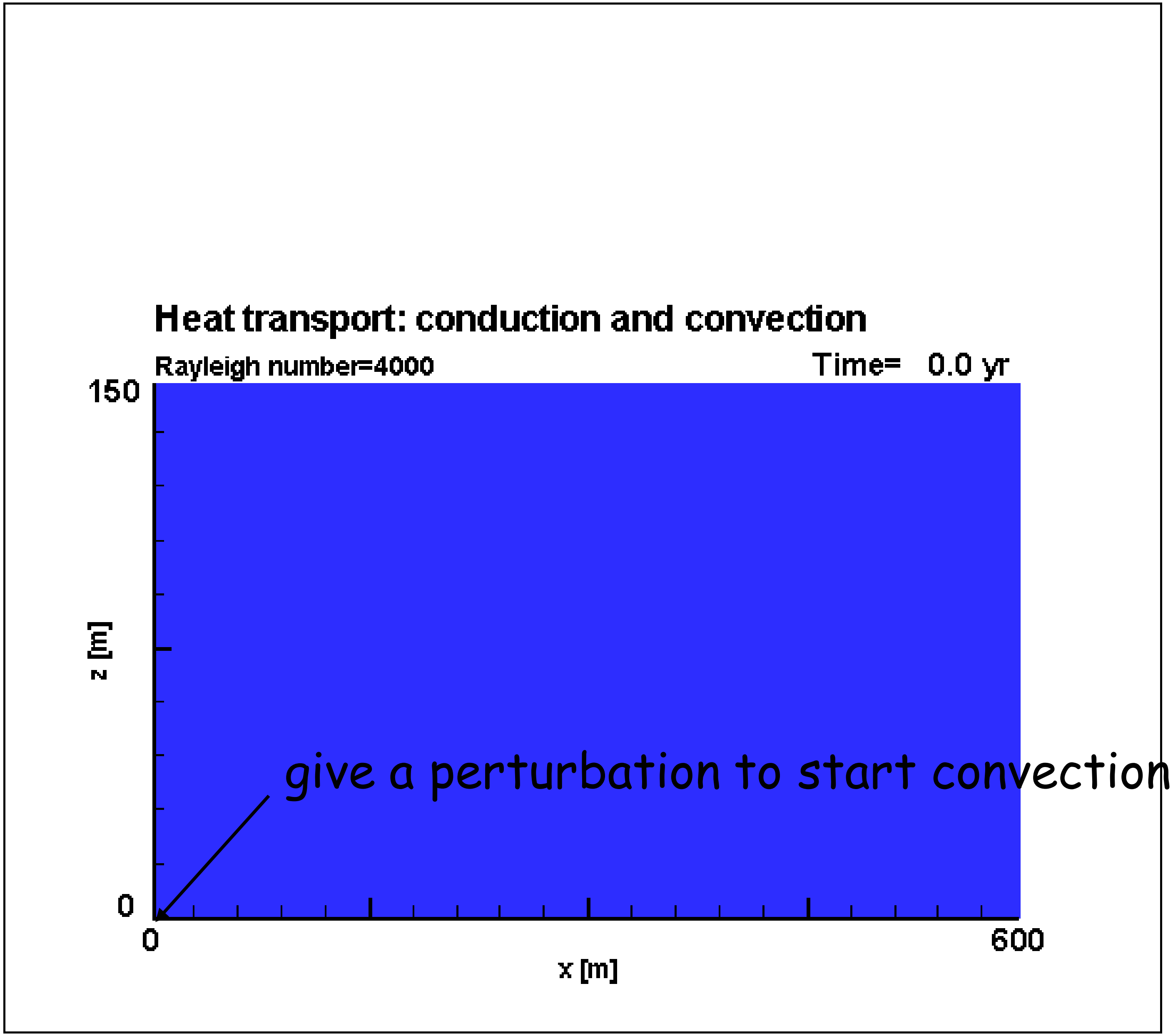


Elder problem (III)

Development of convection cells (Rayleigh number=400)



Heat transport (Rayleigh number=4000)



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

Sri Lanka
Some days after December 26th, 2004

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

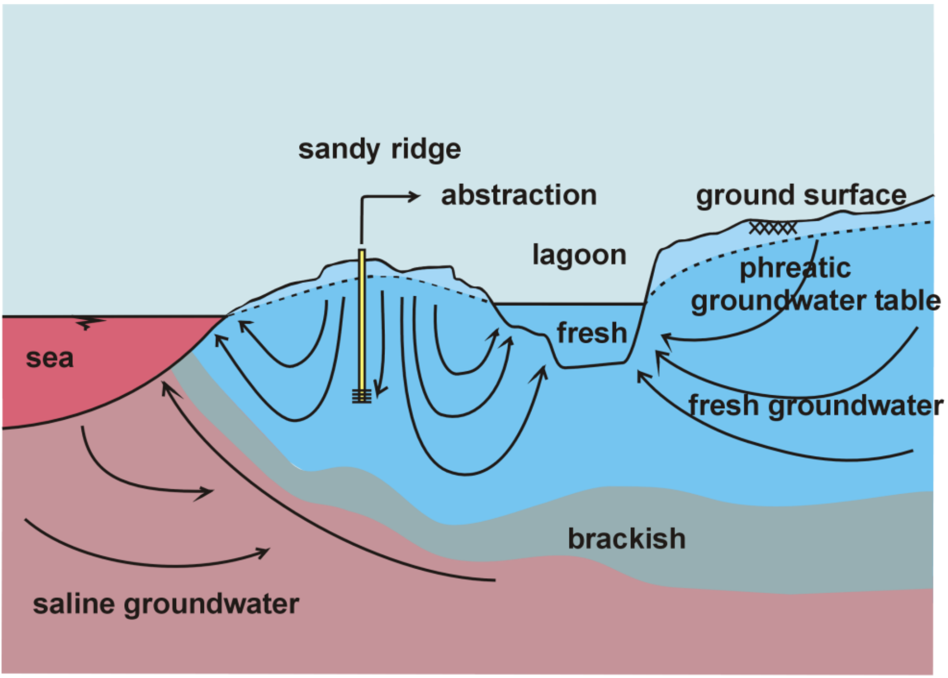
Impression of relevant salinisation processes by conceptual models of salt water intrusion in coastal aquifers:

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

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

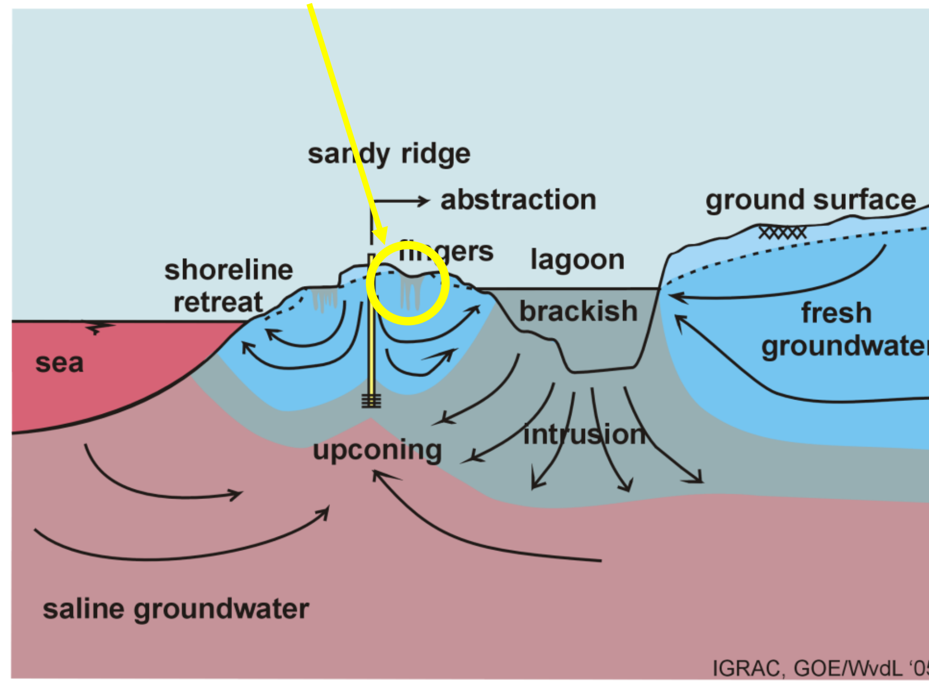
Concept 1: Fingering processes in the subsoil

Case Sri Lanka: lagoon setting



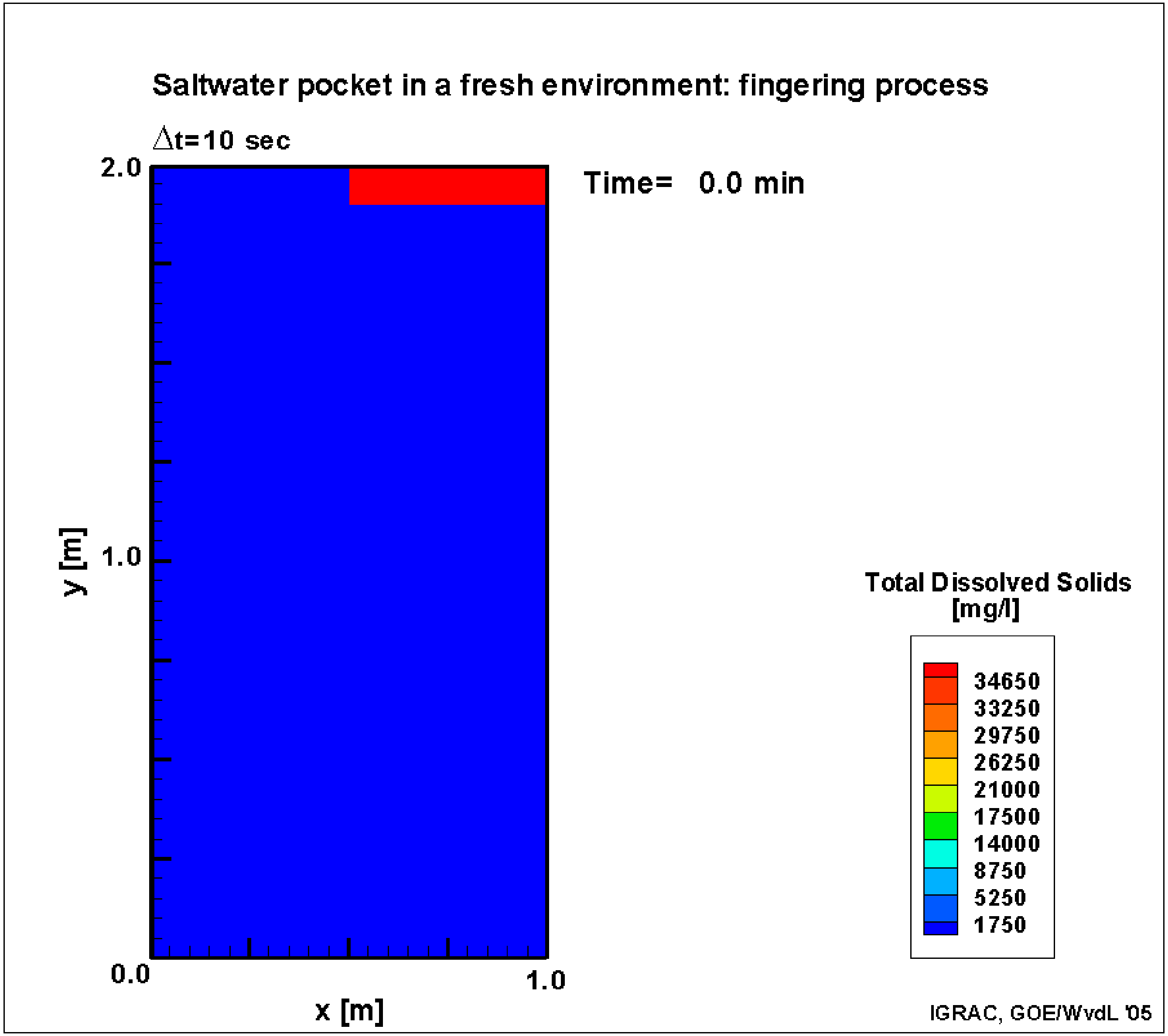
Before the Tsunami

fingering processes

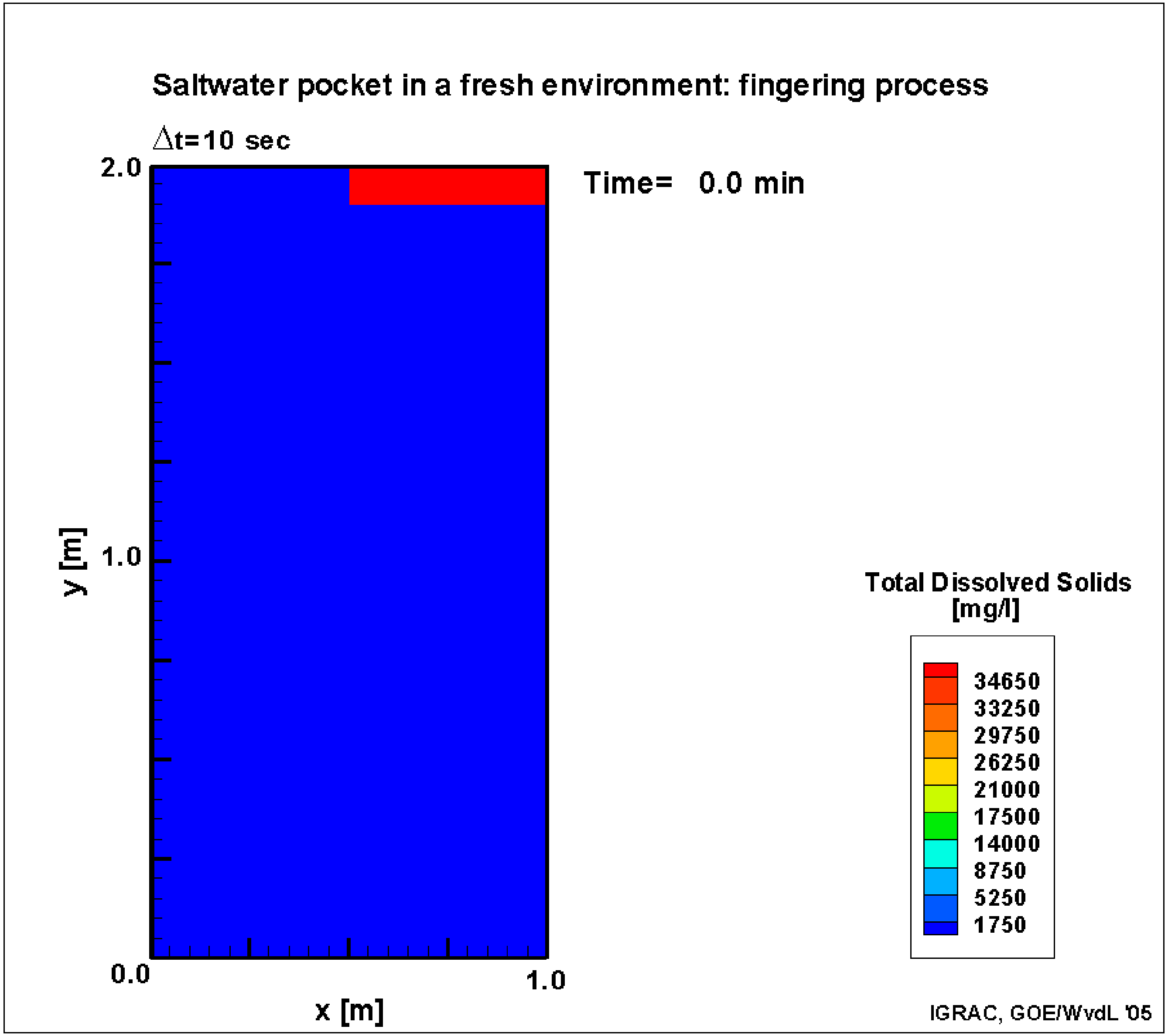


After the Tsunami

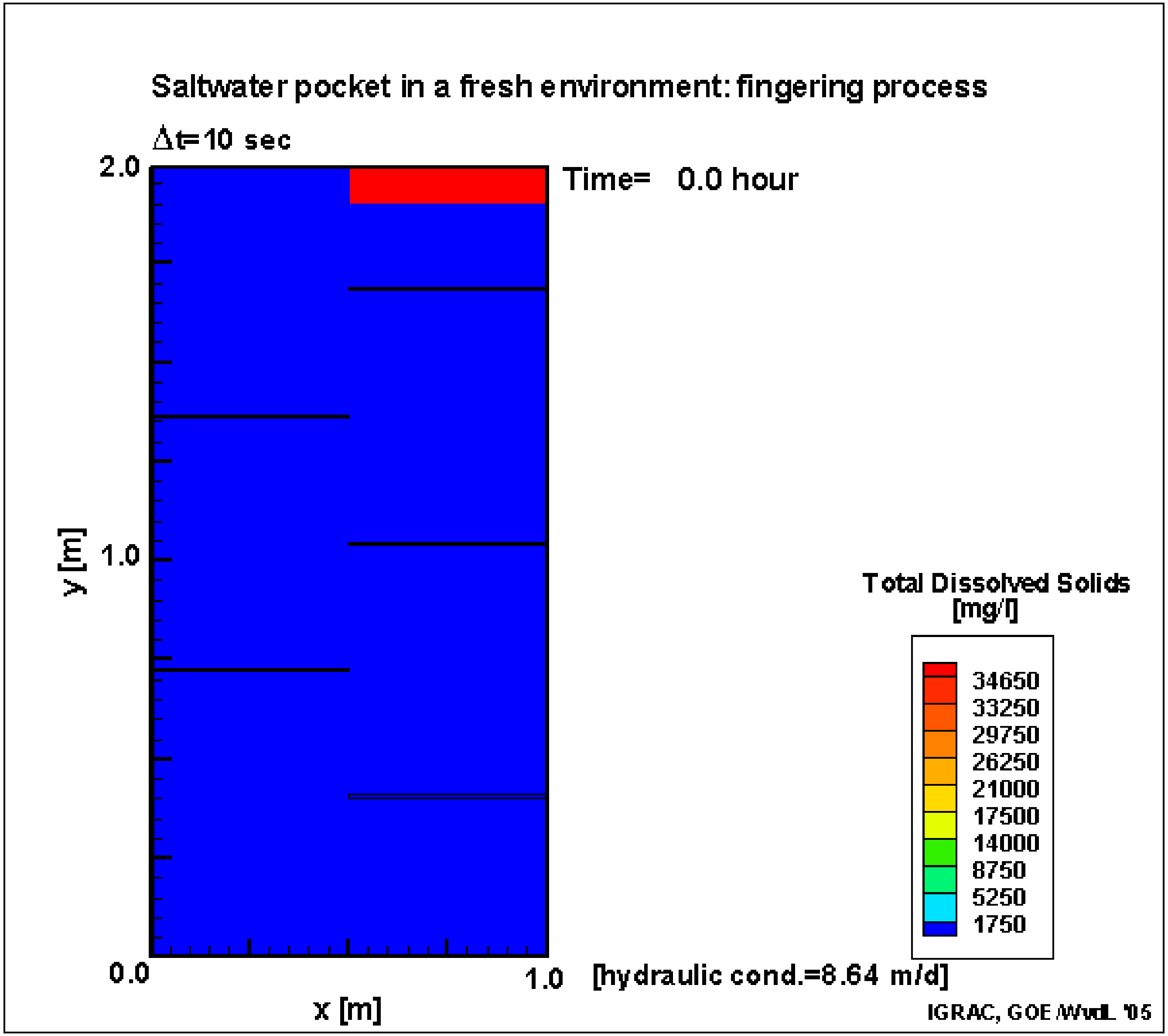
Concept 1: Fingering processes in the subsoil



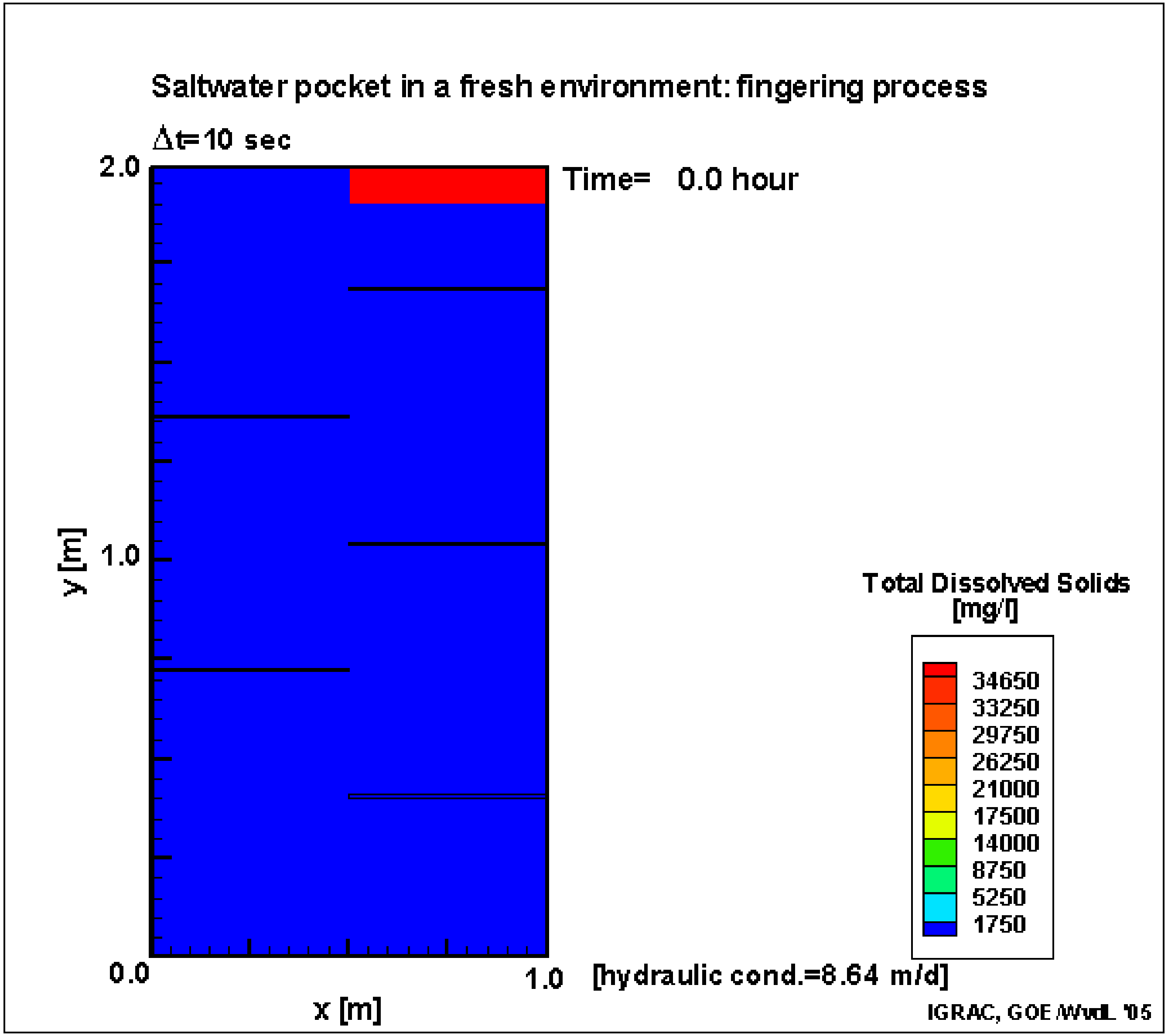
Concept 1: Fingering processes in the subsoil



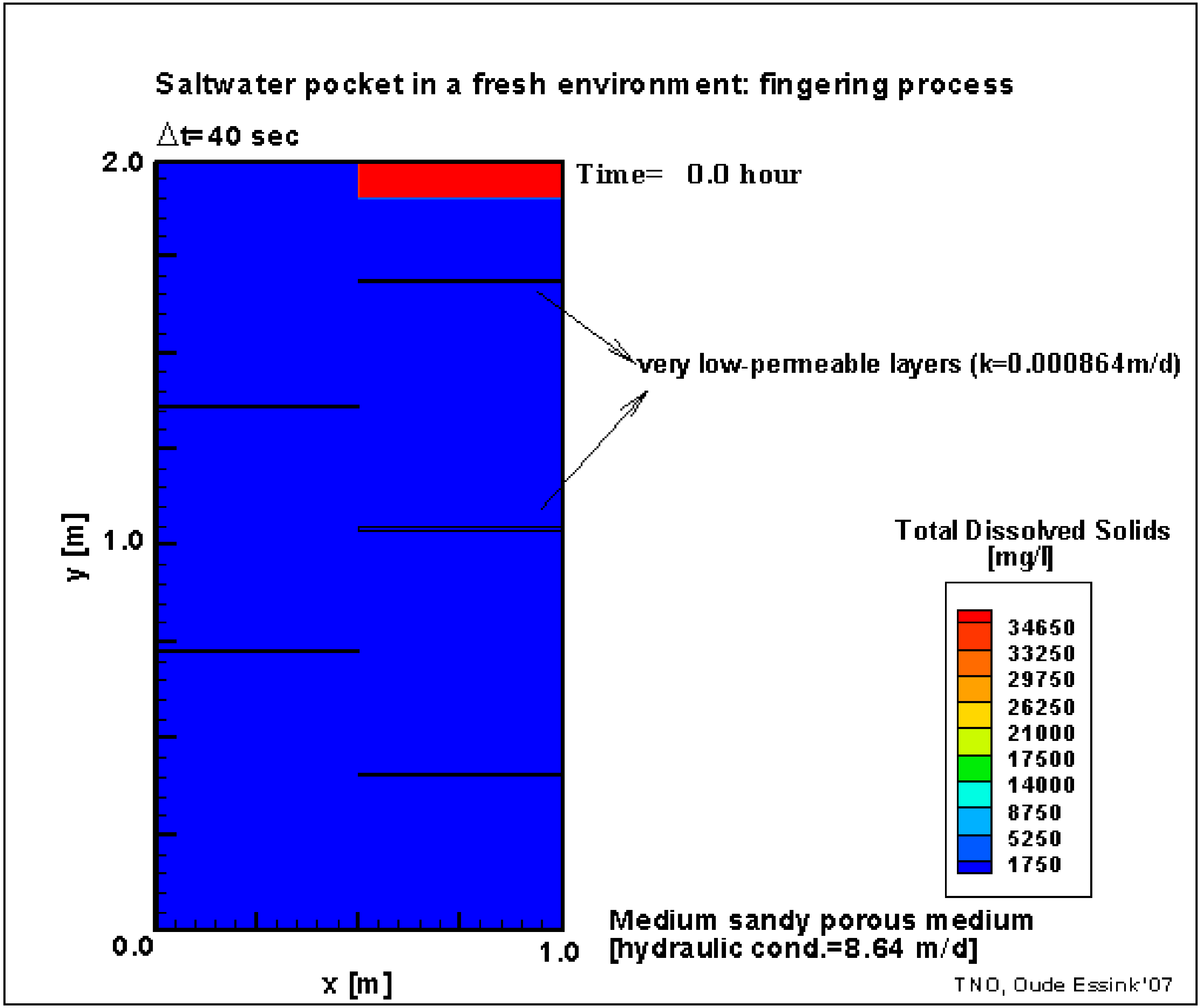
Concept 1: Fingering processes in the subsoil



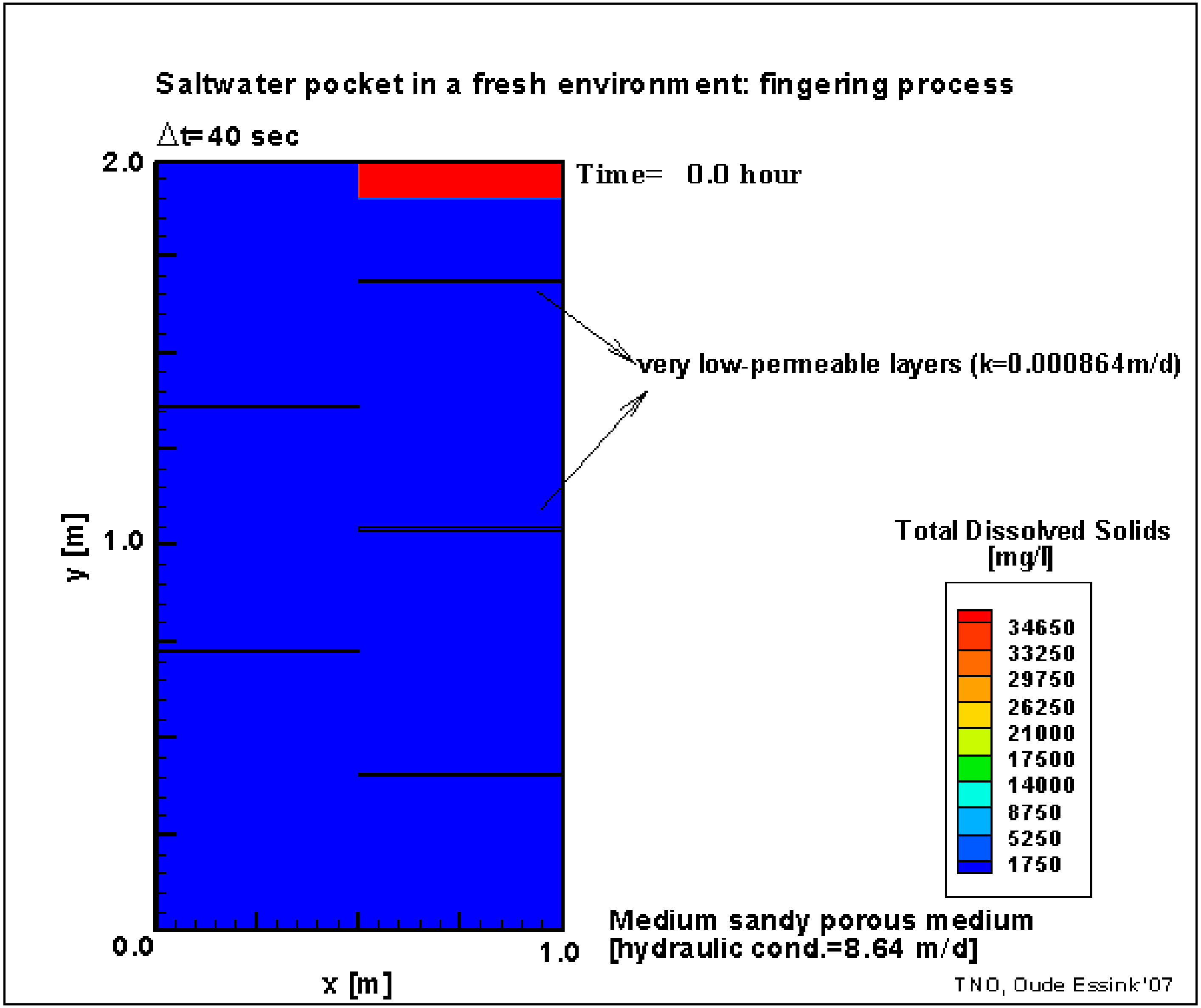
Concept 1: Fingering processes in the subsoil



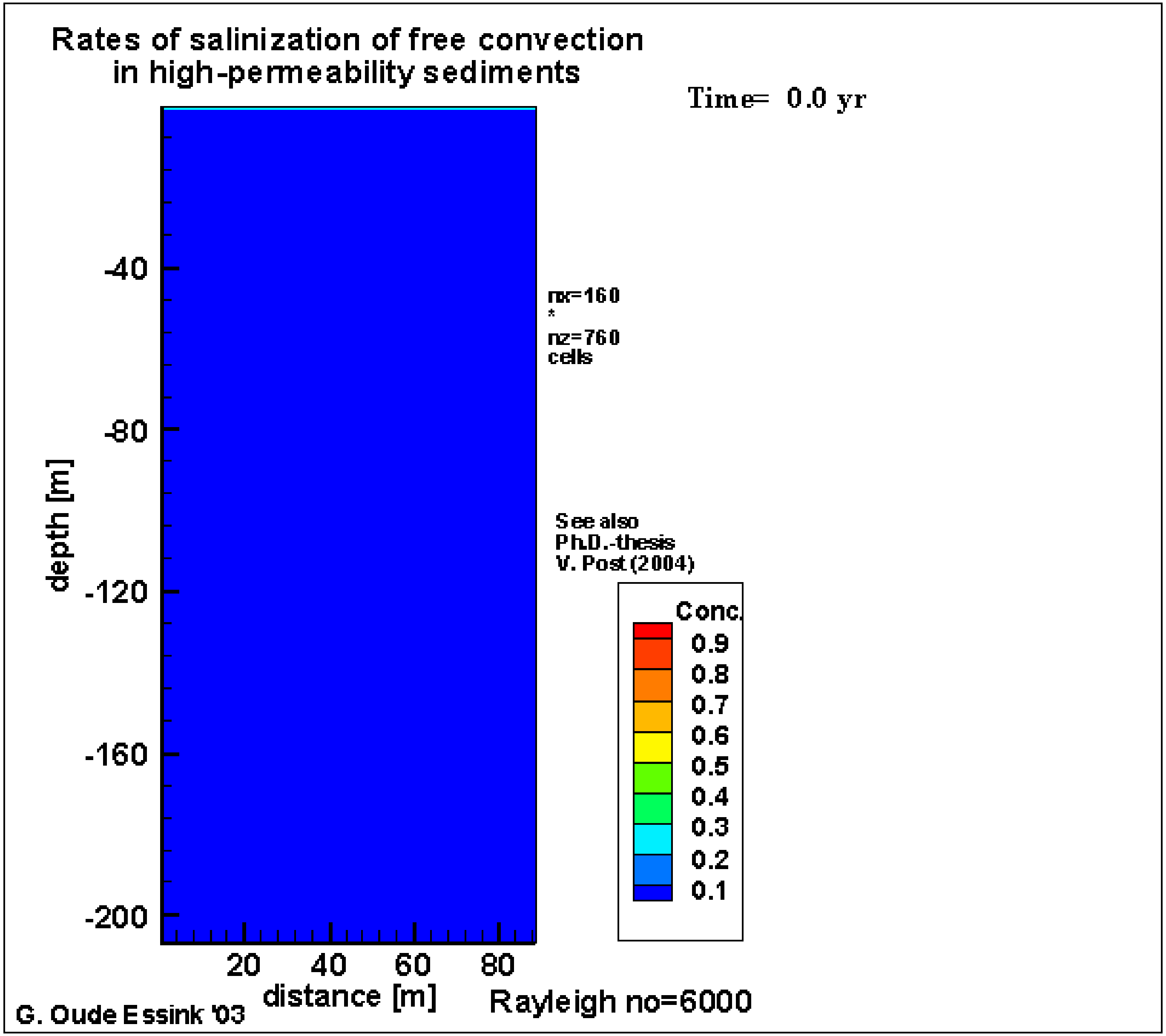
Concept 1: Fingering processes in the subsoil



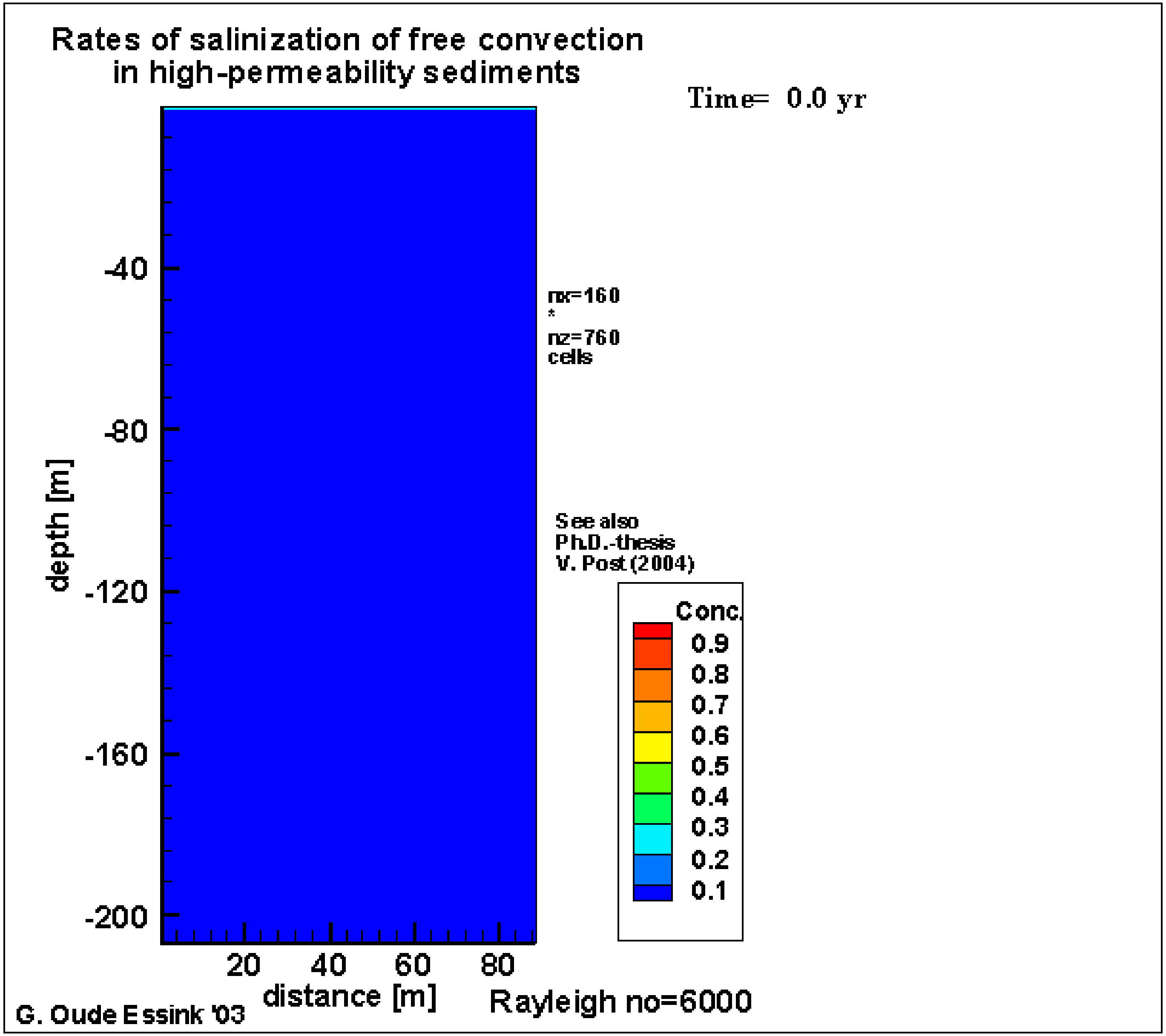
Concept 1: Fingering processes in the subsoil



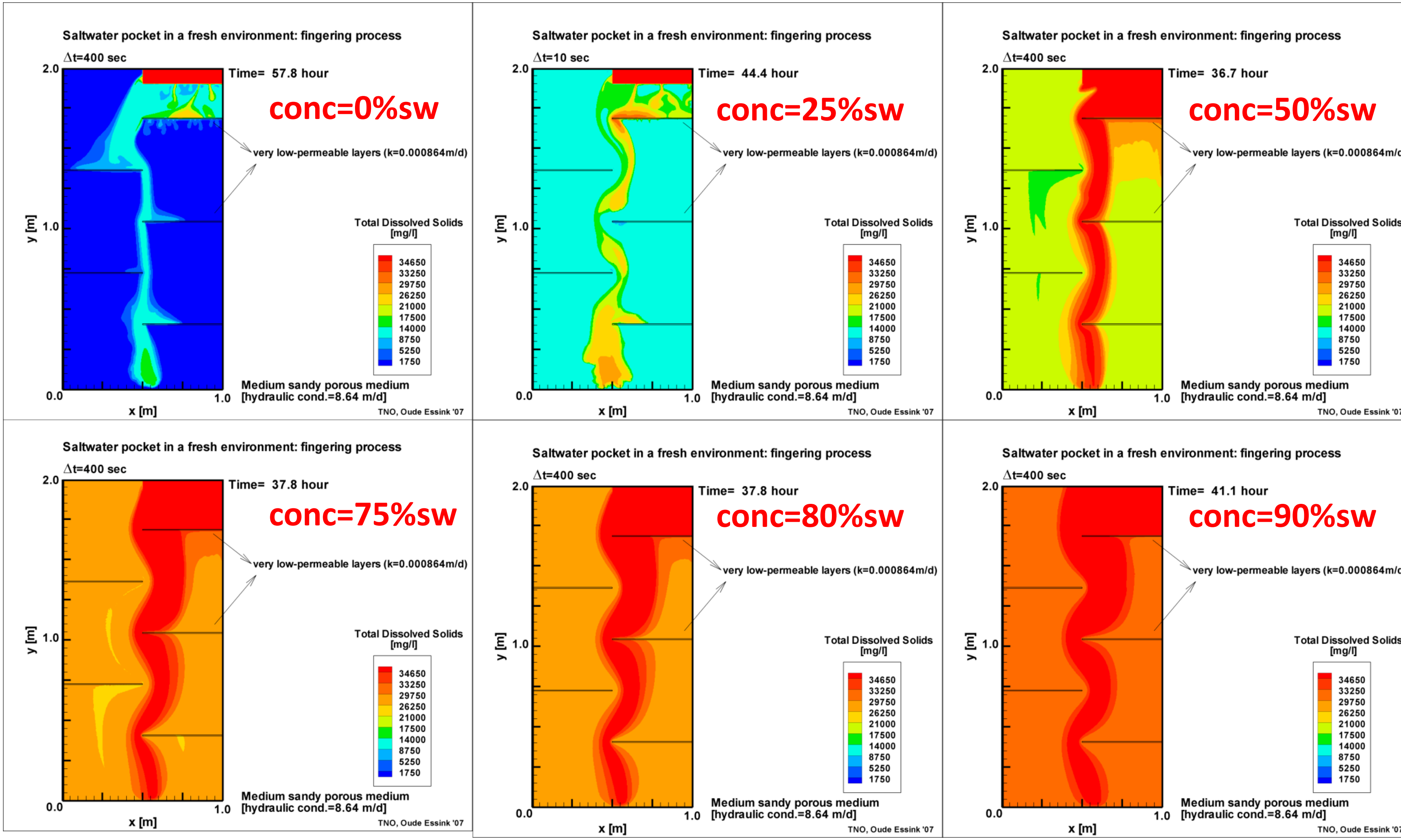
Concept 1: Fingering processes in the subsoil



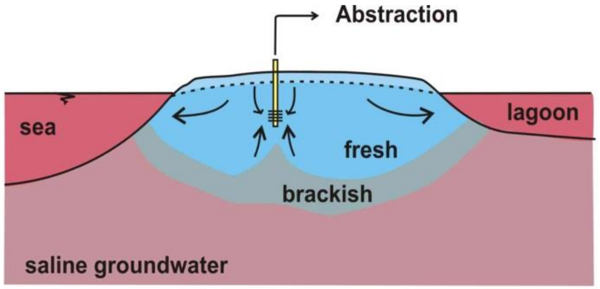
Concept 1: Fingering processes in the subsoil



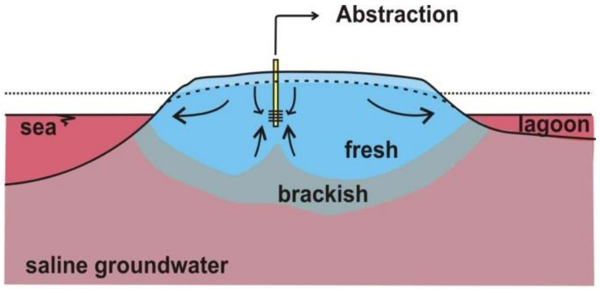
Fingering processes in the subsoil



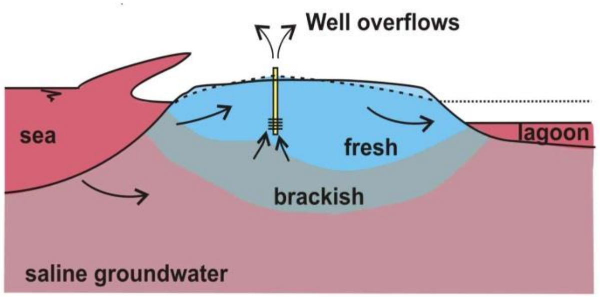
Concept 2: Evolution of a freshwater lens after flooding



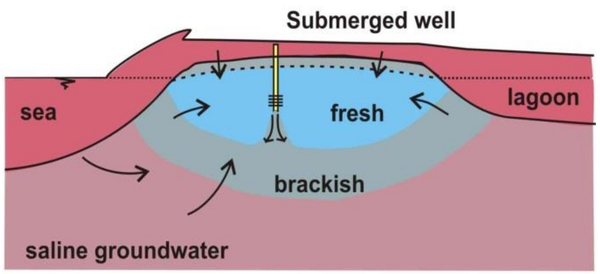
1. Before the Tsunami



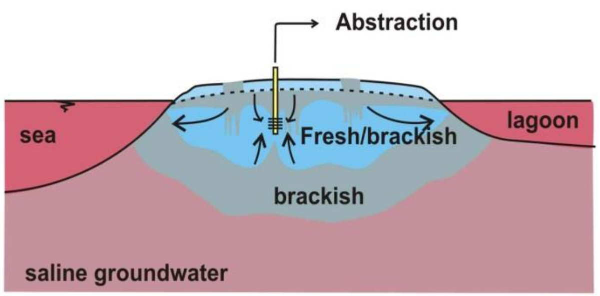
2. Just before the Tsunami:
Lowering of sea- and lagoonwater level



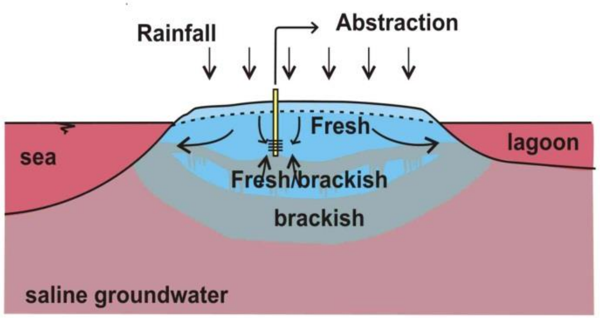
3. Just before the Tsunami:
Subsurface pressure wave precedes surface wave



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

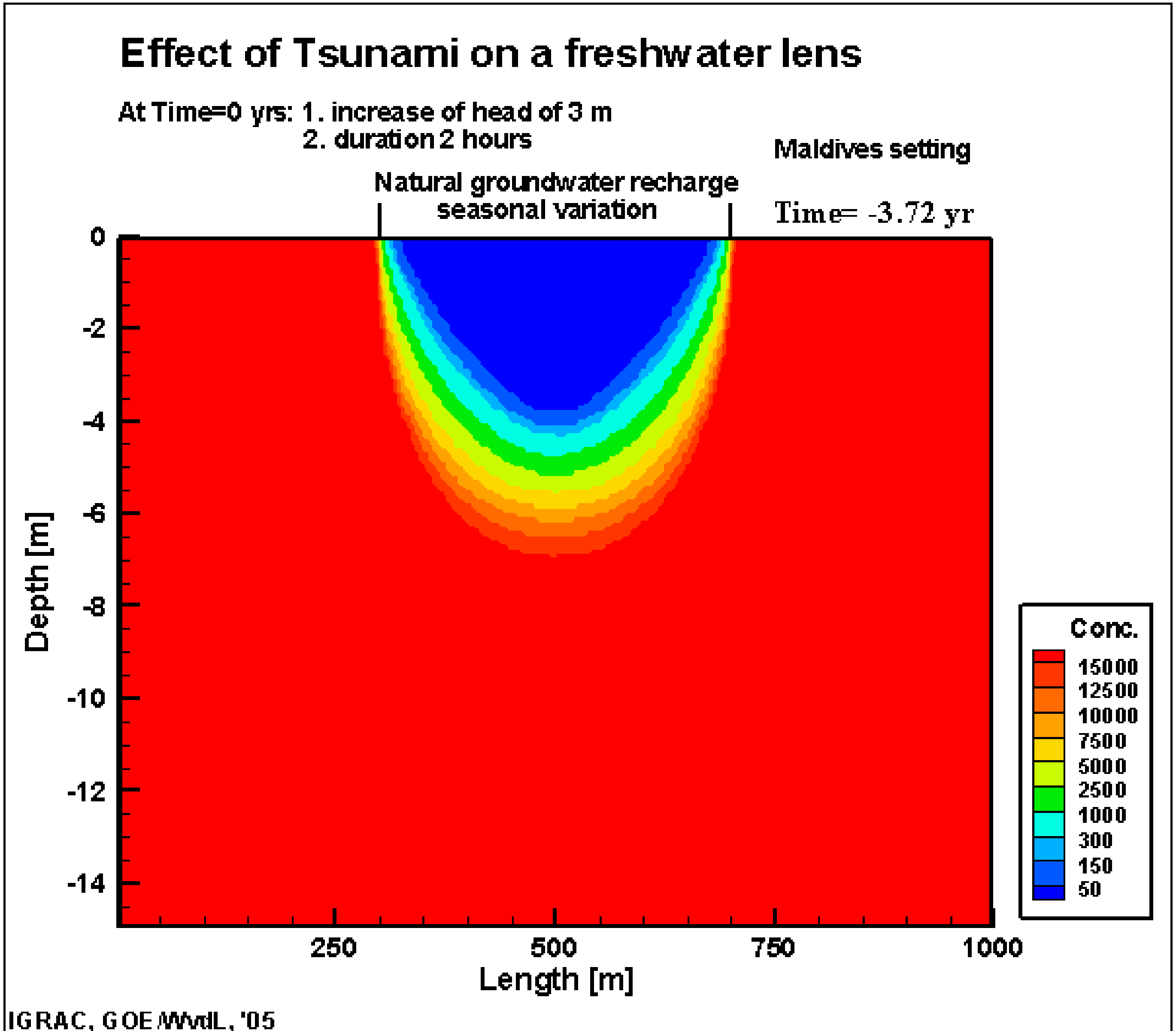


5. After the Tsunami
Freshwater mixed with brackish water

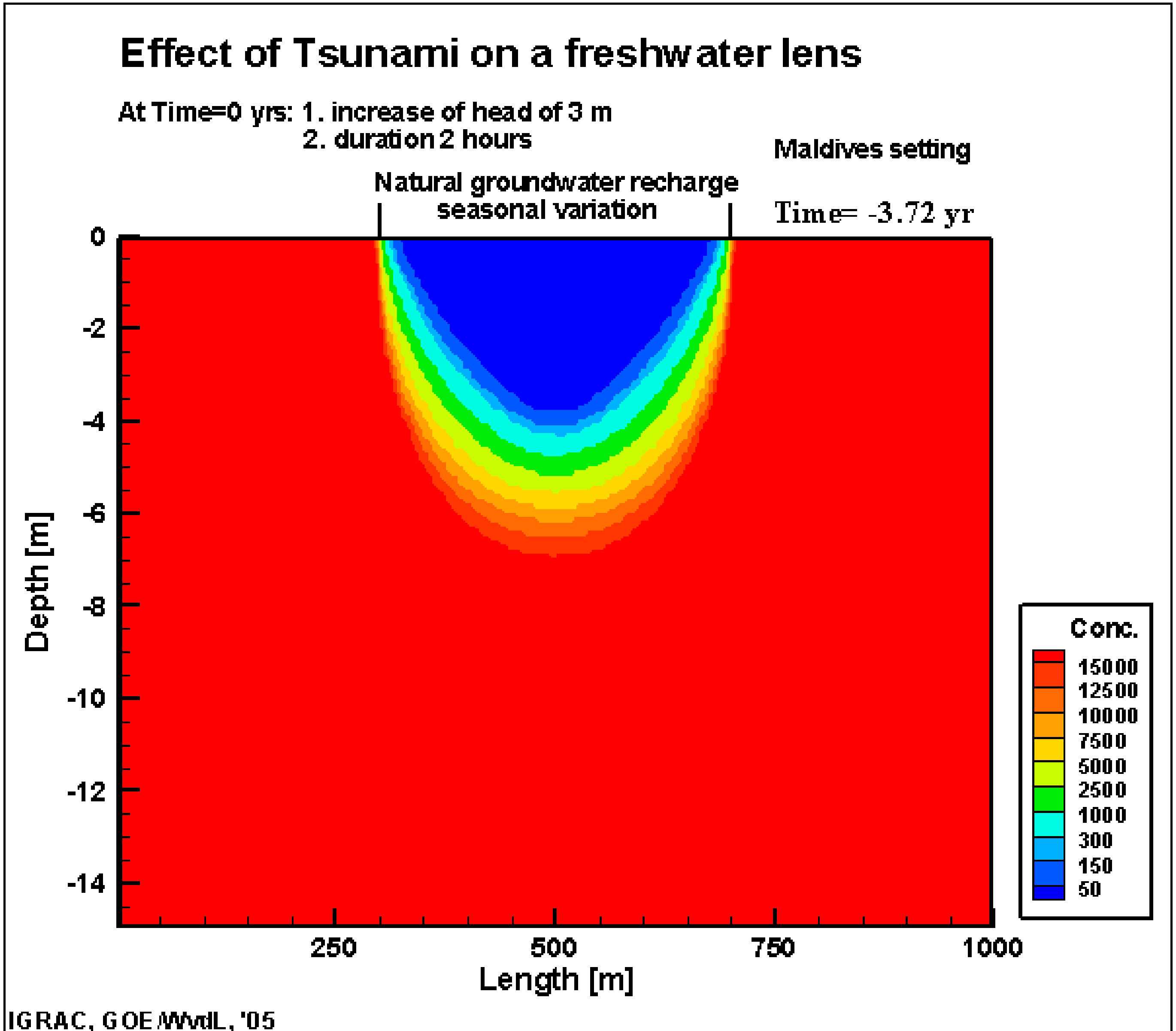


6. After the Tsunami
Recharge by rainfall replaces brackish water

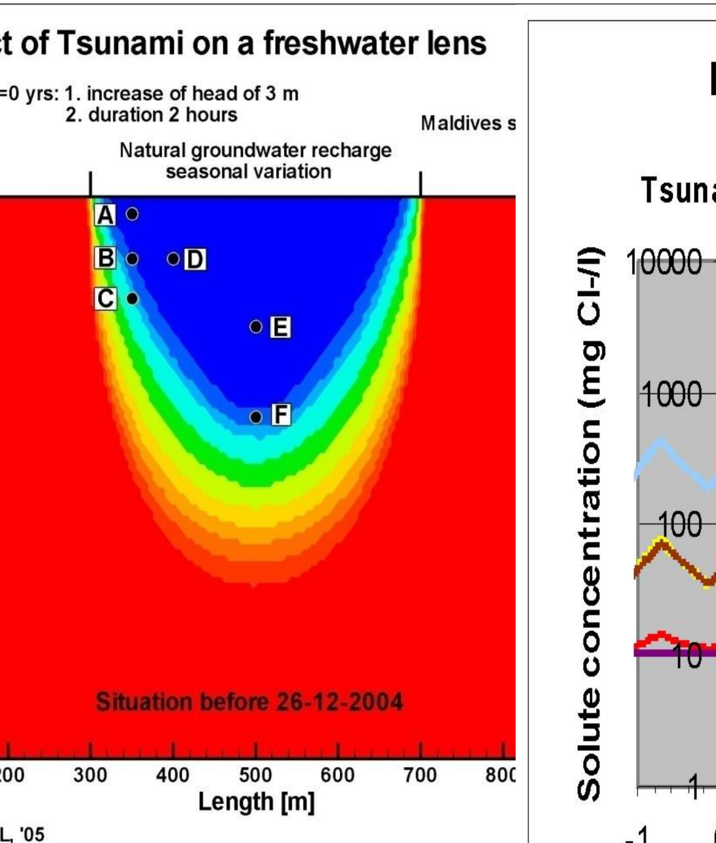
Concept 2: Evolution of a freshwater lens after flooding

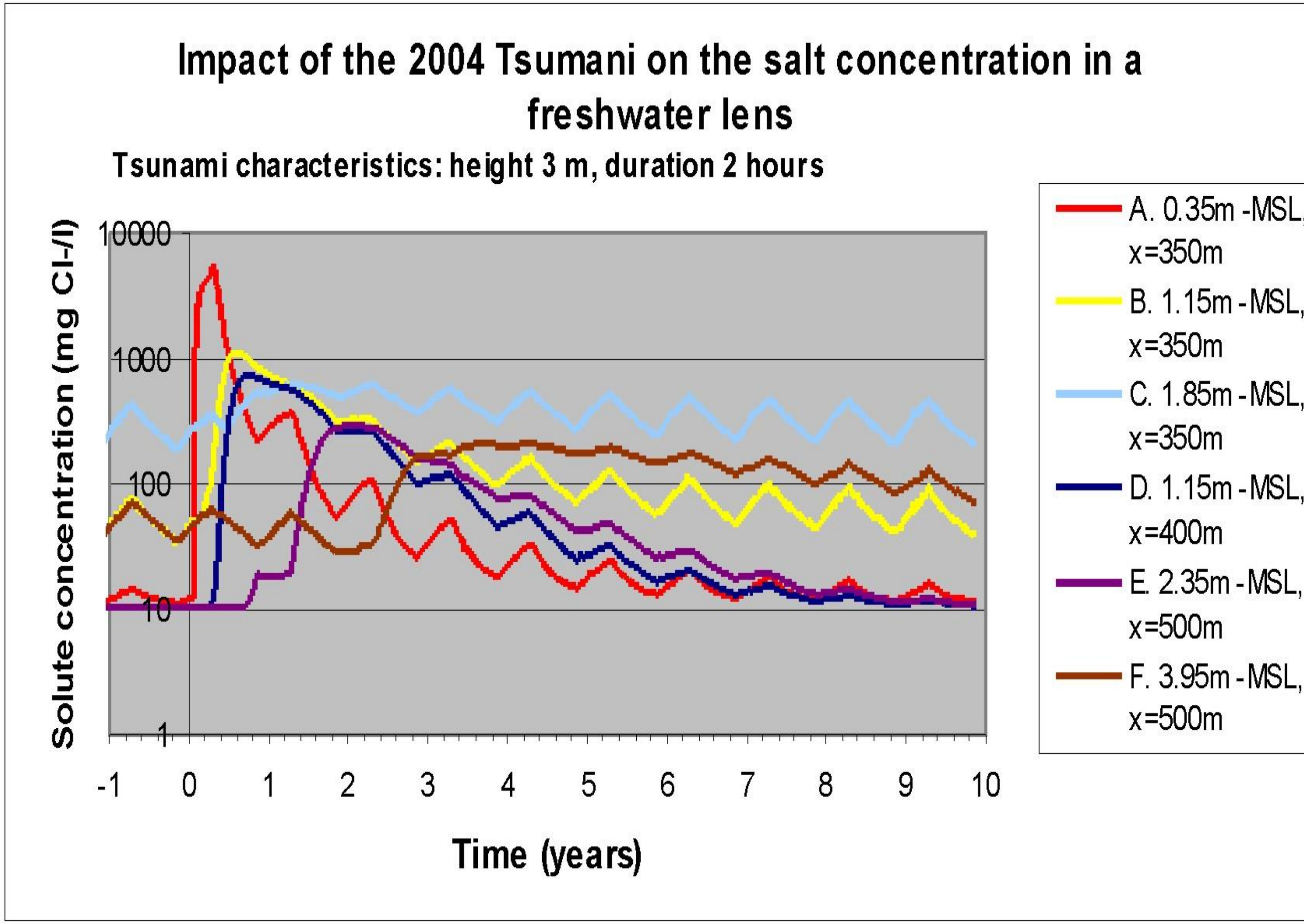


Concept 2: Evolution of a freshwater lens after flooding



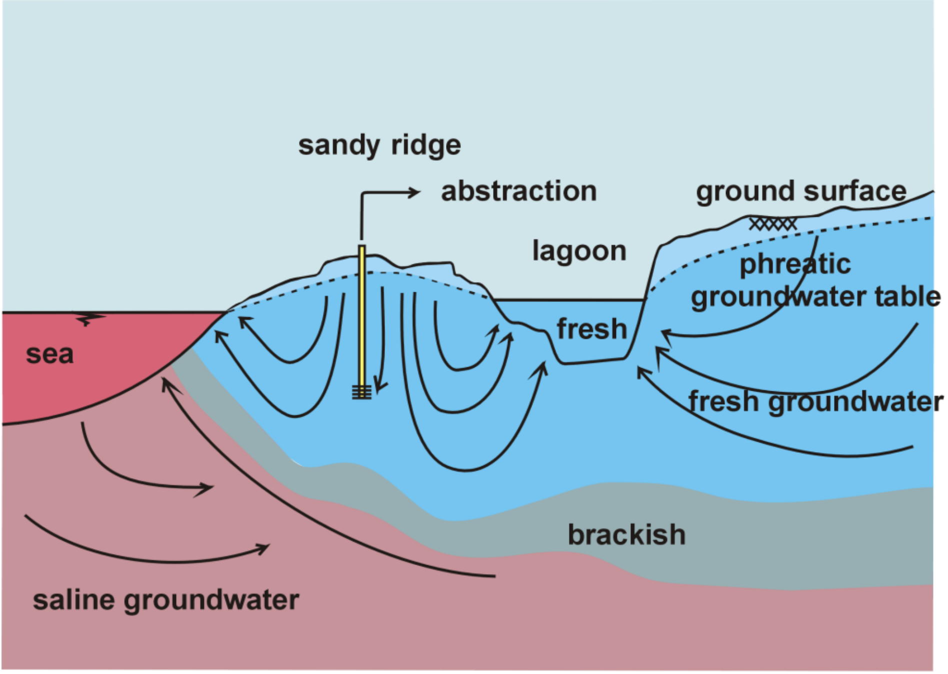
Concept 2: Evolution of a freshwater lens after flooding



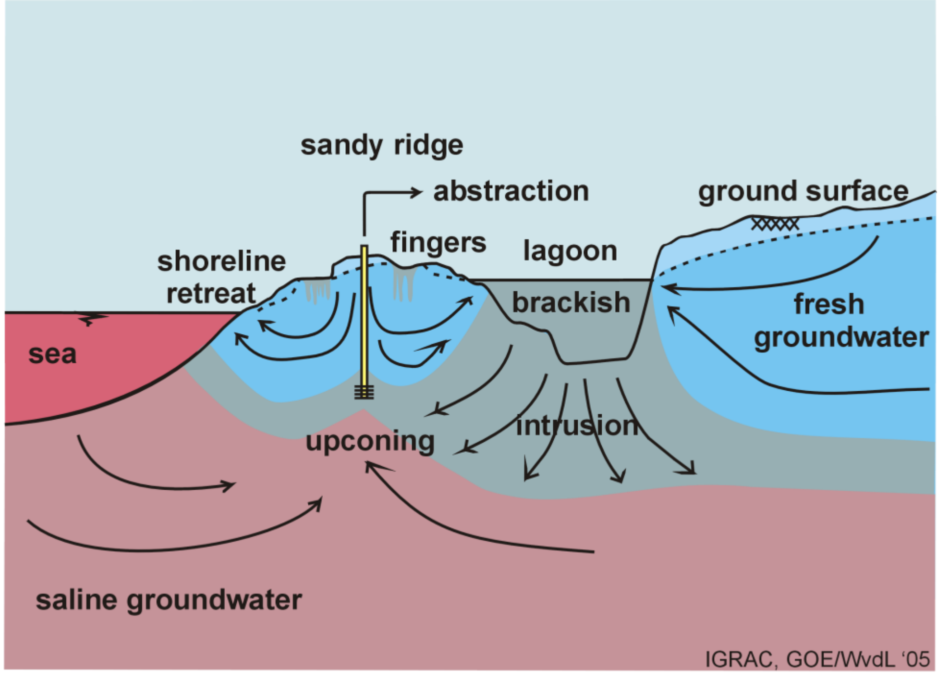


Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

Case Sri Lanka: lagoon setting

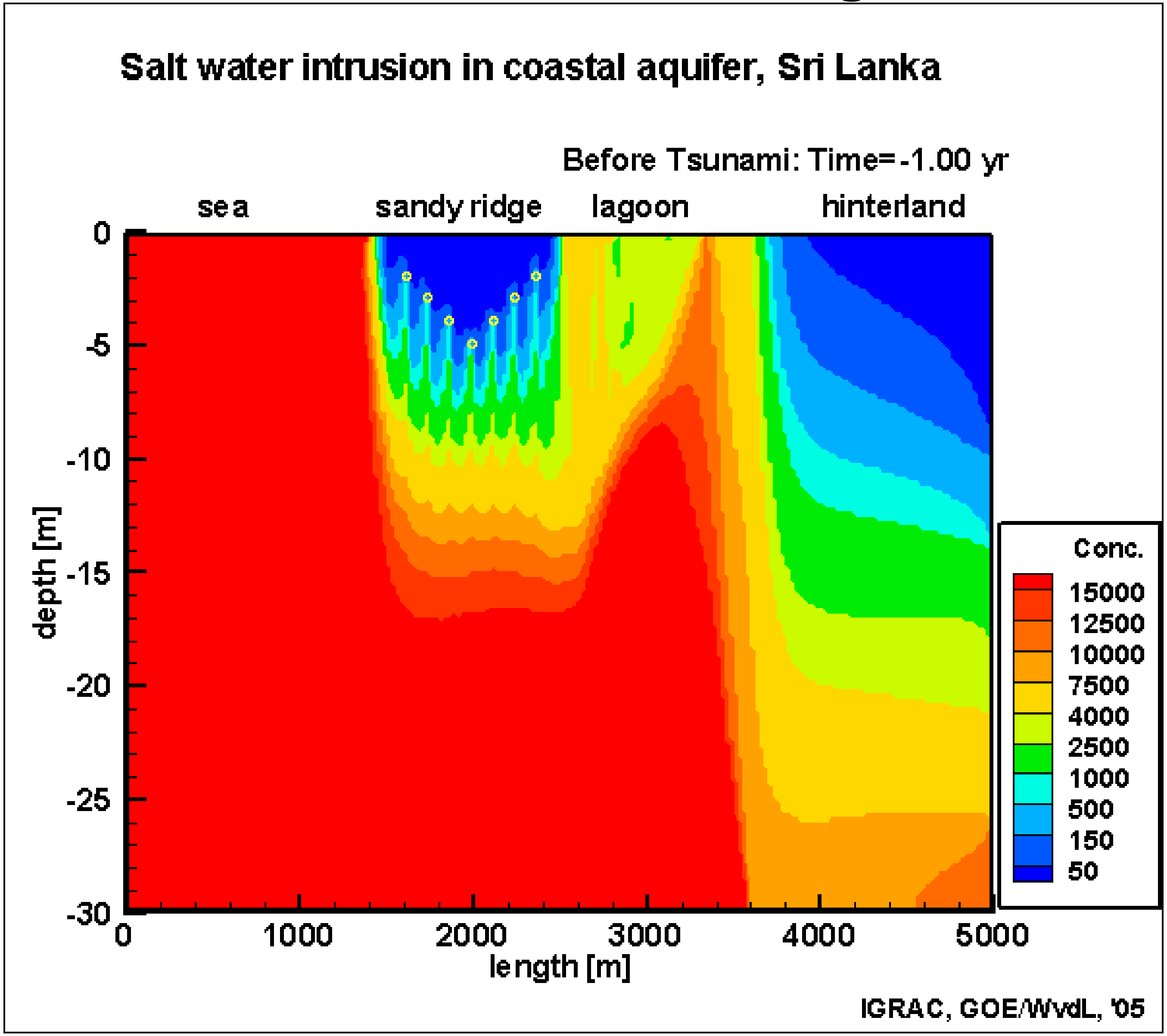


Before the Tsunami

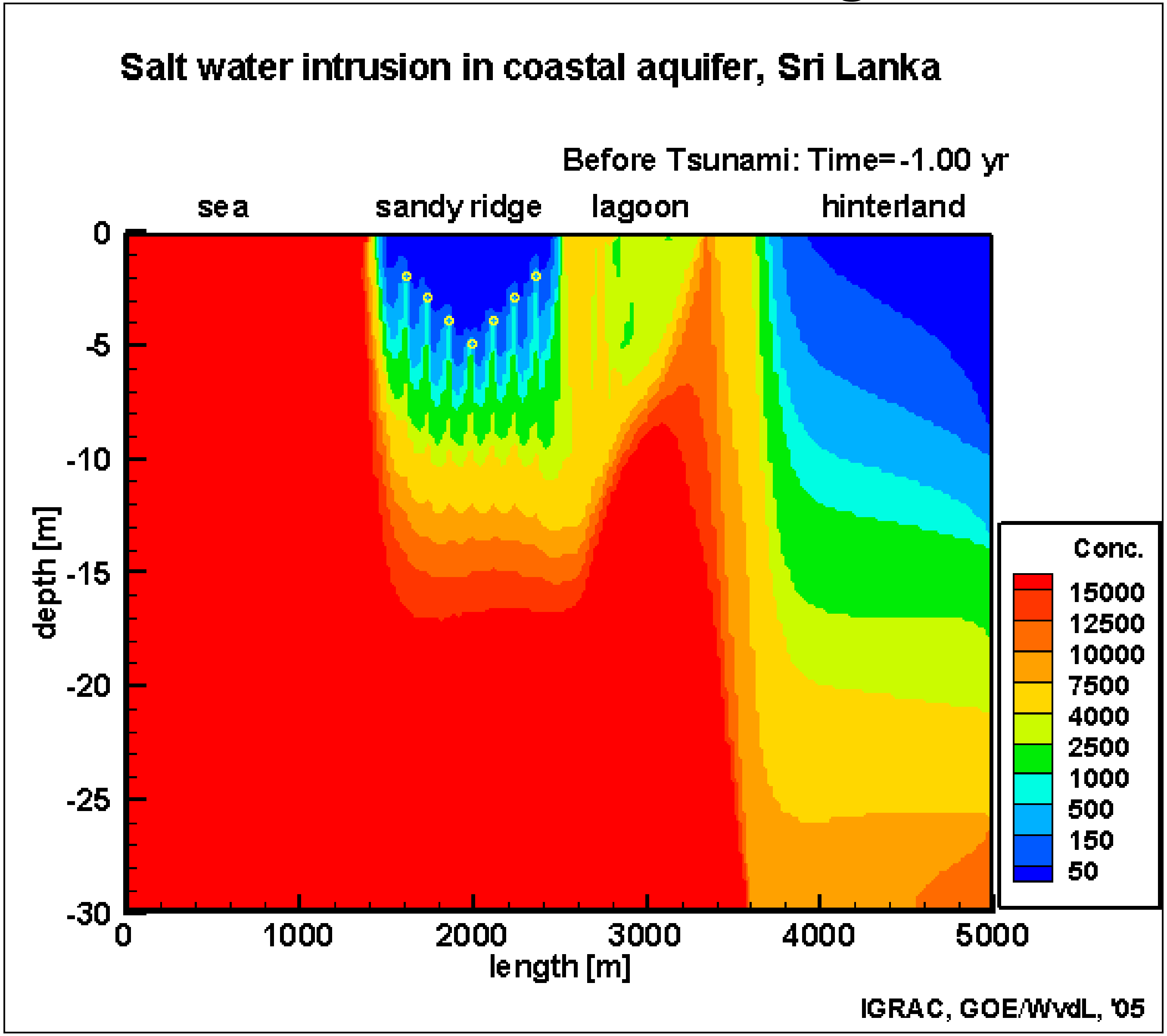


After the Tsunami

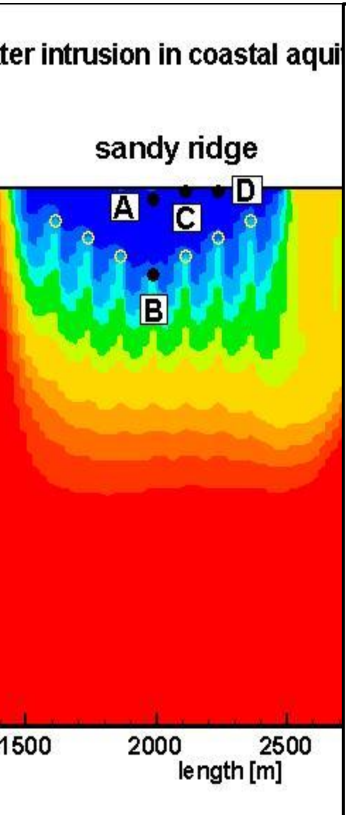
Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon

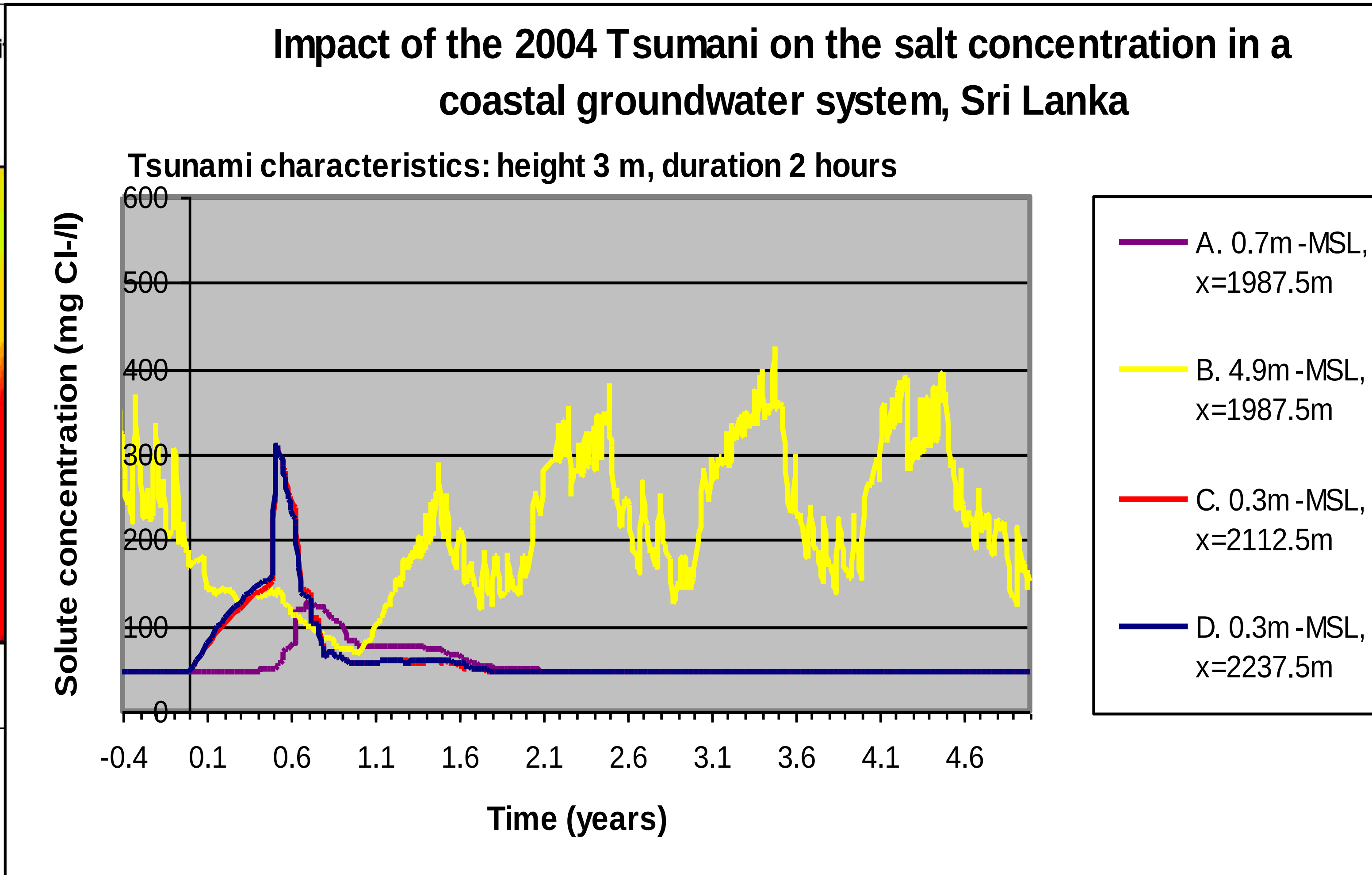


Concept 3: Freshwater lens in a coastal aquifer with a brackish lagoon



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

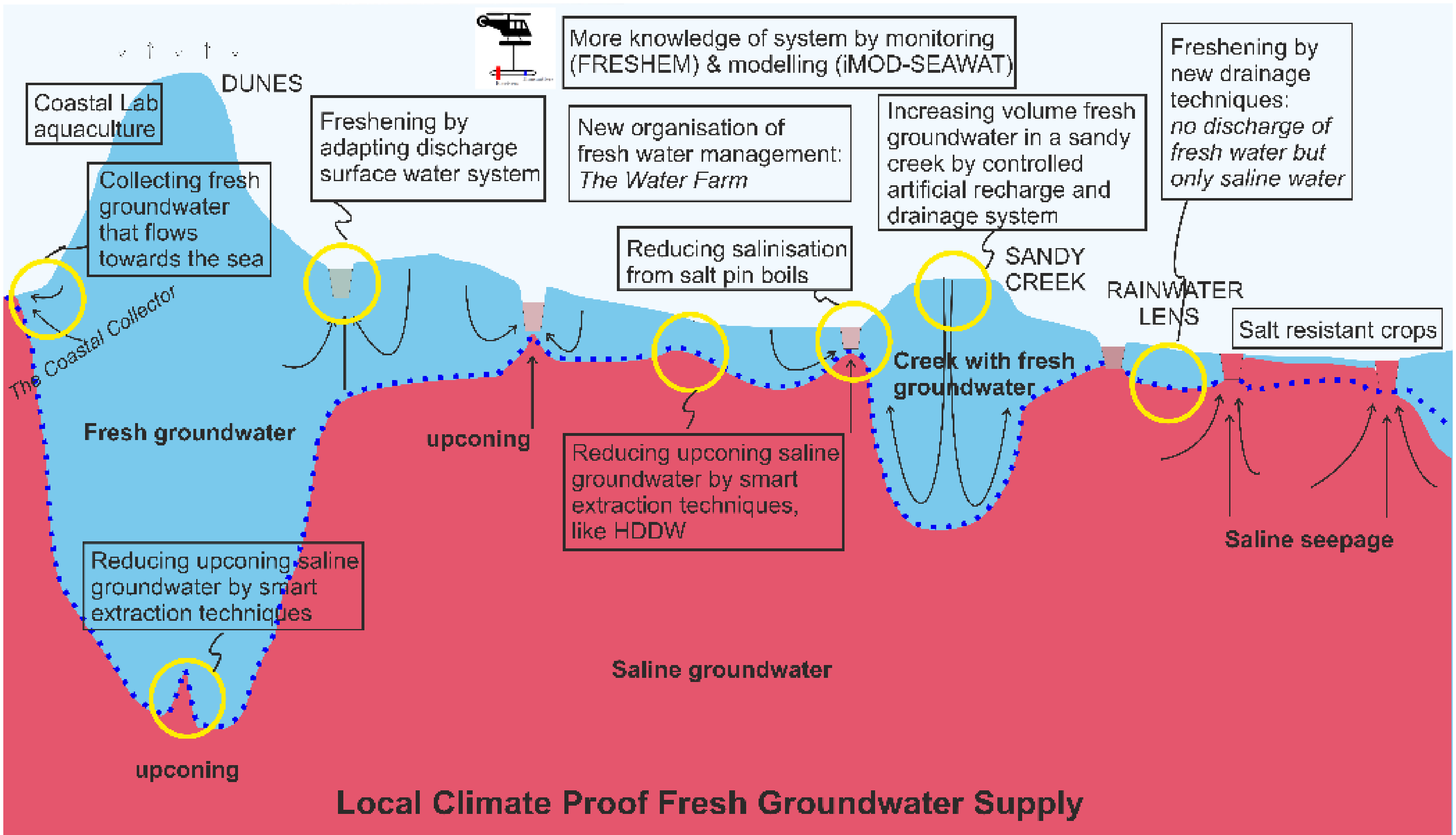




Compensating measures

Setting up piloting solutions/strategies

Combination of different strategies for improving local climate-proof fresh groundwater supply
There is no solution that fits all



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

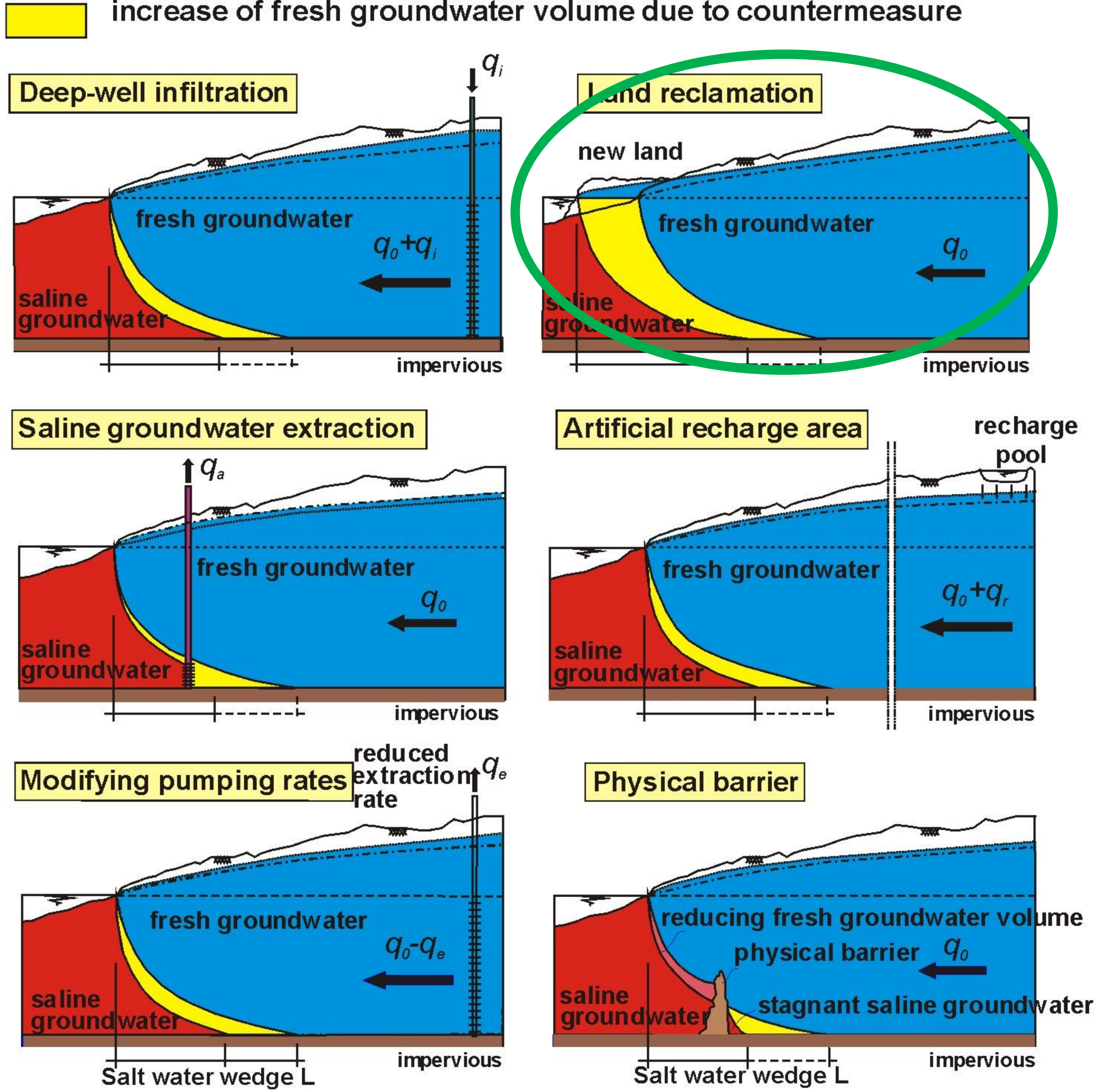
Tools to understand salt water intrusion:

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

Measures to compensate salt water intrusion

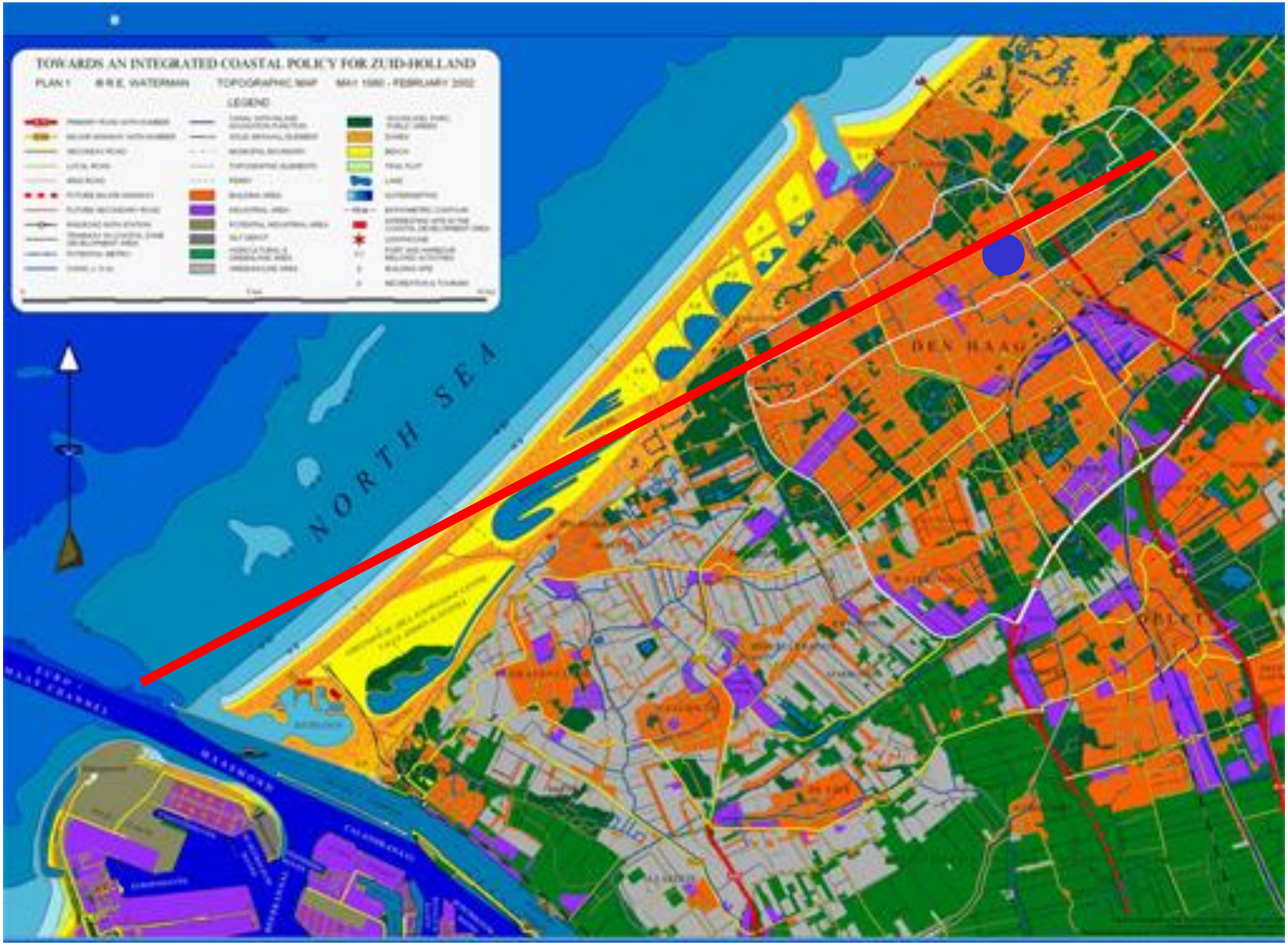
- ‘The Fresh Holder’
- Extraction of saline/brackish groundwater
- Infiltration of fresh surface water
- Modifying pumping rates
- Land reclamation in front of the coast
- Creating physical barriers (chrystallisation or biosealing)
- Inundation of low-lying polders

Technical measures to compensate salt water intrusion



Land reclamation

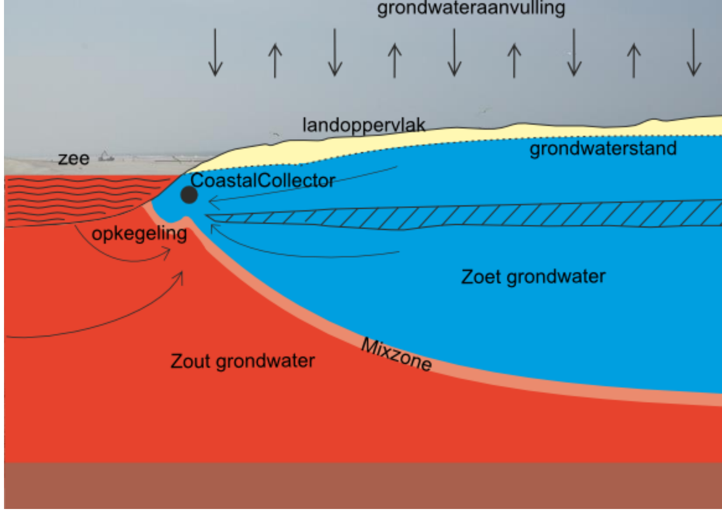
The Zandmotor: effects at the hinterland?

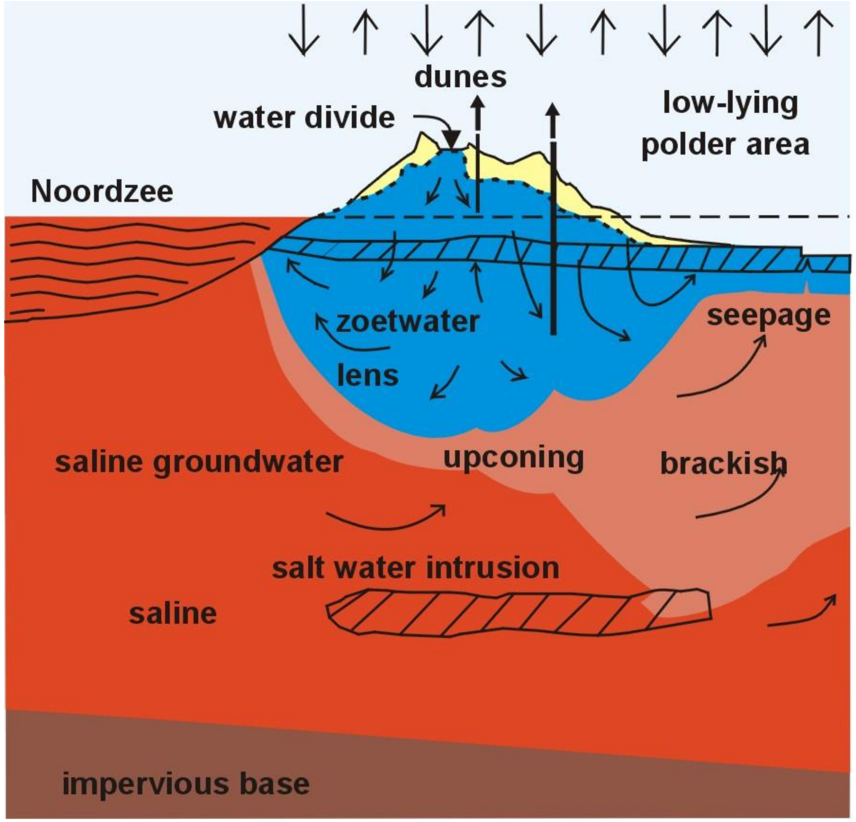

TOWARDS AN INTEGRATED COASTAL POLICY FOR ZUID-HOLLAND
PLAN 1
® R.E. WATERMAN
TOPOGRAPHIC MAP
LEGEND
NORTH SEA
DEN HAAG

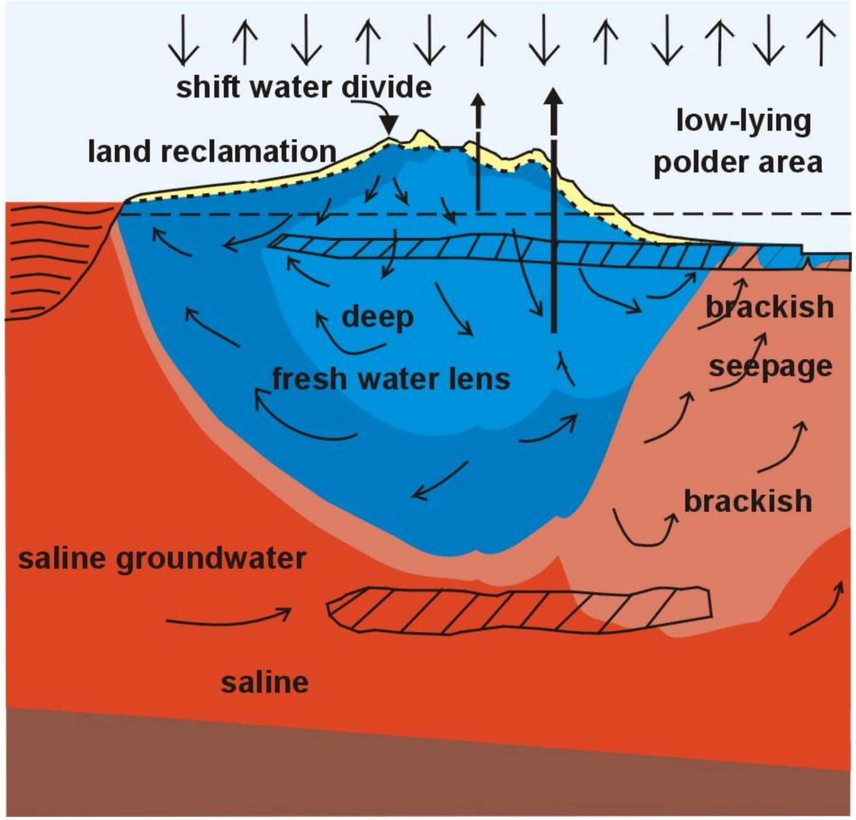
The Sand Motor: effects at the hinterland?

The Zandmotor

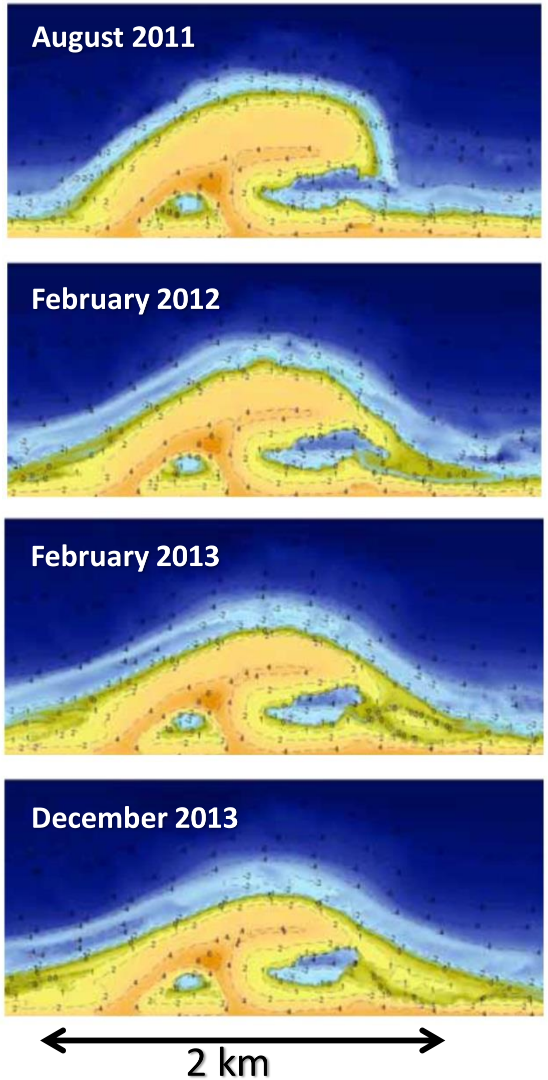
storage extra fresh water?



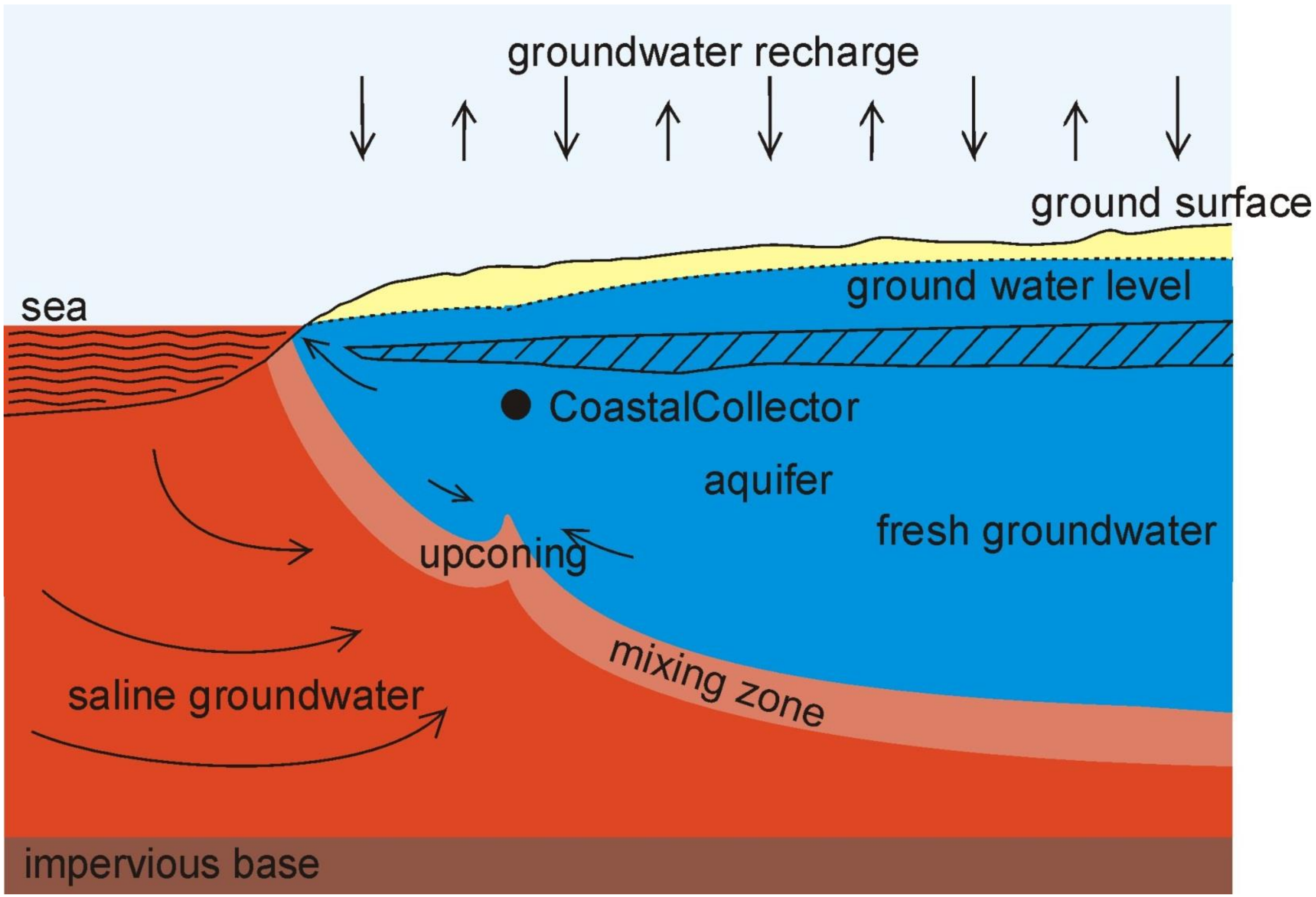




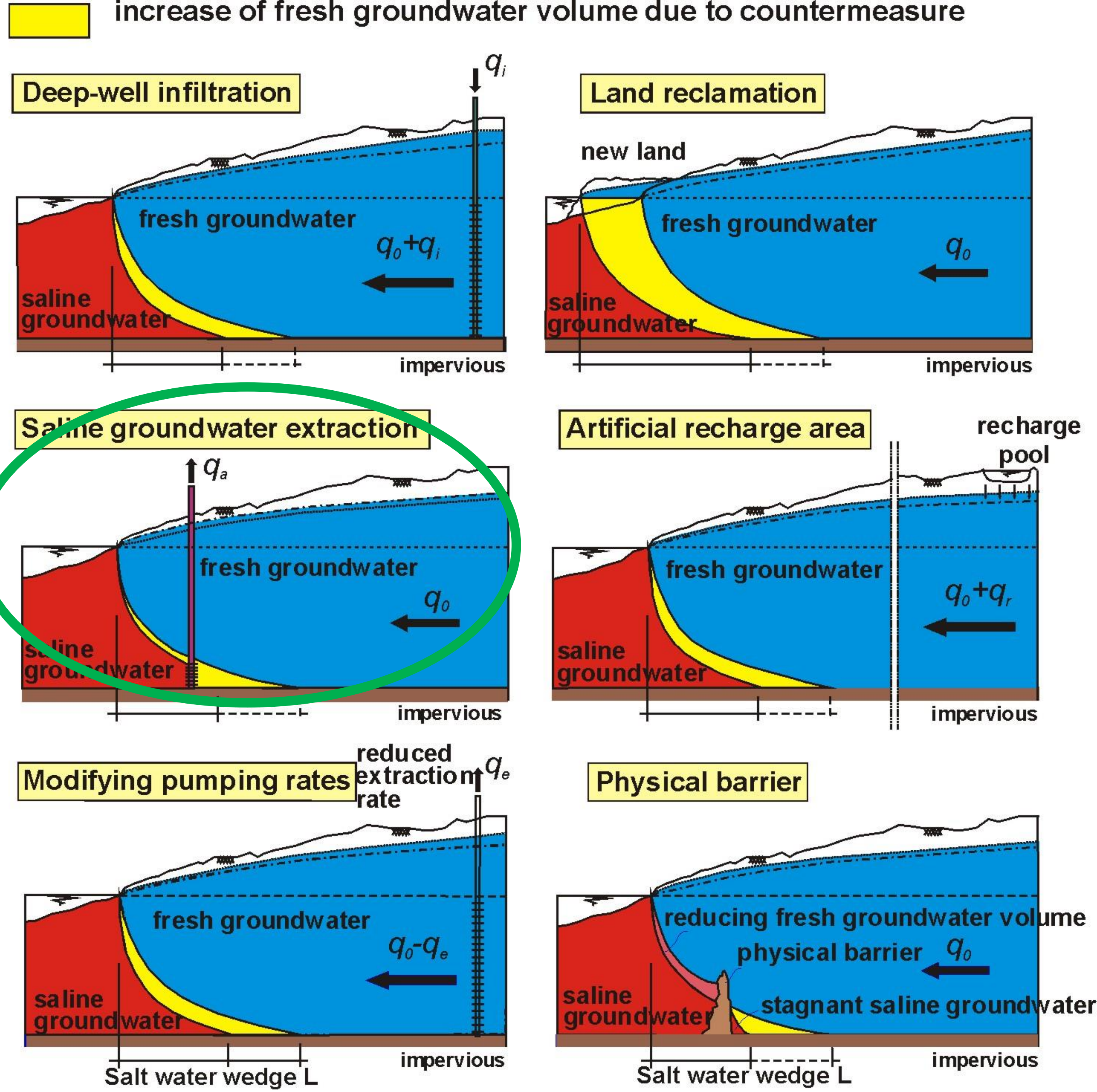

Jul 2011
Development of the Sand Motor
0 years
5 years
10 years
20 years


August 2011
February 2012
February 2013
December 2013
2 km

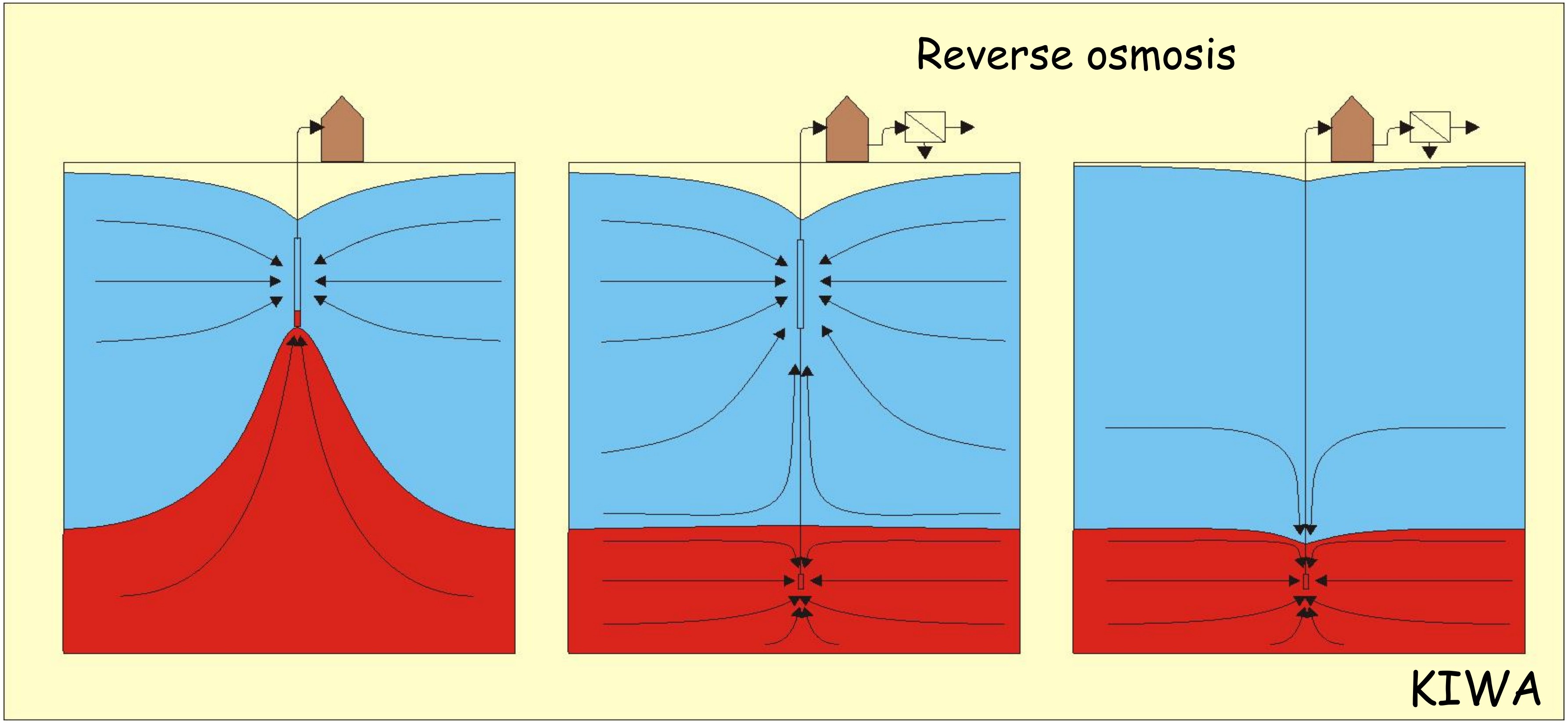
The Coastal Collector



Technical measures to compensate salt water intrusion



Solution: The Fresh Holder



Upconing can be prevented by the extraction of brackish groundwater

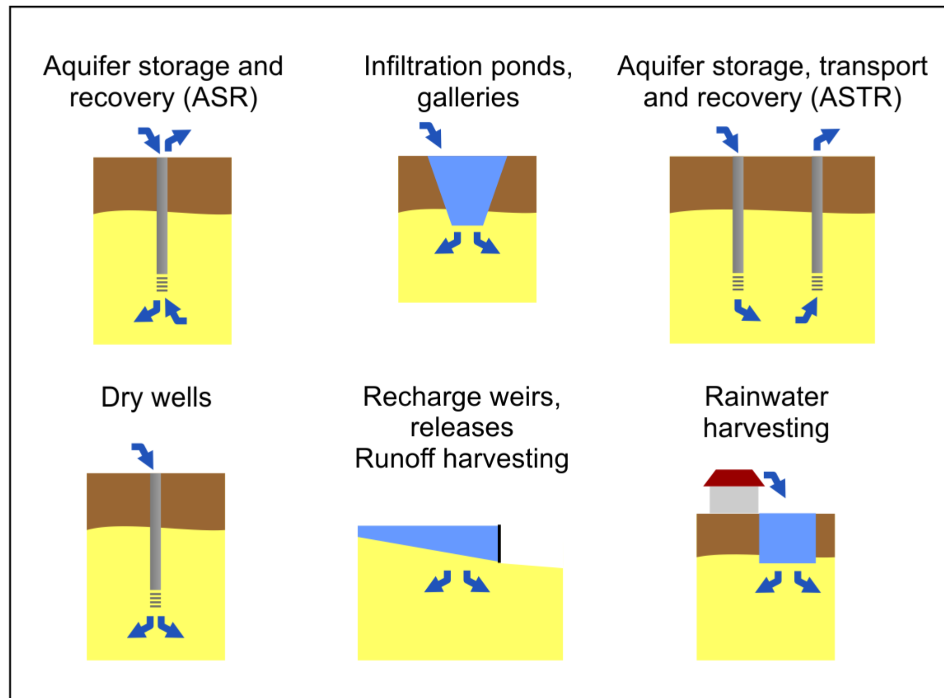
This brackish groundwater can be transformed to water of agricultural water quality by using the membrane filtration technique

Dillon, P.J. et al., 2019. Sixty years of global progress in managed aquifer recharge. Hydrogeol. J. 27, 1–30.

Aquifer Storage Recovery
or
Managed Aquifer Recharge

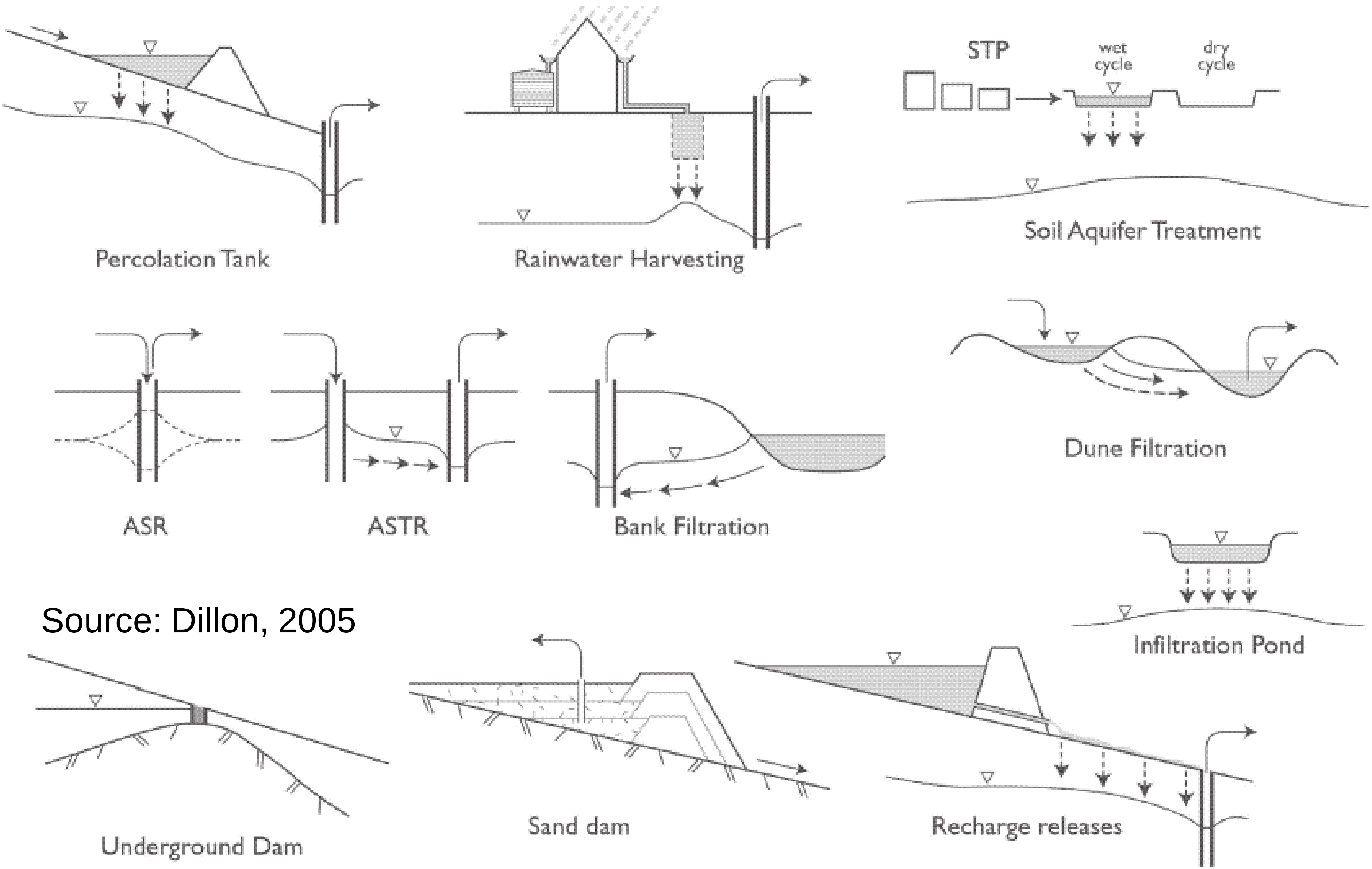
Closing the gap between water supply and water demand.

Depending on the water use characteristics: small or large-scale; shallow and deep.



Aquifer Storage and Recovery

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



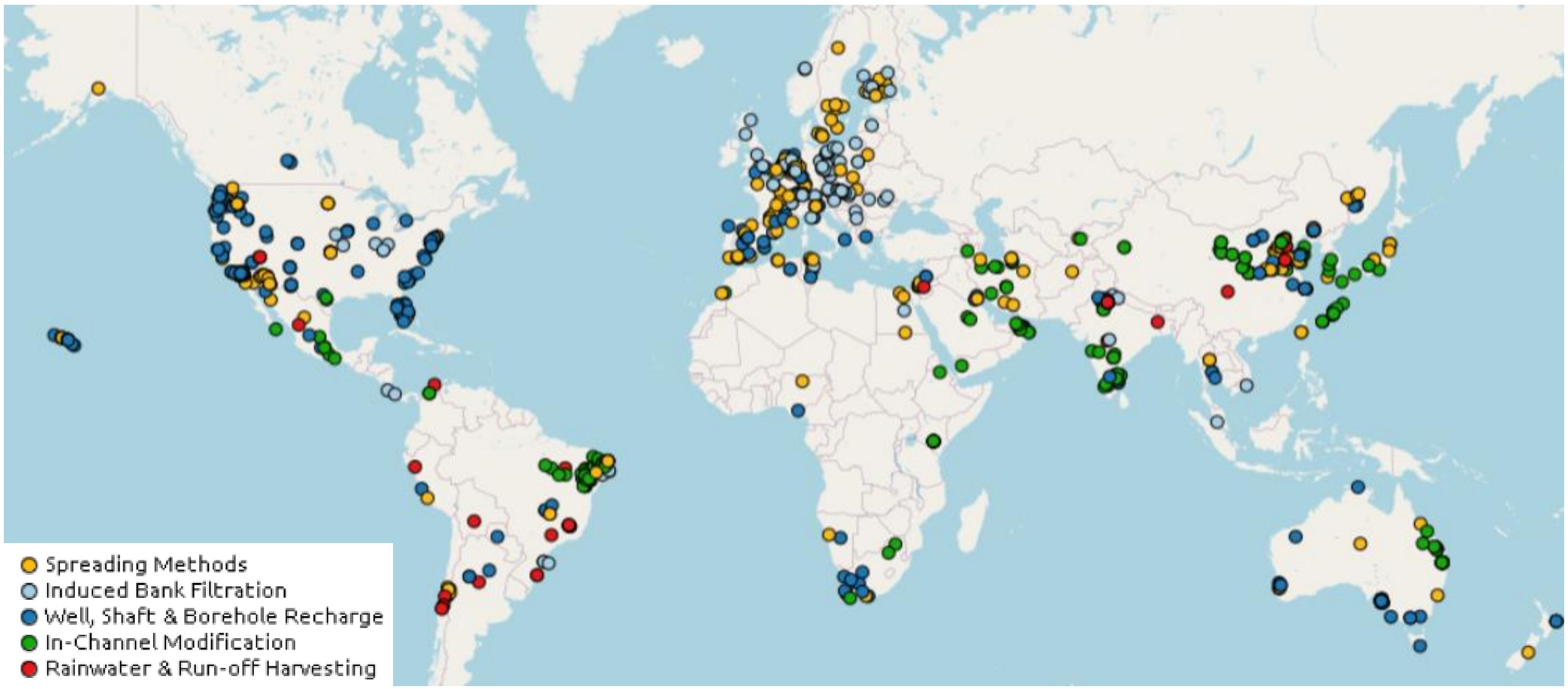
Source: Dillon, 2005

Advantages Aquifer Storage Recovery / Managed Aquifer Recharge

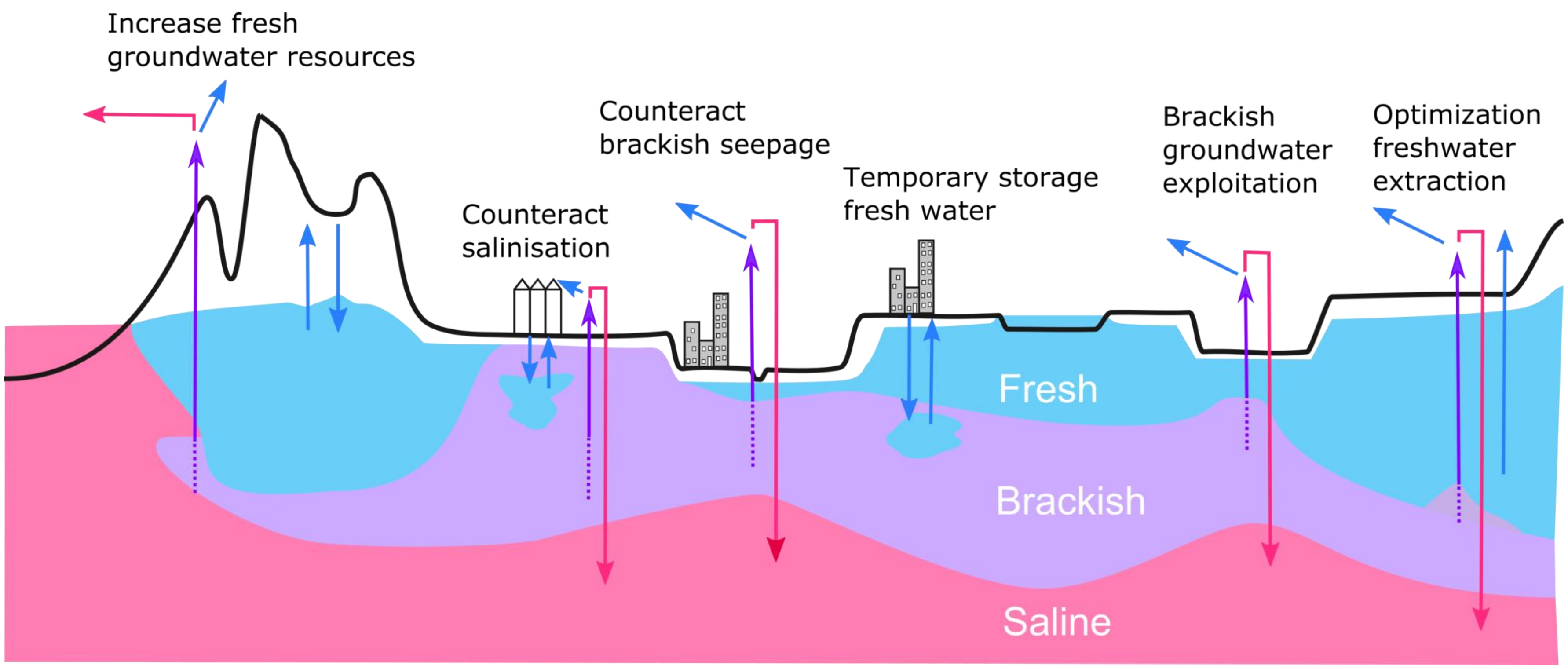
1. Store water for long-term storage
2. Buffer capacity for seasonal droughts
3. Smooth out demand and supply fluctuations
4. Reduce evaporation loss
5. Improve water quality
6. Store excess storm/flood water
7. Manage salt water intrusion
8. Manage land subsidence
9. Strategic reserve for emergency situations
10. Raising groundwater table
11. Provide water for domestic, agricultural & industrial use
12. Protect sewers of water overload during intense rain events

Areas around the world with MAR systems

https://ggis.un-igrac.org/view/marportal

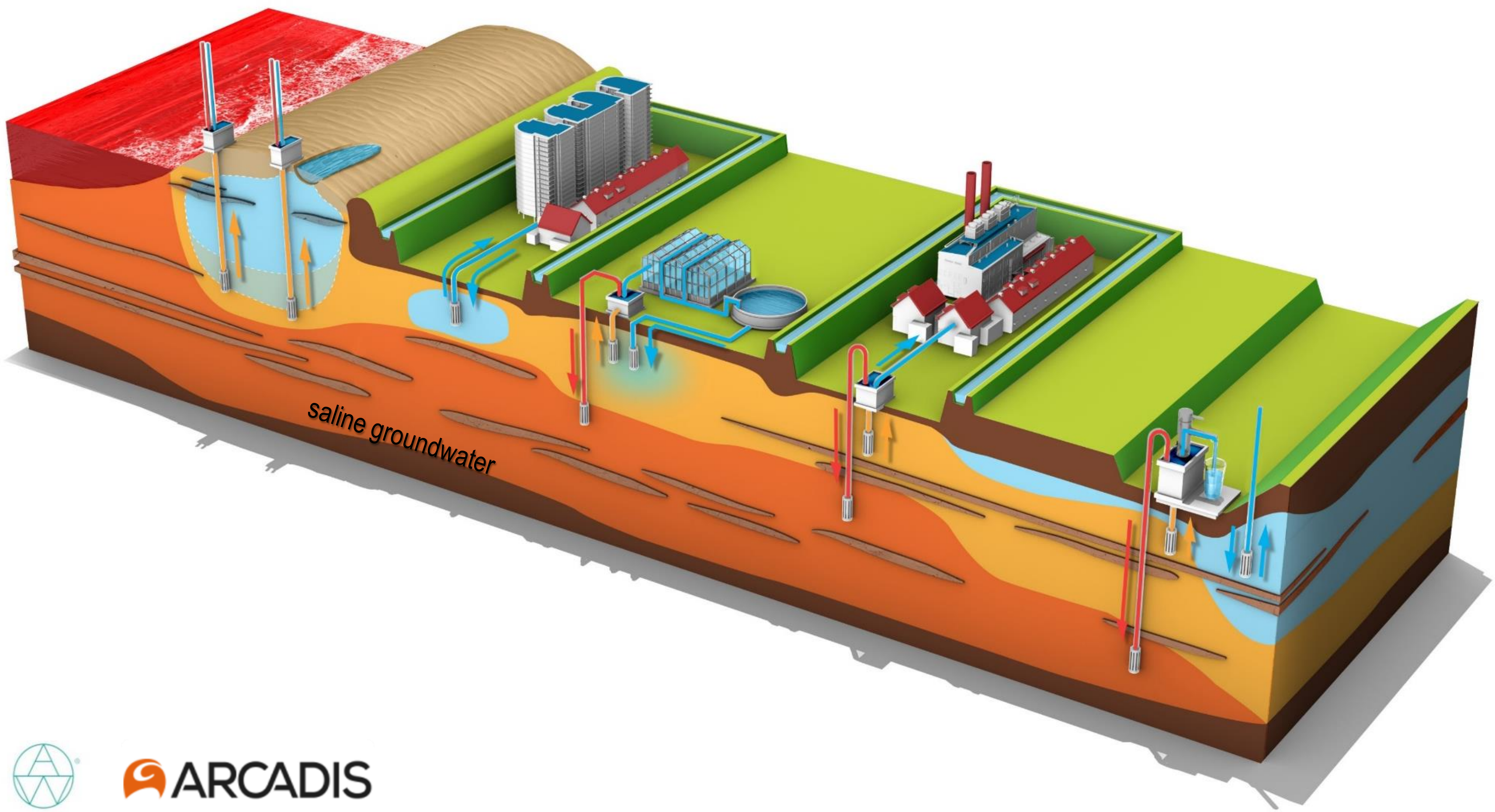


COASTAR: COastal Aquifer STorage And Recovery



COASTAR, a subsurface solution

for sustainable water management in coastal zones



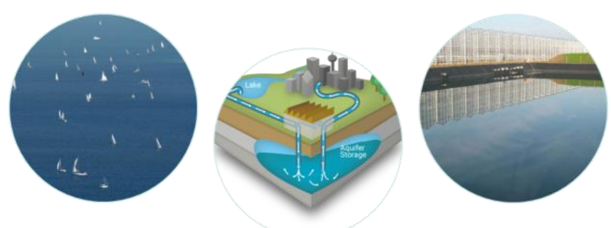
COastal Aquifer STorage And Recovery

as a subsurface solution to improve water availability, in areas around the world with water scarcity ánd salinization issues

- Close the water gap between water supply and demand in space and time
- Prevent salinization by using brackish groundwater for fresh water production

Water sources

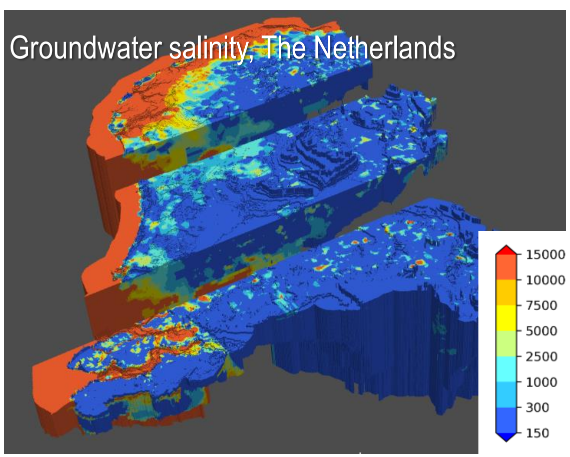
Water storage



Water demand

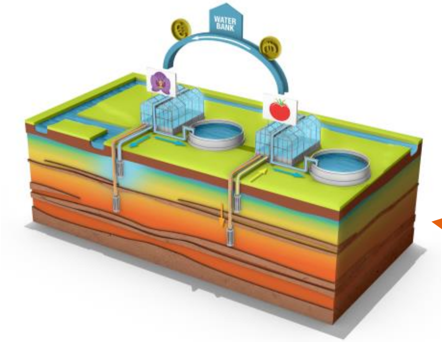
Why COastal Aquifer STorage And Recovery?

- Growing population and urbanization, increasing demand for water of higher quality
- Climate change: sea level rise, longer periods of drought
- The subsurface offers integral solutions to deal with coastal water management challenges
- *Brackish Groundwater is the New Fresh*

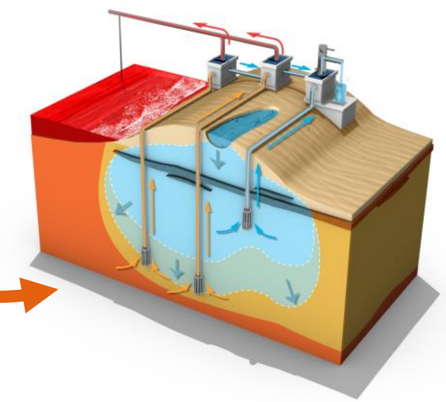


COASTAR solutions in the Netherlands - Cases

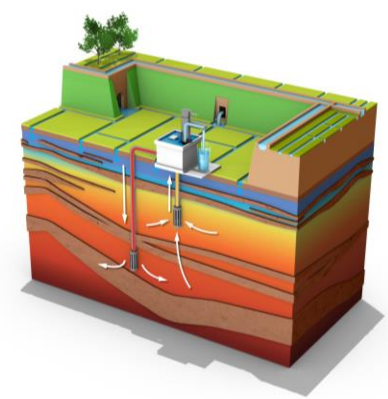
1. Waterbank Westland



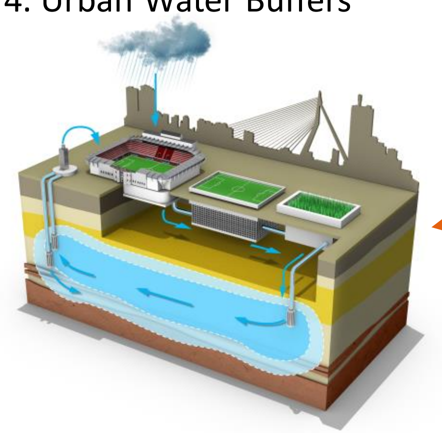
2. Brackish water extraction dunes



3. Brackish groundwater extraction deep polders



4. Urban Water Buffers



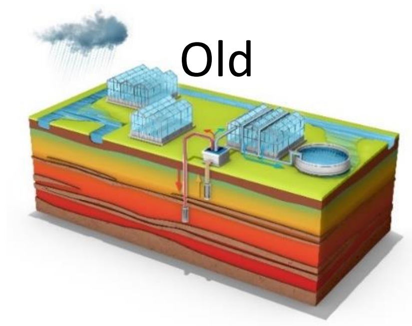
COASTA
R

Waterbank Westland

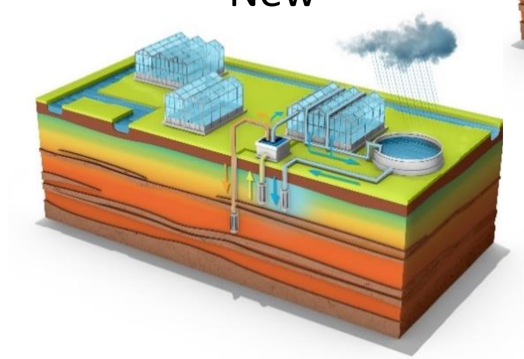
Towards sufficient irrigation water

- Horticulture companies infiltrate excess rain water in the subsurface, to compensate extractions.
- It helps preventing salinization and diminishes overflow.
- Brings in the perspective on sustainable fresh water supply in the horticulture sector.

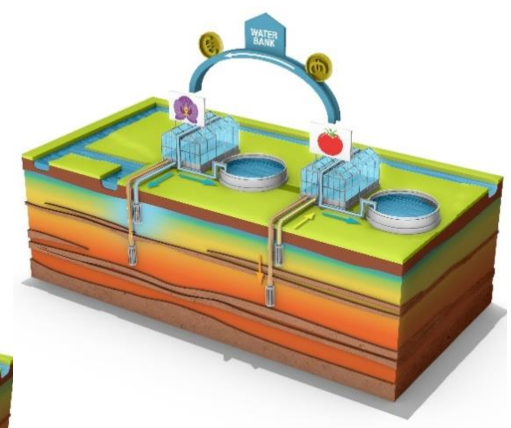
Old



New



Waterbank



- Cooperation in some form is necessary:

  The waterbank

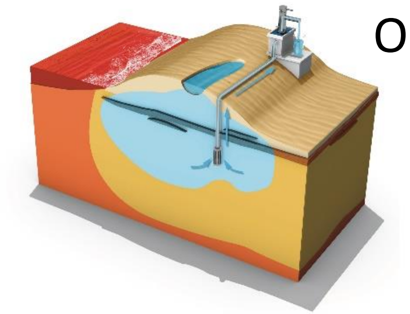
Three variants:

- <u>1. Basic</u>: individual companies infiltrate excess rain water
- <u>2, Clusters</u>: multiple companies infiltrate excess rain water together
- <u>3. With other companies</u>: in addition other company roofs will be added to the system

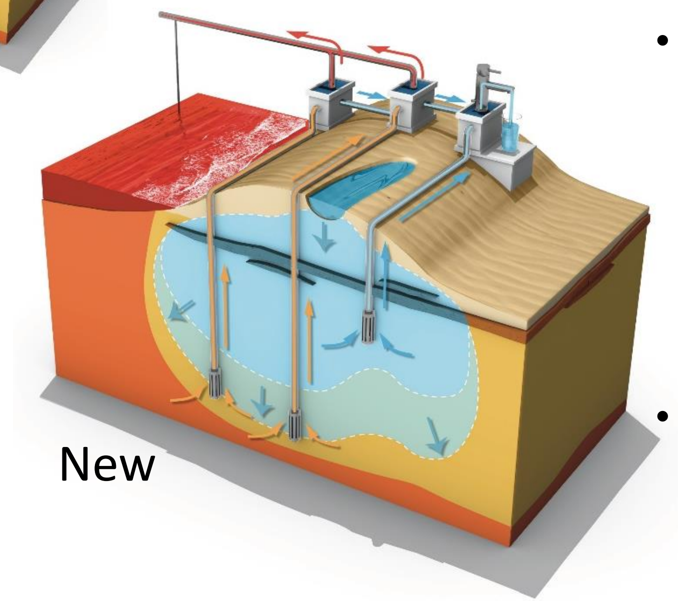
Brackish water extraction coastal dunes
Drinking water company Dunea

COASTAR

- Dunea searches for new drinking water sources in addition to the river water sources.
- Brackish groundwater is a potential source.
- By extracting from below the freshwater lens, this lens grows
- Double benefit: new drinking water source and a larger strategic fresh water resource.



Old



New

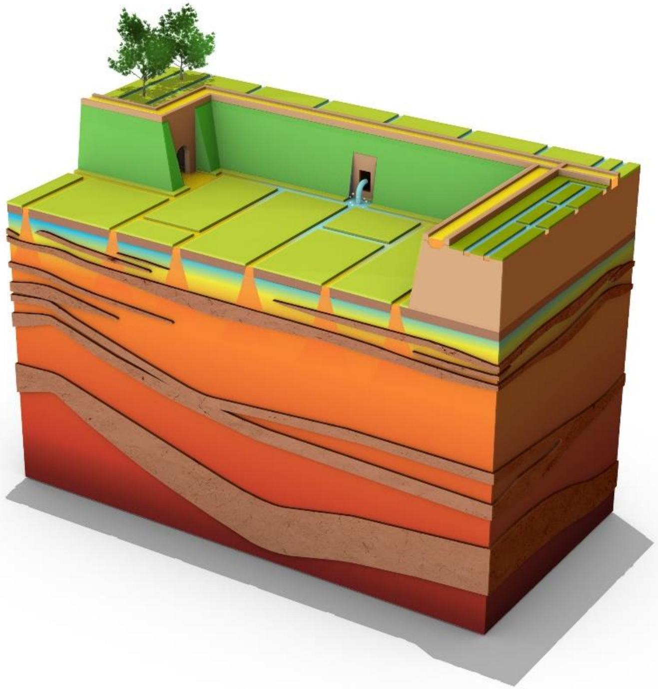
- Groundwater modelling results show it is likely to recover around 20 million m^3 brackish groundwater
- Interesting cost-related: extraction on existing location saves on new expensive pipelines.
- Effluent (‘brine groundwater’) can be easily discharged at sea.

Allied Waters · Deltares · KWR · ARCADIS · dunea DUIN & WATER

Brackish groundwater exploitation low-lying polders

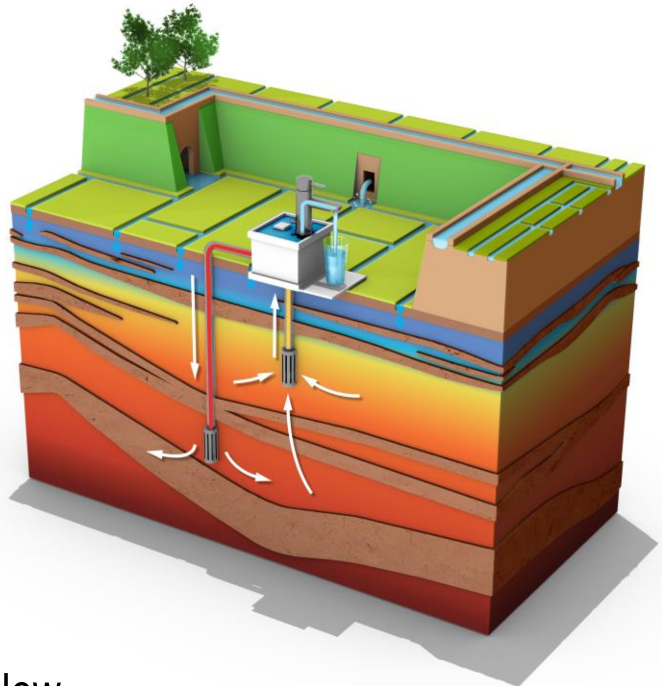
Drinking water and desalinisation for agriculture

COASTAR



Oud

- Brackish ground- and surface water
- Reducing the number of salty boils



New

- Brackish groundwater exploitation
- Reduction brackish seepage (salty boils)
- Deminishing water- and salt loads to polder

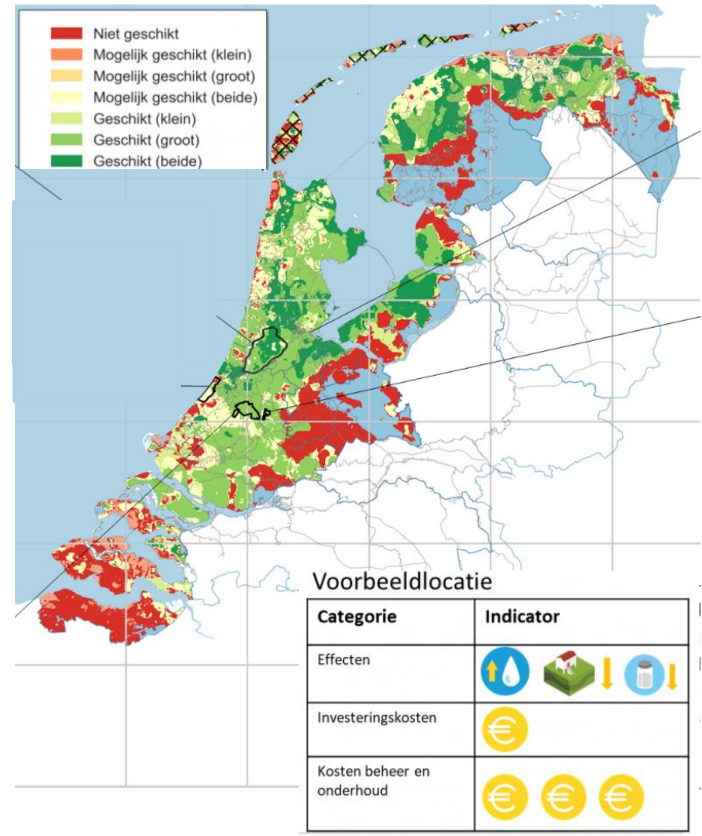
Potential maps COASTAR for the Netherlands

- Hydrogeological analyses for the COASTAR solutions:
  - Brackish water extraction
  - Fresh water storage in the subsurface

- Effect analyses on the application of the COASTAR solutions:
  - Preventing salt water intrusion
  - Preventing salinization
  - Crating an additional drinking water source
  - Preventing land subsidence
  - Preventing (groundwater) flooding

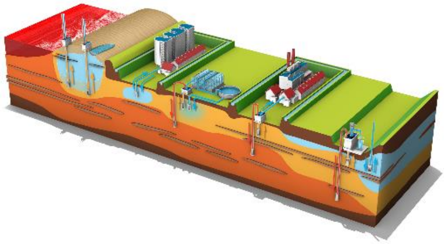
- Cost and benefit analysis on case level

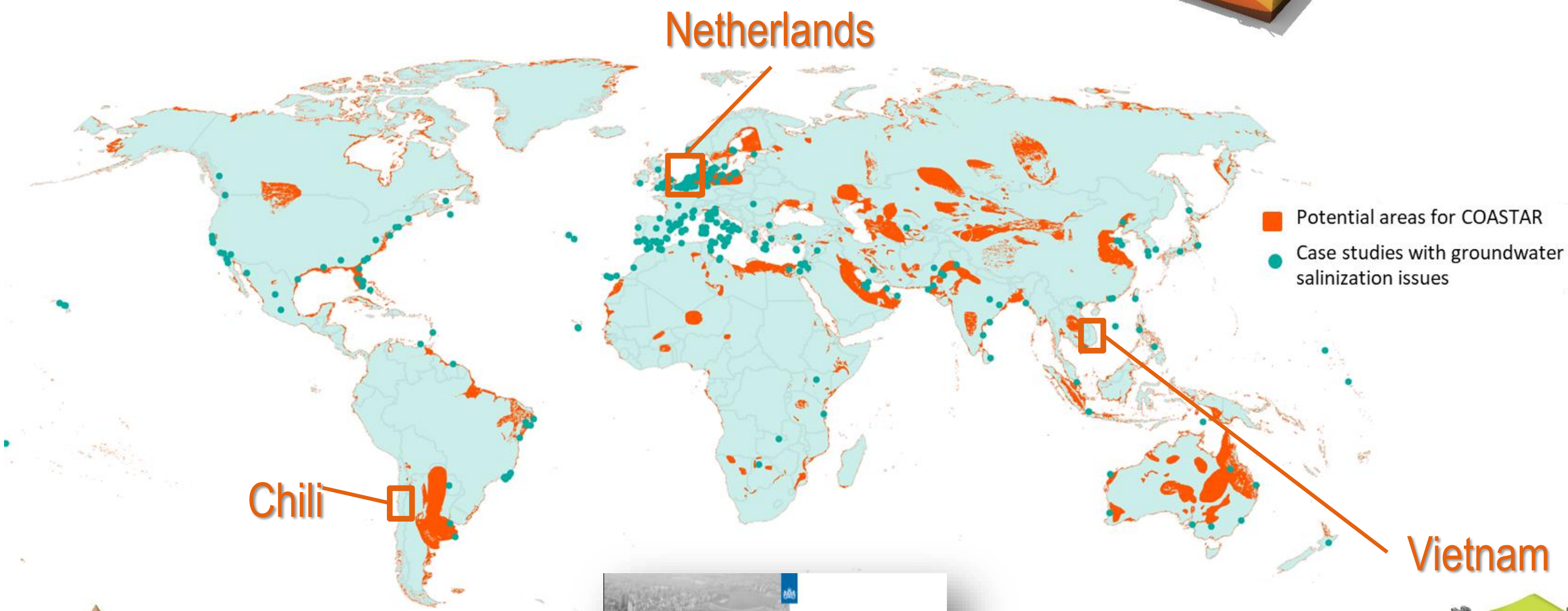
- Result:
  - **Potential maps** =
  - hydrogeological suitability + effect analyses + economic analysis

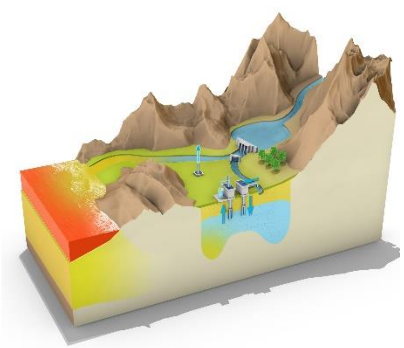


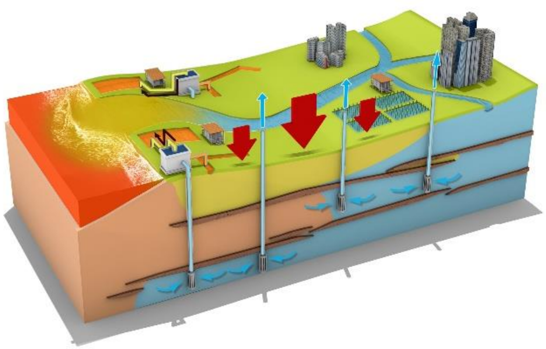
More information: www.deltares.nl/en/news/78351/

COASTAR opportunities International

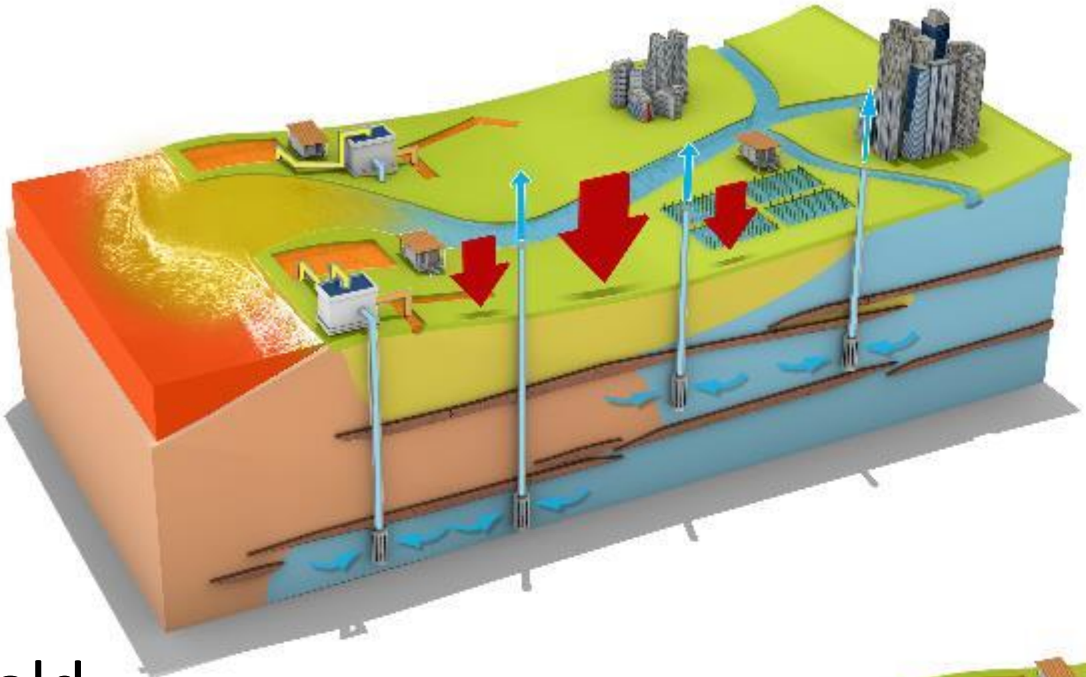




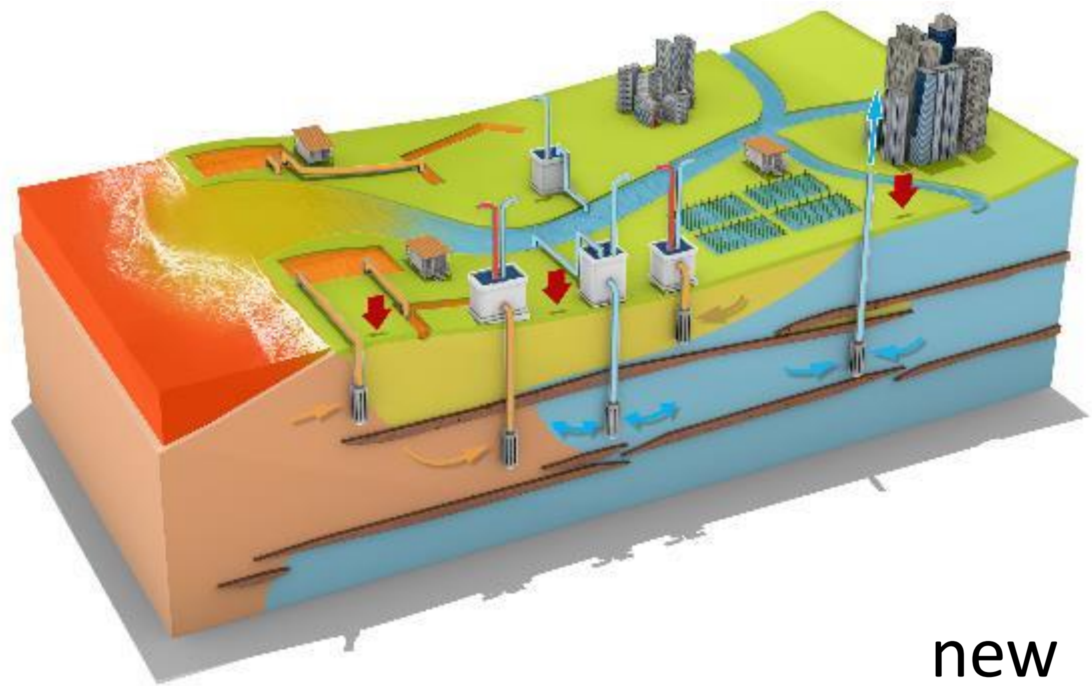




Case deep-well Aquifer Storage and Recovery (Mekong delta, Vietnam)



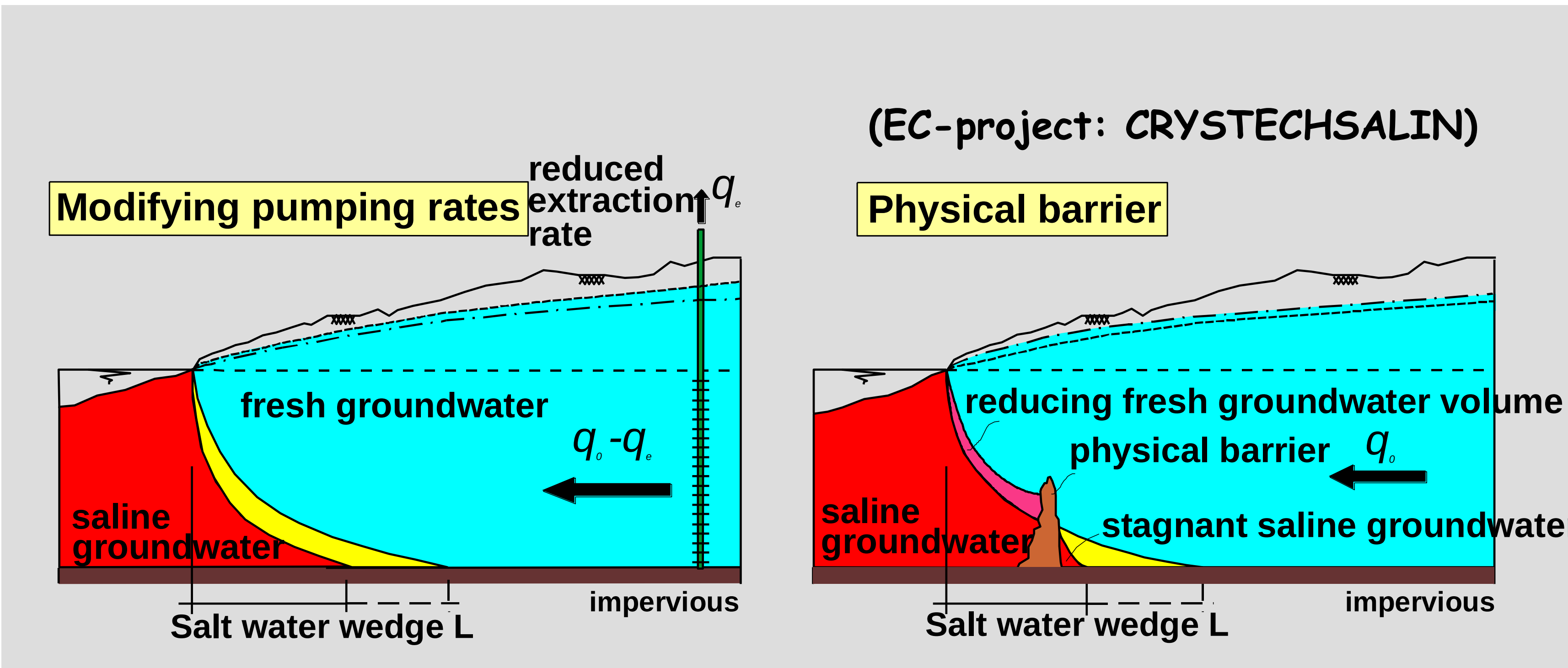
old



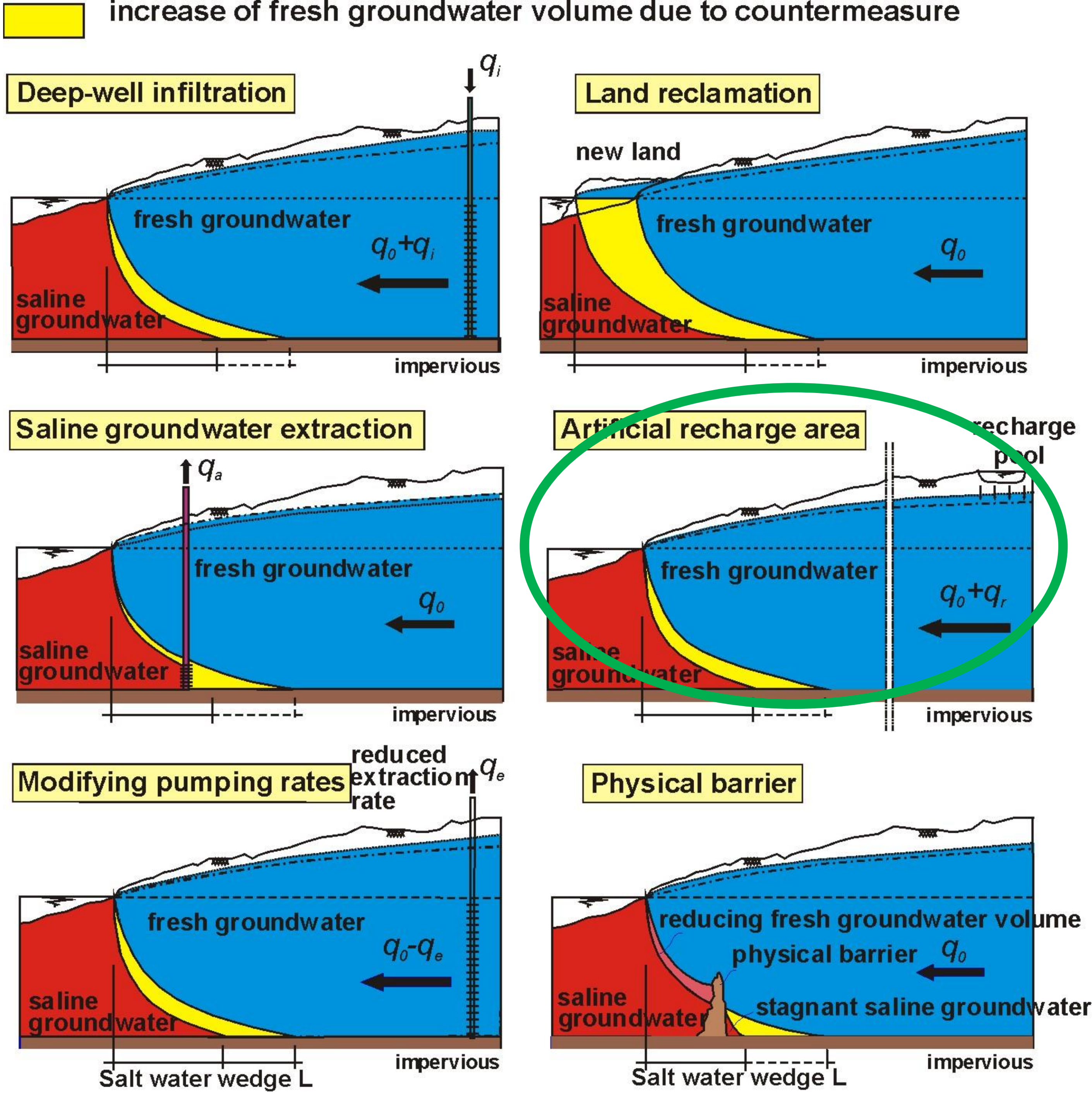
new

Deltares KWR ARCADIS

Countermeasures of salt water intrusion



Technical measures to compensate salt water intrusion



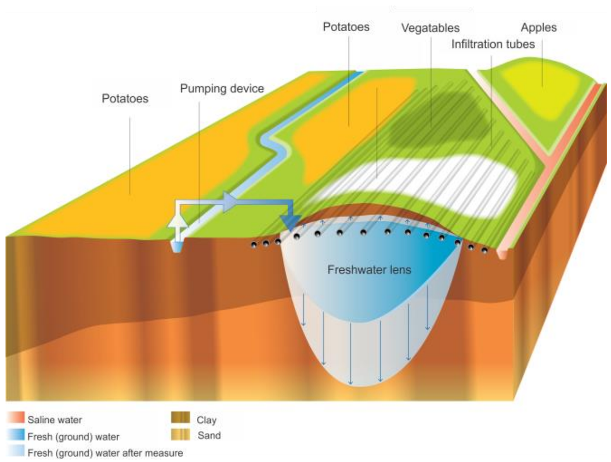
Aquifer Storage and Recovery in the coastal zone

www.go-fresh.info

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

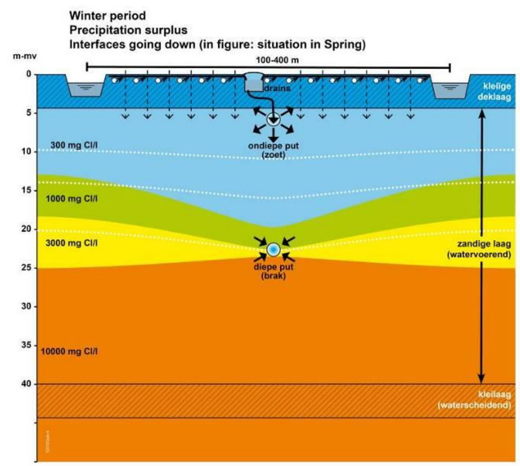
Methods:
3 pilot studies: infiltration of fresh water in times of water excess and extraction in times of droughts

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



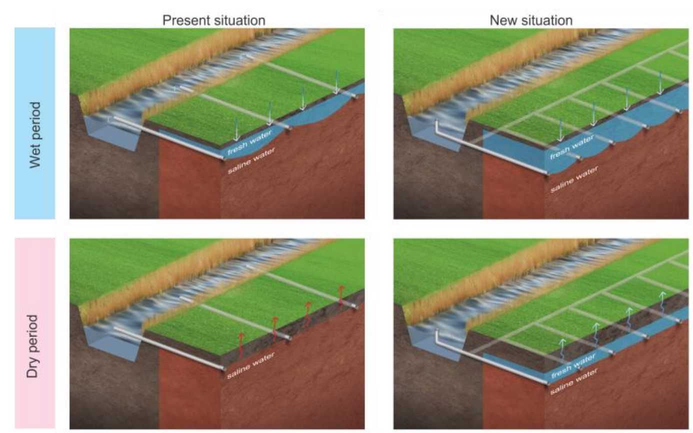
Creekridge Infiltration Test

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



The Freshmaker

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



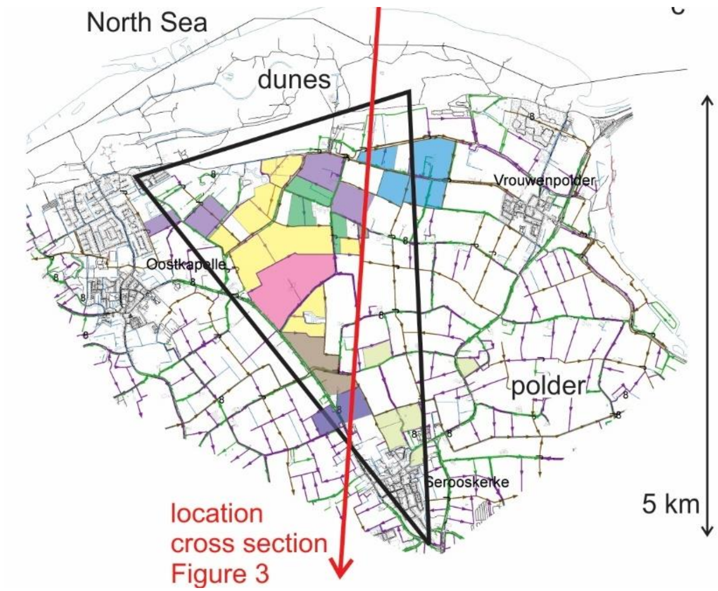
Drains2Buffer

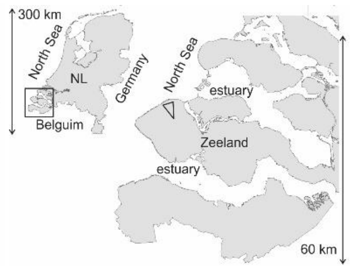
Maintain fresh water volume in shallow rainwater lenses by smart deep controlled drainage

Problem statement

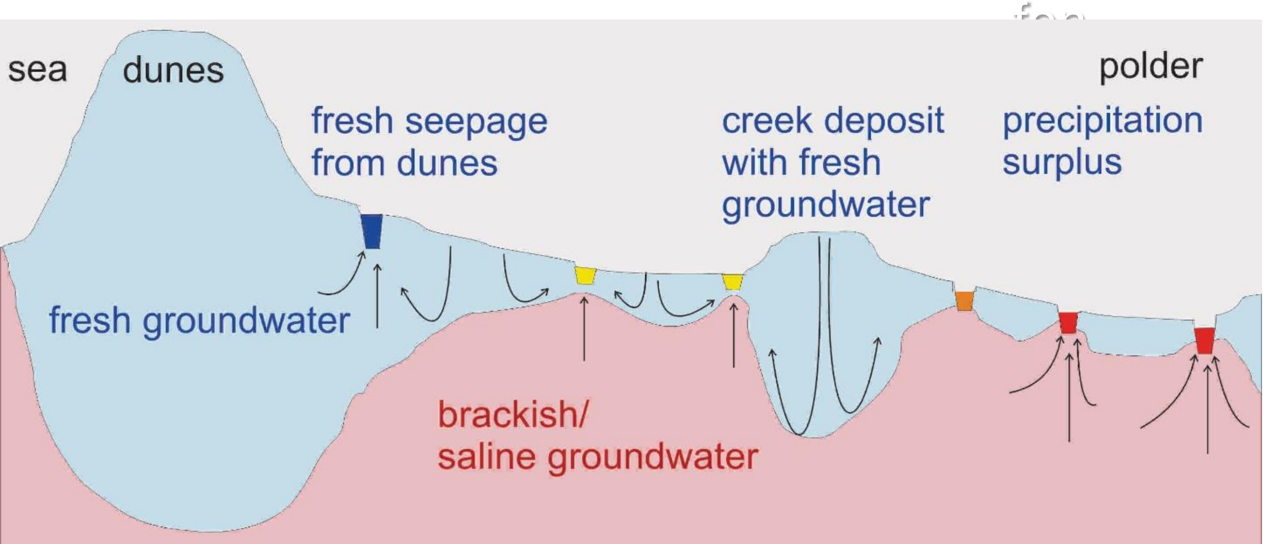
- Crop damage southwestern part of the Netherlands
- Fresh groundwater below creek ridges

Case study: Water Farm



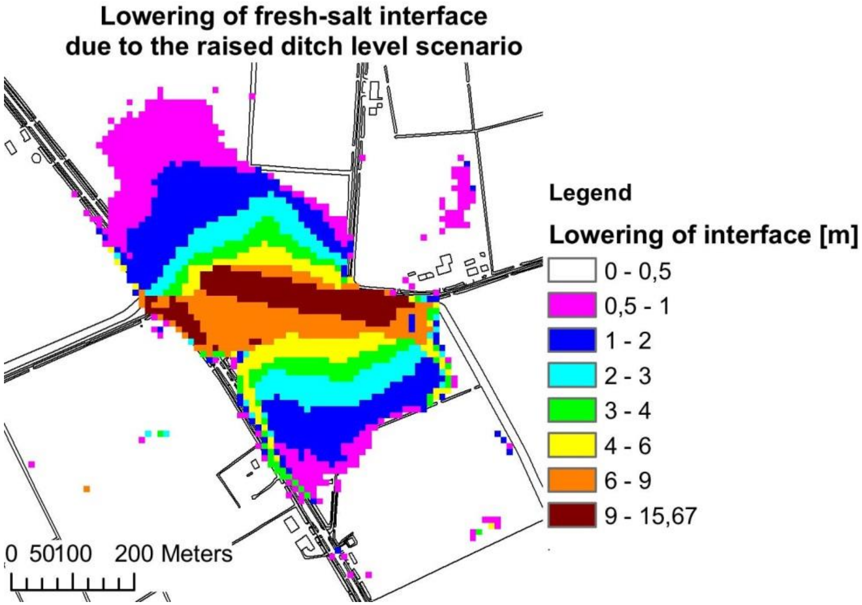


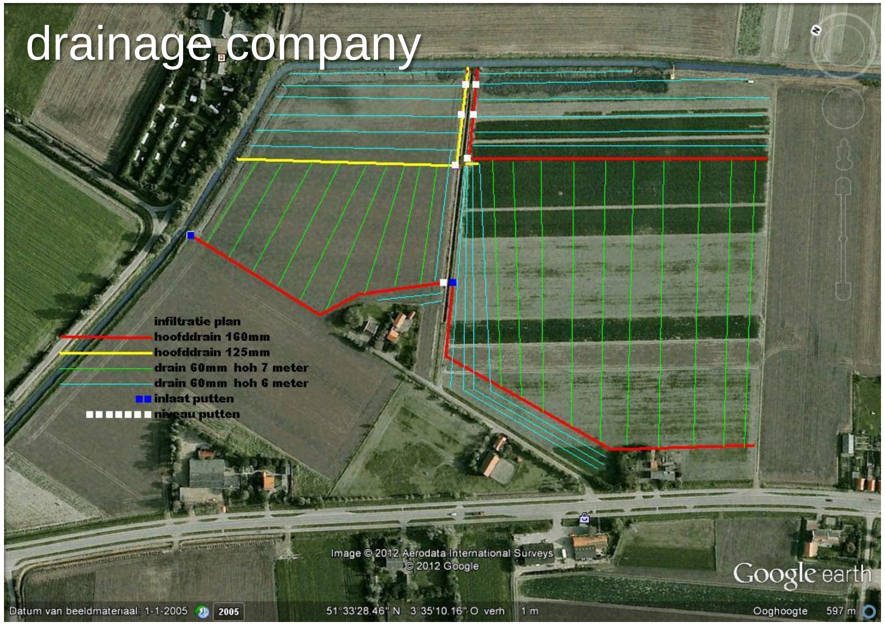
- 3 km2 area
- 8 farms
  - 4 arable farming
  - 2 horticulture
  - 2 fruit
- start case study 2010



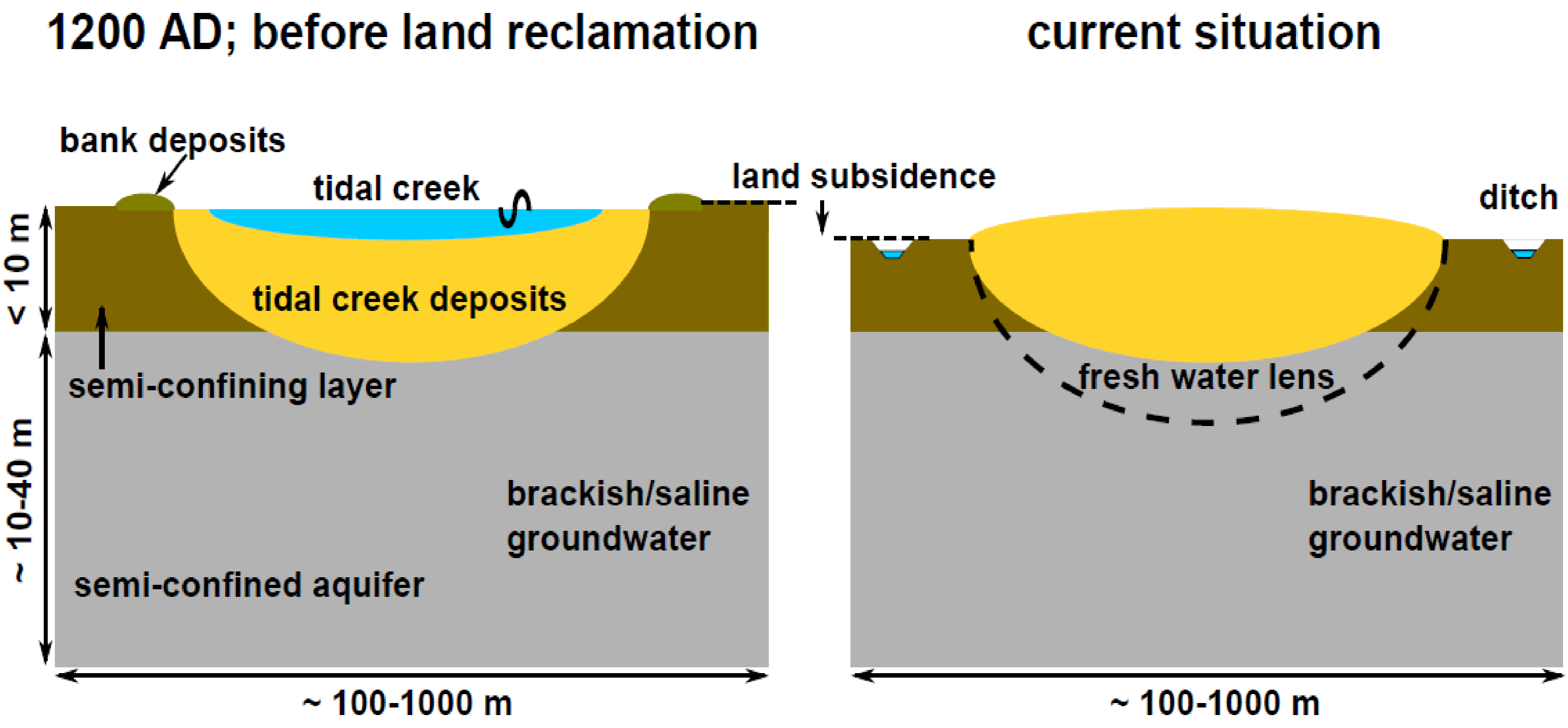
- measures
- communication to outside world

Researchers: scenario analysis



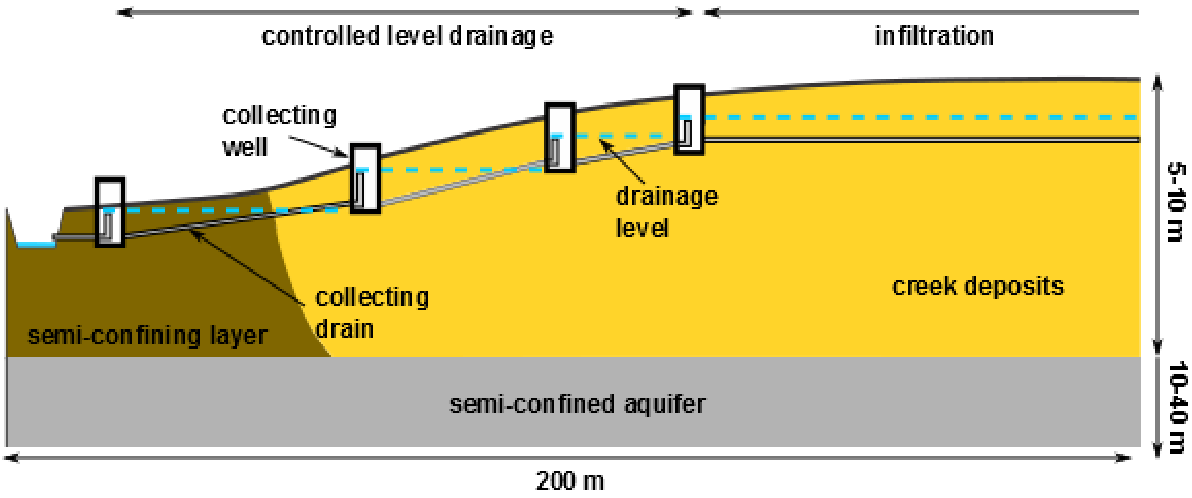


Creek ridges

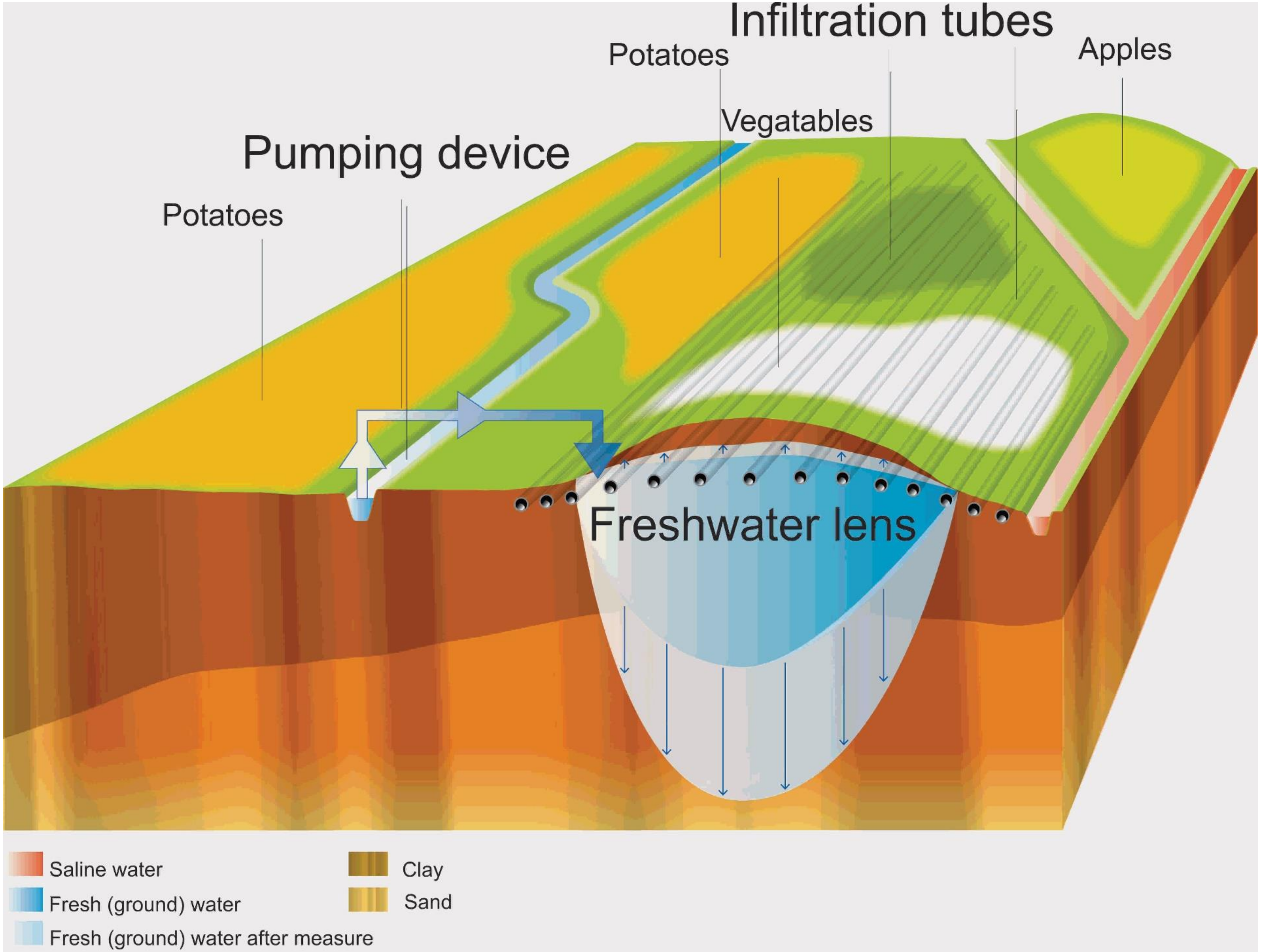


Measure

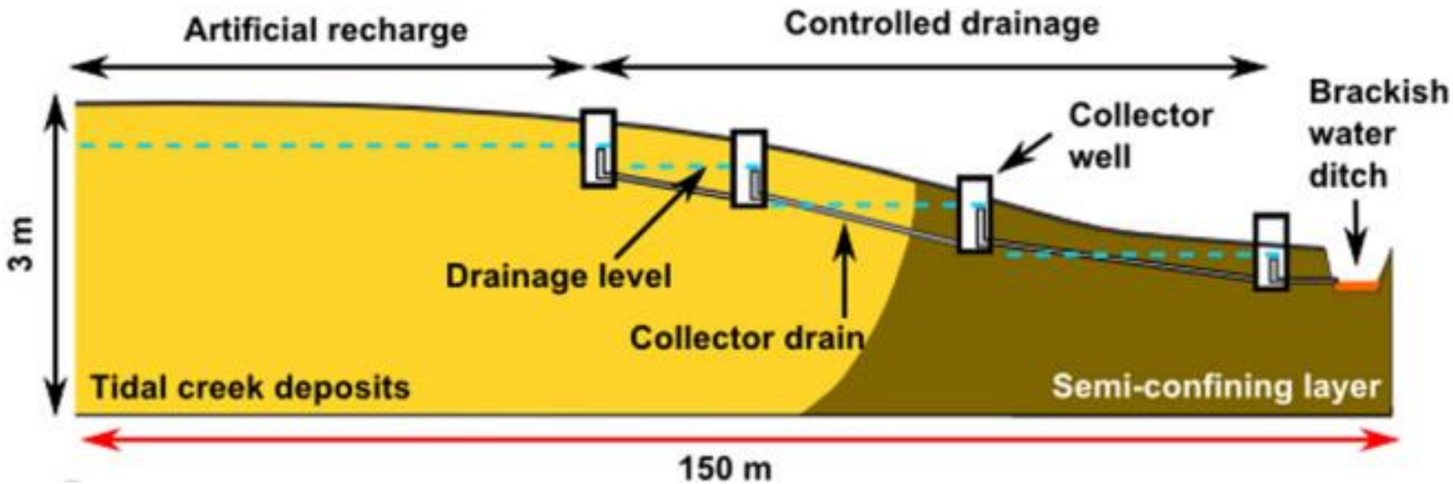
- Controlled level drainage
- Increase groundwater level

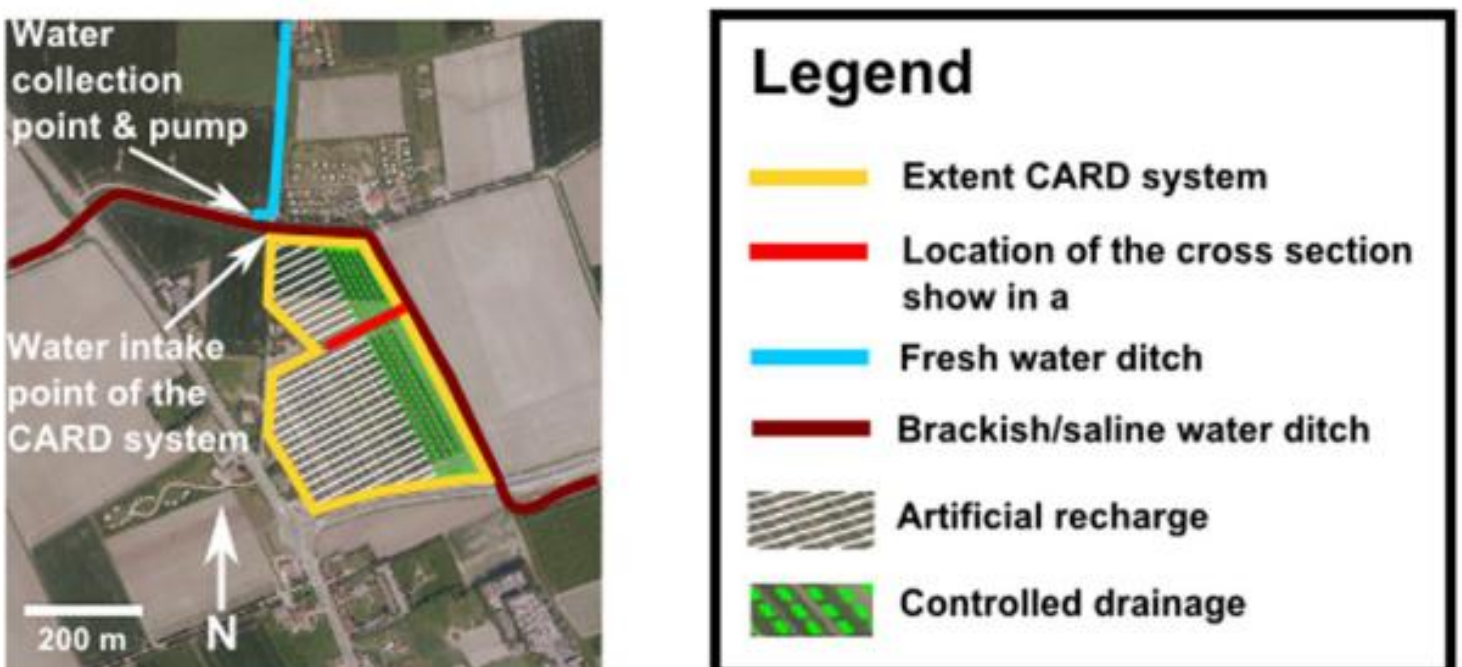


Creekridge Infiltration System



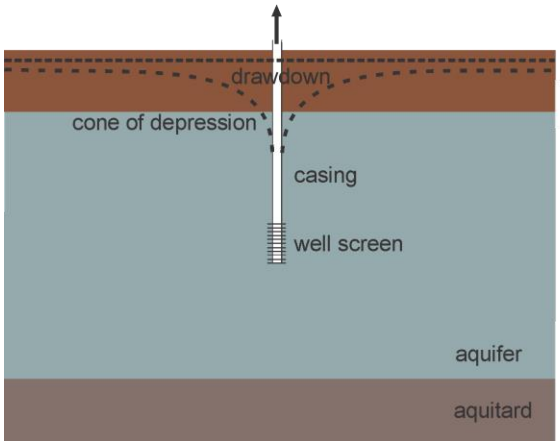
Concept of CARD and pilot layout

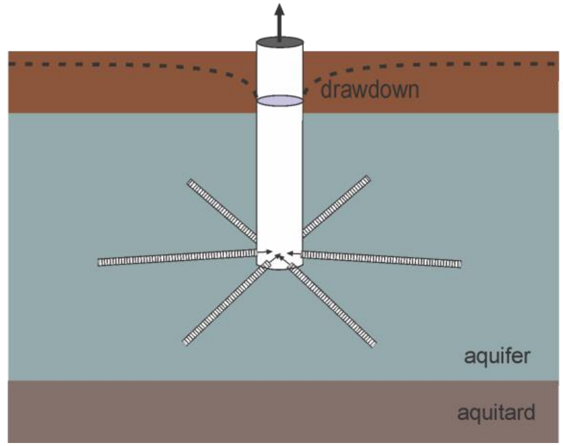


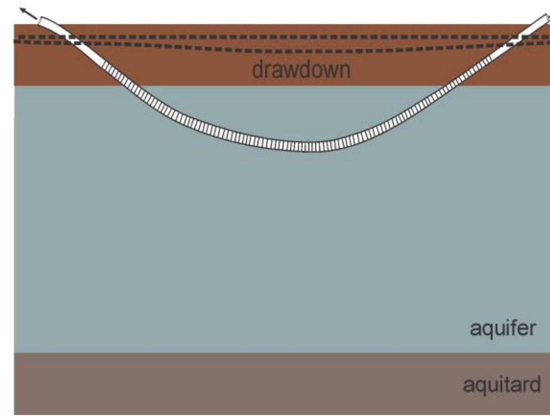


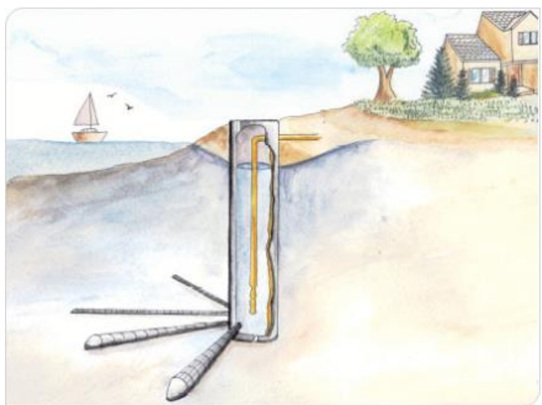
2017/0615:

Types of extraction systems

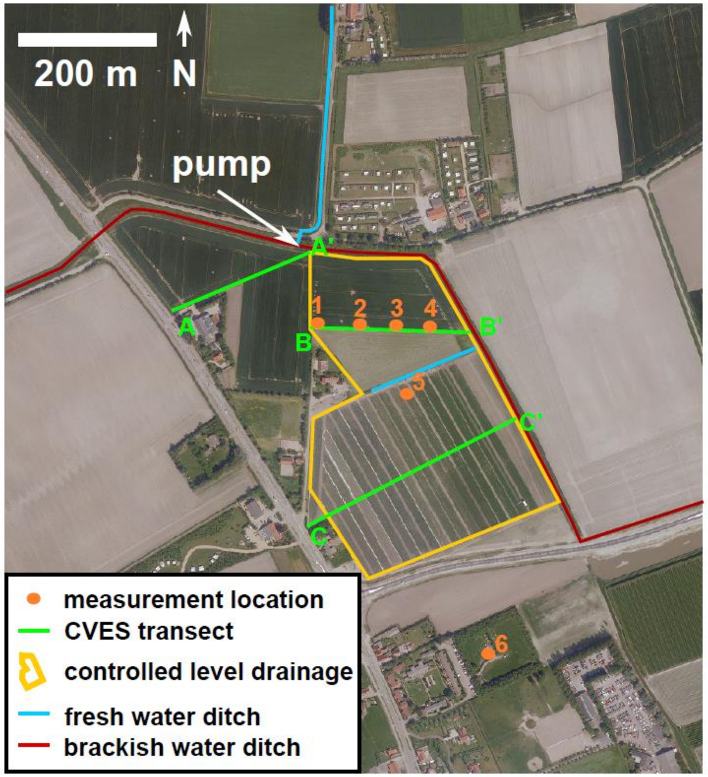








Installation of drainage and monitoring network

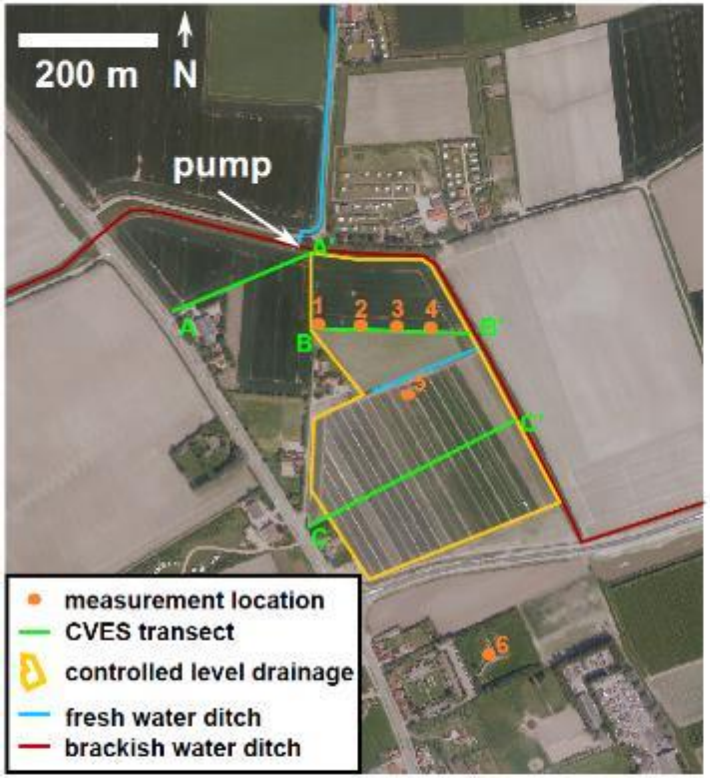


various types of field measurements

Different types of field measurements applied

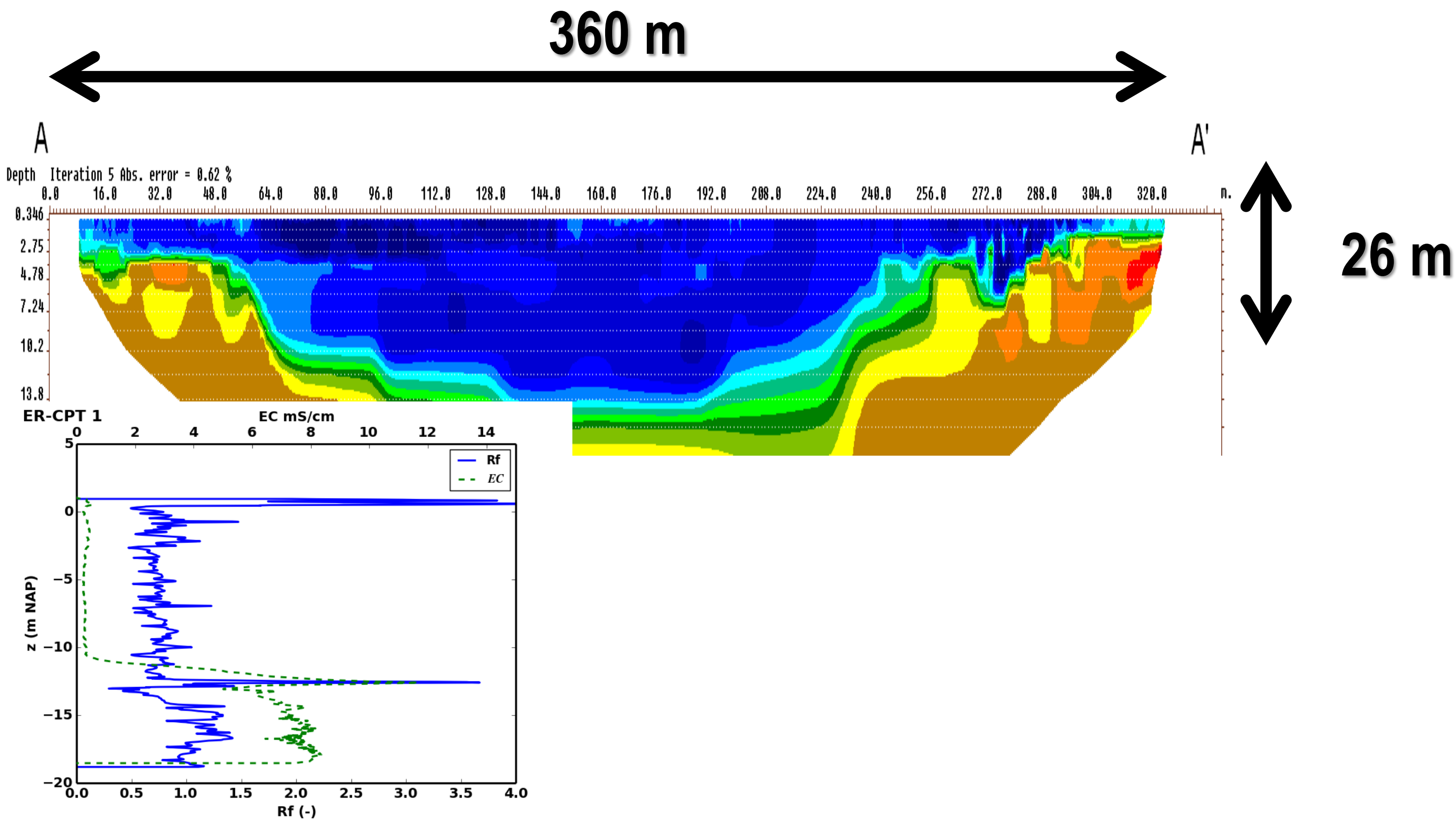
Measurement type	Purpose
Pressure transducers[a]	Groundwater levels
Sampling using piezometer nest	EC_{w20}
SLIMFLEX[b]	EC_{bulk}
CPT[c]	Lithology and EC_{bulk}
CVES[d]	EC_{bulk}
SMD[e]	EC_{bulk}

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



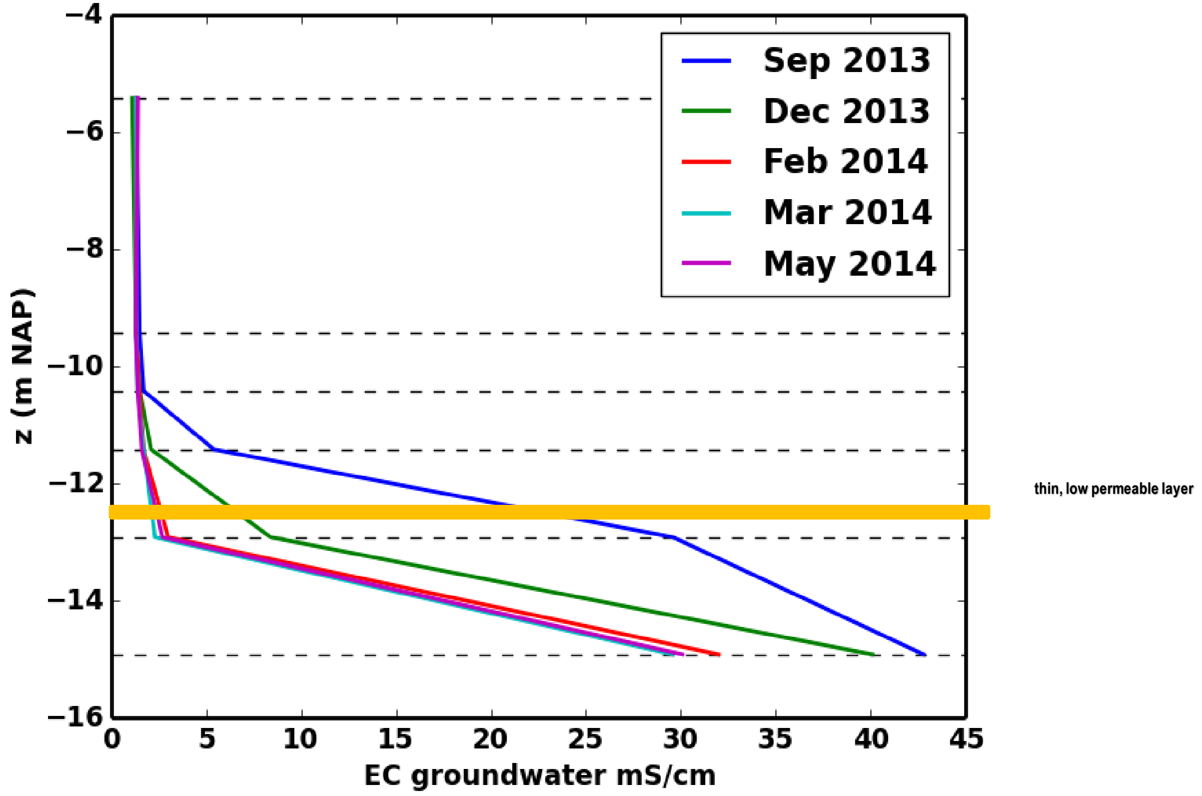
Key field observations (1)

- Fresh groundwater up to -12 m NAP

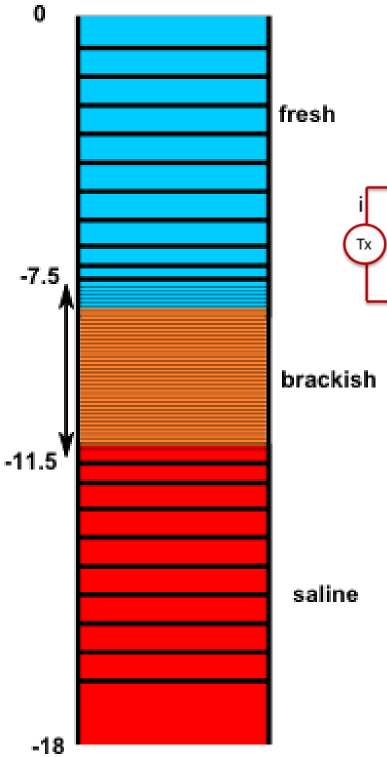


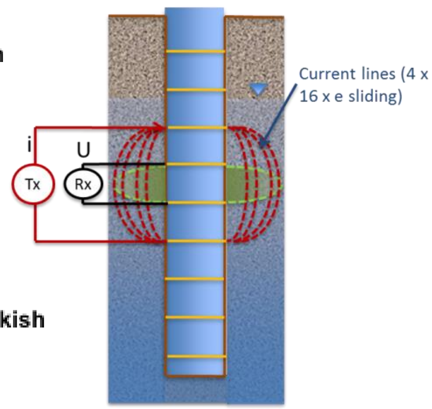
Key field observations (2)

- Freshening up to 2m

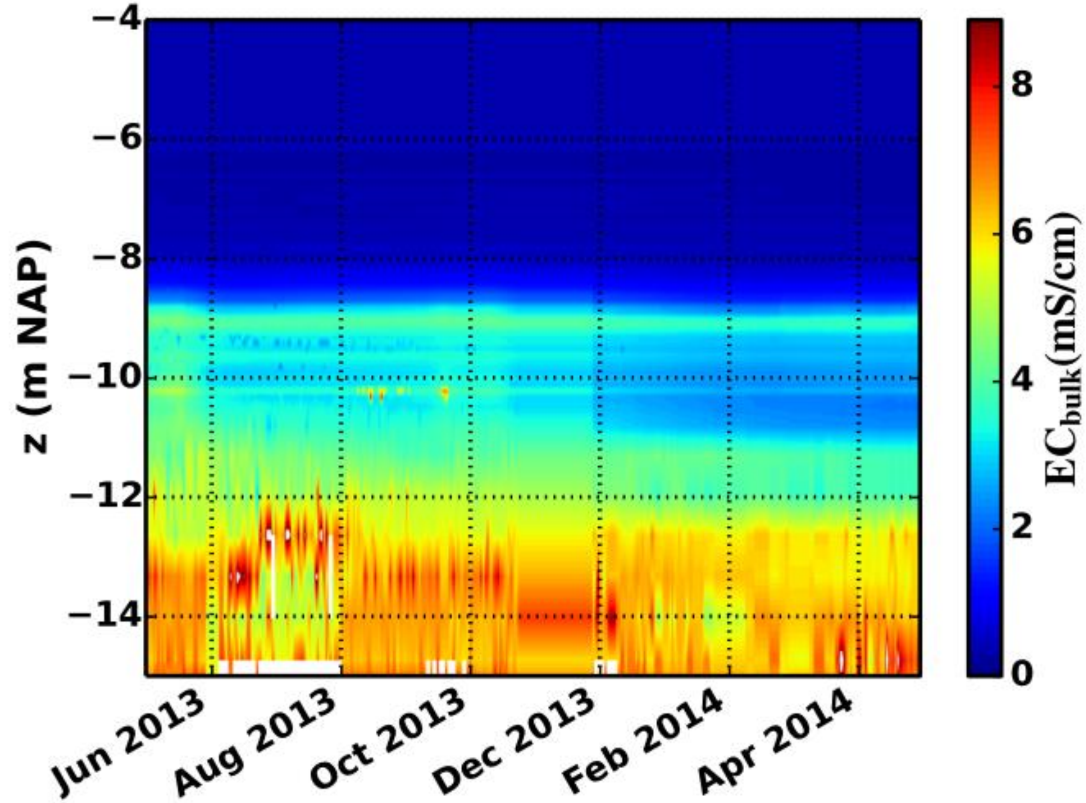


Subsurface Monitoring Device (SMD): Monitoring salinities





«Different electrical methods are applied : Dipole-Dipole, Pole- Dipole or Wenner »

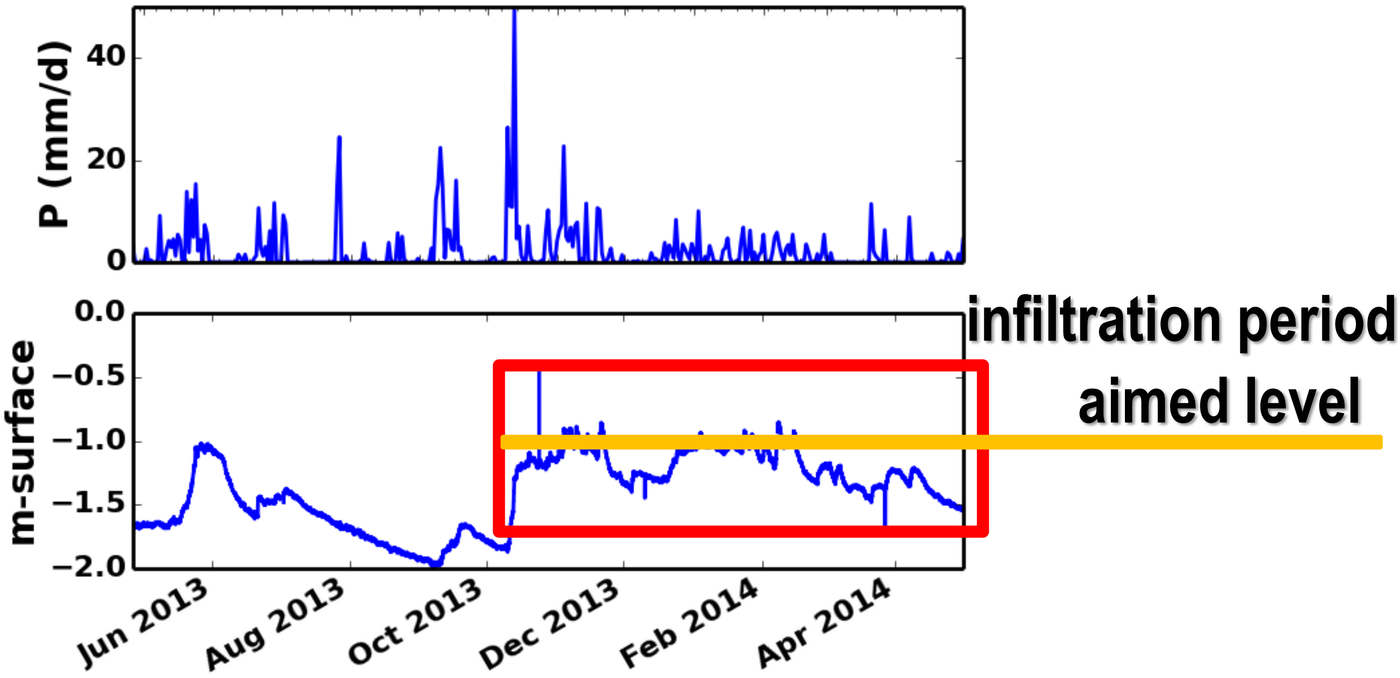


imaGeau instrumentation du sous-sol

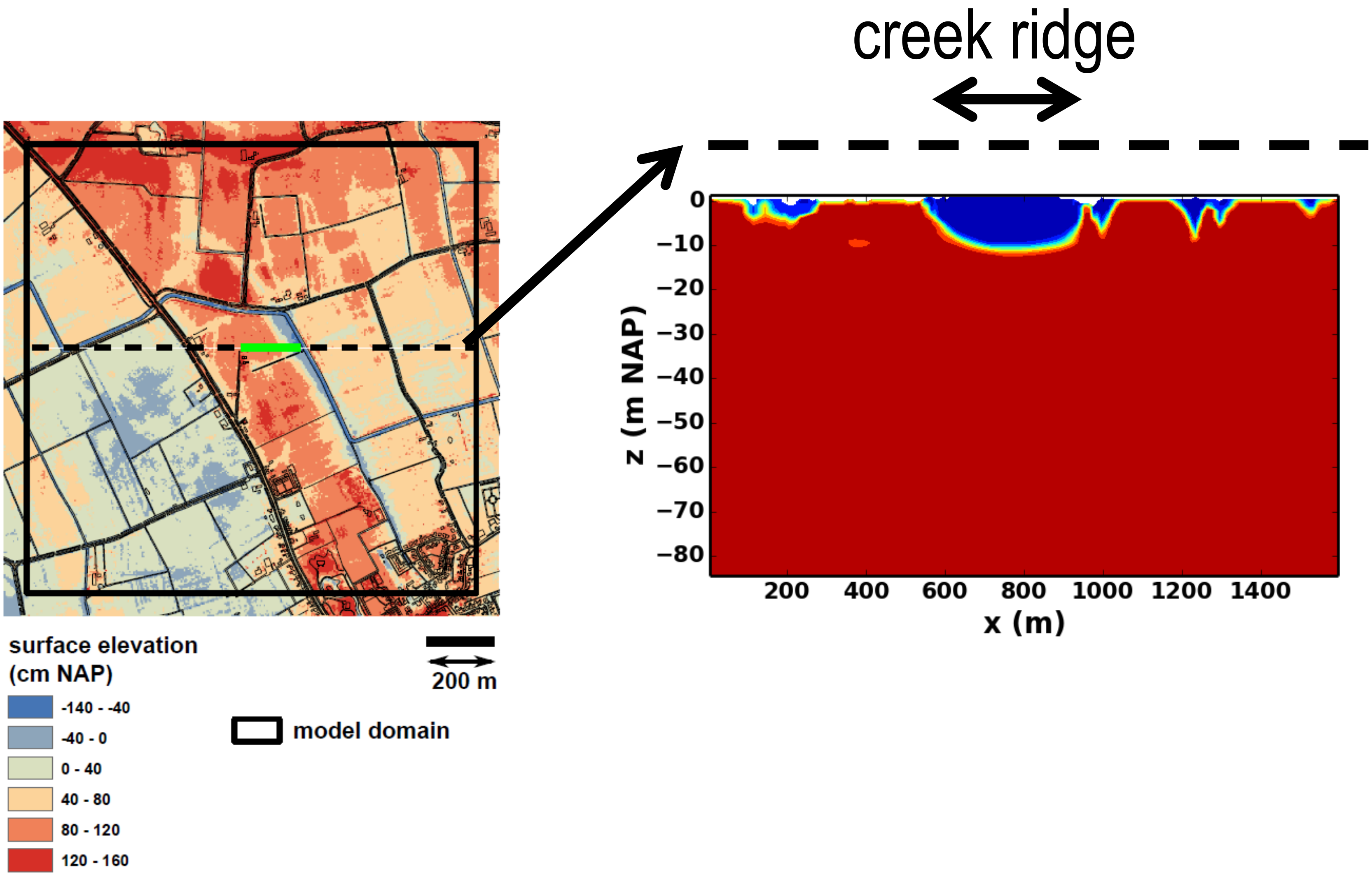
FUGRO

Key field observations (3)

- Groundwater levels and precipitation

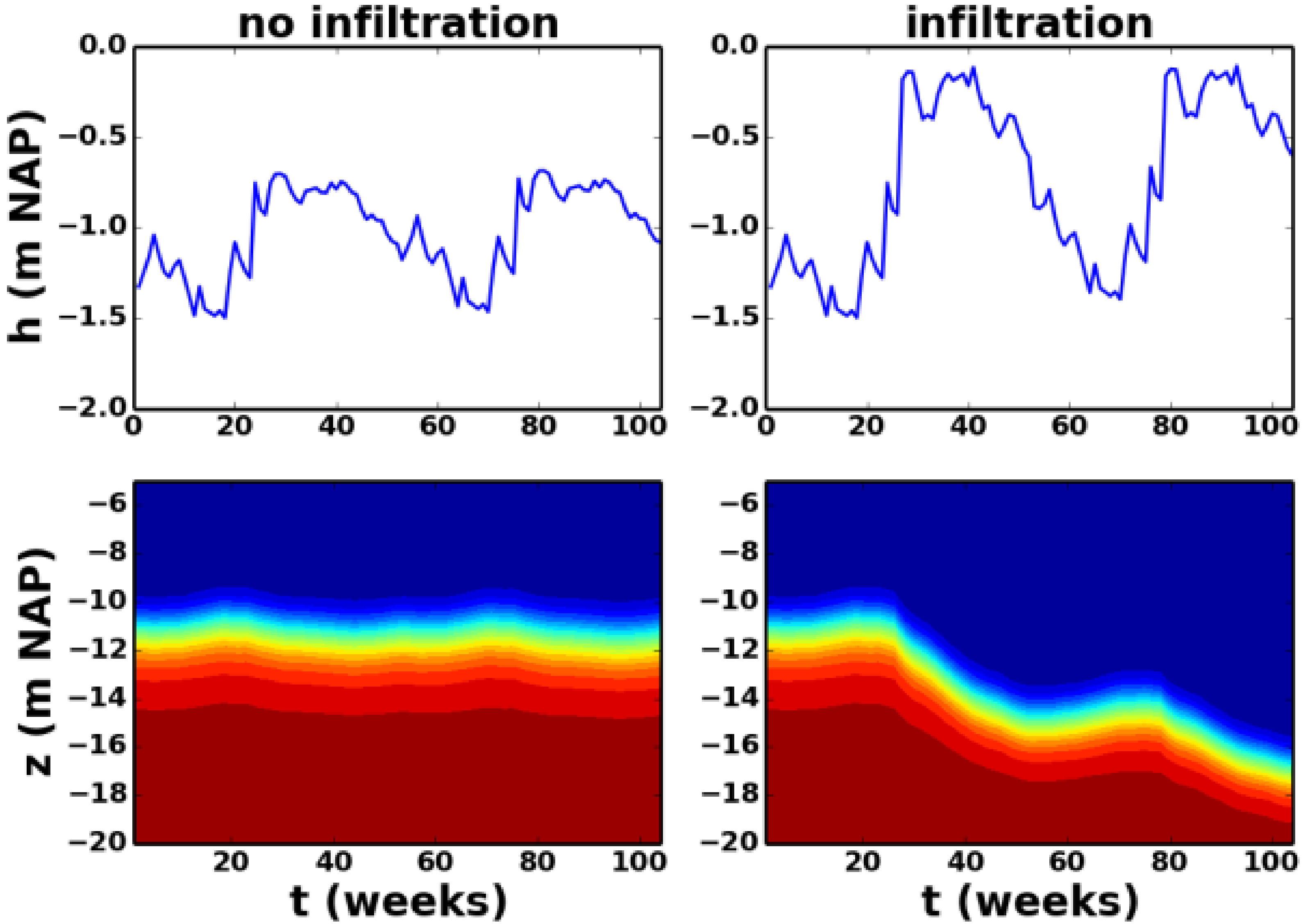


Modeling



creek ridge
0
−10
−20
−30
−40
−50
−60
−70
−80
z (m NAP)
200
400
600
800
1000
1200
1400
x (m)
surface elevation
(cm NAP)
-140 - -40
-40 - 0
0 - 40
40 - 80
80 - 120
120 - 160
model domain
200 m

Influence of infiltration



Example NL:
Salt resistant crops on salty boils

Cl-conc seepage:

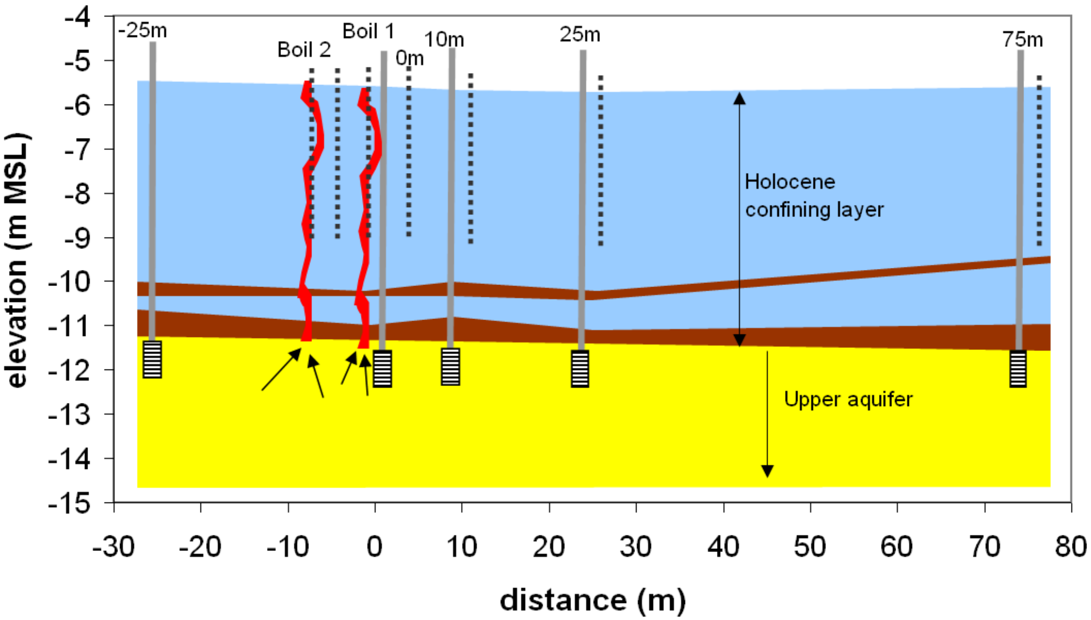
(Polder Noordplas)

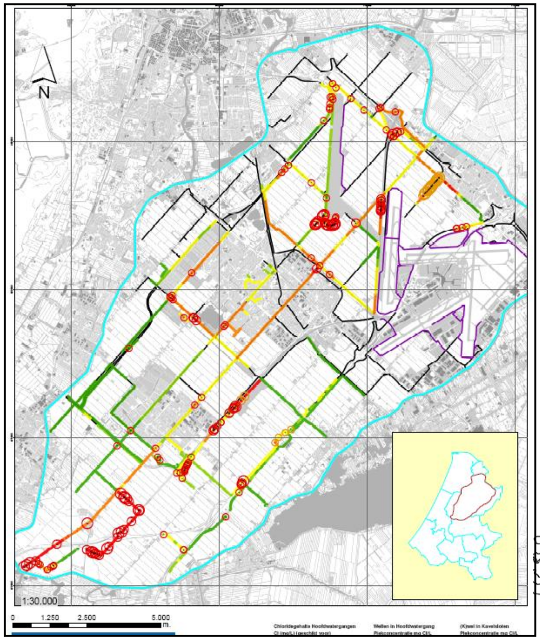
Diffuse : 100 mg/l

Paleochannel : 600 mg/l

Boils : 1100 mg/l

Ask Perry de Louw for details





Modelling

salt water intrusion

density dependent groundwater flow

Why mathematical modelling anyway?

A model is only a schematisation of the reality!

Why mathematical modelling anyway?

+:

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

-:

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

Numerical modelling variable density flow

Type:

- sharp interface models
- solute transport models

State of the art:

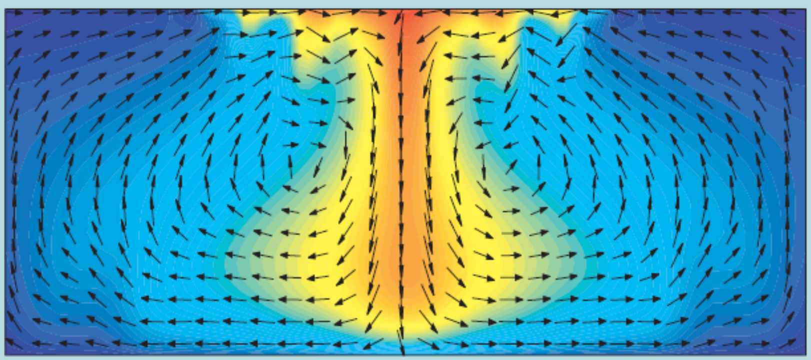
- three-dimensional
- solute transport
- transient

2002

USGS
science for a changing world

User's Guide to SEAWAT:

A Computer Program For Simulation of Three-Dimensional Variable-Density Ground-Water Flow



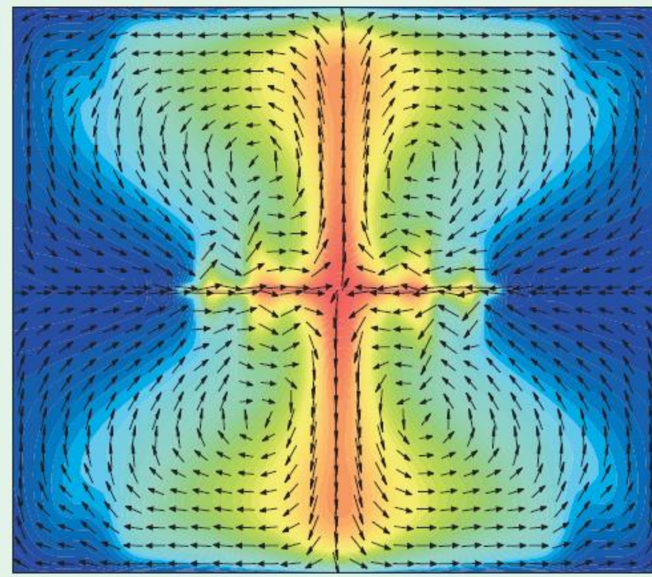
Techniques of Water-Resources Investigations of the U.S. Geological Survey

BOOK 6
Chapter A7

2007/2008

USGS
science for a changing world

SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport



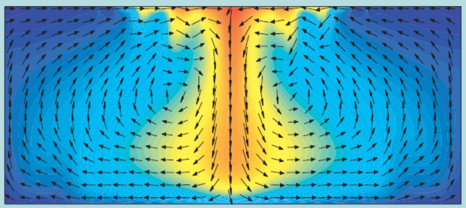
Techniques and Methods Book 6, Chapter A22

U.S. Department of the Interior
U.S. Geological Survey

2002/2003

User's Guide to SEAWAT:

A Computer Program For Simulation of Three-Dimensional Variable-Density Ground-Water Flow



Techniques of Water-Resources Investigations of the U.S. Geological Survey

BOOK 6
Chapter A7

MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model—Documentation of the SEAWAT-2000 Version with the Variable-Density Flow Process (VDF) and the Integrated MT3DMS Transport Process (IMT)

By Christian D. Langevin, U.S. Geological Survey, Miami, Fla.,
W. Barclay Shoemaker, U.S. Geological Survey, Miami, Fla.,
and Weixing Guo, CDM Missimer, Ft. Myers, Fla.

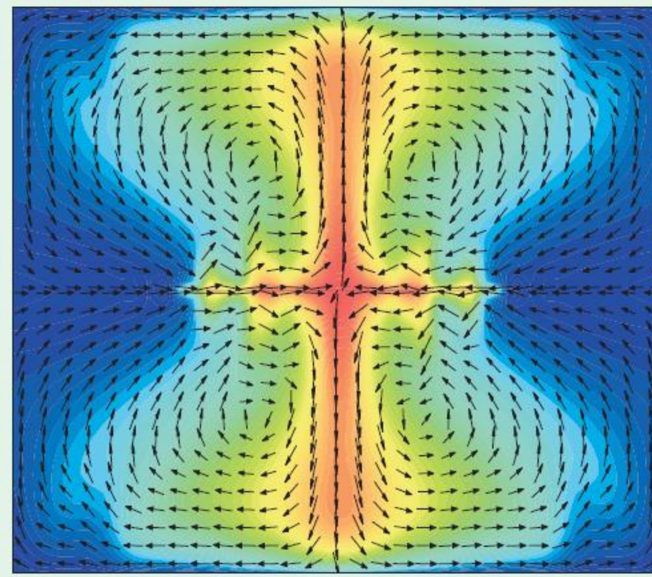
U.S. GEOLOGICAL SURVEY
Open-File Report 03-426

Prepared in cooperation with the
U.S. GEOLOGICAL SURVEY OFFICE OF GROUND WATER

Tallahassee, Florida
2003

2007/2008

SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport



Techniques and Methods Book 6, Chapter A22

U.S. Department of the Interior
U.S. Geological Survey

MT3D 1999

Supplement 2010

Strategic Environmental Research and Development Program

Contract Report SERDP-99-1
December 1999

MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide

by Chunmiao Zheng, P. Patrick Wang

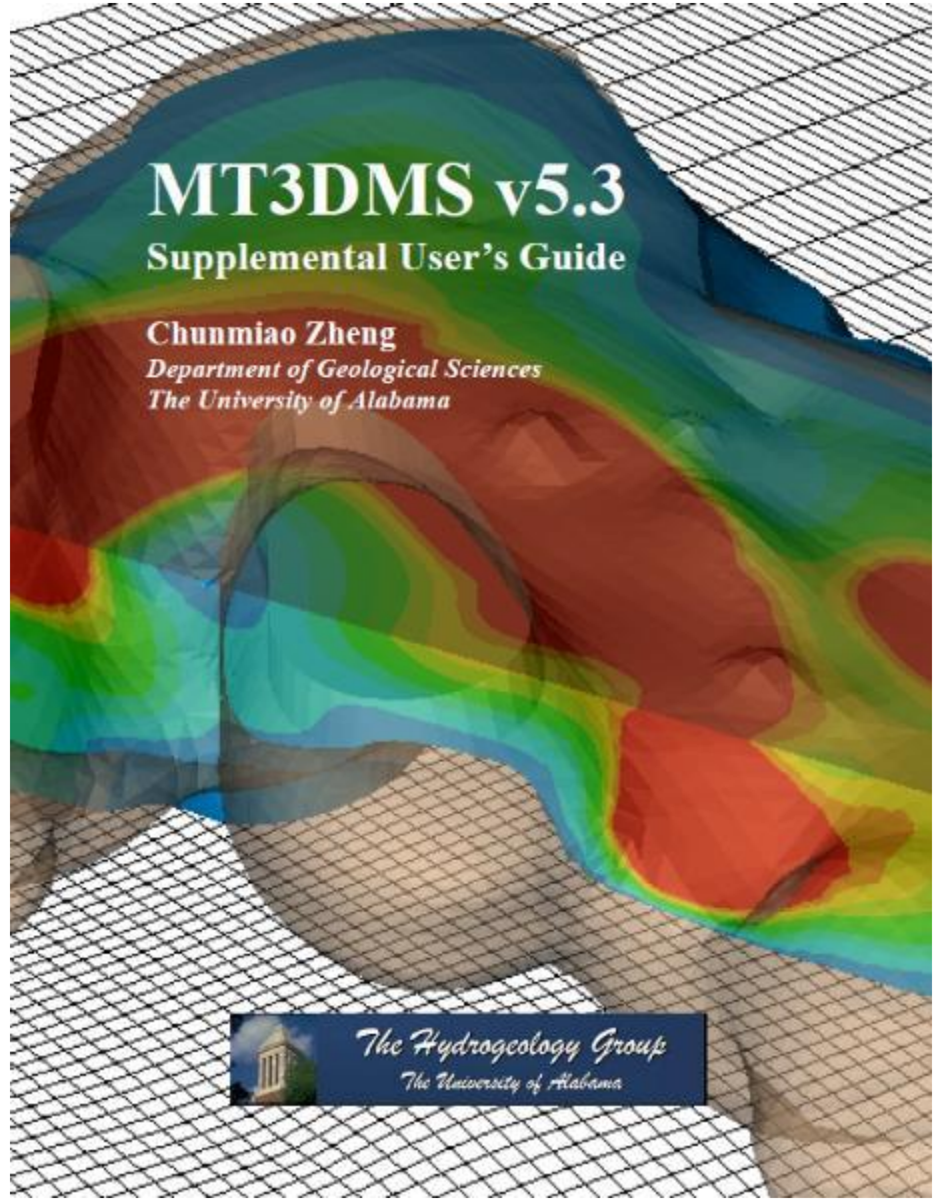
Department of Geological Sciences
University of Alabama
Tuscaloosa, AL 35487

Final report

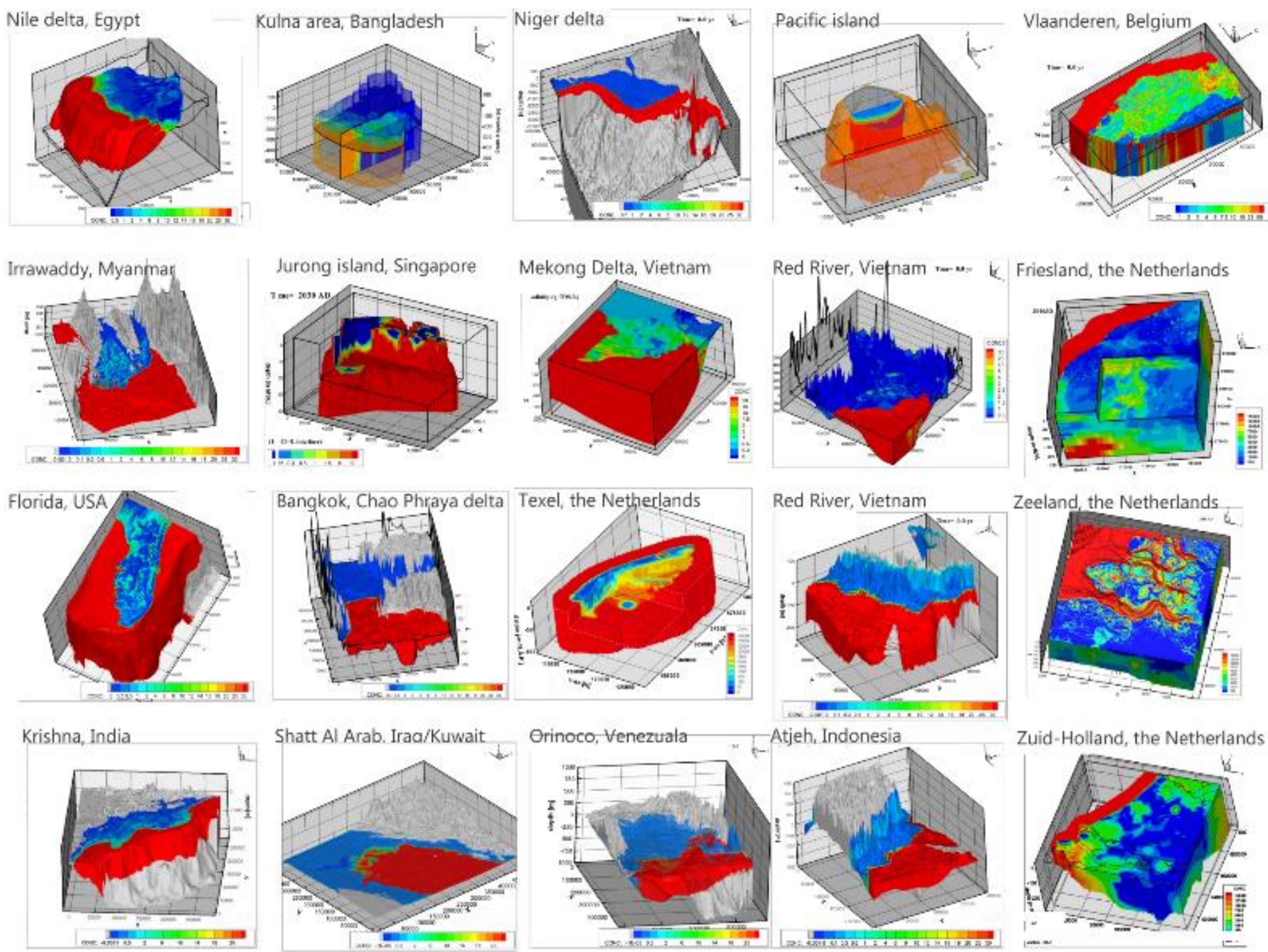
Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit No. CU-1062

Monitored by Environmental Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199



3D numerical models groundwater coastal zone



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

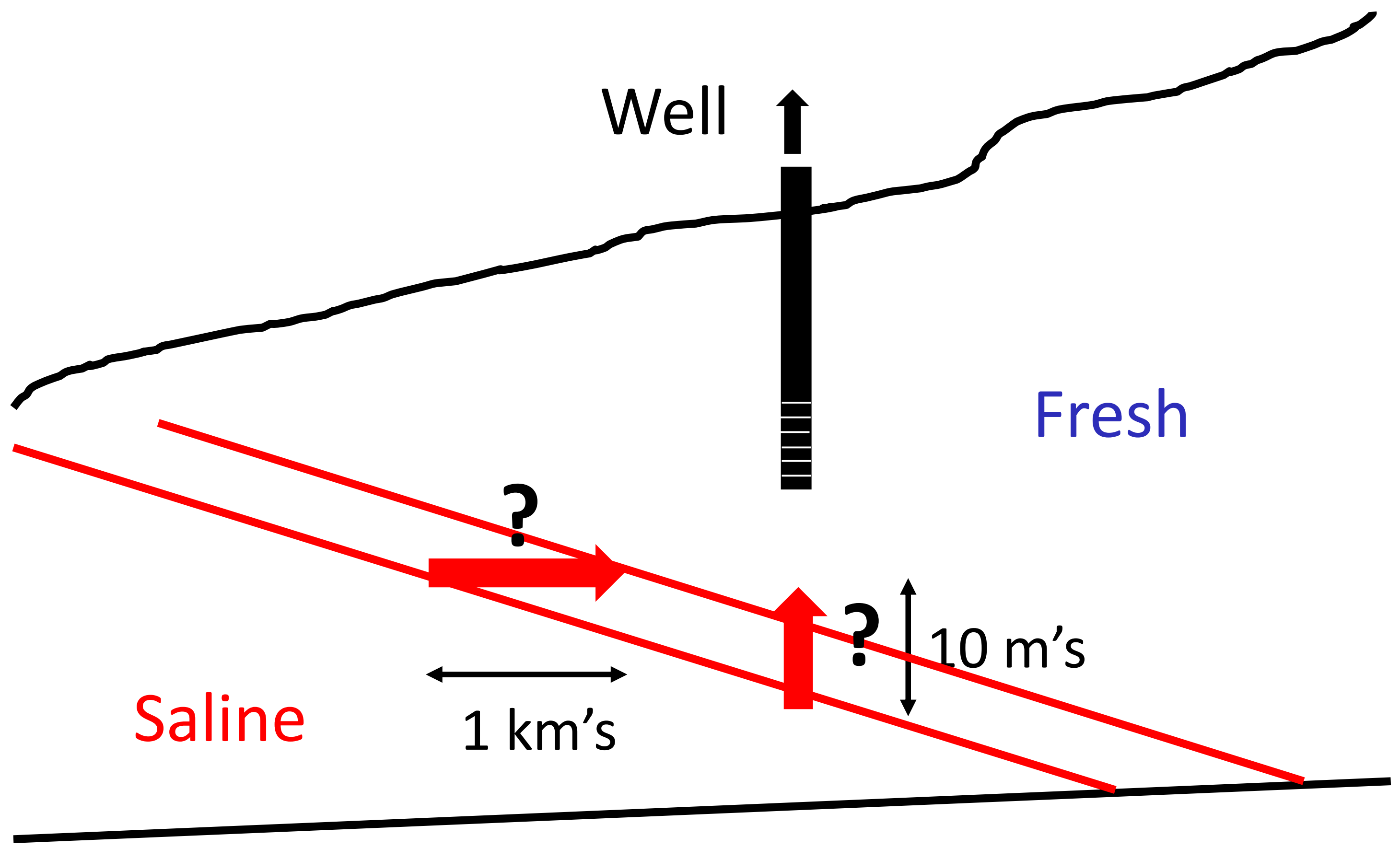
SEAWAT (*Guo & Bennett, 98*)
METROPOL (*Sauter, '87*)
FEFLOW (*Diersch, '94*)
MVAEM (*Strack, '95*)
D3F (*Wittum et al., '98*)
MOCDENS3D (*Oude Essink, '98*)
HydroGeoSphere (*Therrien, '92*)

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

Fresh-salt groundwater modelling issues

1. Grid convergence
2. Vert-hor displacement interface
3. Transient versus Steady-state
4. Salt BC: e.g. far enough for the area of interest, BC zz 3D model
5. Do not trust solvers default: e.g. Case Nile delta
6. Rotation mixing, effect of dispersion
7. Big delta systems and drain-river packages: there is always a drainage system around
    a. Conductance for large cells
    b. Sof okay, but check it
8. Rule of Thumb: Lambda (GHB)
9. Animation over more times than just Stress Periods
10. Focus velocity field, including high DEM contrast!

Movement of interface: hor. of vert.?



Visualisation tools

- Tecplot https://www.tecplot.com/
- Paraview https://www.paraview.org/
- iMOD https://oss.deltares.nl/web/imod
- Flopy https://www.usgs.gov/software/flopy-python-package-creating-running-and-post-processing-modflow-based-models
- Modelviewer https://www.usgs.gov/software/model-viewer-a-program-three-dimensional-visualization-ground-water-model-results

SEAWAT

$$\nabla \cdot \left[\rho K_o \left(\nabla h_f + \frac{\rho - \rho_f}{\rho_f} \nabla z \right) \right] = \rho S_s \frac{\partial h_f}{\partial t} + \theta \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} - \rho_{ss} q_{ss}$$

where ρ is the density of the groundwater (M L^{-3}); K_0 is the hydraulic conductivity tensor (L T^{-1}); h_f is the freshwater head (L); z is the vertical coordinate (L); ρ_f is the density of fresh groundwater (M L^{-3}); S_s is the specific storage coefficient (L^{-1}); t is the time (T); ϕ is the effective porosity (-); C is the concentration (M L^{-3}); ρ_{ss} is the density of the sink or source (T^{-1}); and q_{ss} is the sink and source term (T^{-1}).

$$\rho = \rho_f + \frac{\partial \rho}{\partial C} C$$

$$\frac{\partial (\theta C)}{\partial t} = \nabla \cdot (\theta D \cdot \nabla C) - \nabla \cdot (qC) - q_{ss} C_{ss}$$

where D is the hydrodynamic dispersion tensor (L^2 T^{-1}); q is the specific discharge vector (L T^{-1}) and C_{ss} is the source and sink concentration (M L^{-3}).

Restrictions 3D salt water intrusion modelling

- the data problem:

  -not enough hydrogeological data available

  -e.g. the initial density distribution

  -especially important issue in data-poor countries

- the computer problem:

  -modelling transient 3D systems: computer only
  good enough at high costs

- the numerical dispersion problem:

  -numerical dispersion is large in case of coarse grid

Restrictions 3D salt water intrusion modelling now

- the data problem:

  -not enough hydrogeological data available

  -e.g. the initial density distribution

  -especially important issue in data-poor countries

- the computer problem:

  -modelling transient 3D systems: computer only good enough at high costs

  solution is 64 bits computer

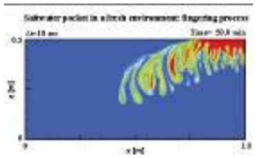
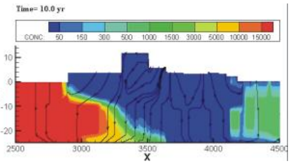
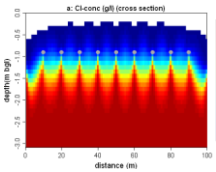
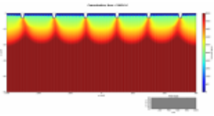
- the numerical dispersion problem:

  -numerical dispersion is large in case of coarse grid

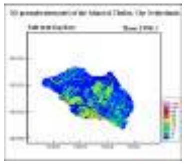
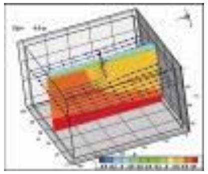
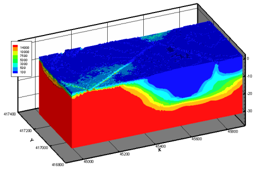
  solution is better solvers

Modelling fresh-salt groundwater on different scales

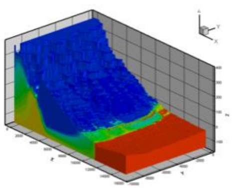
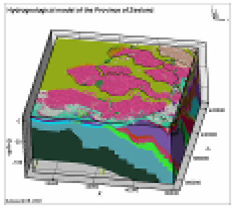
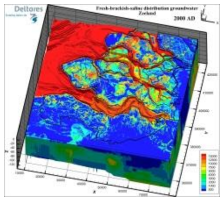
Sub-local: fingering, salty sand boils storm surges (e.g. Tsunami 2004)
cell size=1cm-1m

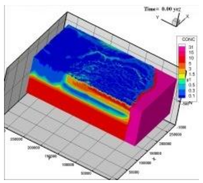
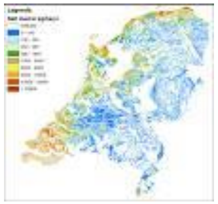
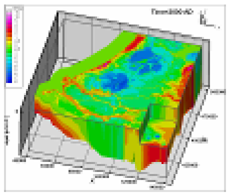
Local: rainwaterlenses, Aquifer Storage and Recovery, heat-cold
cell size=5-25m

Regional: fresh groundwater volumes farmer level
cell size=100m

National: salt load, national fresh groundwater volumes, impact SLR
cell size=250m-2km

Goal:

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

Boundary Conditions Models

Dirichlet: head

- fixed head (DEM minus unsaturated zone)

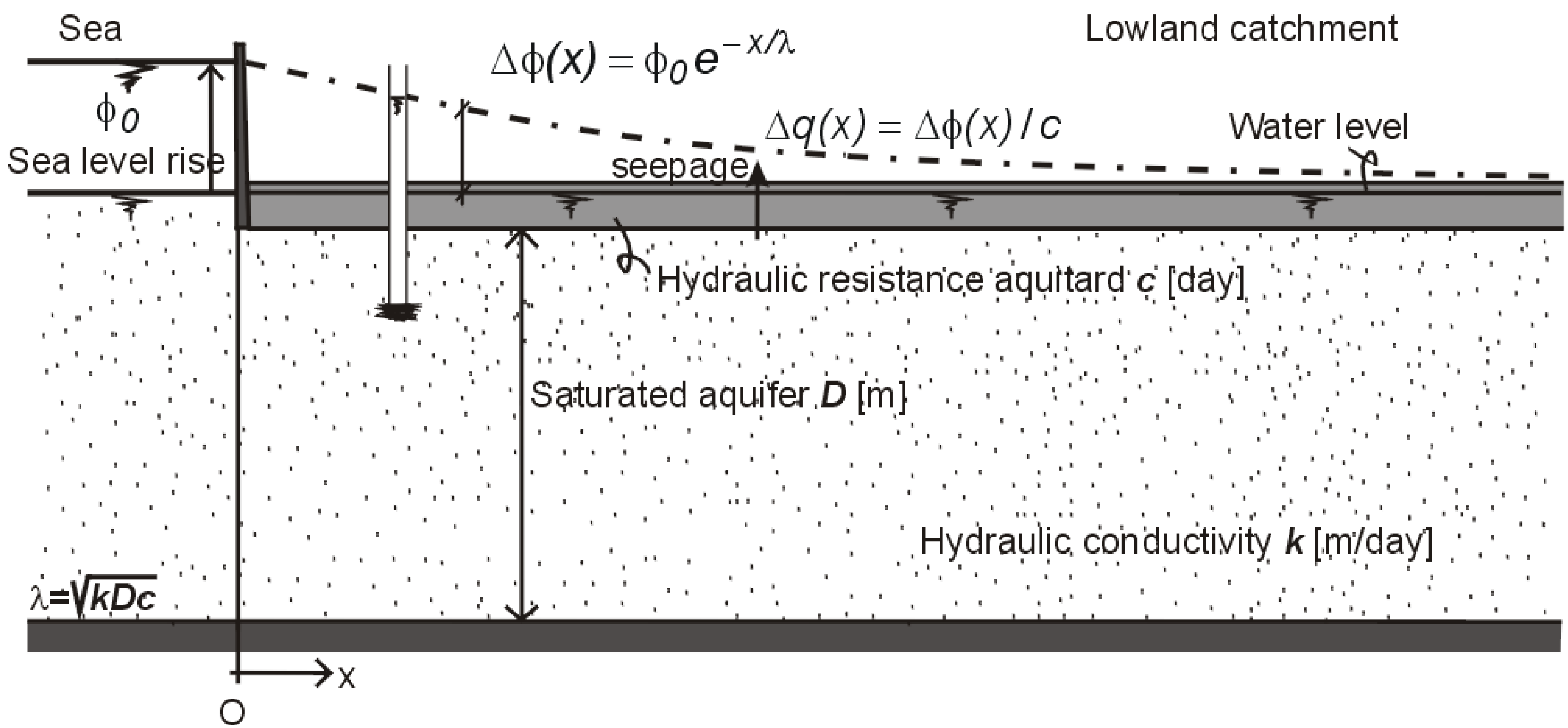
Neumann: flux

- Zero = no-flow
- Constant

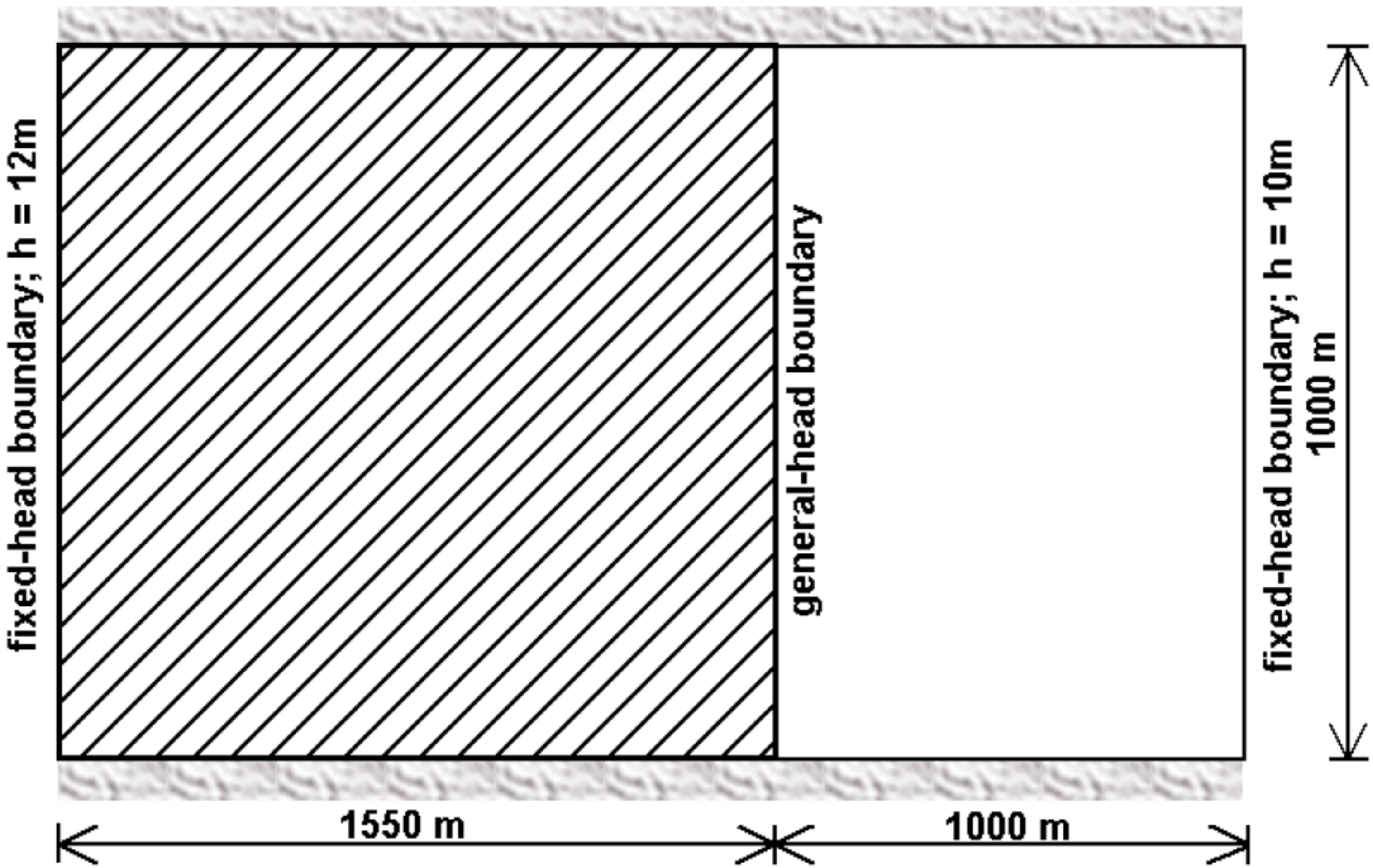
Robin / Cauchy: mixed

- Like General Head Boundary!

Formula of Mazure, zone of influence head



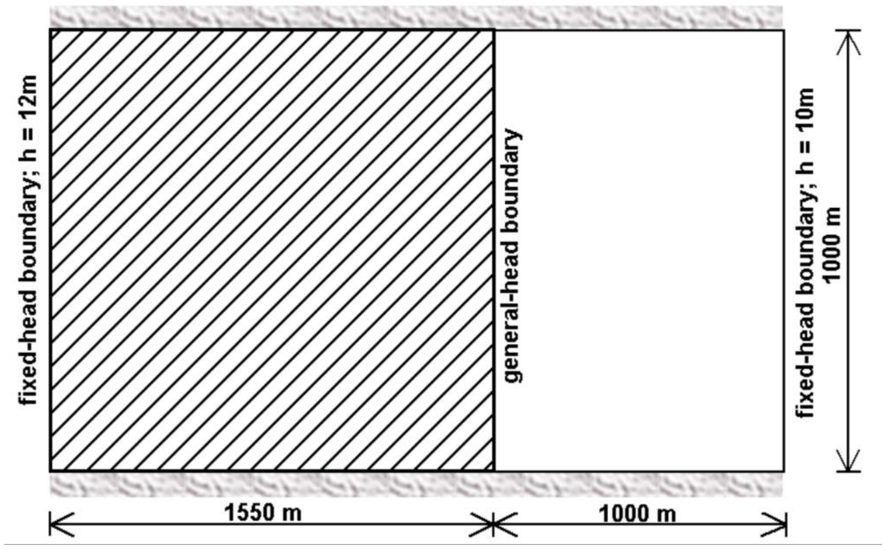
Using the GHB for the head BC



Using the GHB for the head BC

$$\text{Conductance}_{GHB} = K_{GHB} \cdot A/L$$

- K_{GHB} is the (horizontal) hydraulic conductivity,
- L is the distance from the actual fixed-head boundary to the modeled GHB cell,
- A is the area of the cell face, which is perpendicular to the groundwater flow in the unmodeled area.



Solute transport models

Combine

the groundwater flow equation

and

the advection-dispersion equation

by means of

an equation of state

Solute transport equation

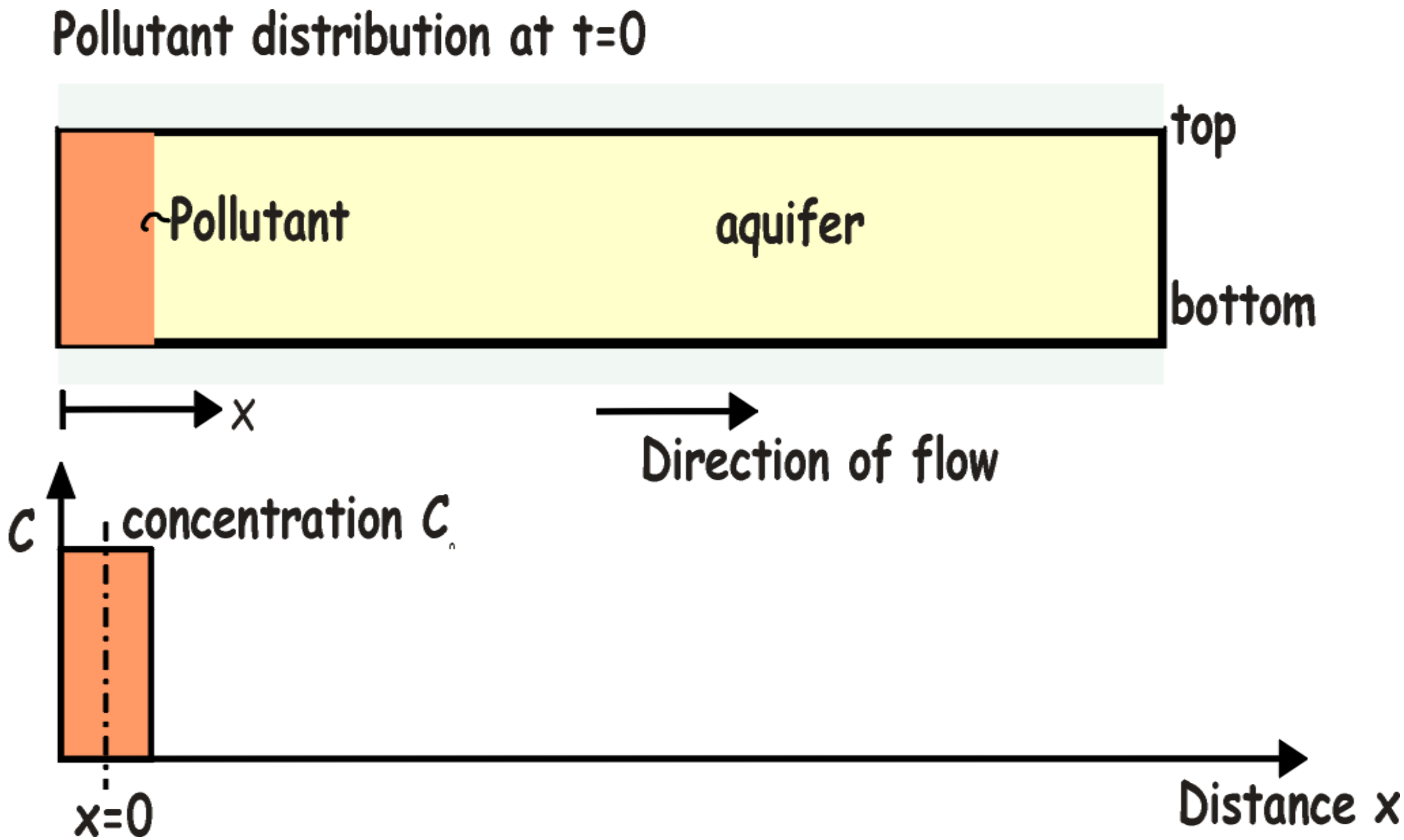
Partial differential equation (PDE):

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

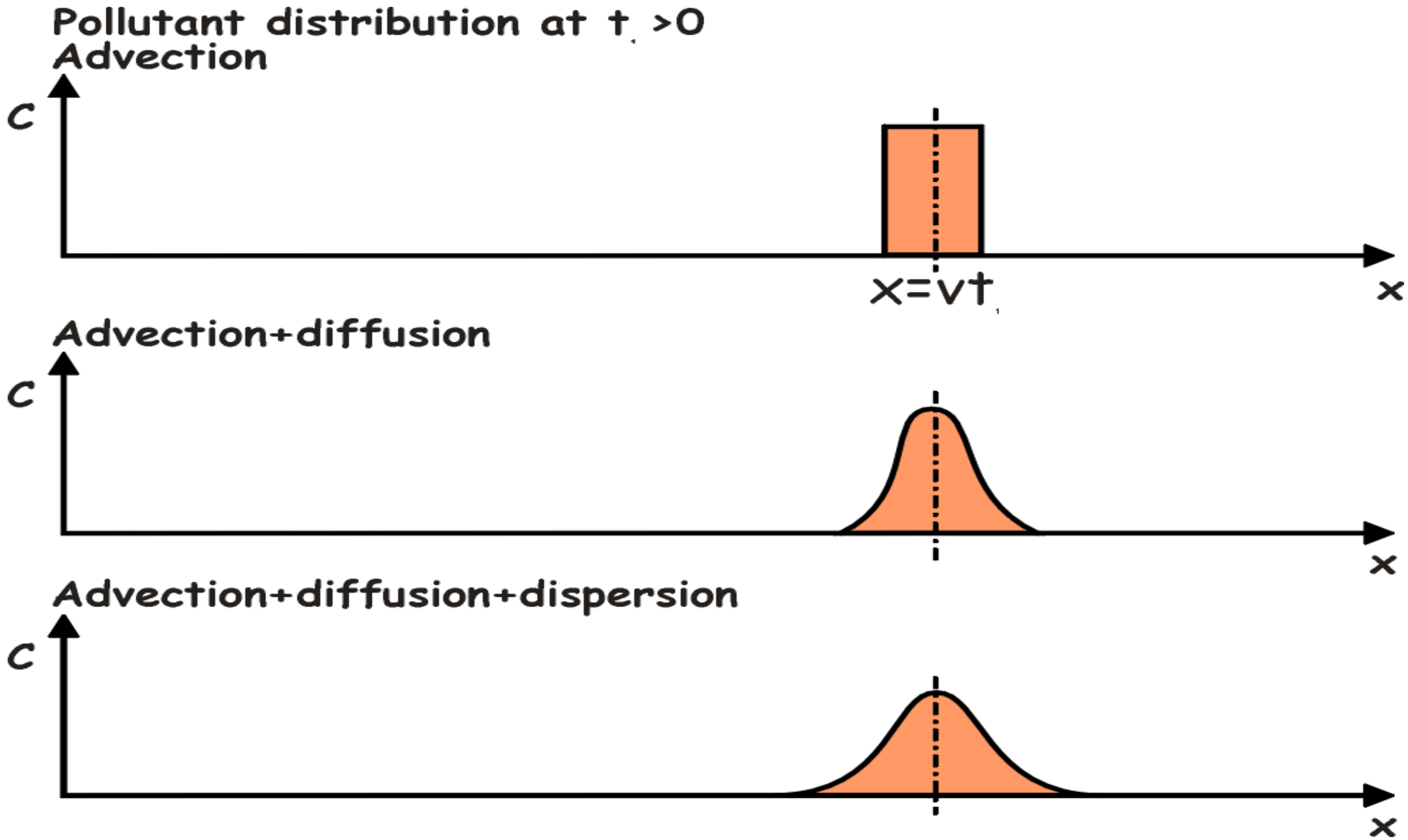
change in concentration | dispersion diffusion | advection | source/sink | decay

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

Solute transport equation: column test (I):

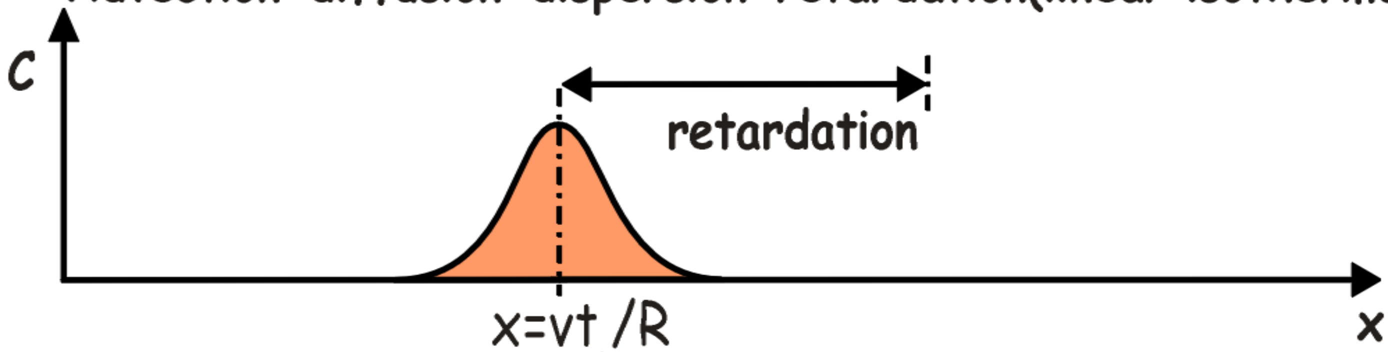


Solute transport equation: column test (II):

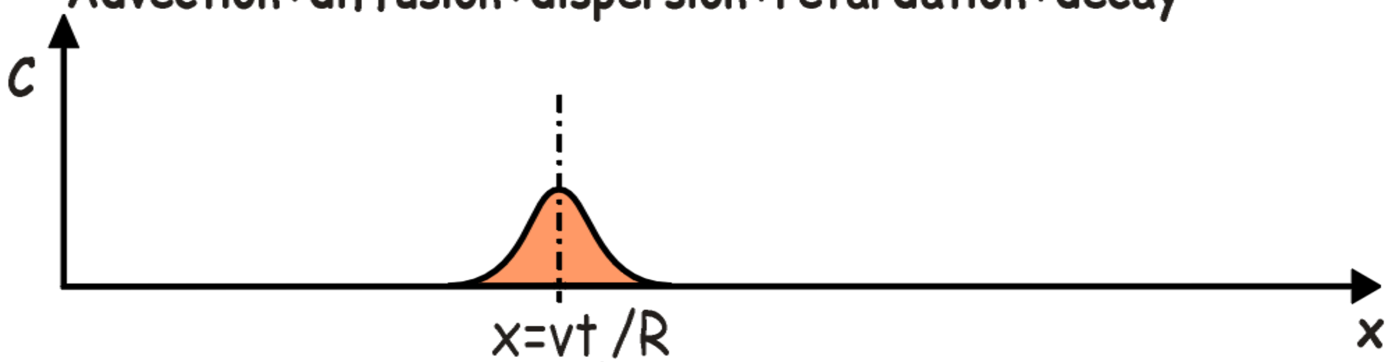


Solute transport equation: column test (III):

Advection+diffusion+dispersion+retardation(linear isothermal)



Advection+diffusion+dispersion+retardation+decay



Hydrodynamic dispersion

hydrodynamic dispersion
=
mechanical dispersion+ diffusion

mechanical dispersion:

tensor

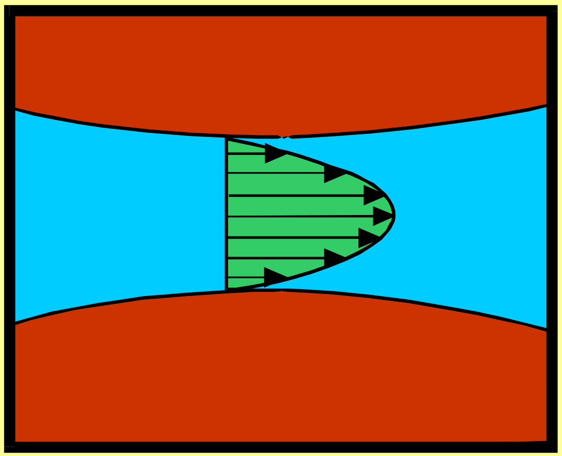
velocity dependant

diffusion:

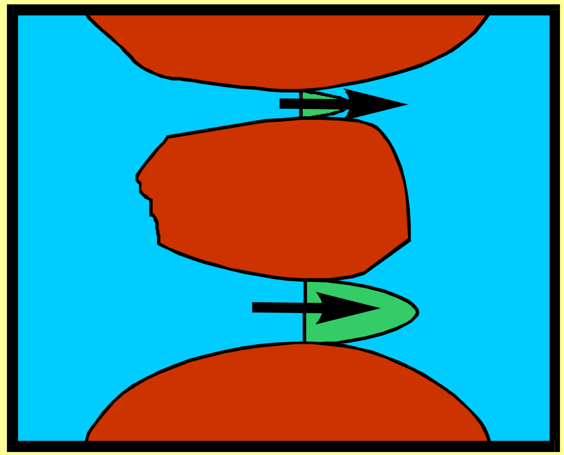
molecular process

solutes spread due to concentration differences

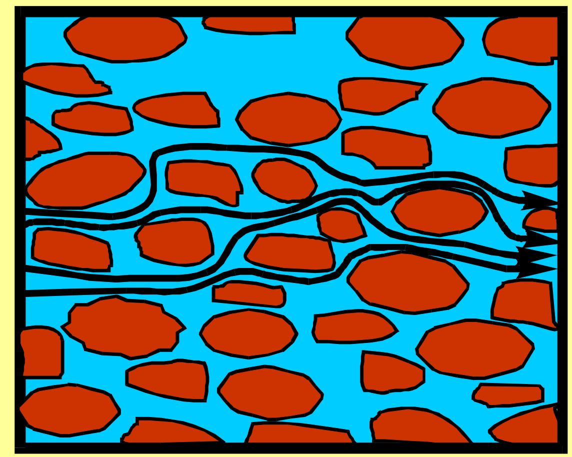
Mechanical dispersion



Differences in velocity in the pore

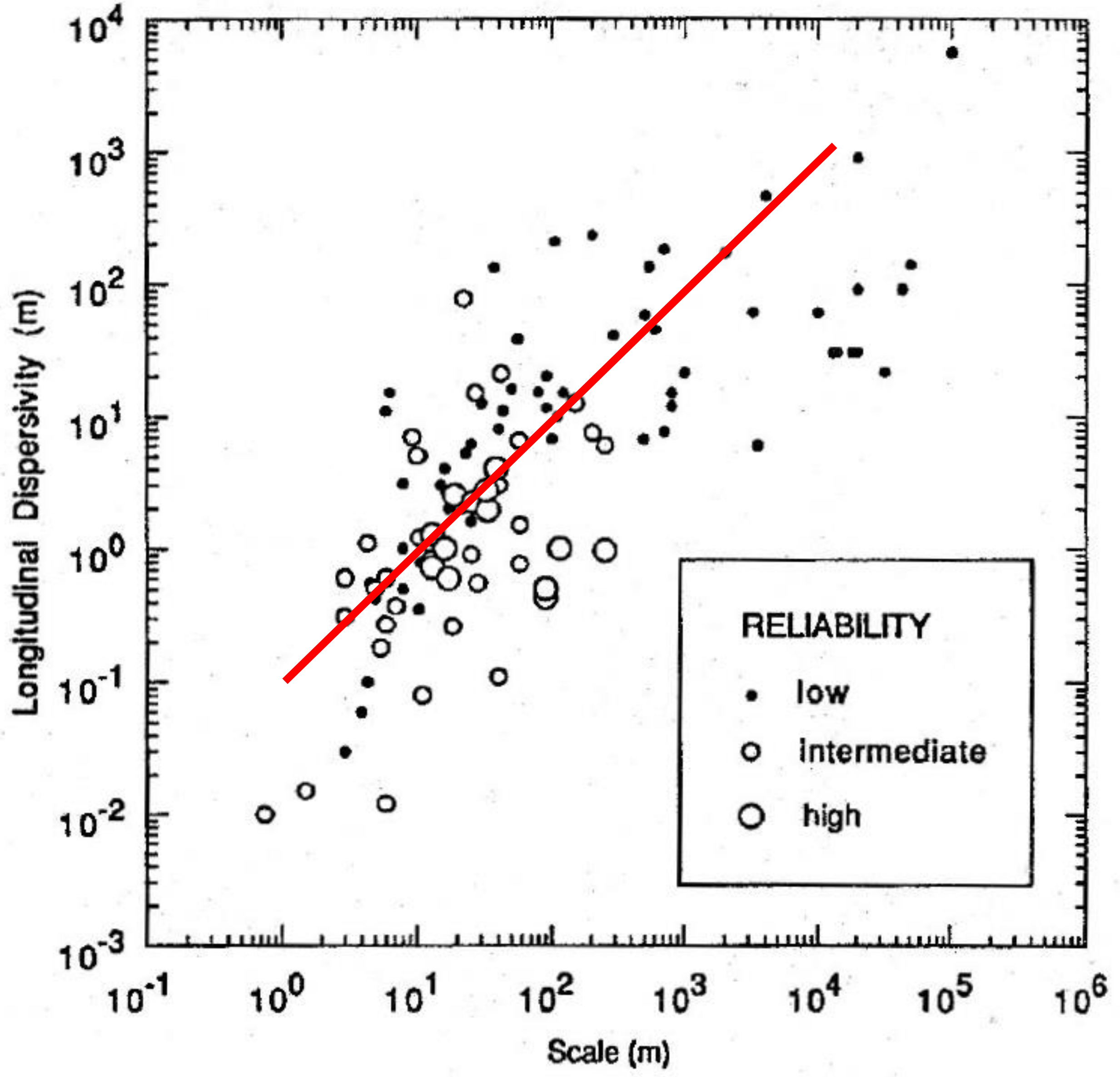


Differences in velocity due to variation in pore-dimension



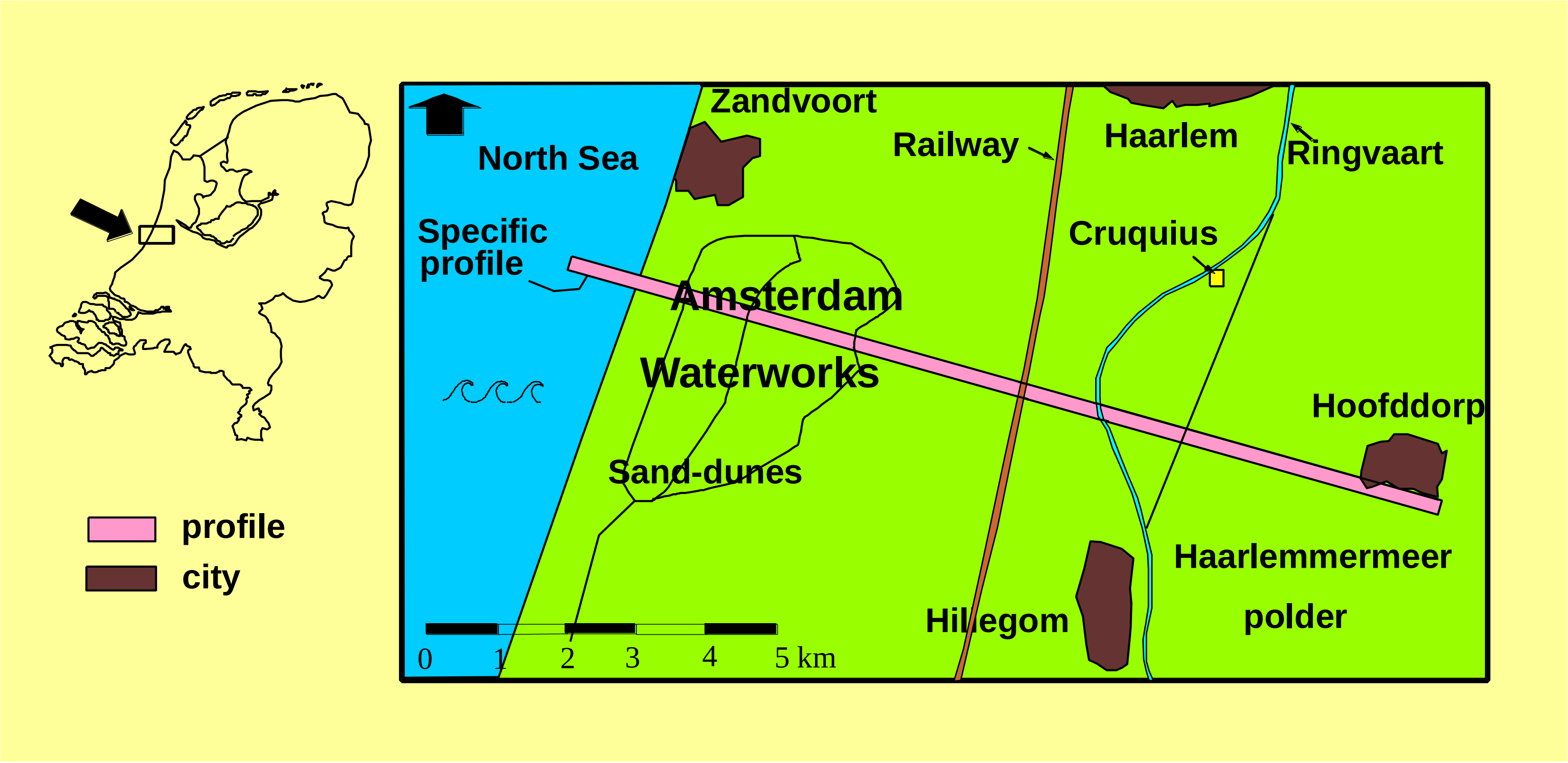
Differences in velocity due to variation in velocity direction

Scale-dependency longitidinal dispersivity



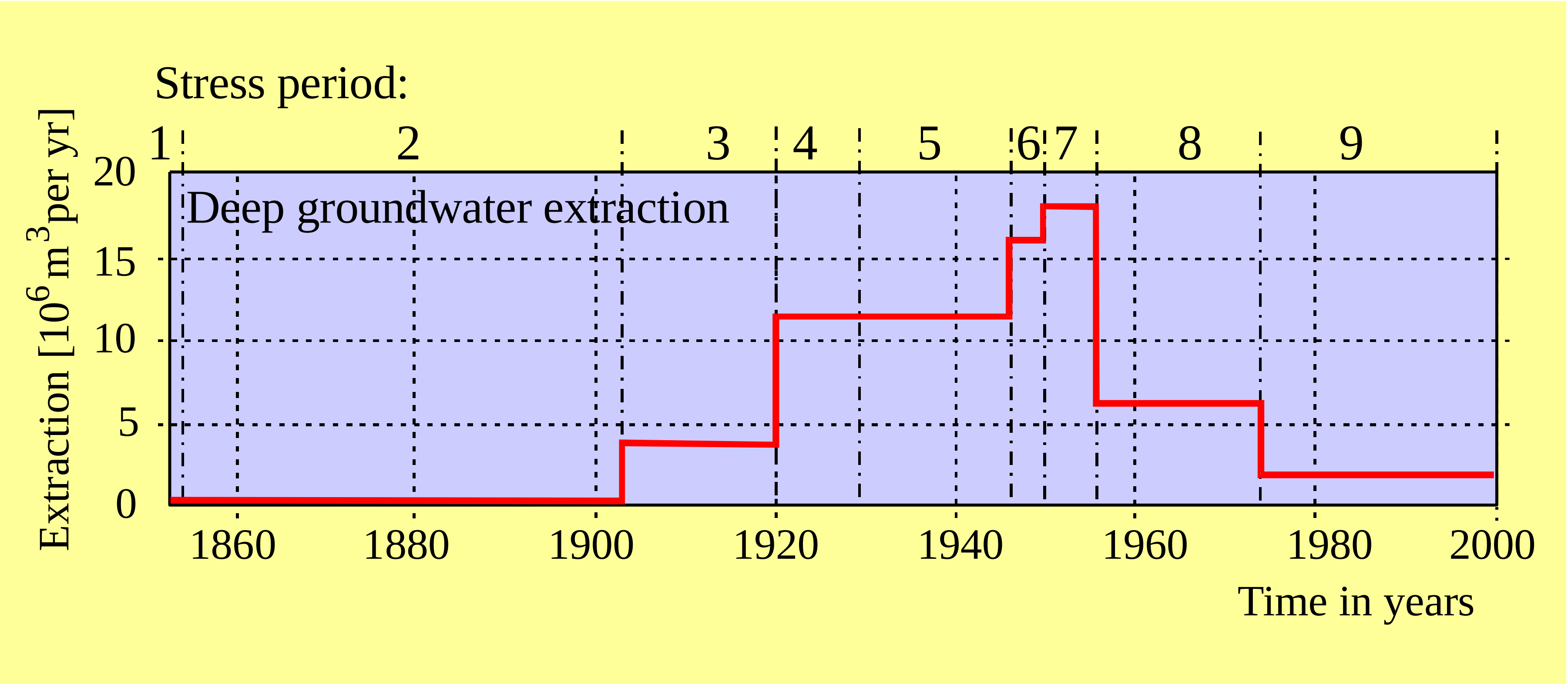
Effect of α_L on the salinisation of the aquifer (I)

Position profile through Amsterdam Waterworks, Rijnland polders and Haarlemmermeer polder



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

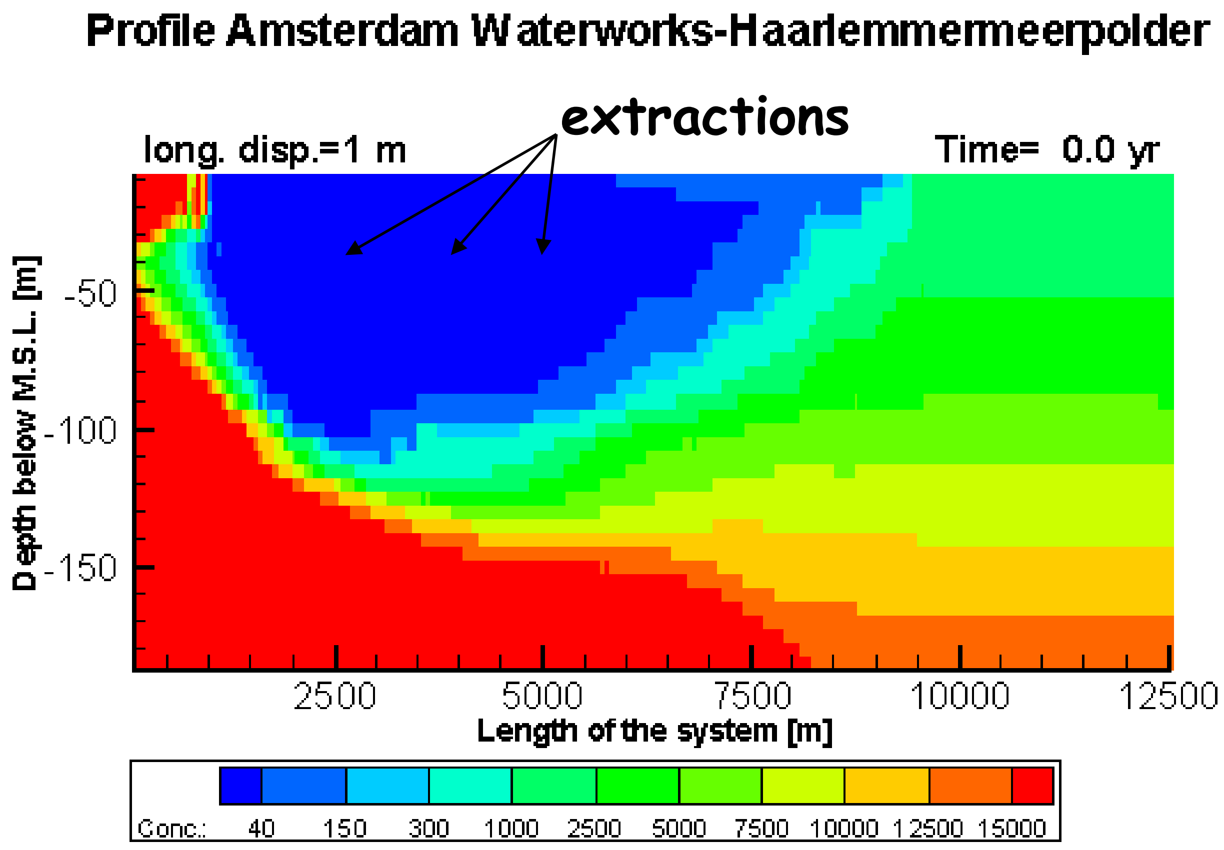
Grondwater extractions out of the middle aquifer in the sand-dune area of Amsterdam Waterworks



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

α_L=1 m

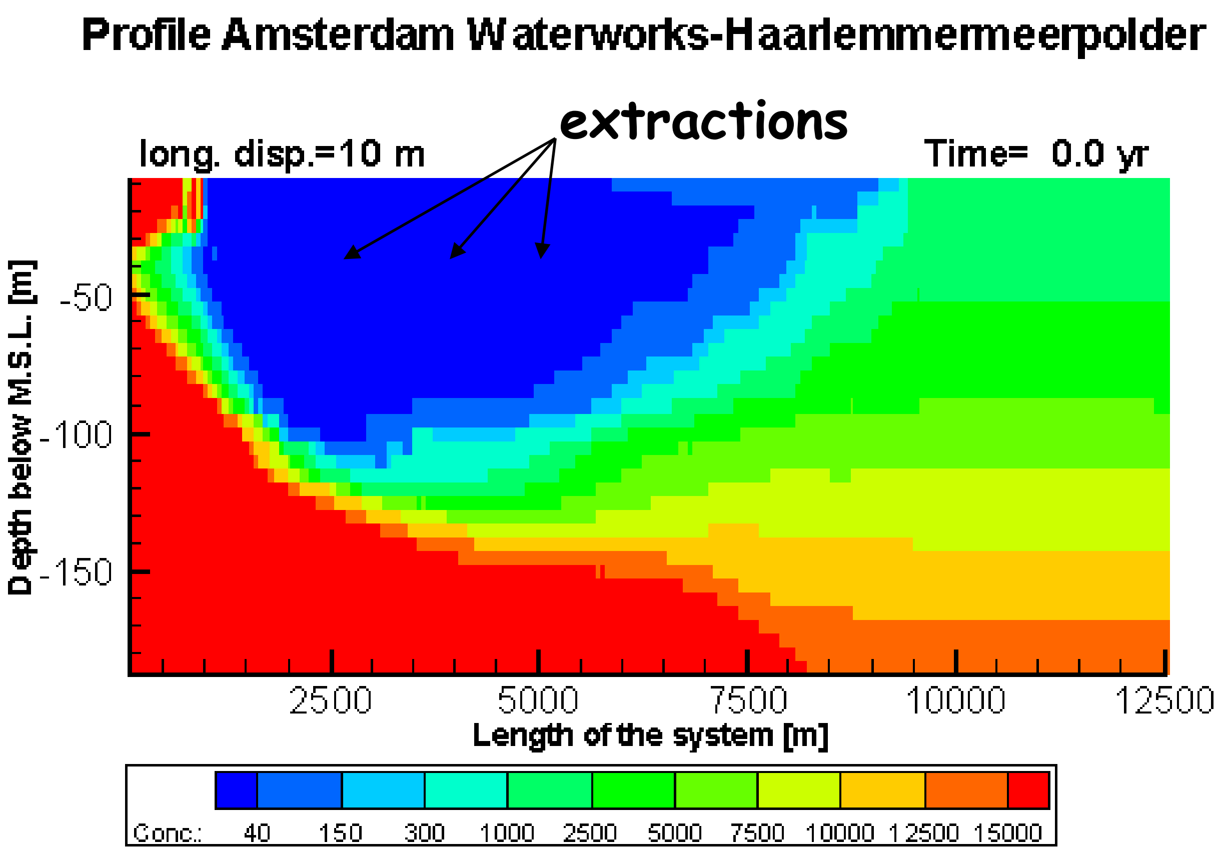
Initial situation: 154 years ago



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

α_L=10 m

Initial situation: 154 years ago



Solute transport equation: diffusion (I)

diffusion is a slow process: diffusion equation

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

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

similarity with non-steady state groundwater flow equation

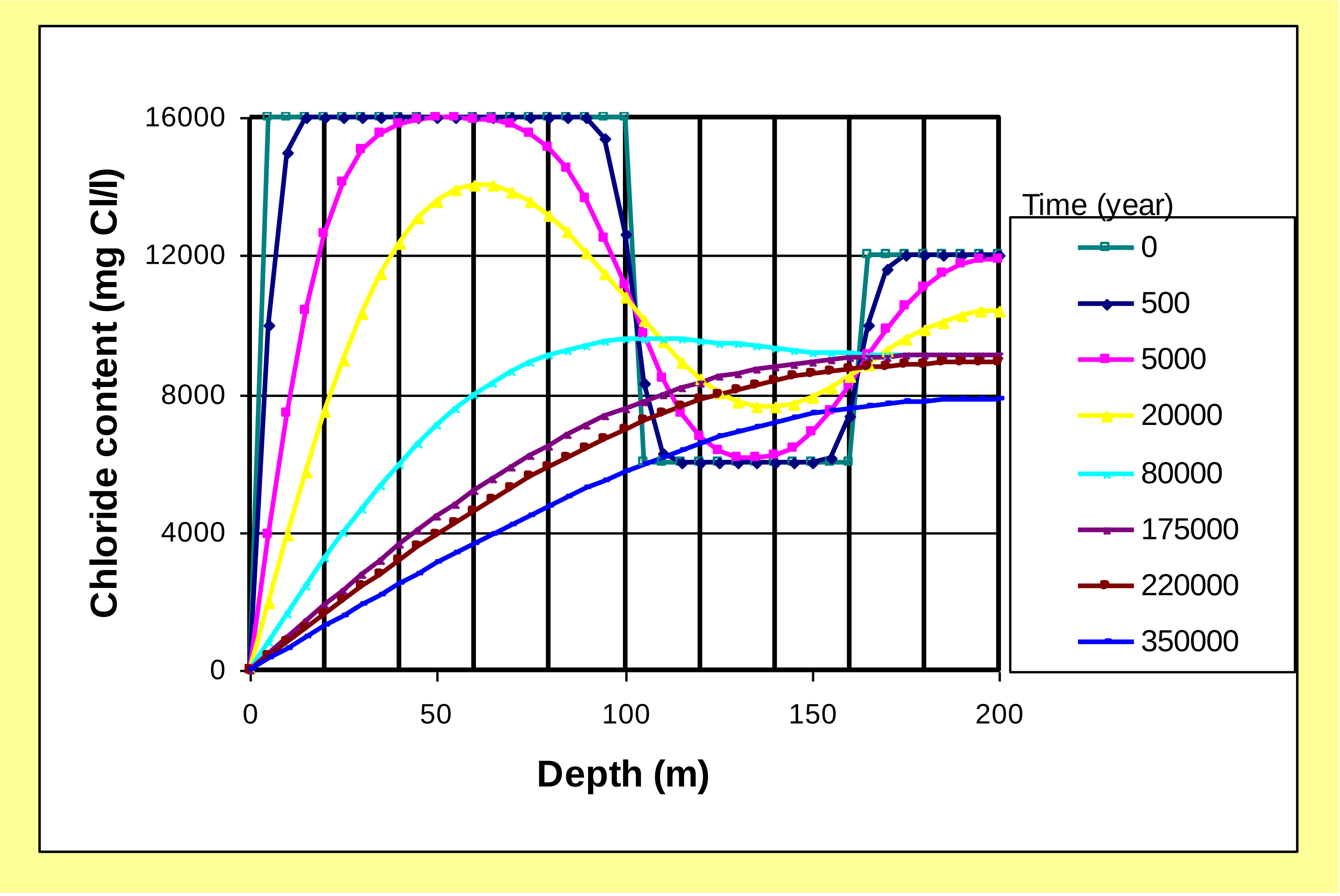
$$S\frac{\partial \phi}{\partial t} = T\frac{\partial^2 \phi}{\partial x^2} + N \qquad \frac{T\Delta t}{S\Delta x^2} < 0.5$$

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

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

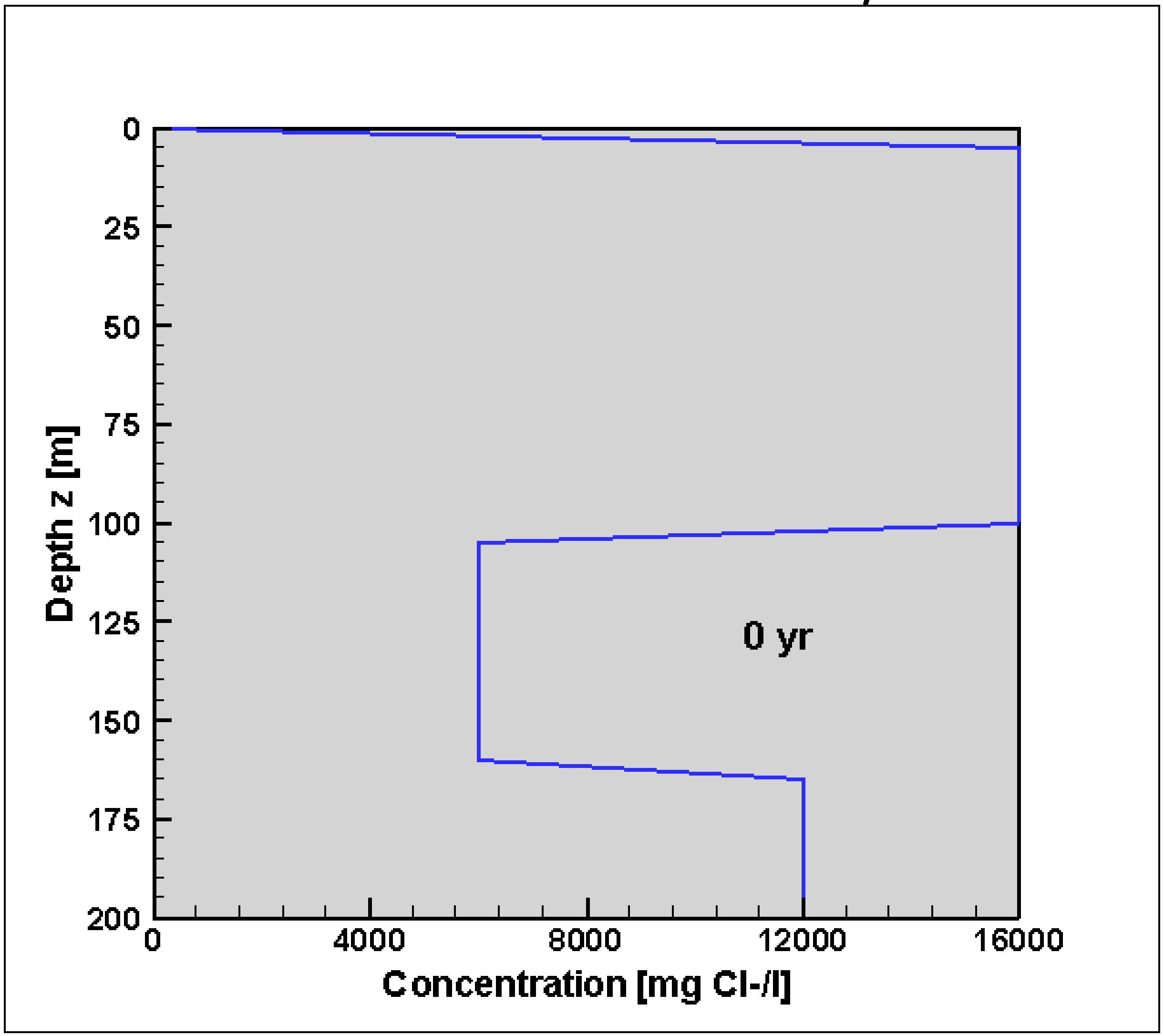
Solute transport equation: diffusion (II)

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



Solute transport equation: diffusion (III)

Animation as a function of 350.000 years



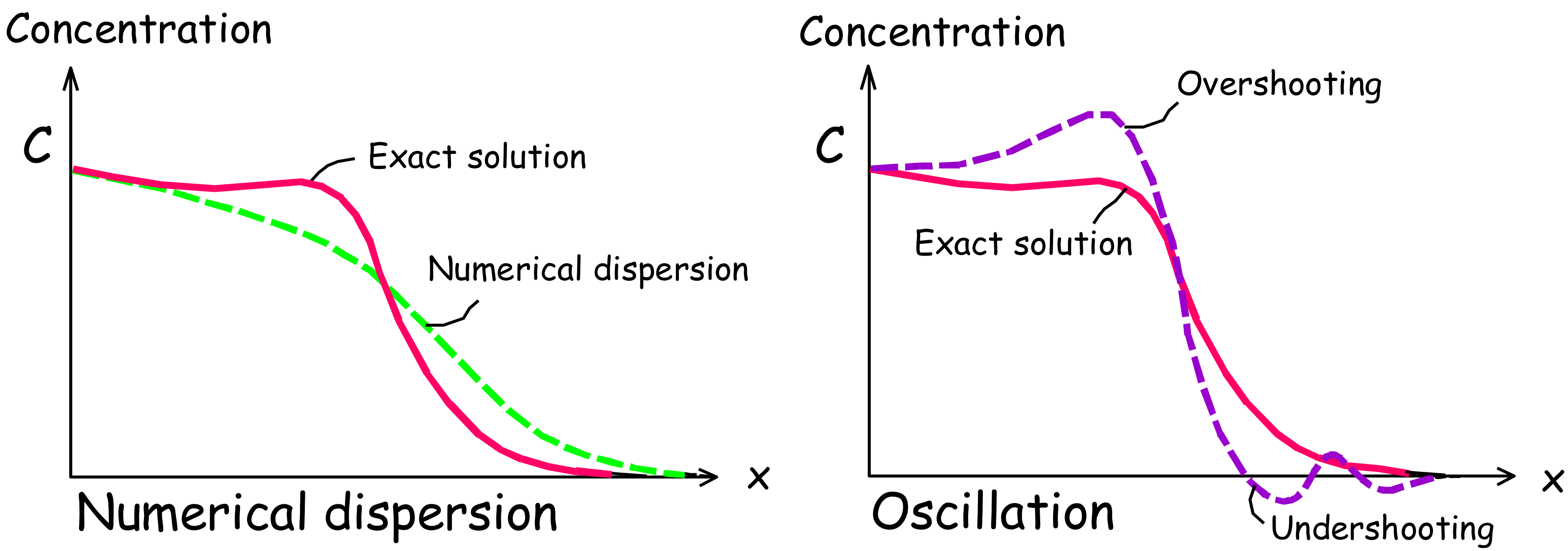
Stability criteria for solute transport equation (I)

1. Neumann criterion:

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

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

Numerical dispersion and oscillation



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

Stability criteria for solute transport equation (II)

2. Mixing criterion:

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

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

Stability criteria for solute transport equation (III)

3. Courant criterion:

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

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

Stability criteria (III)

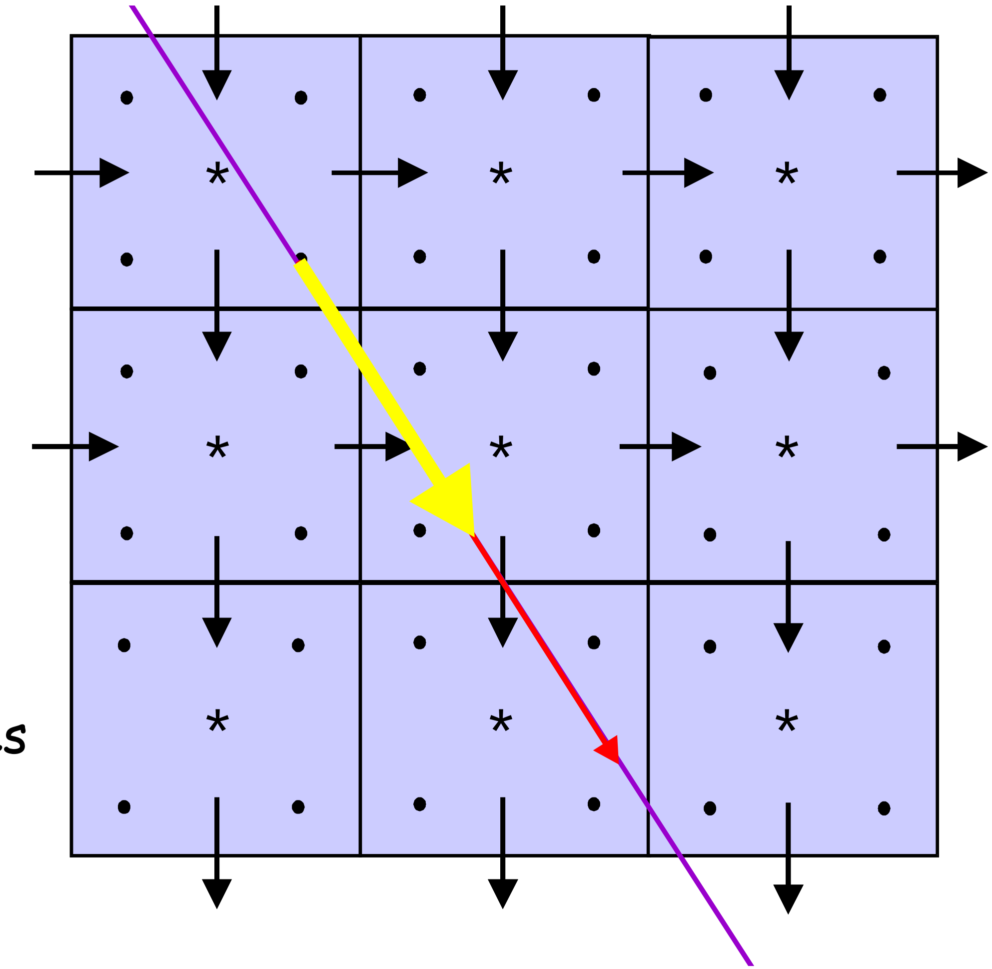
3. Courant criterium

* Node element

• Particle

Velocity direction

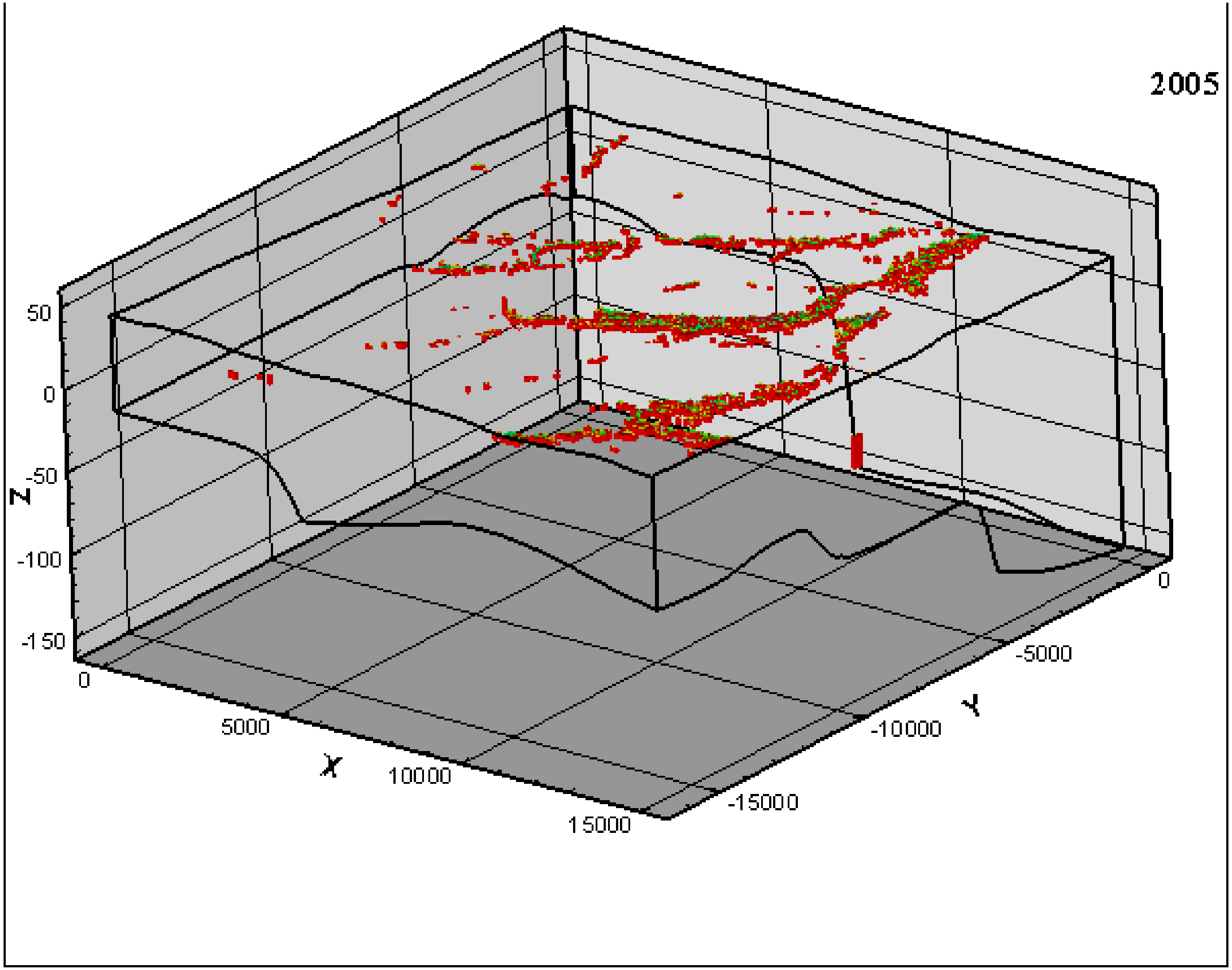
Movement particles



0<x<=~1

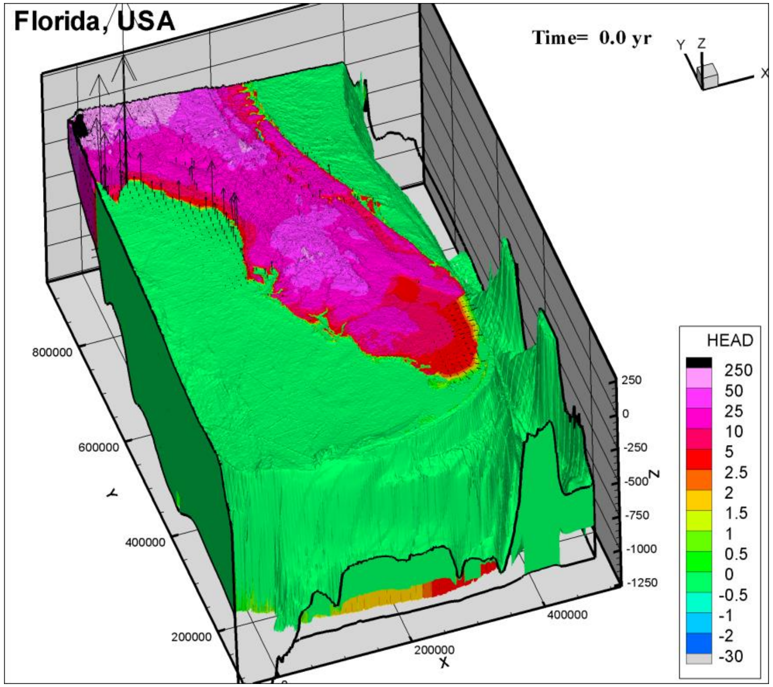
$$\Delta t_s \leq \frac{\xi \Delta x}{V_{x,\max}} \qquad \Delta t_s \leq \frac{\xi \Delta y}{V_{y,\max}} \qquad \Delta t_s \leq \frac{\xi \Delta z}{V_{z,\max}}$$

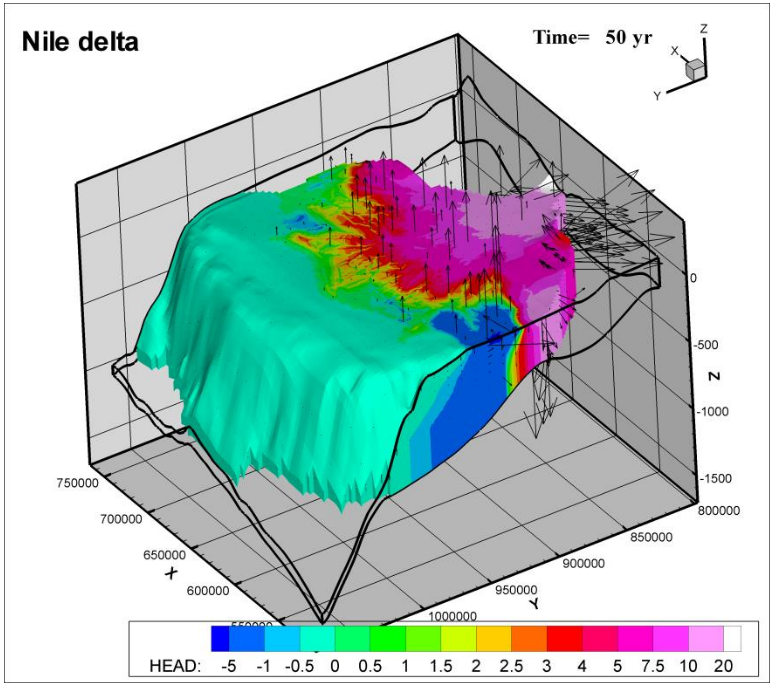
Courant criterion: places where timestep is smaller than 40 days

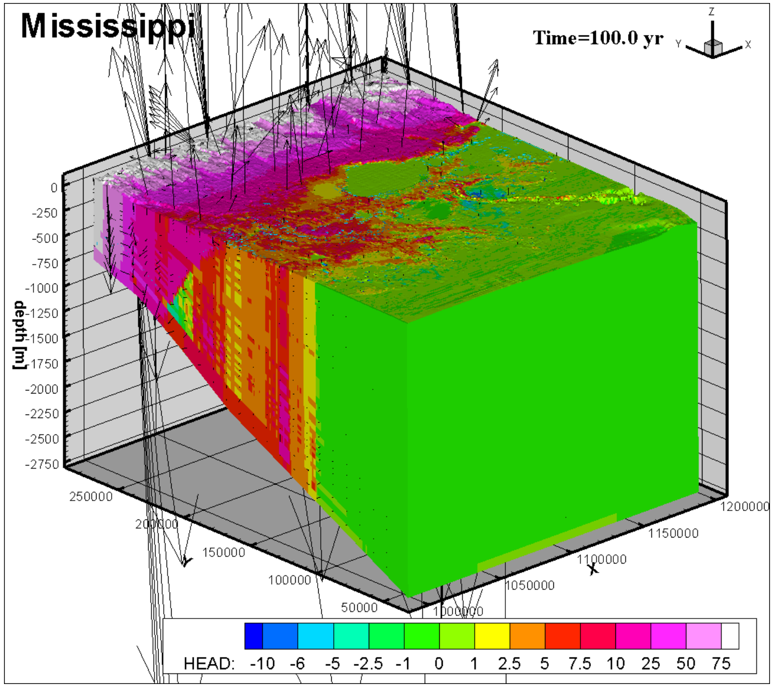


Check the velocity field!

Tool: tecplot / paraview

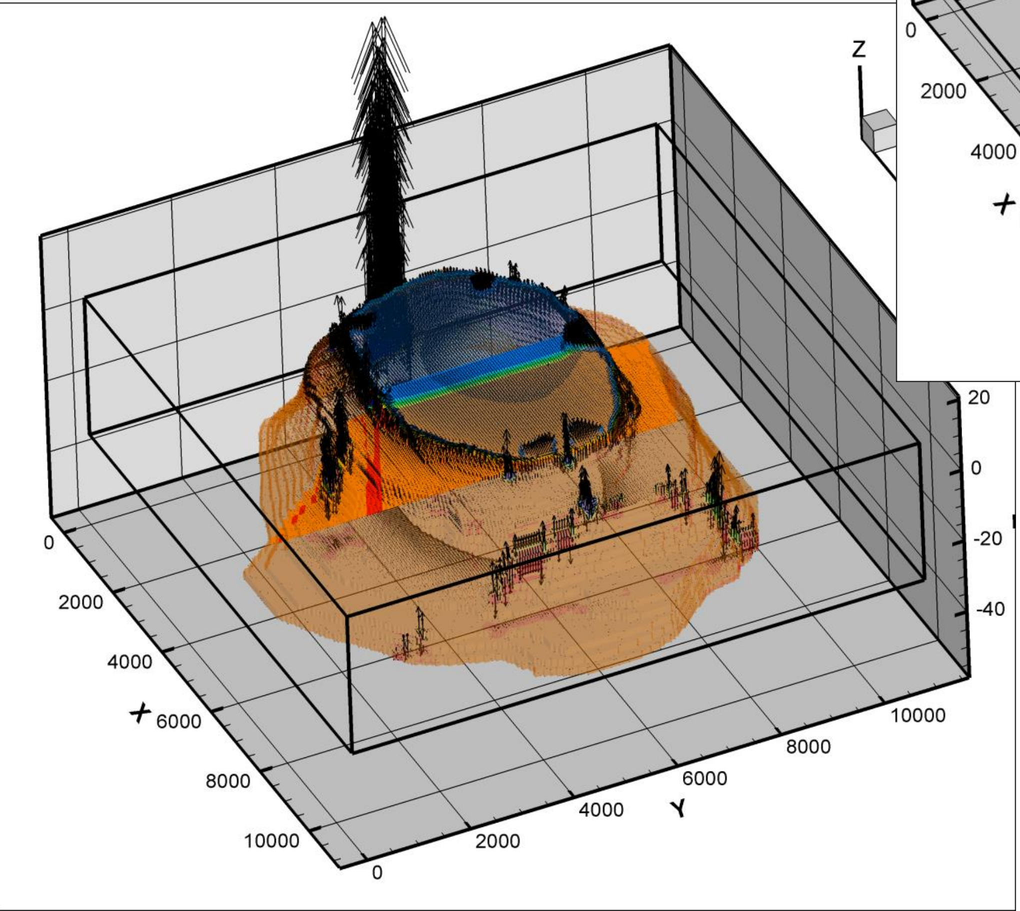


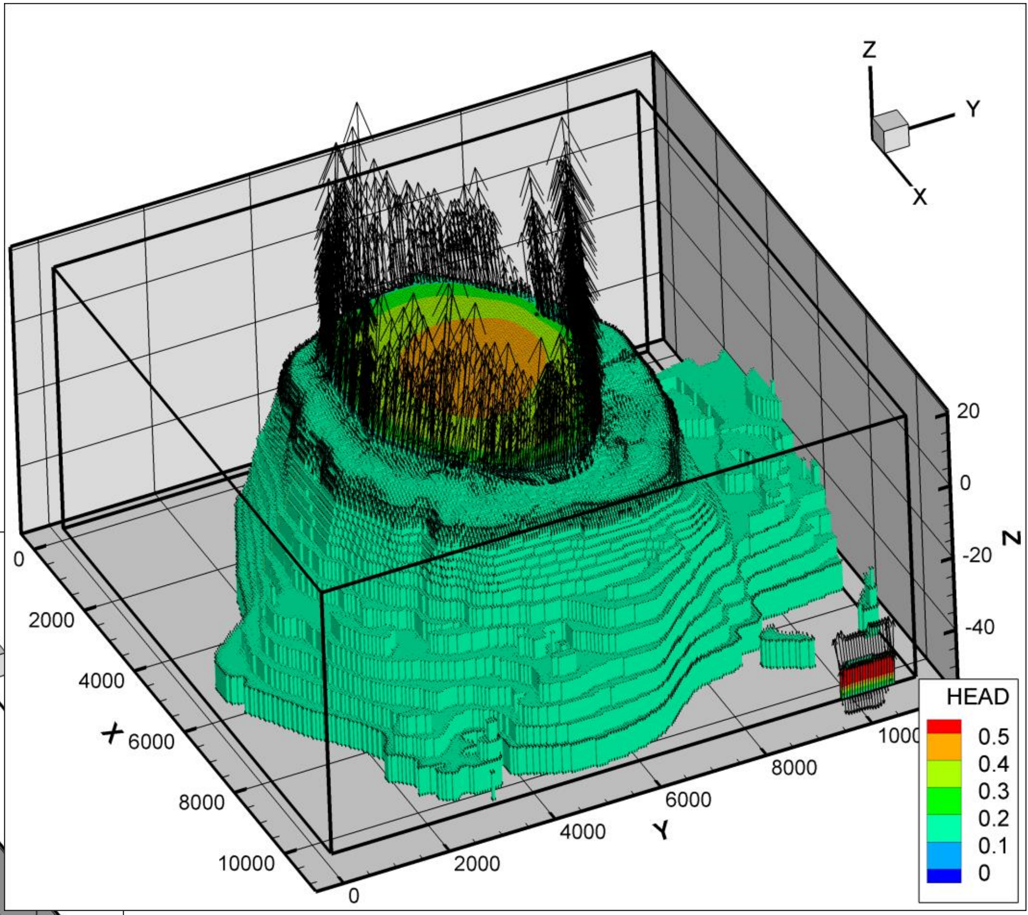




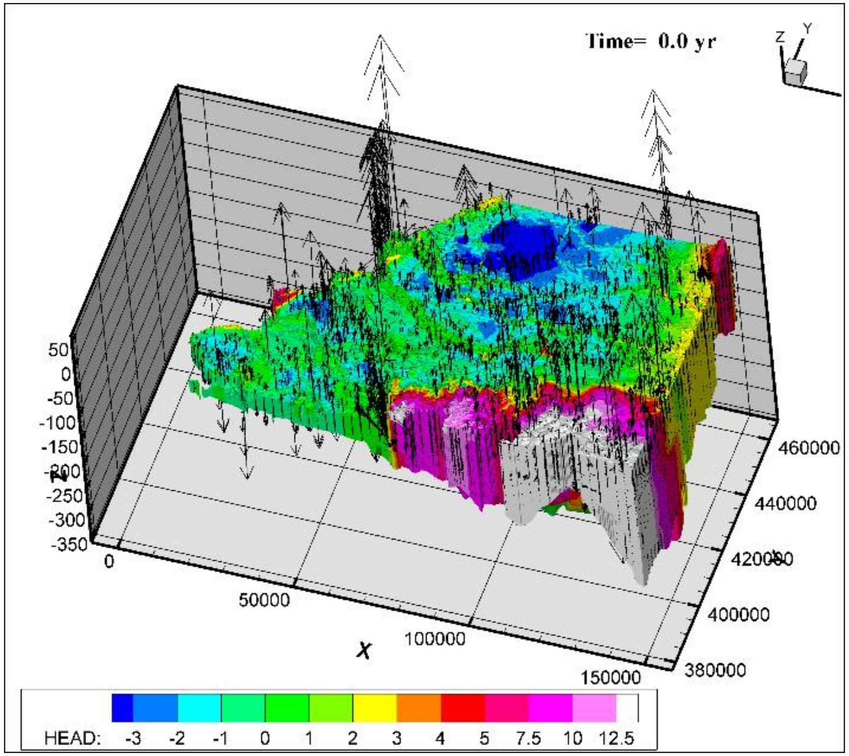
Case Nippon Koei:

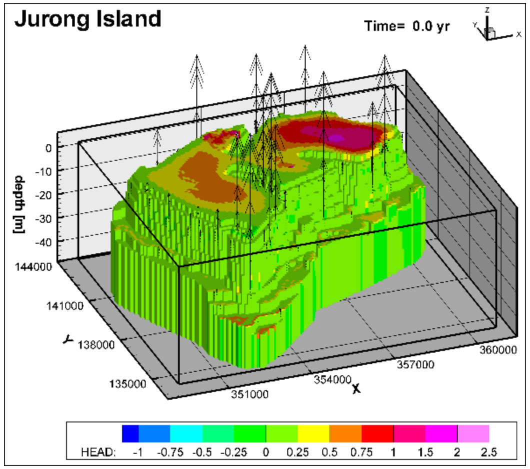
parallel version

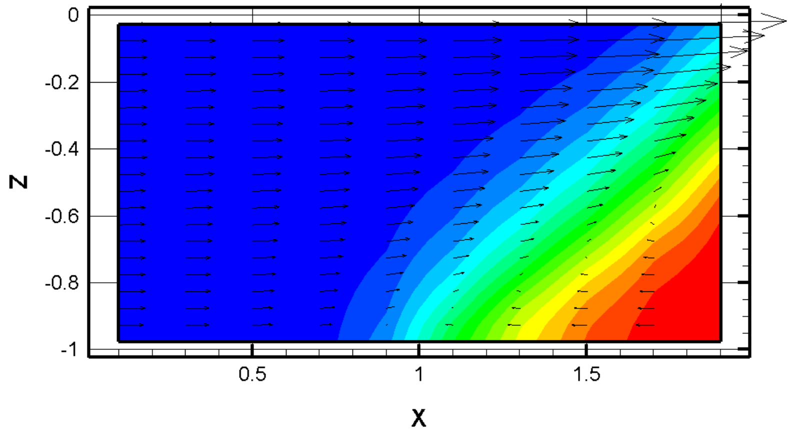


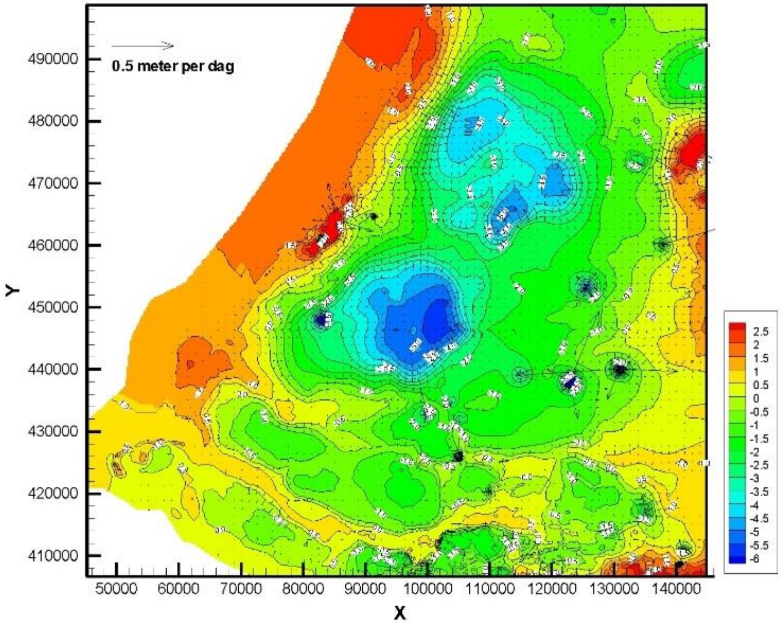


Check the velocity field!



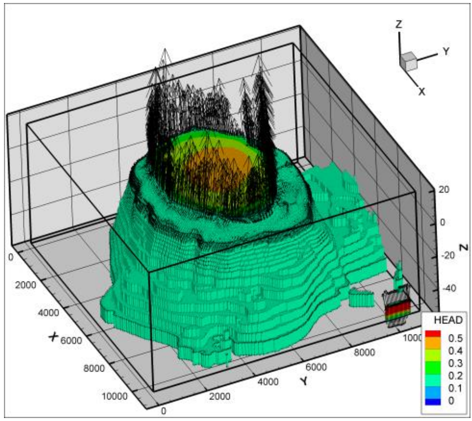


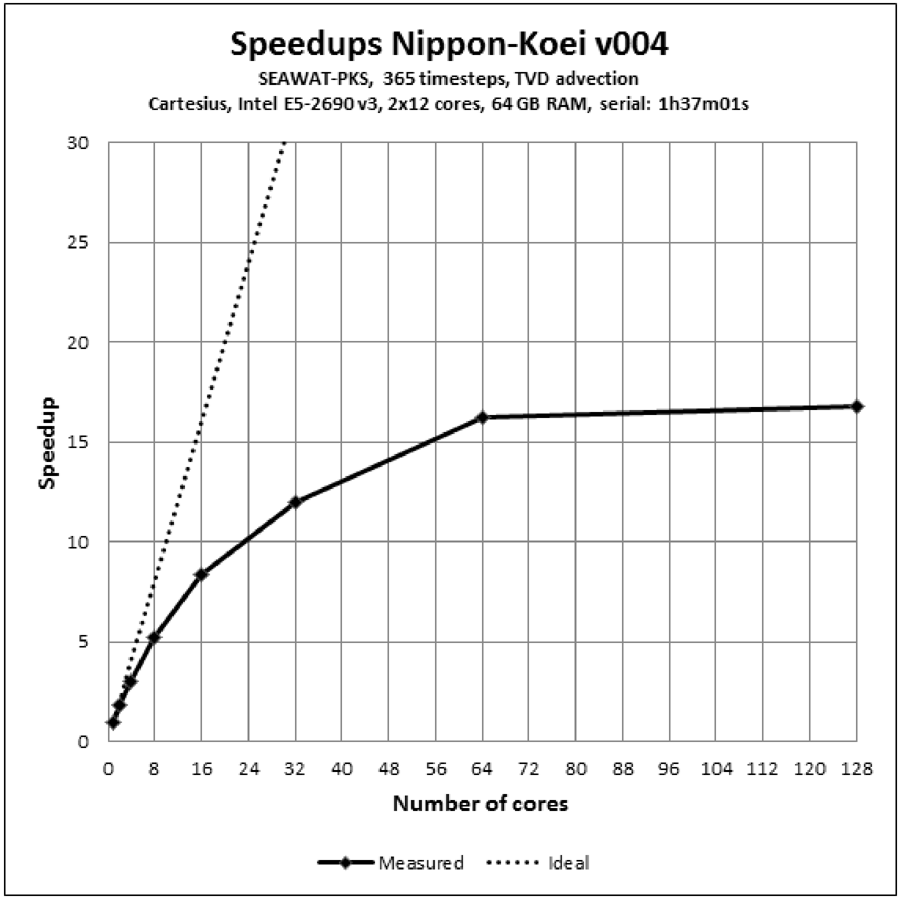


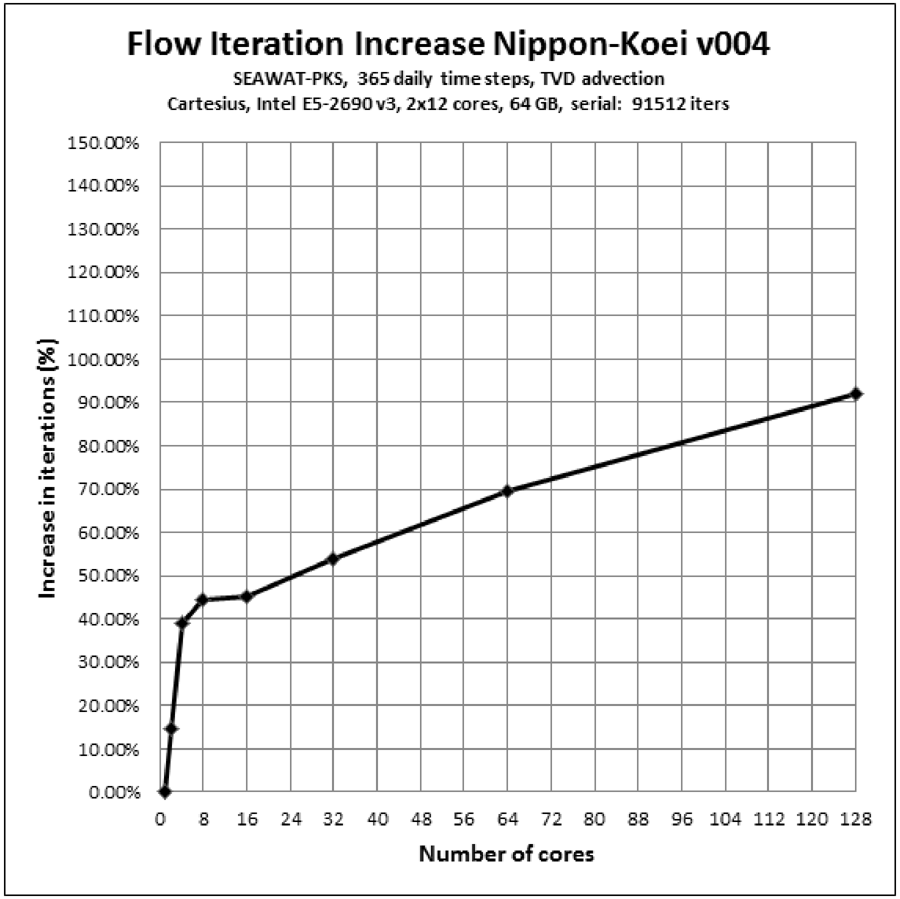


Case Nippon Koei:

parallel version

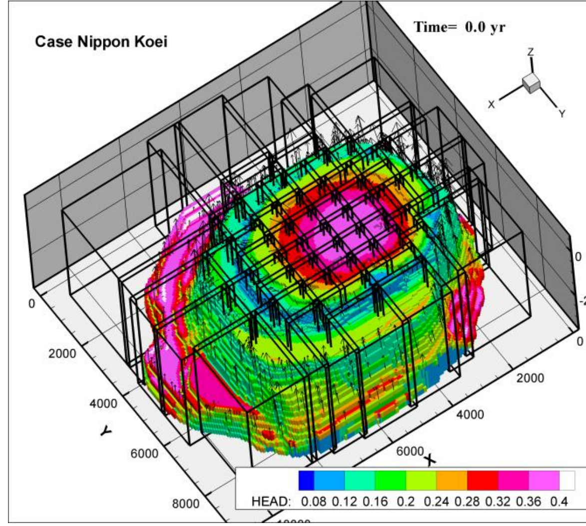


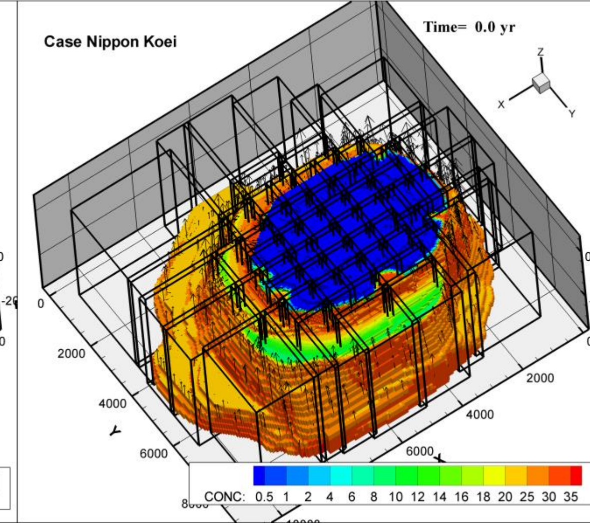




Case Nippon Koei:

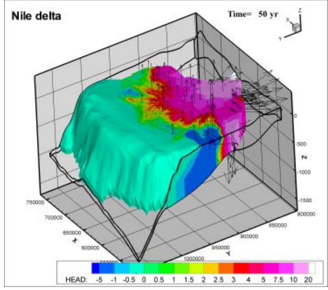
parallel version

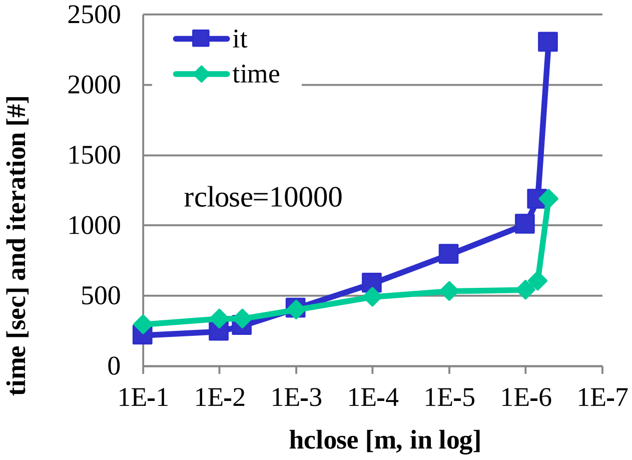


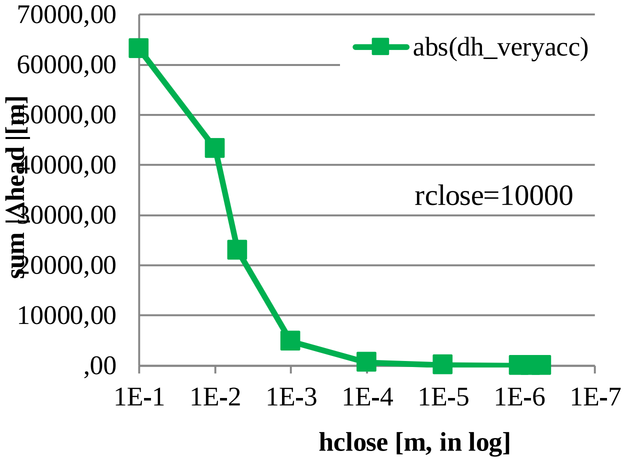


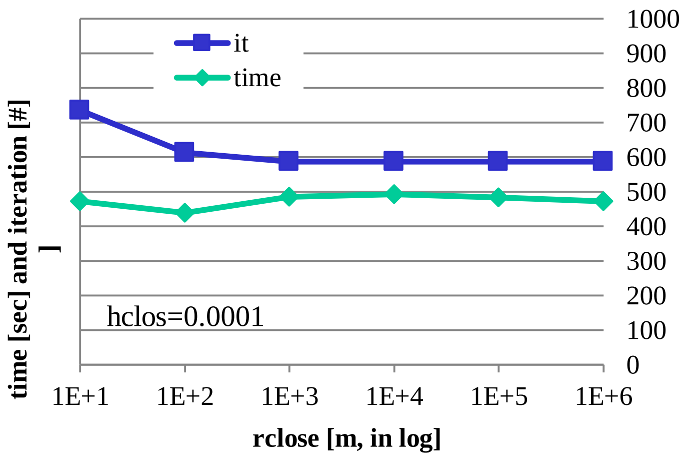
Name	seawat005_gv23	seawat006_gv23	seawat-3-004	seawat-3-004	seawat-3-004
parallel	no	no	no	yes	yes
name 'nam' file	gv23	gv23	gv23	gv23	gv23
software	SEAWAT	SEAWAT	SEAWAT	iMOD-SEAWAT	iMOD-SEAWAT
computer	Quad 2.60 GHz	Quad 2.60 GHz	Quad 2.60 GHz	Cartesius 1 core	Cartesius 64 cores
date input data	21-11-17	08-12-17	21-12-2017	21-12-2017	21-12-2017
calc.time	5d0h36m43s	0d10h2m52s	0d6h41m14s	~0d1h30m0s	0d0h5m59s
speedup factor	1	12.0	18.0	44.0	1209.5

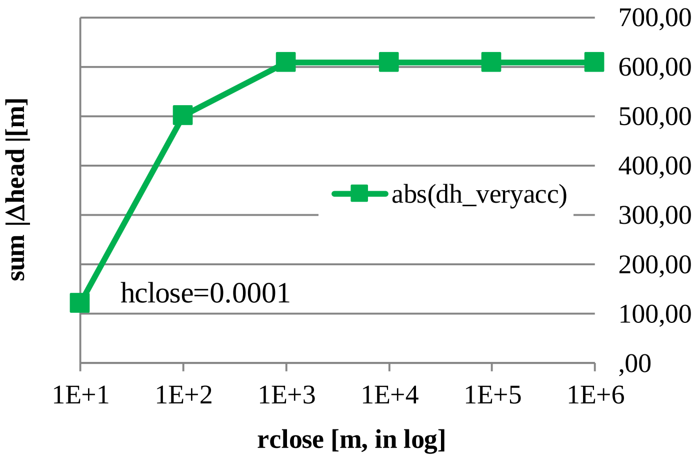
hclose, rclose (Nile Delta model)



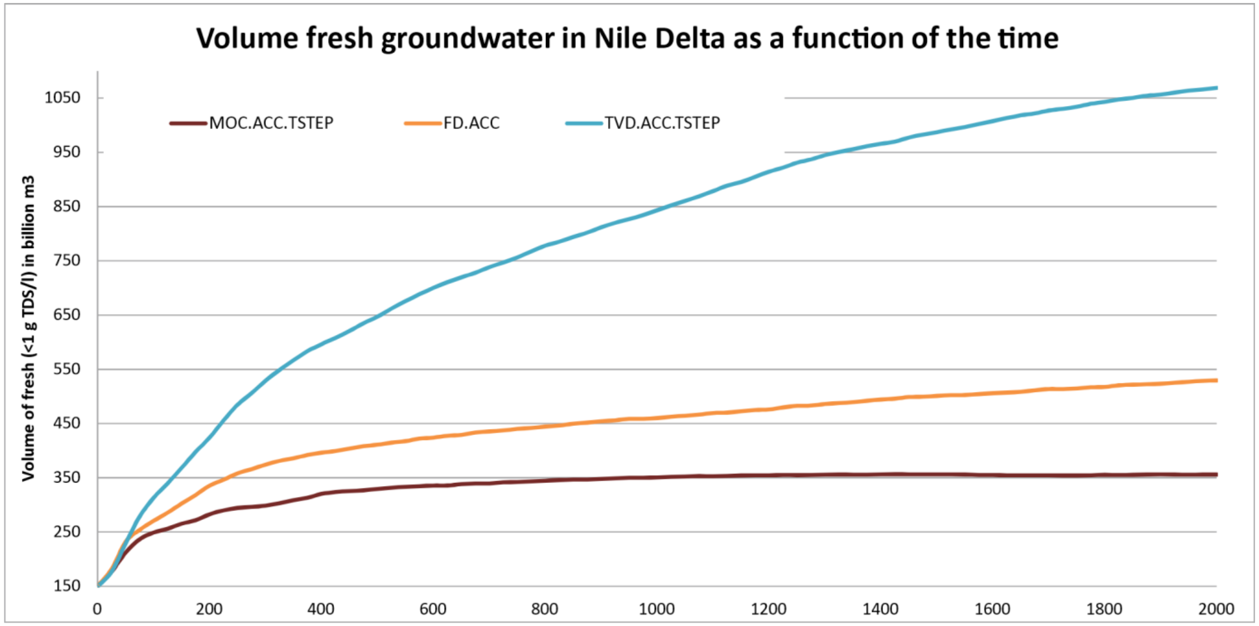








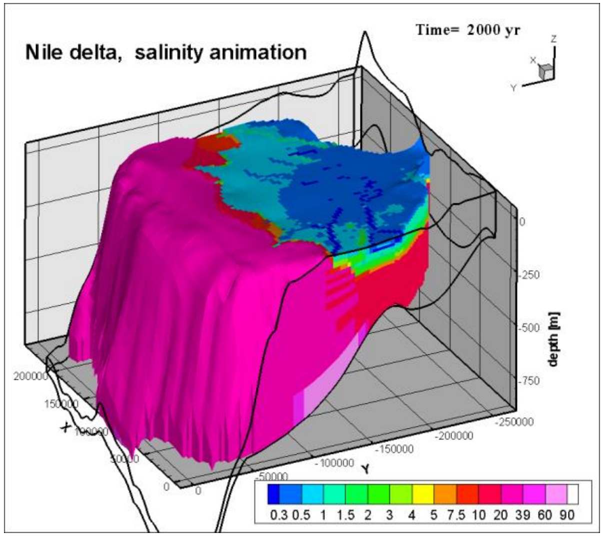
Test your SEAWAT SOLVERS

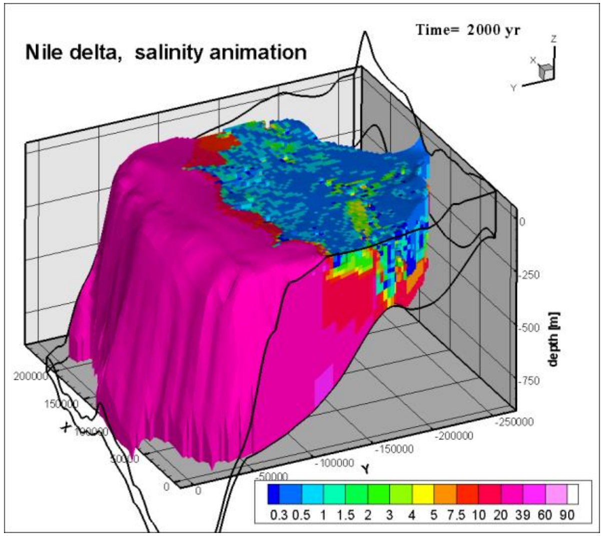


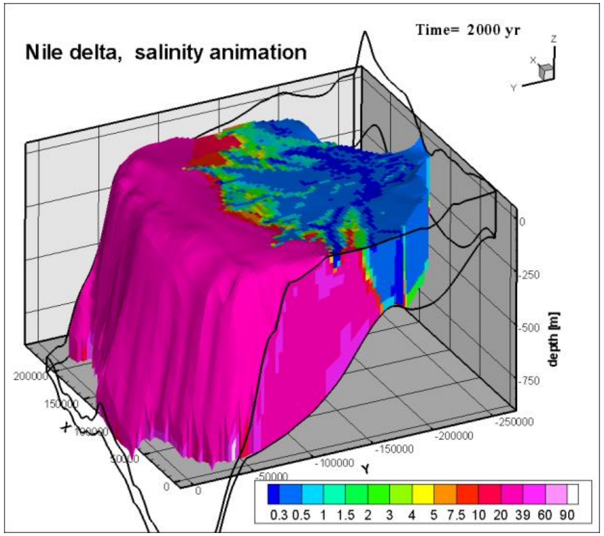
MOC.ACC.TSTEP

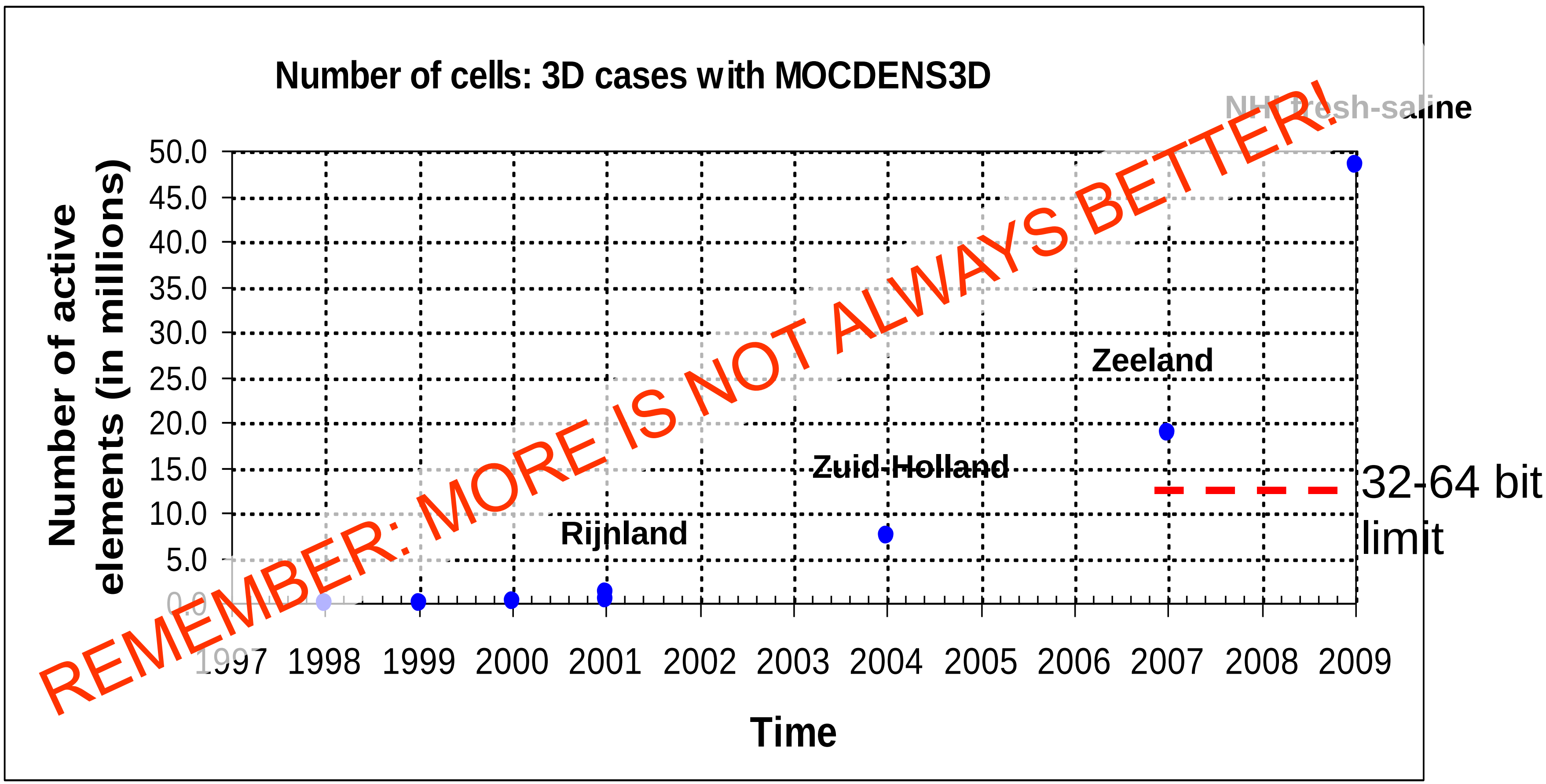
FD.ACC

TVD.ACC.TSTEP









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

Modelling effect climate change on fresh-salt groundwater

Modelling:

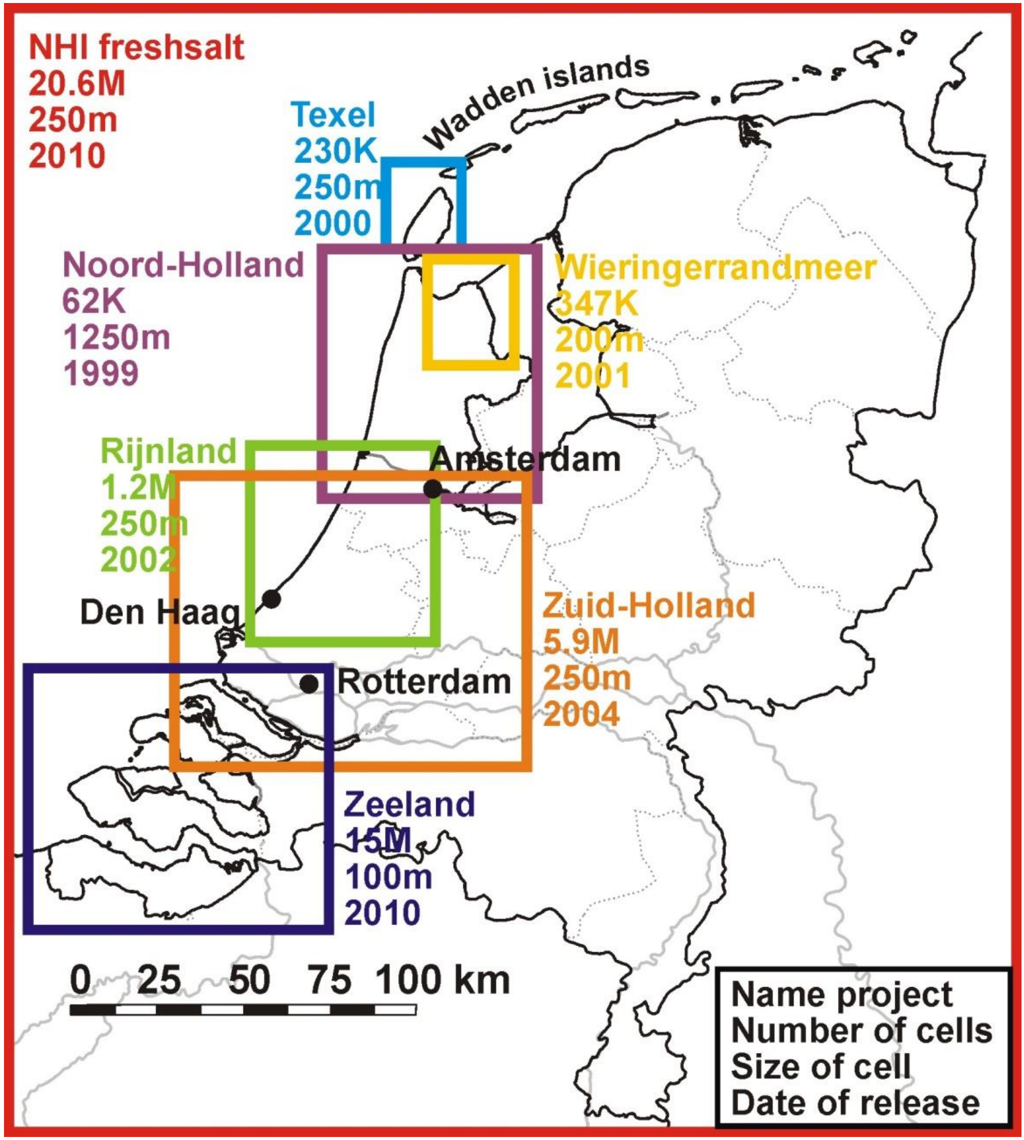
- variable-density
- 3D, non-steady
- groundwater flow
- coupled solute transport

Code:

MOCDENS3D (MODFLOW family) similar to SEAWAT

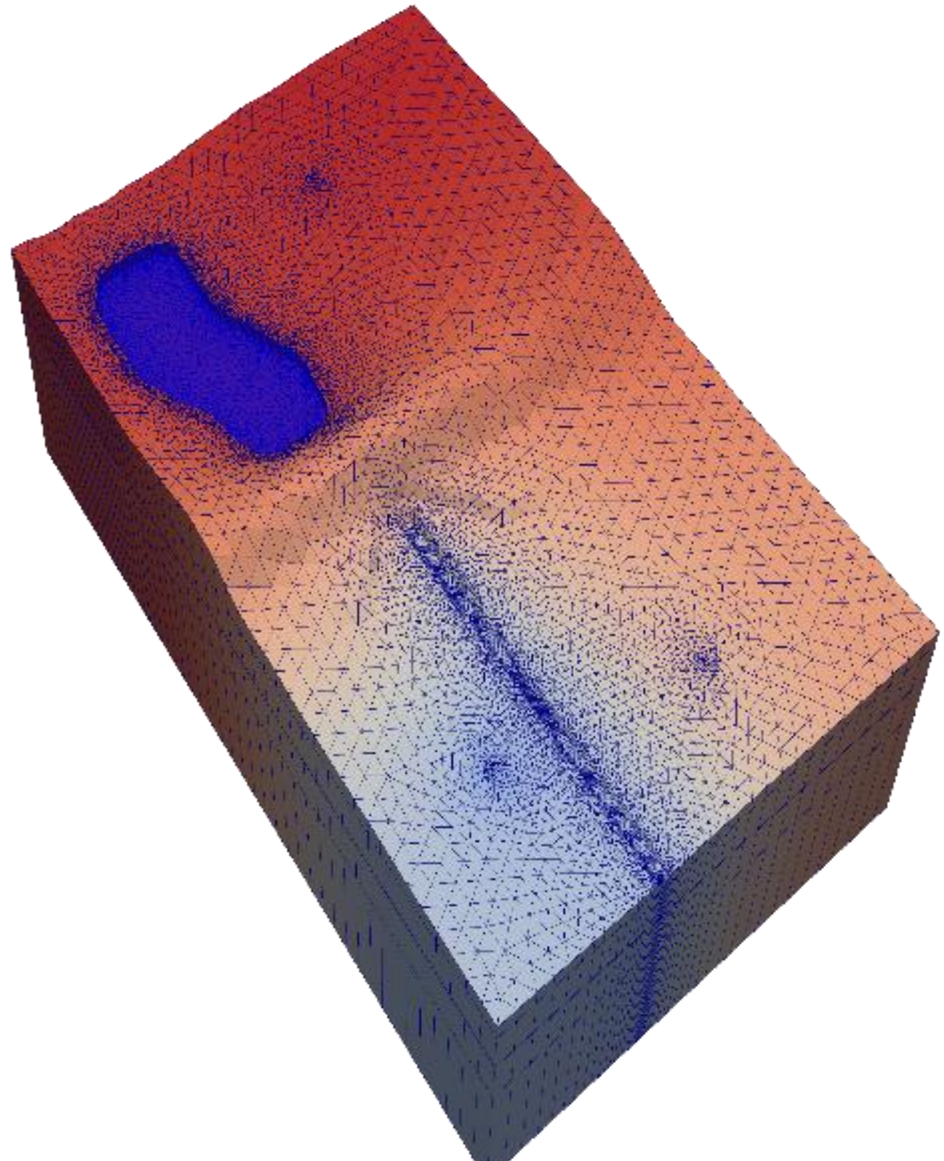
Assessing effects:

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



MODFLOW 6: fresh-salt

- Detail / computer power where needed (extractions/ surface water)
- Unstructured grid
- XT3D package for full 3D anisotropy

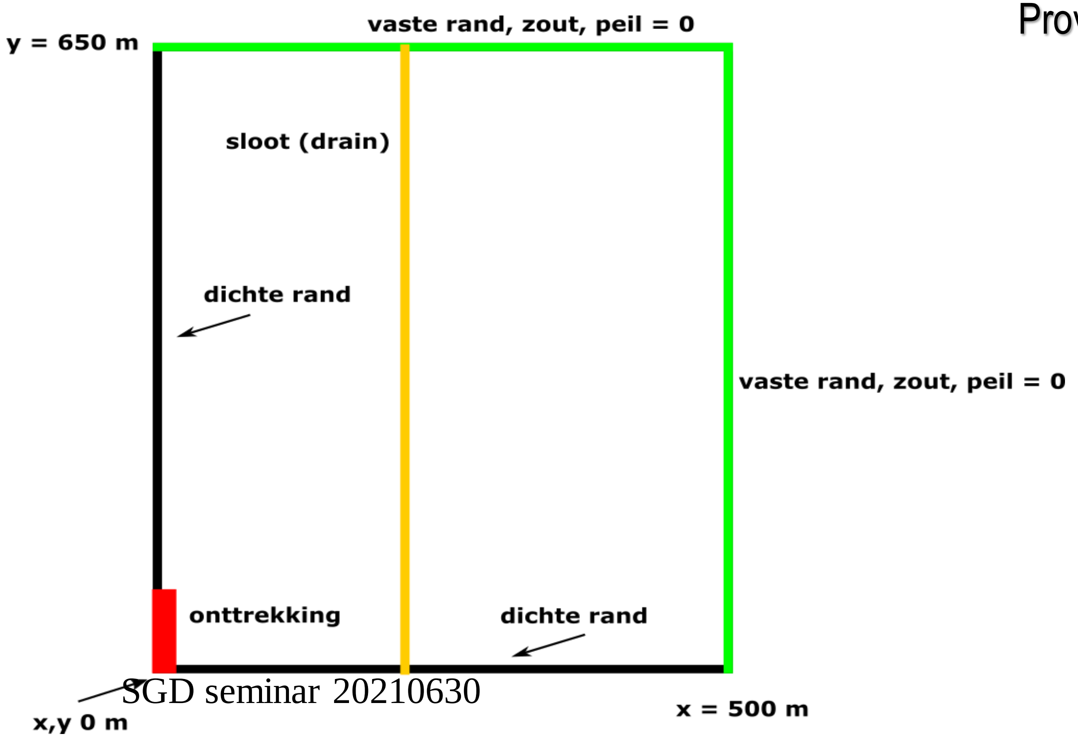


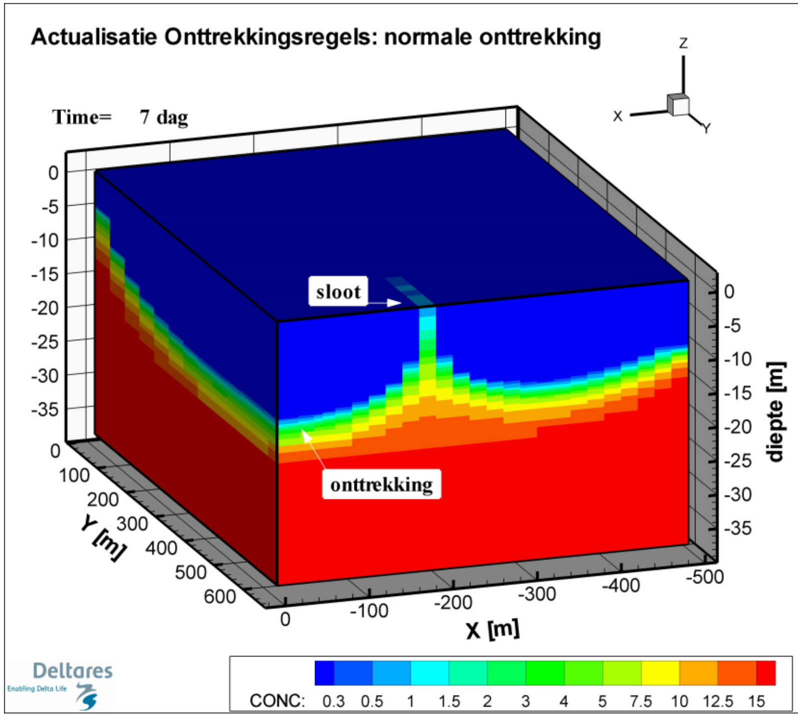
0

Performed activities

- Code from Github and compiled it (september 2018)
- Built a test model in MF6 with structured and unstructured grid, to compare with SEAWAT v4.

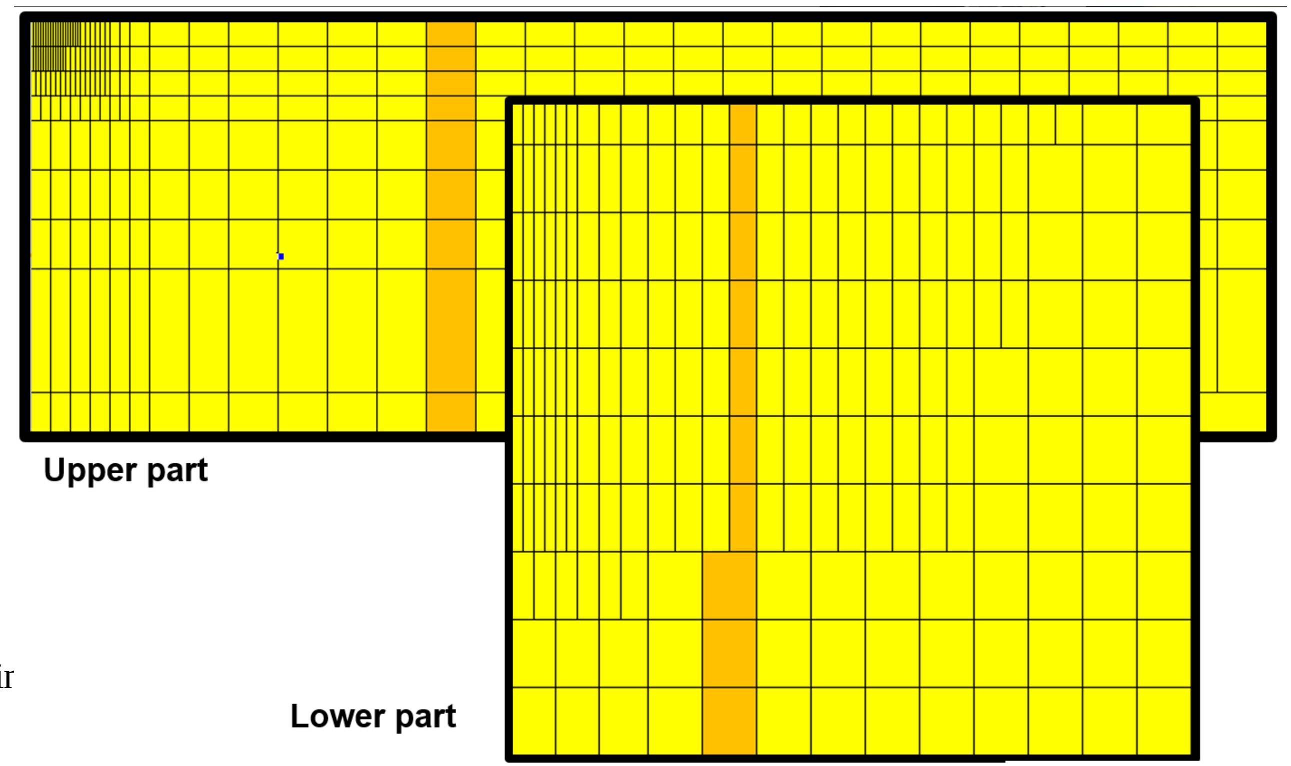
Case: 3D Model as used in Oude Essink & Pauw (2018) for the derivation of extraction rules for the Province of Zeeland



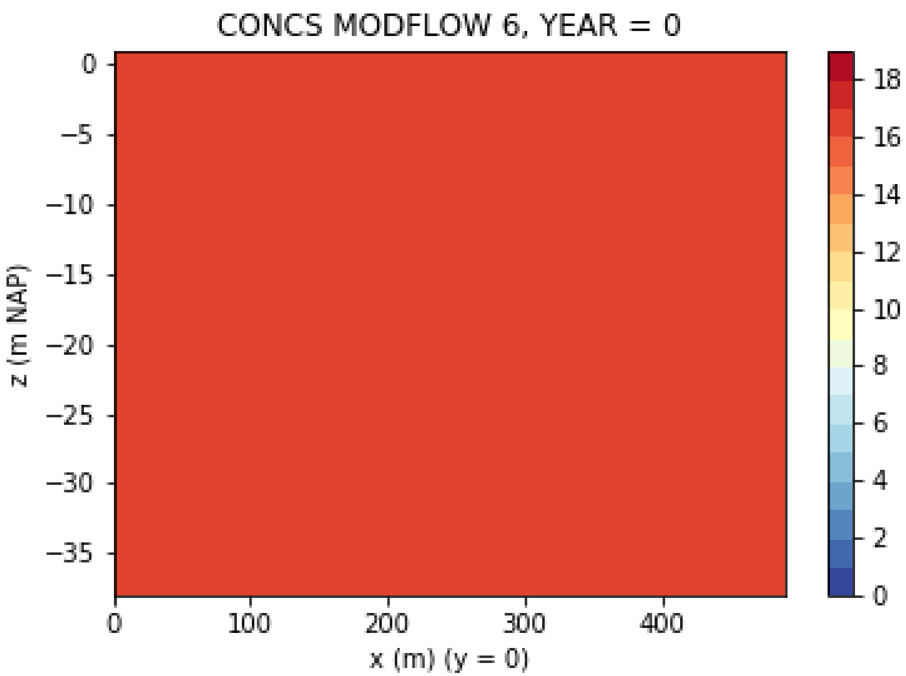


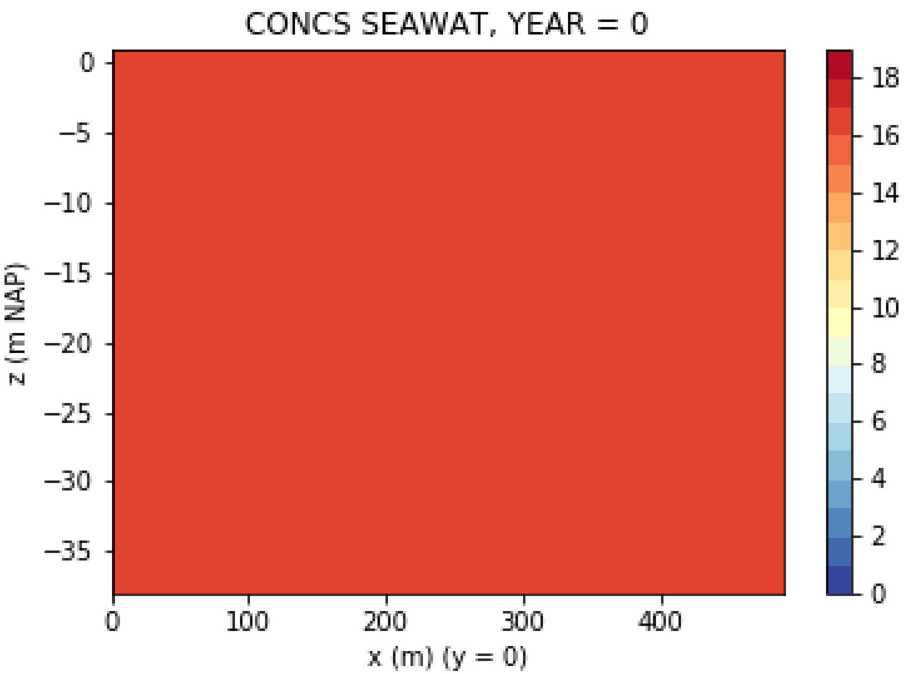
Testing different grids and run times in this 3D synthetic case

- Original grid: 77112 cells (already optimized using non-equidistant grid)
- Unstructured grid: 40068 cells
- Therefore reduced simulation times are expected, but large velocities around e.g. extraction wells limit practical applications



Regular grid, with density effects



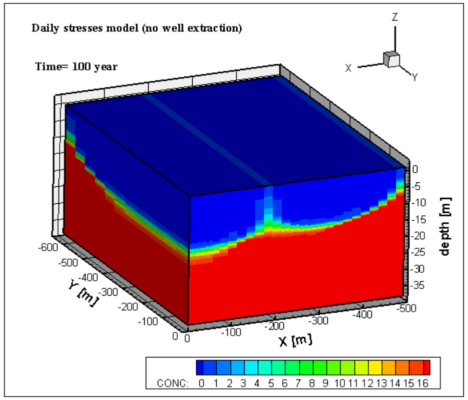


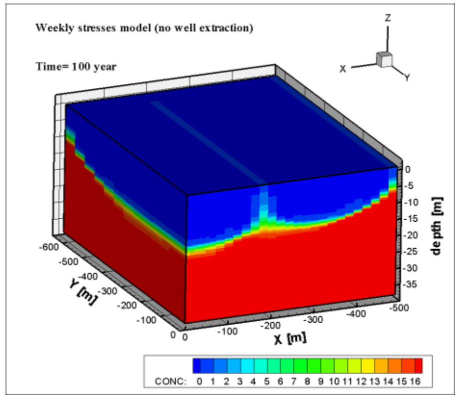
MF6

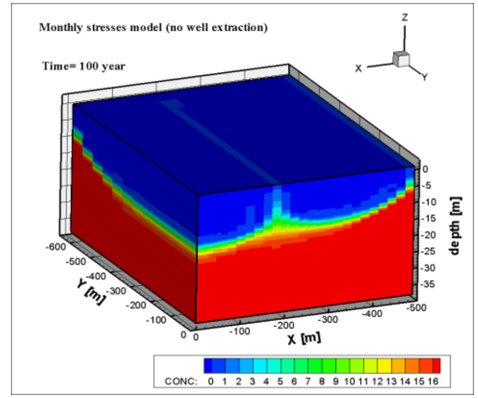
SEAWAT v4

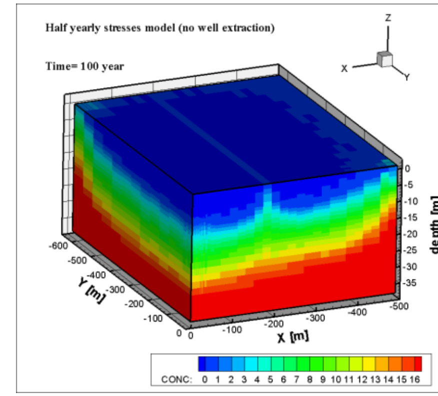
To be continued…

MODFLOW6: Effect temporal discretisation

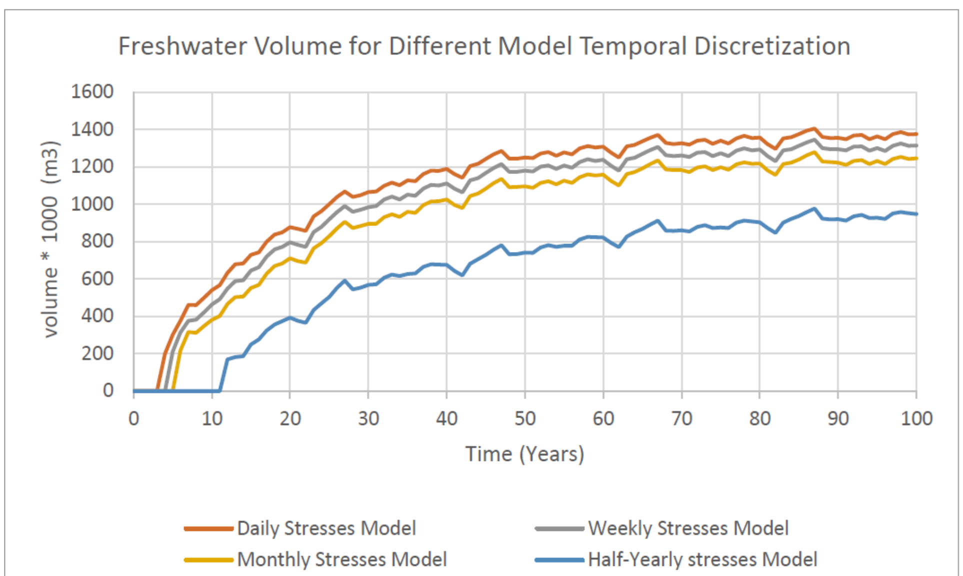


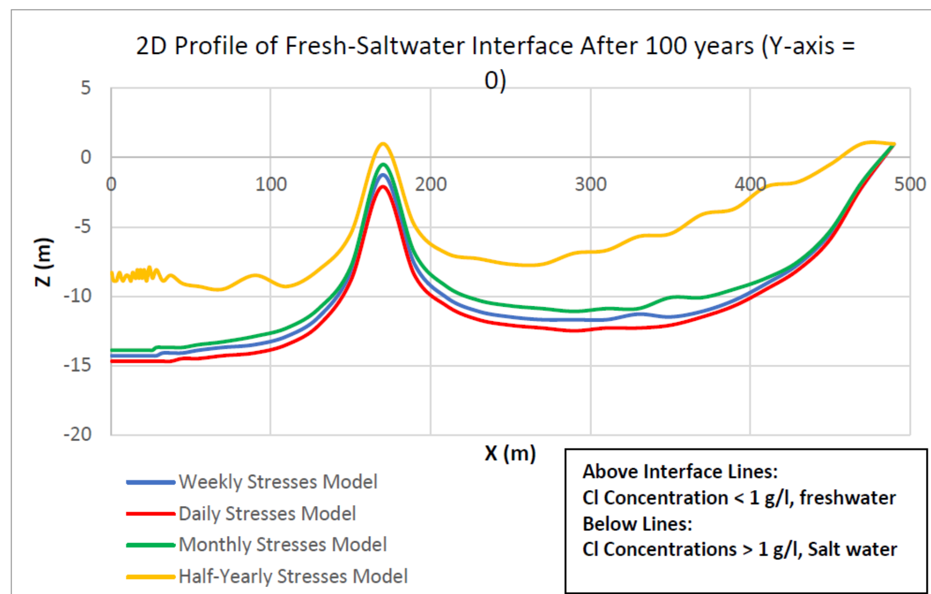




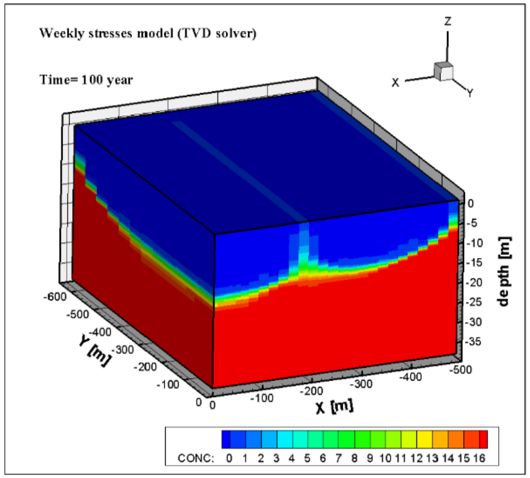


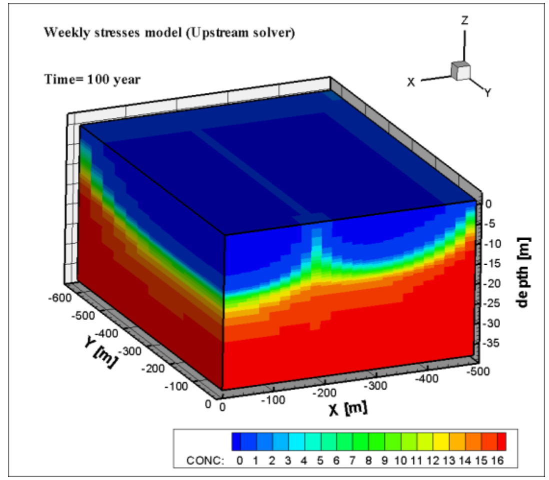
Daily Weekly Montly Half-yearly

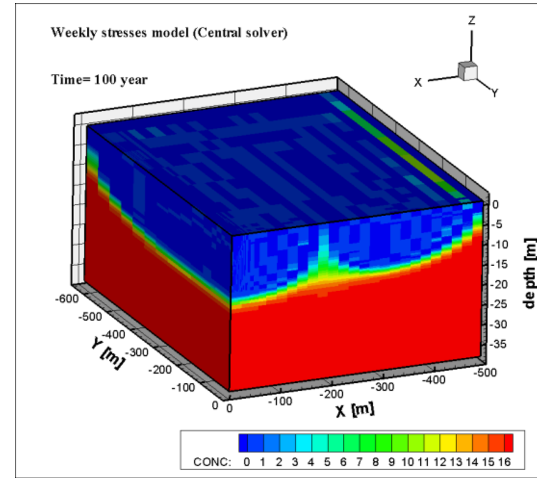




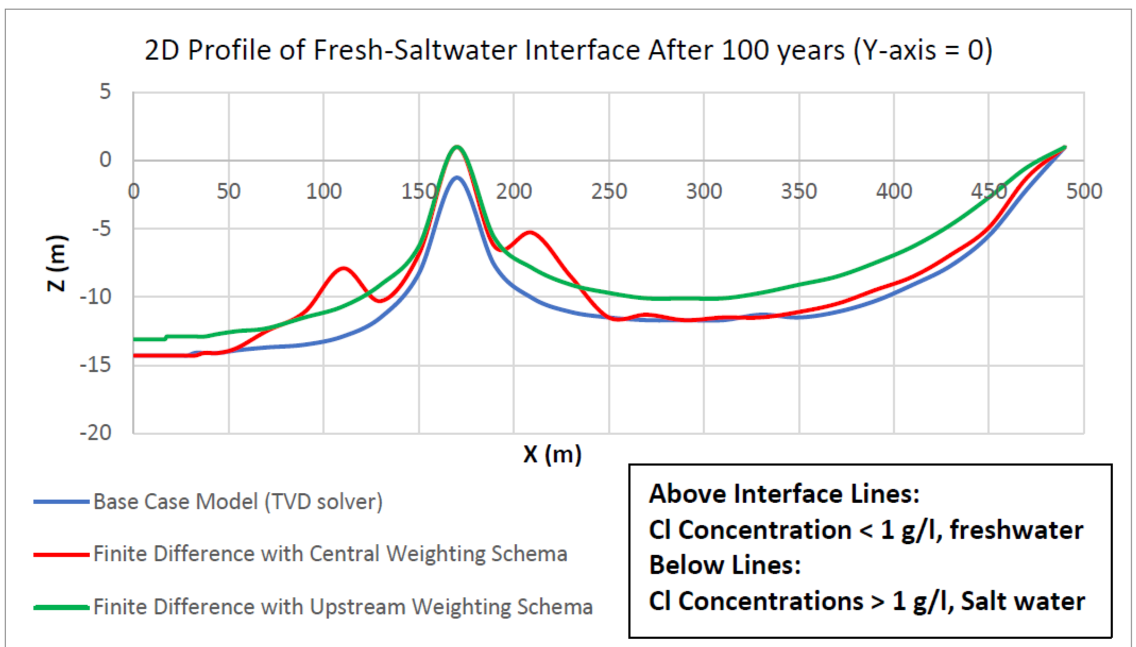
MODFLOW6: Effect solver







TVD   Upstream   Central in Space



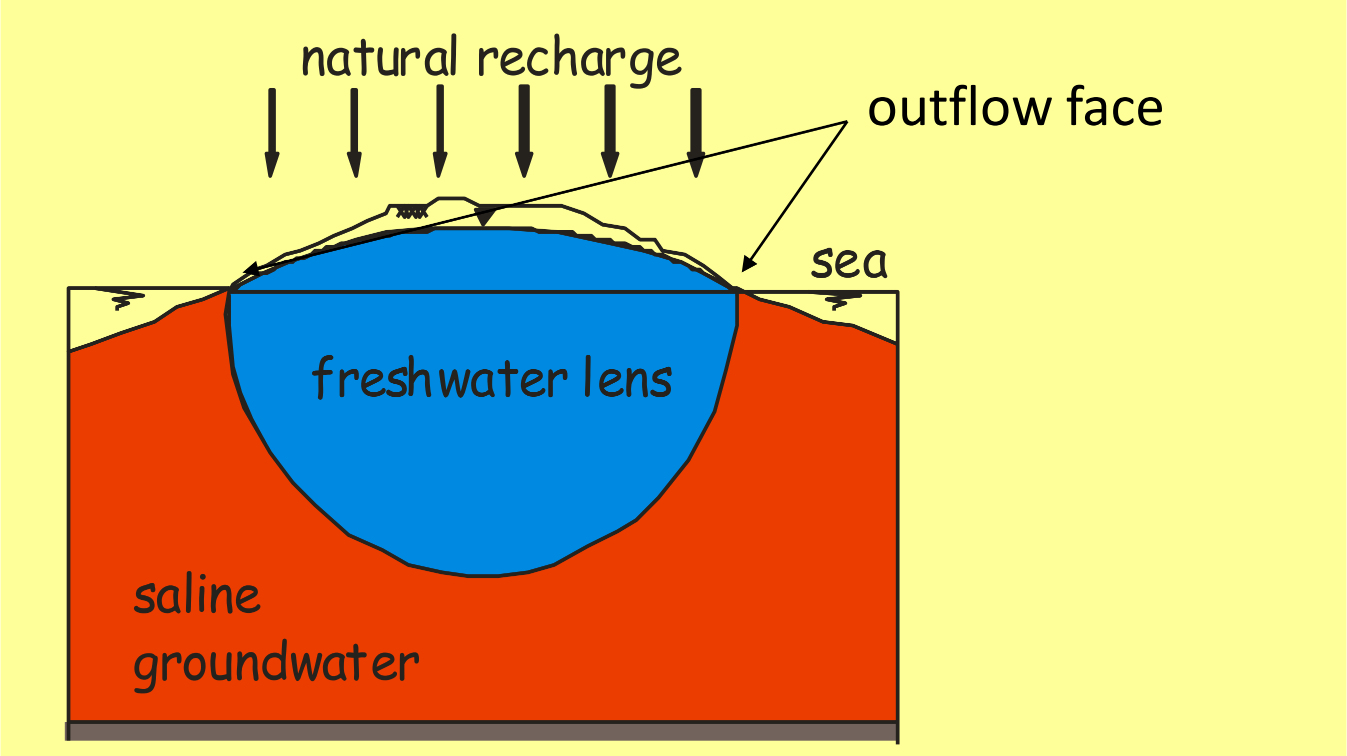
Fields of application of fresh-saline groundwater models

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

Difficulties with variable density groundwater flow

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

Outflow face at the coast is difficult to model



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

This is numerically difficult to handle

A good initial density distribution is essential

- Because groundwater and solute transport are coupled, the density influences grondwater velocities

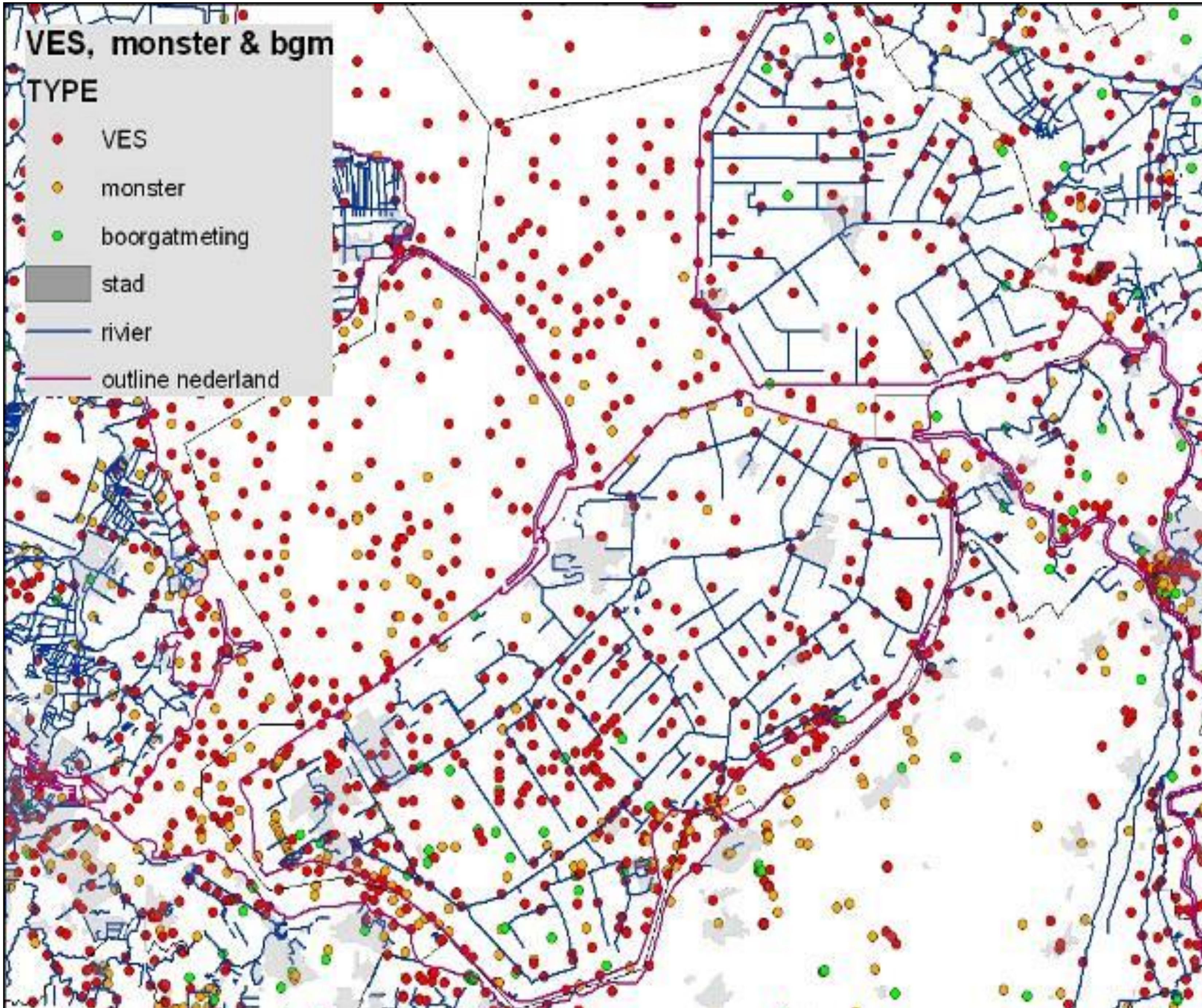
- Numerous density measurements are necessary to get a reliable 3D density matrix

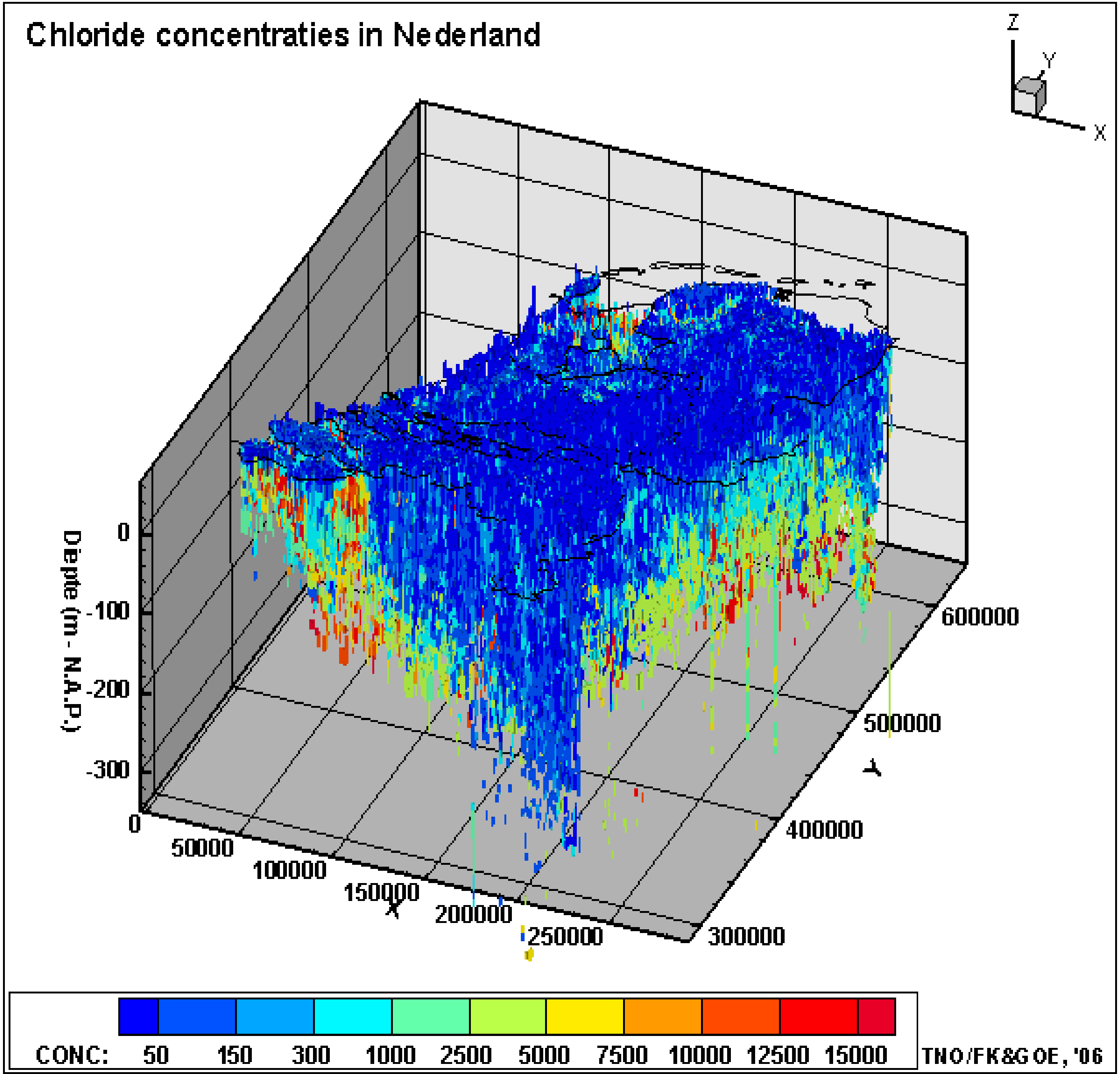
‘Procedure’ to improve initial density distribution

- Implement all chloride data
  - Analyses, Borehole, VES, Airborne techniques (HEM, SkyTem)
  - Better old then nothing
  - Better VES then nothing

- Interpolate and extrapolate
  - Sea = easy (salt)
  - Inland = fresh?

- Start with simulation (10/20/30 years) with mol.diffusion*1000 to smooth out artificial densities


VES, monster & bgm
TYPE
VES
monster
boorgatmeting
stad
rivier
outline nederland



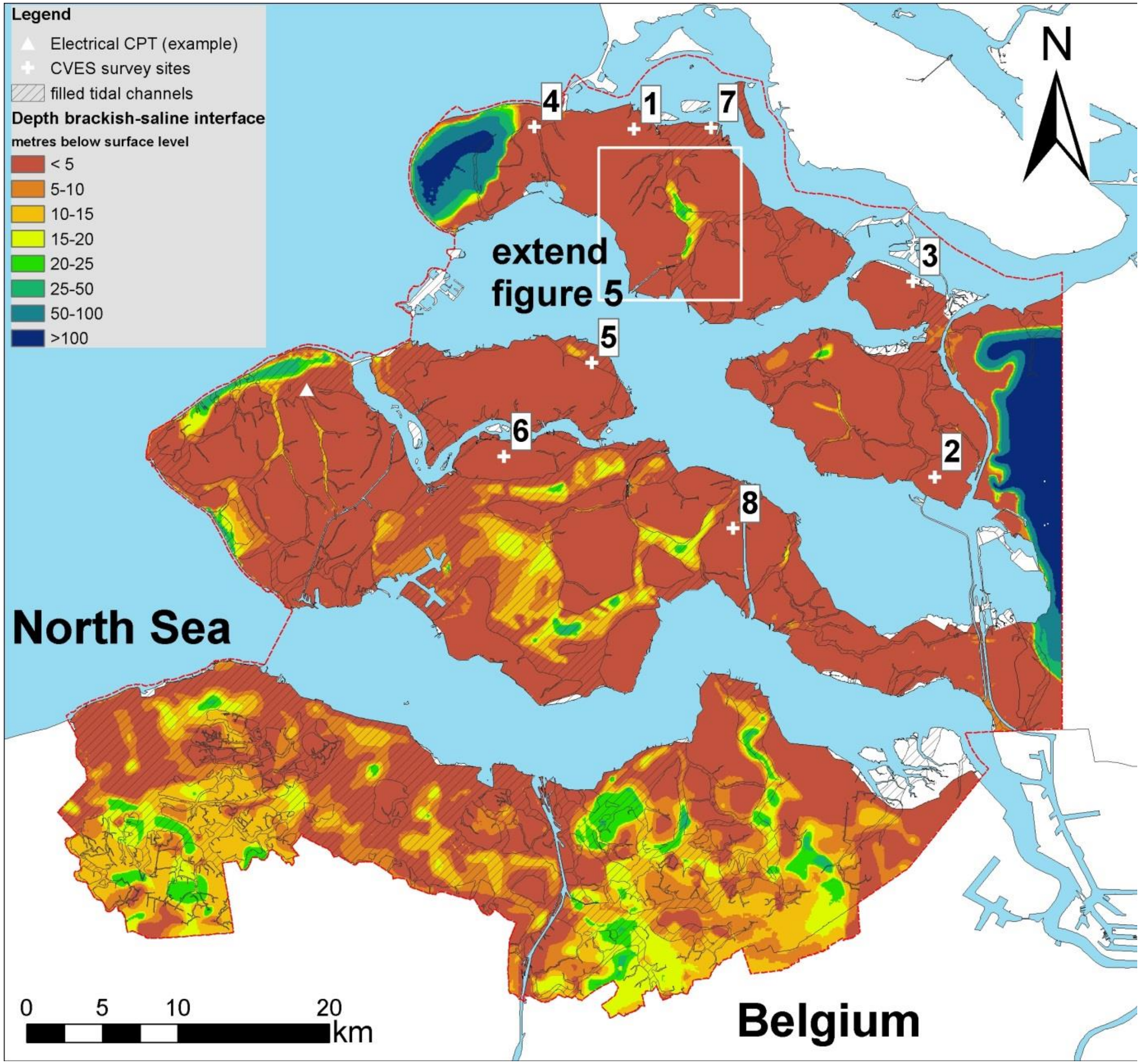
Chloride concentraties in Nederland
Z
Y
X
Diepte (m - N.A.P.)
0
-100
-200
-300
0
50000
100000
150000
200000
250000
300000
400000
500000
600000
CONC: 50 150 300 1000 2500 5000 7500 10000 12500 15000
TNO/FK&GOE, '06

Mapping brackish-saline interface Zeeland

Combining different types of data sources:

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

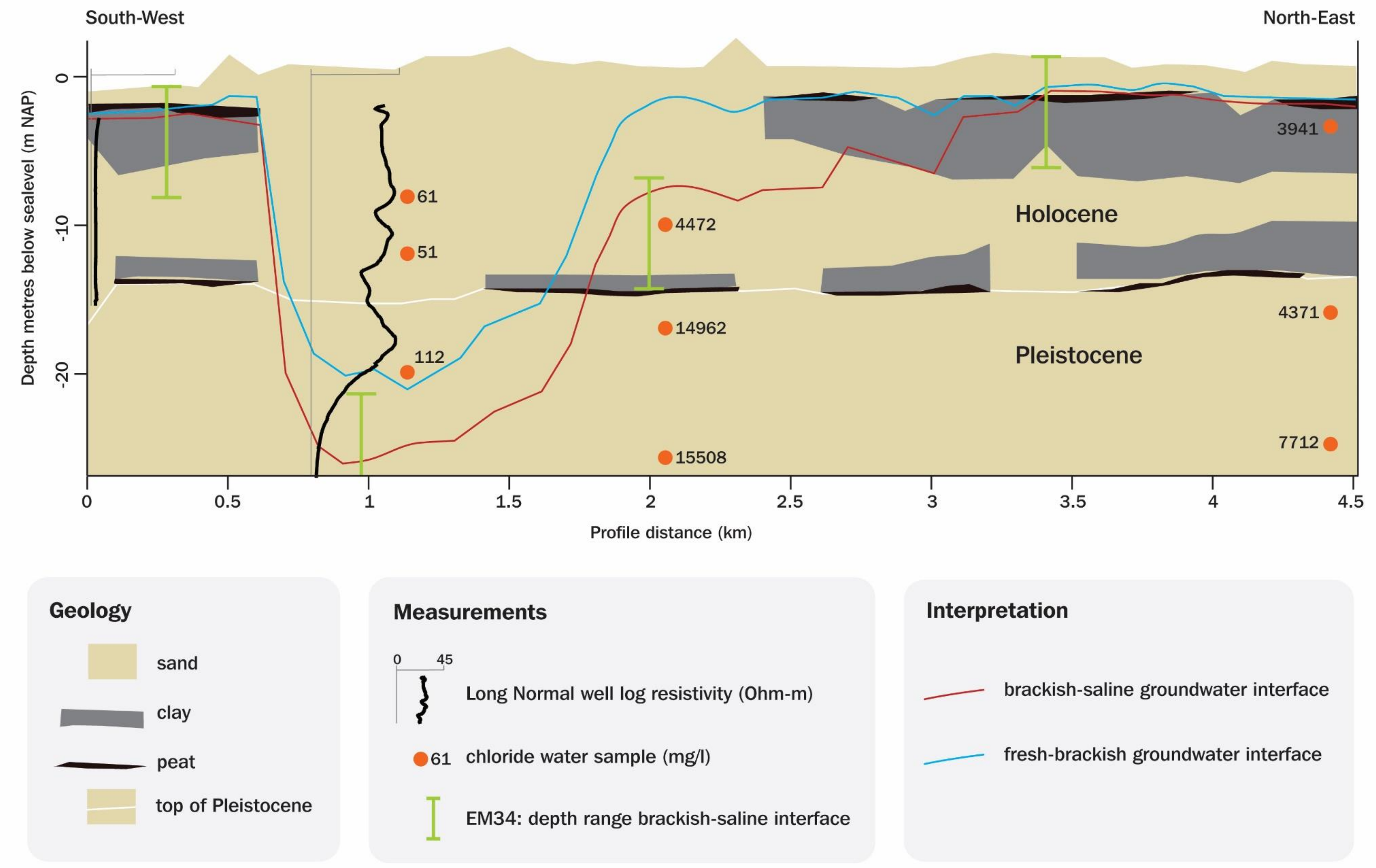
Mapping brackish-saline interface



Goes et al, 2009

Mapping brackish-saline interface

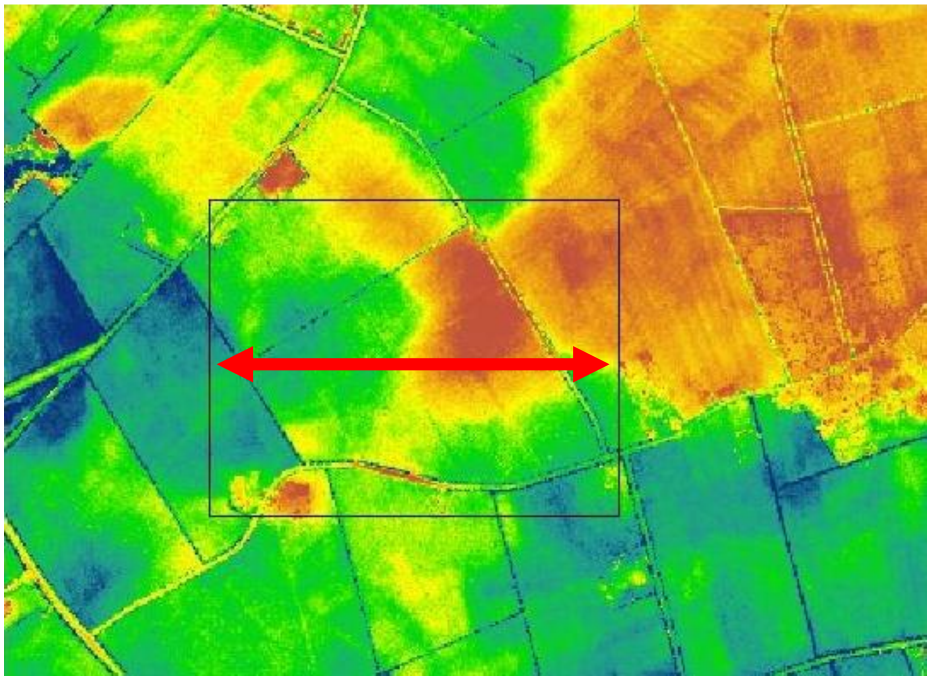
Combining different types of data sources

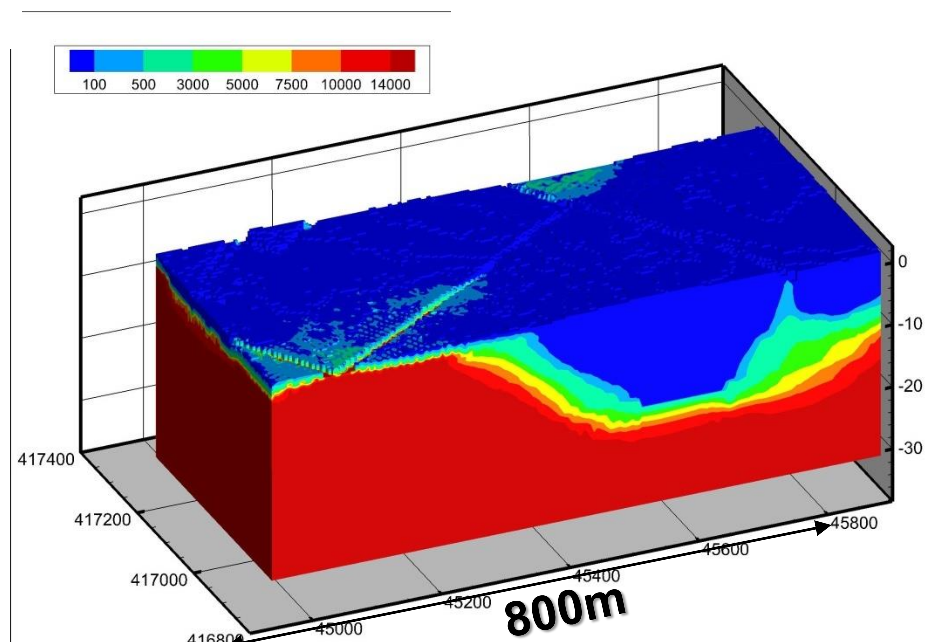


Use variable-density groundwater flow modelling

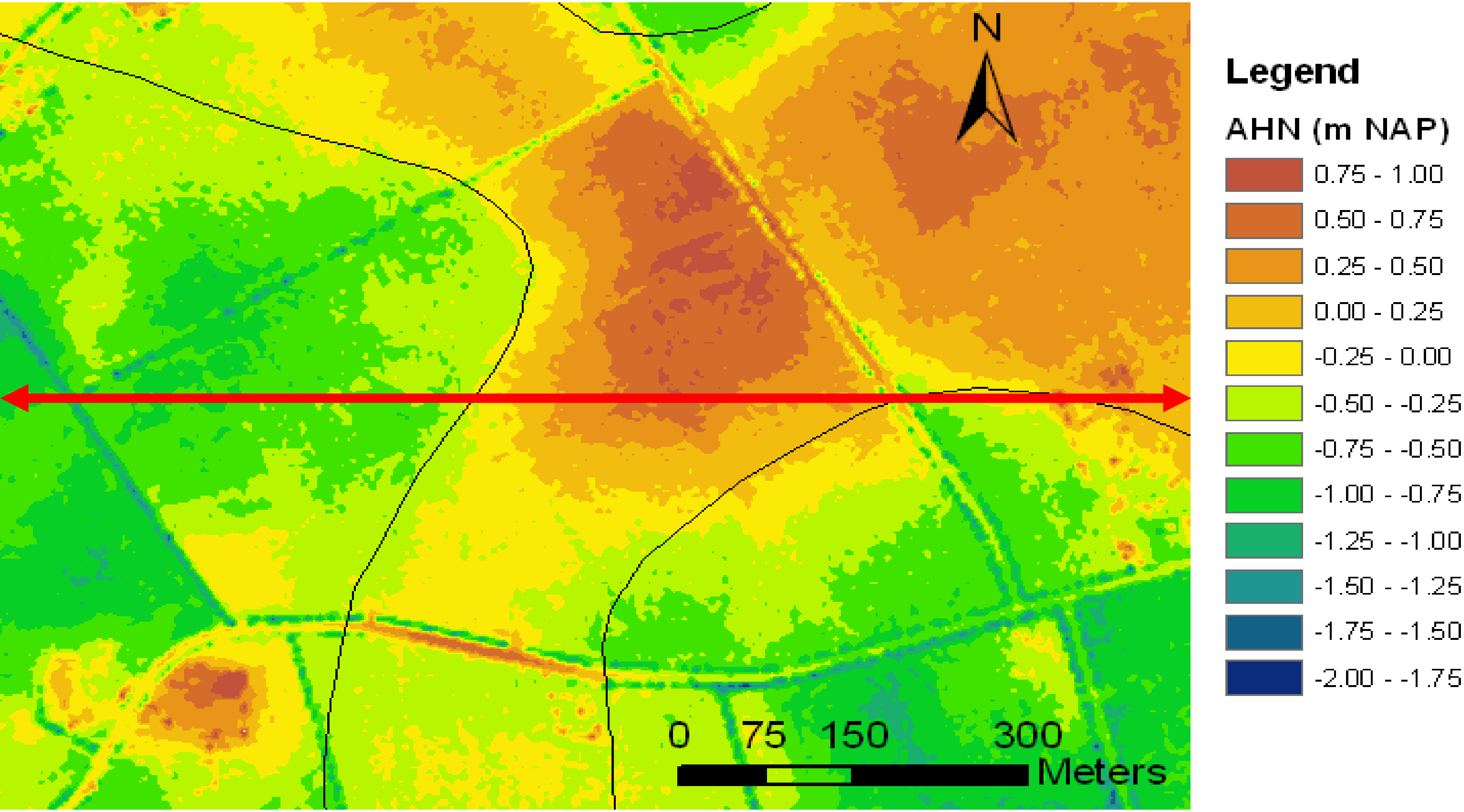
Why a model?

- variation in ground surface directly affects fresh-saline disribution

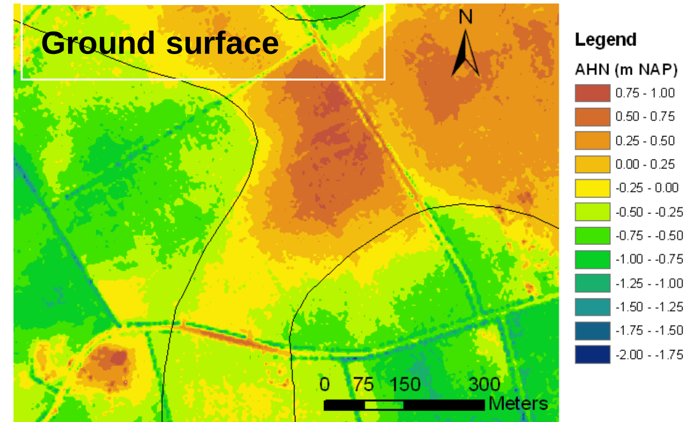




Use variable-density groundwater flow modelling



Local 3D model of the agricultural plot

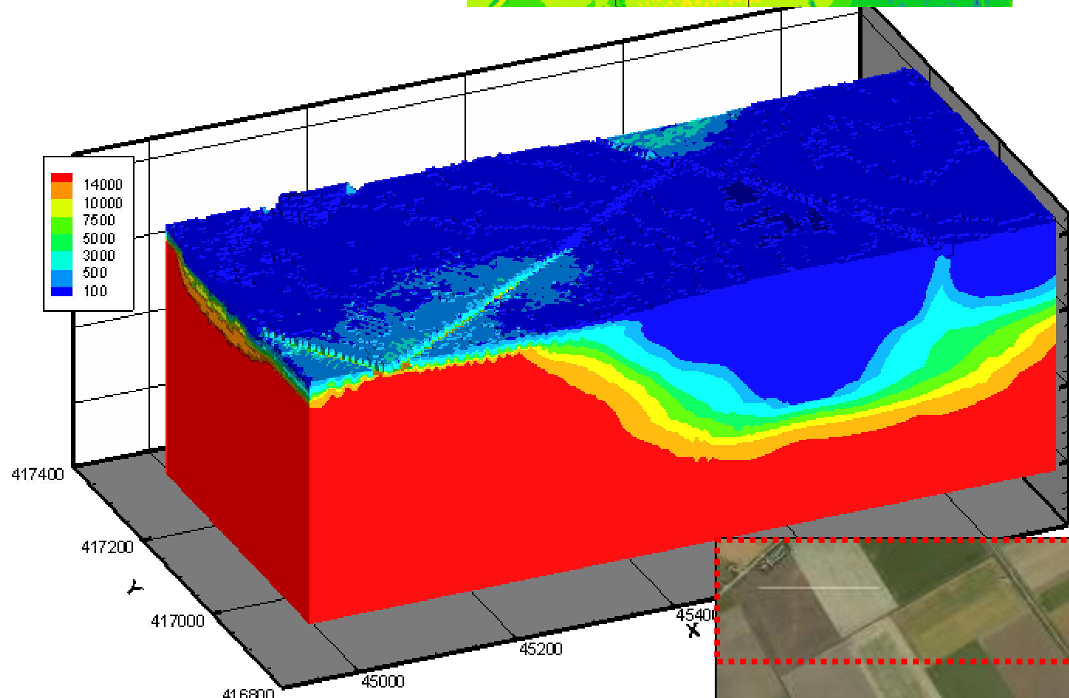


Modelling:

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

Code:

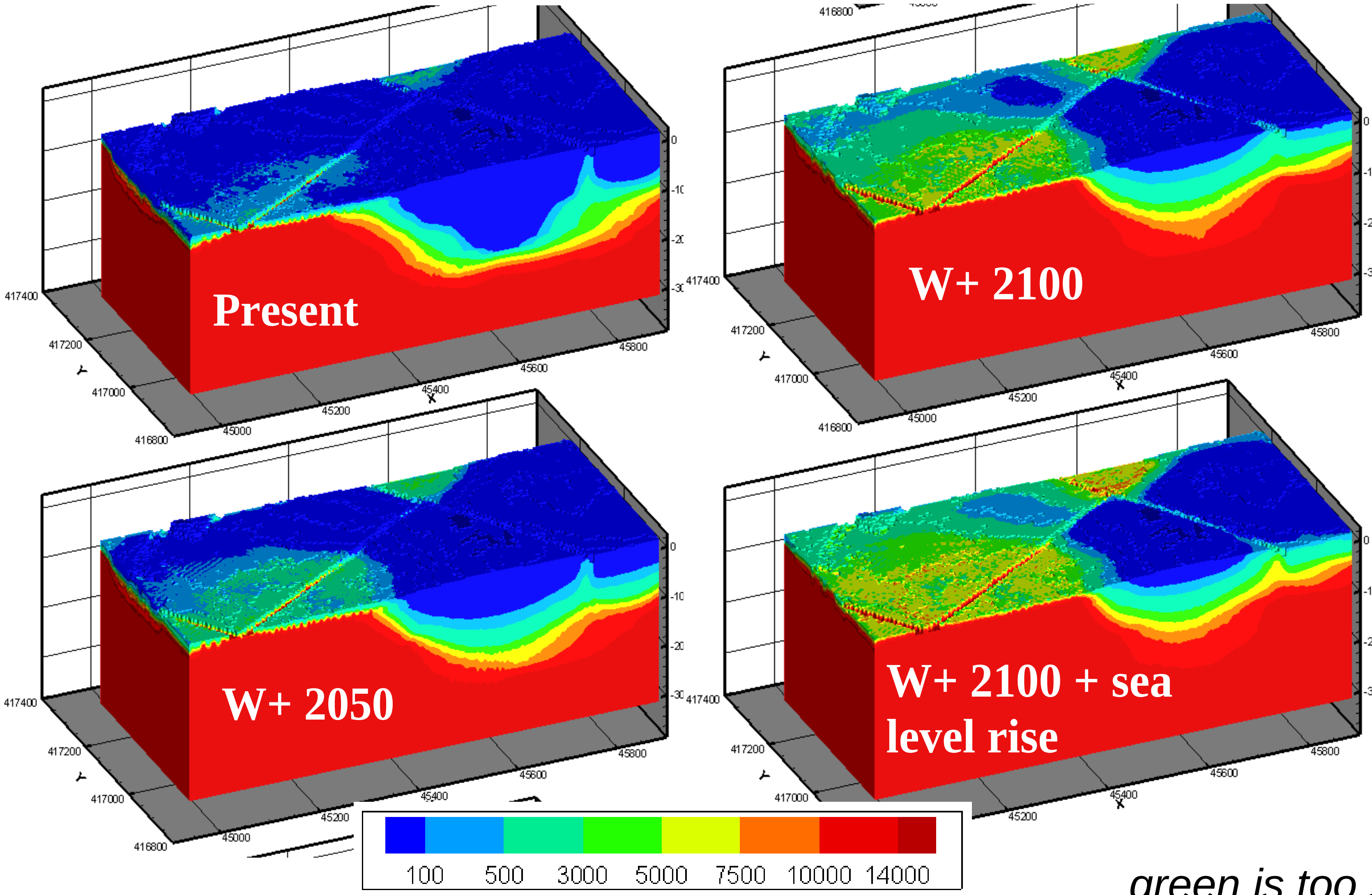
MOCDENS3D



Assessing effects:

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

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

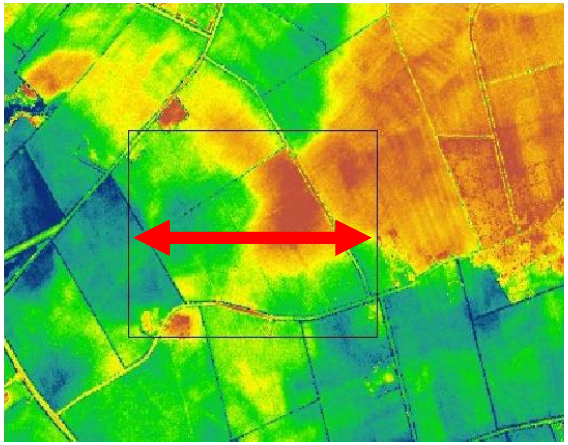


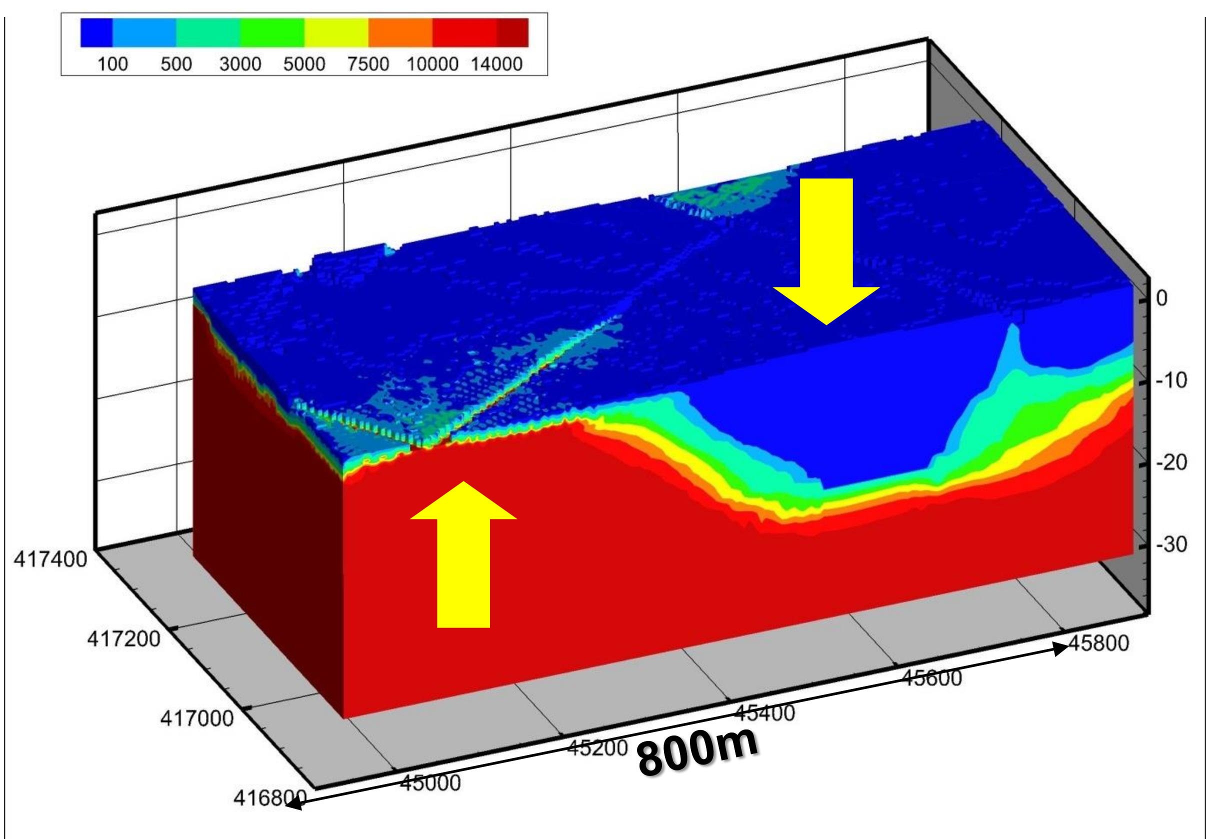
green is too salty to grow fresh crops

Use variable-density groundwater flow modelling

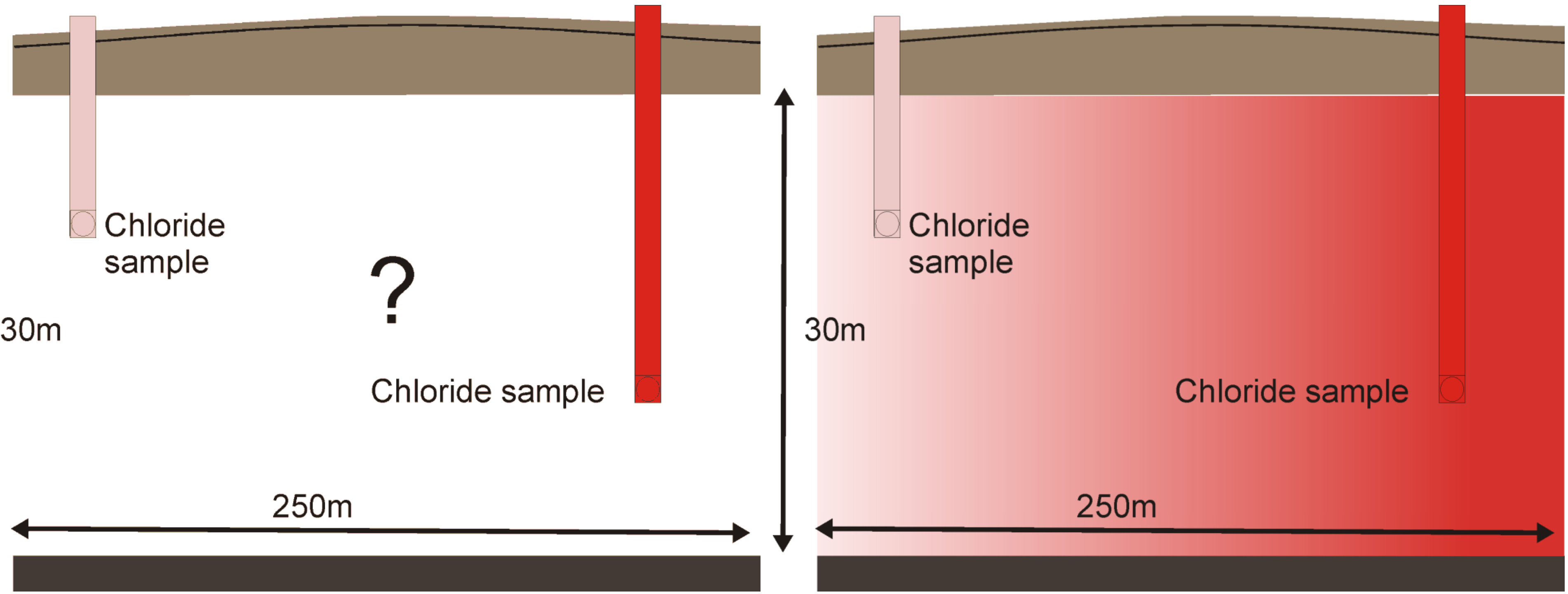
Why a model?

- variation in ground surface directly affects fresh-saline disribution

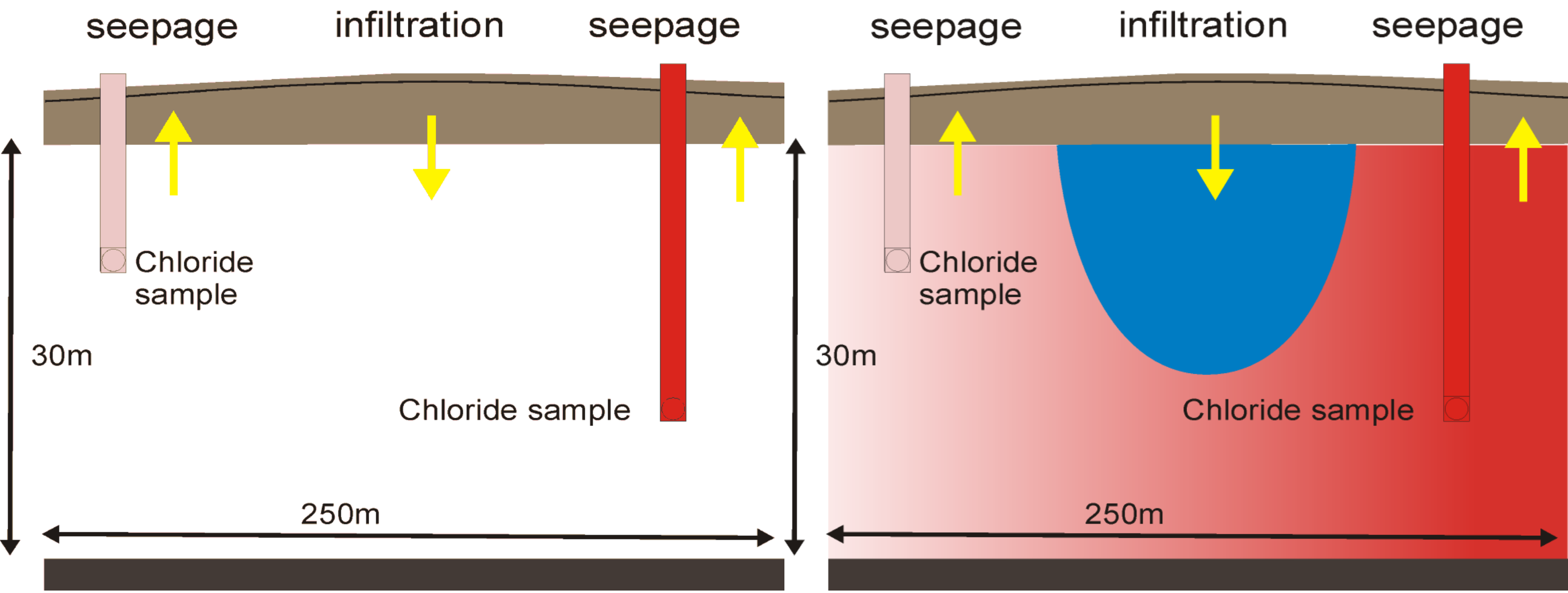




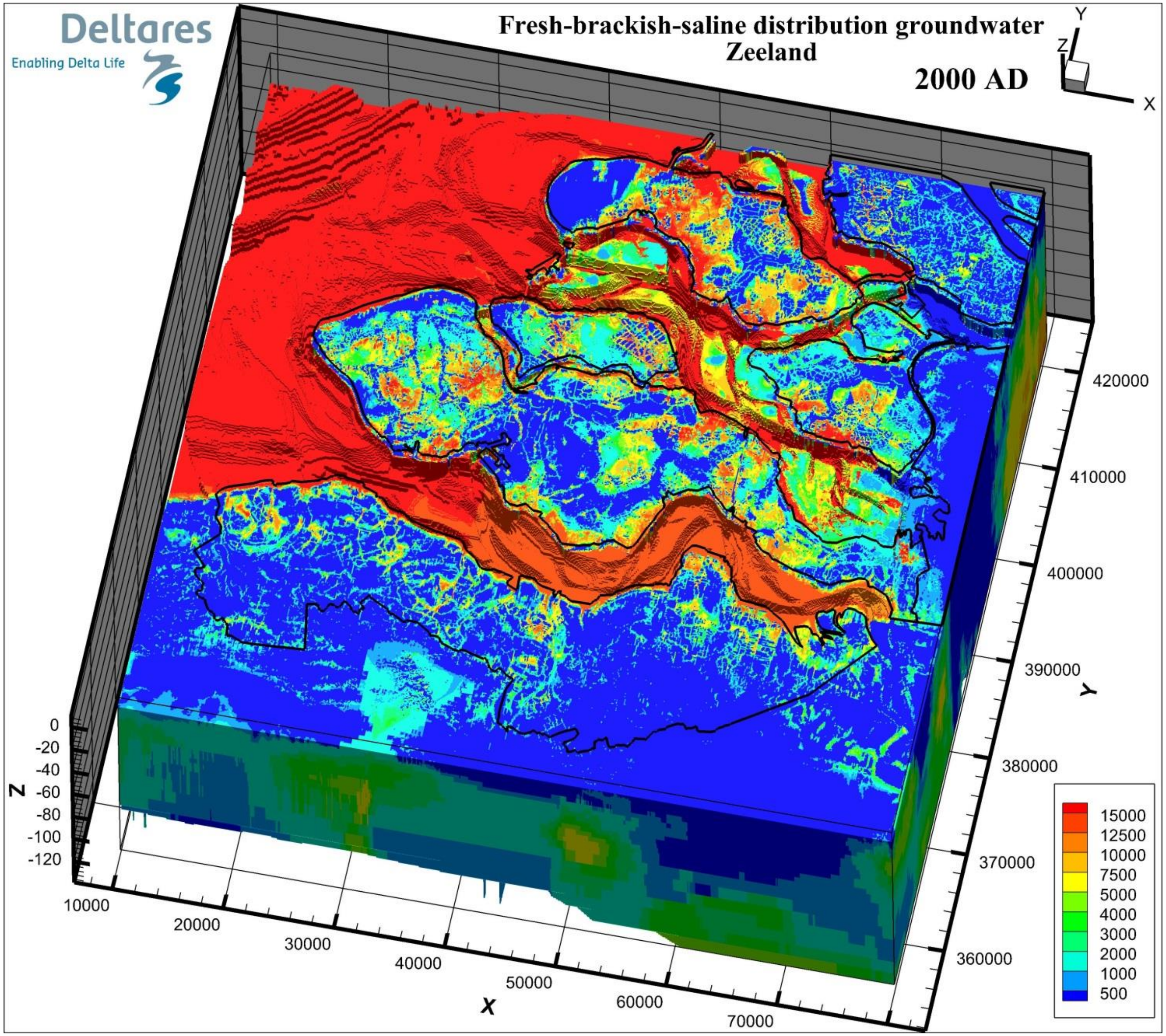
Interpolation chloride



Using flow model for better interpolate chloride

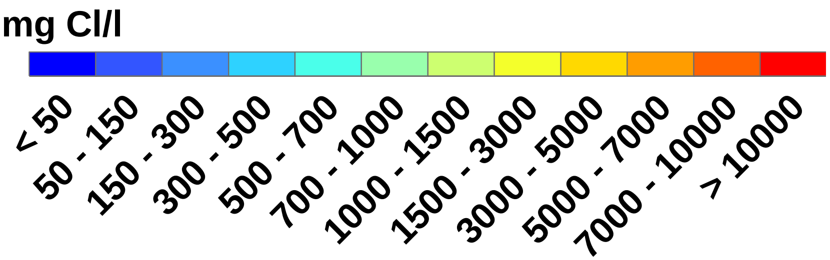


3D fresh-saline groundwater distribution

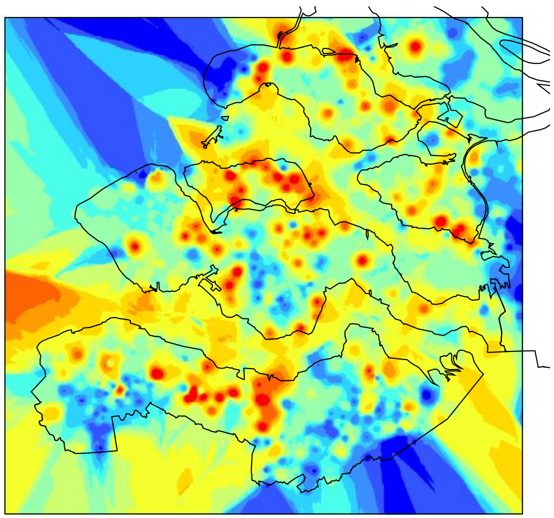


Regional groundwater model:

From chloride measurements to a 3D distribution



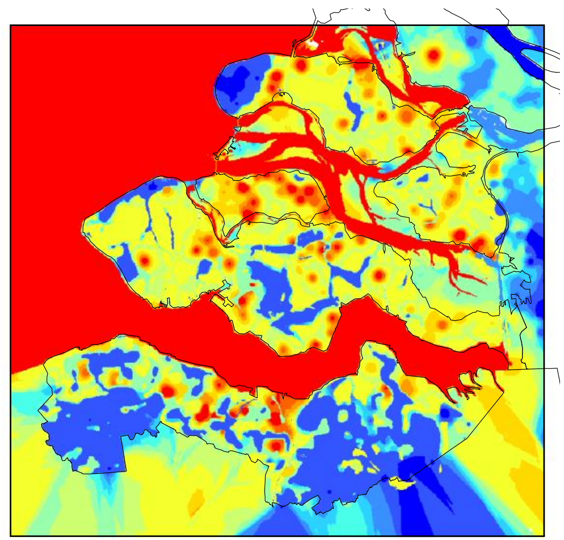
results at - 6.5 m msl



Step 1:

interpolating data:

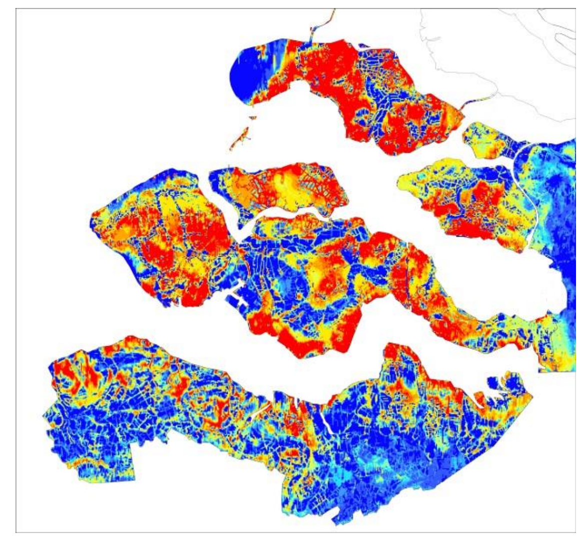
- *Groundwater samples*
- *Geo-electrical borehole logs*
- *(C)VES, EM, electrical CPT*



Step 2:

including interfaces

- *Mapped fresh-brackish*
- *Mapped brackish-salt*

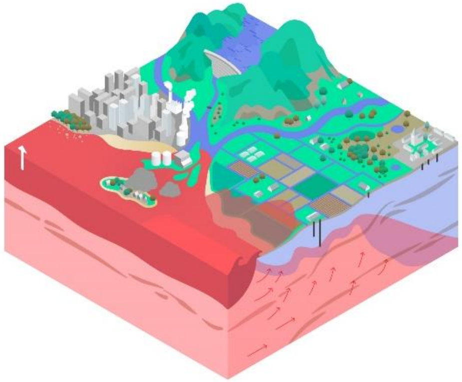


Step 3:

model result 2010:

- *Model as interpolator*

Level of modelling saltwater intrusion depends on e.g.:



1. data availability
2. time to work on
3. available budget
4. technical knowledge base (data science, coding, python, hydro-informatics)

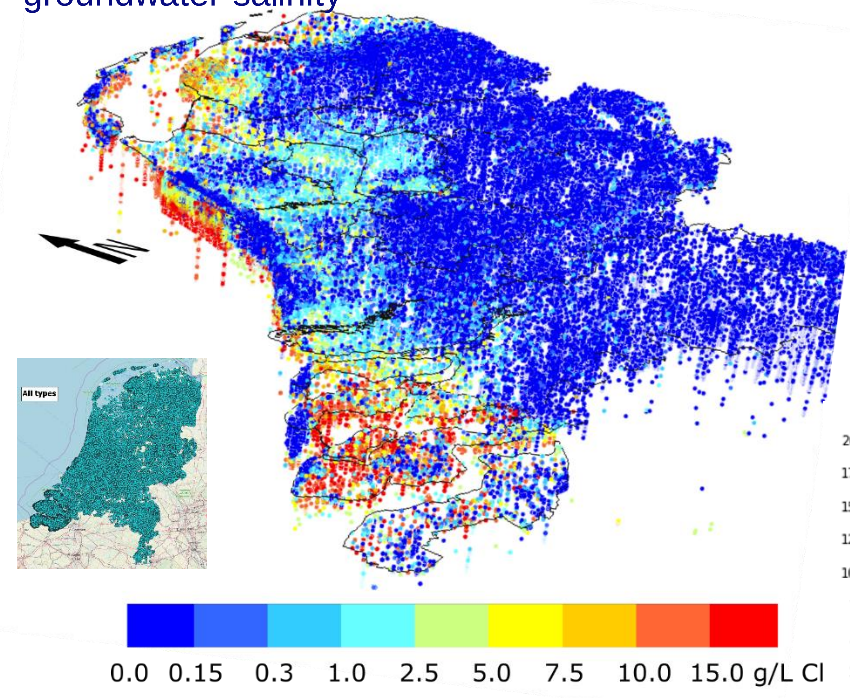
Examples of cases <u>we have worked on </u>(not generic applicable)

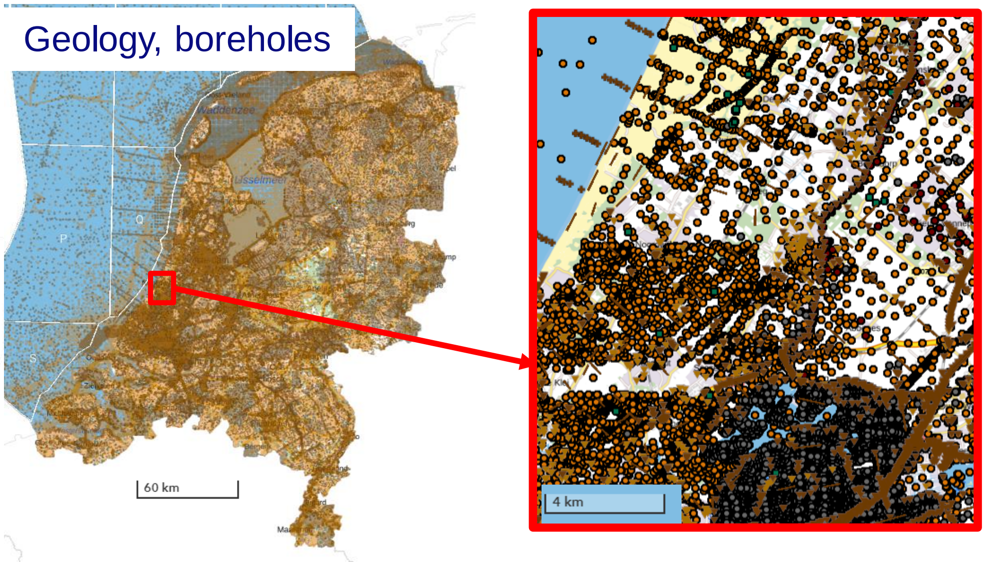
	Intensity	Data	Time	Budget	Technology needed	Case examples
1	very high	+++	>10 yr	>1M€/yr	+++	Netherlands
2	high	++	3-5 yr	>100k€/yr	++	Mekong delta
3	medium	+	1-2 yr	max 200k€	+	Nile data
4	low	global data	<0.2 yr	<50 k€	++	Oman

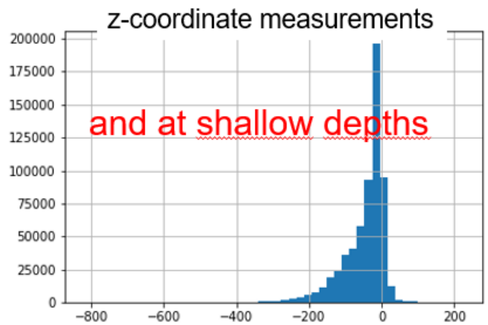
1 Case Netherlands

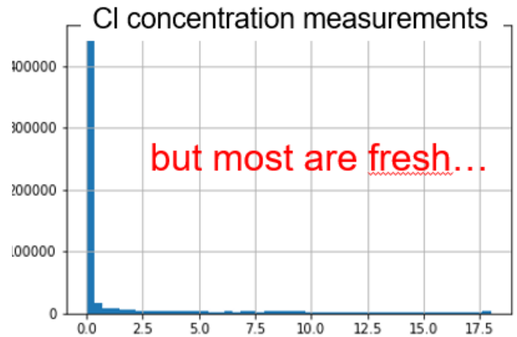
Data availability NL

groundwater salinity





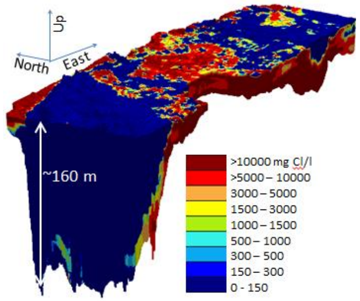




1 Case Netherlands

FRESHEM: fresh-salt mapping groundwater

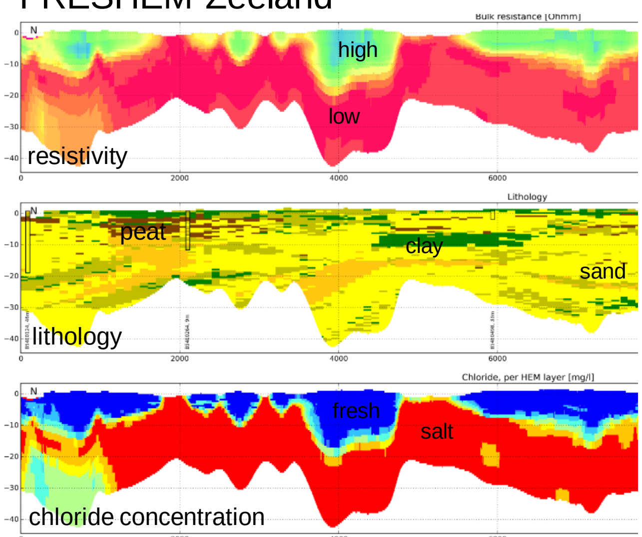
TNO innovation for life · BGR · Deltares



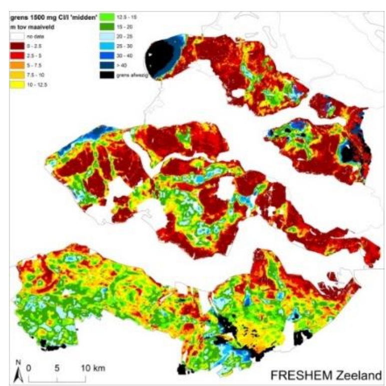
Method:
Combination helicopter measurements with data and knowledge about subsurface and processes in fresh-saline groundwater

Results:
- Mapping of 3D groundwater salinity
- Mapping of clay layers

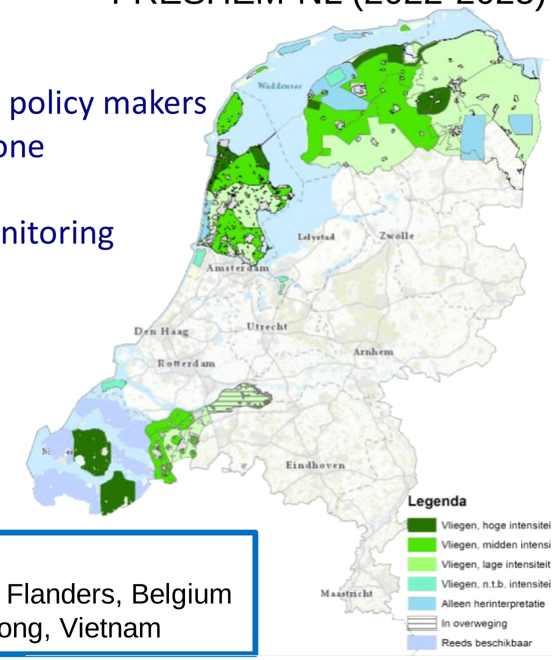
FRESHEM Zeeland



Applications:
- strategic fresh groundwater users & policy makers
- support ASR (COASTAR) in coastal zone
- identify brackish water potential
- improve groundwater models & monitoring



FRESHEM NL (2022-2025)



International:
- Project in Flanders, Belgium
- Pilot Mekong, Vietnam

1 Case Netherlands

Modelling: NHI fresh-salt
(National Hydrological Instrument)

iMOD-WQ model, parallel:

SEAWAT + M3TD + bells & whistles

39 layers, 1300 rows, 1200 columns

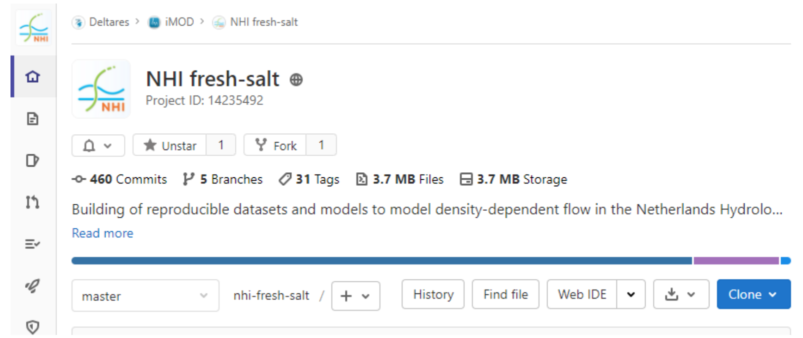
- Fully scripted, python based
- In version control
- One workflow from external data to figures

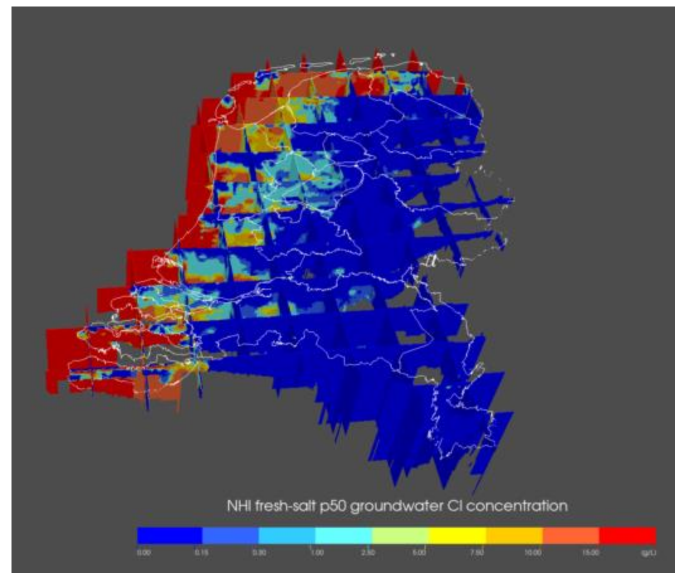
Openly available at:

https://gitlab.com/deltares/imod/nhi-fresh-salt

https://deltares.gitlab.io/imod/imod-python/

https://deltares.github.io/iMOD-Documentation/



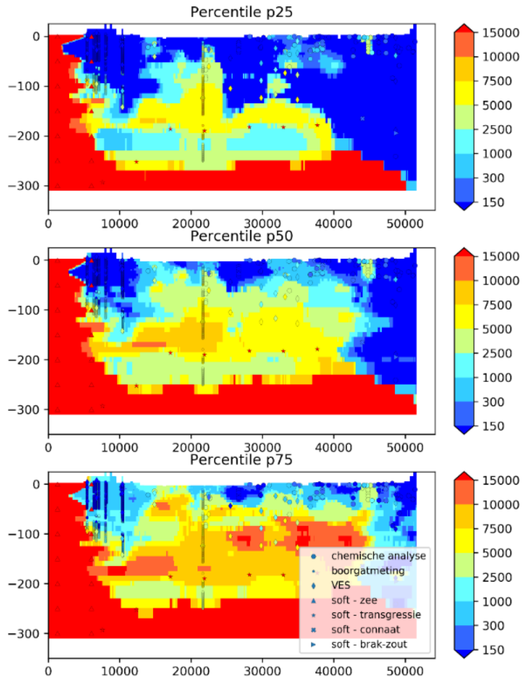


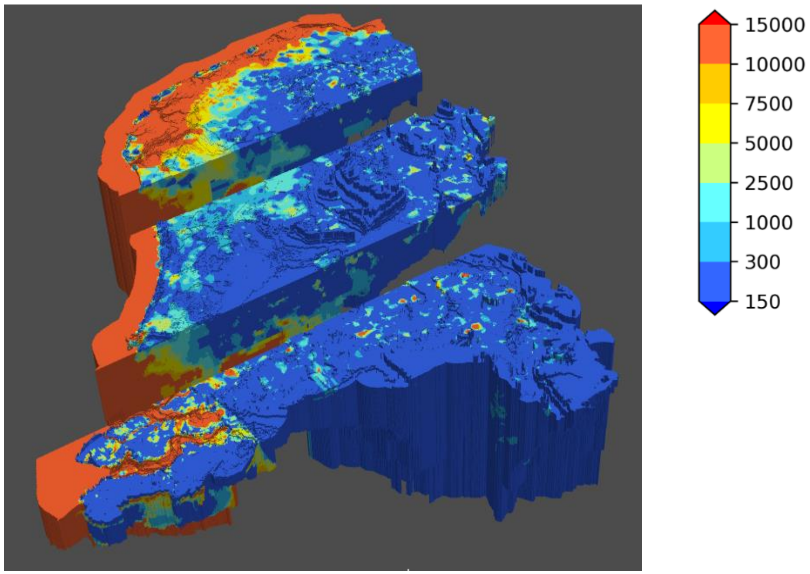
1 Case Netherlands

Model transient groundwater salinity

- Present-day groundwater salinity
- Extended model 20 km seaward
- Vertically detailed model layers
- Constructed using Toolbox NHI fresh-salt

- 250 x 250m, 39 layers (31M active cells)
- Runtime ~ 2 days for 100 year simulation, parallel (16 cores) and after speed-ups



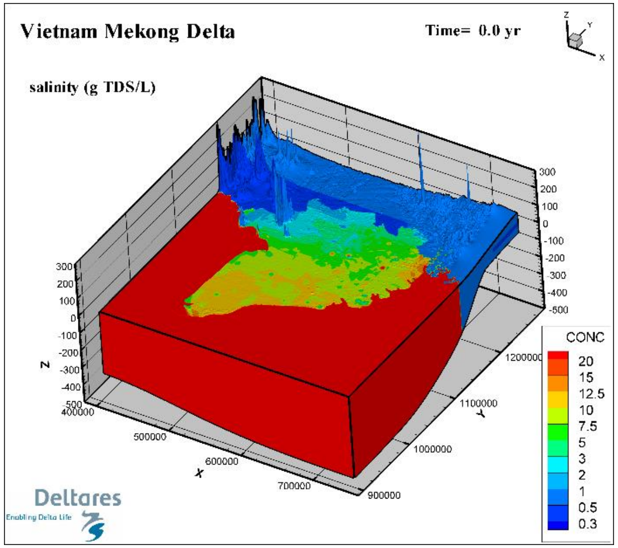


Delsman, J.R., Oude Essink, G.H.P., Huizer, S., Bootsma, H., Mulder, T., Zitman, P., Romero Verastegui, B., 2020. Actualisatie zout in het NHI - Toolbox NHI zoet-zout modellering en landelijk model, Deltares rapport 11205261-003-BGS-0001. Utrecht.

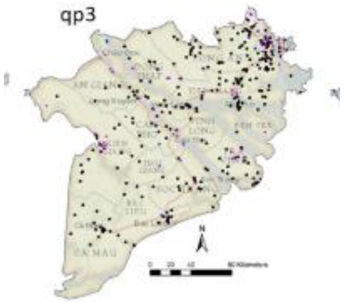
2. Case Mekong

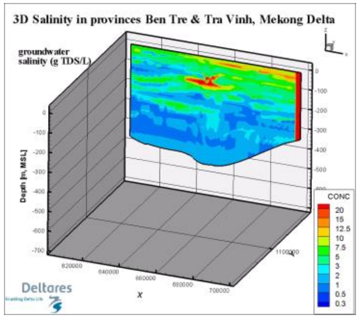
Quite some hydrogeological data, time and budget

Geology and groundwater salinity data from existing databases

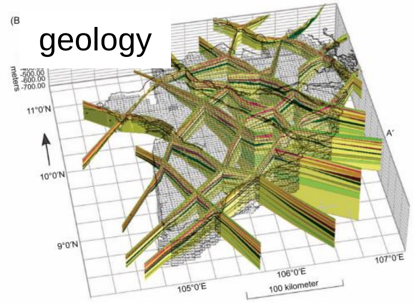


extractions aquifer qp3

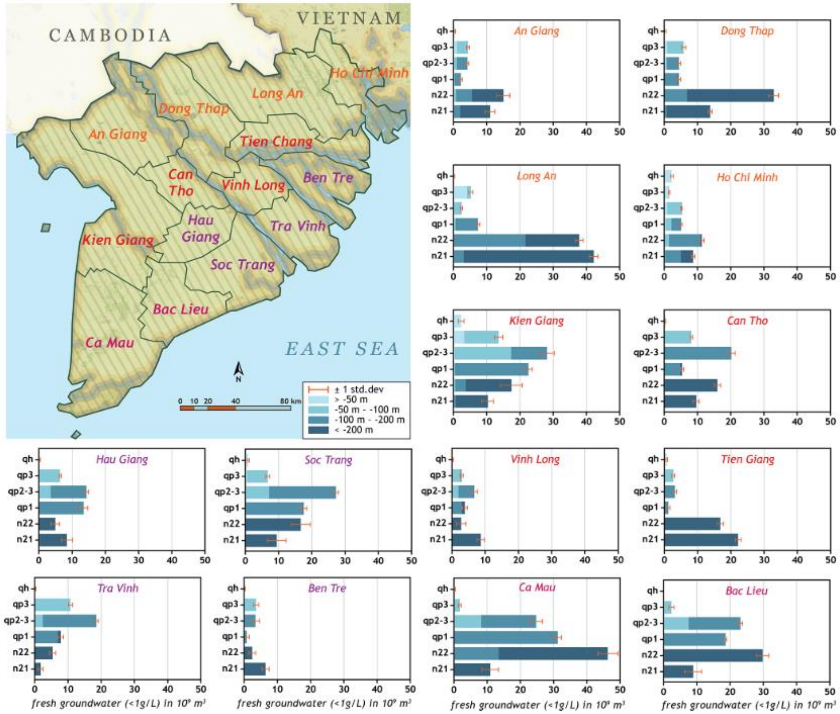




geology



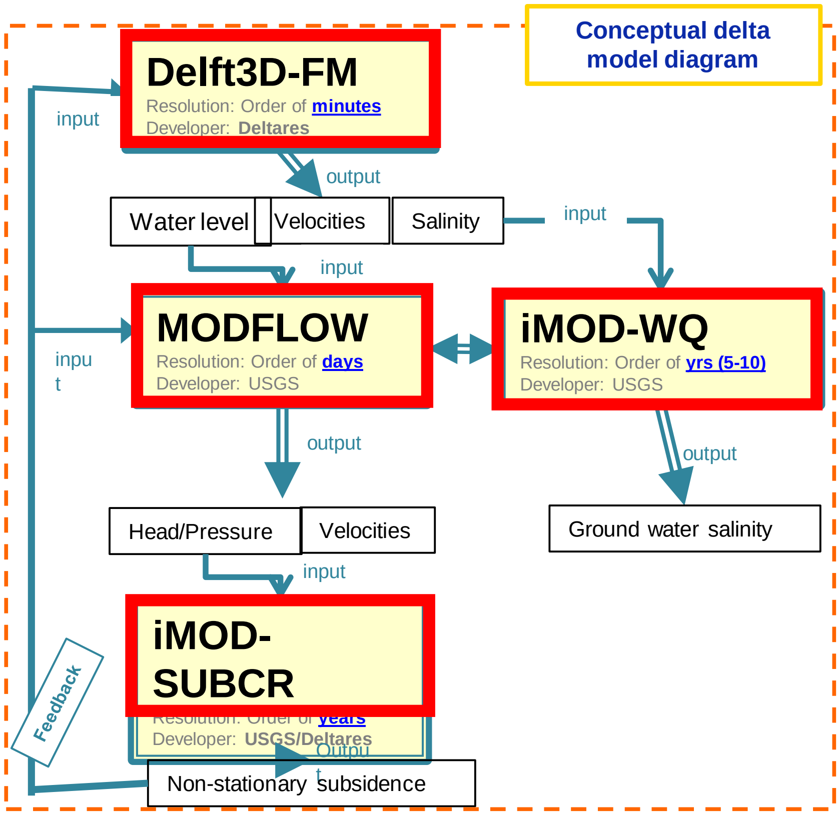
GUI: iMOD-WQ



Gunnink, J.L., Pham, V.H., Oude Essink, G.H.P., Bierkens, M.F.P., 2021. The 3D groundwater salinity distribution and fresh groundwater volumes in the Mekong Delta, Vietnam, inferred from geostatistical analyses. Earth Syst. Sci. Data 13, 3297–3319. https://doi.org/10.5194/essd-13-3297-2021

2. Case Mekong

Use (integrated) modeling toolboxes to quantify stresses and pathways



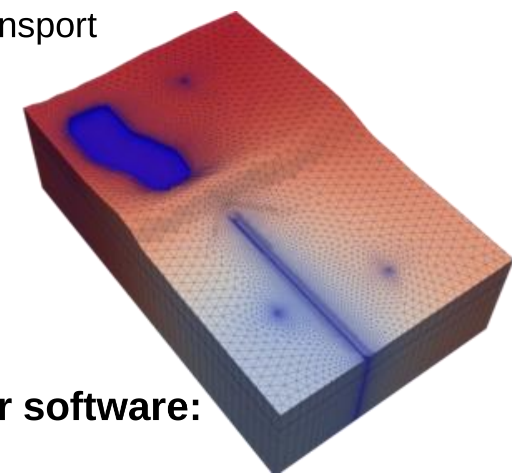
Open Source software Deltares

iMOD-WQ-SUBCR (SEAWAT, parallel):

- Modeling salt transport, variable-density groundwater flow and subsidence

Delft3D-FM:

- Modeling surface water, fresh and saline water and sediment transport



MODFLOW6!

Check Deltares site for software:
https://oss.deltares.nl/

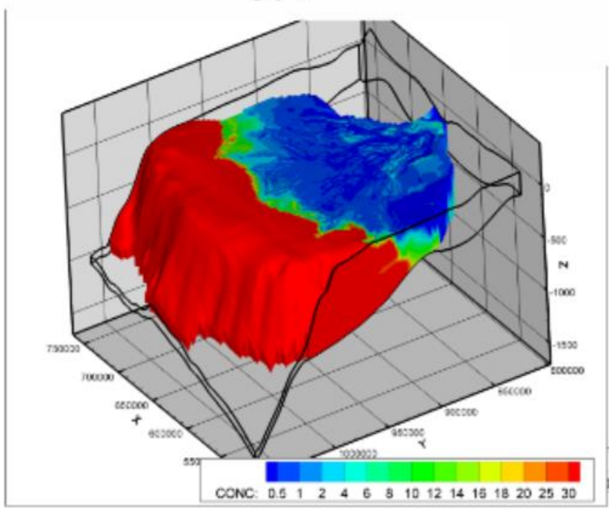
3. Case Egypt, Nile

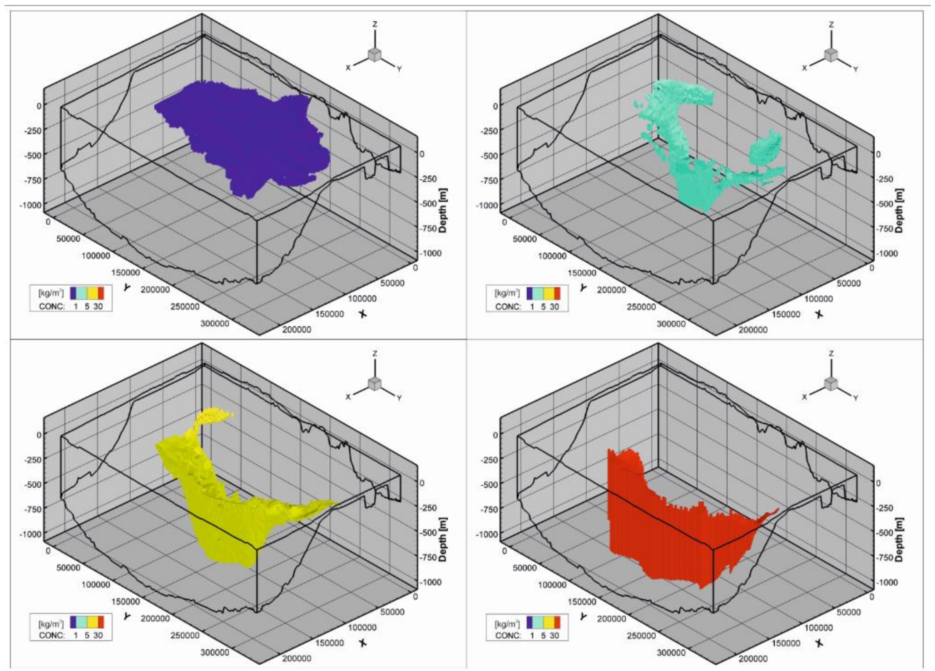
Limited amount of hydrogeological data, time and budget

Salt water intrusion understanding using 3D variable-density groundwater models

Nile delta, Egypt

GUI: PMWIN



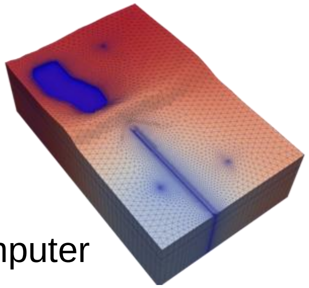


Mabrouk, M.B., Jonoski, A., Oude Essink, G.H.P., Uhlenbrook, S., 2019. Assessing the fresh-saline groundwater distribution in the Nile Delta Aquifer using a 3D variable-density groundwater flow model. Water (Switzerland) 11, 1–22. https://doi.org/https://doi.org/10.3390/w11091946

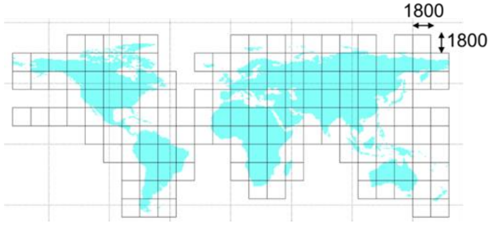
4. Case Oman

Only global hydrogeological data, limited time and budget

Development global groundwater model



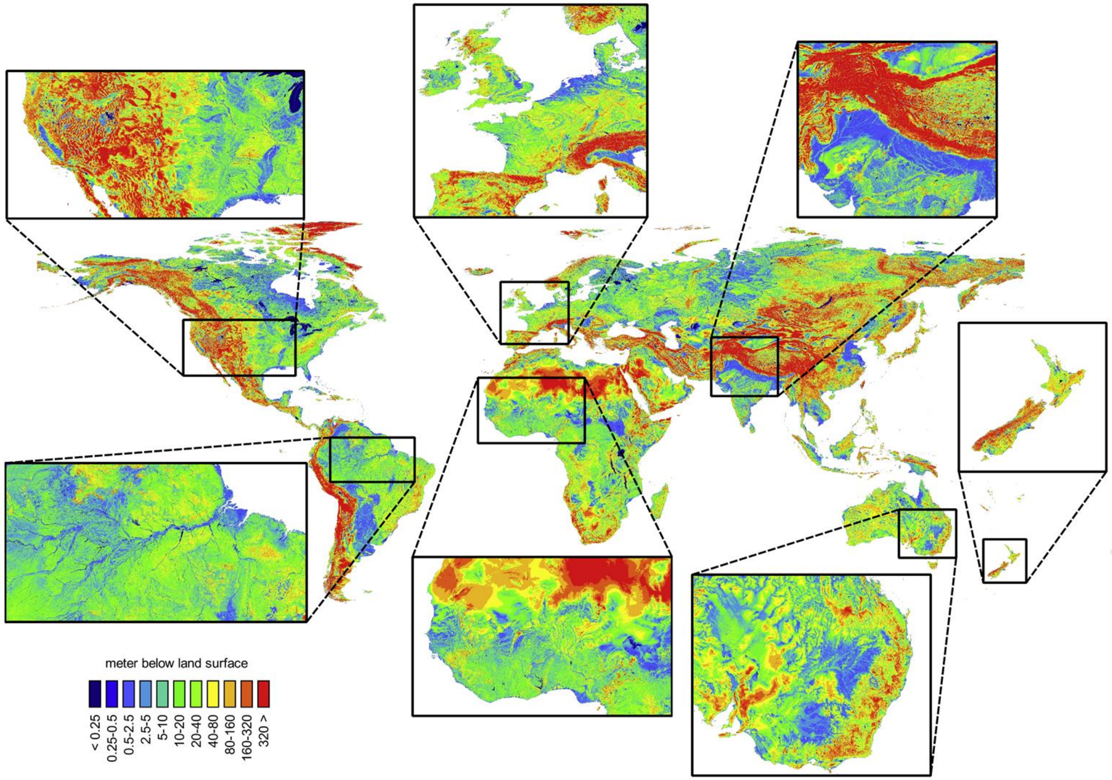
1. Hyper resolution groundwater modelling on a global scale (**1*1km²**)
2. MODFLOW (6) / iMOD-WQ / SEAWAT **parallel codes**, using normal and supercomputer
3. Components: **quantity, salinity**
   - subsidence, groundwater quality (later, >2023)
   - heat transport (later, >2023)
4. **Downscaling clipping features** for continental <-> national <-> regional <-> local
5. Work in process: calibration/validation, improve geology (by adding extra geological databases), collect extractions, 3D groundwater salinity
6. Data processing:
   - 163 tiles of 15° (1800 x 1800 pixels) following landmass
   - python scripting transient data for 1958-2015
   - monthly data for recharge, storage, rivers, drains and wells
   - runtime using 12 nodes and 384 cores: ~ 3.5 hours
   - storage: 163 x 85 GB = 13.5 TB



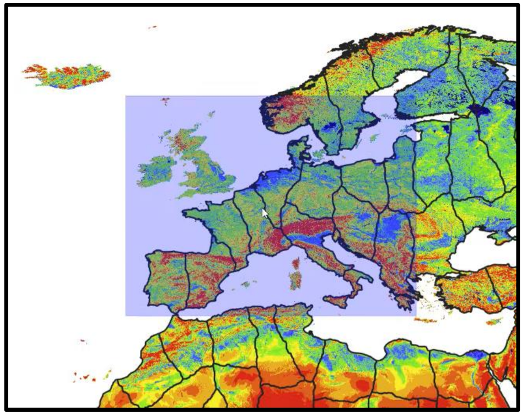
Model	Name	# cells (M)	# nodes	# cpn	#cores
1	Afro-Eurasia	167.51	7	32	224
2	Americas	77.13	3	32	96
3	Australia	16.34	1	32	32
4	Other	17.35	1	32	32
		278.33	12		384

4. Case Oman

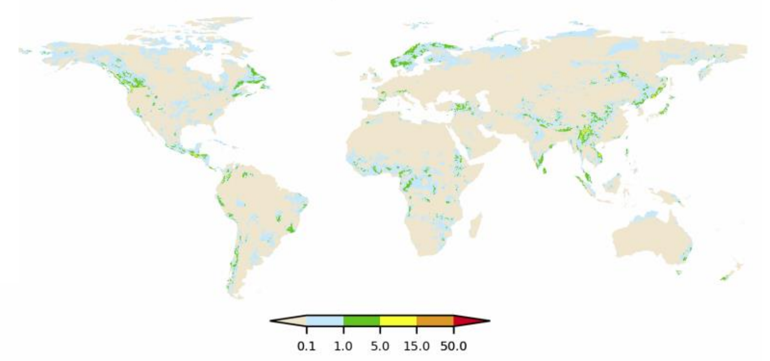
Some results: piezometric heads: 1*1km2, transient



Verkaik, J., Sutanudjaja, E.H., Oude Essink, G.H.P., Lin, H.X., Bierkens, M.F.P., 2022. GLOBGM v1.0: a parallel implementation of a 30 arcsec PCR-GLOBWB-MODFLOW global-scale groundwater model. Geosci. Model Development, submitted



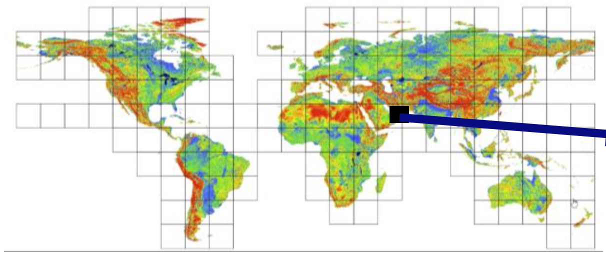
Year-averaged water table depth (in m) relative to initial state for 1970

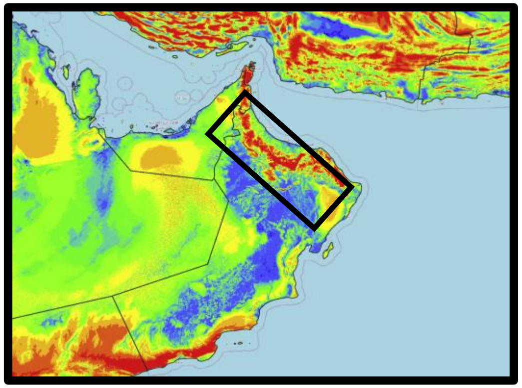


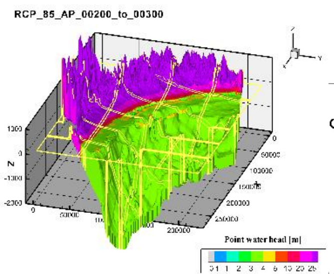
4. Case Oman

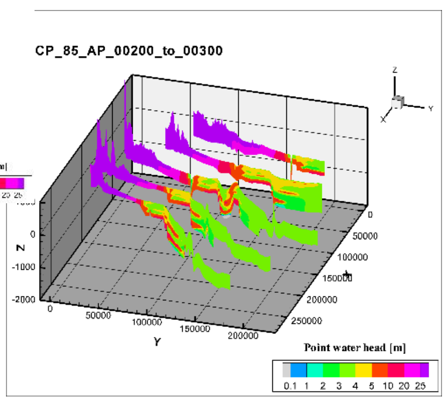
Using global groundwater modelling, example

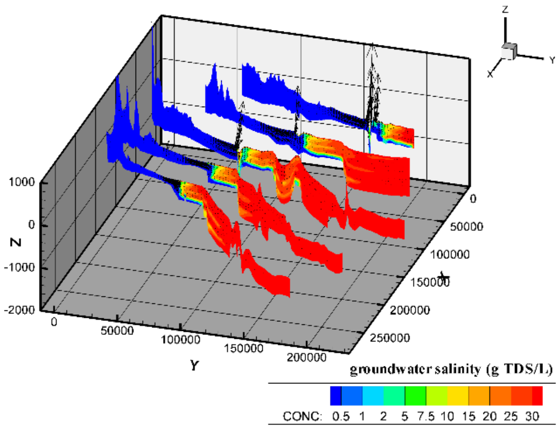
- Based on work of Zamrsky et al., (2020, 2022) results in 2D sections of salinity and hydraulic properties globally.
- Data converted to 3D using innovative interpolation methods (global estimates of 3D salinity).
- Model ran 100 years in < 1 day on a fast machine (24 core).

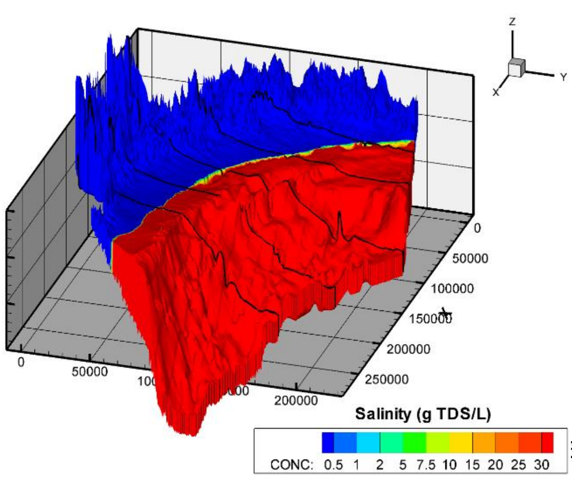








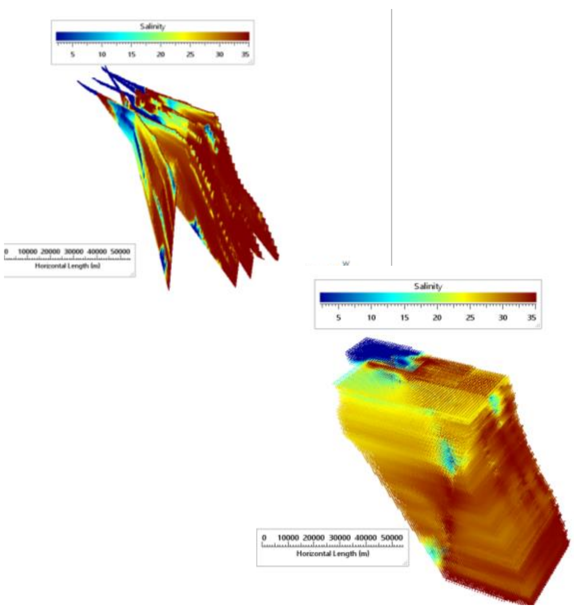




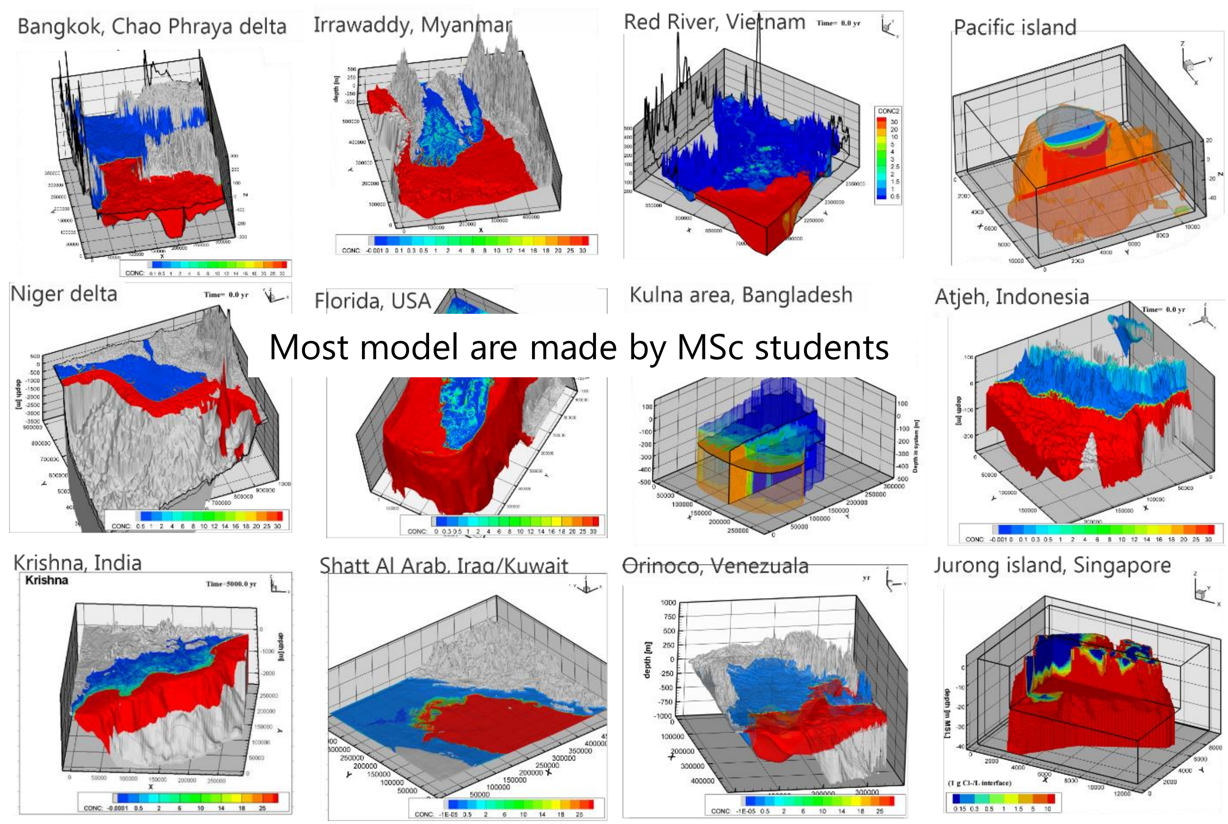
4. Case Oman, examples

Only global hydrogeological data, limited time and budget

Using 3D groundwater salinity models, local and global data



GUI: iMOD-WQ



Most model are made by MSc students

4. Case Oman, examples

Data mining and machine learning to determine coastal groundwater salinity

Table S1 Hydrochemical and stable isotopic data from water samples in study area.

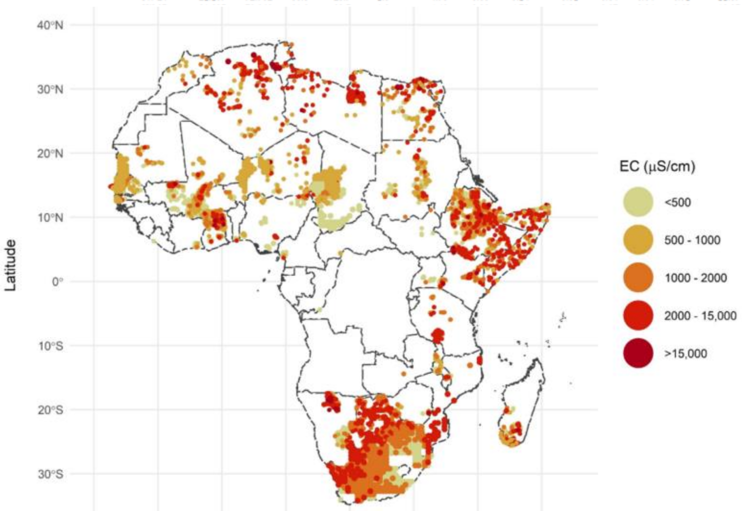
K⁺	Na⁺	Ca²⁺	Mg²⁺	Cl⁻	SO₄²⁻	HCO₃⁻	Br⁻	TDS (g/L)	pH	δ D(‰, VSMOW)	δ ¹⁸O(‰, VSMOW)	Uncertainty ‰ δ D	Uncertainty ‰ δ ¹⁸O
ρ(mg/L)													
21.22	14.11	43.34	17.65	19.52	21.48	246.18		0.384	7.60	-58.9	-8.2	±0.39	±0.04
2.39	73.33	127.27	55.26	79.74	184.82	451.77		0.975	7.32	-44.1	-8.0	±1	±0.2
3.01	64.53	171.10	67.88	173.94	133.59	410.34		1.159	8.42				
0.973	32.2	144	18.2	64.5	116	199	0.074	0.575	7.78	-57.1	-7.5	±1	±0.2
1.142	13.3	53.7	16.1	14.0	23.5	151	0.037	0.384	8.20	-58.8	-7.9	±1	±0.2
5.17	209	110	66.4	391	204	338	1.06	1.324	7.59	-59.1	-8.2	±0.37	±0.08

Table 1
Geographical position, sampling depth, temperature, conductivity, concentrations of major ions, Mn, and Sr, as well as Sr isotope ratio of the groundwater samples.

Sample ID	Lat. (°N)	Long. (°E)	Depth (m)	Temp. (°C)	Cond. (mS/cm)	HCO₃ (mM)	F	Cl	Br	NO₃	PO₄	SO₄	Na	K	Ca	Mg	Mn (μM)	Sr	⁸⁷Sr/⁸⁶Sr	2 se
Monsoon (Sep. 2016)																				
GW-3	21.116	72.823	25.0	30.1	0.4	1.49	0.05	1.08	BDL	BDL	BDL	0.16	1.81	0.07	0.31	0.57	0.77	7.7	0.70830	0.00006
GW-4	21.108	72.843	12.2	30.0	3.3	2.62	0.14	19.46	0.02	1.31	0.05	3.74	17.45	BDL	0.88	6.85	0.52	60.4	0.70918	0.00002
GW-5	21.124	72.858	–	29.4	0.4	1.22	0.07	1.08	BDL	BDL	BDL	0.15	1.66	0.11	0.33	0.64	0.68	4.0	0.70826	0.00006
GW-6	21.167	72.962	61.0	30.3	1.4	3.42	0.07	4.52	BDL	0.83	0.05	0.85	12.04	0.02	0.13	1.29	0.53	9.7	0.70878	0.00007
GW-7	21.363	72.960	76.2	30.3	8.7	1.20	0.06	57.92	0.05	0.95	BDL	26.09	68.56	0.26	5.01	5.30	0.67	47.6	0.70937	0.00003
GW-8	21.463	72.992	25.0	29.0	0.8	1.29	0.07	2.59	BDL	0.05	0.04	0.93	3.75	0.04	0.98	0.74	3.14	12.6	0.70940	0.00006
GW-9	21.416	72.823	24.0	28.5	2.6	6.55	0.21	14.98	0.02	0.14	0.05	1.97	29.69	0.09	0.05	0.34	0.63	8.9	0.70856	0.00007
GW-10	21.341	72.744	–	28.3	1.4	3.18	0.10	7.26	0.01	0.09	0.05	0.76	12.35	0.15	0.24	1.03	0.89	9.9	0.70873	0.00006
GW-11	21.449	73.151	27.4	29.1	3.8	3.79	0.08	26.00	0.04	0.05	0.06	0.57	32.83	0.04	0.18	0.72	0.67	11.7	0.70879	0.00004
GW-12	21.572	73.162	–	28.9	1.2	0.95	0.05	7.04	0.01	1.06	0.04	0.92	6.29	0.25	1.65	1.09	0.62	11.4	0.70879	0.00004
GW-13	21.706	73.151	–	27.6	2.3	2.92	0.10	14.28	0.02	0.01	0.04	2.11	21.89	0.10	0.30	1.95	0.53	16.8	0.70925	0.00004
GW-14	21.634	73.021	–	30.1	4.8	0.44	0.04	33.47	0.05	BDL	0.04	3.27	28.66	0.20	3.38	3.15	2.05	33.7	0.70855	
GW-15	21.703	73.001	–	29.9	3.4	1.46	0.09	32.47	0.04	1.62	0.05	0.79	30.63	0.05	0.68	3.47	0.47	22.1	0.70890	
GW-16	21.932	73.085	–	29.9	4.2	3.61	0.05	30.87	0.04	0.13	0.07	1.58	20.66	0.08	0.77	10.91	0.67	28.4	0.70949	
GW-17	22.062	73.136	36.6	31.0	1.9	1.63	0.05	13.00	0.03	0.81	0.04	0.53	9.90	0.07	0.36	3.98	0.55	22.5	0.70944	
GW-18	22.061	73.222	–	32.1	2.9	1.31	BDL	24.05	0.07	0.54	BDL	0.91	14.34	0.13	0.70	9.13	0.62	27.1	0.71013	
Post-monsoon (Dec. 2016)																				
GW-20	21.168	72.736	12.2	26.6	3.4	11.71	0.09	15.05	0.03	BDL	0.07	1.41	40.71	0.22	0.12	0.39	0.70	4.0	0.70818	
GW-21	21.125	72.772	–	28.0	5.3	5.75	0.09	40.09	0.07	BDL	0.06	0.89	49.49	0.26	0.09	1.33	1.04	10.6	0.70874	
GW-23	21.106	72.851	10.7	28.5	1.8	4.99	0.07	7.76	0.02	0.09	0.04	1.71	14.65	0.02	0.39	1.62	0.63	27.9	0.70910	
GW-24	21.167	72.962	85.3	28.7	1.5	4.95	0.05	5.14	0.01	0.84	0.04	0.91	11.87	0.03	0.32	1.63	0.93	10.3	0.70879	
														BDL	0.19	0.82	0.43	10.9	0.70923	
														BDL	1.38	1.47	0.74	7.4	0.70837	
														0.02	1.74	3.08	0.83	31.9	0.70850	
														2.90	0.44	1.16	0.48	11.1	0.70883	
														0.01	0.04	0.20	0.54	9.1	0.70845	
														0.03	0.14	0.18	1.06	4.3		
														0.30	4.37	4.39	1.96	31		
														0.06	0.80	3.85	0.56	19		
														BDL	0.23	2.54	0.69	7.8		
														0.06	0.55	4.41	1.98	19		
														0.03	0.81	3.67	0.54	19		
														0.12	0.66	3.08	0.48	29		
														0.03	0.22	2.15	0.90	18		
														0.04	2.20	2.56	2.64	19		

Table 1
Physicochemical parameters, stable isotopes and major ions of the water samples. Water samples acronyms: CSB: Coastal ridges; SW: sea water.

Sample	EC (uS/cm)	pH	δ¹⁸O ⁰/₀₀	δ²H	CO_3^{2-} meq/L	HCO_3^-	Cl⁻	SO_4^{2-}	Ca²⁺	Mg²⁺	Na⁺	K⁺
CSB-1	7960	7.7	–	–	0.00	4.96	59.41	2.29	3.22	13.13	60.90	3.58
CSB-2	630	7.9	–	–	0.00	3.92	2.47	0.14	2.26	1.88	3.13	0.23
CSB-3	573	7.5	–	–	0.00	4.01	1.83	0.21	2.68	1.51	2.78	0.10
CSB-4	783	8.1	–	–	0.63	4.69	2.70	0.19	0.85	2.77	5.00	0.61
CSB-5	694	7.0	–	–	0.00	5.11	2.20	0.47	2.16	1.66	4.44	0.17
CSB-6A	1385	8.2	–	–	2.60	3.35	7.44	0.29	0.76	1.65	13.05	0.41
CSB-6B	947	7.9	–	–	0.63	4.48	3.74	0.44	1.24	1.59	7.83	0.28
CSB-7	1682	7.8	−5.35	−35.5	0.00	10.37	7.44	0.23	3.56	3.98	10.87	0.36



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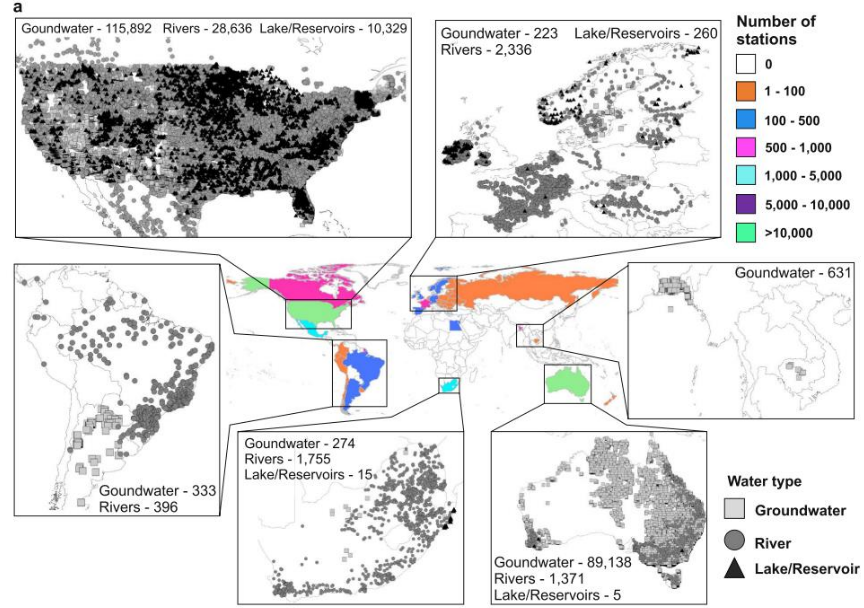
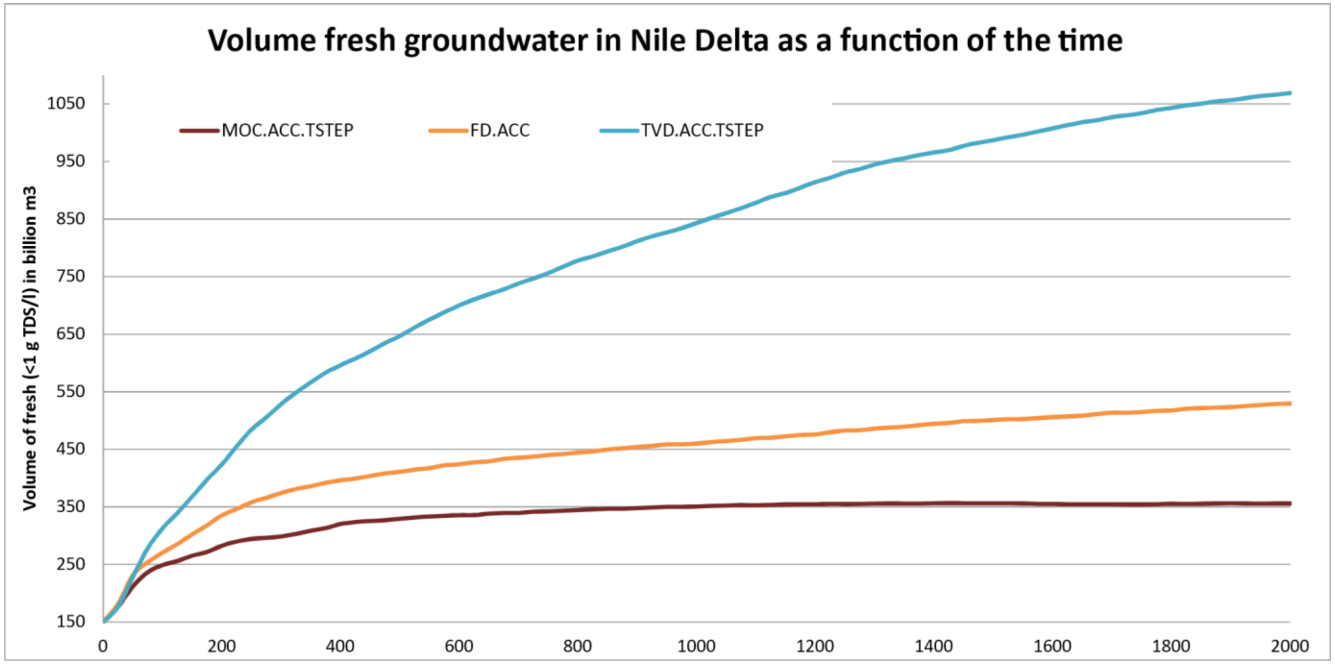


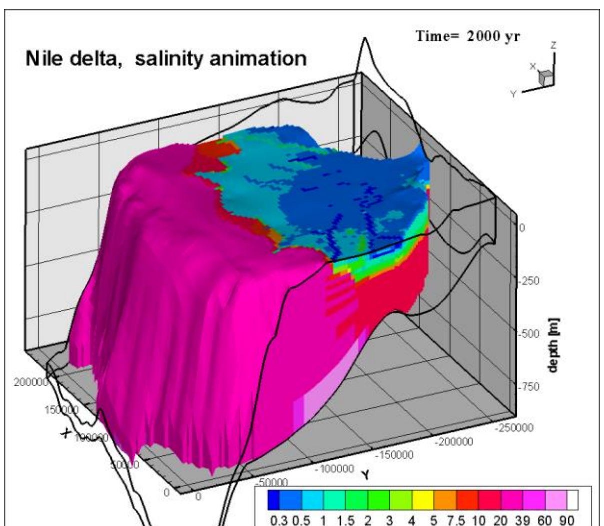
Thorslund, J., Van Vliet, M.T.H., 2020. A global dataset of surface water and groundwater salinity measurements from 1980–2019. Sci. Data 7, 1–11. https://doi.org/10.1038/s41597-020-0562-z

Gurmessa, S.K., MacAllister, D.J., White, D., Ourdraog, I., Lapworth, D., MacDonald, A., 2022. Assessing groundwater salinity across Africa. Sci. Total Environ. 828, 154283. https://doi.org/10.1016/j.scitotenv.2022.154283

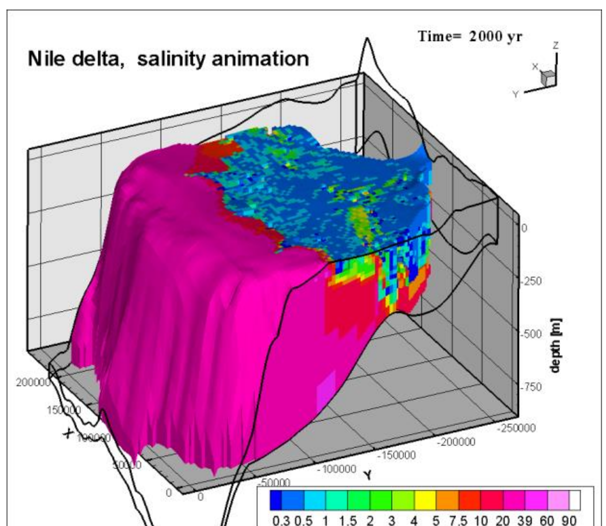
Case Nile delta, effect of solvers



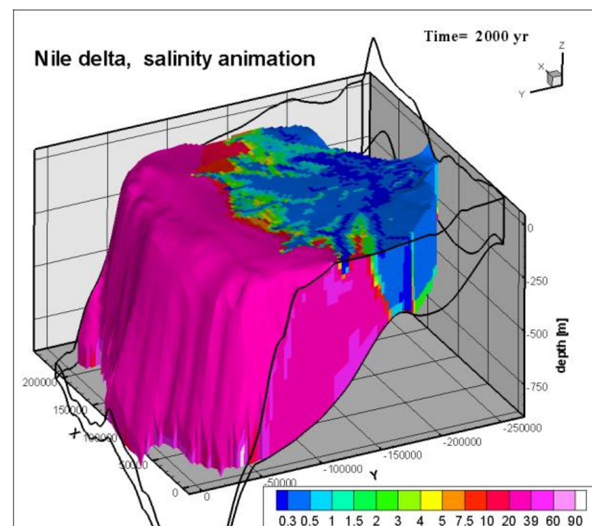
MOC.ACC.TSTEP



FD.ACC



TVD.ACC.TSTEP



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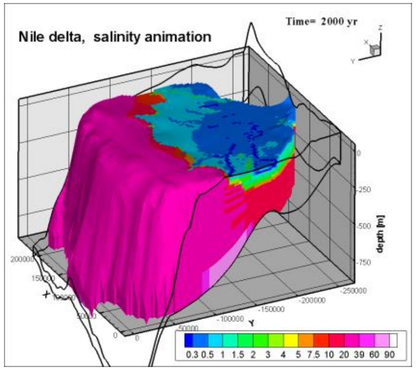
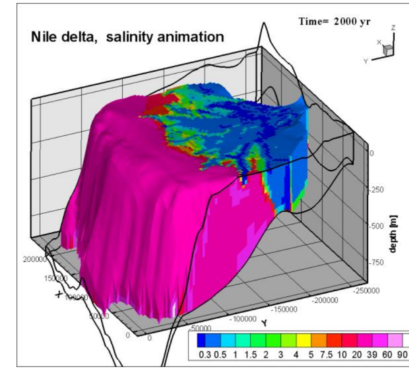
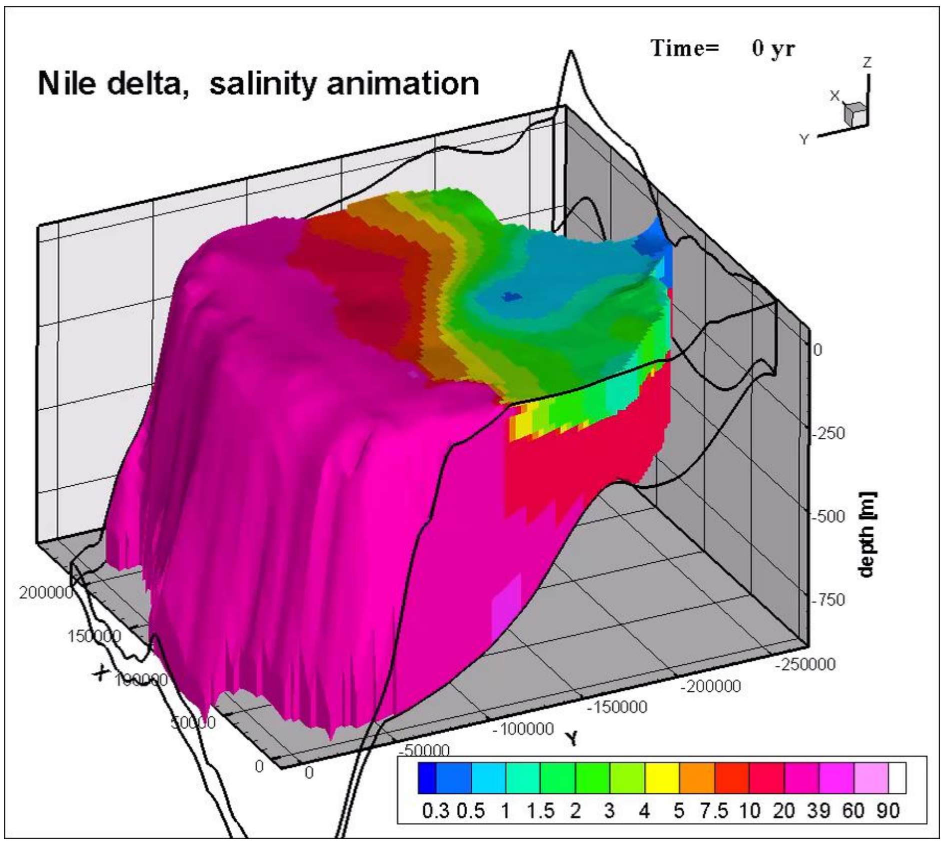
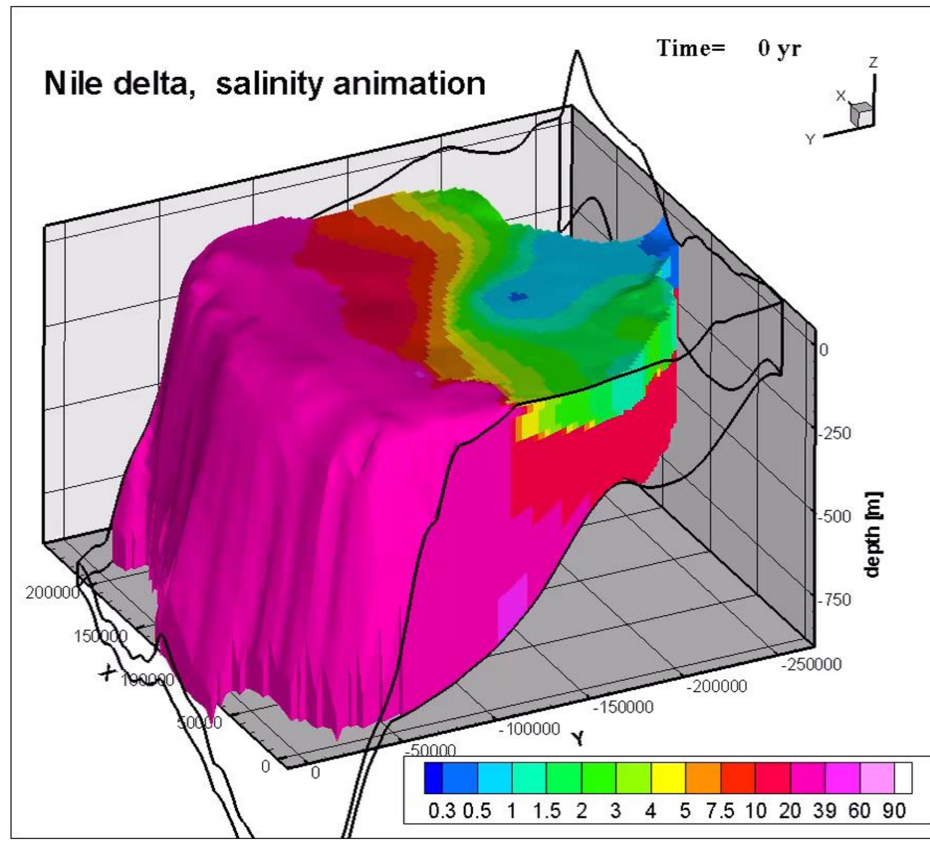


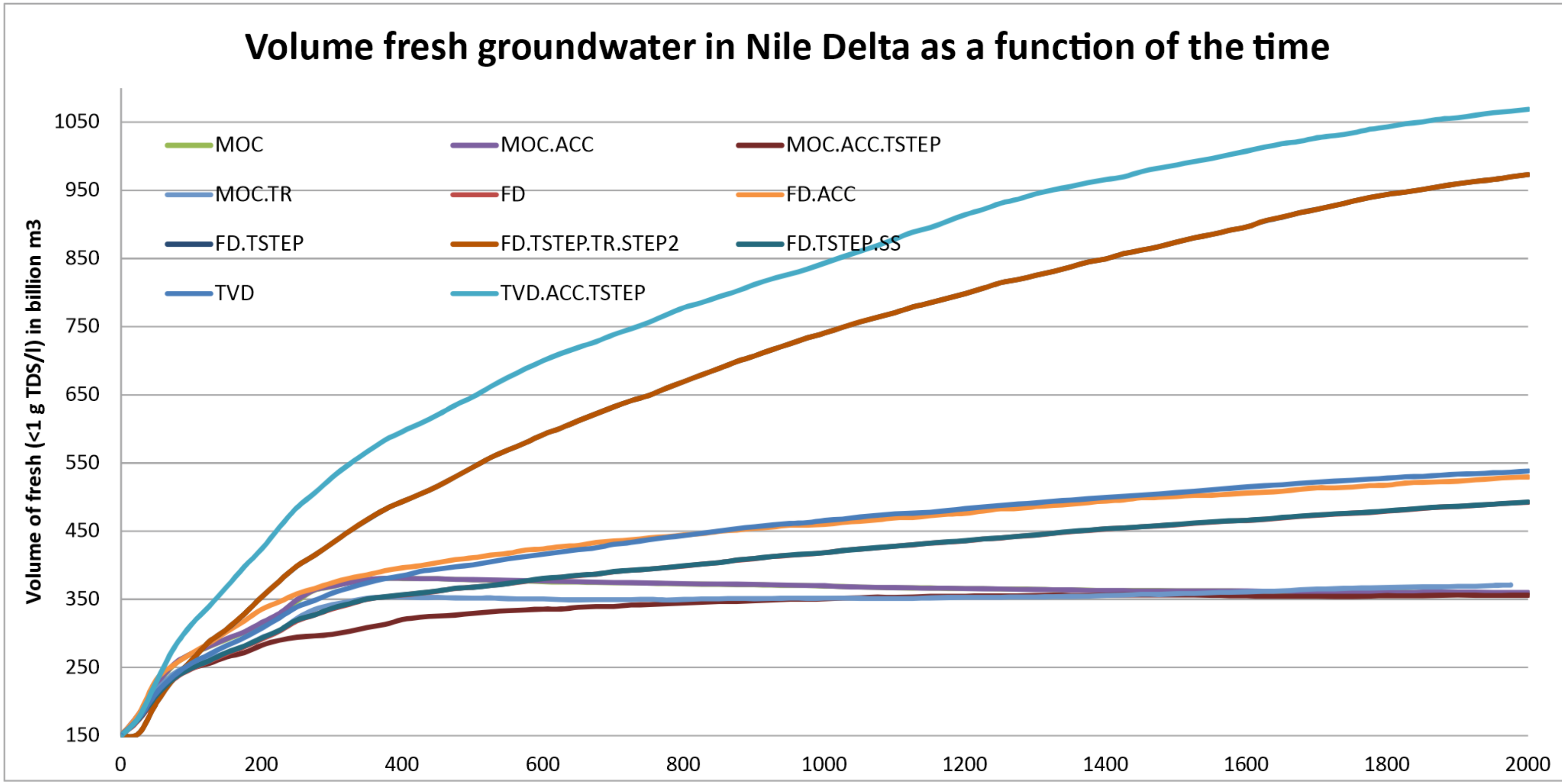
TVD.ACC.TSTEP



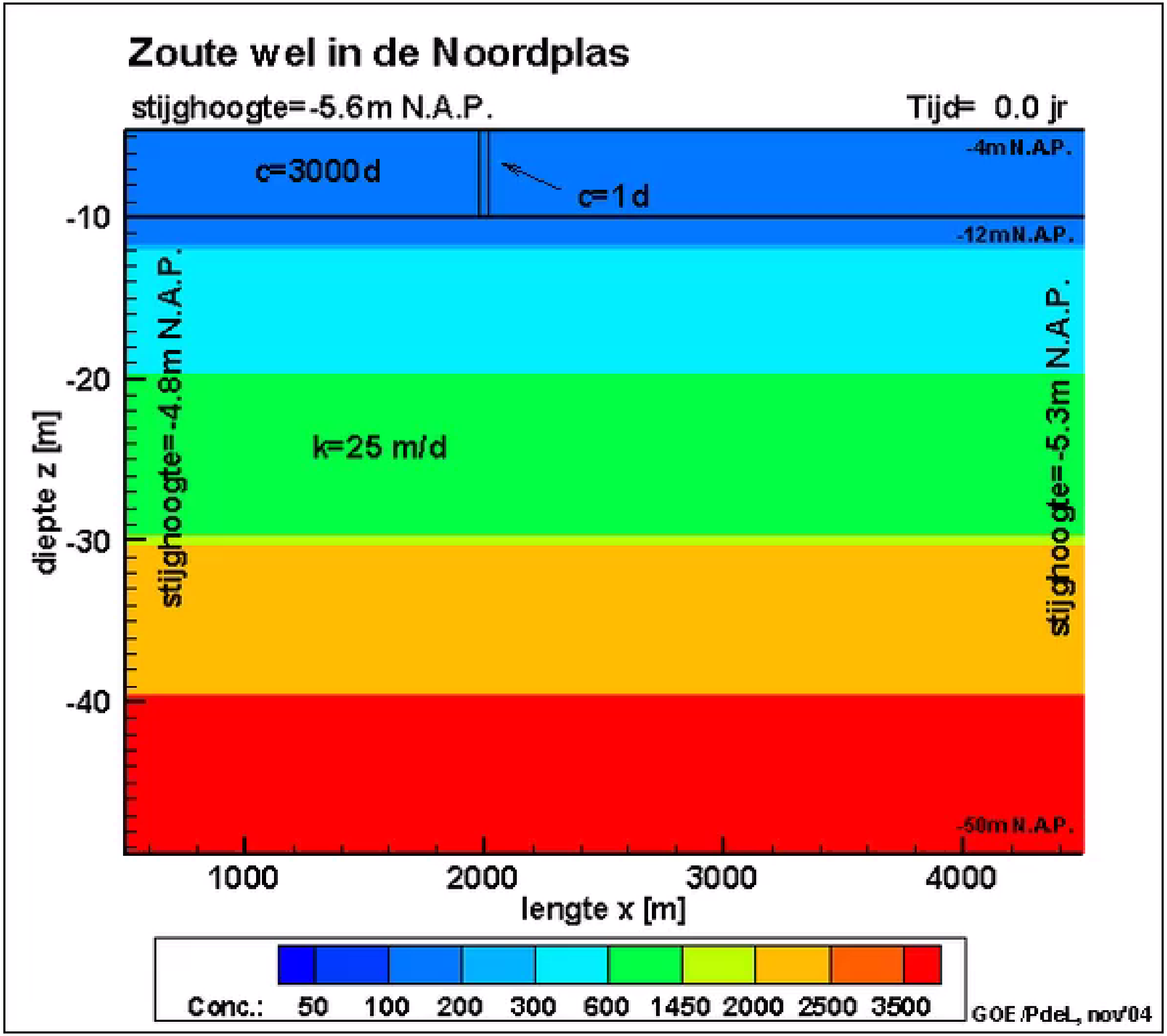




Case Nile delta, effect of solvers, and different settings (e.g. Courant number, number of time steps, SS/TR)



Find the two errors!

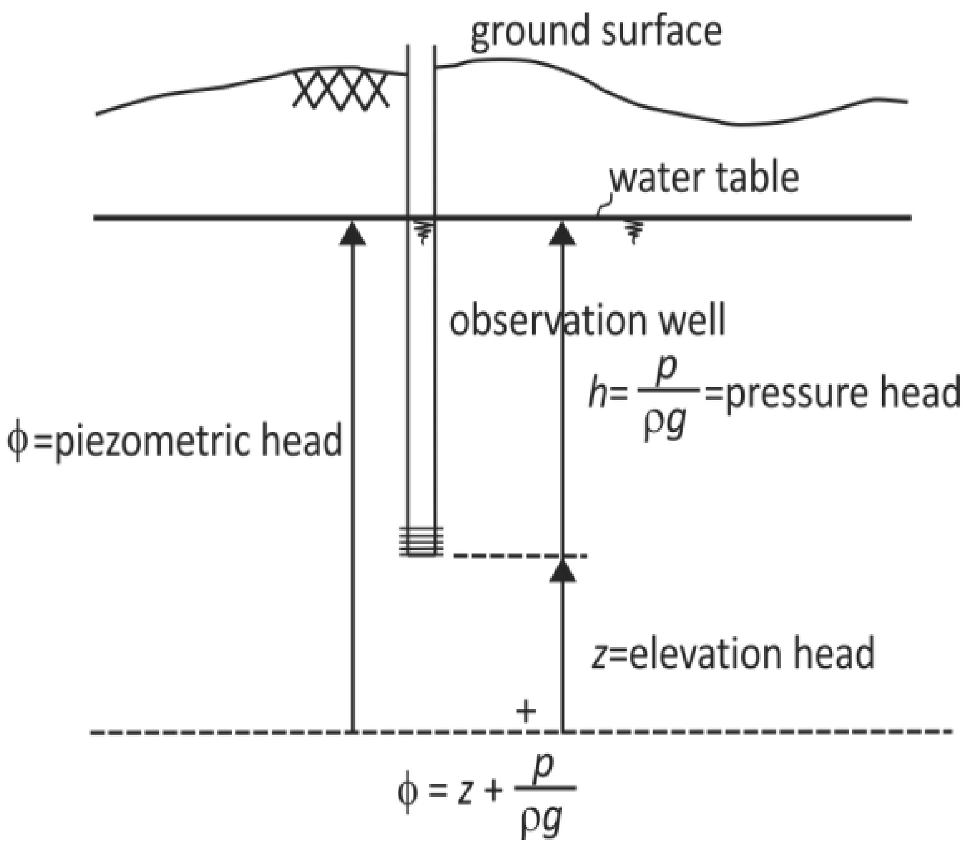


Point water head

and

Freshwater head ϕ_f

Piezometric head ϕ



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

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

Freshwater head ϕ_f

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

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

Freshwater head ϕ_f

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

$$\phi_f = h_f + z$$

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

e.g.:
ρ_s=1025kg/m3
h=10m
ϕ_f=10.25m

Special case: hydrostatic pressure: q_z=0

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

no vertical flow

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

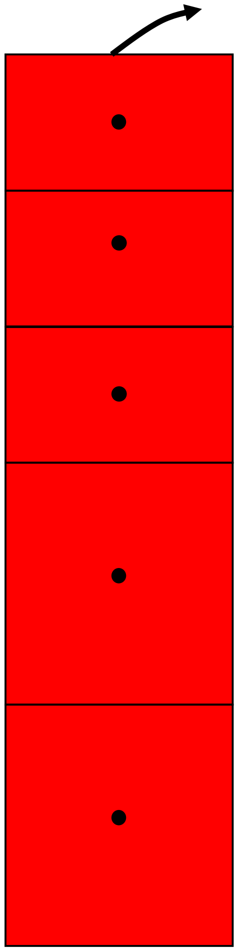
$$\partial \phi_f = -\frac{\rho - \rho_f}{\rho_f}\partial z$$

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

↓ +

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

Hydrostatic boundary condition at the sea



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

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

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

$\rho = 1025\,\text{kg/m3} \longrightarrow$

$\phi_{f4} = 0.3125 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.50\,\text{m}$

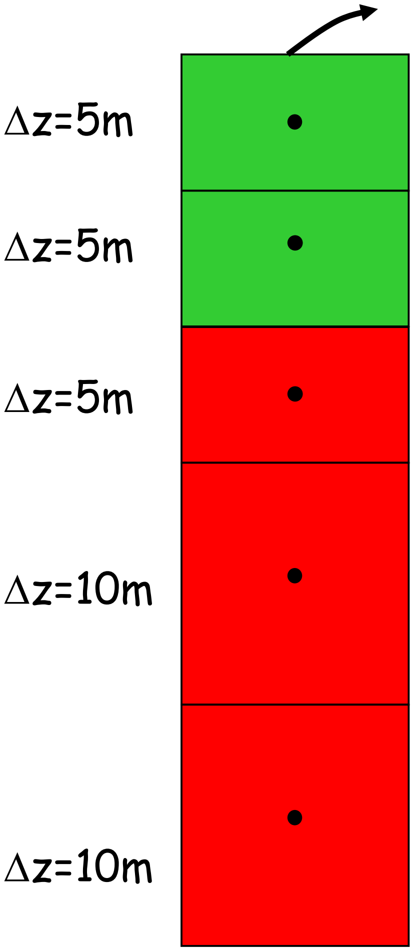
$\rho = 1025\,\text{kg/m3} \longrightarrow$

$\phi_{f5} = 0.50 + 0.025 * (5\text{m} + 5\text{m}) = 0.75\text{m}$

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

Hydrostatic boundary condition at the sea

Water level=+0m MSL



$\rho = 1010\,\text{kg/m3} \longrightarrow \phi_{f1} = 0\text{ m} + 0.010 * 2.5\text{m} = 0.025\,\text{m}$

$\rho = 1010\,\text{kg/m3} \longrightarrow \phi_{f2} = 0.025 + 0.010 * 5\text{m} = 0.075\,\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow$

$\phi_{f3} = 0.075 + 0.010 * 2.5\text{m} + 0.025 * 2.5\text{m} = 0.1625\,\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow$

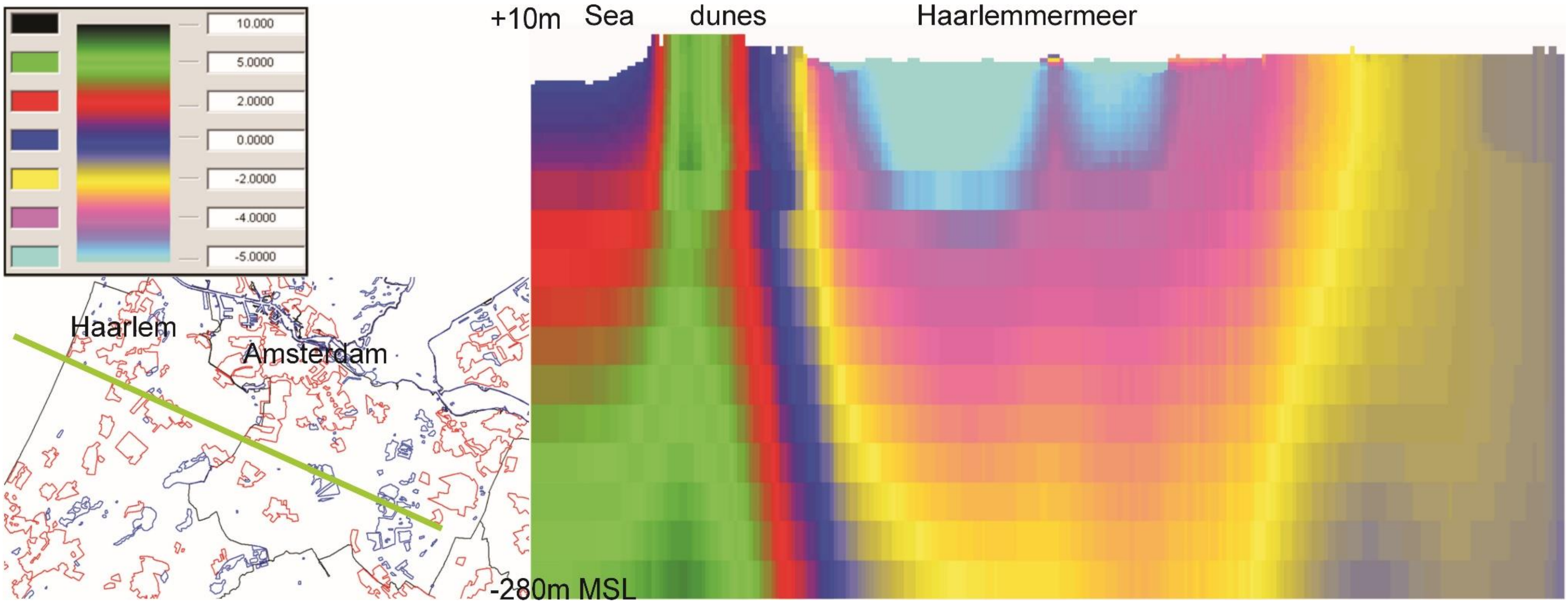
$\phi_{f4} = 0.1625 + 0.025 * (2.5\text{m} + 5\text{m}) = 0.35\text{m}$

$\rho = 1025\,\text{kg/m3} \longrightarrow$

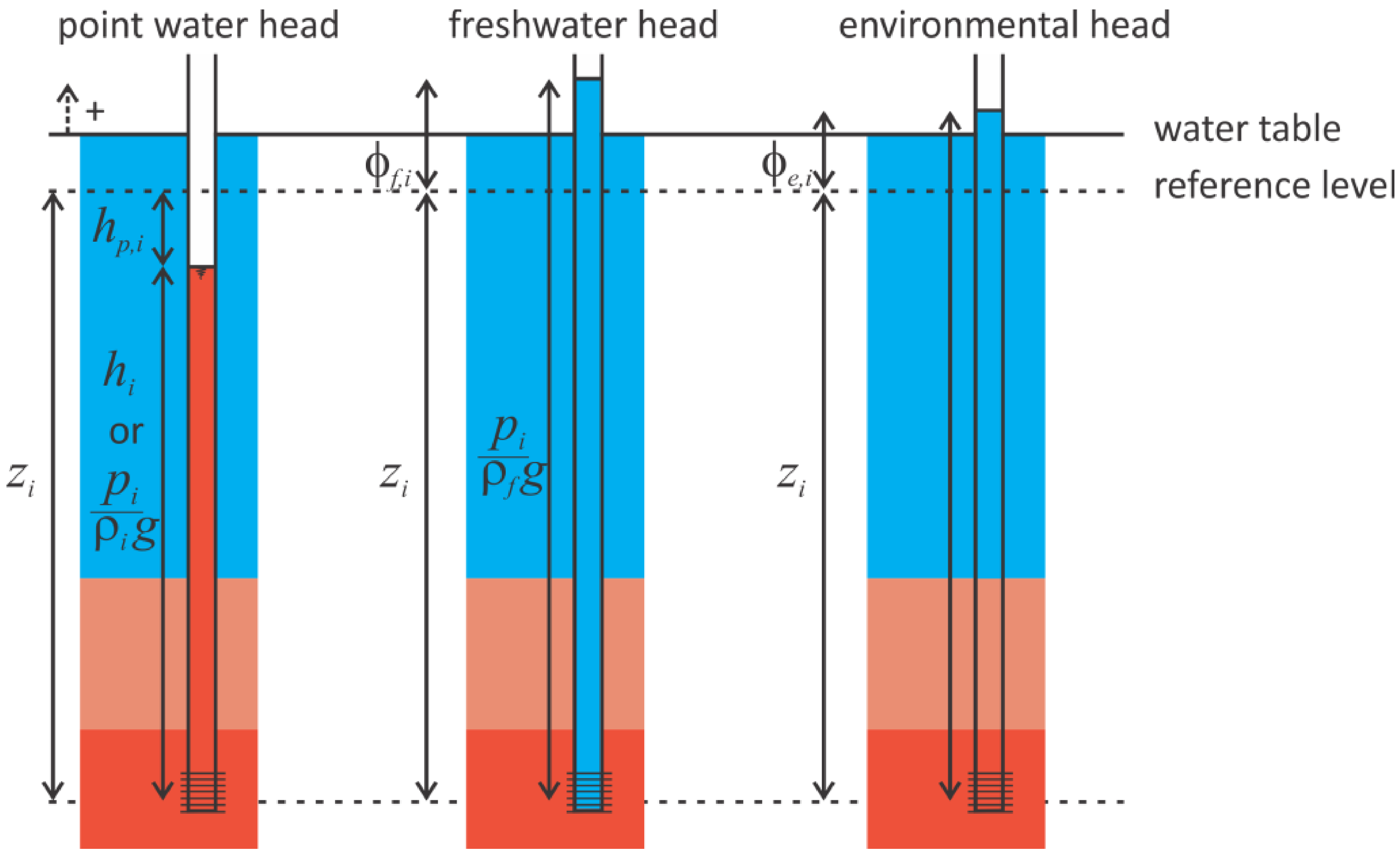
$\phi_{f5} = 0.35 + 0.025 * (5\text{m} + 5\text{m}) = 0.60\,\text{m}$

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

Example 2D profile NHI model freshwater head ϕ_f



Which one is useful?



Post, Kooi and Simmons, 2007, Ground Water

Point water head

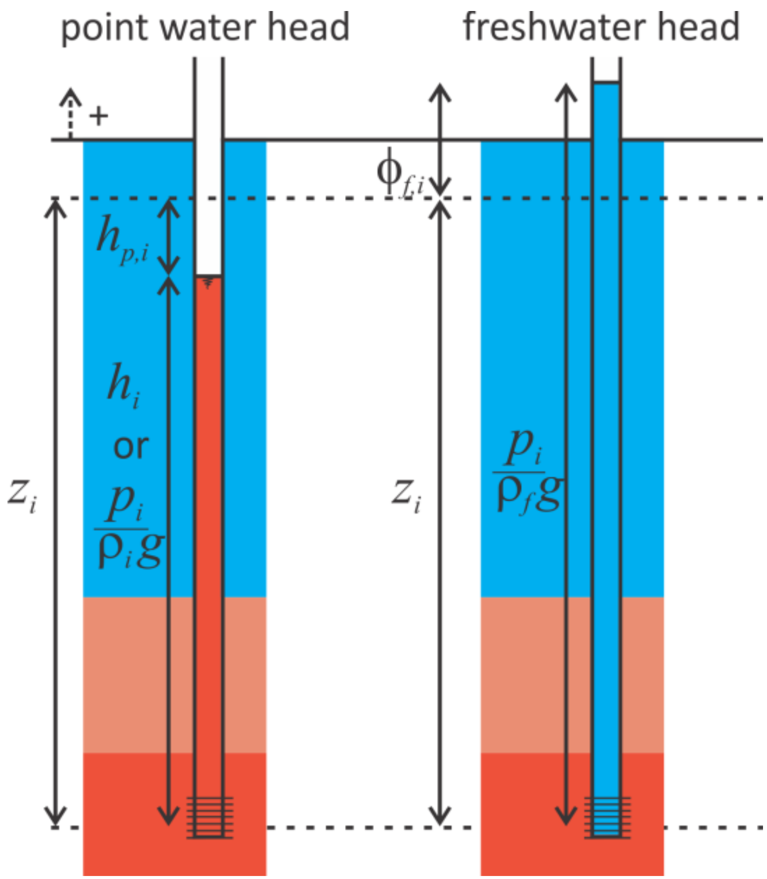
$$h_{p,i} = z_i + h_i \longleftrightarrow h_i = h_{p,i} - z_i$$

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

Freshwater head

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

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



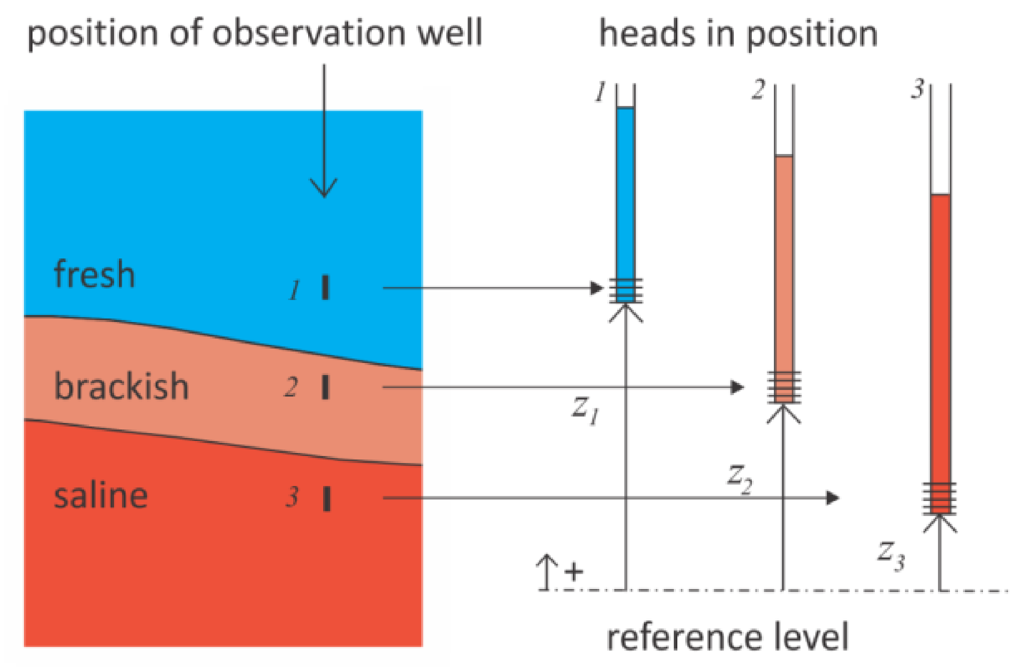
Post, Kooi and Simmons, 2007, Ground Water

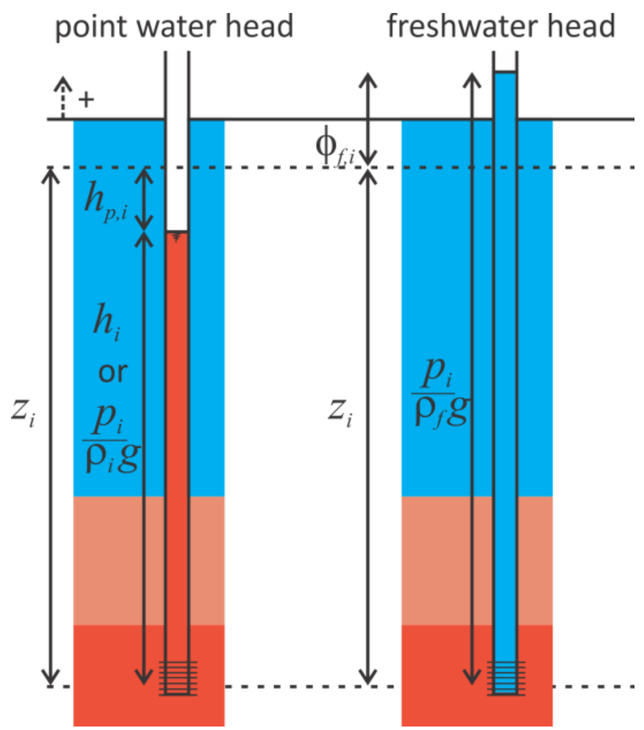
Point water head **Freshwater head**

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

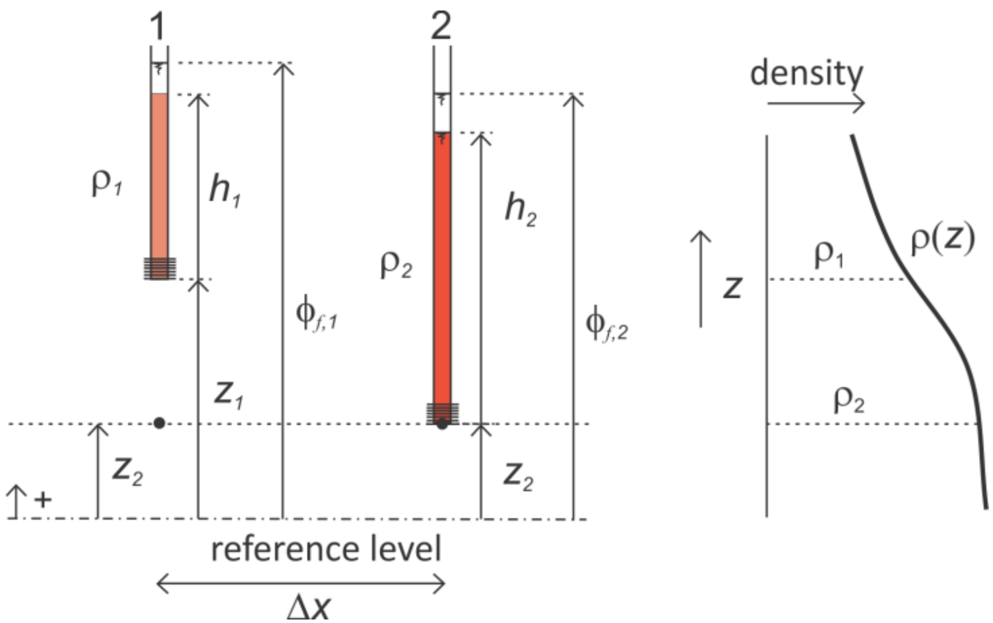
Example 2: $h_{p,i}$=0 $m\ MSL$, ρ_i=1025 kg/m^{-3}, z_i=-10$m\ MSL$: $\phi_{f,i}$=0.25$m\ MSL$.

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





Freshwater head ϕ_f: horizontal flow?

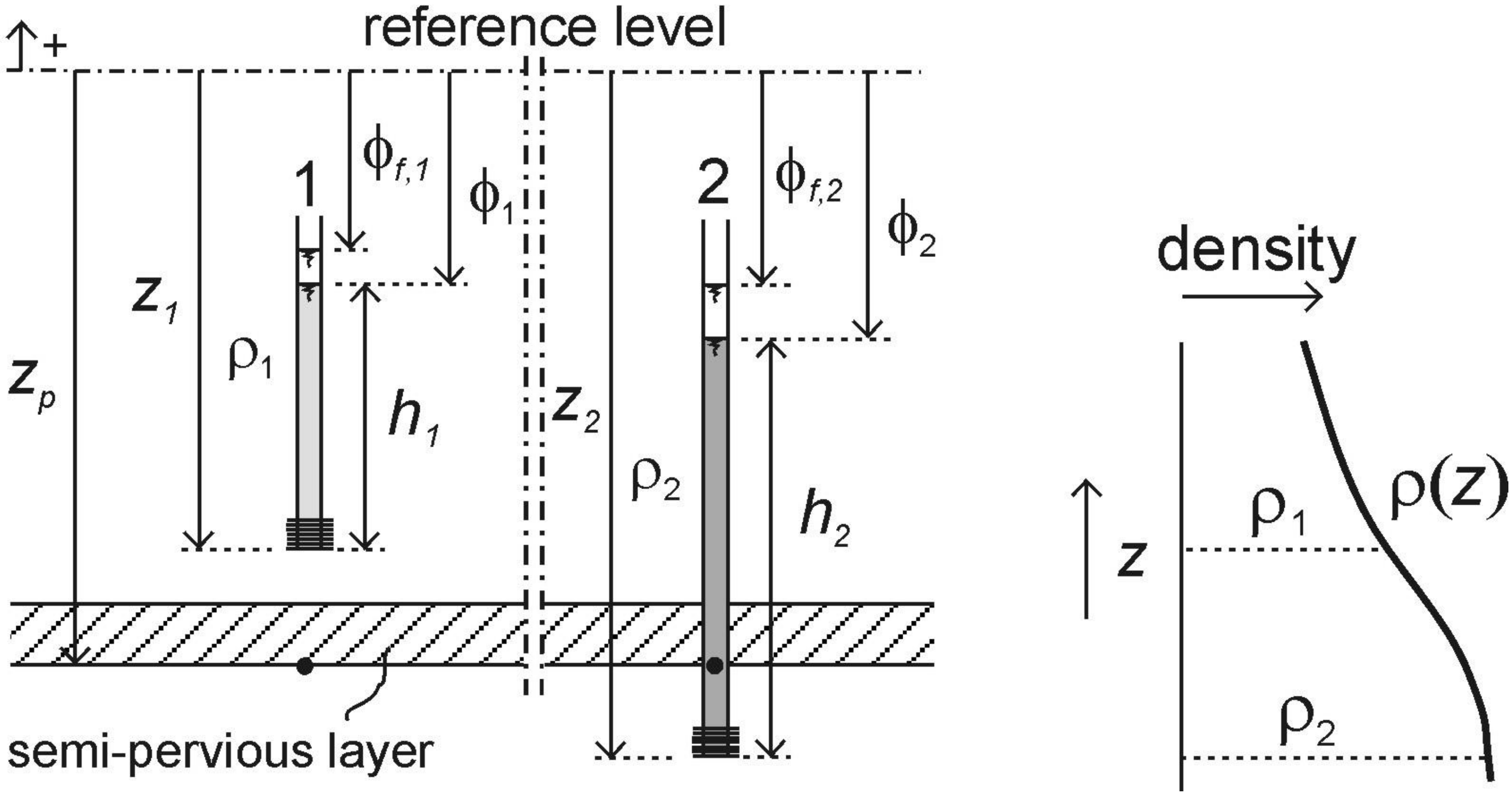


$$p_1^{at\ z=z_2} = \rho_1 g h_1 + \int_{z_2}^{z_1} \rho(z) g dz \qquad \phi_{f,1}^{at\ z=z_2} = z_2 + \frac{\rho_1}{\rho_f} h_1 + \frac{1}{\rho_f g} \int_{z_2}^{z_1} \rho(z) g dz$$

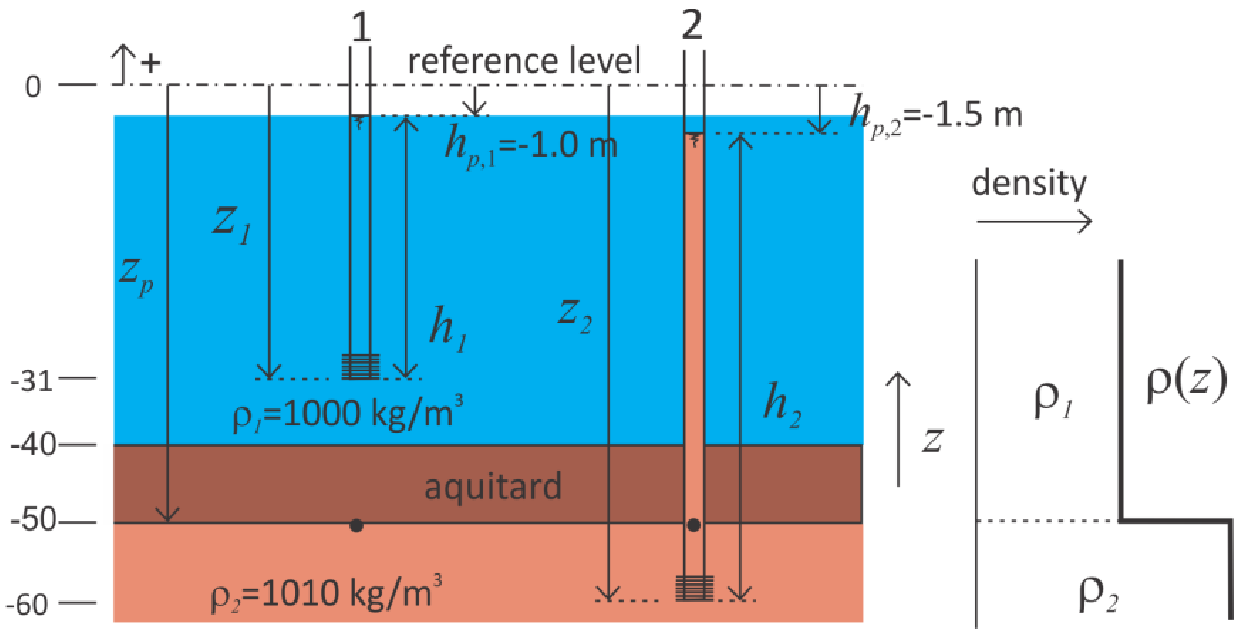
$$p_2^{at\ z=z_2} = \rho_2 g h_2 \qquad \phi_{f,2}^{at\ z=z_2} = z_2 + \frac{\rho_2}{\rho_f} h_2$$

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

Freshwater head ϕ_f : vertical flow?

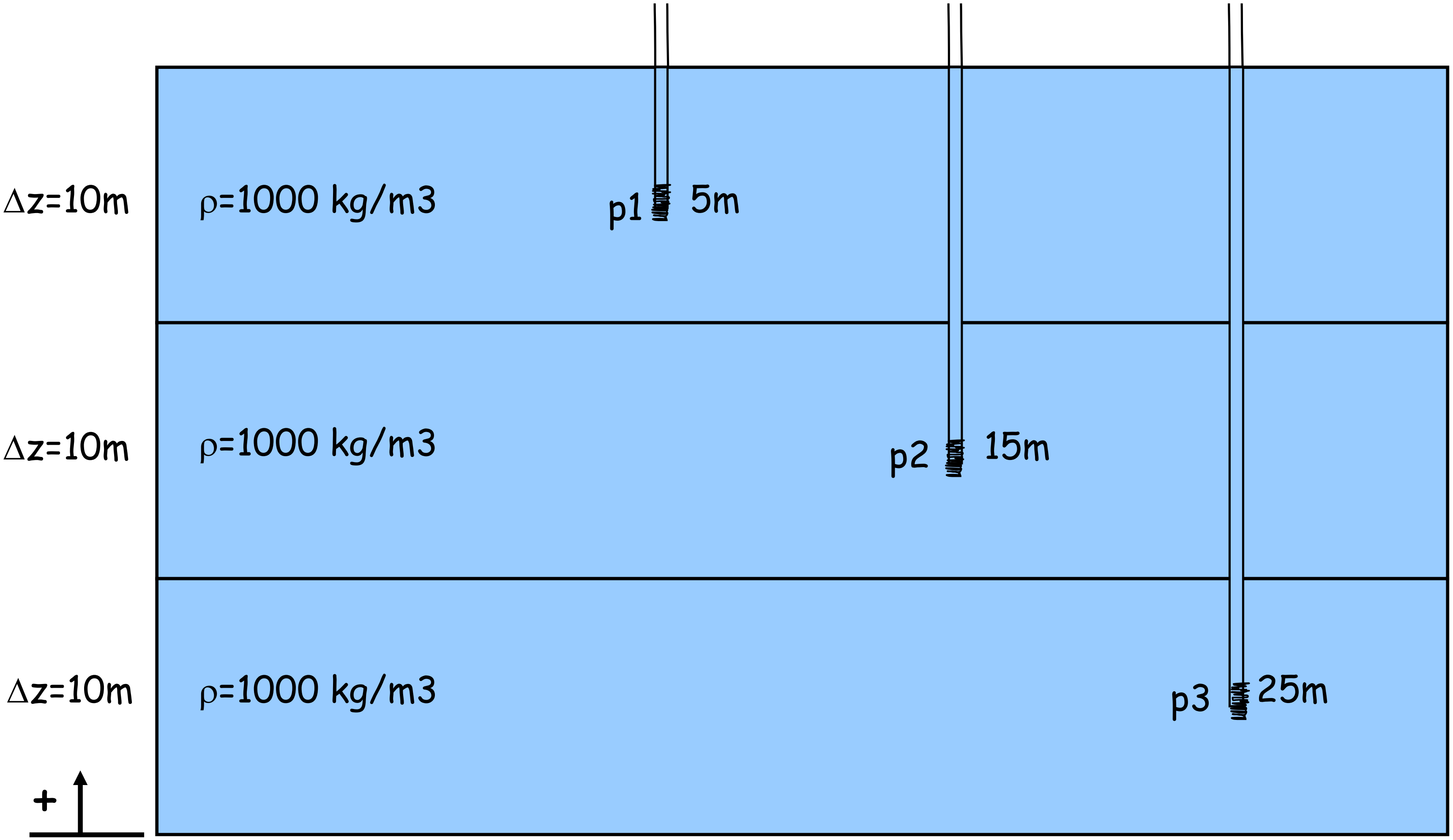


Freshwater head ϕ_f



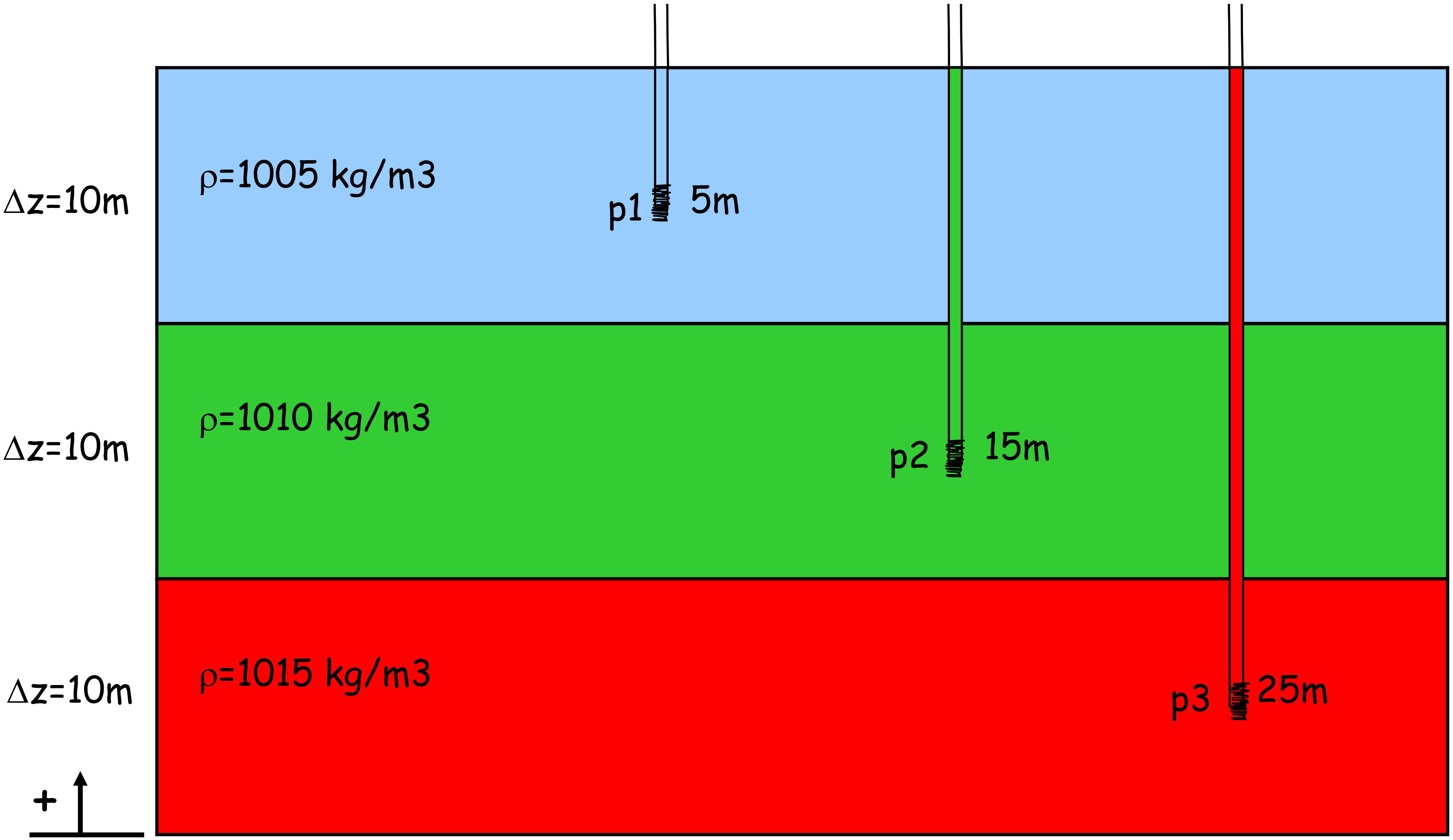
$$\phi_{f,1}^{z=-50} = -50 + \frac{1000}{1000}30 + \frac{1}{1000g}\int_{-50}^{-31} 1000 g dz = -50 + 30 + 19 = -1.0$$

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



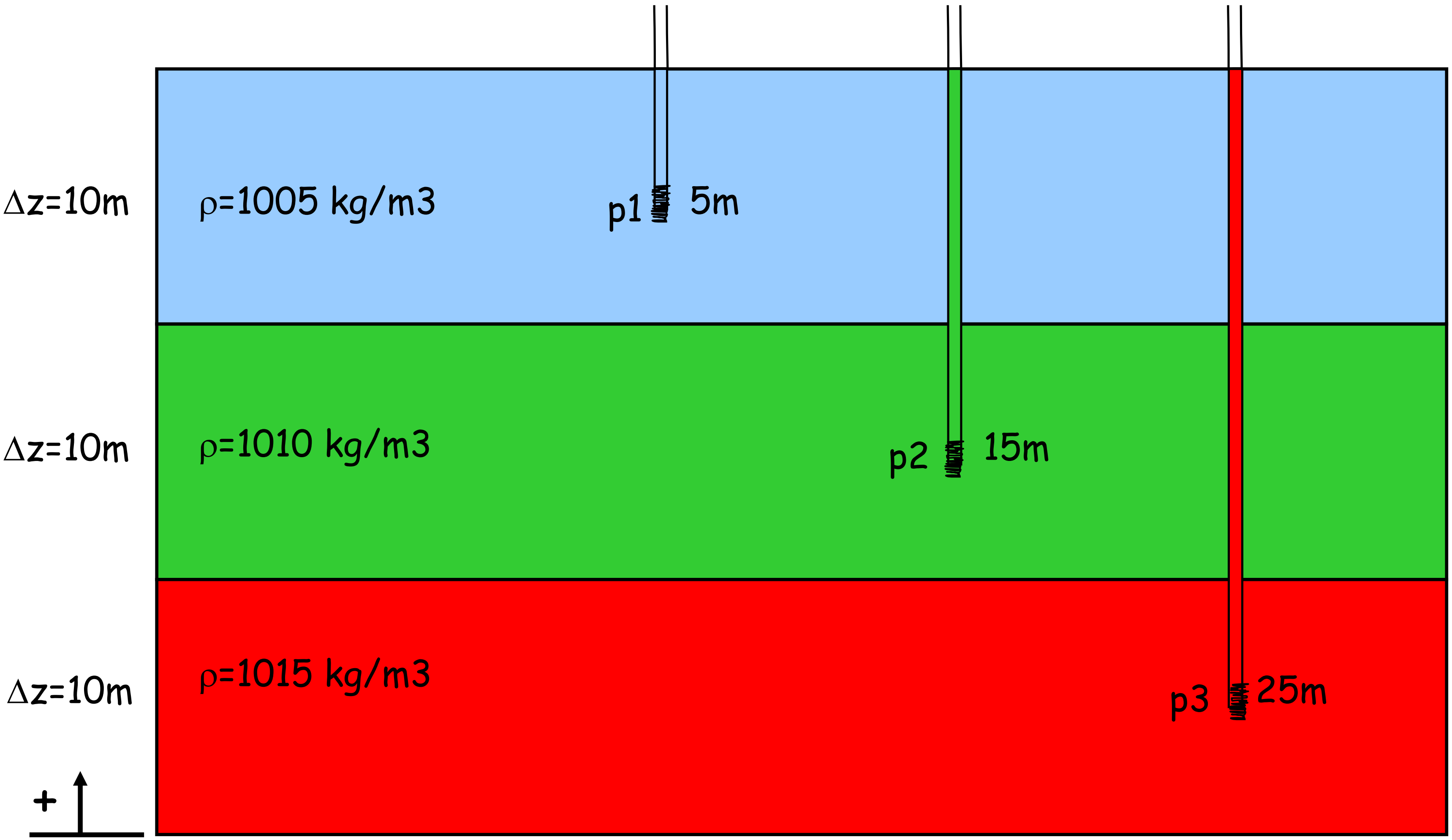
Δz=10m
ρ=1000 kg/m3
p1
5m
Δz=10m
ρ=1000 kg/m3
p2
15m
Δz=10m
ρ=1000 kg/m3
p3
25m
+

No flow



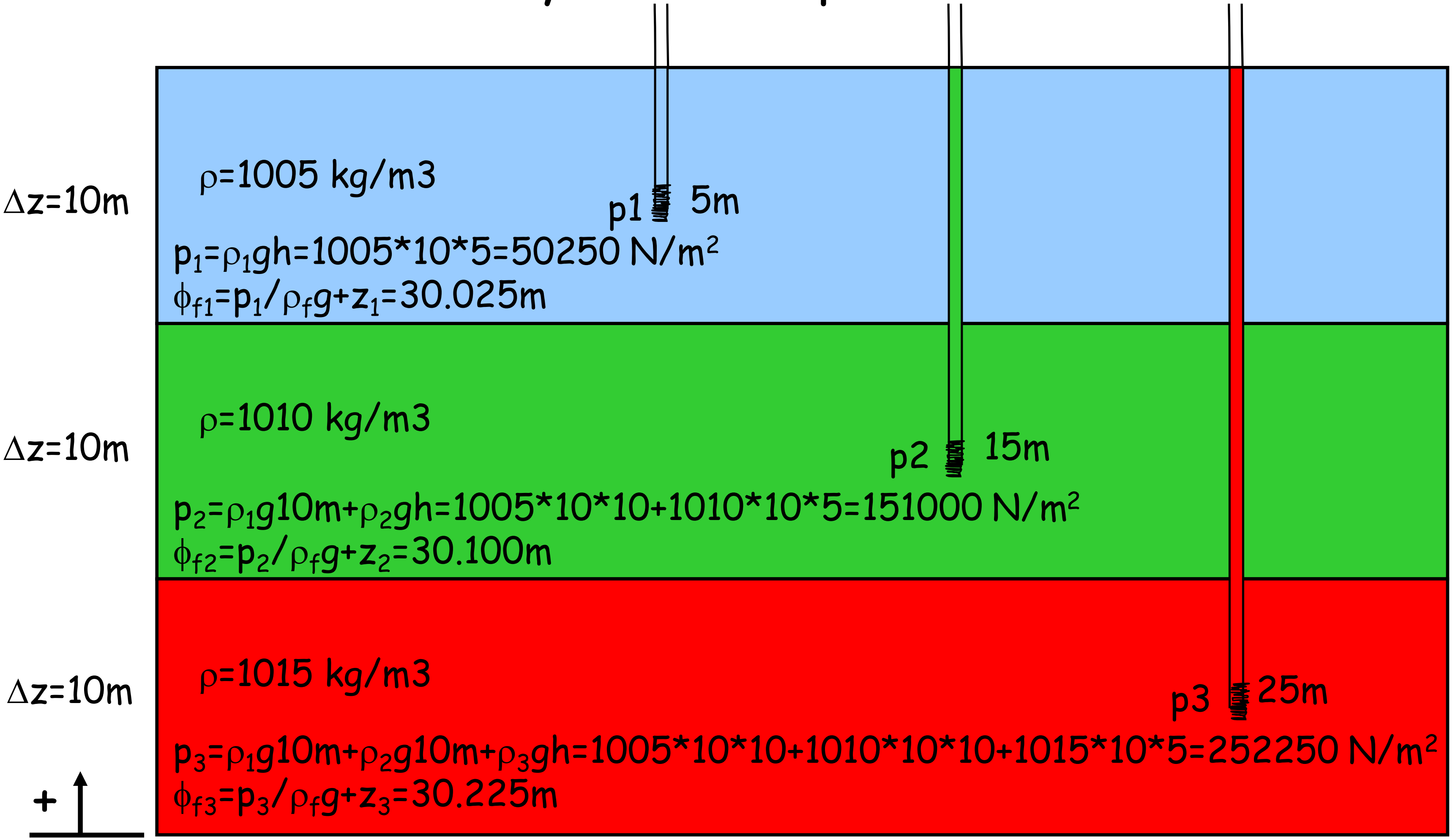
Flow or no flow? (if p≠hydrostatic than flow)

Calculate to freshwater head!



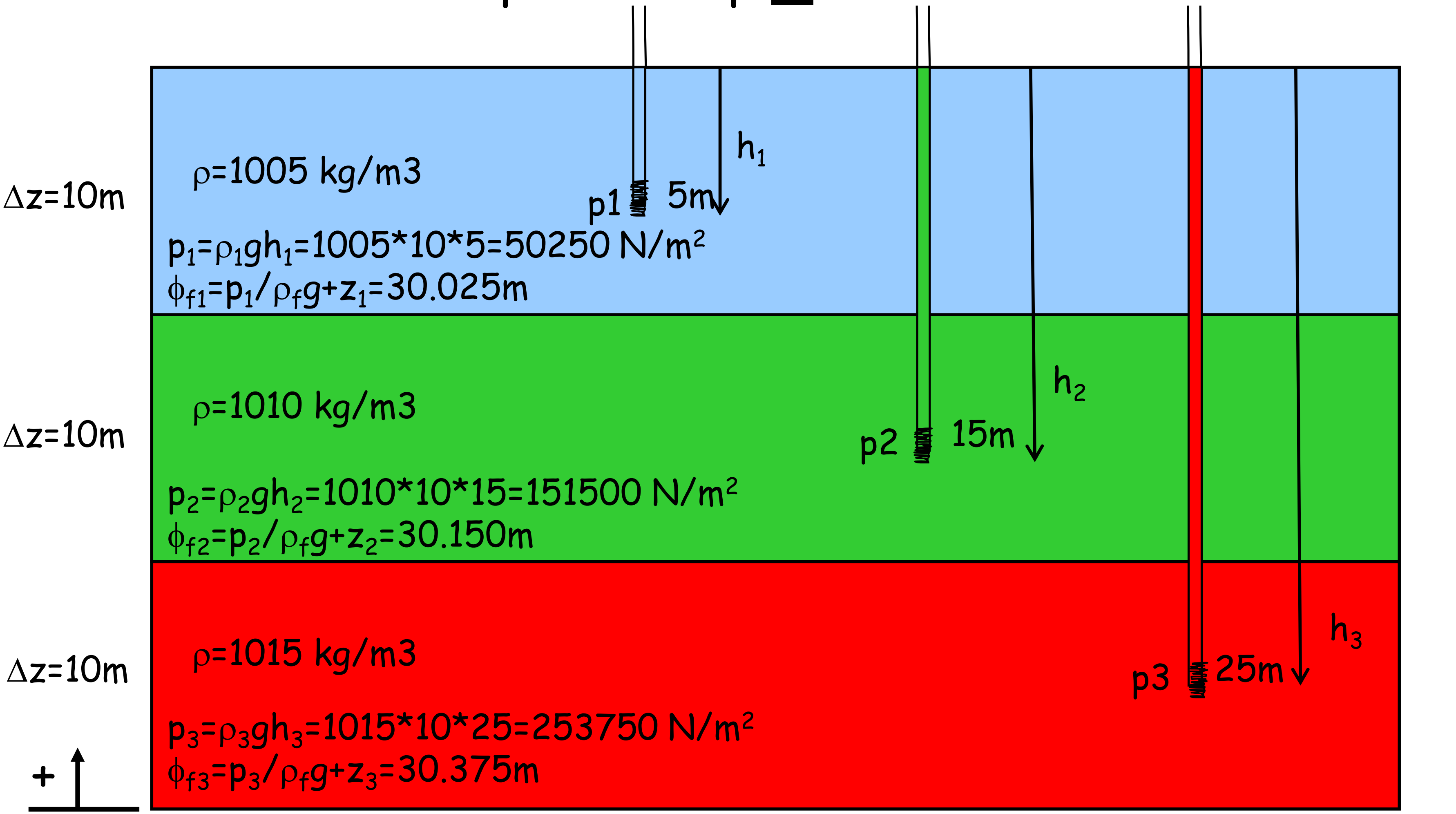
1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)

1. Determine hydrostatic pressure and frwhead



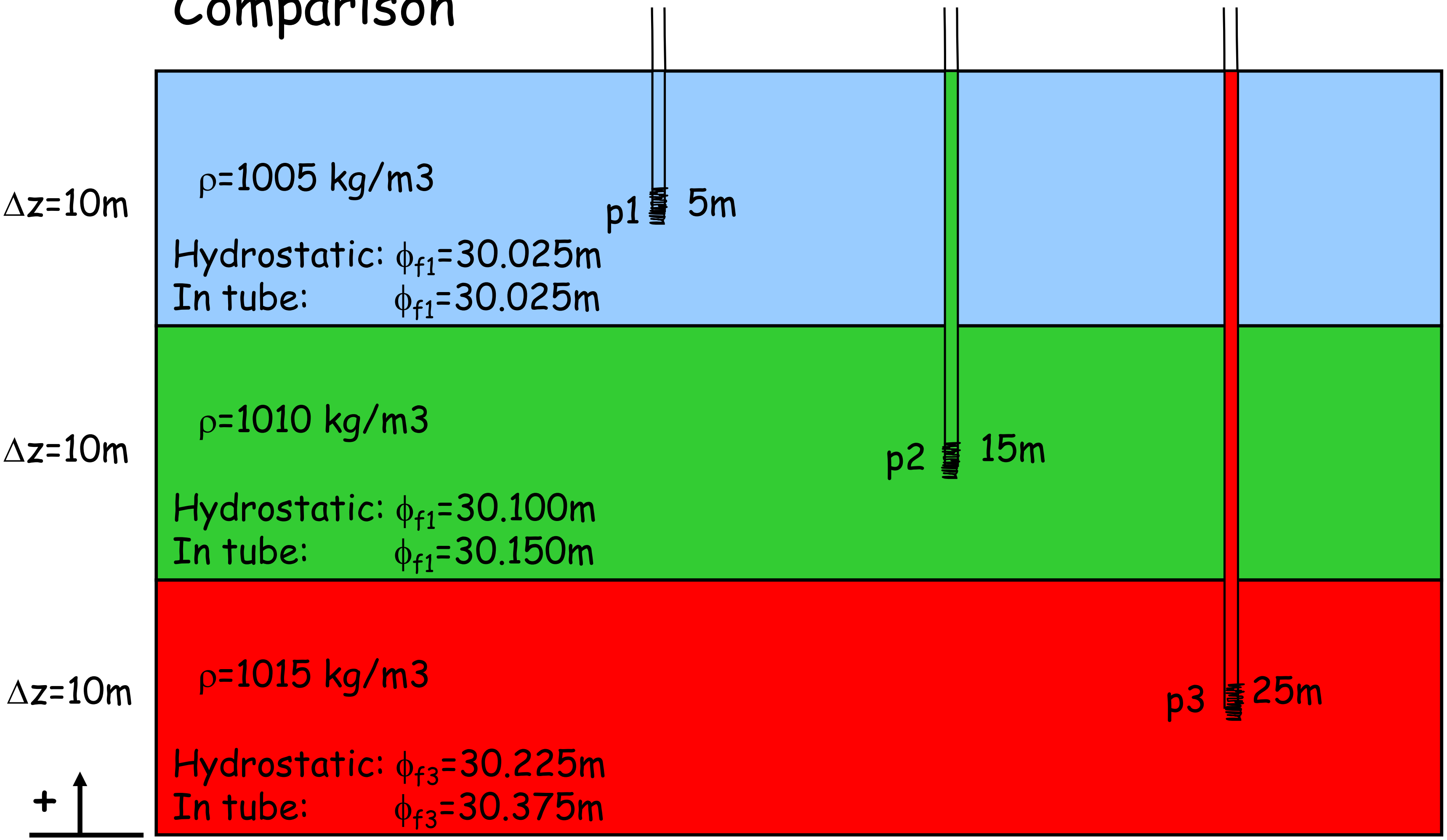
1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)

2. Determine pressure p <u>in</u> well and frwhead



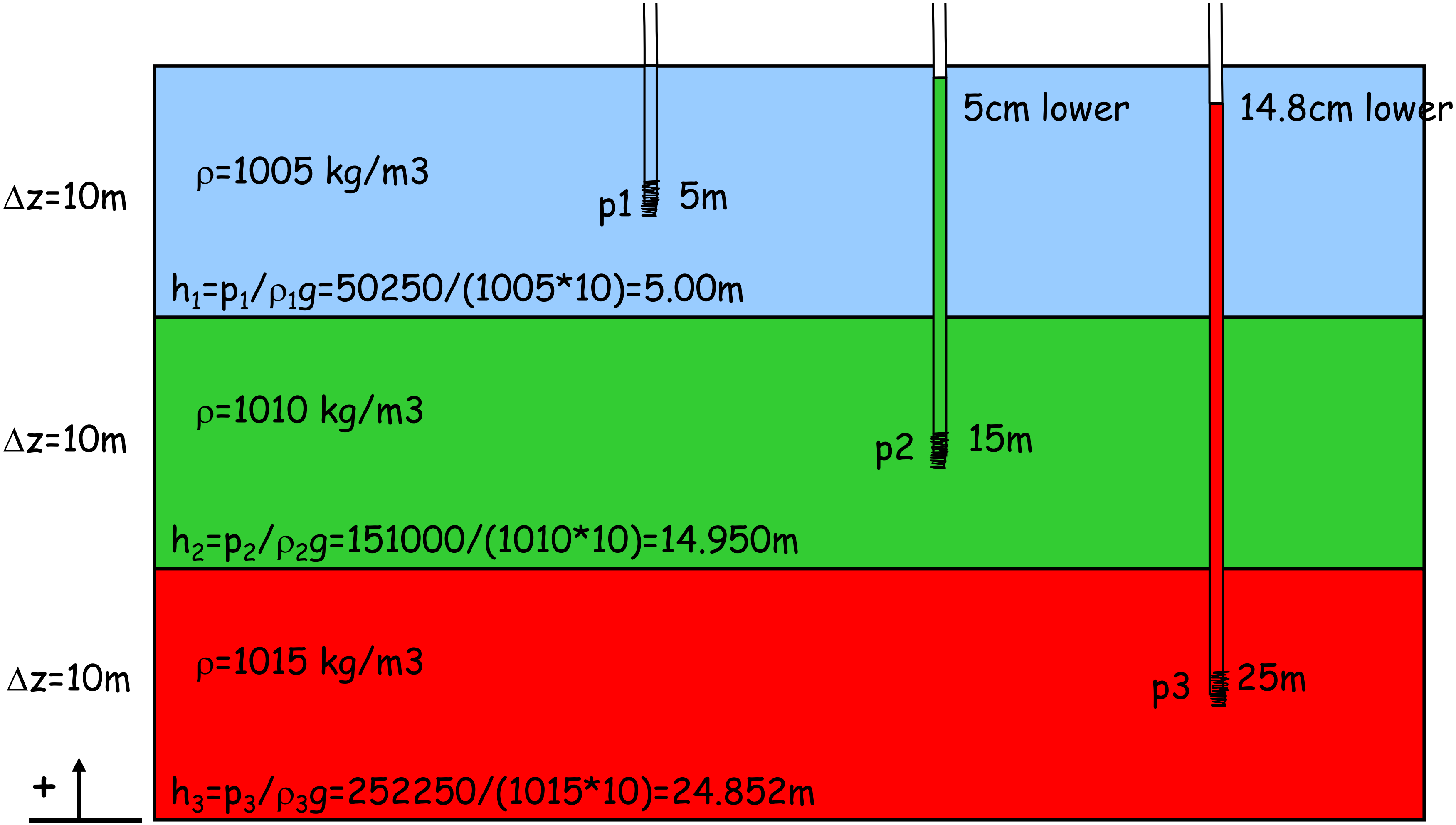
1. Determine hydrostatic pressure (and freshwater head ϕ_f)
2. Determine pressure p <u>in</u> well! (and freshwater head ϕ_f)

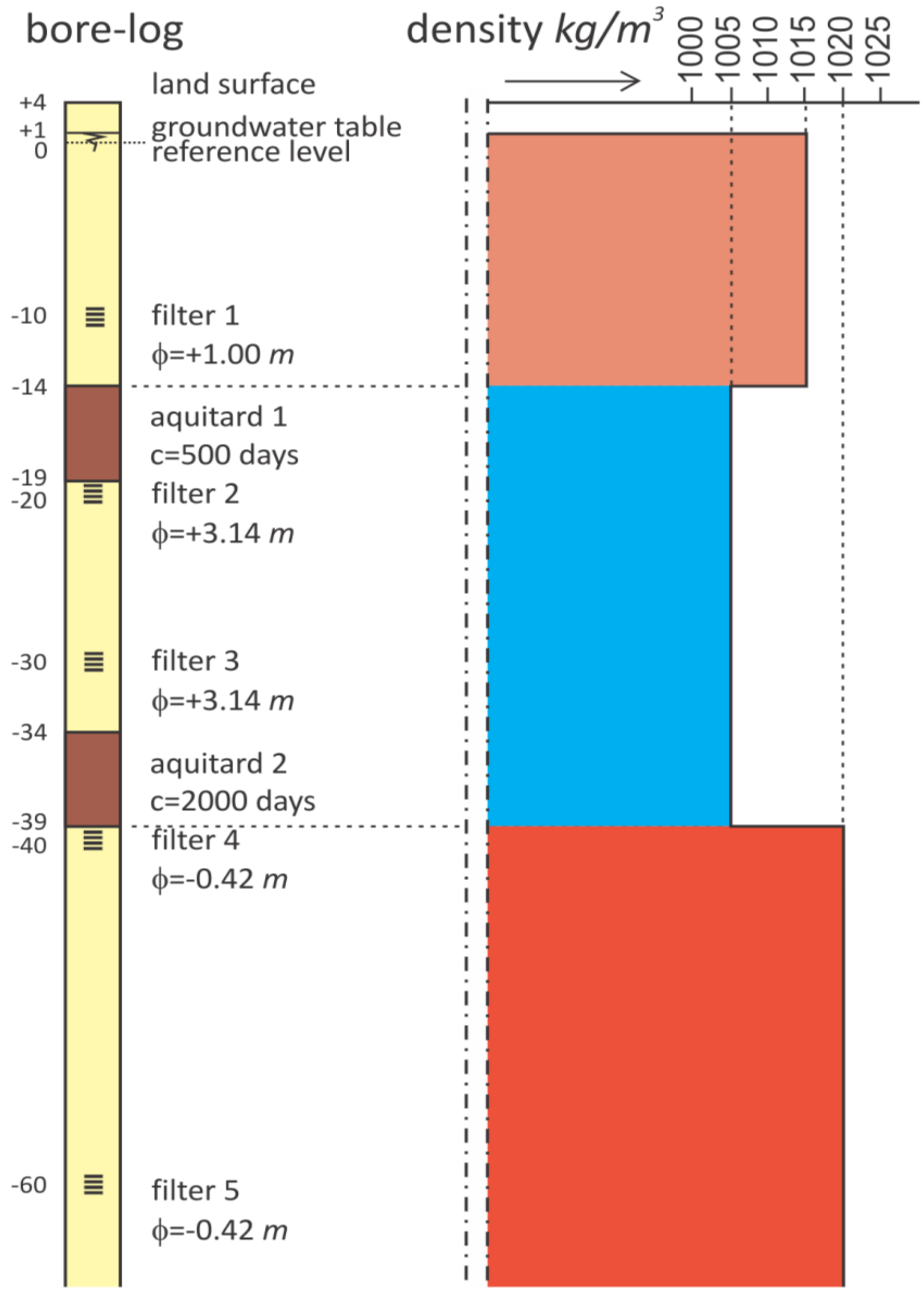
Comparison



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

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





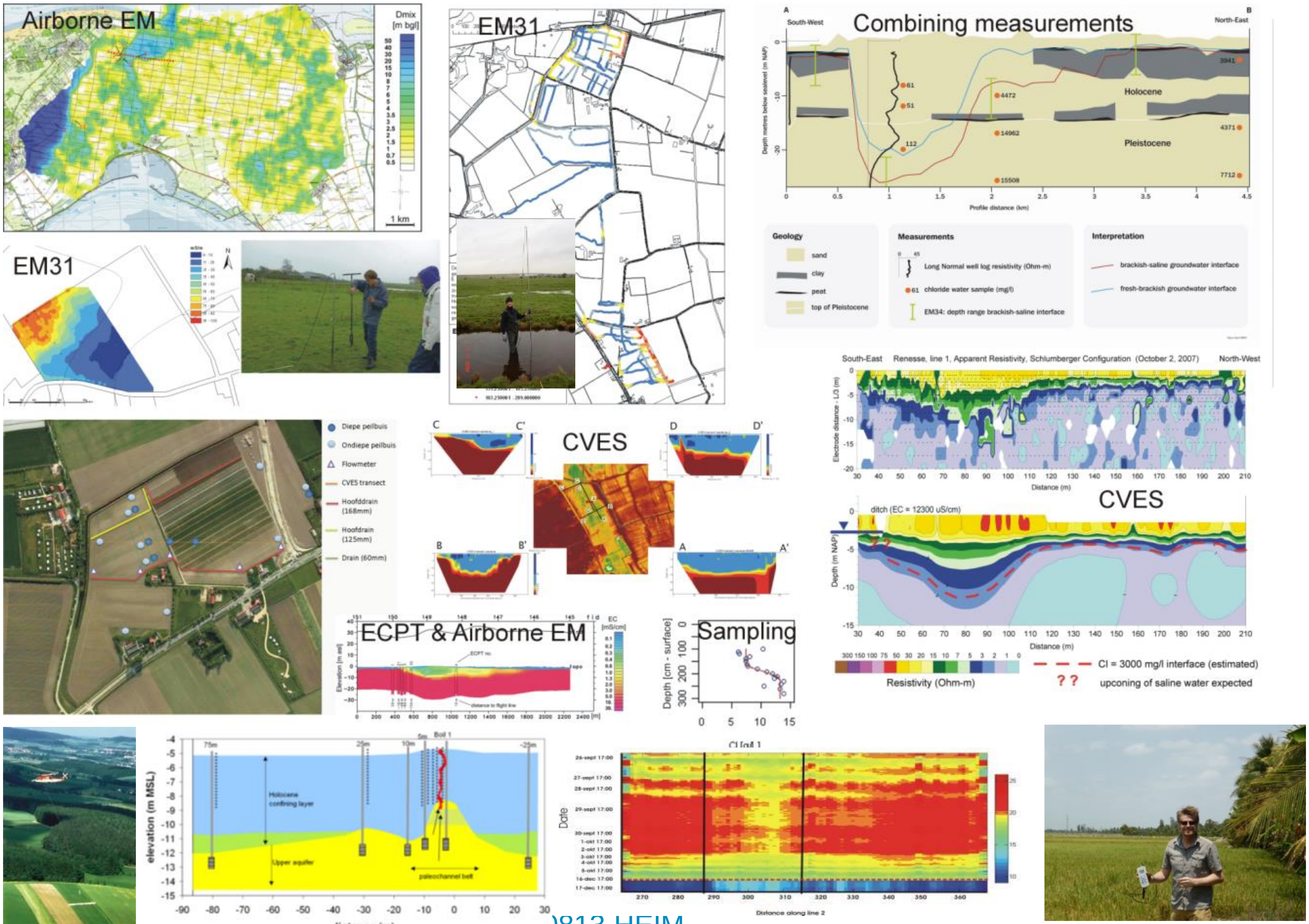
bore-log
density kg/m^3
1000
1005
1010
1015
1020
1025
land surface
+4
+1
0
groundwater table
reference level
-10
filter 1
ϕ=+1.00 *m*
-14
aquitard 1
c=500 days
-19
-20
filter 2
ϕ=+3.14 *m*
-30
filter 3
ϕ=+3.14 *m*
-34
aquitard 2
c=2000 days
-39
-40
filter 4
ϕ=-0.42 *m*
-60
filter 5
ϕ=-0.42 *m*

Take home message

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

Monitoring

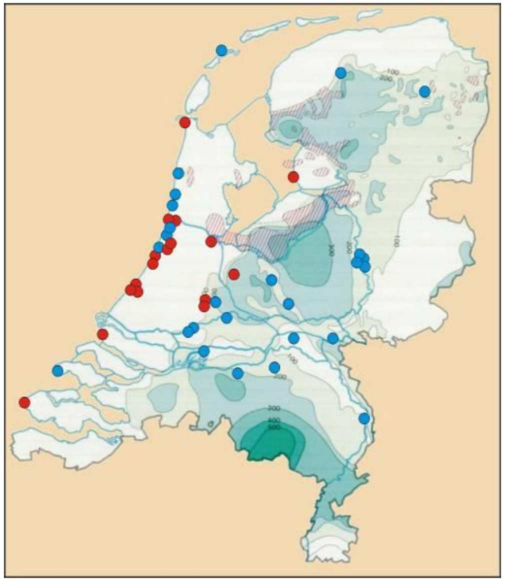
Different (fresh-salt) monitoring techniques



)813 HEIM

Monitoring salt in groundwater

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



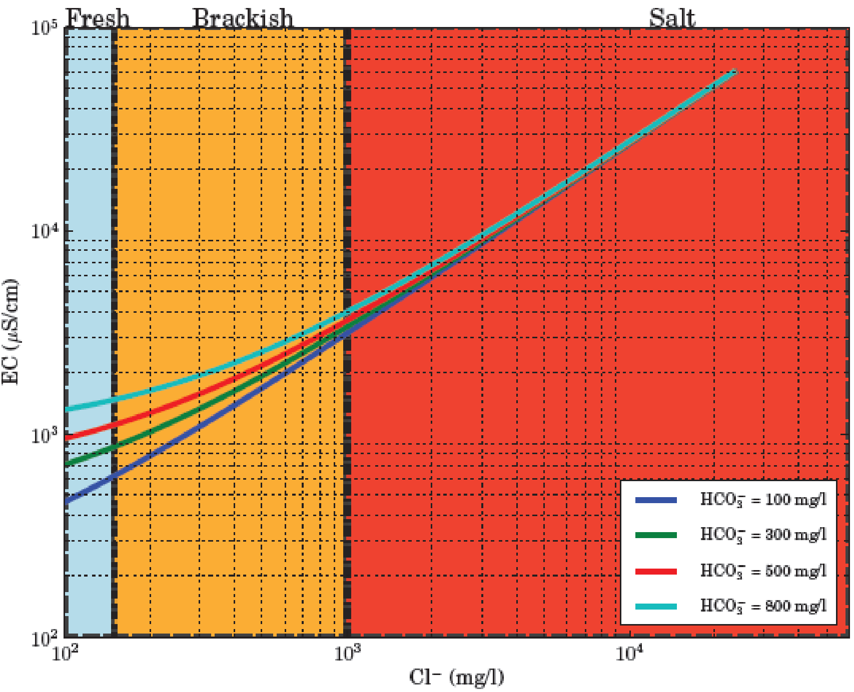
Pumping stations with salinisation

Pumping stations closed due to salinisation

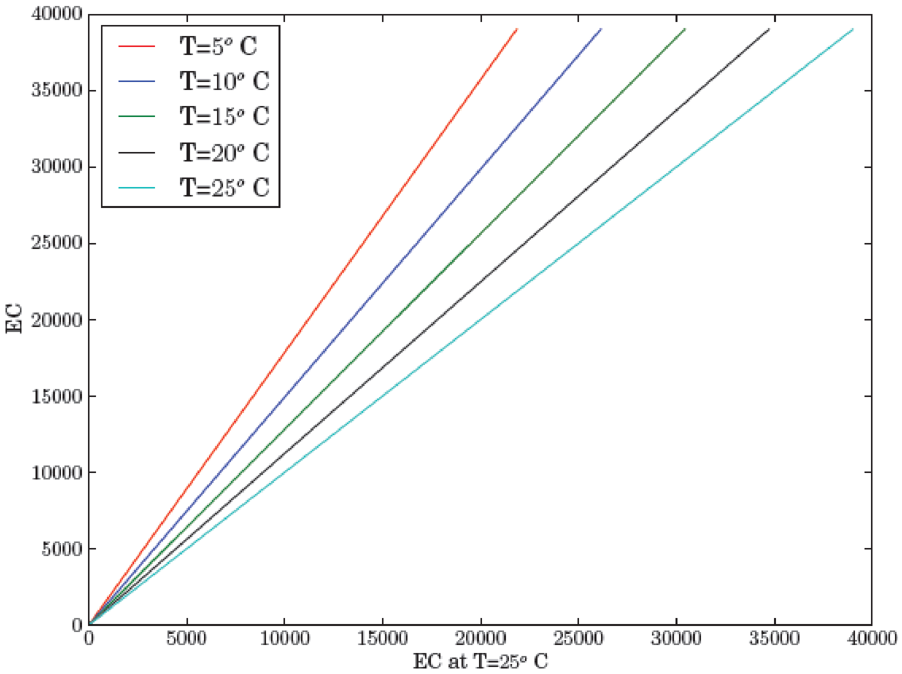
- Methods:
  1. Direct: water sample available
  2. Indirect: conductance of the subsoil

Source: V. Post, 2007

EC and Chloride



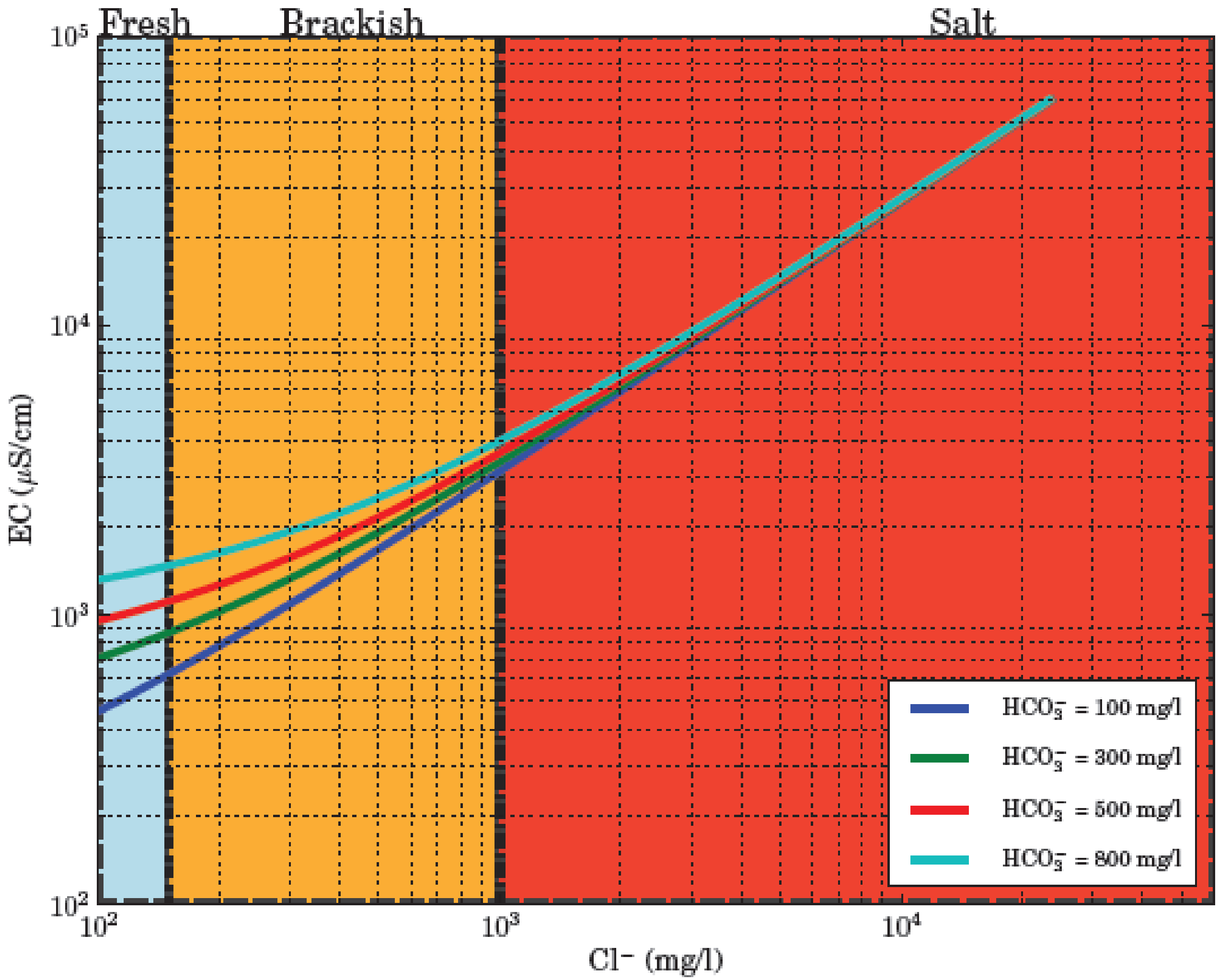
EC-Cl at different HCO_3^- concentrations.



(b) EC and temperature standardized EC.

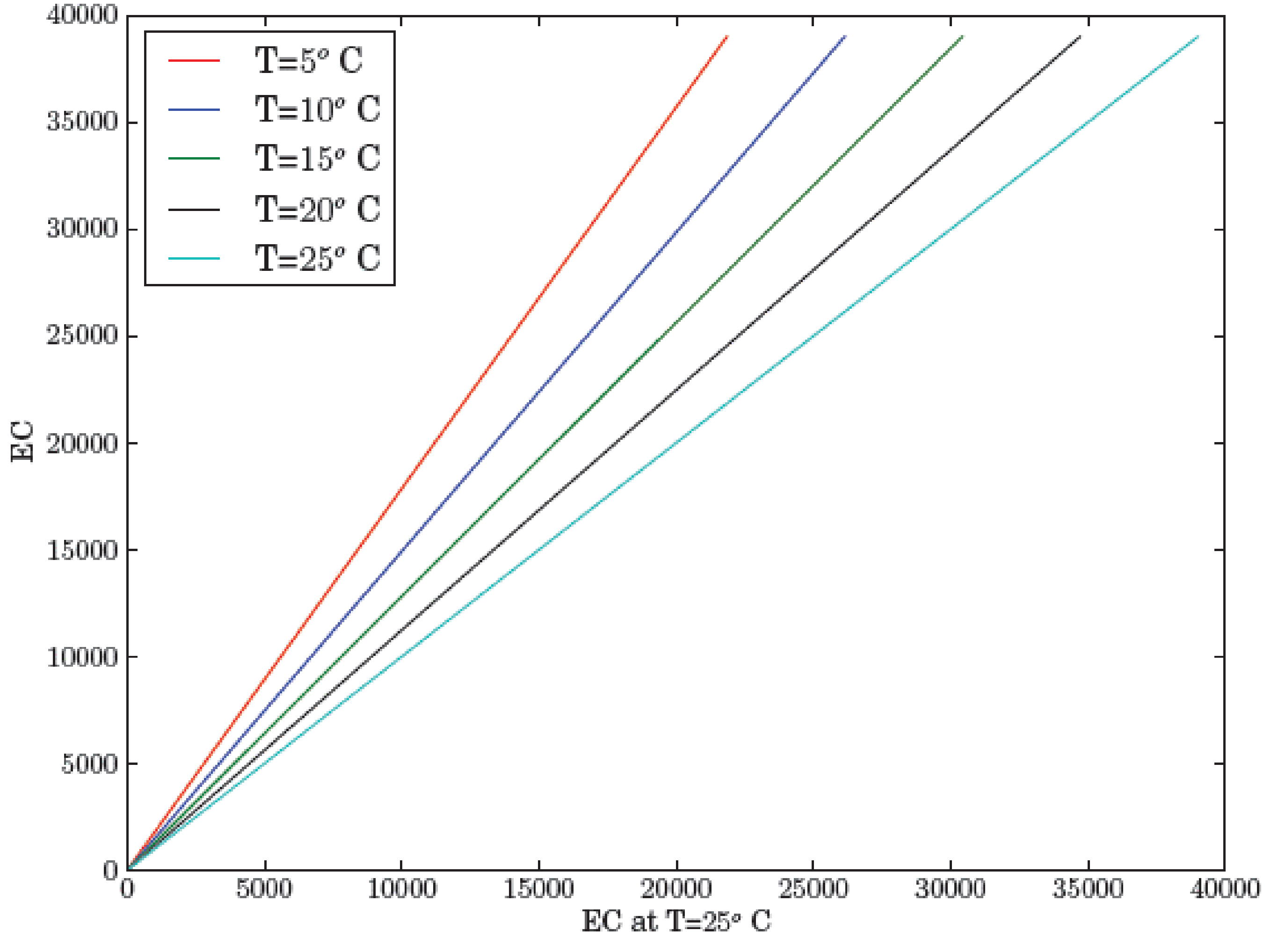
P. Pauw, 2009

EC and Chloride



EC-Cl at different HCO_3^- concentrations.

EC and Chloride



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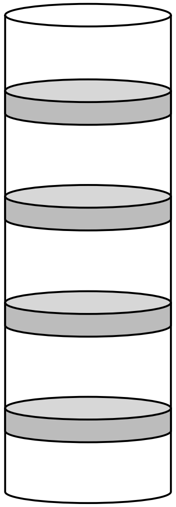
(b) EC and temperature standardized EC.

Monitoring salt in groundwater: Direct methods

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

Direct methods 1 and 2



Source: V. Post, 2007

Monitoring salt in groundwater: Indirect methods

Indirect methods measure the **conductance** of:

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

AND

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

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

Source: V. Post, 2007

Monitoring salt in groundwater: Indirect methods

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

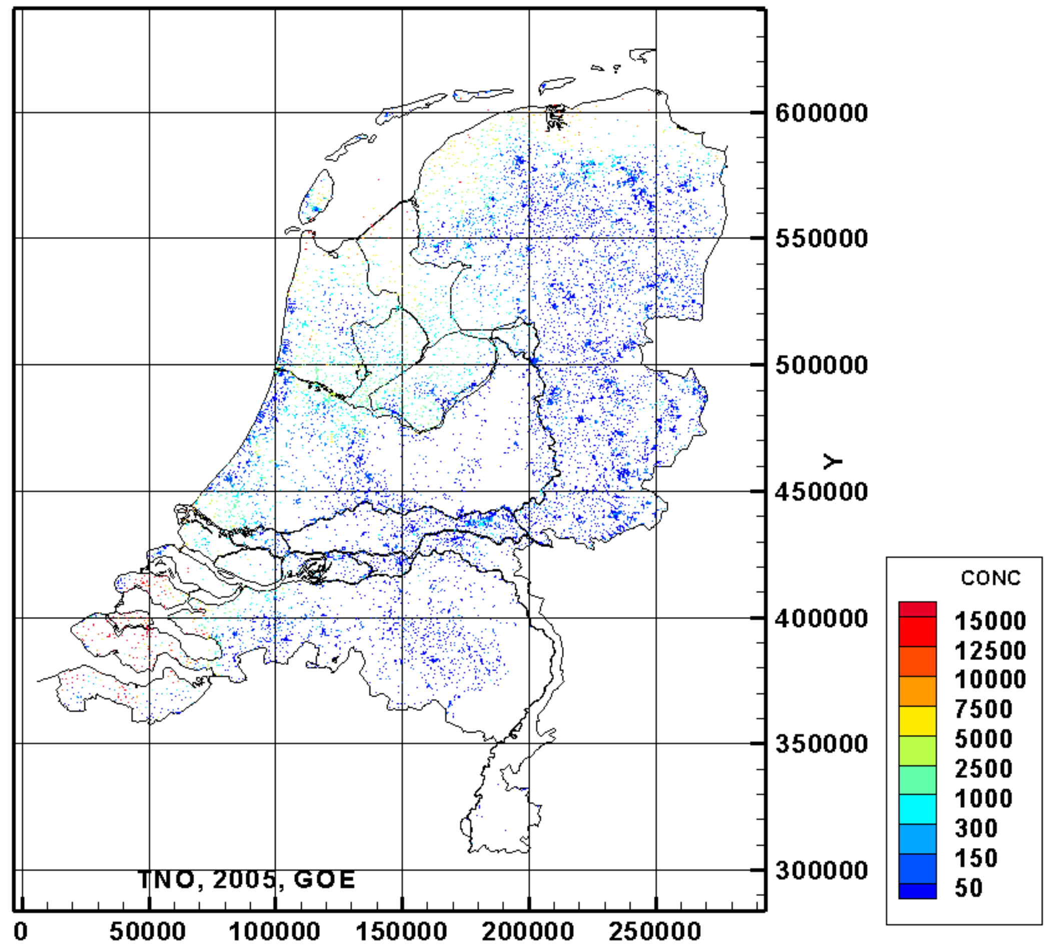
Source: V. Post, 2007

Method used at Deltares

Combination of:

- Direct measurements
- Electrical conductance measurements
  - Surface (VES)
  - Borehole

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



Source: Oude Essink et al (2005)

Electrical conductance measurements

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


Source: TNO

Source: V. Post, 2007

Electrical conductance measurements

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

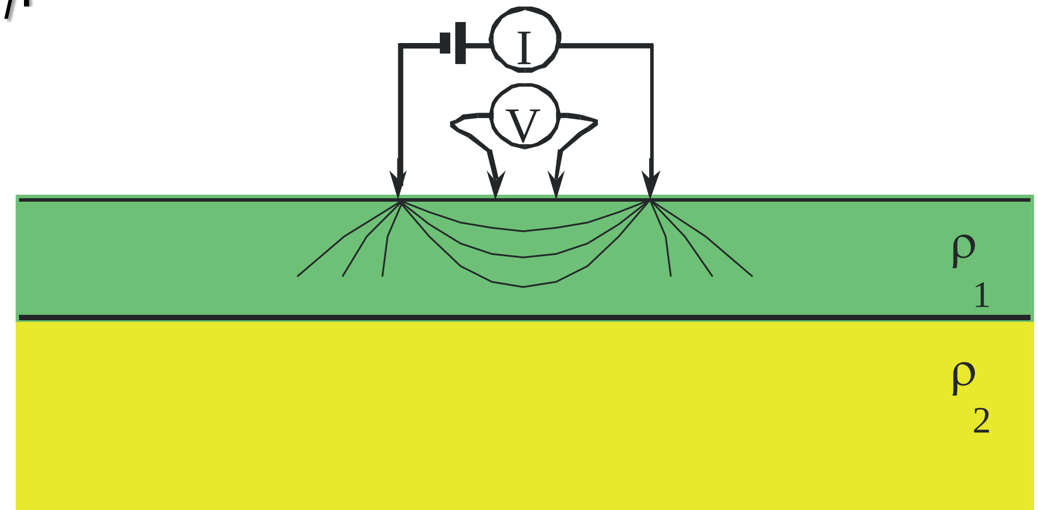
Source: V. Post, 2007

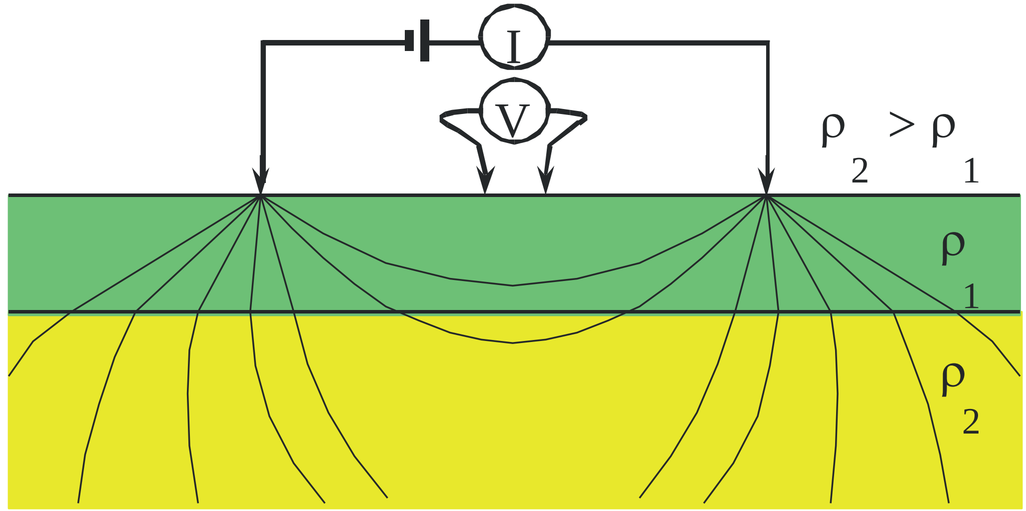
Source: Vitens

Principle geo-elektrical measurement

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

Ra = constant * V/I

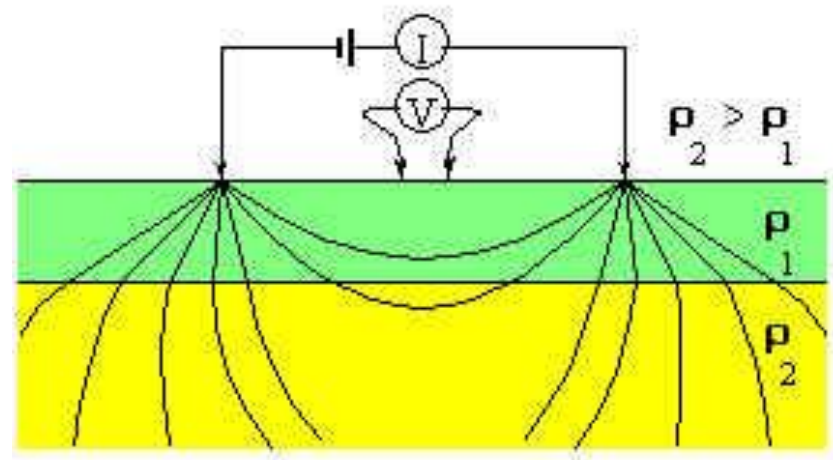




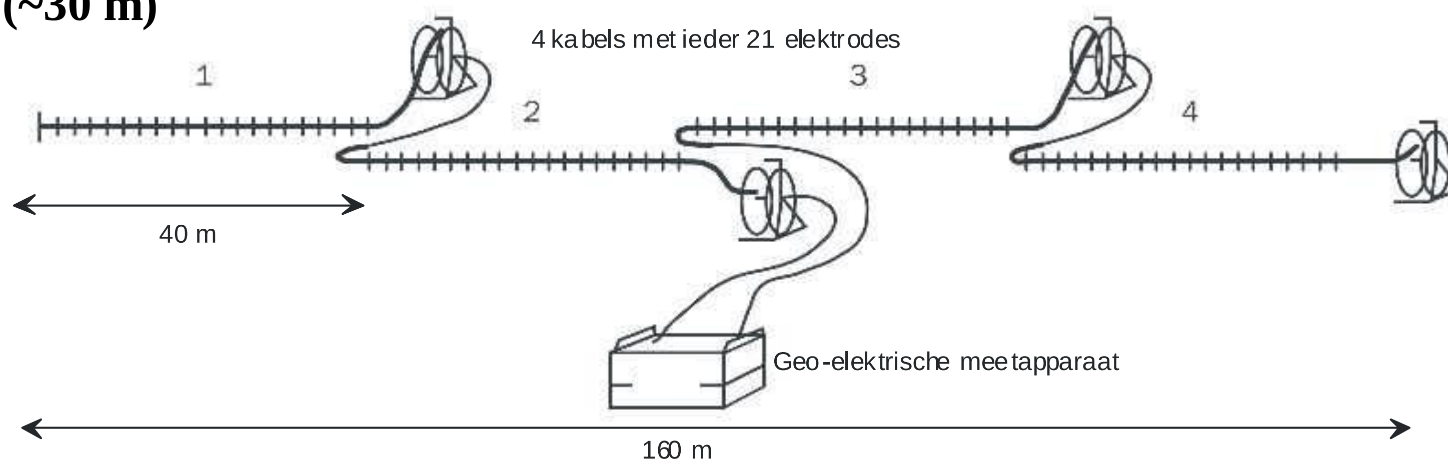
20120622 SWIM22

Types geo-electrical measurements

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



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

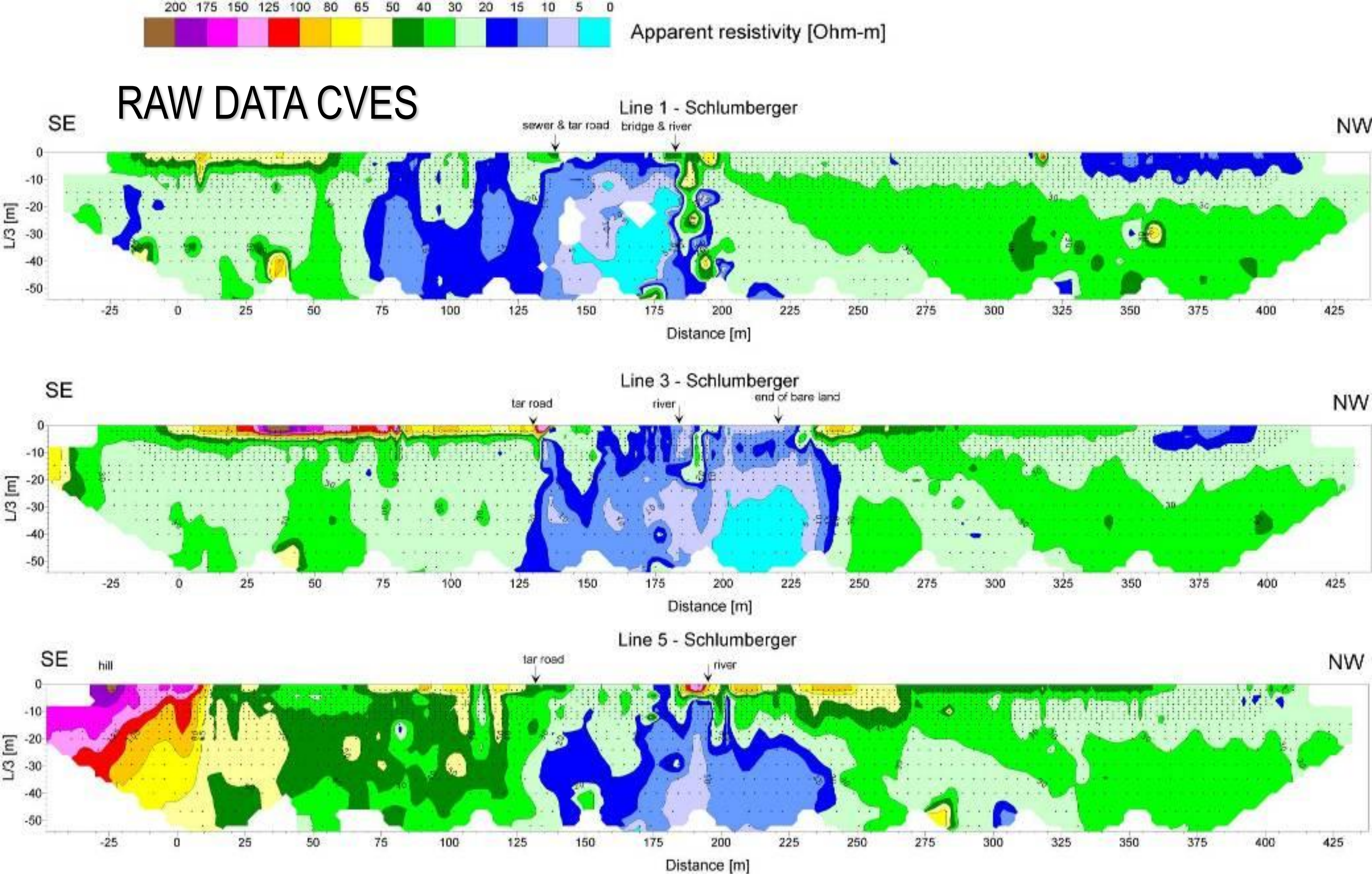


20120622 SW

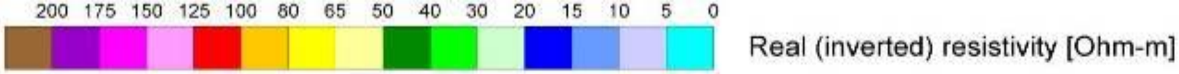
VES measurement end 1950s/begin 1960s

CVES
measurements 2010s

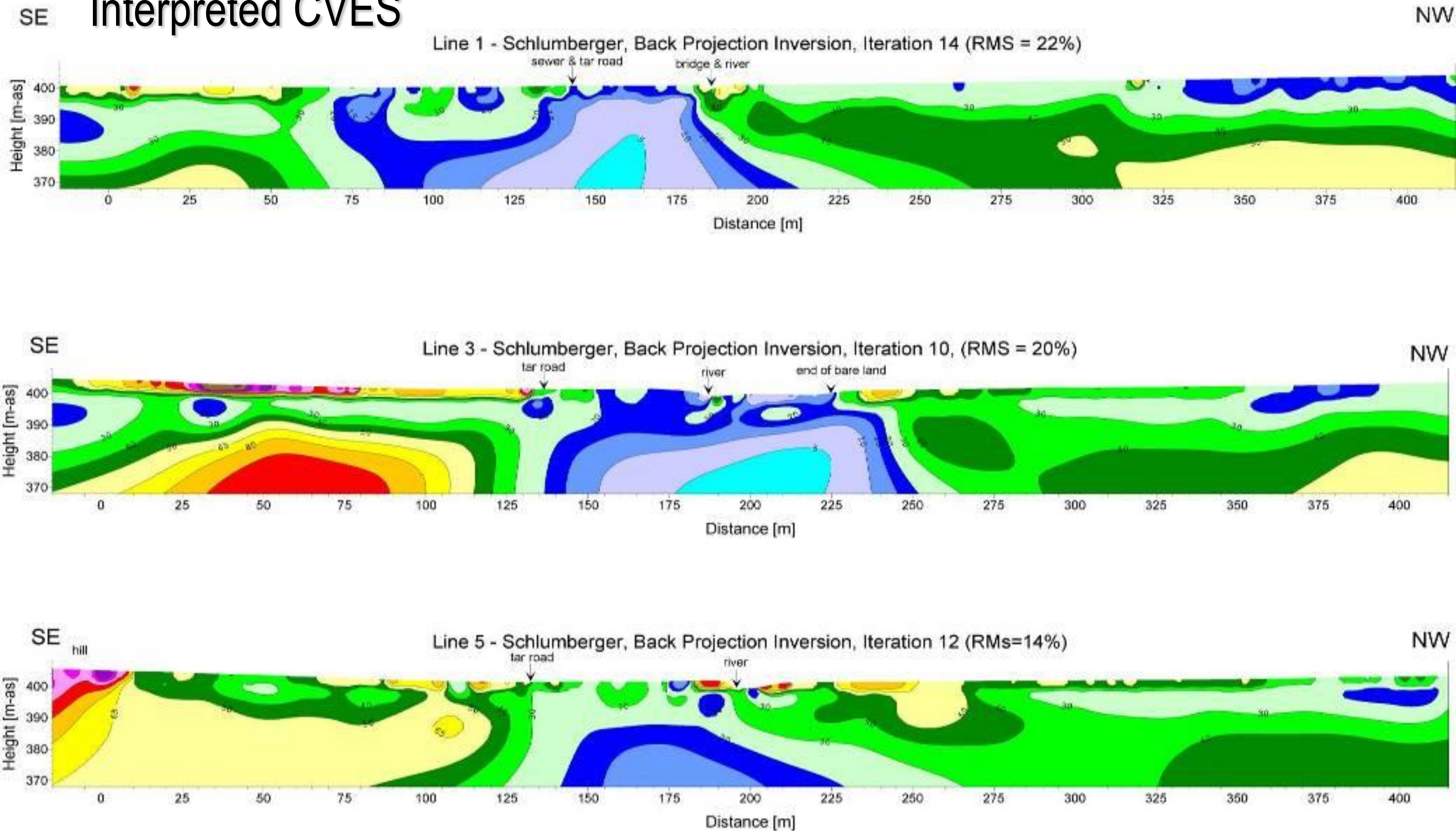
RAW DATA CVES



water met hoge EC (lage weerstand)



Interpreted CVES



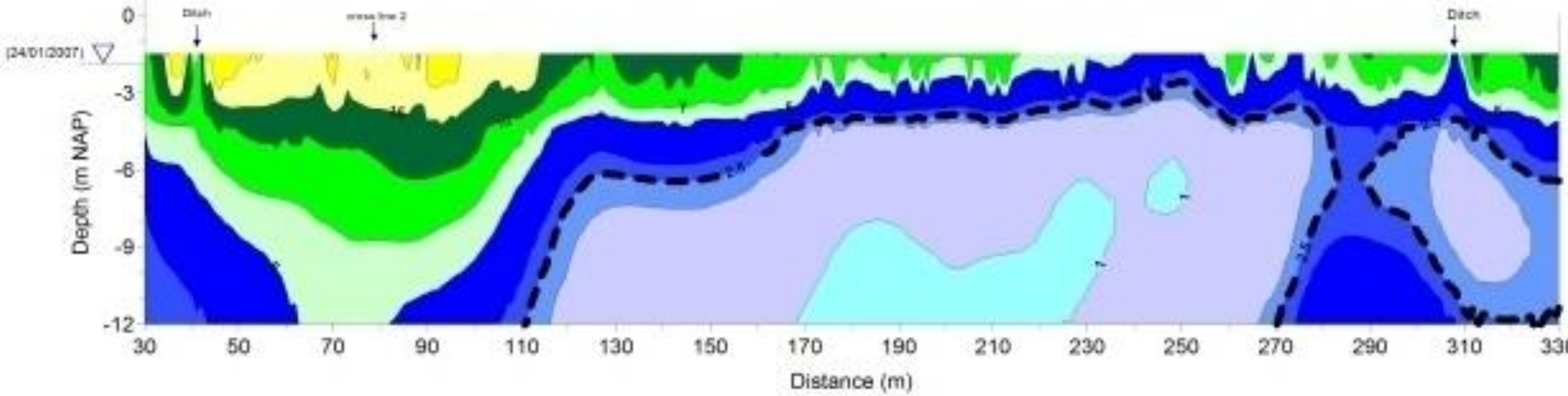
water met hoge EC (lage weerstand)

Site 11 - Renesse

South-East

North-West

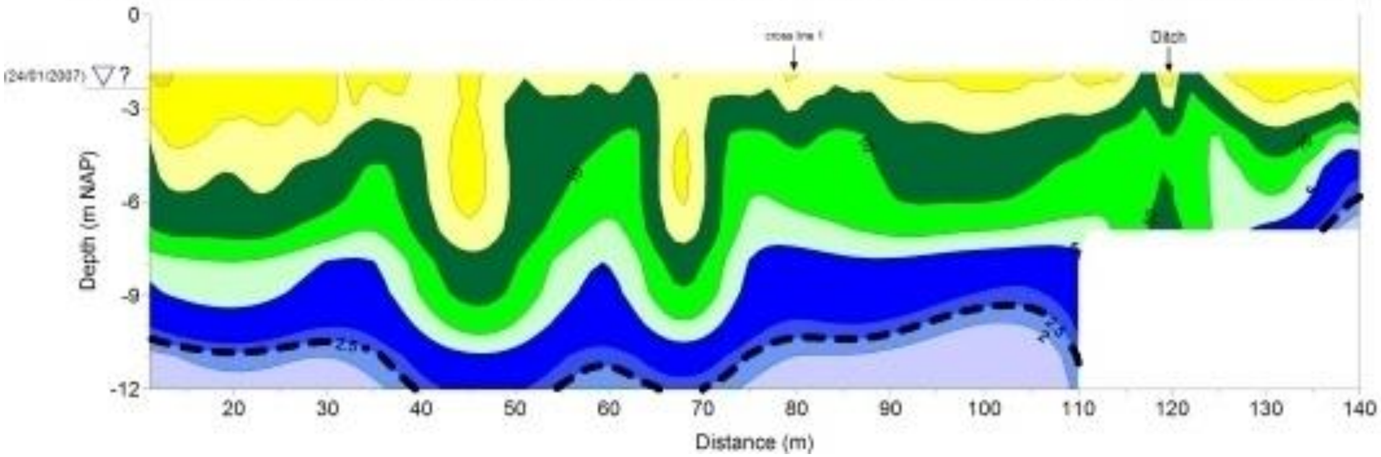
Line 1 - 26 March 2007, Schlumberger, Back Projection Inversion, Iteration 2 (RMS = 38%) - Cl = 3000 mg/l estimate between 3.6 and 1.8 Ohm-m



North-East

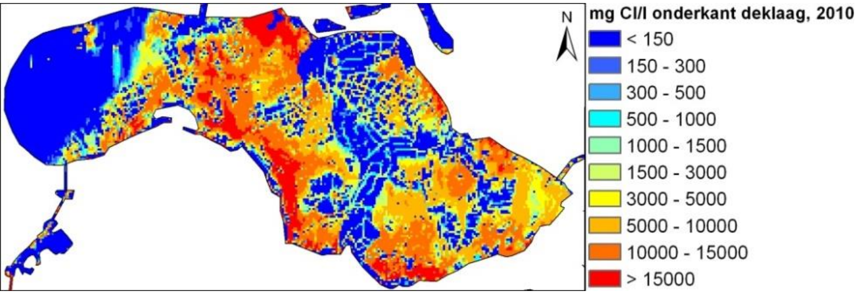
South-West

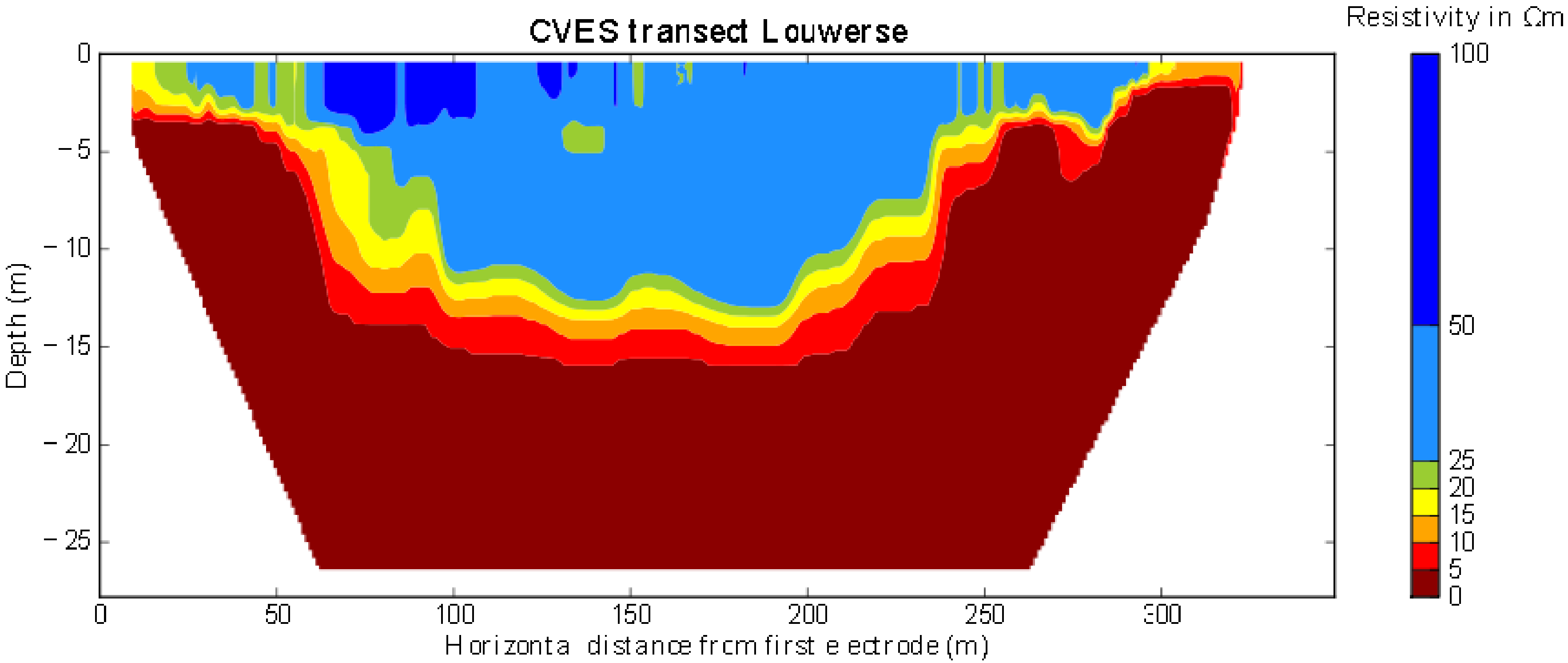
Line 2 - 25 March 2007, Schlumberger, Back Prpjection Inversion, Iteration 14 (RMS = 21%) - Cl = 3000 mg/l estimate between 3.6 and 1.8 Ohm-m



water met hoge EC (lage weerstand)

Possible measures for sandy creeks





Monitoring salt in groundwater: Indirect methods

- Electrical conductance measurements

$\rho_s = F^* \rho_w$

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

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

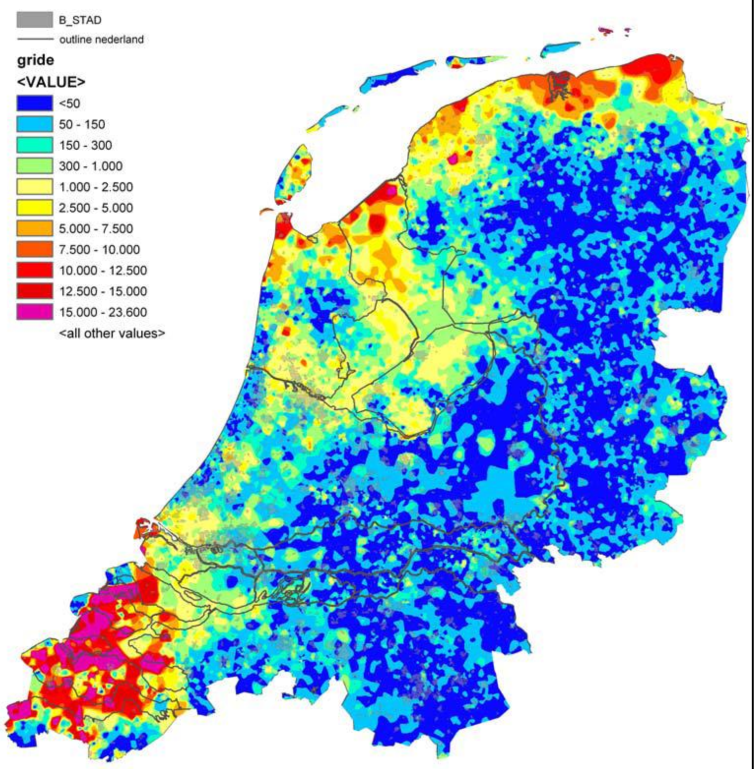
F varies with the resistance of the groundwater (applies to Clay and peat)

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

VES measurements are used in combination with borehole logging

Source: Oude Essink, 2005

Result: chloride concentration bottom Holocene toplayer



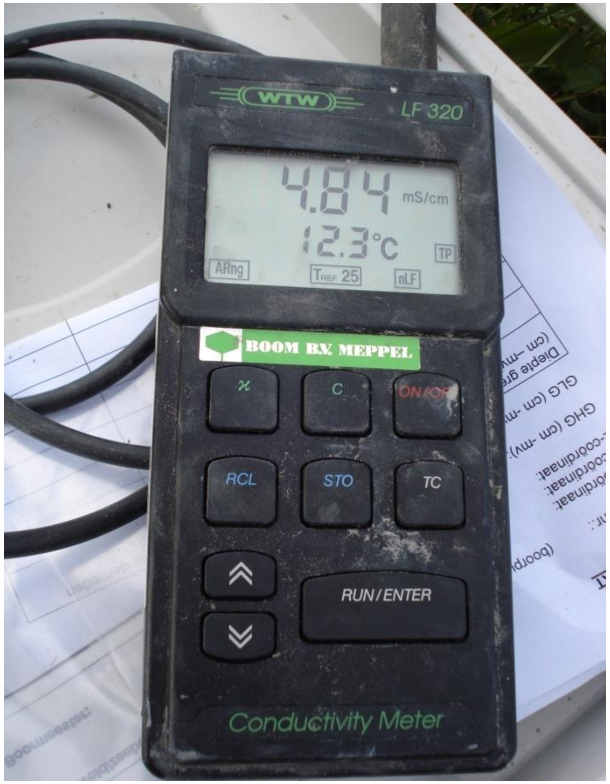
Source: Oude Essink, 2005

- Software Geological Survey of the Netherlands (TNO) is used to determine the salt concentration of the groundwater in the measurements

- Inter- and extrapolation is used to make a continuous field

- 2D Result is an combination of:
  1. Direct measurements (3500)
  2. Electrical conductance in boreholes (2000)
  3. Vertical Electric Sounding (VES) measurements (10.000)

T-EC probe



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T EC fieldwork

Altitude measurements

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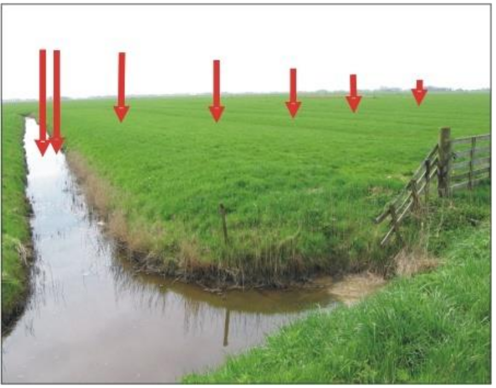
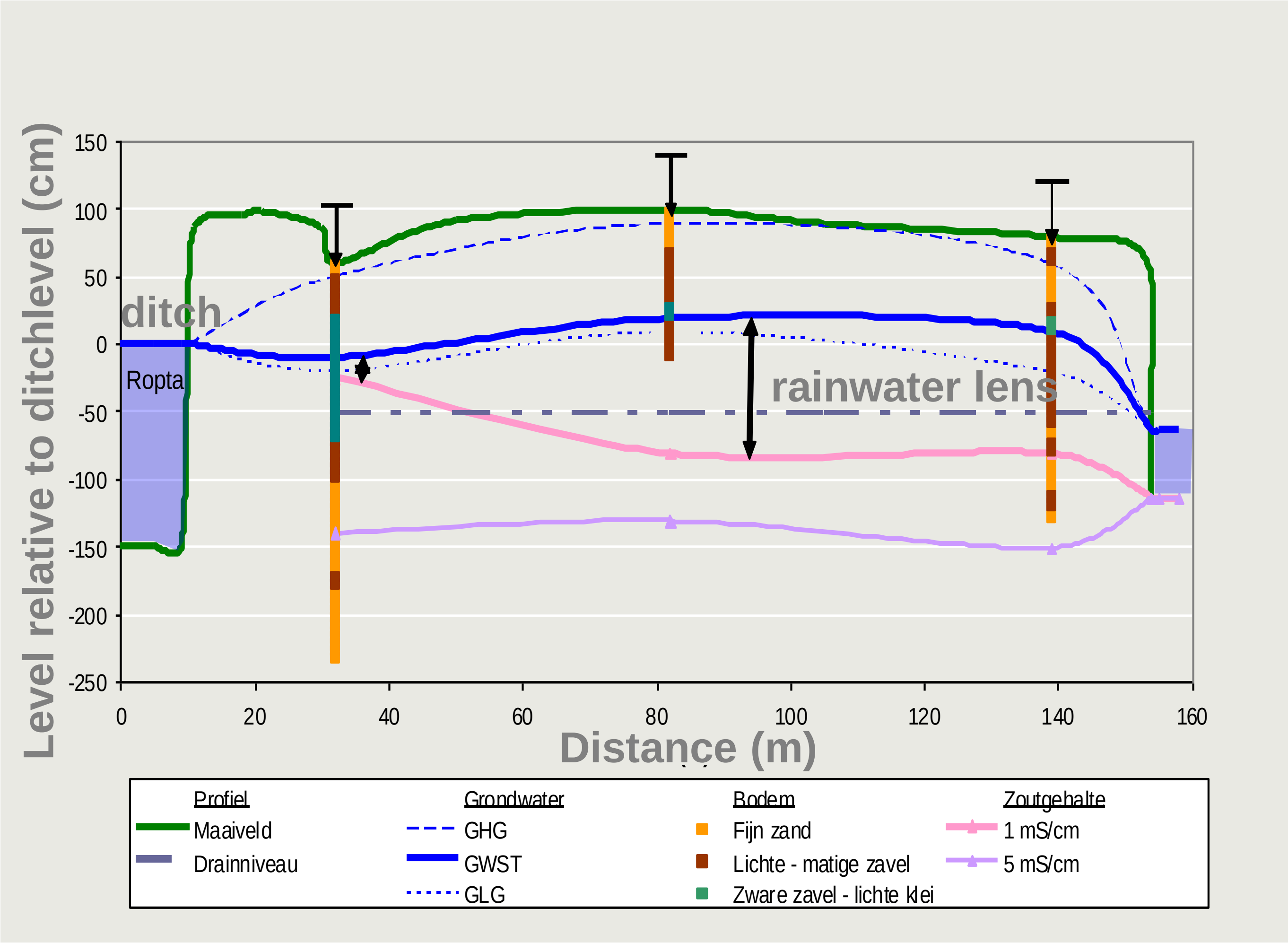
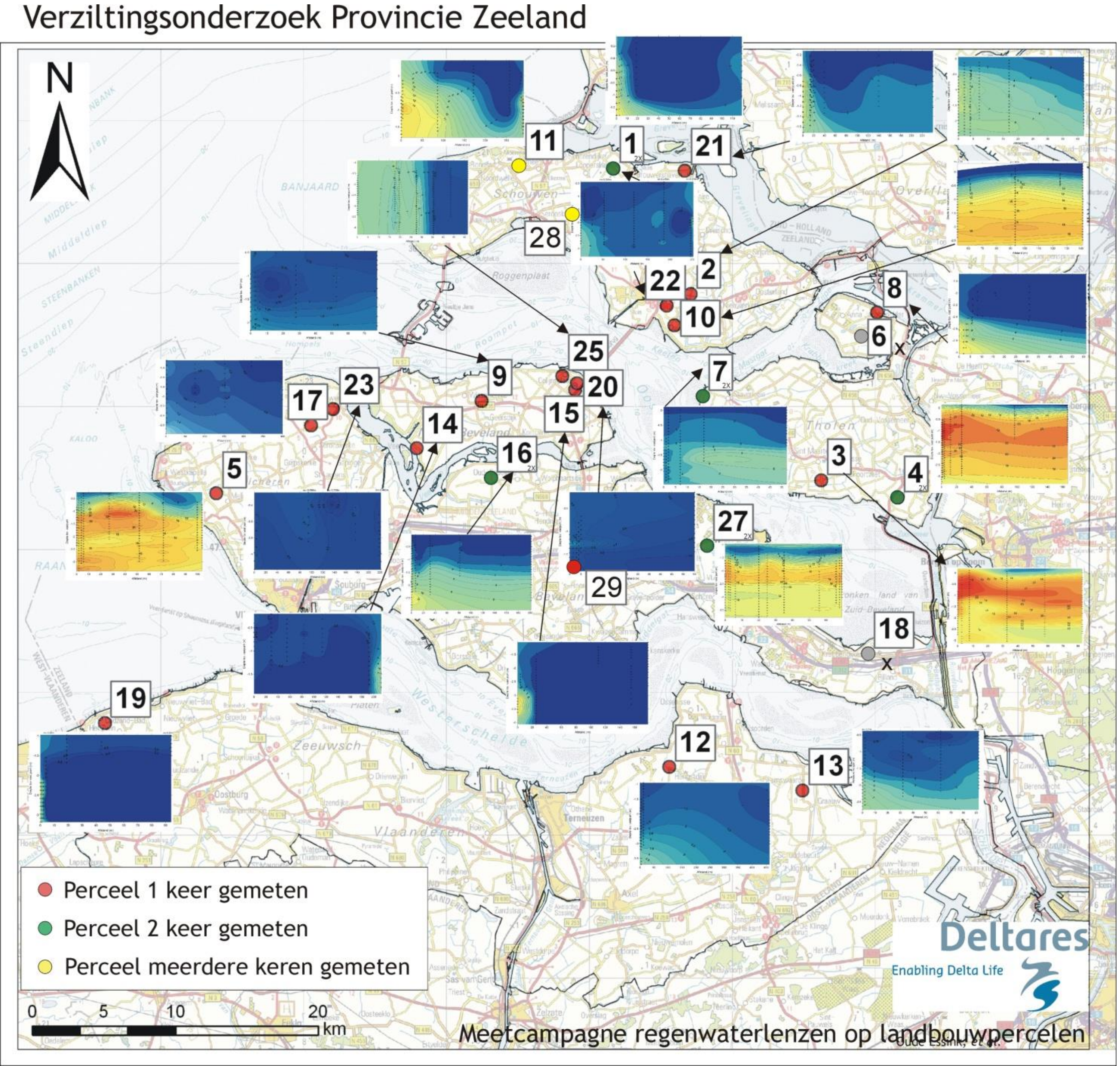
Use field measurements to understand the process





TEC-probe Monitoring campaign 2005-2009



CliWat www.cliwat.eu

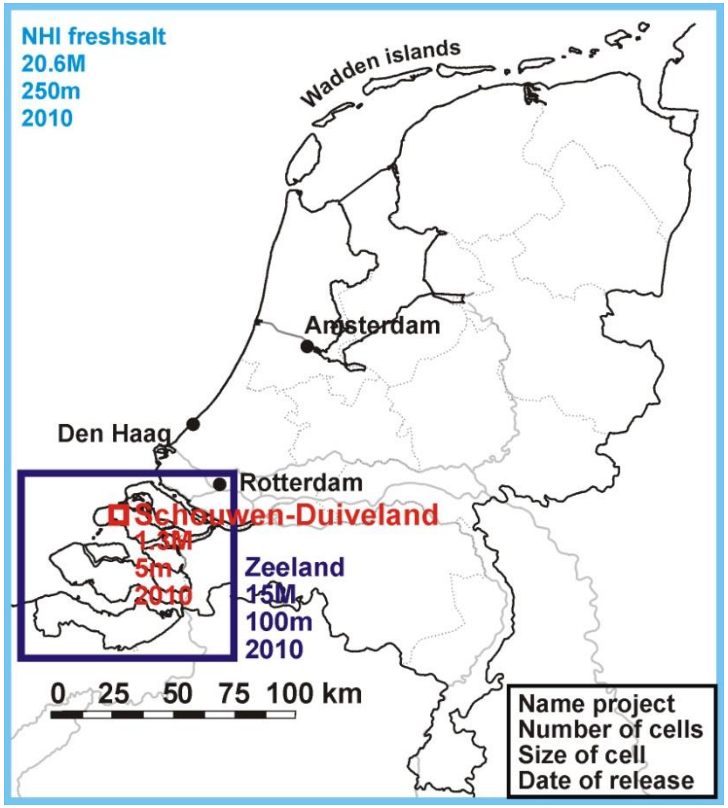
- Transnational project in the North Sea Region
- Main objectives:
  - to evaluate the physical and chemical impacts of climate change on groundwater and surface water systems
  - to provide data for adaptive and sustainable water management and infrastructure.
- Different innovative monitoring techniques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

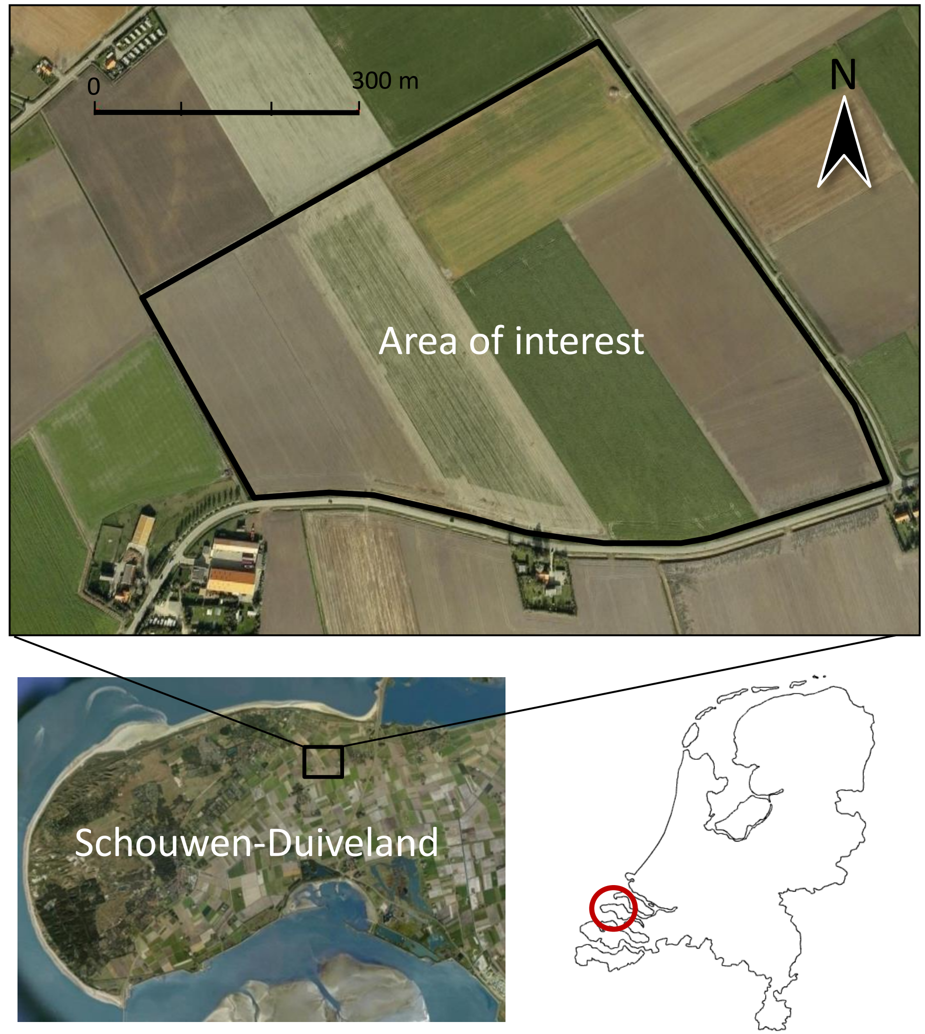
GEUS | midt regionmidtjylland | BGR Bundesanstalt für Geowissenschaften und Rohstoffe | TNO | Miljøcenter Ribe | HORSENS KOMMUNE

Landesamt für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein | LIAG Leibniz Institute for Applied Geophysics | provinsje fryslân provincie fryslân | WETTERSKIP FRYSLÂN | UNIVERSITEIT GENT

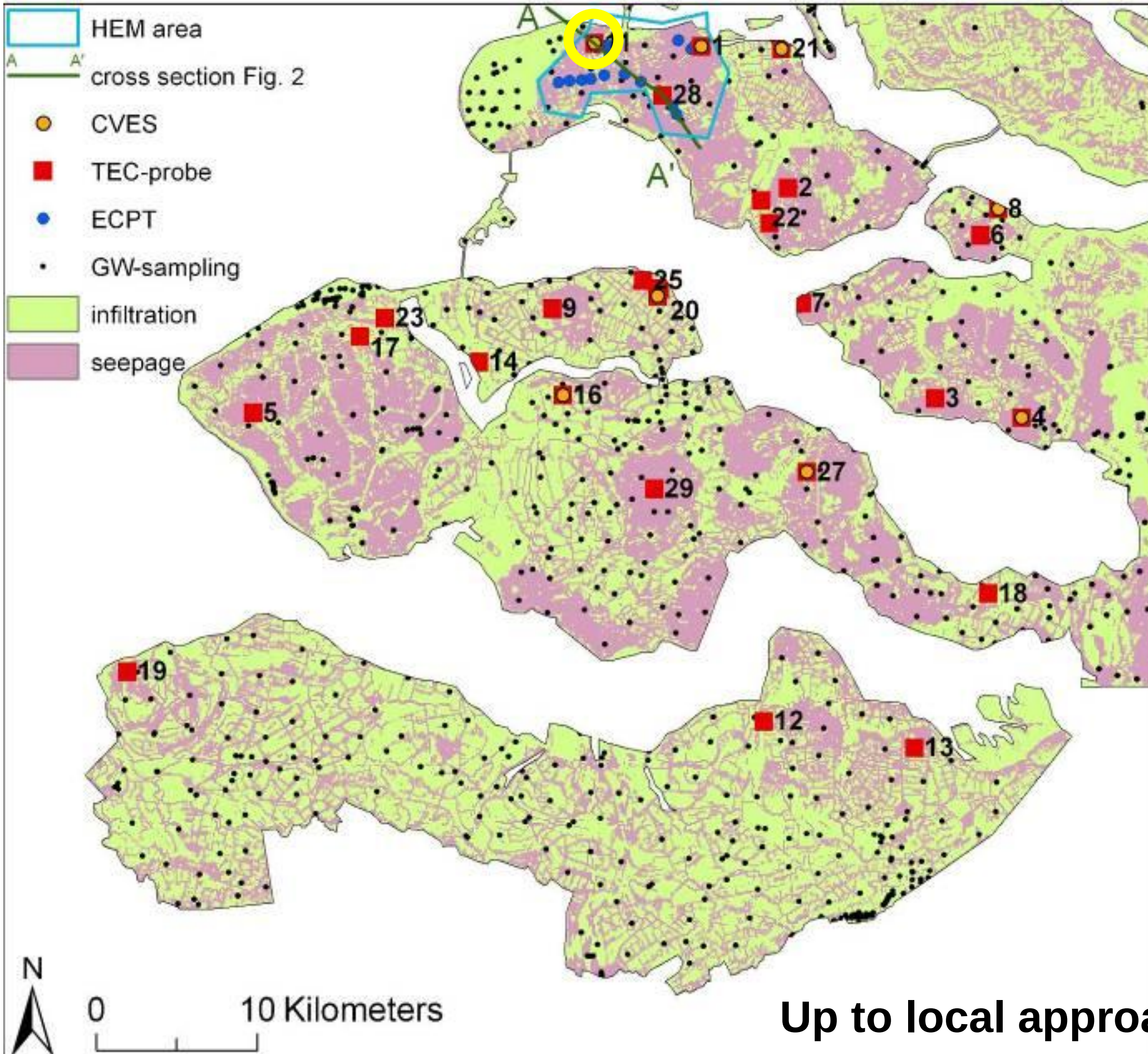
Vitens | Miljøcenter Århus | SOLIDUM PETIT IN PROFUNDIS UNIVERSITAS ARHUSIENSIS | Deltares | Region Syddanmark | seecon

Description local area





Monitoring network in our Pilot Area Zeeland



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GEOZENTRUM HANNOVER

Up to local approach

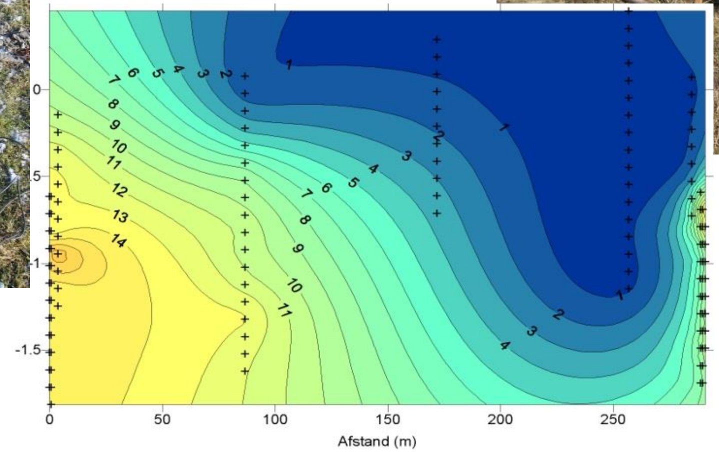
Example: Assessing effect of climate change on salt water intrusion

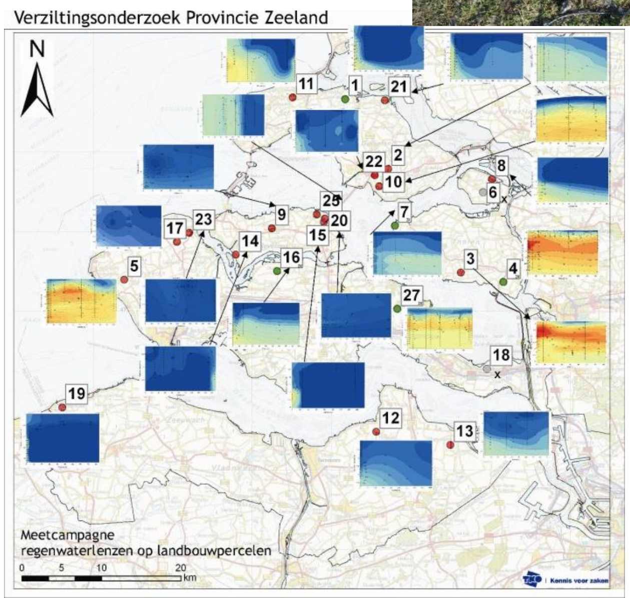
Source: Oude Essink, 2009

Monitoring:

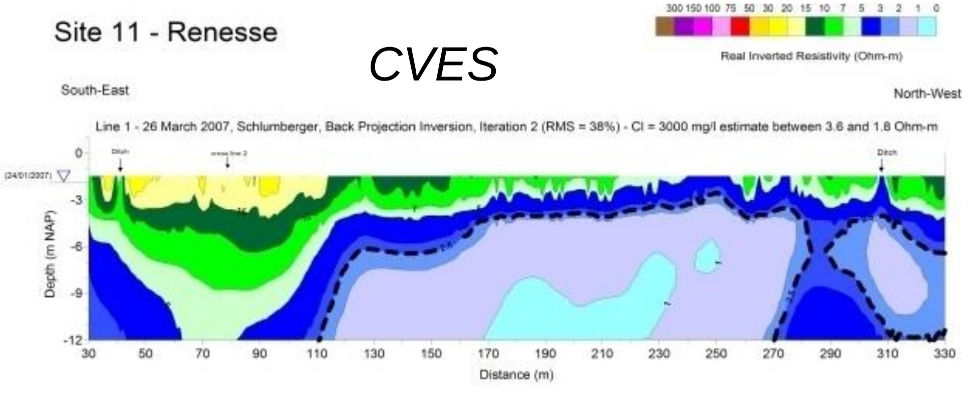
- piezometric head and solute concentration
- TEC probes, CVES
- online

TEC probe

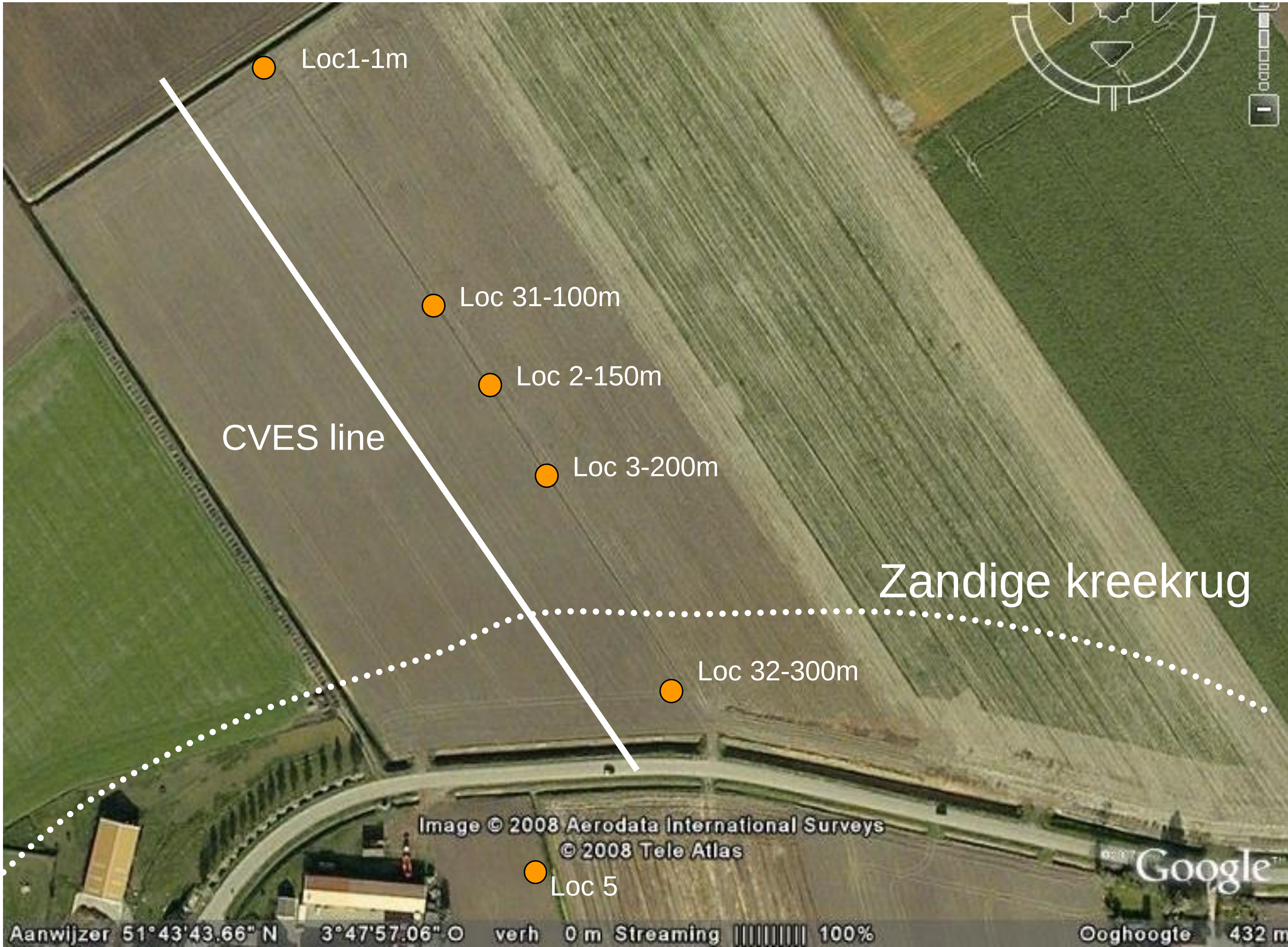




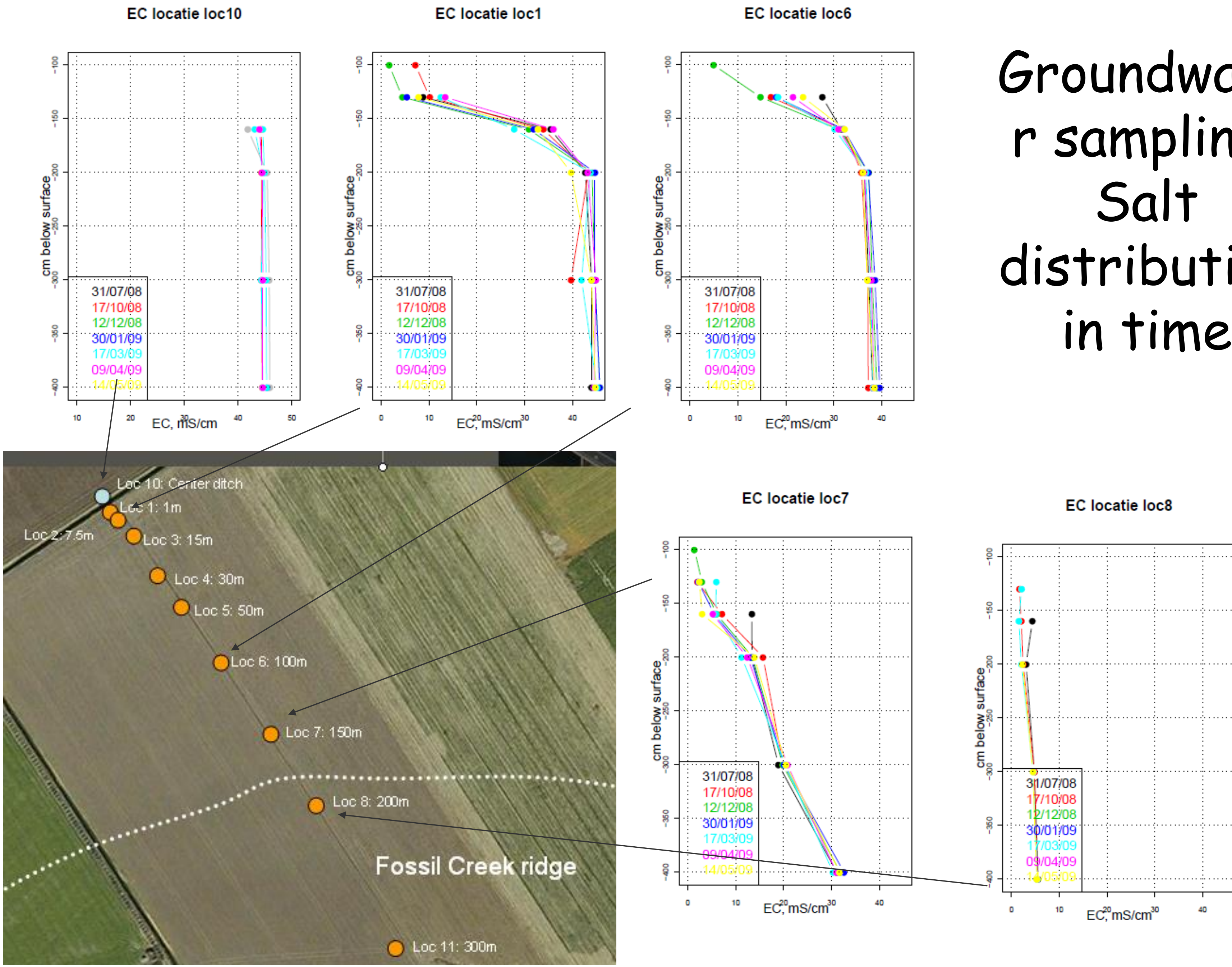
CVES



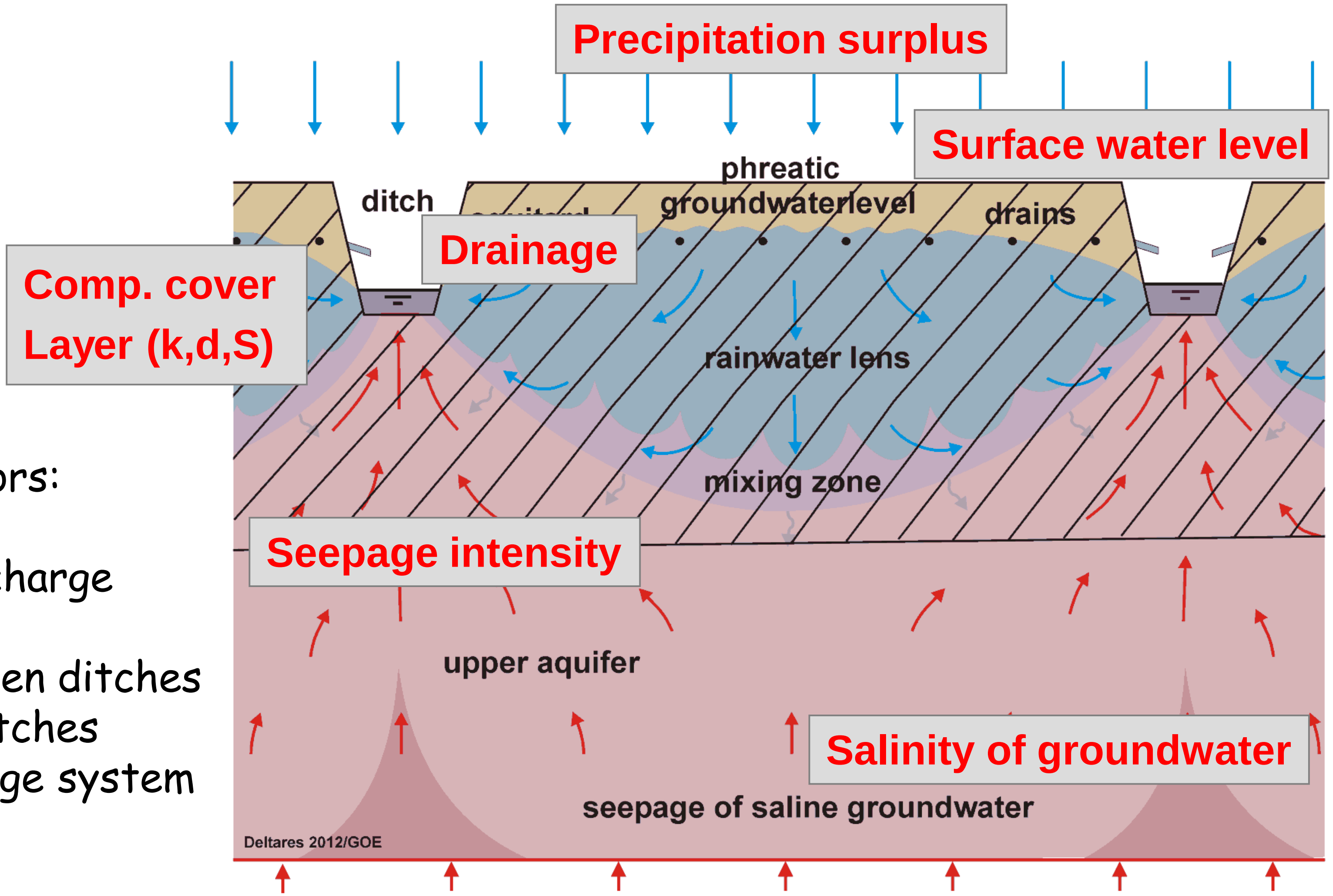
Site 11: from infiltration to seepage



Groundwater sampling: Salt distribution in time



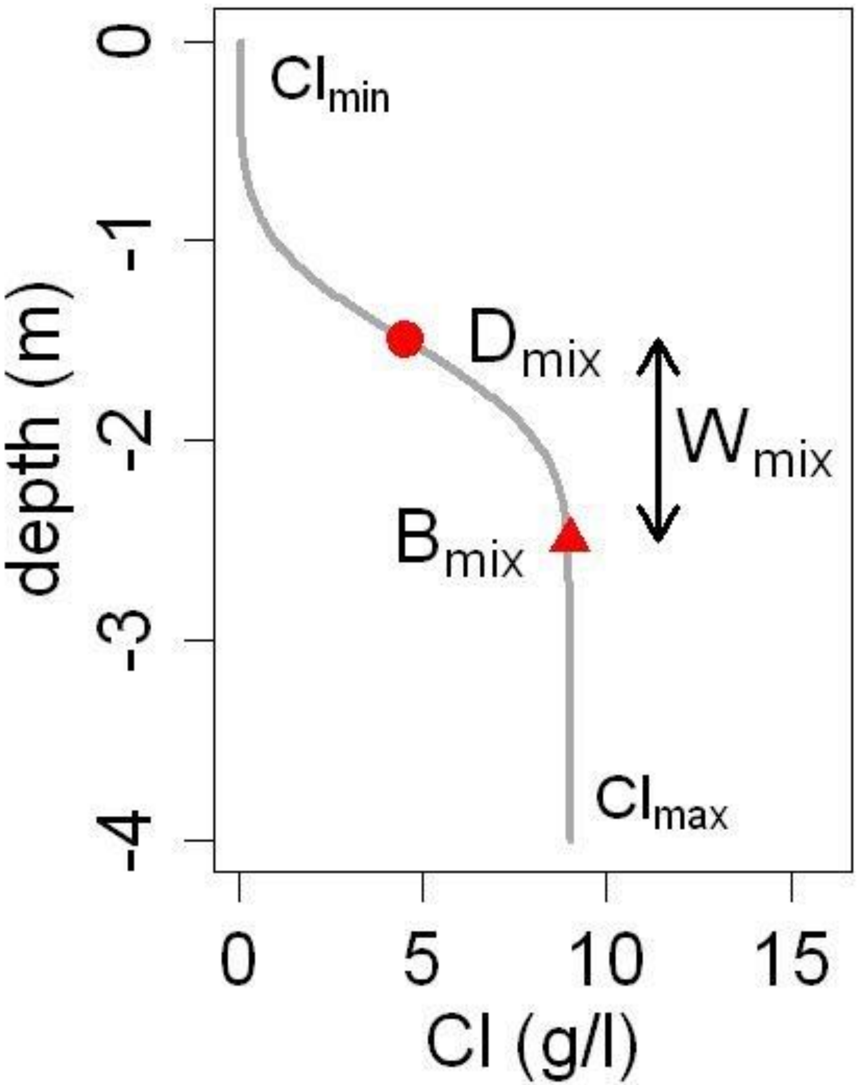
Factors controlling fresh-salt interface

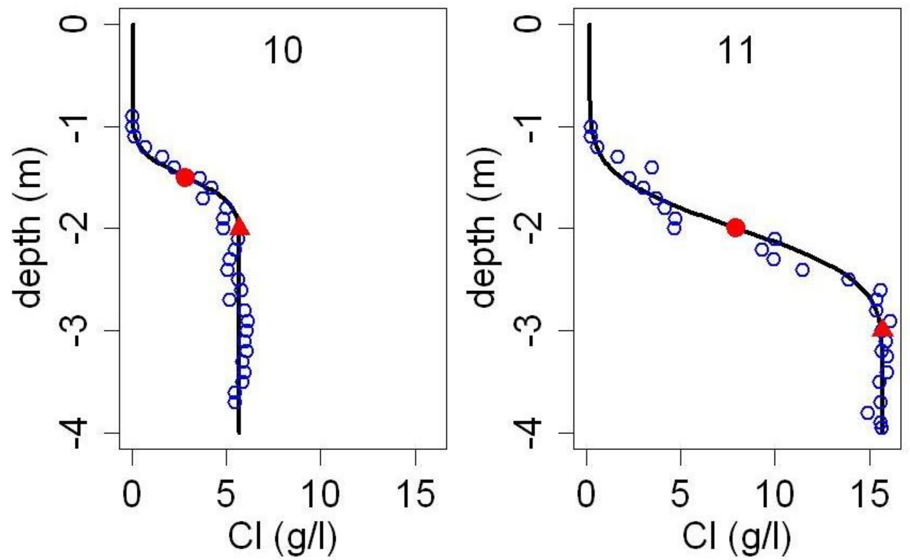


Important factors:

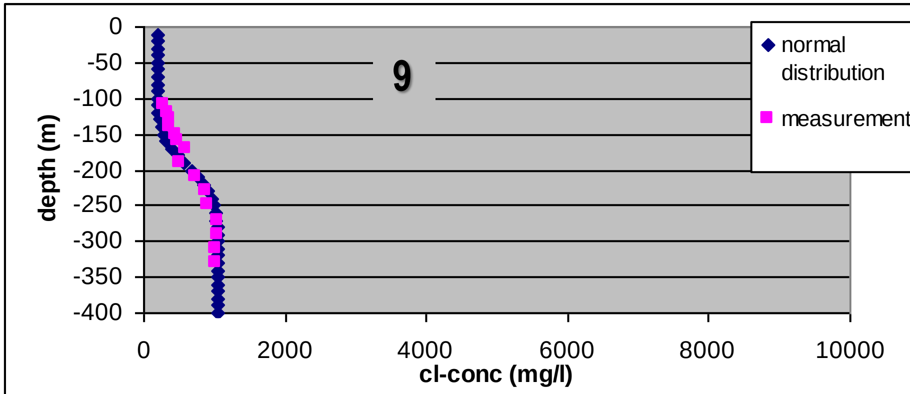
-natural grw recharge
-geology
-distance between ditches
-water levele ditches
-capacity drainage system

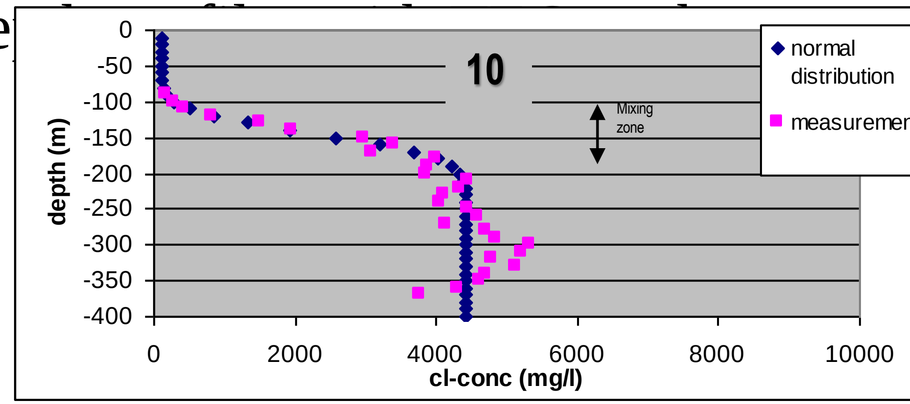
Lens characteristics

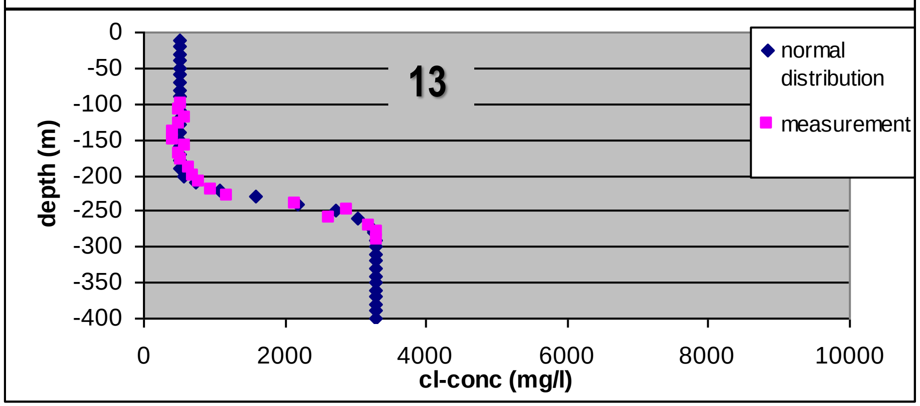


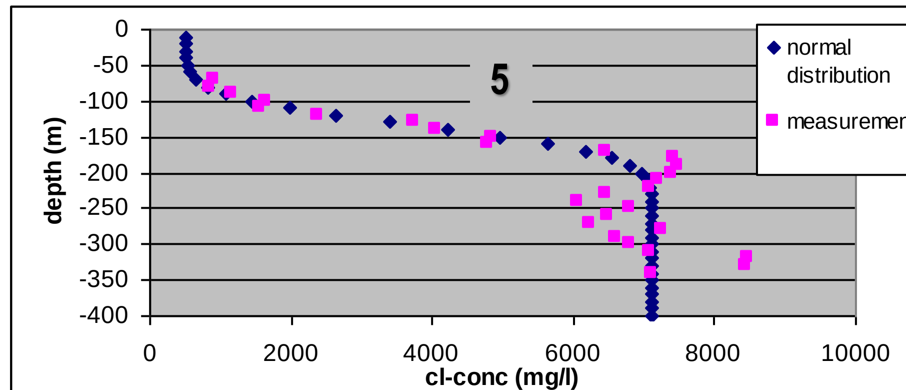


Louw, P.G.B., de, Eeman, S., Siemon, B., Voortman, B.R., Gunnink, J., Baaren, E.S., van and G.H.P. Oude Essink, Shallow rainwater lenses in deltaic areas with saline seepage, *Hydrol. Earth Syst. Sci. Discuss.*, 8, 7657-7707, 2011.


9
normal distribution
measurement
depth (m)
0
-50
-100
-150
-200
-250
-300
-350
-400
0
2000
4000
6000
8000
10000
cl-conc (mg/l)


10
Mixing zone
normal distribution
measurement
depth (m)
0
-50
-100
-150
-200
-250
-300
-350
-400
0
2000
4000
6000
8000
10000
cl-conc (mg/l)


13
normal distribution
measurement
depth (m)
0
-50
-100
-150
-200
-250
-300
-350
-400
0
2000
4000
6000
8000
10000
cl-conc (mg/l)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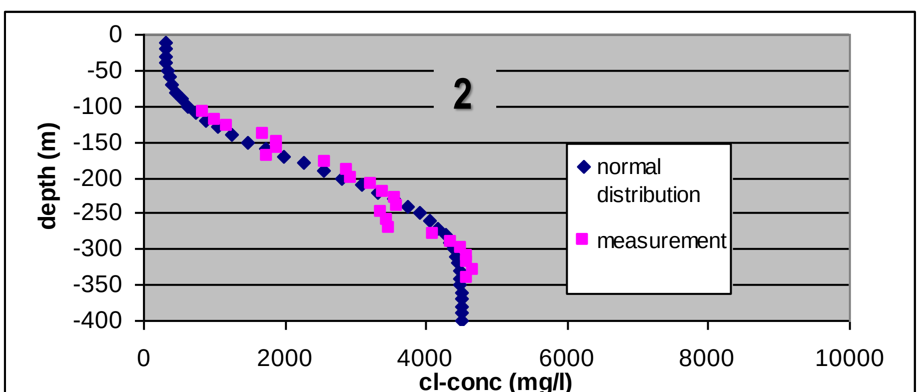
normal distribution
measurement
depth (m)
0
-50
-100
-150
-200
-250
-300
-350
-400
0
2000
4000
6000
8000
10000
cl-conc (mg/l)


2
normal distribution
measurement
depth (m)
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-50
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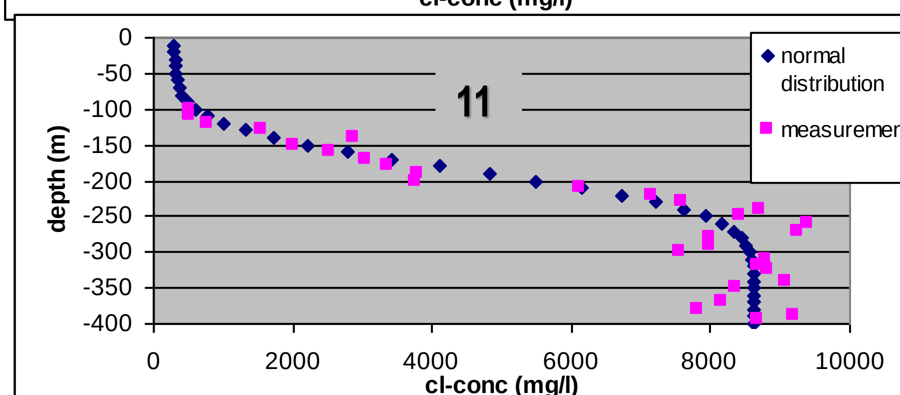
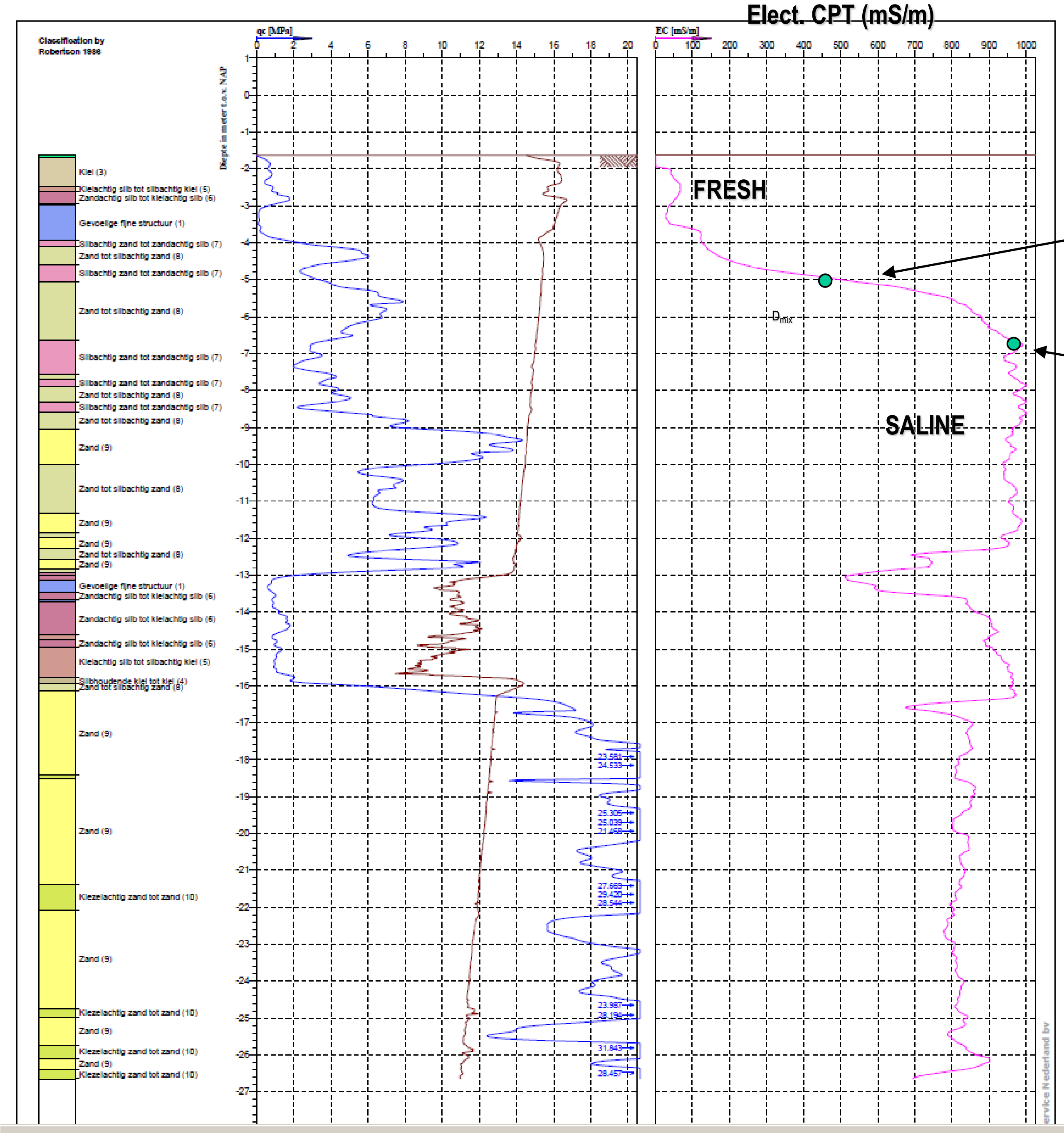
-150
-200
-250
-300
-350
-400
0
2000
4000
6000
8000
10000
cl-conc (mg/l)


11
normal distribution
measurement
depth (m)
0
-50
-100
-150
-200
-250
-300
-350
-400
0
2000
4000
6000
8000
10000
cl-conc (mg/l)

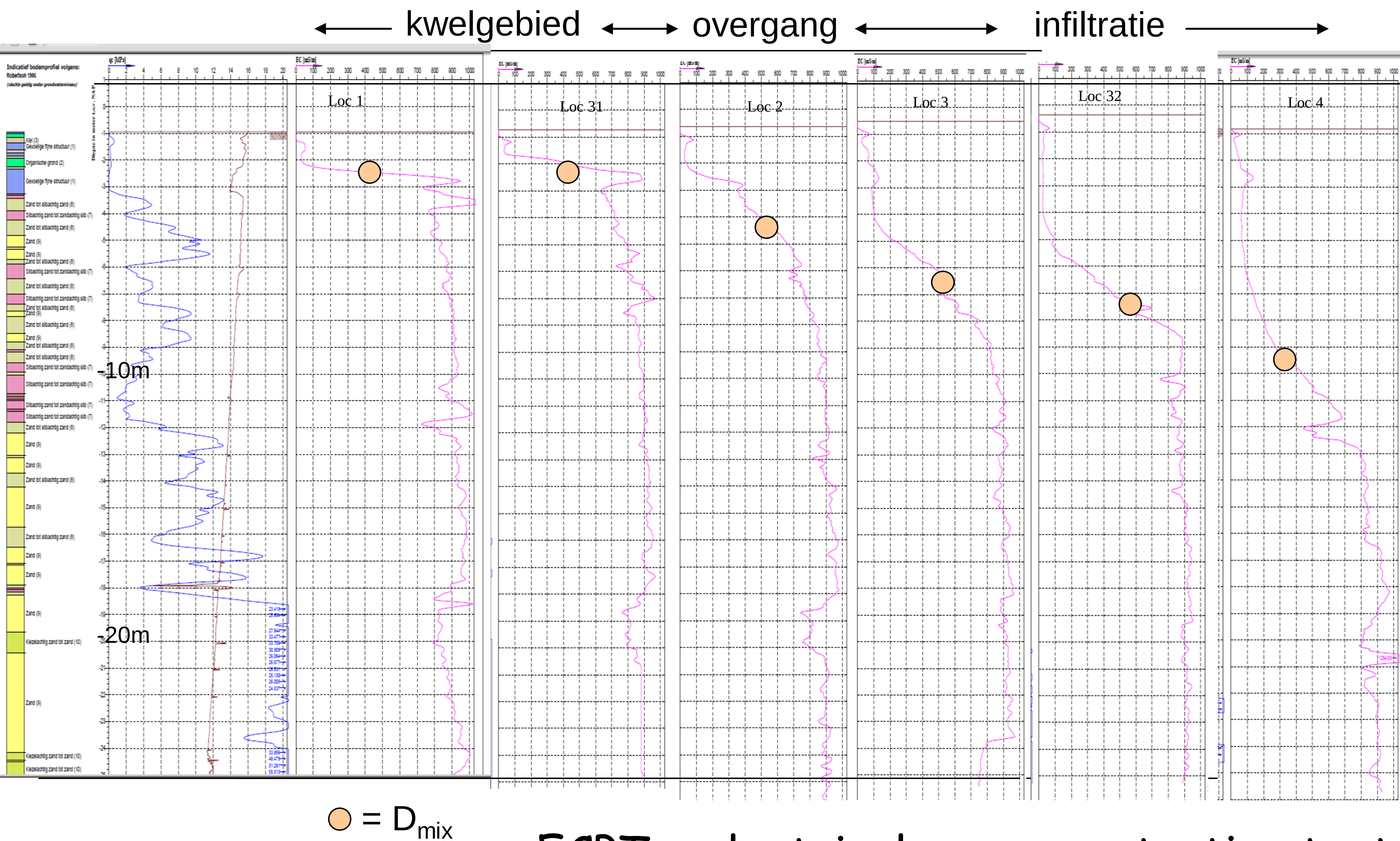
Electrical CPT



a) Depth of transition, D_{mix}, zone between 2 types of groundwater (fresh-saline)

b) Start of transition, S_{mix},

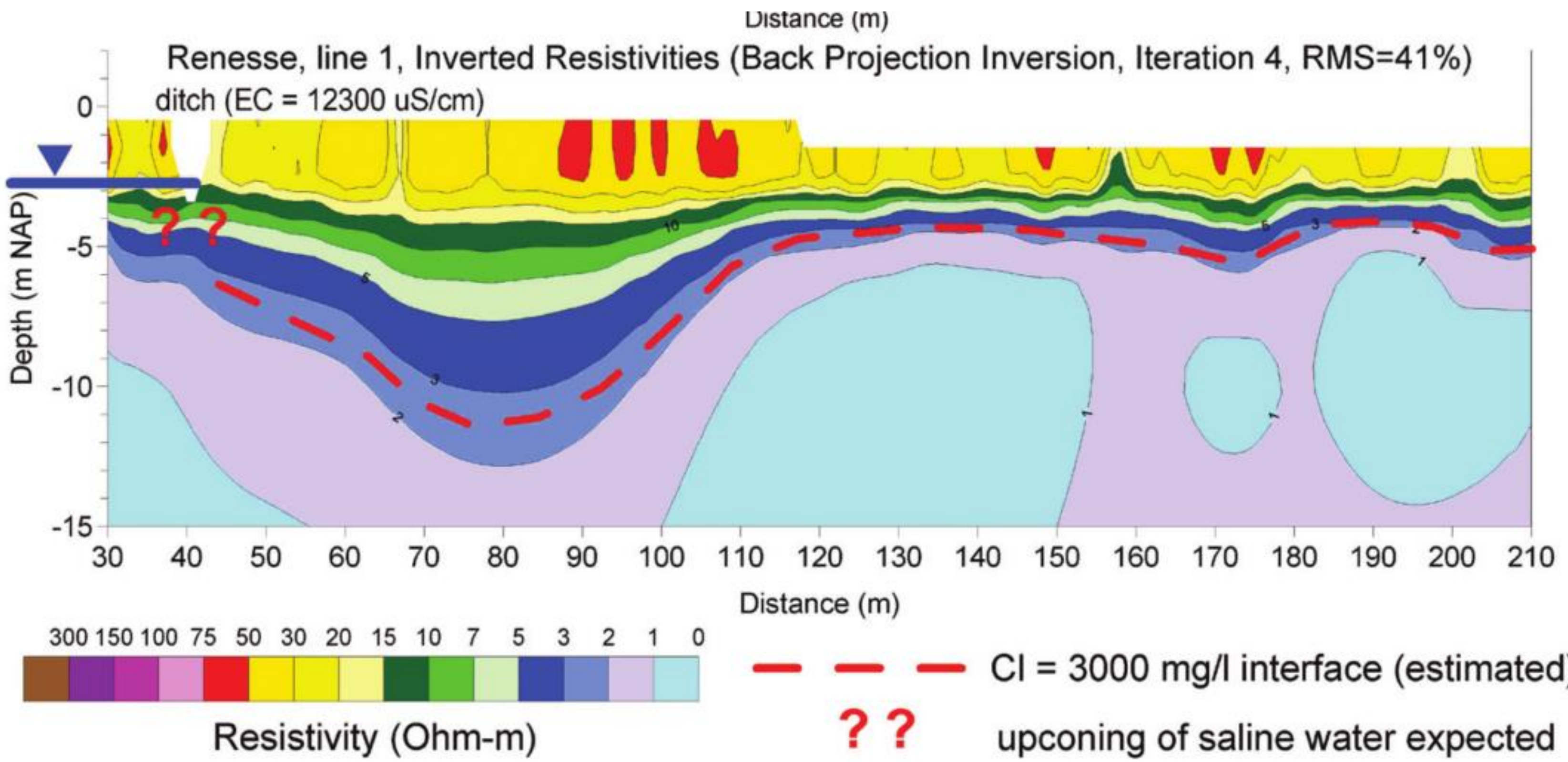
Results from ECPT's (soundings)



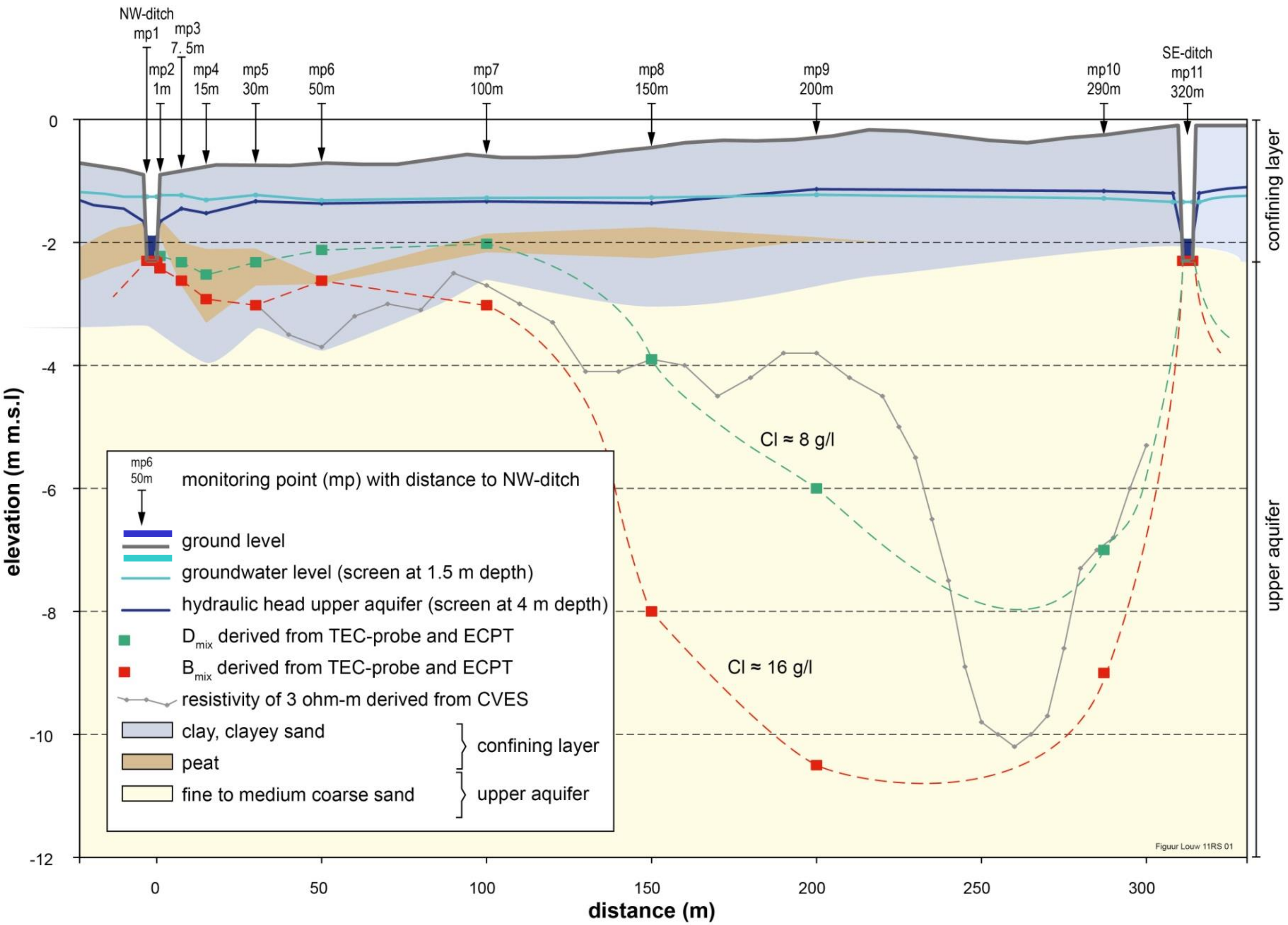
ECPT = electrical cone penetration test

CVES

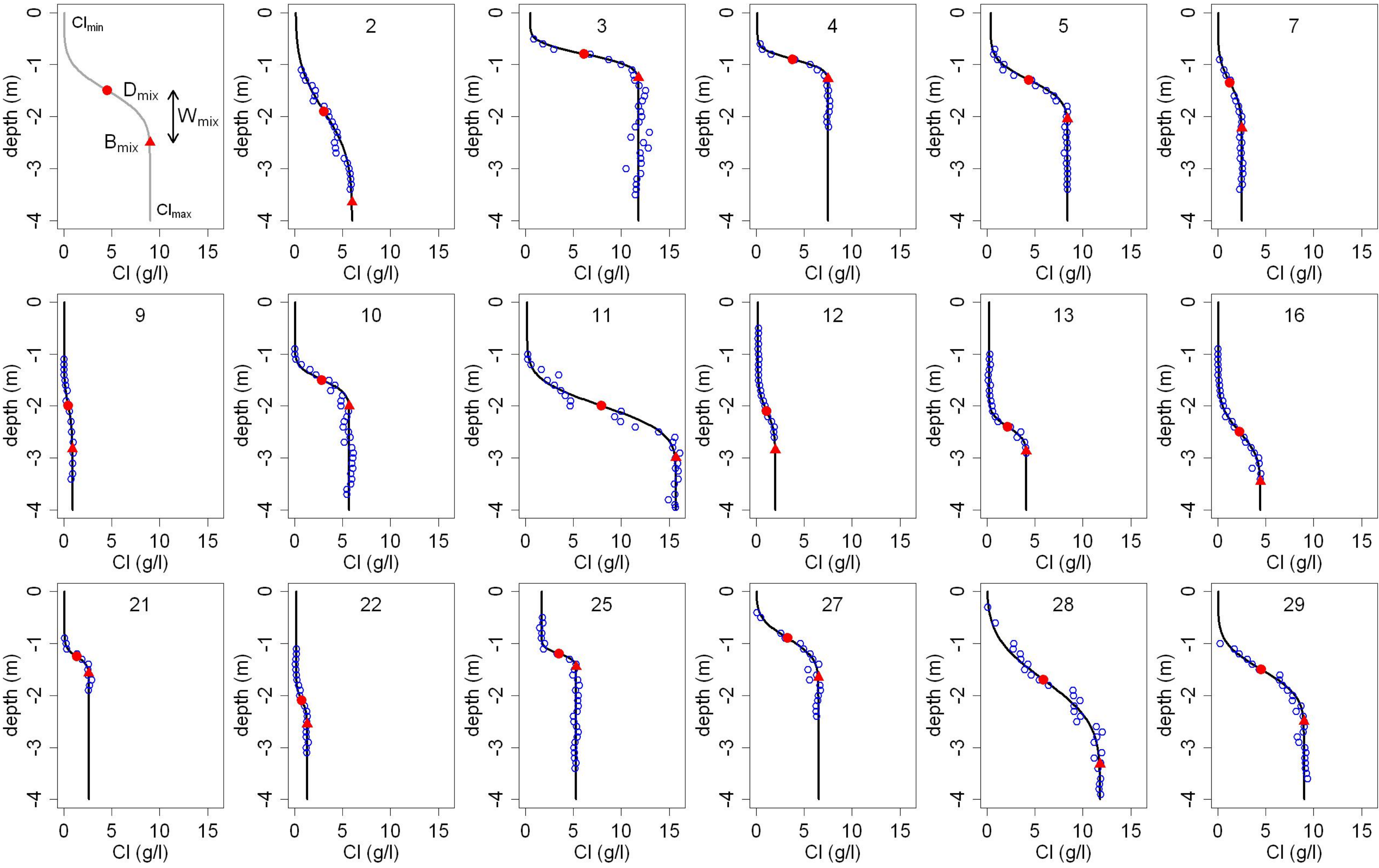
CVES: continuous vertical eletrical sounding



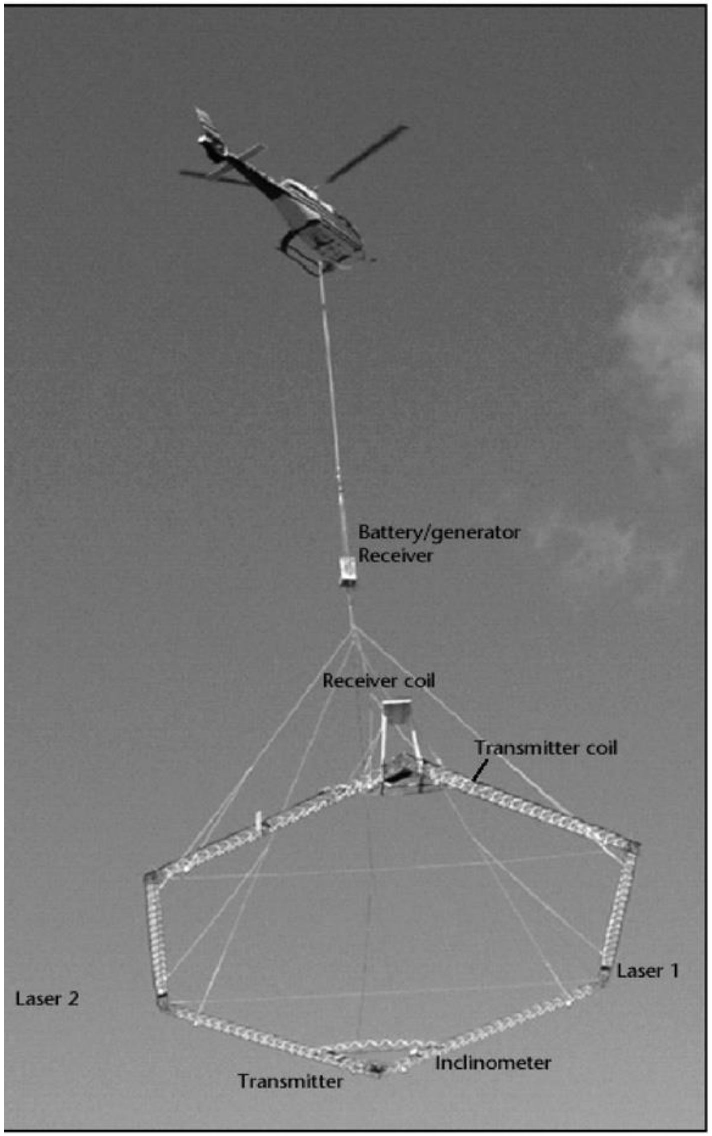
Seepage / infiltration determines thickness rainwaterlens



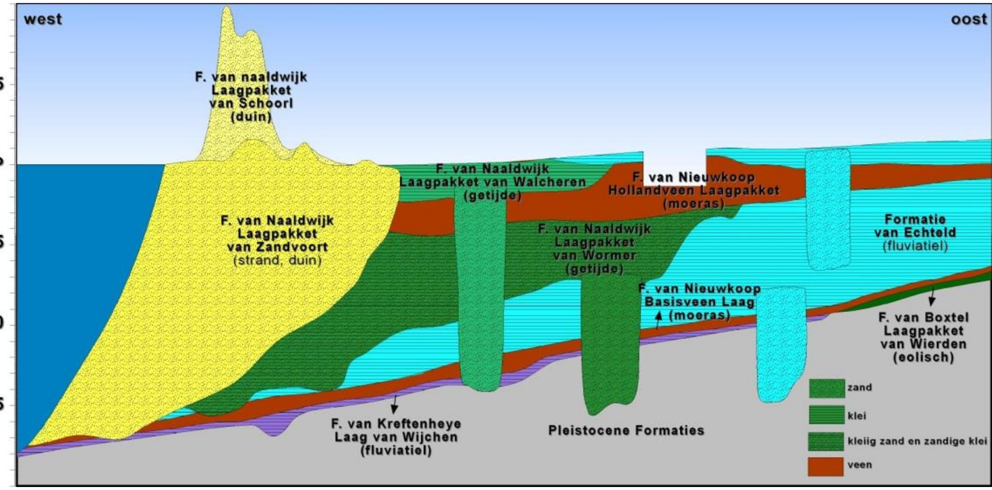
TEC-probe results



Electrical conductance measurements



From bulk to groundwater resistivity

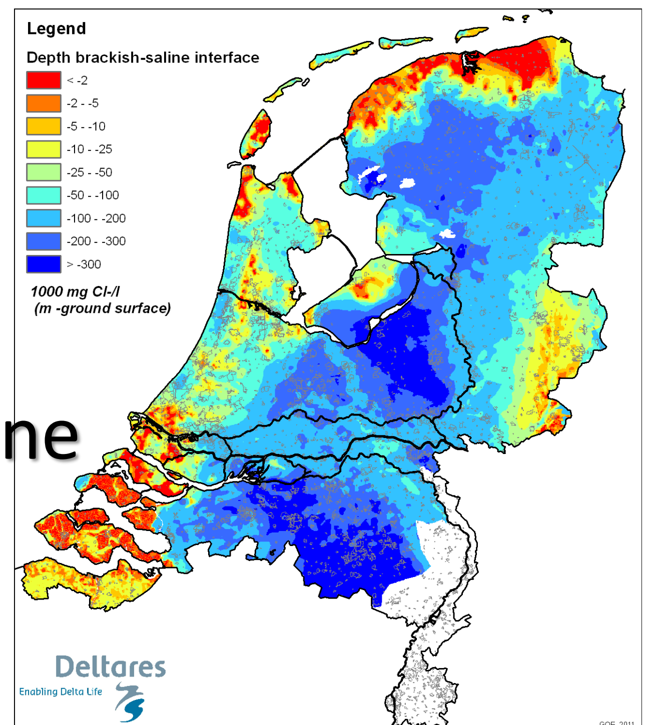


EC lithology

EC^bulk

EC groundwater
→ fresh-brackish-saline

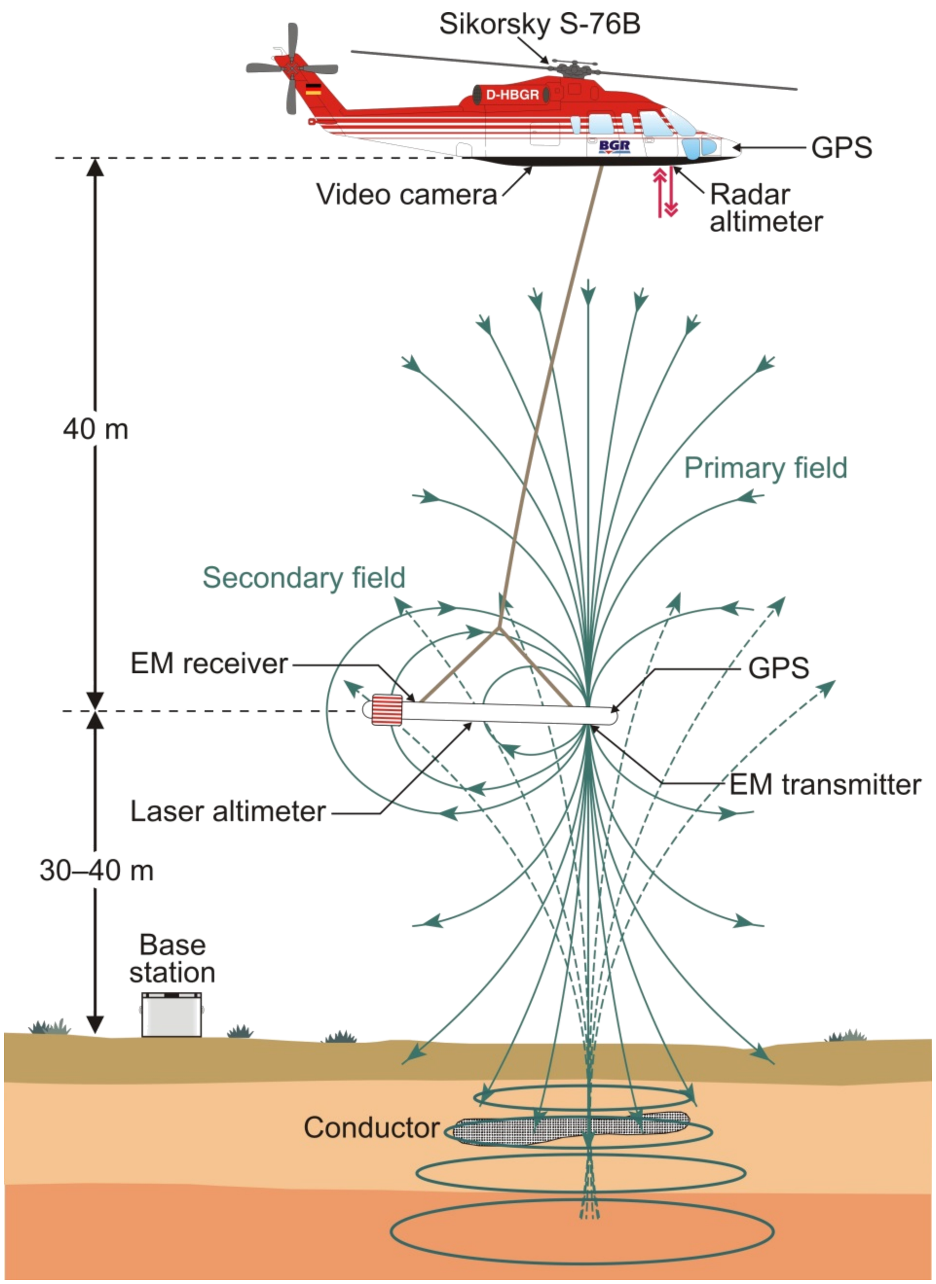
EC



EC = Electrical Conductivity = conductivity

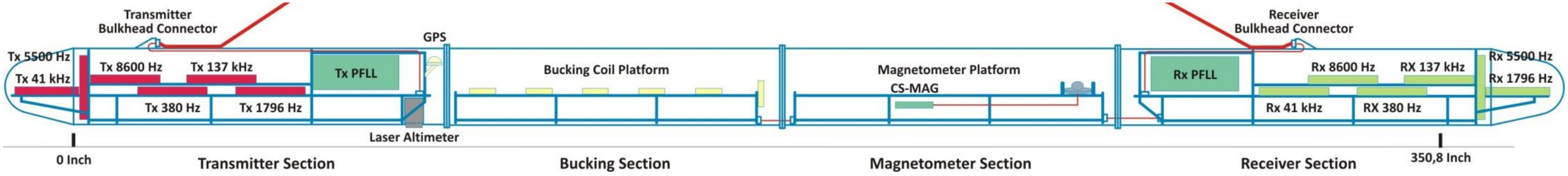
BGR helicopter-borne geophysical system

Airborne geophysical survey system	
Helicopter:	Sikorsky S-76B
Helicopter equipment:	GPS-Navigation GPS-Tracking Radar and barometric altimeters Video camera
Standard equipment:	Electromagnetic system Magnetometer Laser altimeter Gamma-ray spectrometer
Optional equipment:	Laser scanner Pulse radar *Stepped frequency* - Radar Gravimeter Differential GPS Photogrammetric camera Infrared camera
Base station equipment:	Magnetic total field sensor Air pressure sensor Differential GPS
Survey speed:	130 – 160 km/h
Sampling distance:	~ 4 and 40 m
Line separation	50 – 2000 m

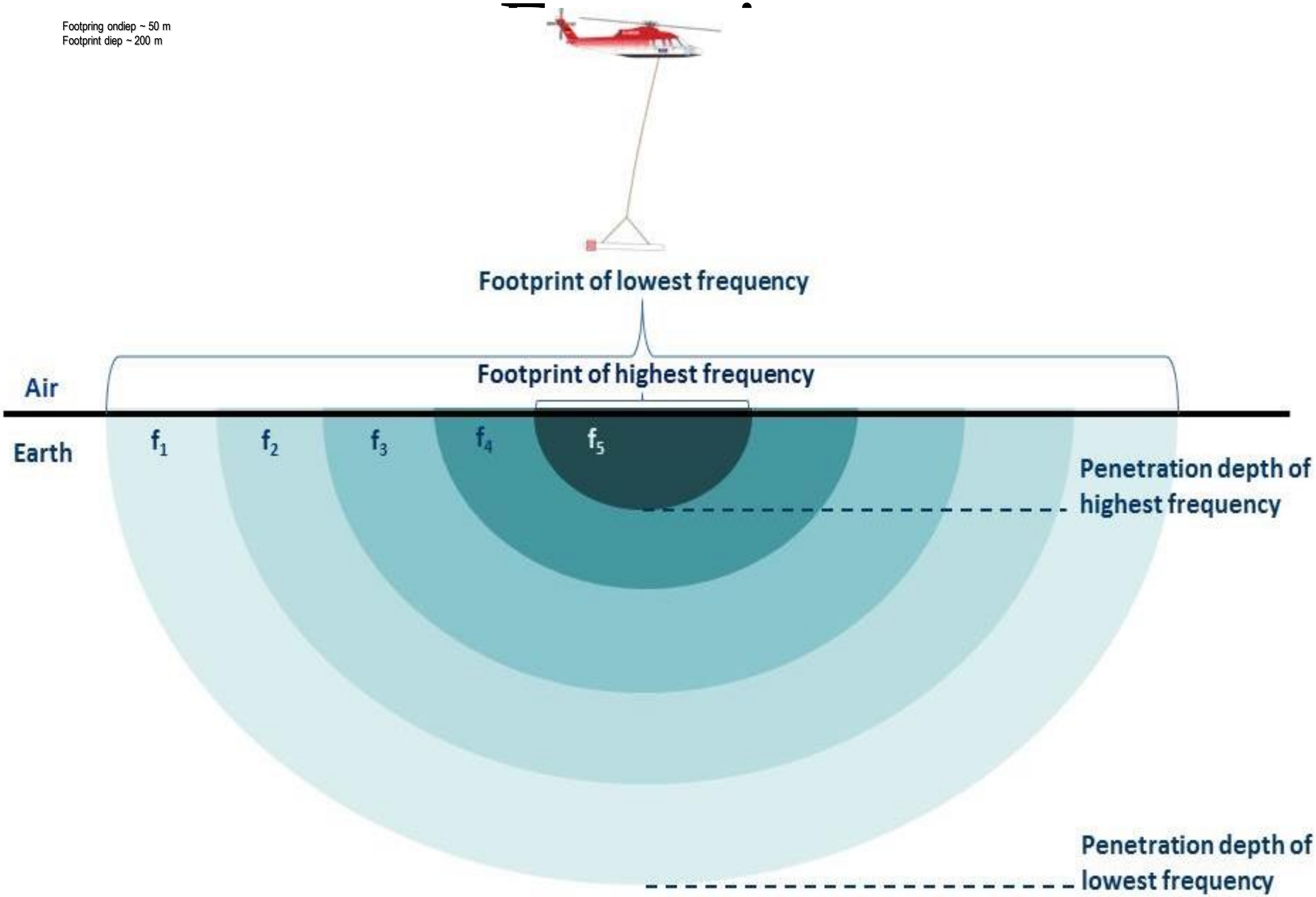


BGR helicopter-borne geophysical system

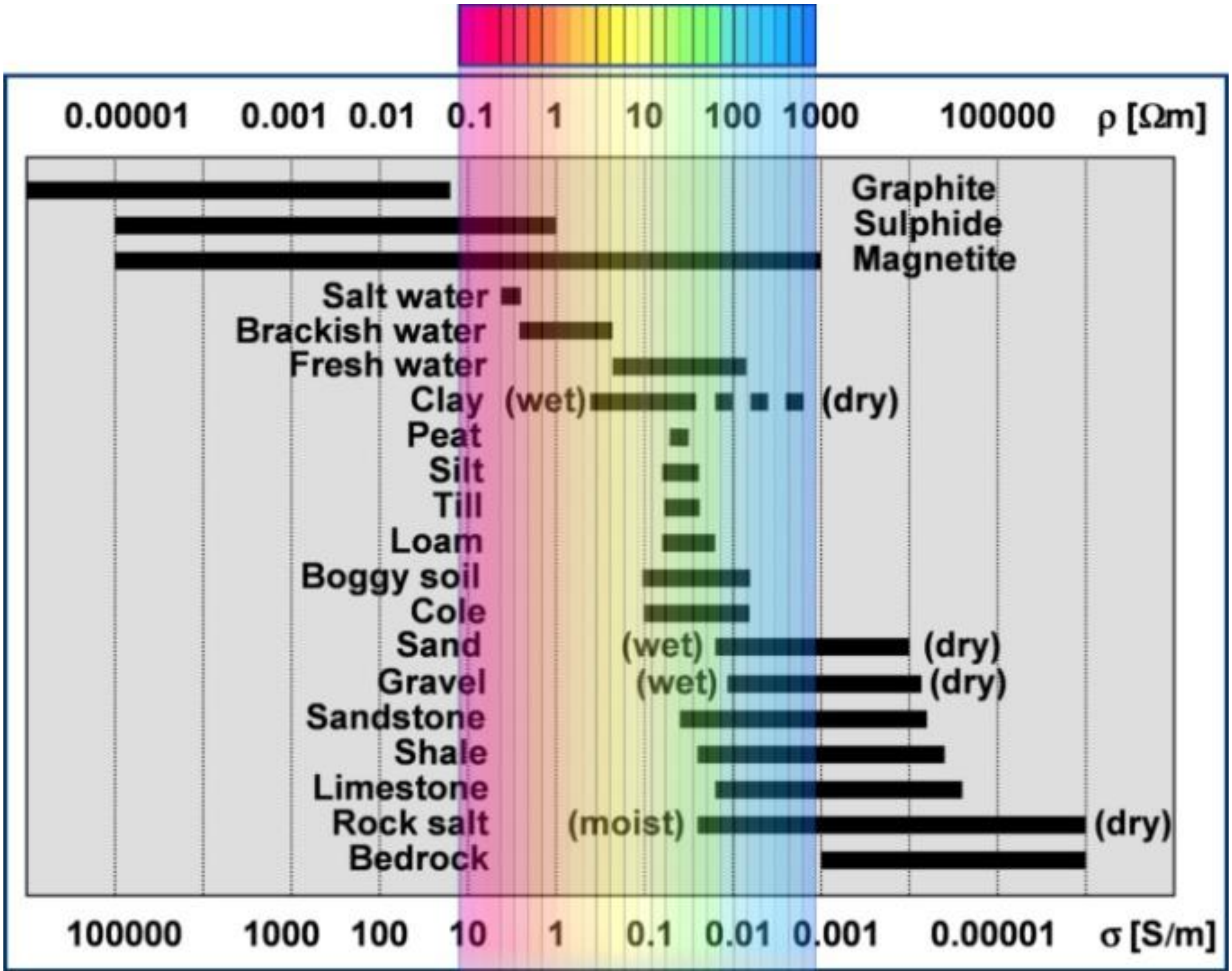
Recent six-frequency HEM system		
Type:	RESOLVE – Digital system Modified BKS36a DSP and BKS60 DSP systems	
Length:	~ 10 m	
Weight:	~ 400 kg incl. cable (80 kg)	
Manufacturer:	Fugro Airborne Systems, Canada	
Frequency [Hz]	Coil separation[m]	Geometry
387	7.94	horizontal coplanar
1820	7.93	horizontal coplanar
5500	9.06	vertical coaxial
8225	7.93	horizontal coplanar
41550	7.91	horizontal coplanar
133200	7.92	horizontal coplanar



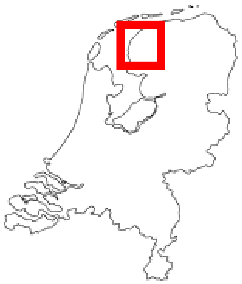
Footpring ondiep ~ 50 m
Footprint diep ~ 200 m

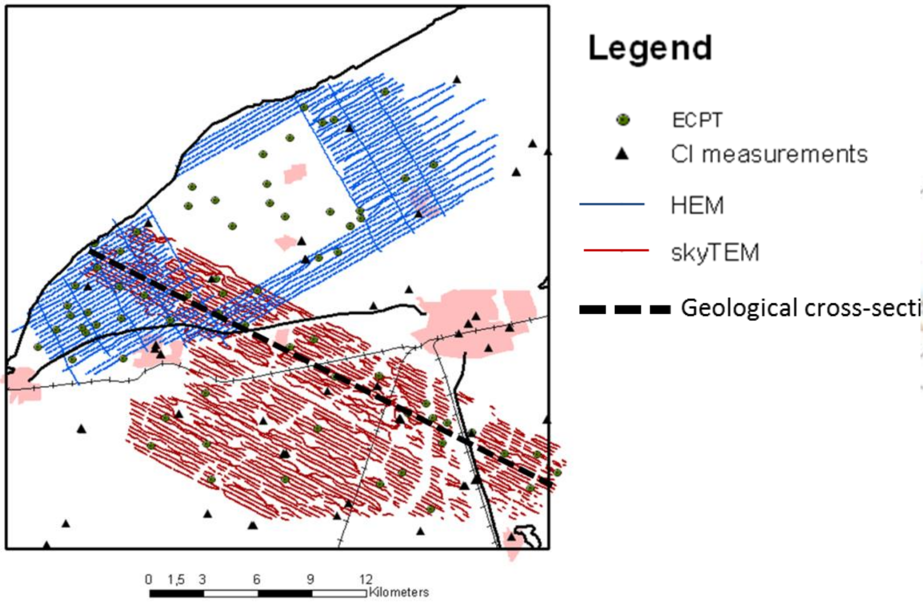


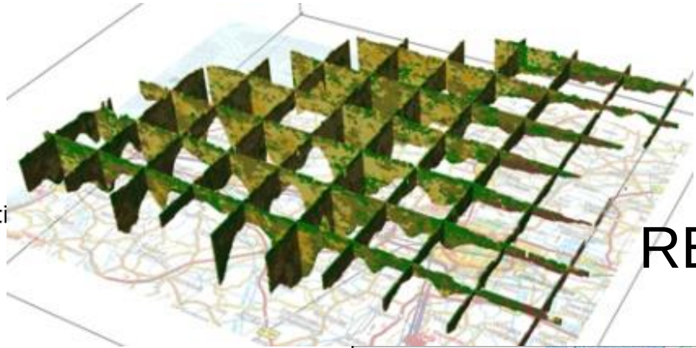
Typical resistivities / conductivities



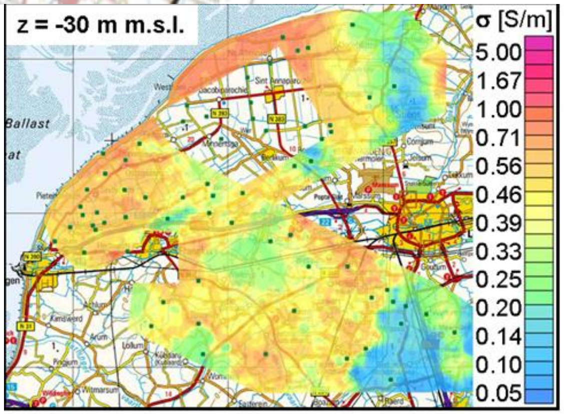
Case Wetterskip Fryslân



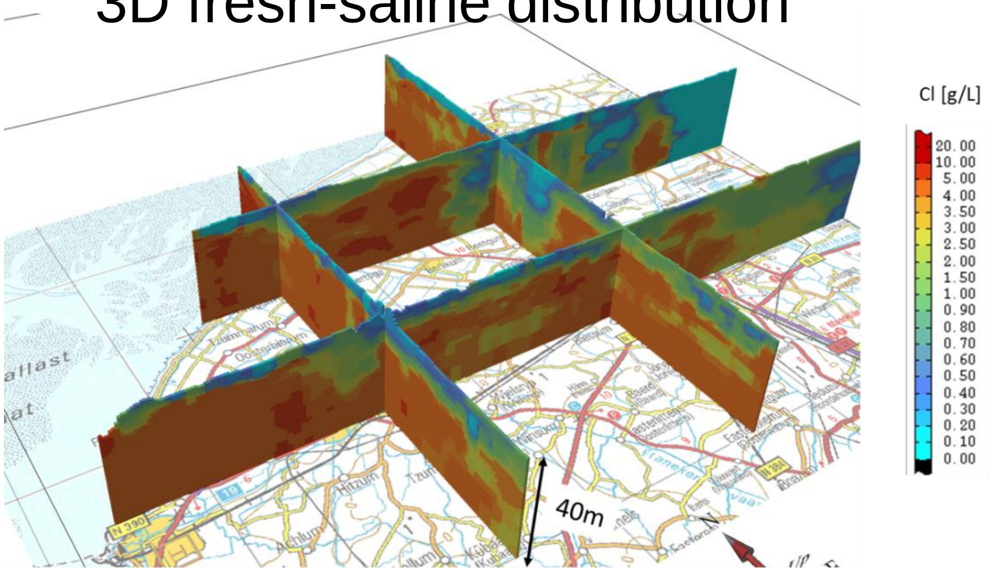




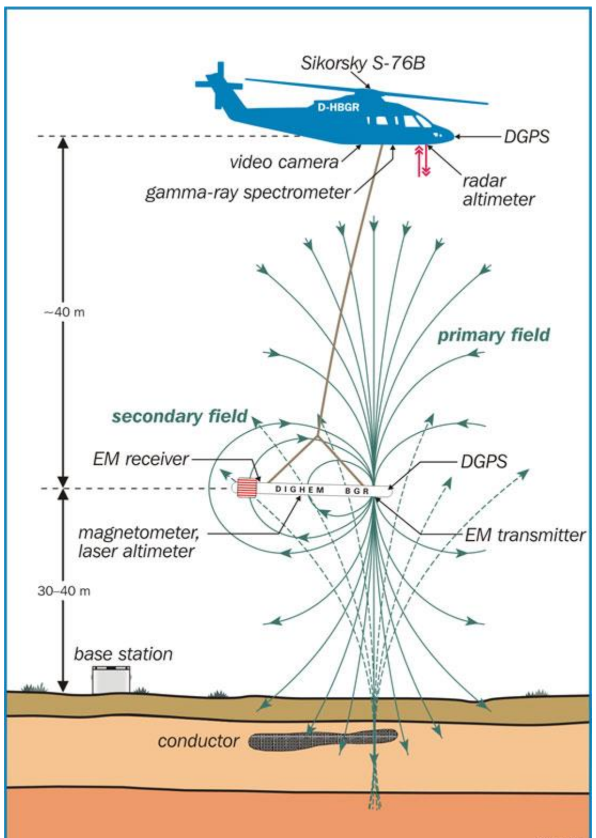
REGIS

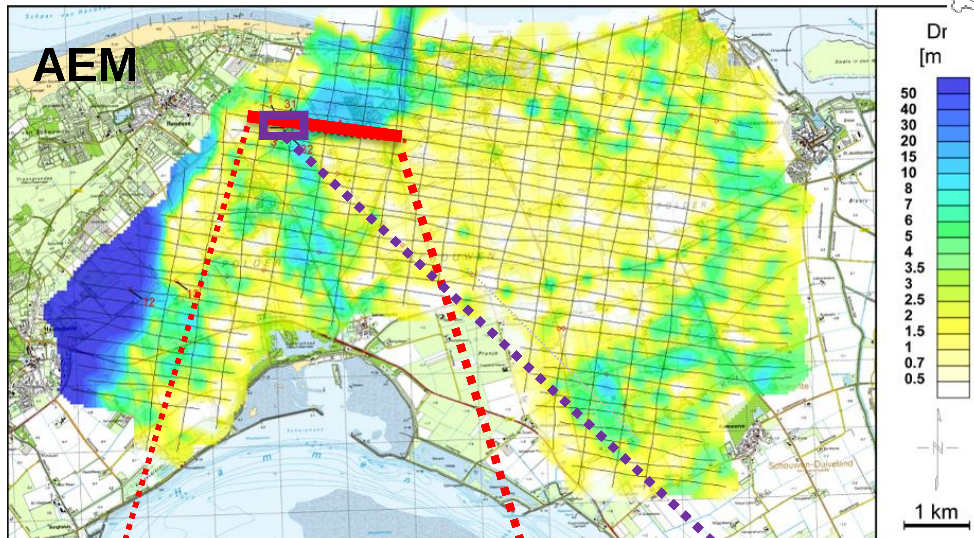


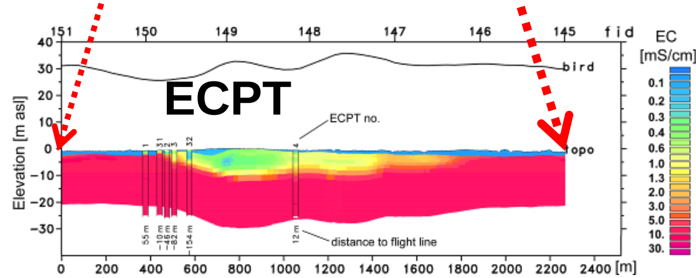
3D fresh-saline distribution

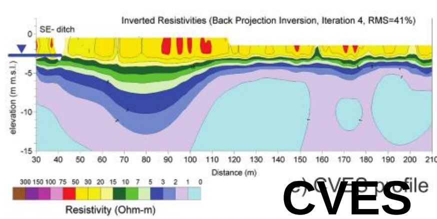


Case Schouwen-Duiveland

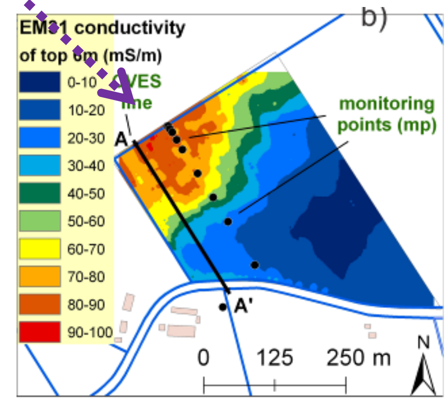






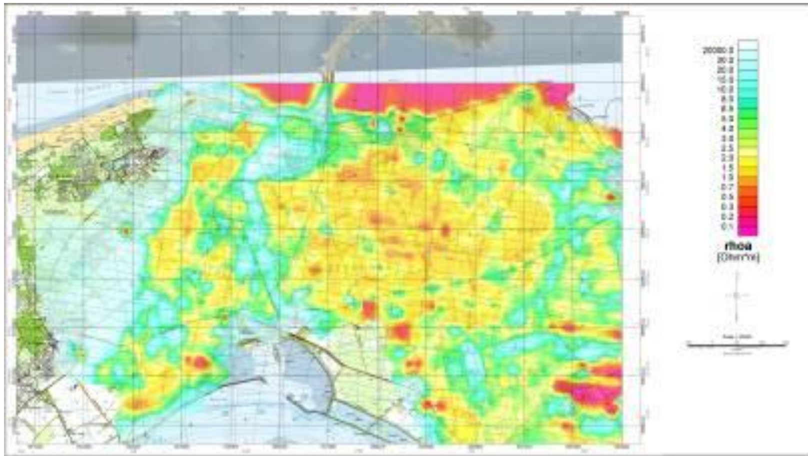


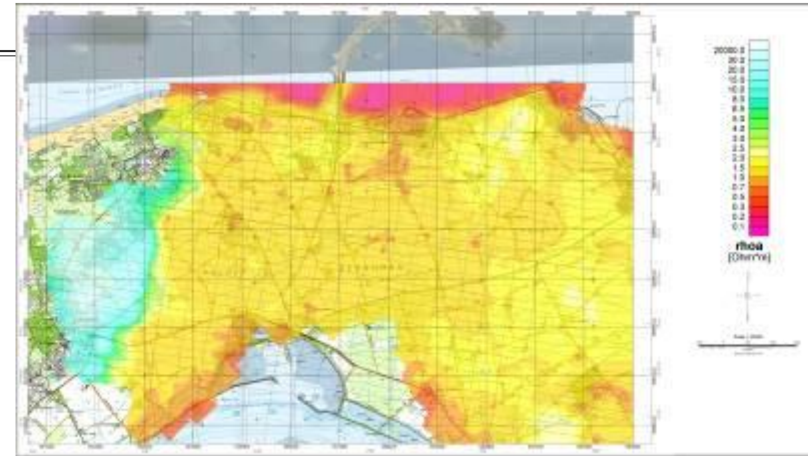
CVES

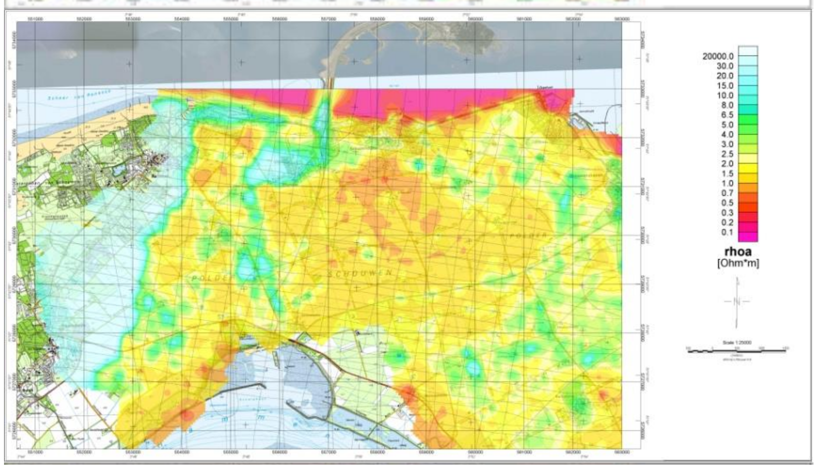


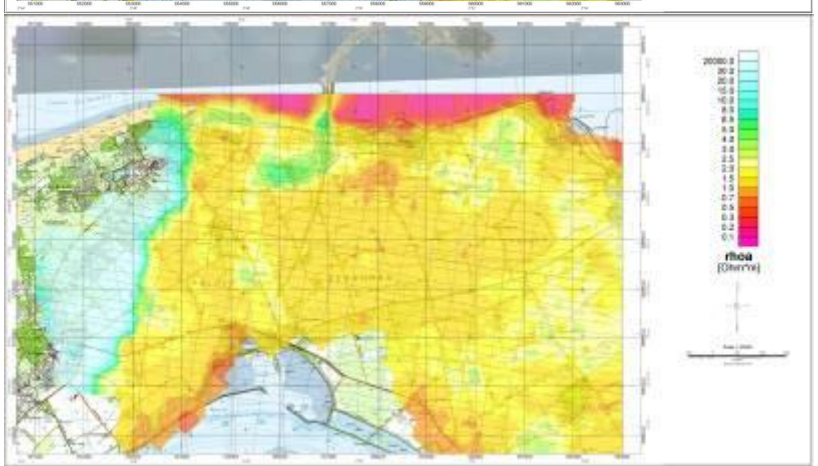
EM31

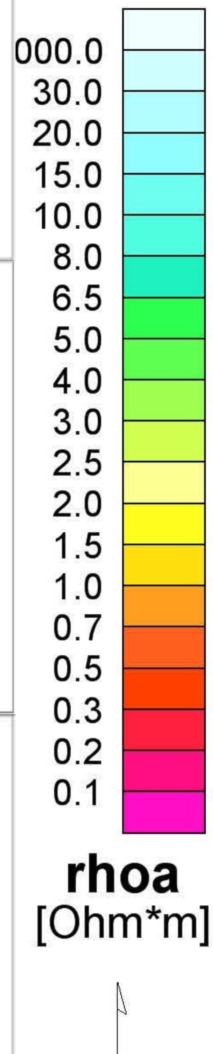
conventional monitoring techniques

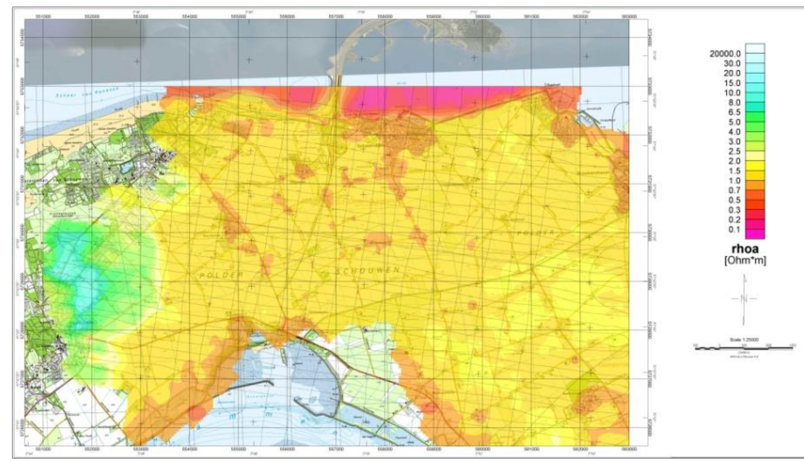






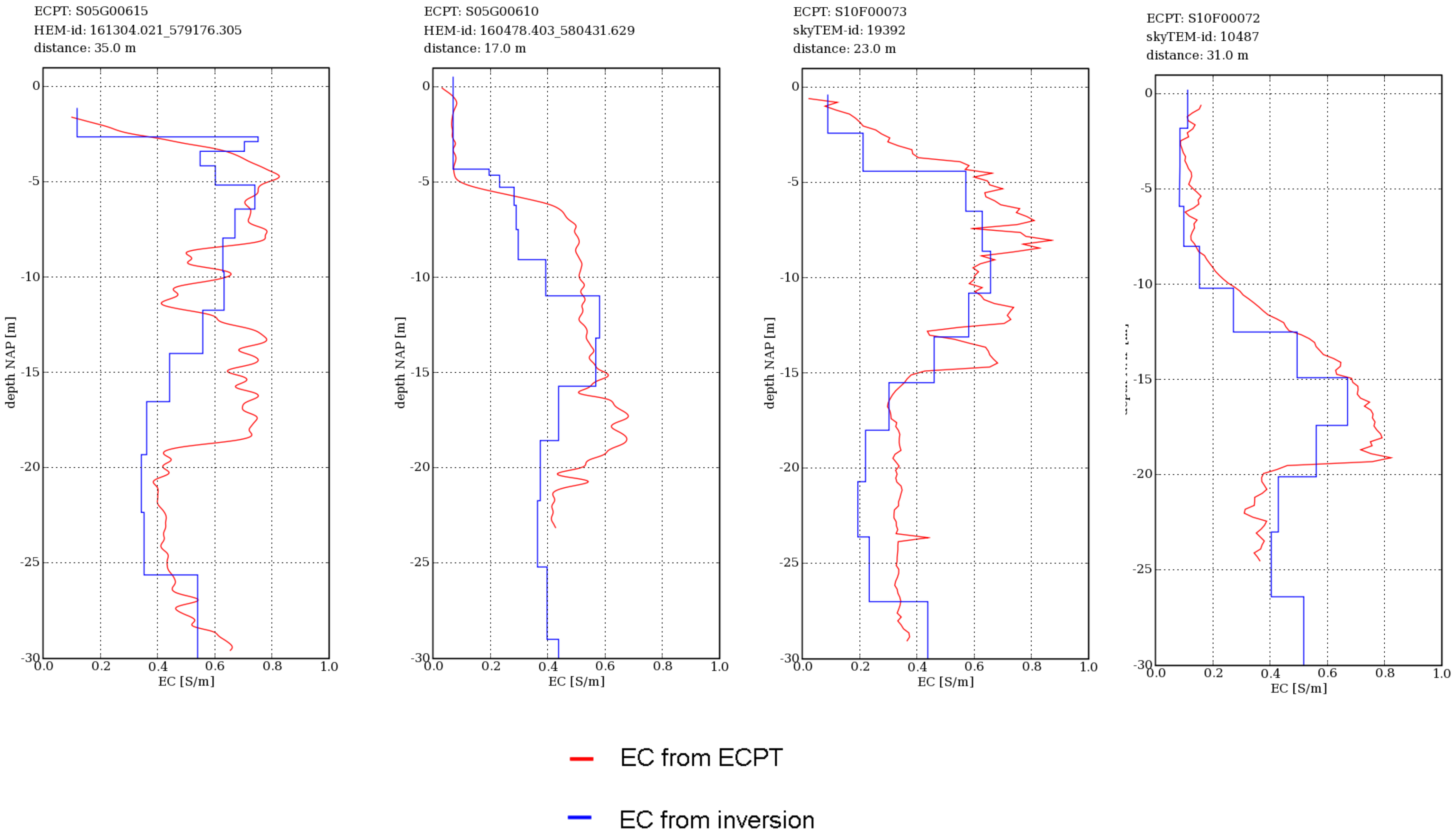






HEM results with depth

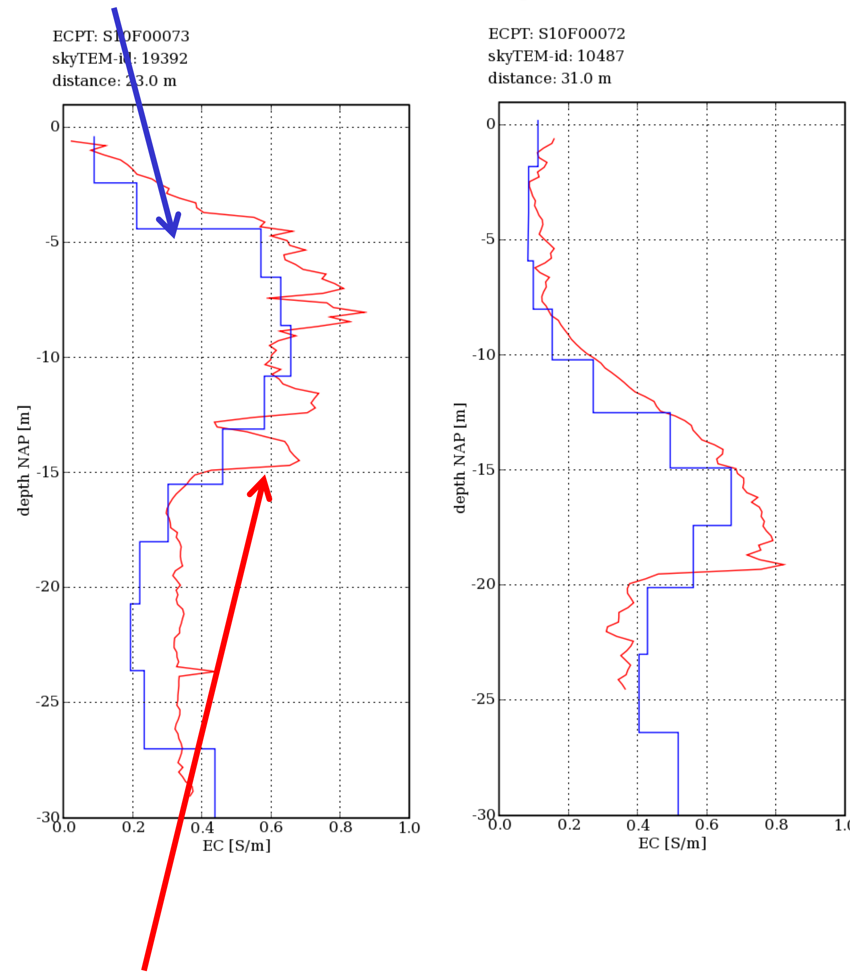
Compare Airborne EM with ECPT
Case Wetterskip Fryslân



3D characterising fresh-saline groundwater

How much samples in 1 week on 900km^2?

AEM: 80000 data points



In-situ: >100 data points

Analysis of the (ground)water system

FRESHEM Zeeland: fresh-salt mapping groundwater

- lithological model and soil measurements
  → translation into chloride
- Validation with ground truth measurements
- 3D distribution chloride concentration

International:

- Project in Flanders, Belgium
- Pilot Mekong, Vietnam

TNO innovation for life

BGR

Deltares

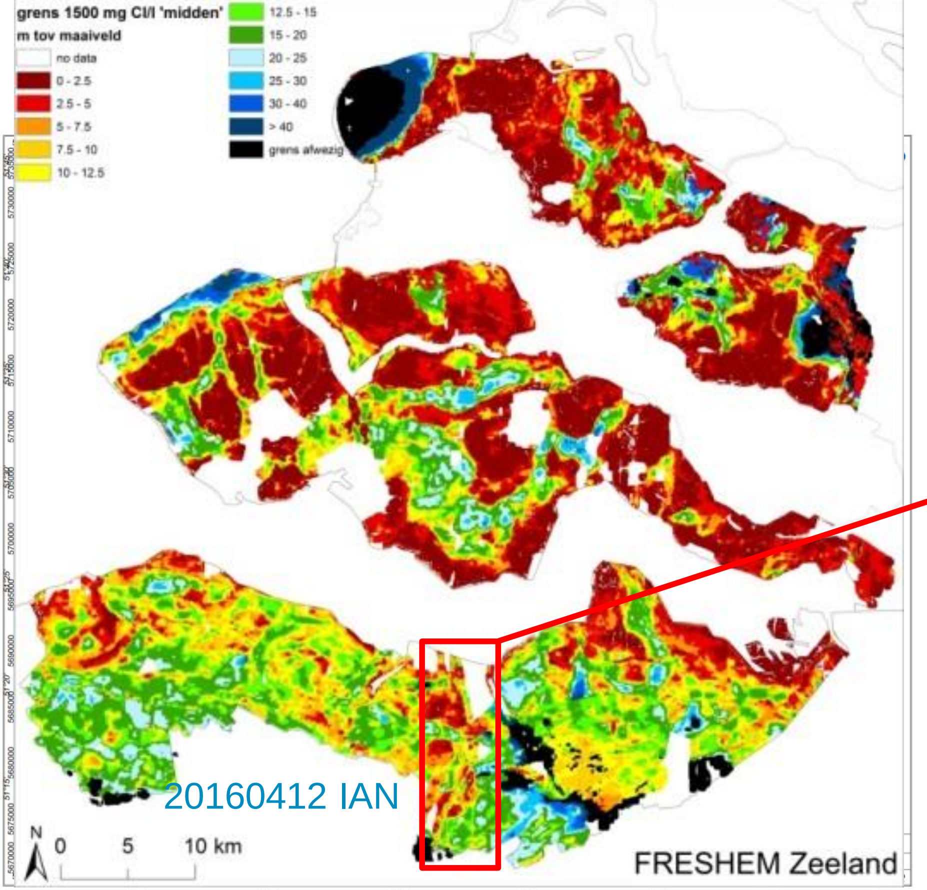
3D Characterisation of the subsoil

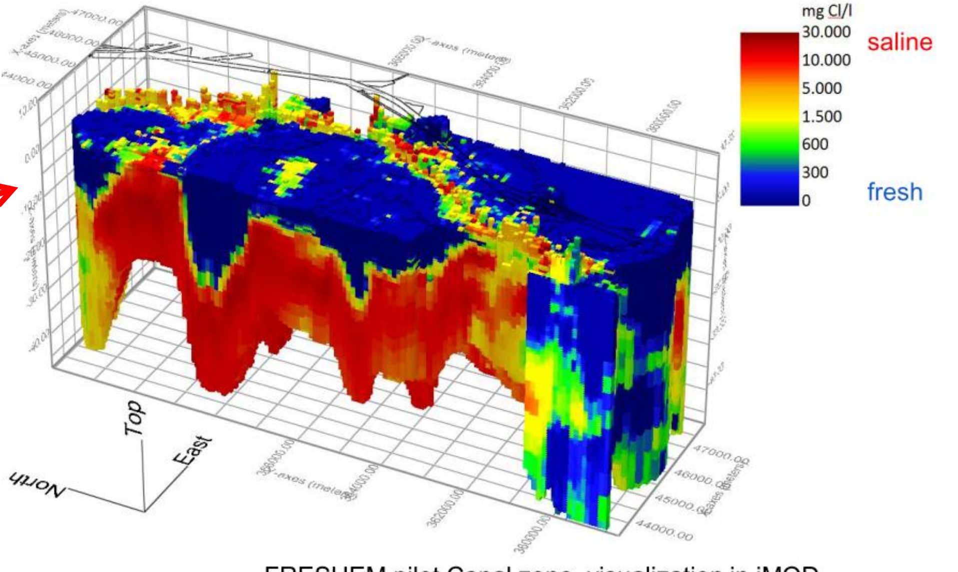
Airborne EM surveys:
much cheaper, faster, 3D,
and as equal accurate as
conventional geophysical methods

TNO innovation for life

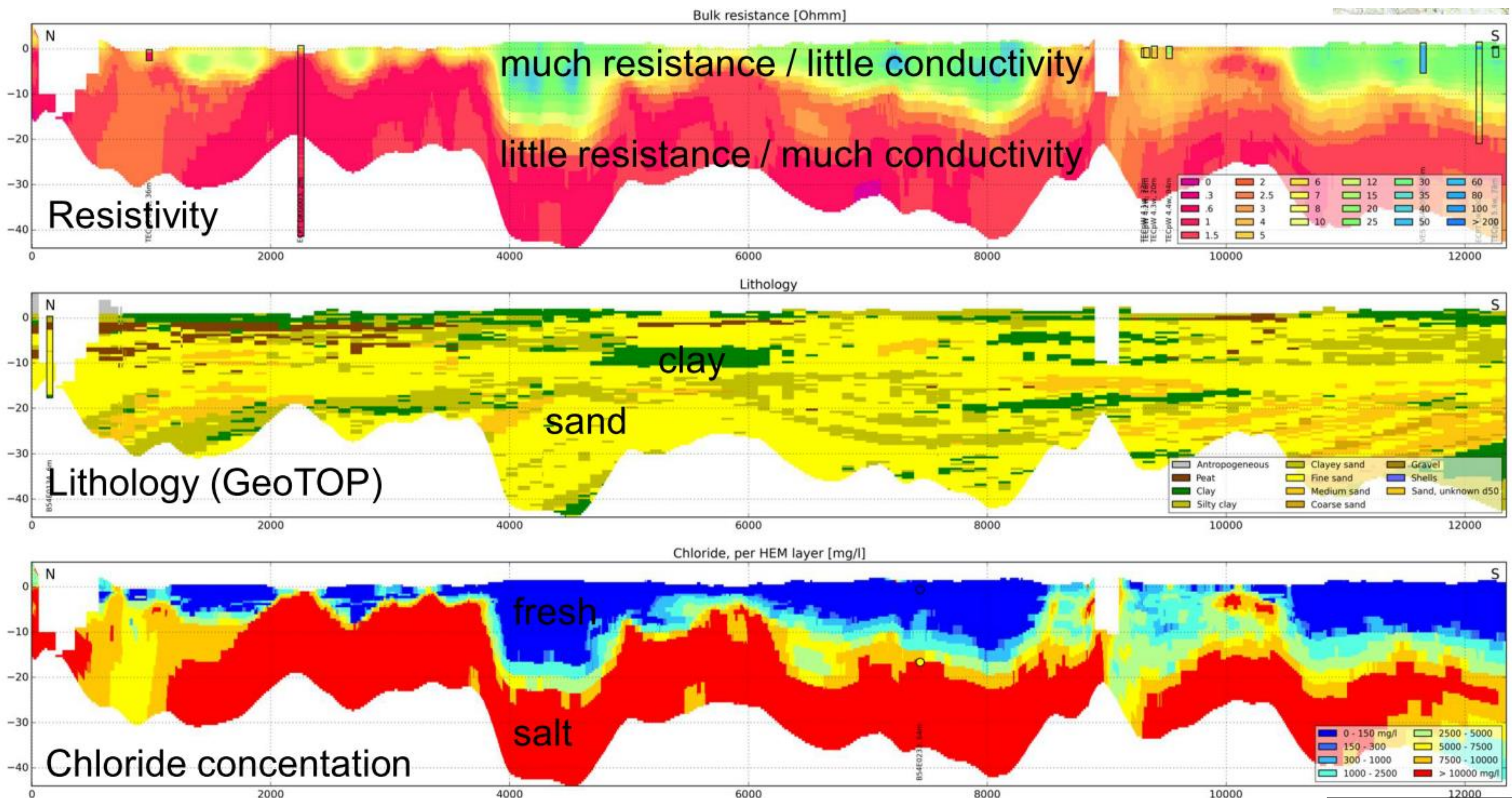
BGR

Deltares
Enabling Delta Life



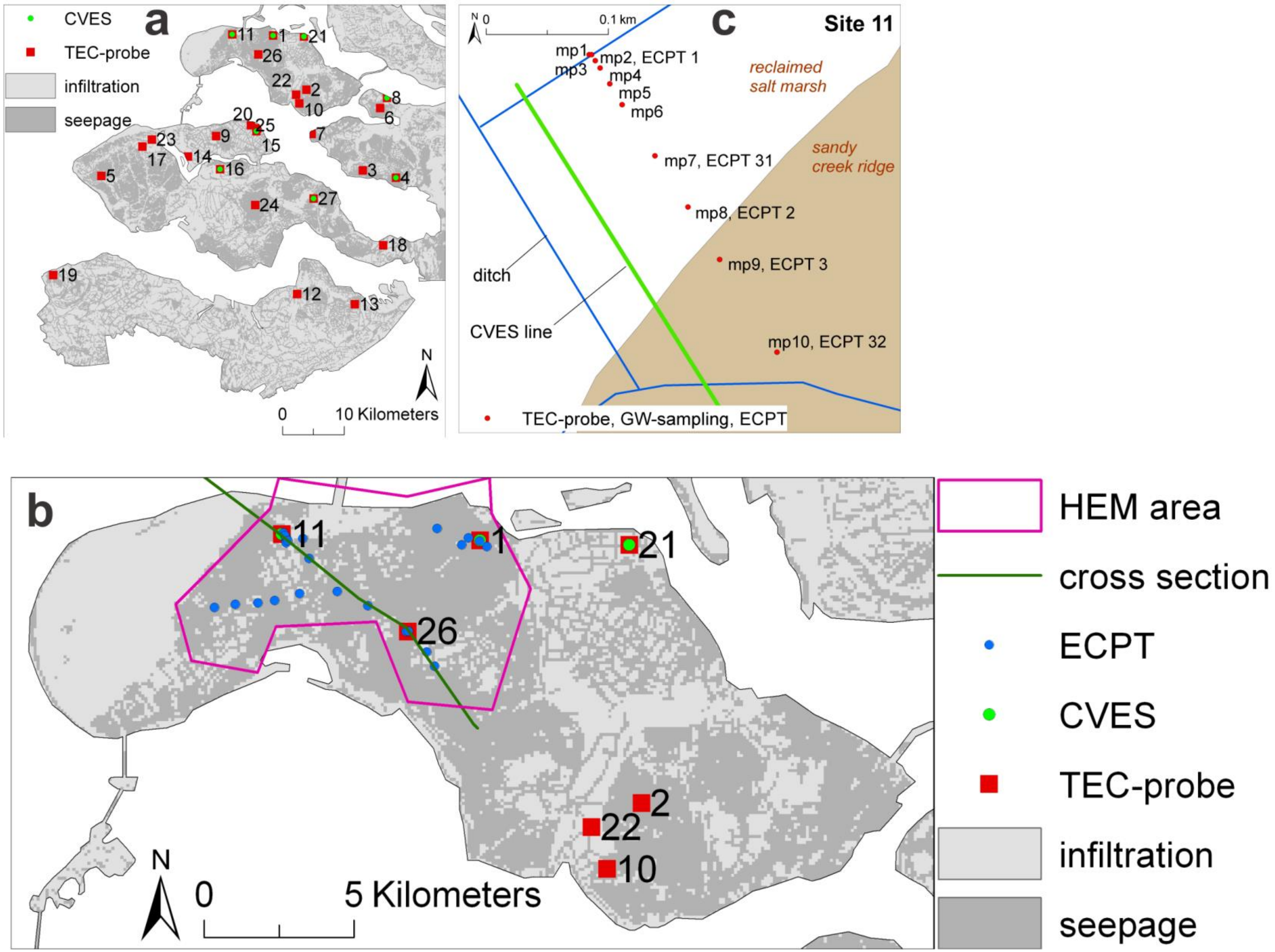


Example NL, Zeeland, project FRESHEM

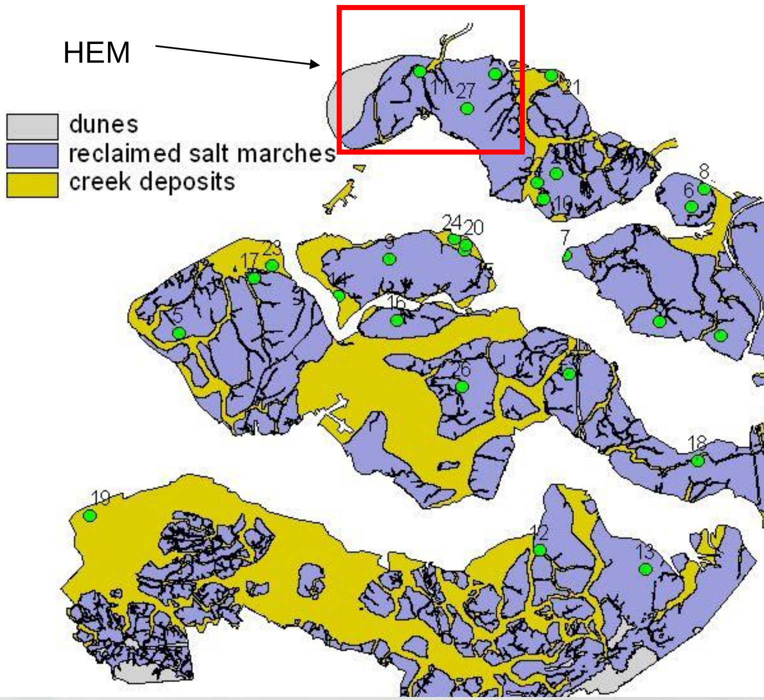


Delsman, J.R., Van Baaren, E.S., Siemon, B., Dabekaussen, W., Karaoulis, M.C., Pauw, P.S., Vermaas, T., Bootsma, H., De Louw, P.G.B., Gunnink, J.L., Dubelaar, W., Menkovic, A., Steuer, A., Meyer, U., Revil, A., Oude Essink, G.H.P., 2018. Large-scale, probabilistic salinity mapping using airborne electromagnetics for groundwater management in Zeeland, the Netherlands. Environ. Res. Lett. 13, 13. https://doi.org/10.1088/1748-9326/aad19e

Combining monitoring techniques



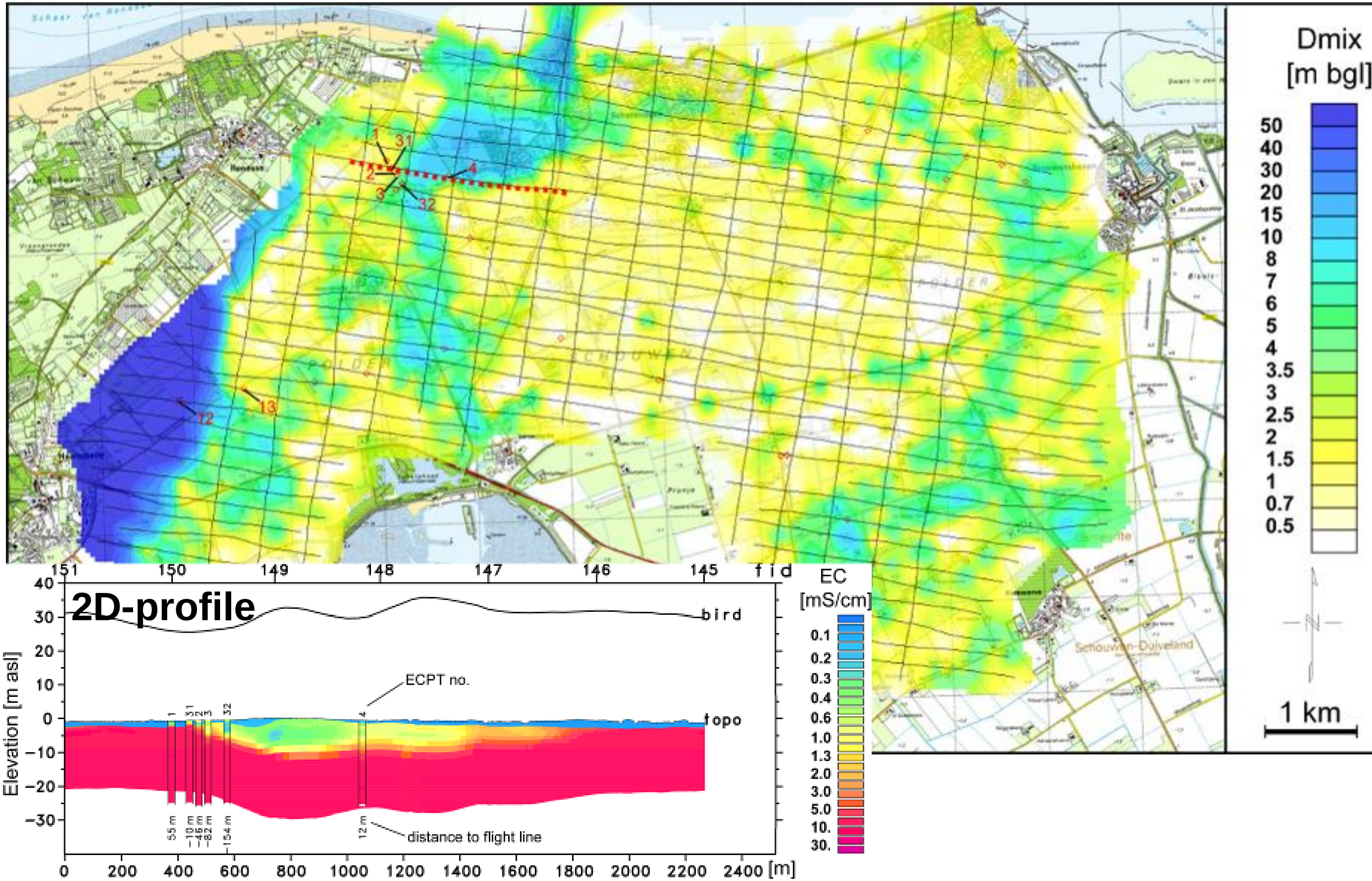
Helicopter-EM data for mapping fresh-saline groundwater



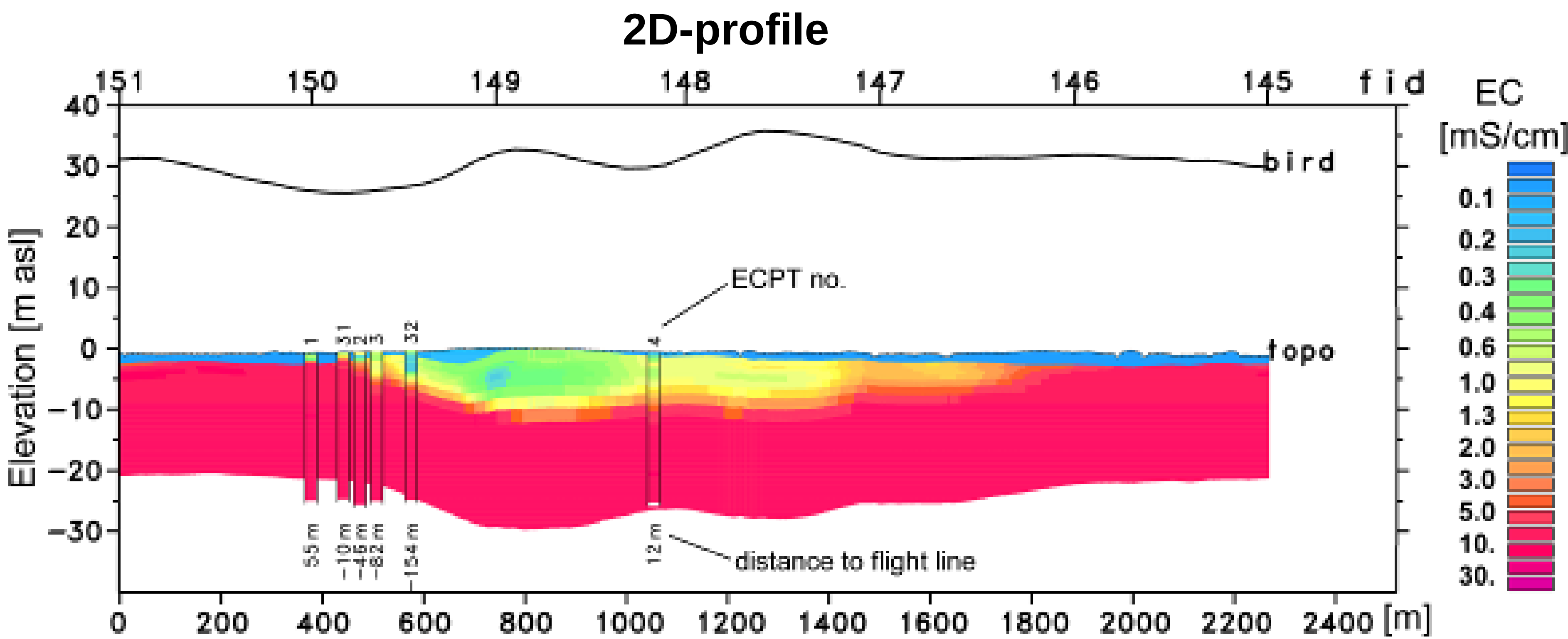
Interreg IV-B

CLIWAT
CLIMATE & WATER

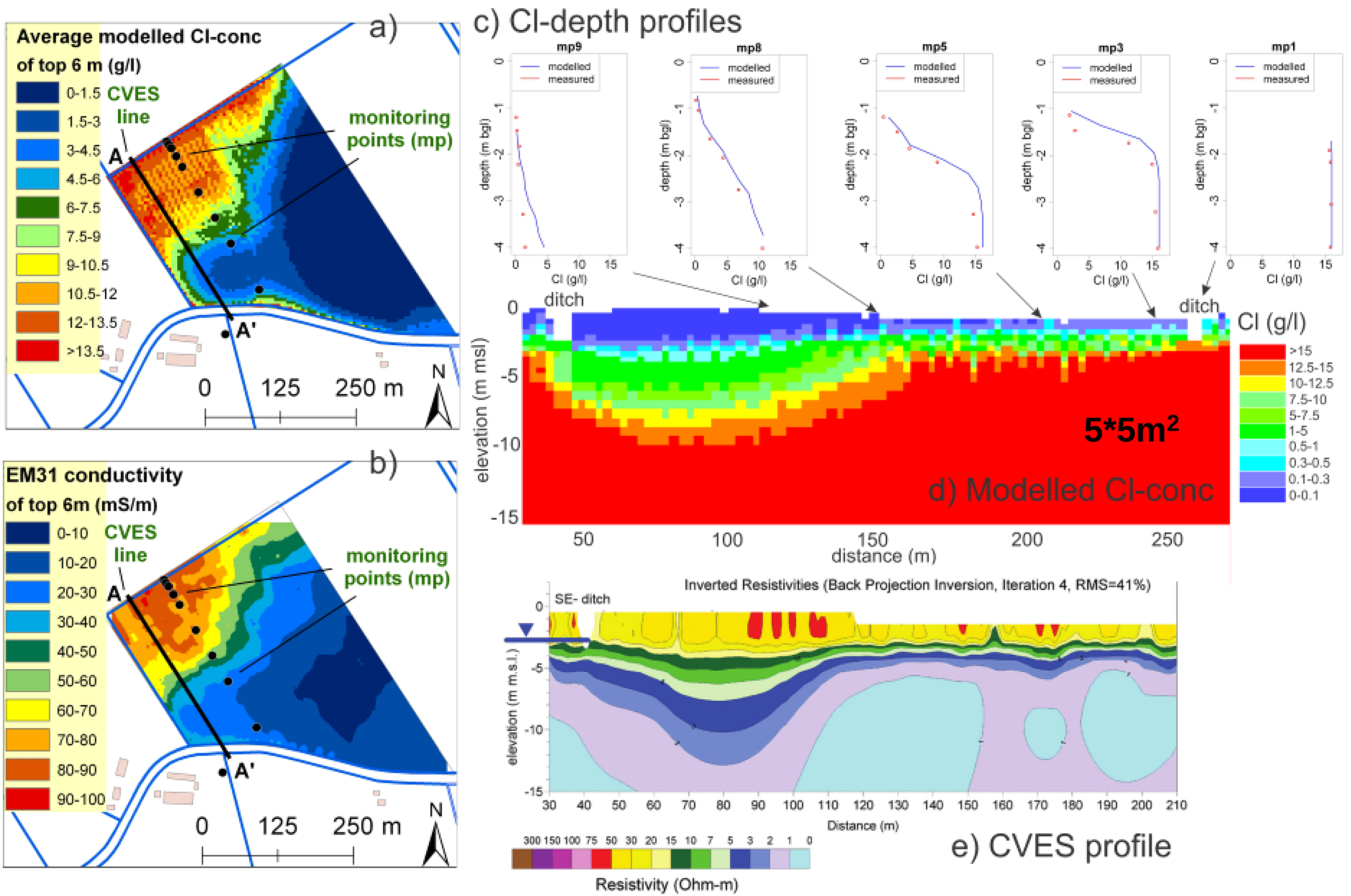
Thickness rainwater lens (D_{mix}) by HEM



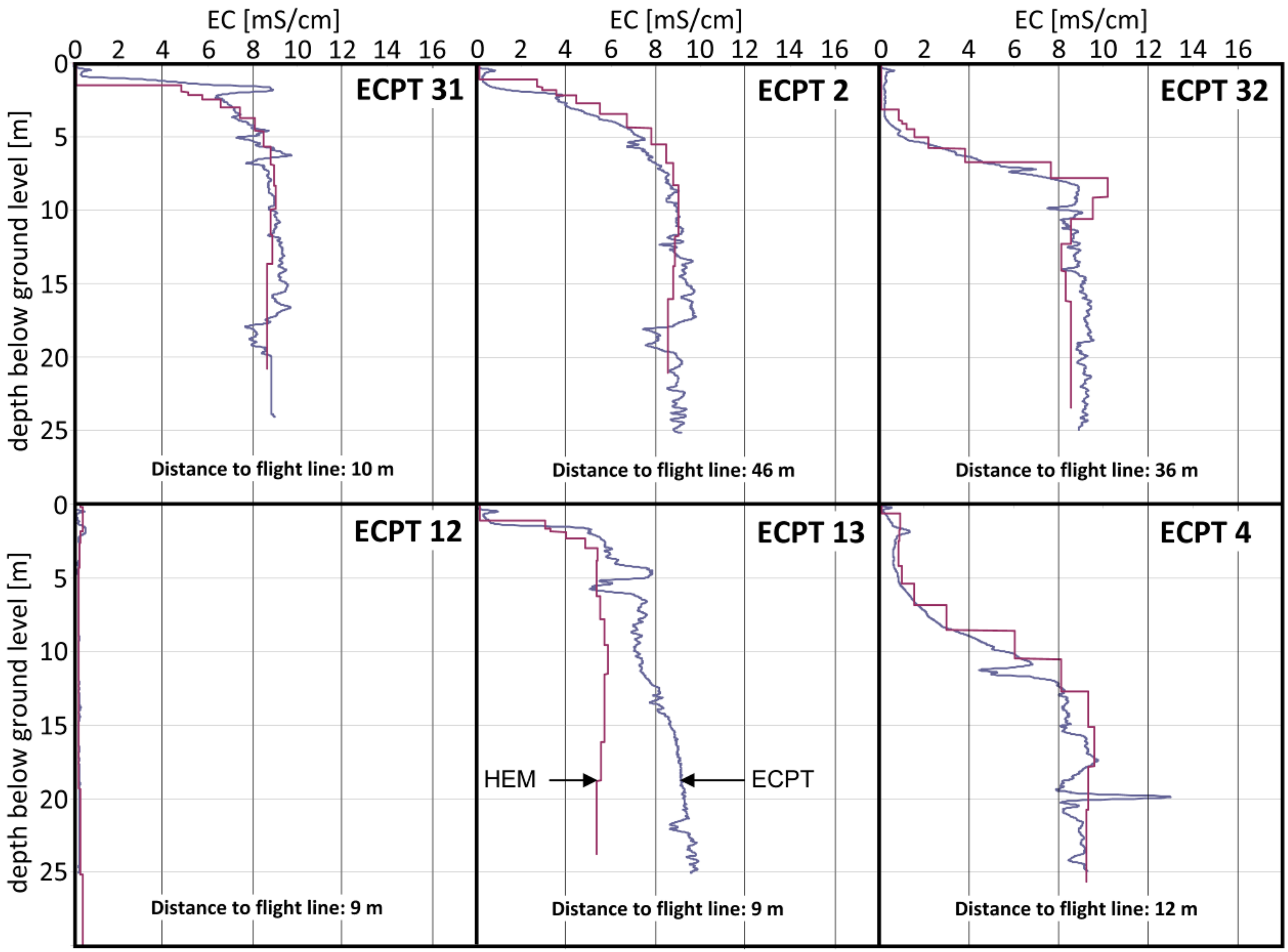
Thickness rainwater lens (D_{mix}) by HEM



Comparison monitoring data with model results



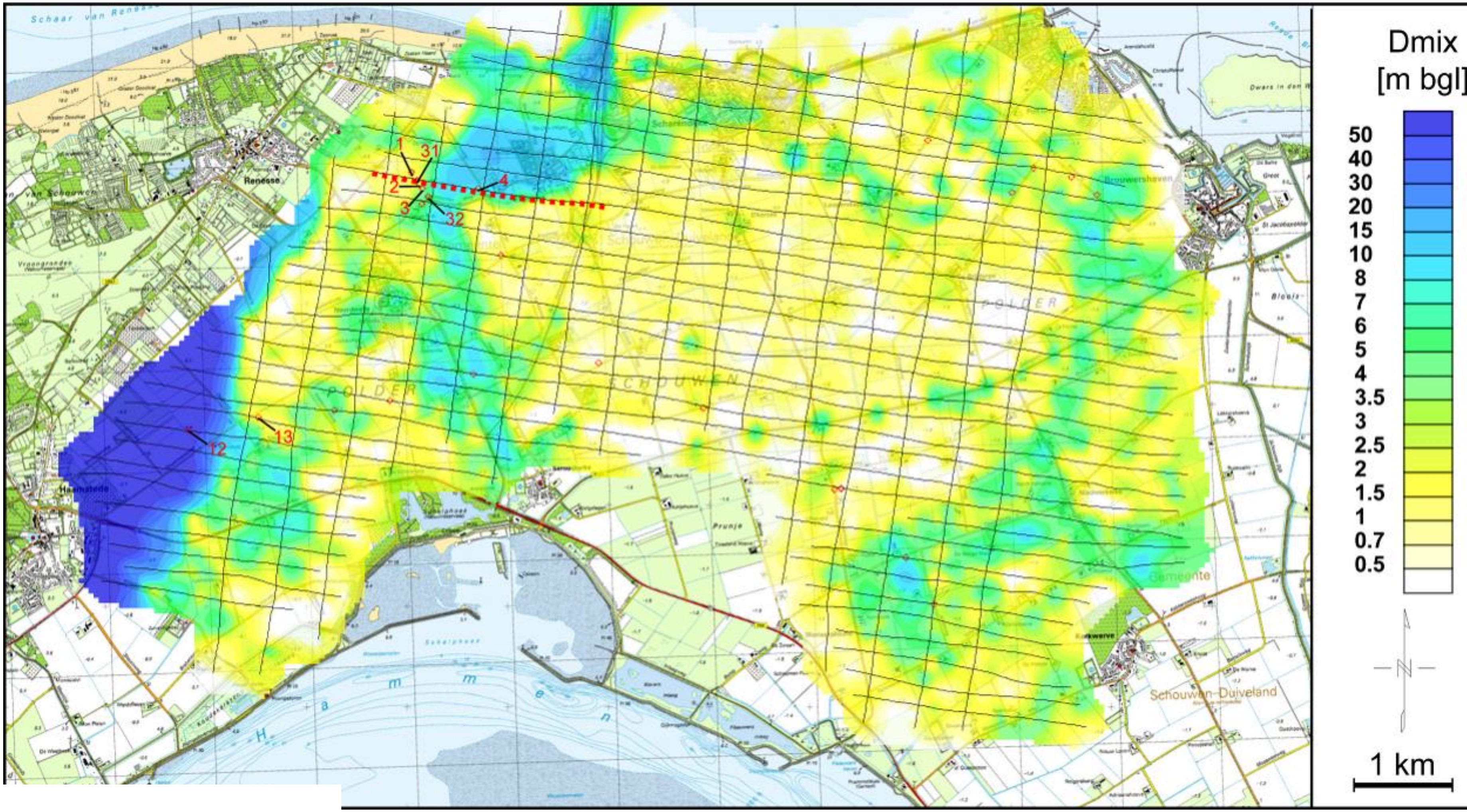
Comparison HEM - ECPT



Bundesanstalt für Geowissenschaften und Rohstoffe

TRUM HANNOVER

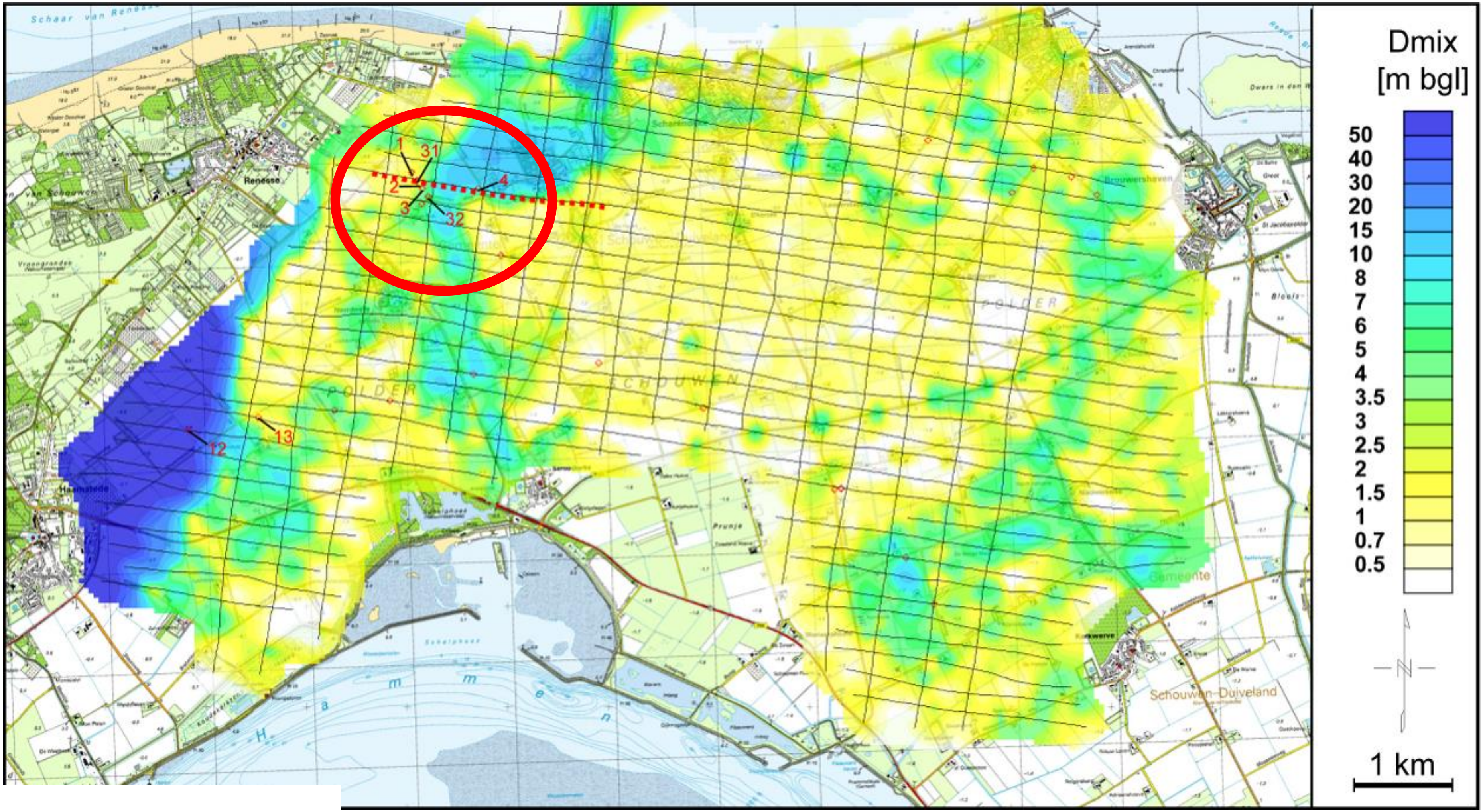
Rainwater lens thickness (D_{mix}= average position mixing zone) mapped with HEM



BGR Bundesanstalt für Geowissenschaften und Rohstoffe

GEOZENTRUM HANNOVER

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



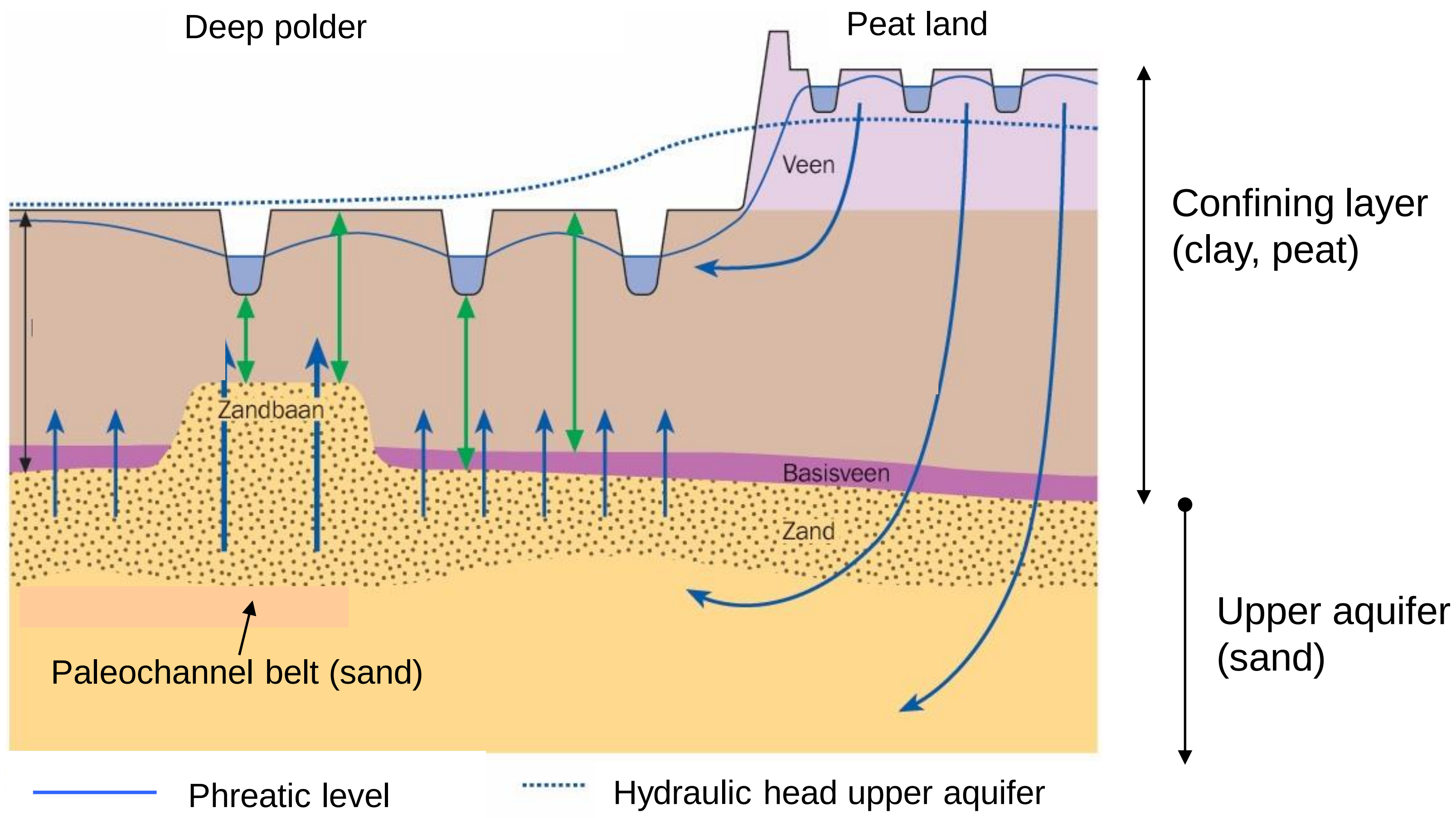
Bundesanstalt für Geowissenschaften und Rohstoffe

GEOZENTRUM HANNOVER

Salty boils

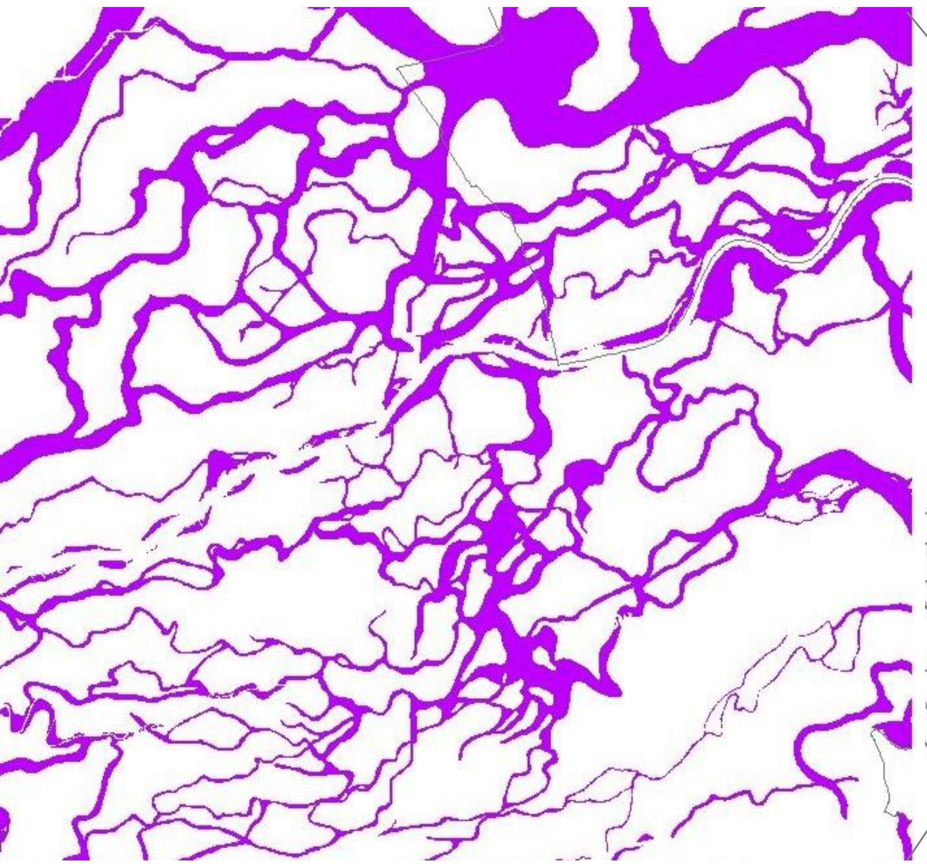
Louw, P.G.B., de, Oude Essink, G.H.P., Stuyfzand, P.J., Zee, van der, S.E.A.T.M., 2010, Upward groundwater flow in boils as the dominant mechanism of salinization in deep polders, The Netherlands, J. Hydrol. 394, 494-506.

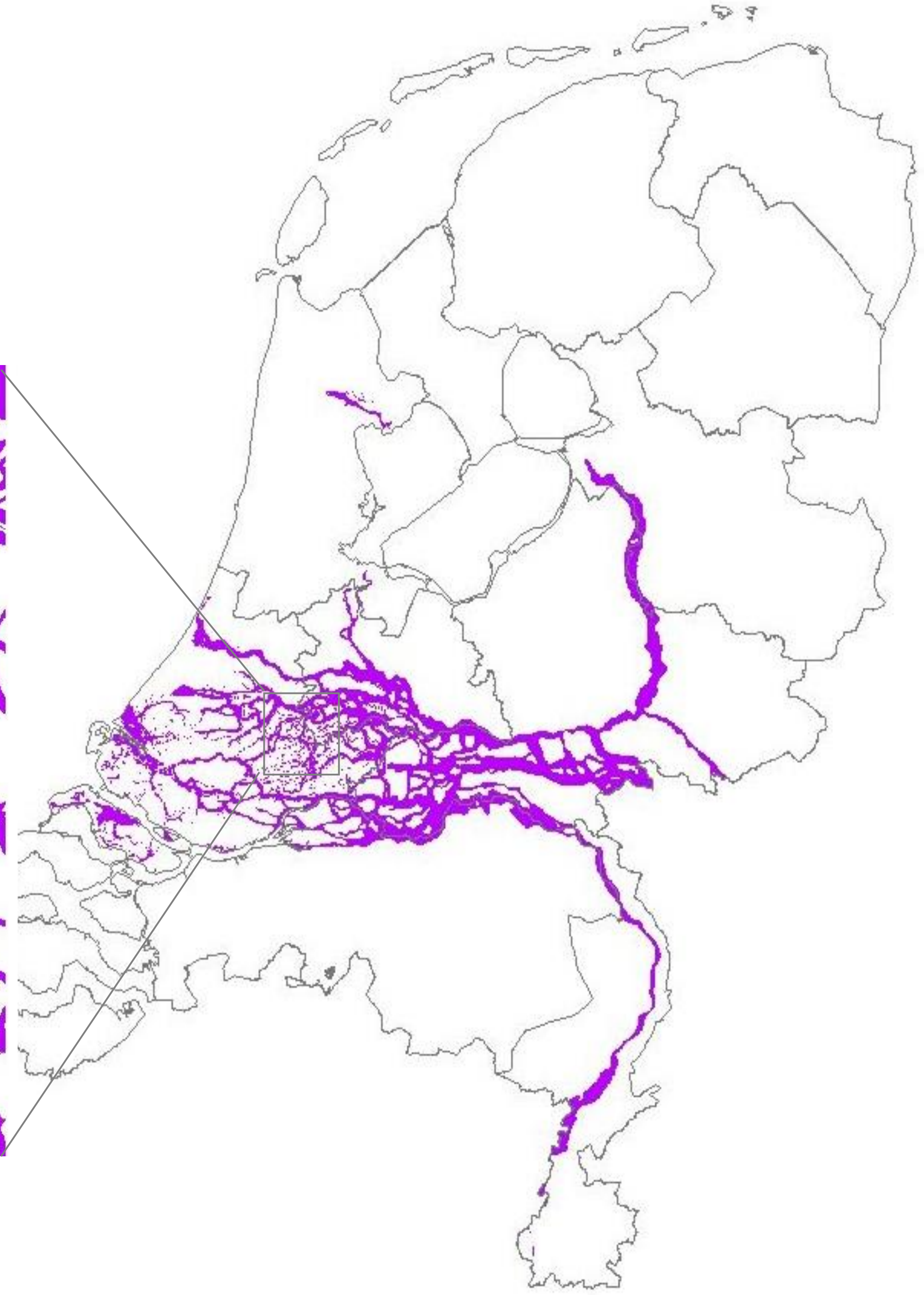
Upward groundwater seepage in a deep polder and paleochannel belts as preferential flow paths



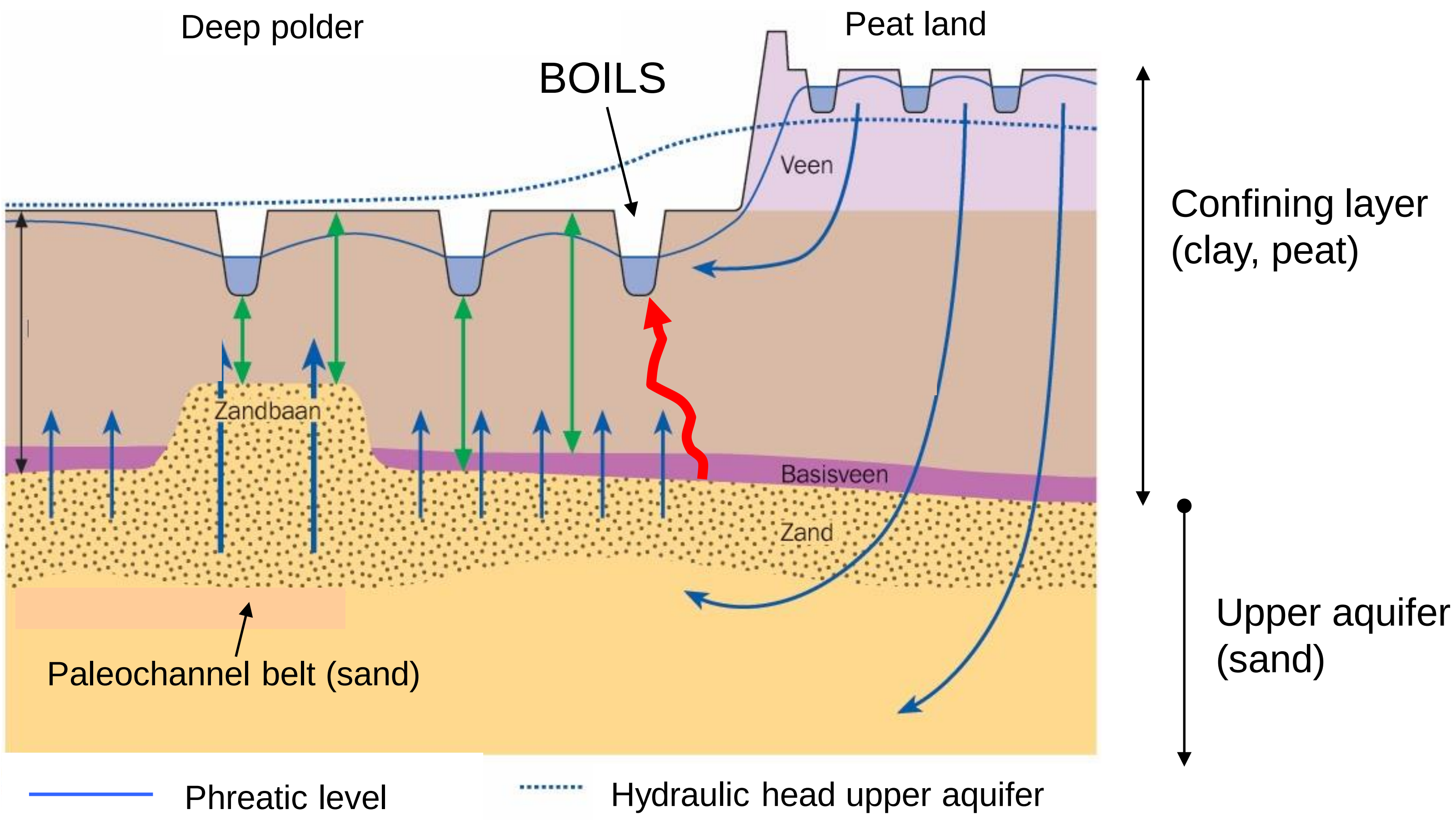
(Burried)

Paleochannel belts

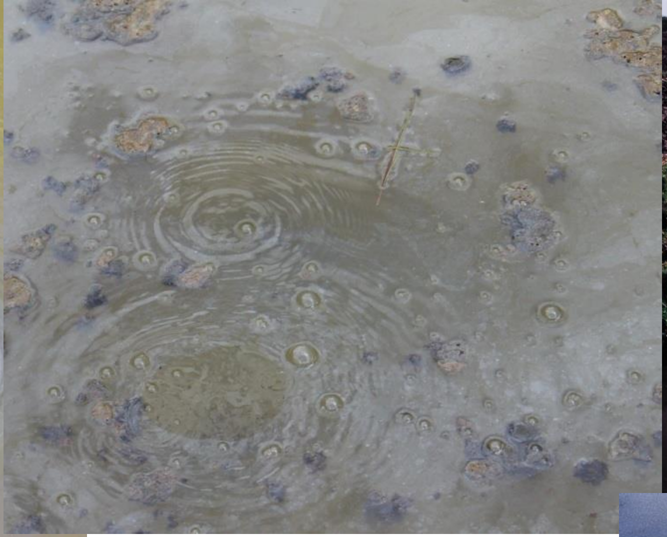




Preferential seepage via boils

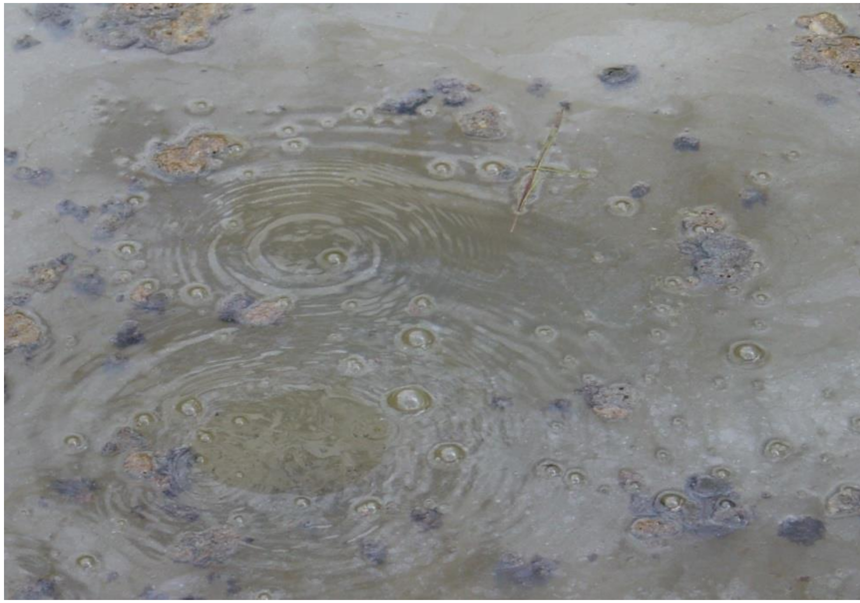


Preferential saline seepage via boils

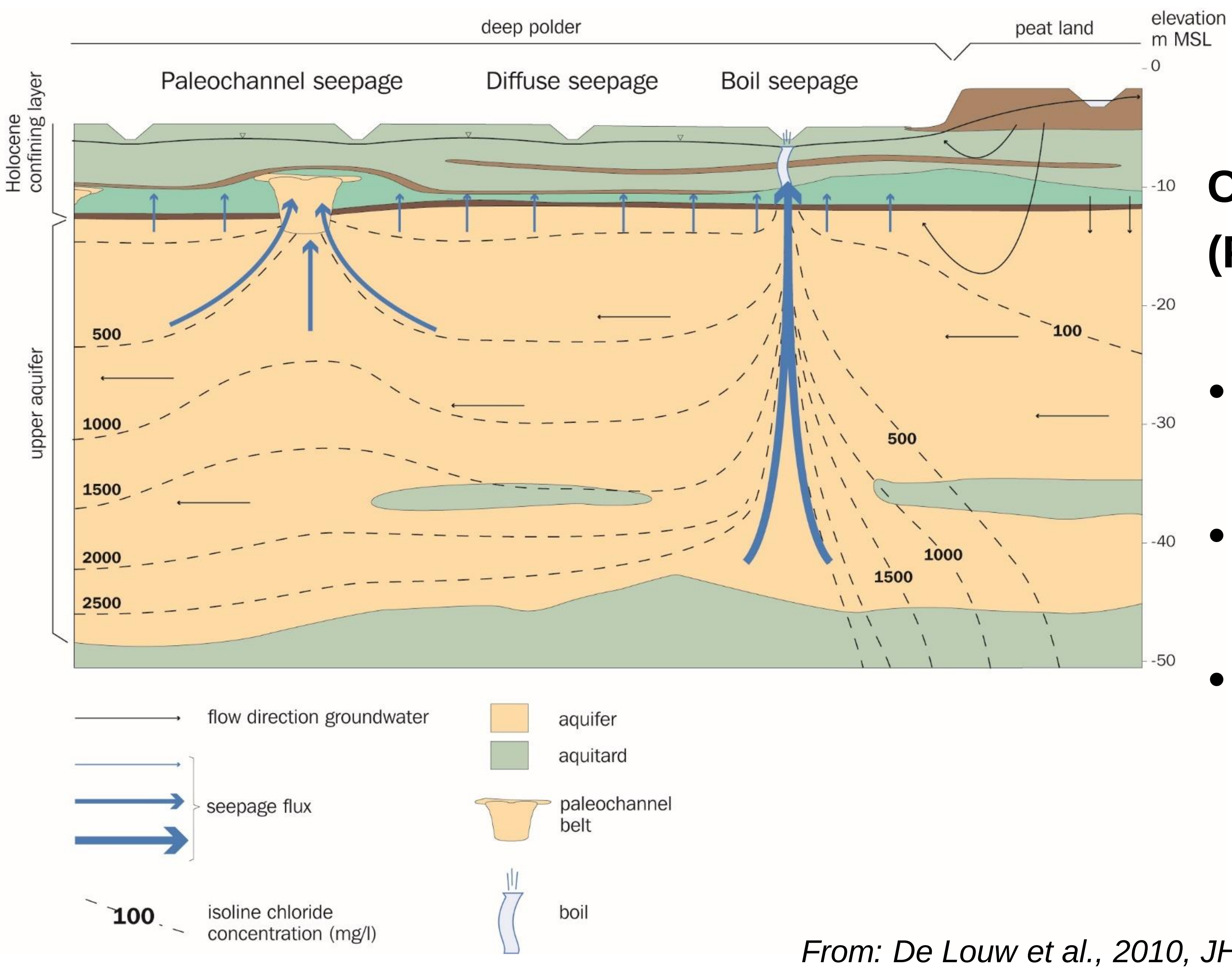




‘*Wells*’ (weak spots in Holocene layer)


Preferential saline seepage via boils



Three types of upward groundwater seepage



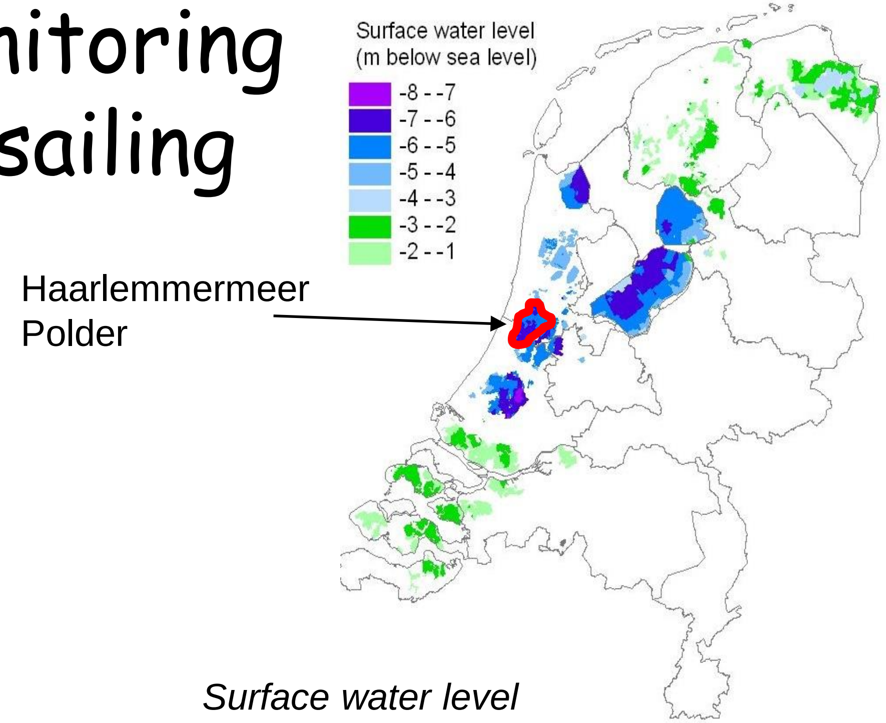
Cl-conc seepage: (Polder Noordplas)

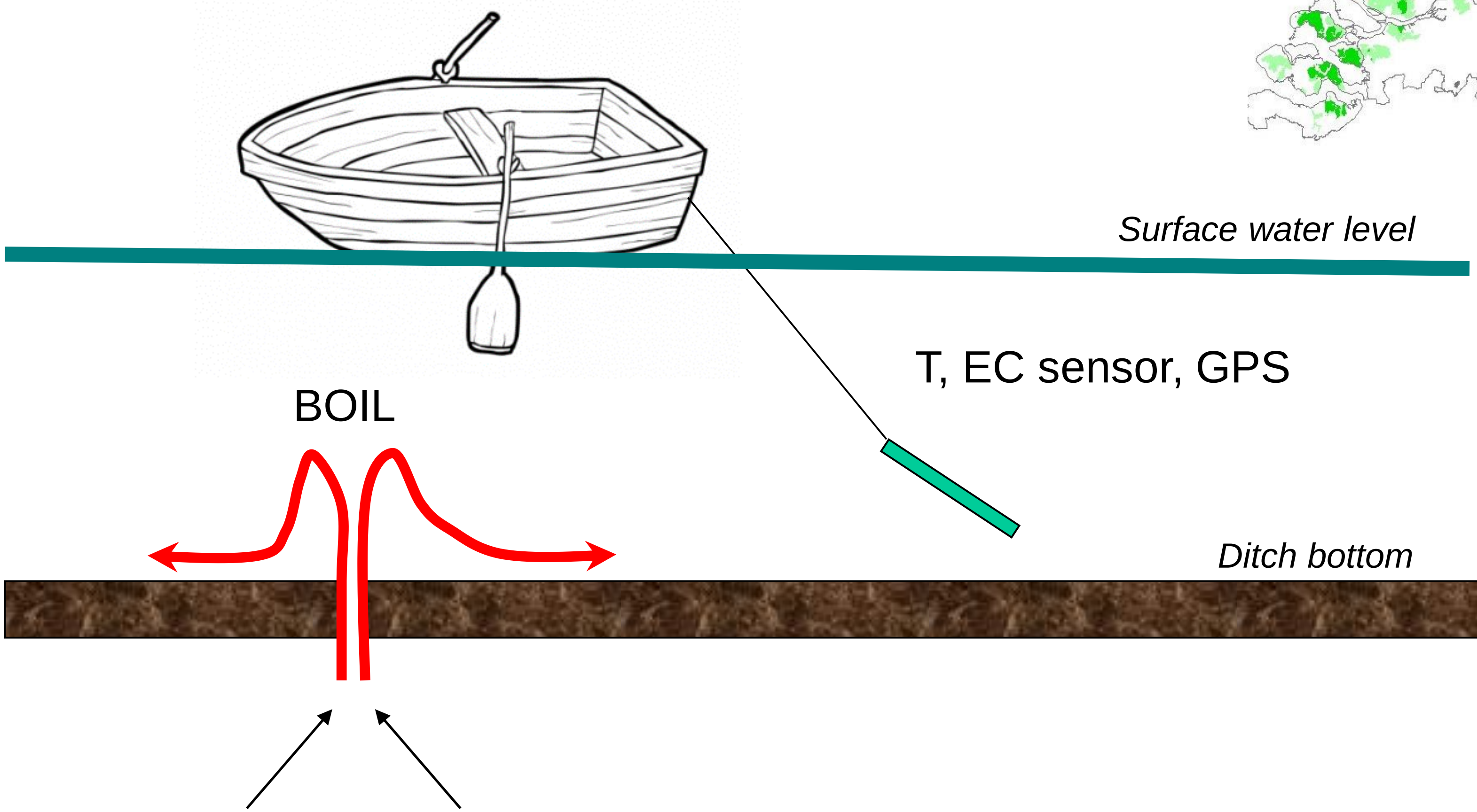
- Diffuse : 100 mg/l
- Paleochannel : 600 mg/l
- Boils : 1100 mg/l

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

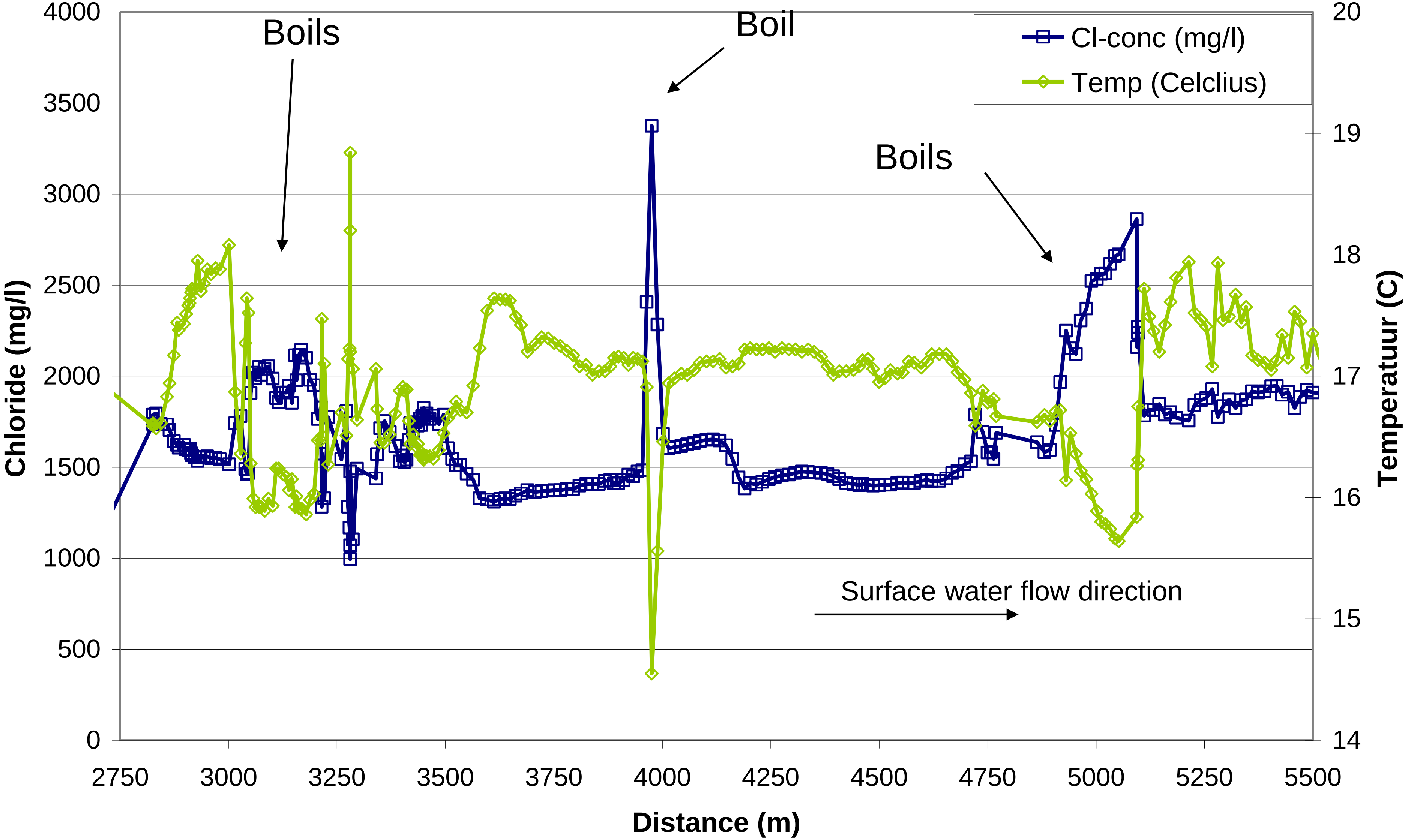

Deltares

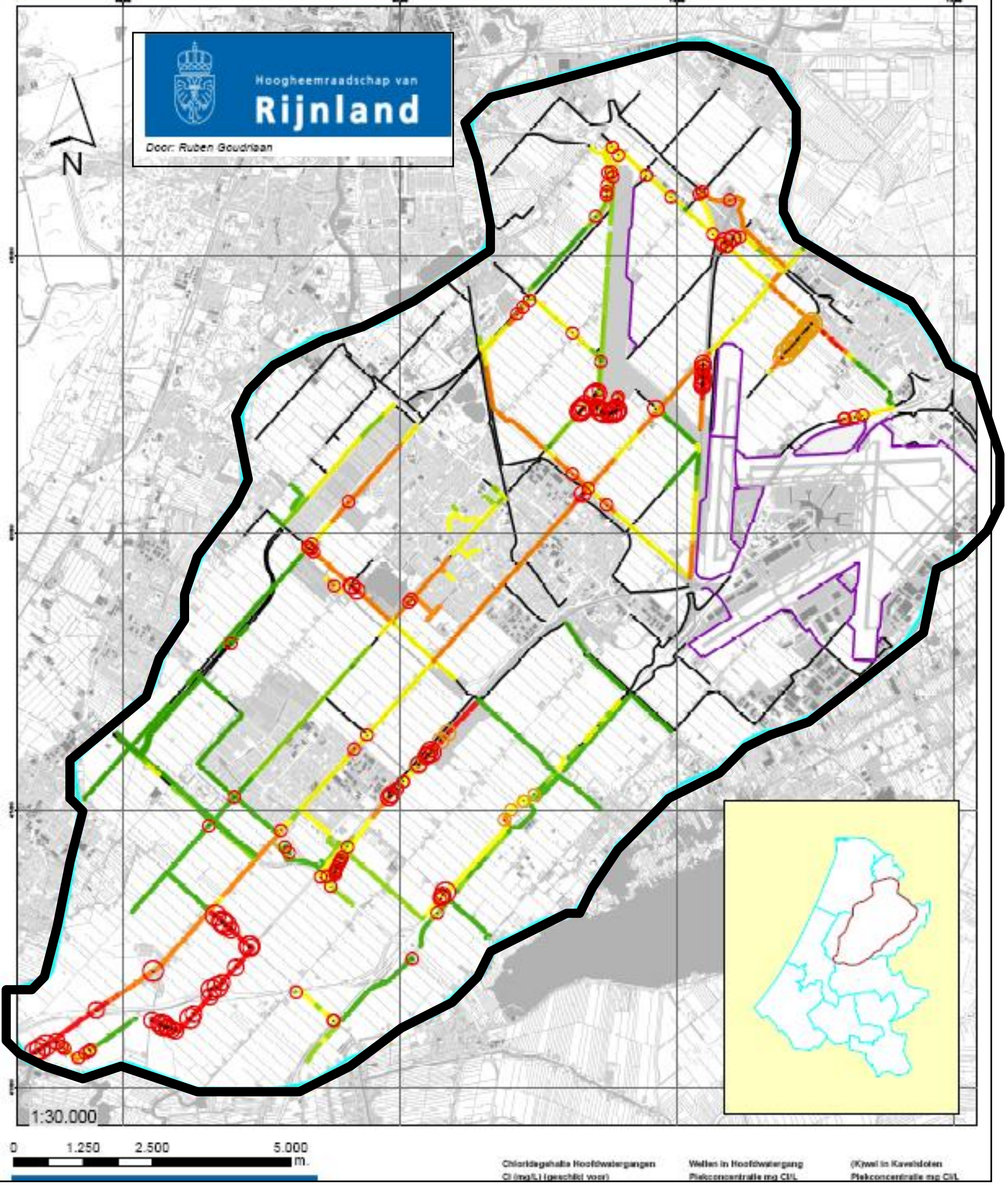
Continuous T and EC monitoring of surface water while sailing





T and EC measurements in surface water (canal)





Mapped boils and Cl-conc. surface water

Boils

Cl = 500 -2000 mg/l

Cl > 2000 mg/l

Cl-conc surface water

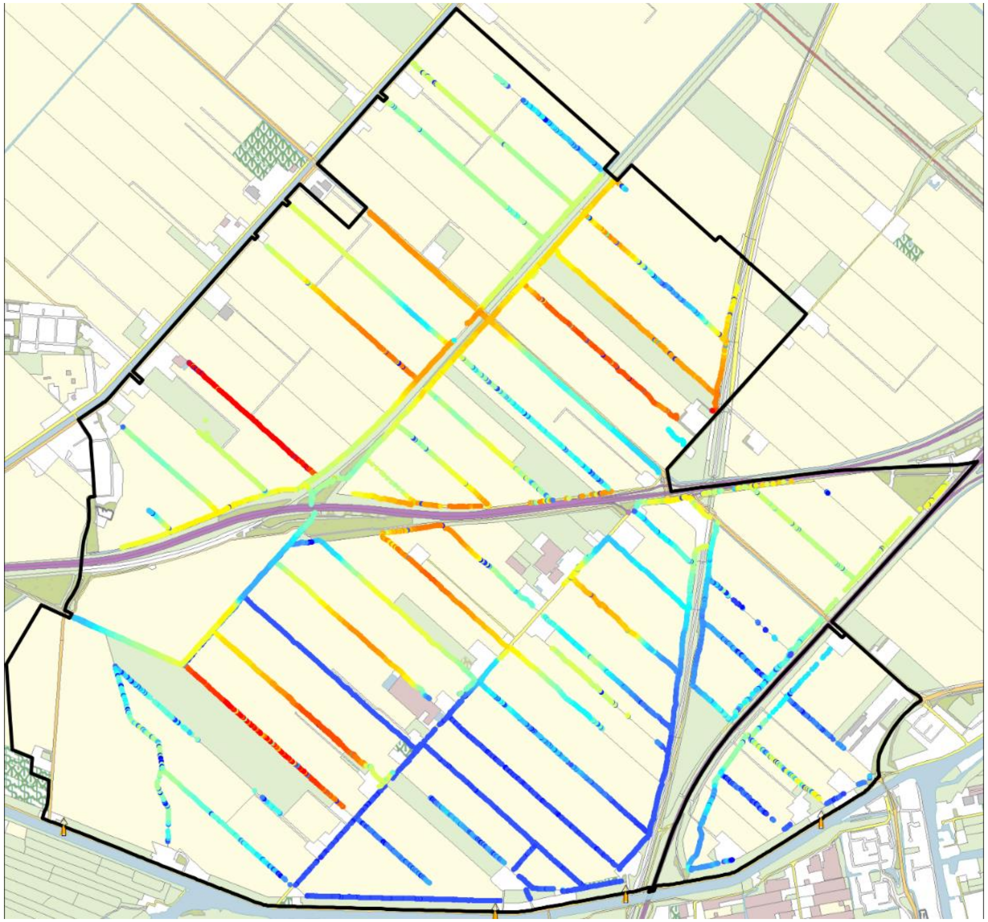
0-300 mg/l

300-600 mg/l

600-1000 mg/l

> 1000 mg/l

Monitoring salt in ditches: *simple can be smart too*

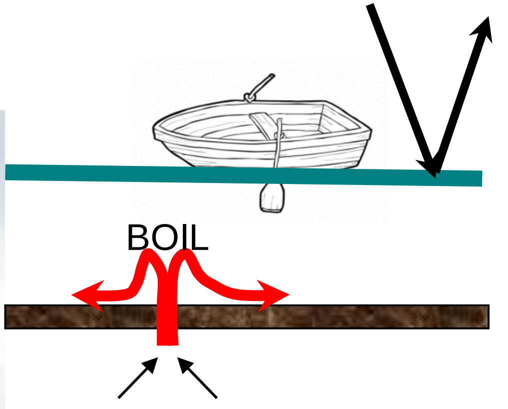


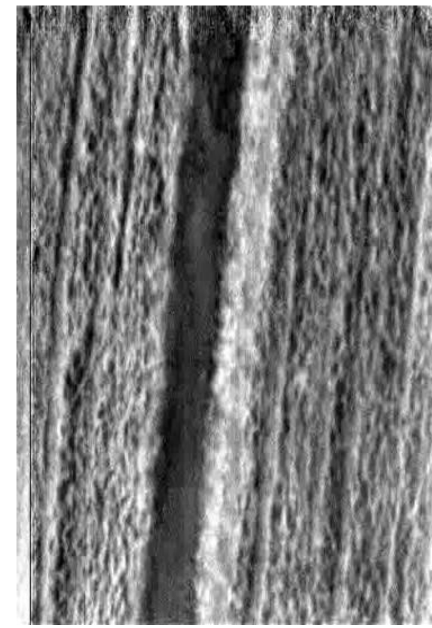
- 70 km ditches…

- blauw: ~150 mg/l
- oranje: ~1500 mg/l
- rood: > 3000 mg/l

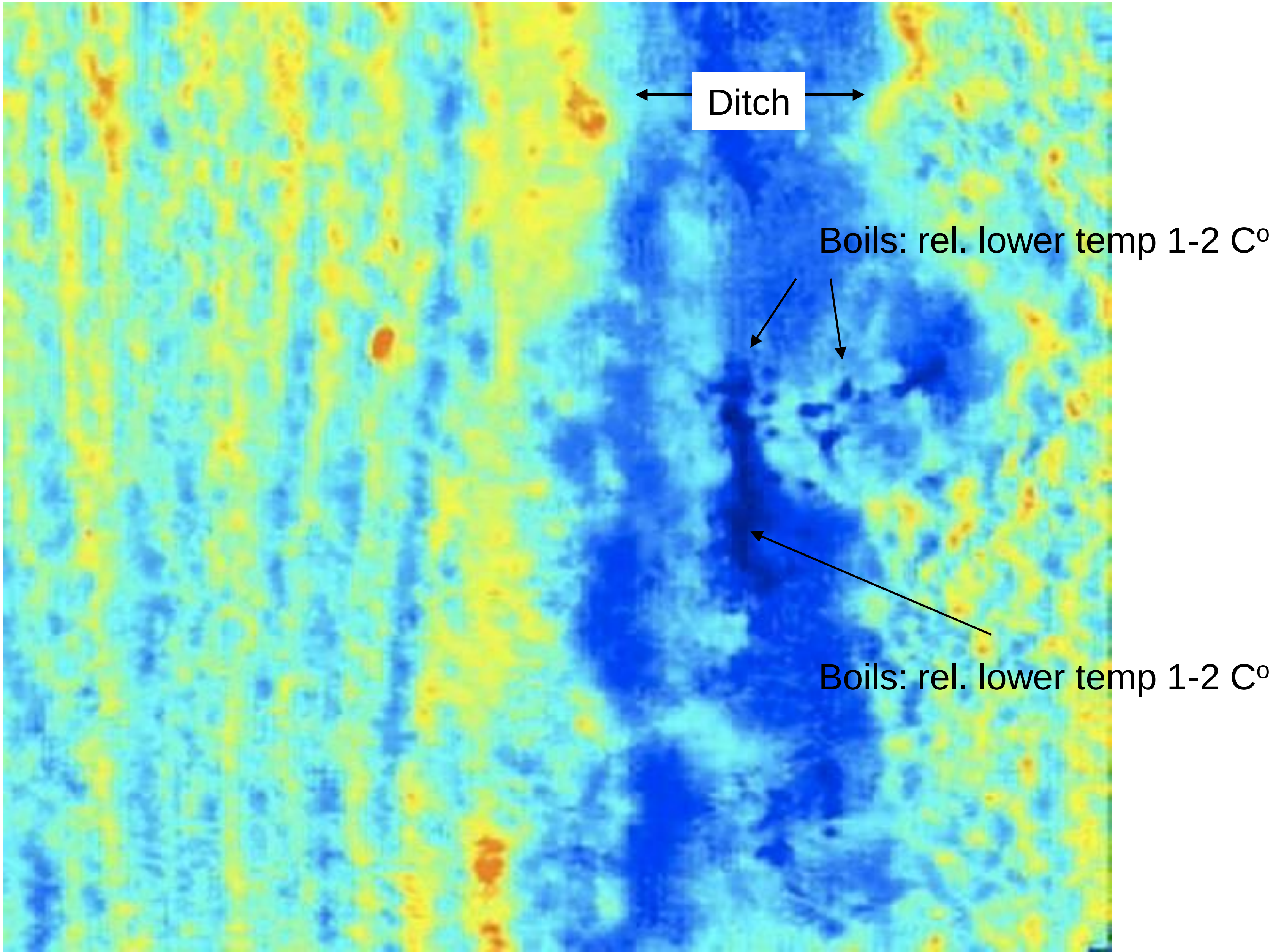
LARS technology (TNO Industry): Thermal Infra-red

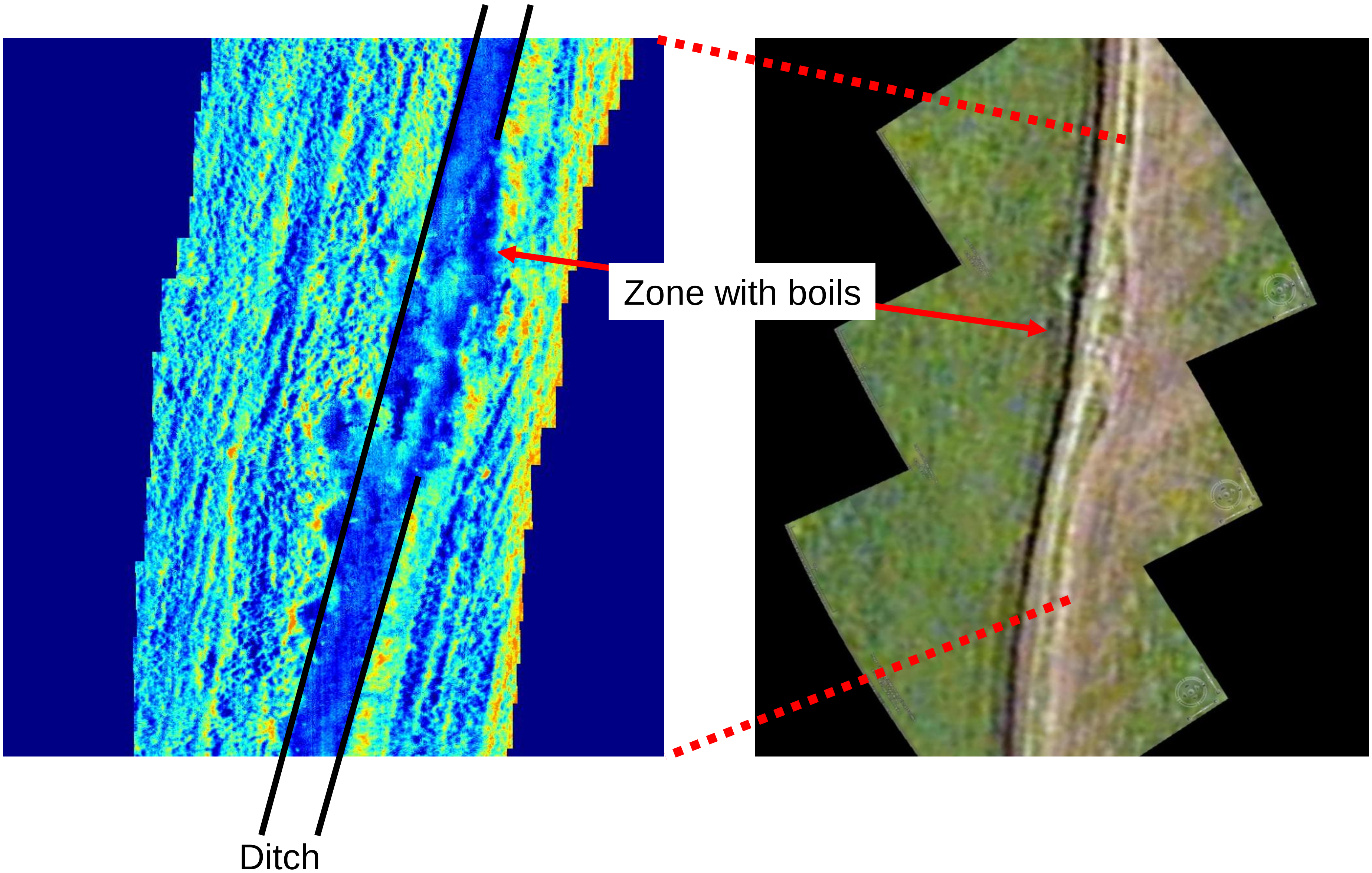
- Altitude: 0-150 m
- Temp-detection using Thermal Infra Red sensors (only surface !)





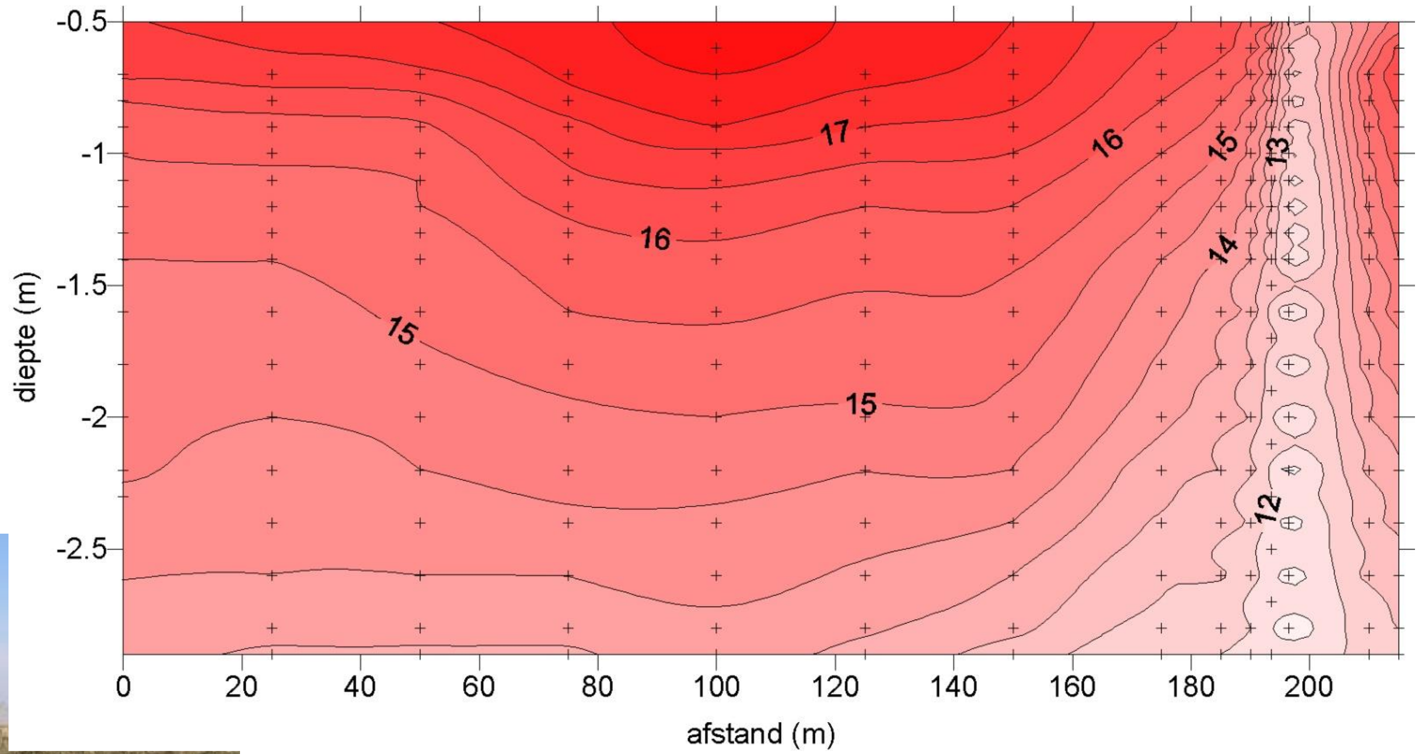
Thermal infra-red results (blue is cold, red is warm)



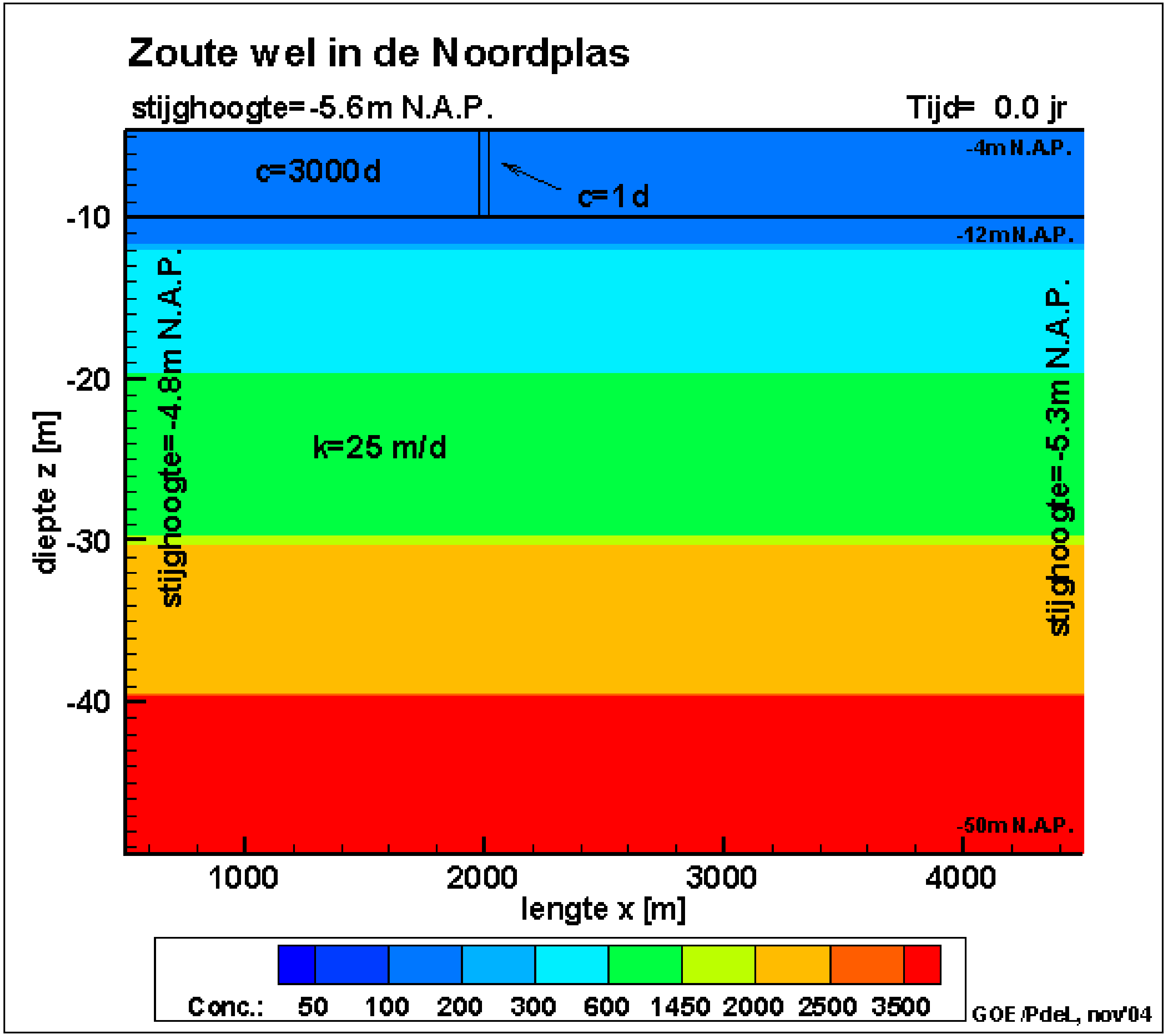


Zone with boils
Ditch

Temperature measurements



Simulation of salt groundwater towards *wells*

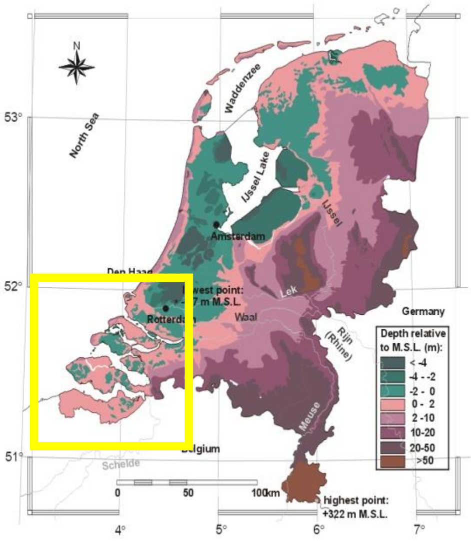


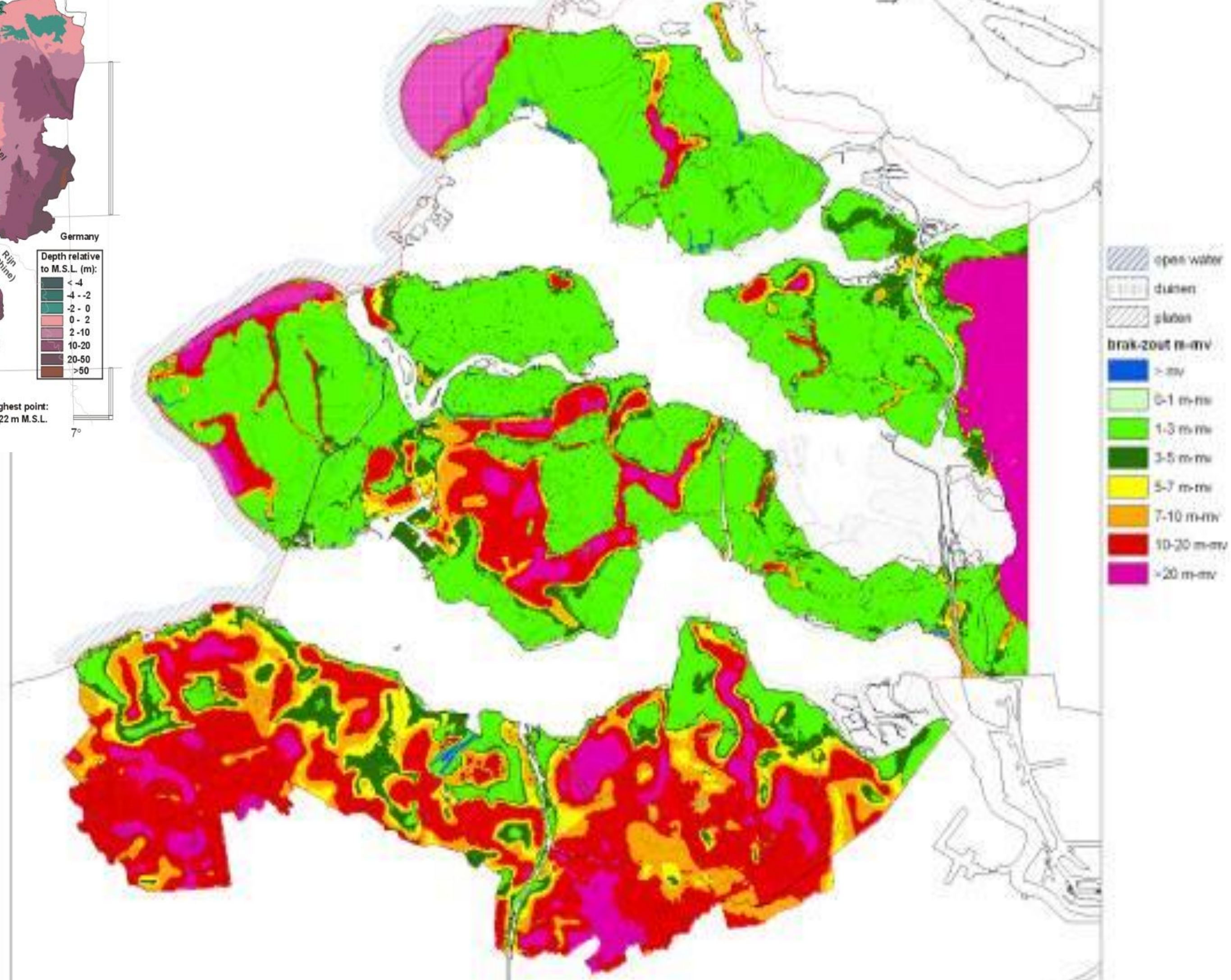
Rainwater lenses in an agricultural setting

Shallow dynamic freshwater bodies flowing upon brackish-saline groundwater

-density dependent
-dynamics: seasonal & long-year

Salinisation of the phreatic groundwater in Zeeland

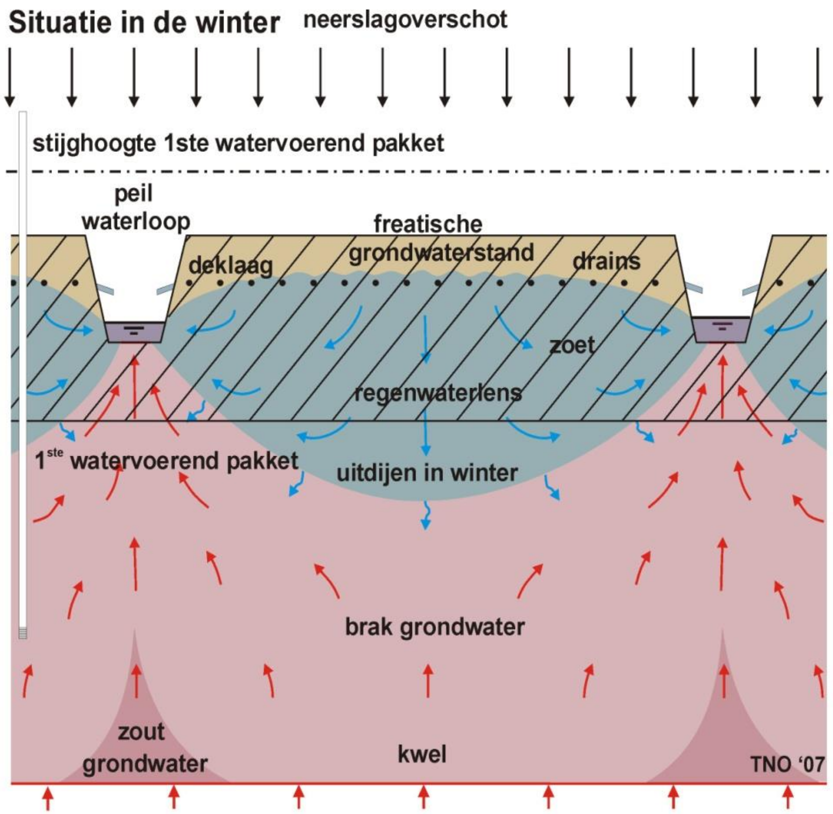




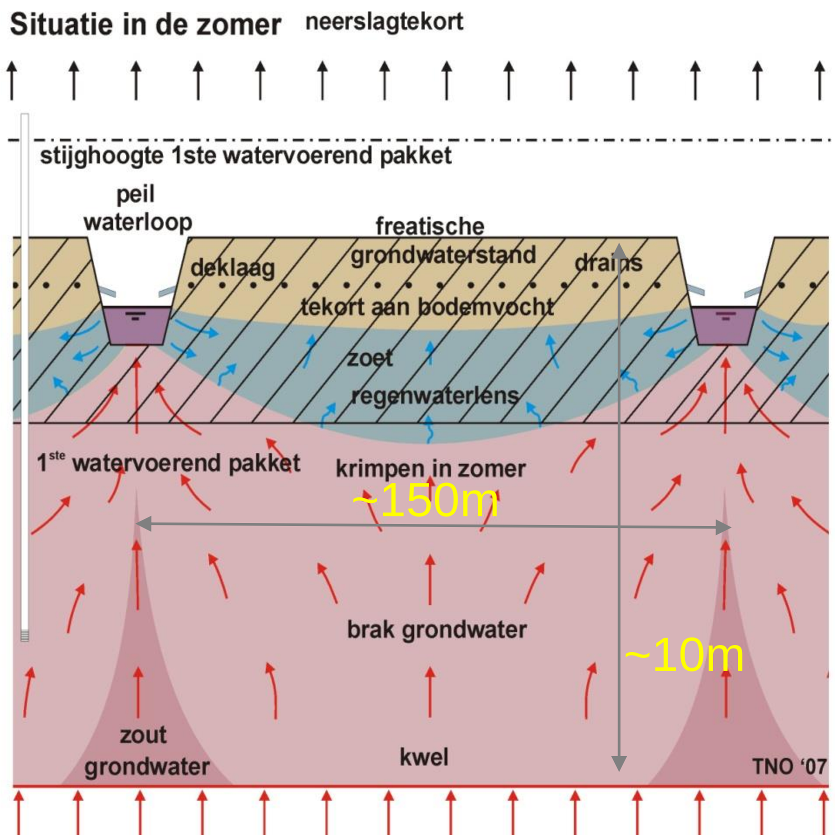
Position of brackish-saline interface

Salinisation of the phreatic groundwater in Zeeland

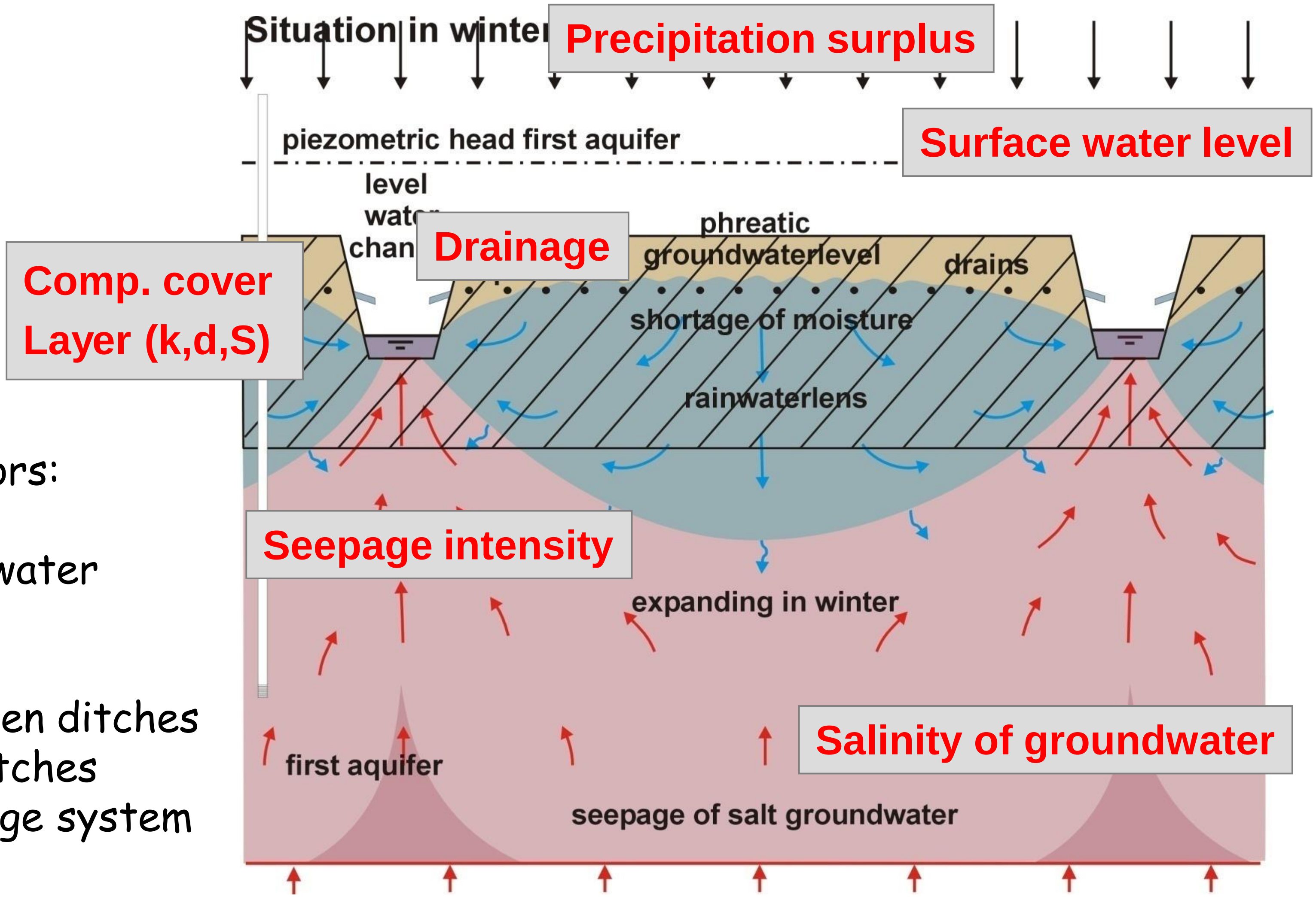
Dynamic rainwater lenses floating on saline groundwater



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



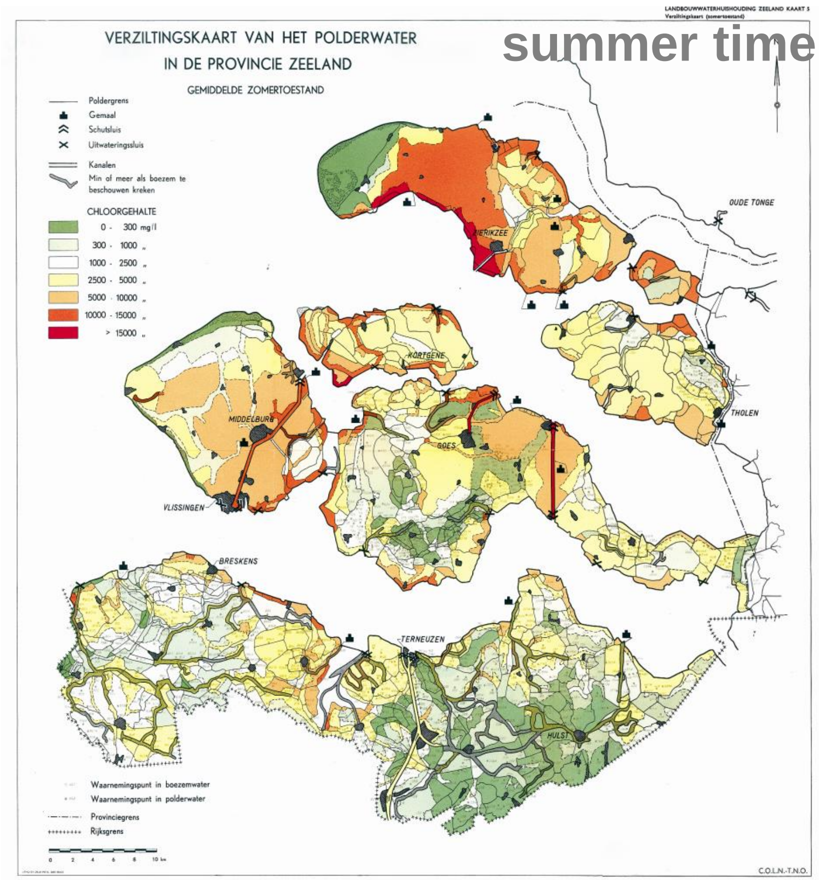
Factors controlling fresh-salt interface

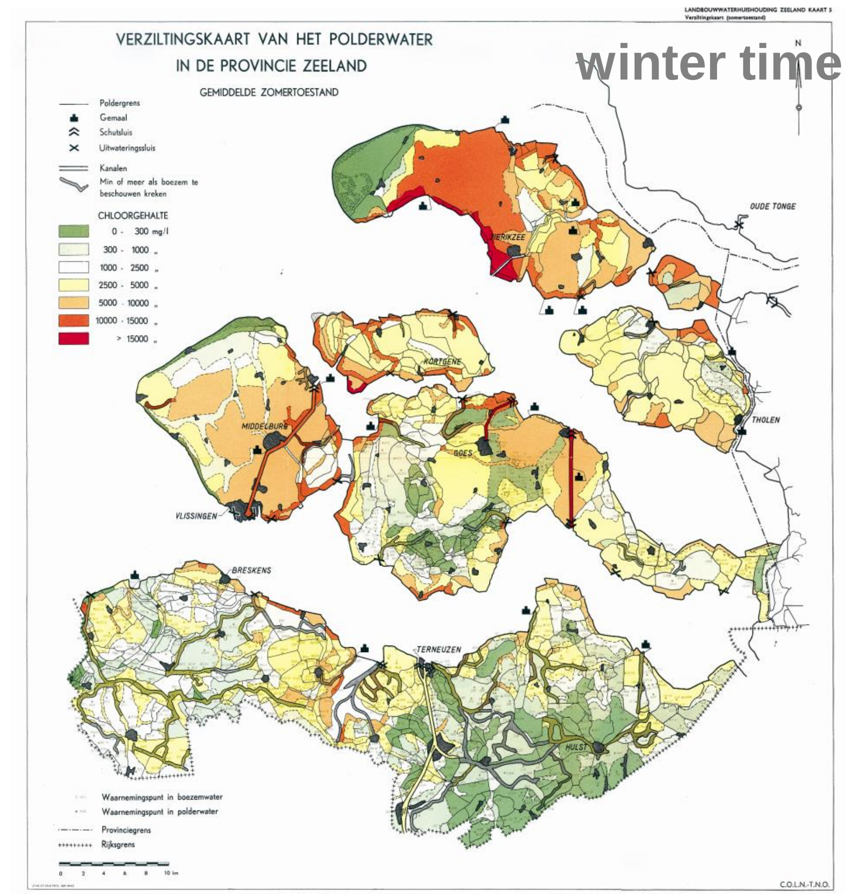


Important factors:

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

Salinisation surface water





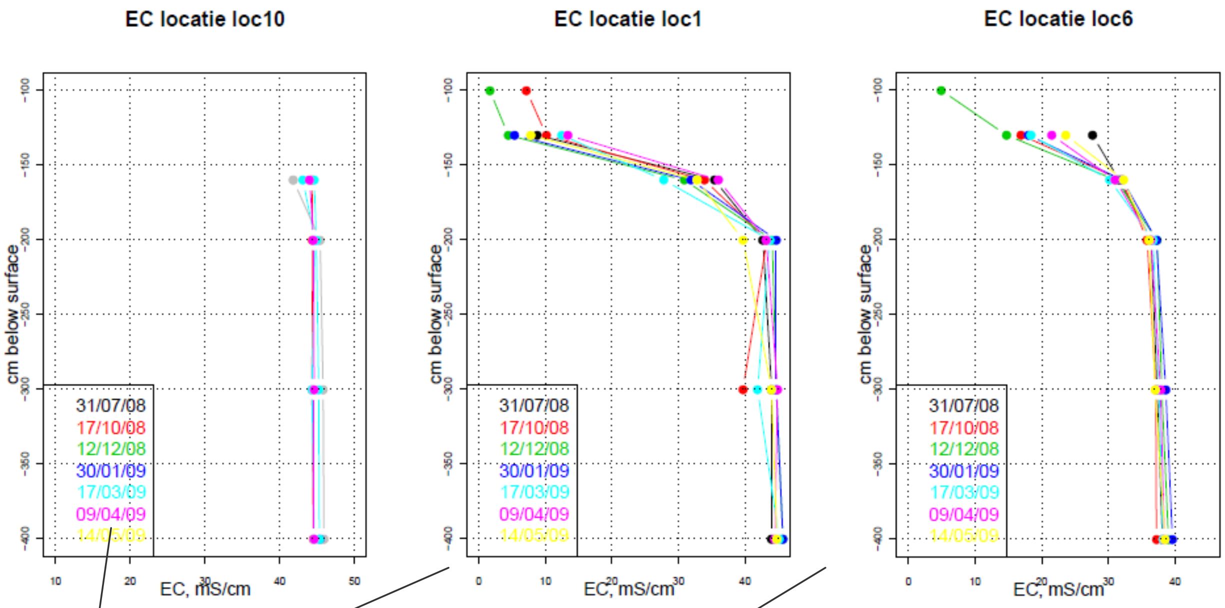
Problem definition dynamic freshwater lenses

Salt in the agricultural plots originates from:

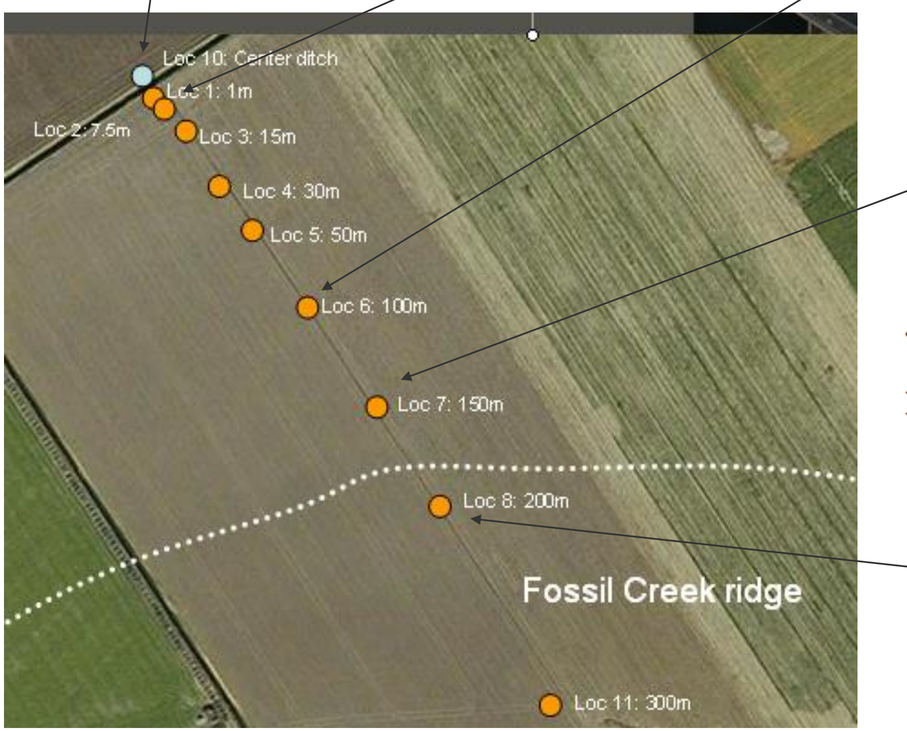
- surface water system (irrigation water)
- groundwater system (salt load to the root zone)

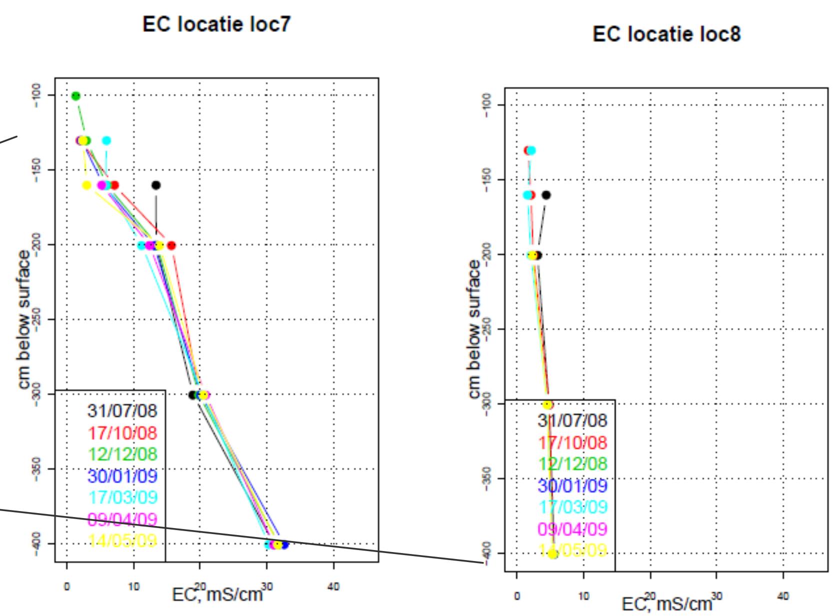
The salinisation will increase due to:

- sea level rise
- climate change
- water level management

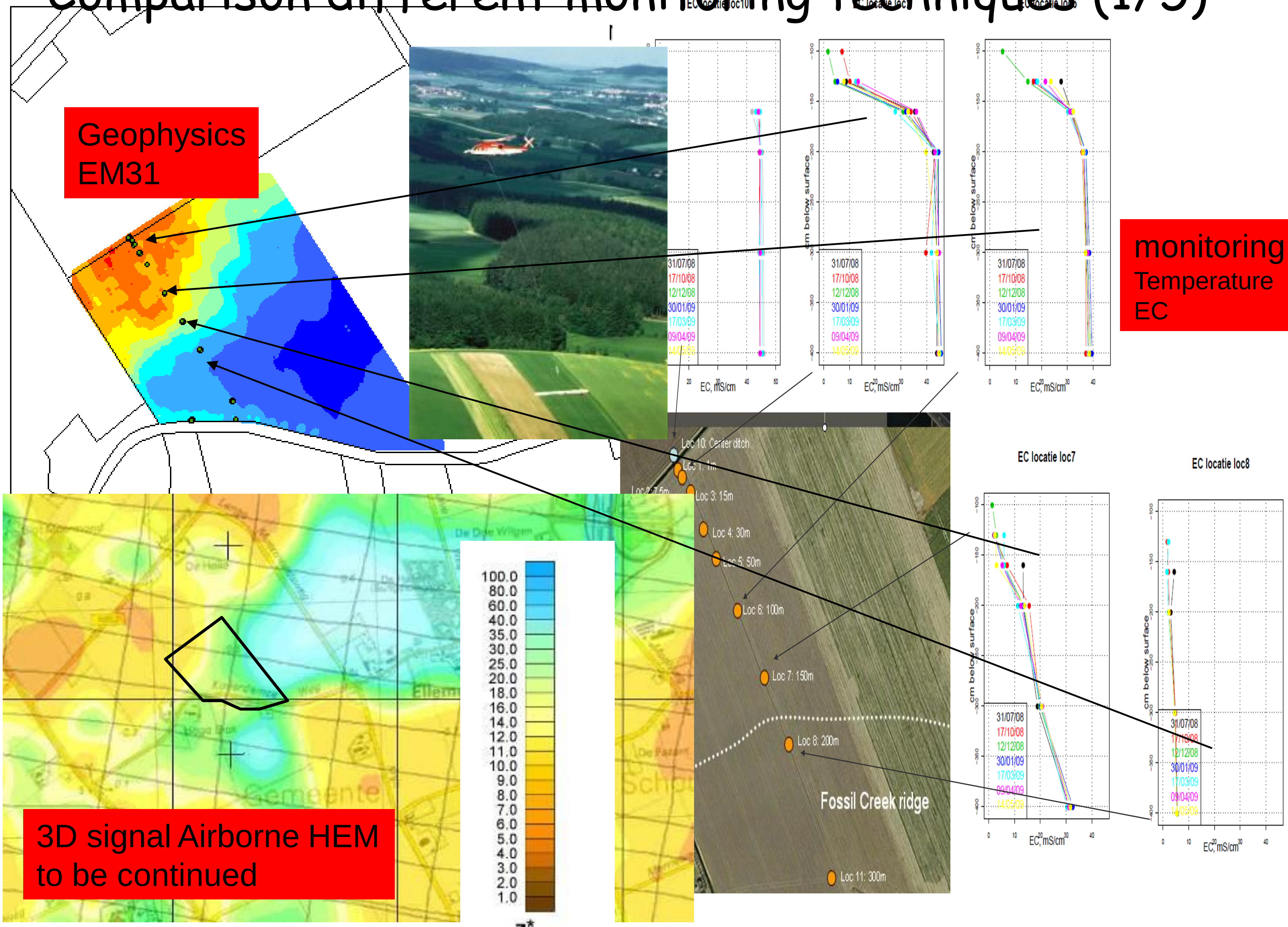
Salt distribution in time





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

Comparison different monitoring techniques (1/5)



Local 3D model of the agricultural plot

Modelling:

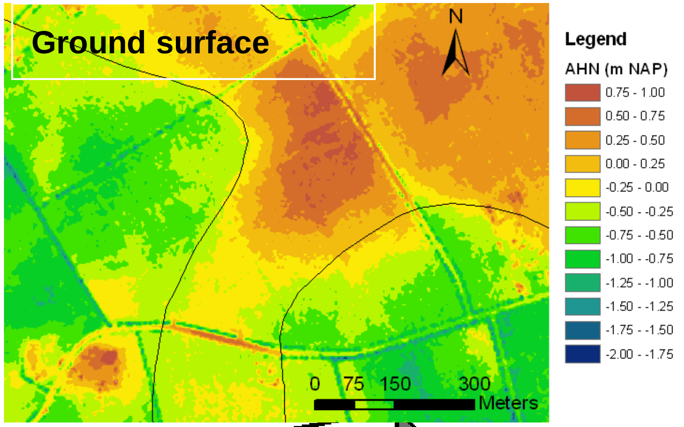
- variable-density
- 3D, non-steady
- groundwater flow & coupled solute transport
- model cell size: 5*5m^2

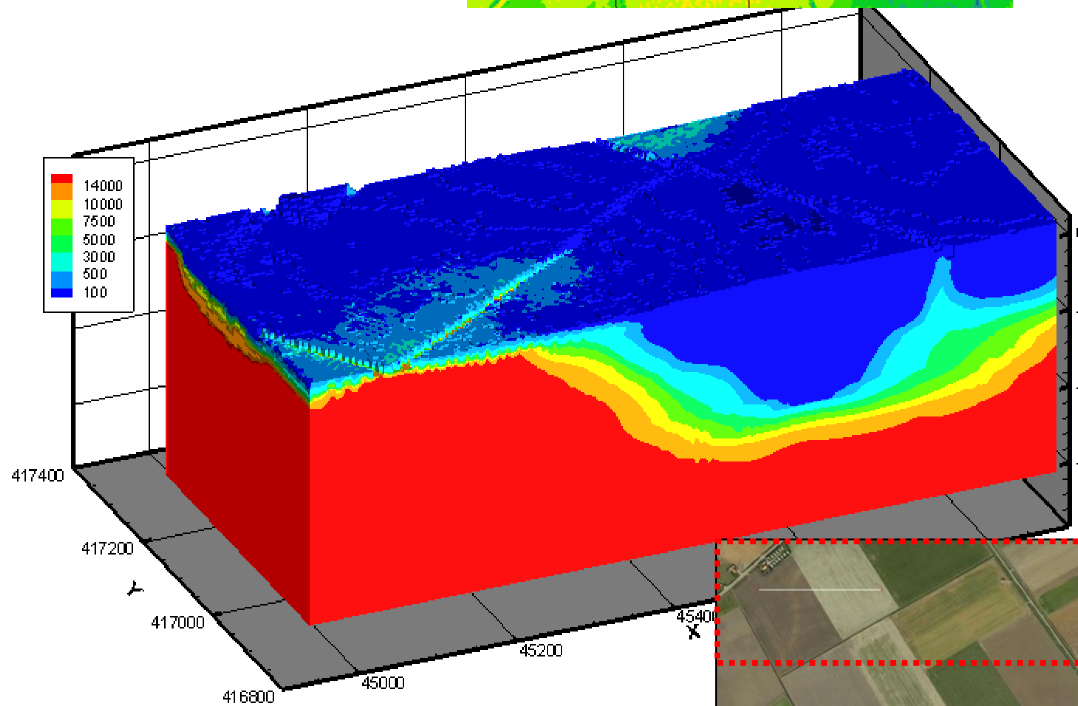
Code:

MOCDENS3D

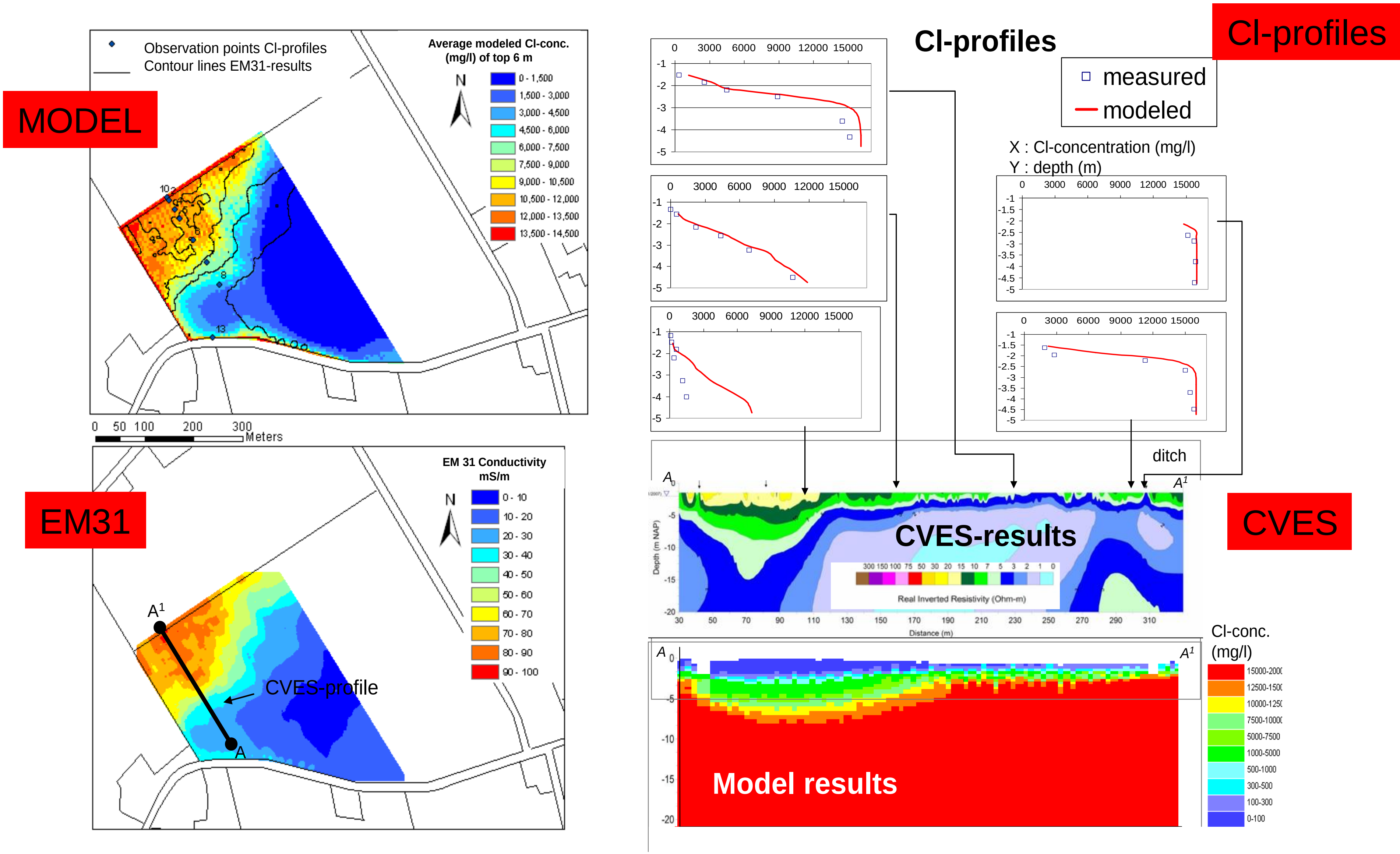
Assessing effects:

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



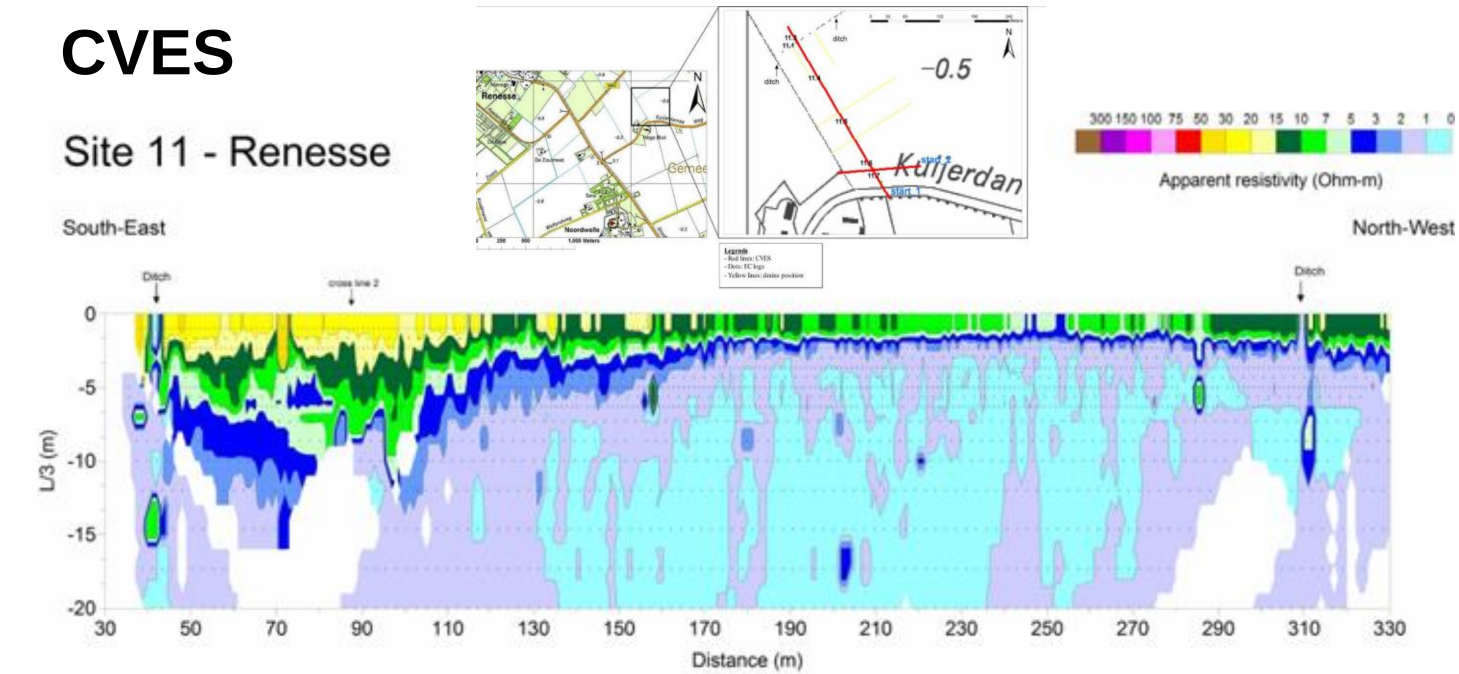


Comparison model with EM31, CVES, profiles

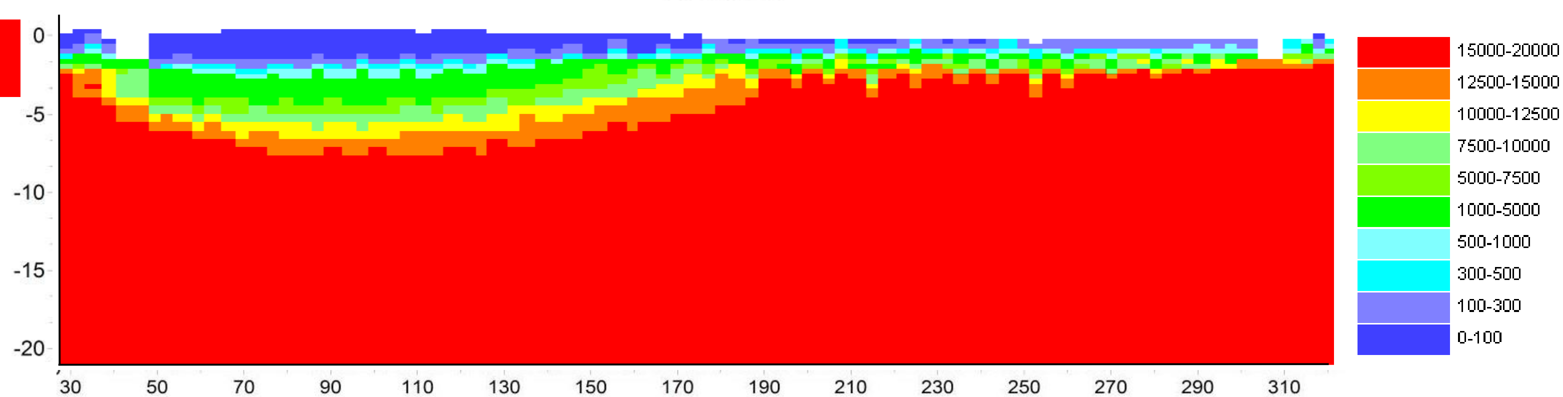


Comparison 3D model and CVES

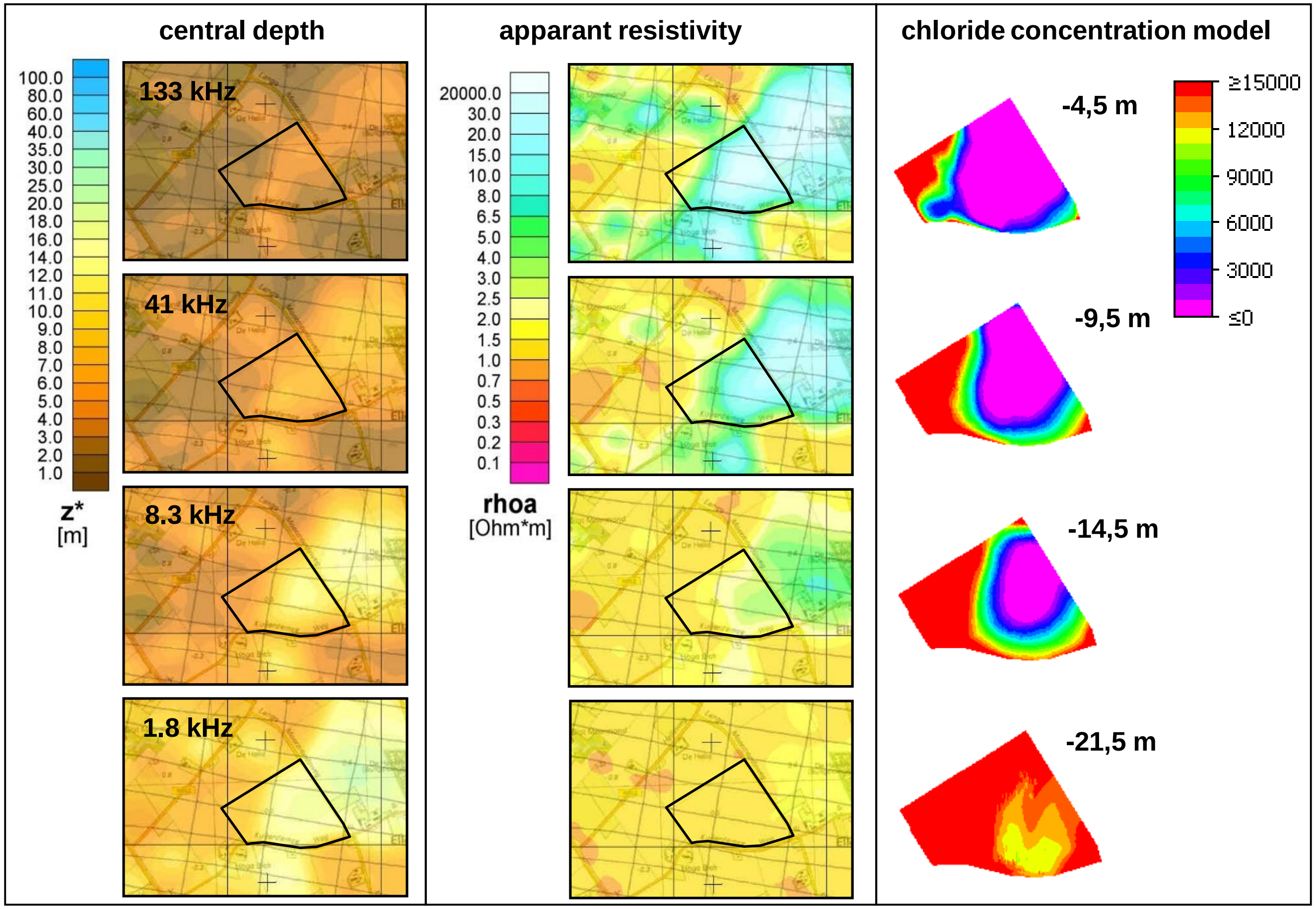
CVES



MODEL



HEM data


central depth
apparant resistivity
chloride concentration model
133 kHz
41 kHz
8.3 kHz
1.8 kHz
100.0
80.0
60.0
40.0
35.0
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25.0
20.0
18.0
16.0
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9.0
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7.0
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z*
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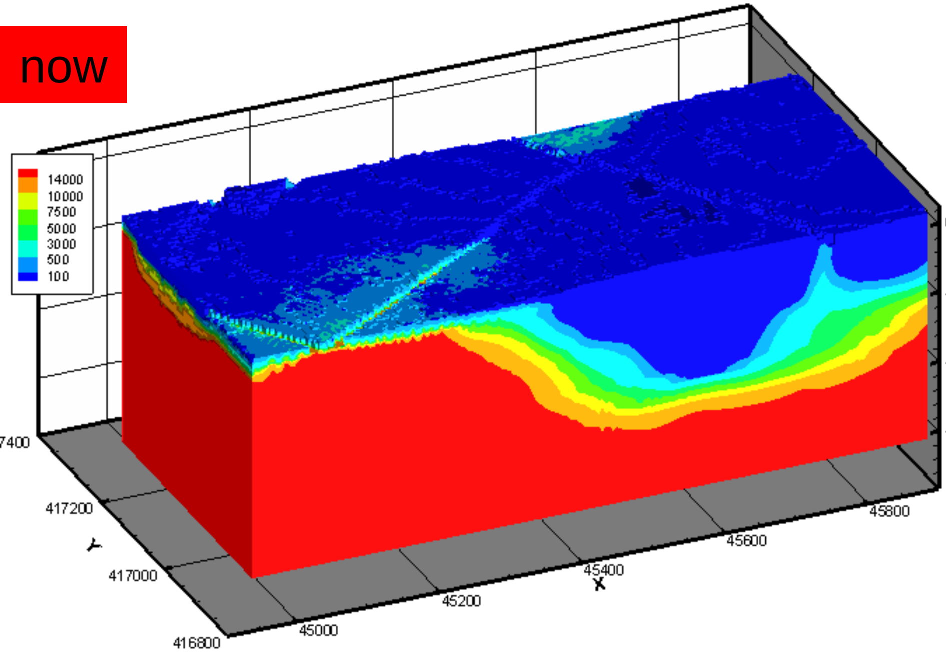
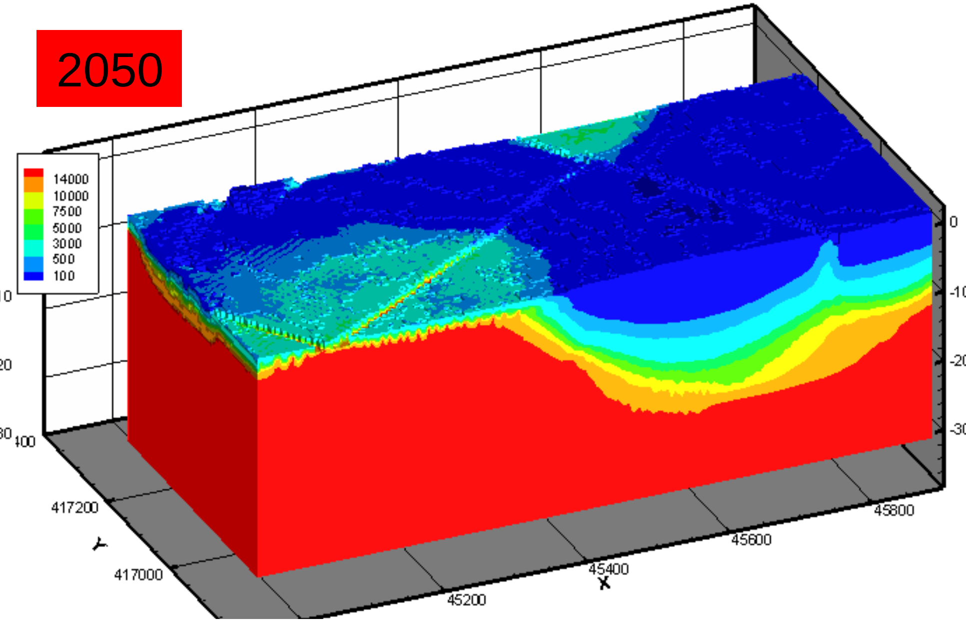
10.0
8.0
6.5
5.0
4.0
3.0
2.5
2.0
1.5
1.0
0.7
0.5
0.3
0.2
0.1
rhoa
[Ohm*m]
-4,5 m
-9,5 m
-14,5 m
-21,5 m
≥15000
12000
9000
6000
3000
≤0

Climate change scenario (dry): model result

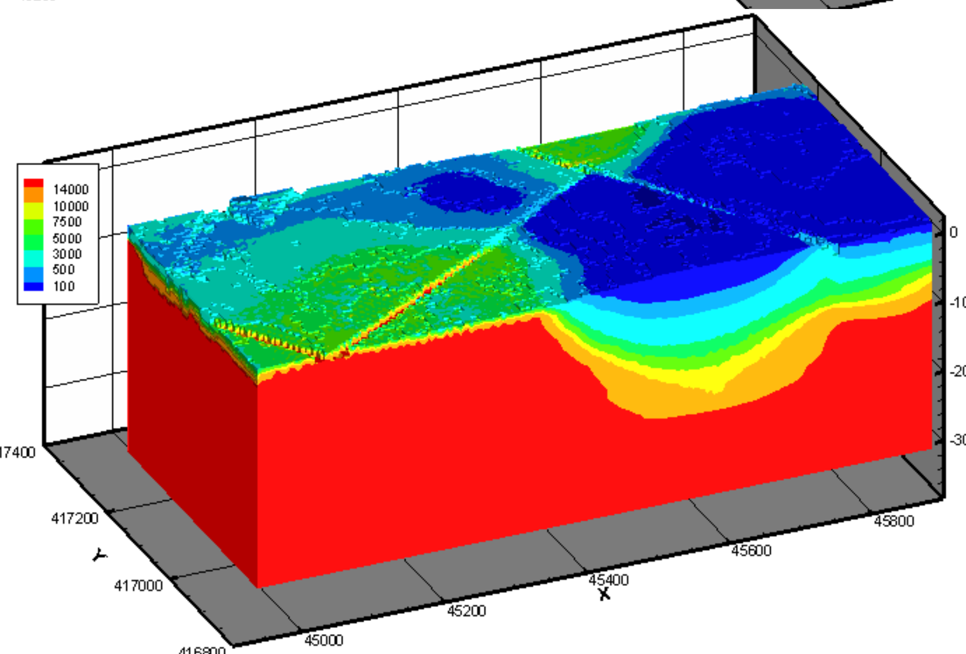
now



2050



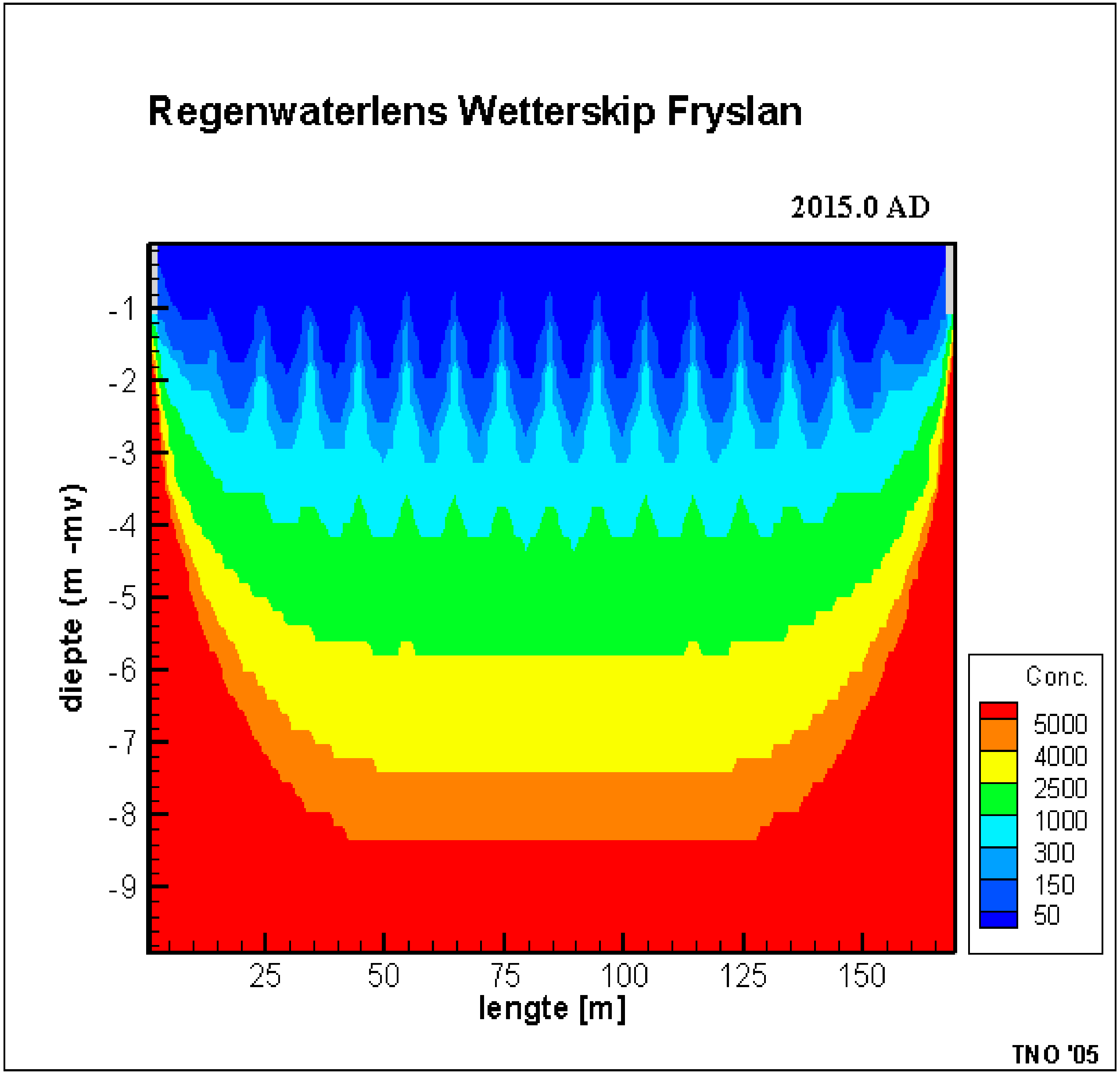
2100



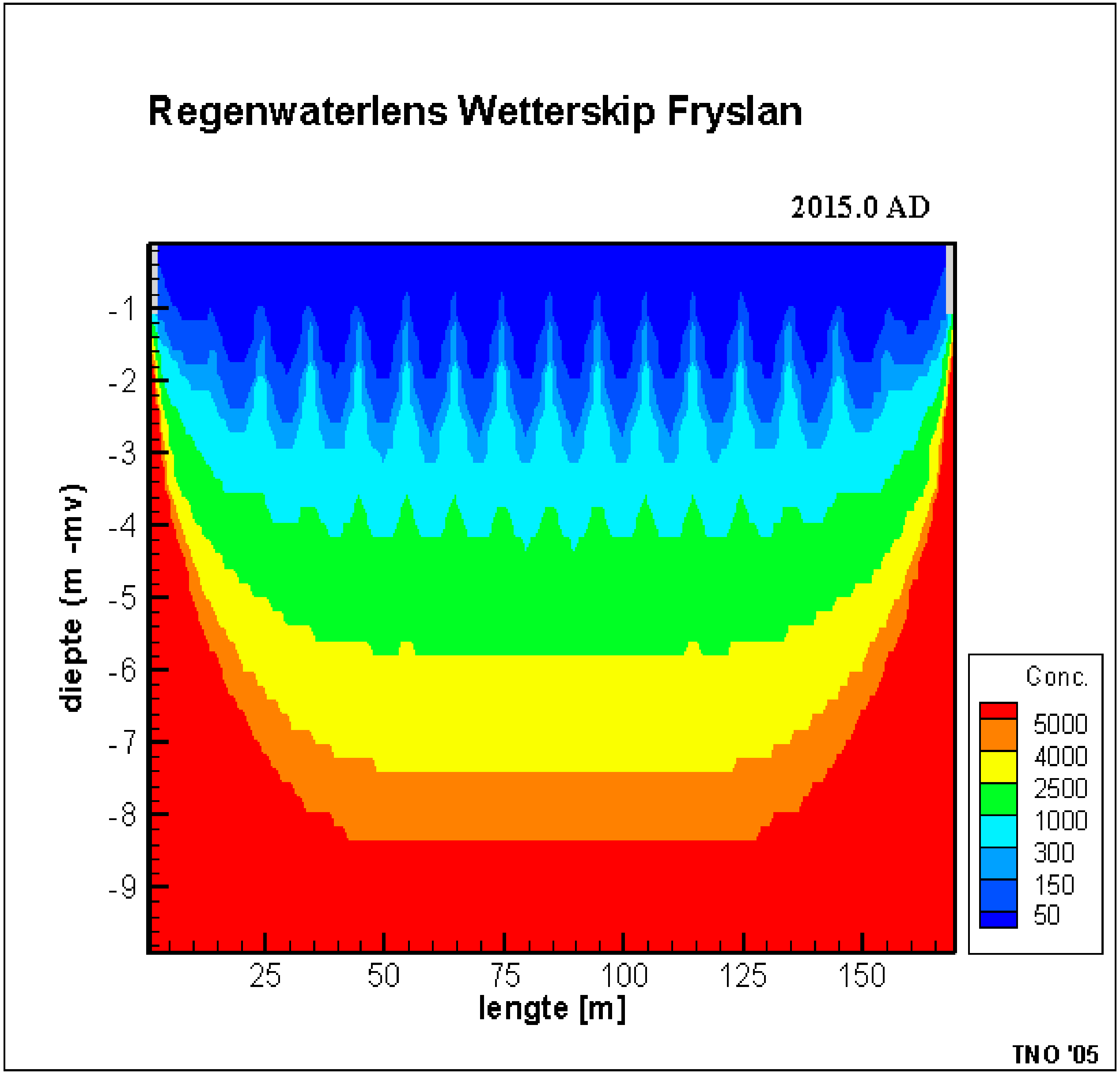
To be continued…

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

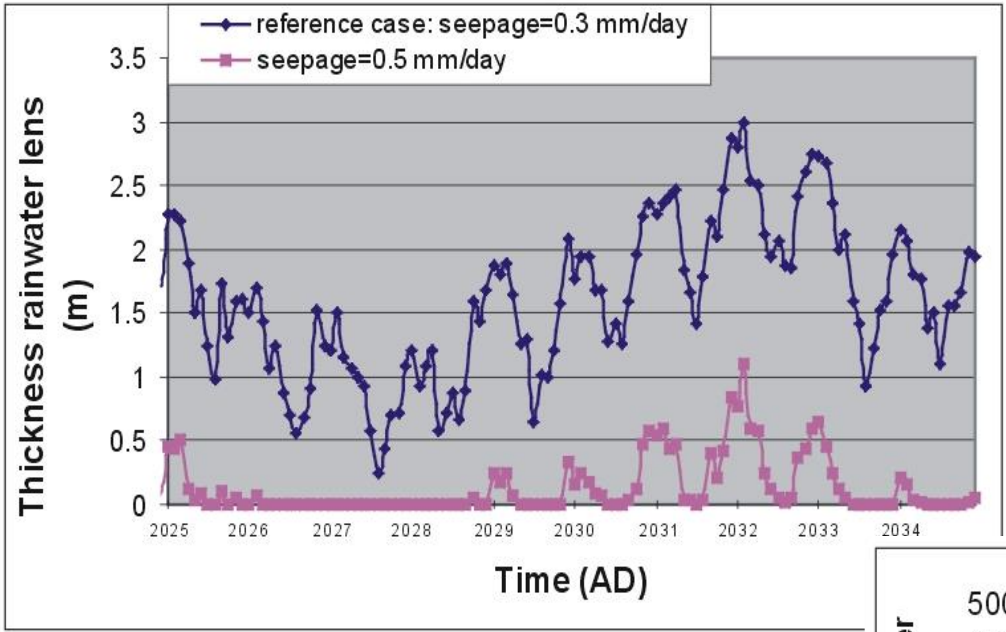
Model the dynamics of fresh-brackish-salt interface



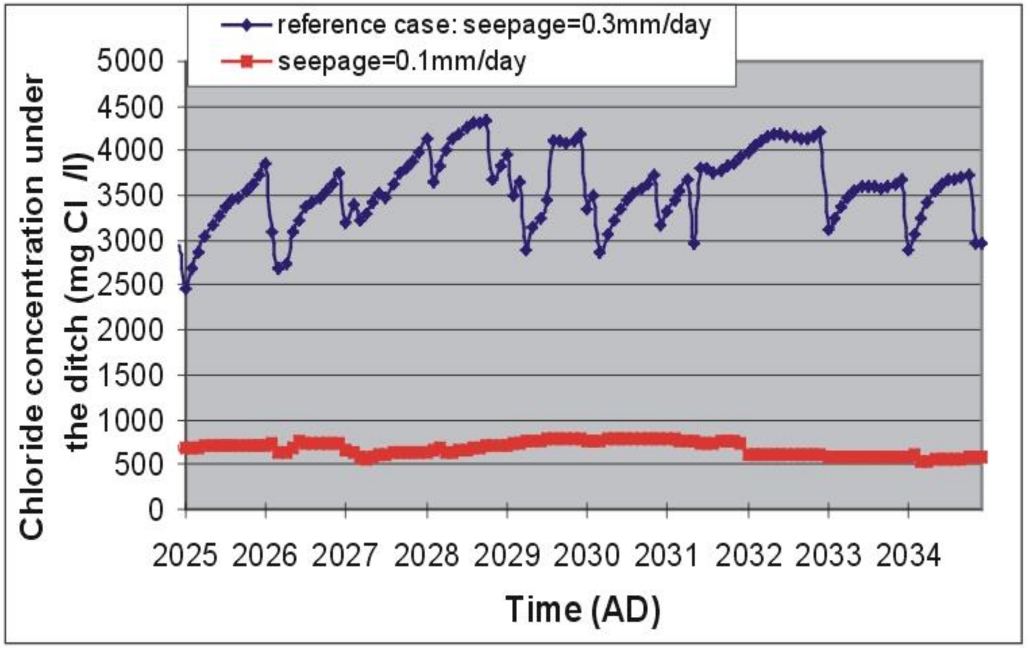
Model the dynamics of fresh-brackish-salt interface



Thickness of the lens and salt load to surface water varies



depends on seepage



Conclusions (modelling of variable-density flow)

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

For modelling 3D systems:

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

Challenges for the future

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

Groundwater flow equation (MODFLOW, 1988)

Darcy

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

↑ buoyancy term

Continuity

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

Freshwater head

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

Advection-dispersion equation (MOC3D, 1996)

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

Equation of state: relation density & concentration

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

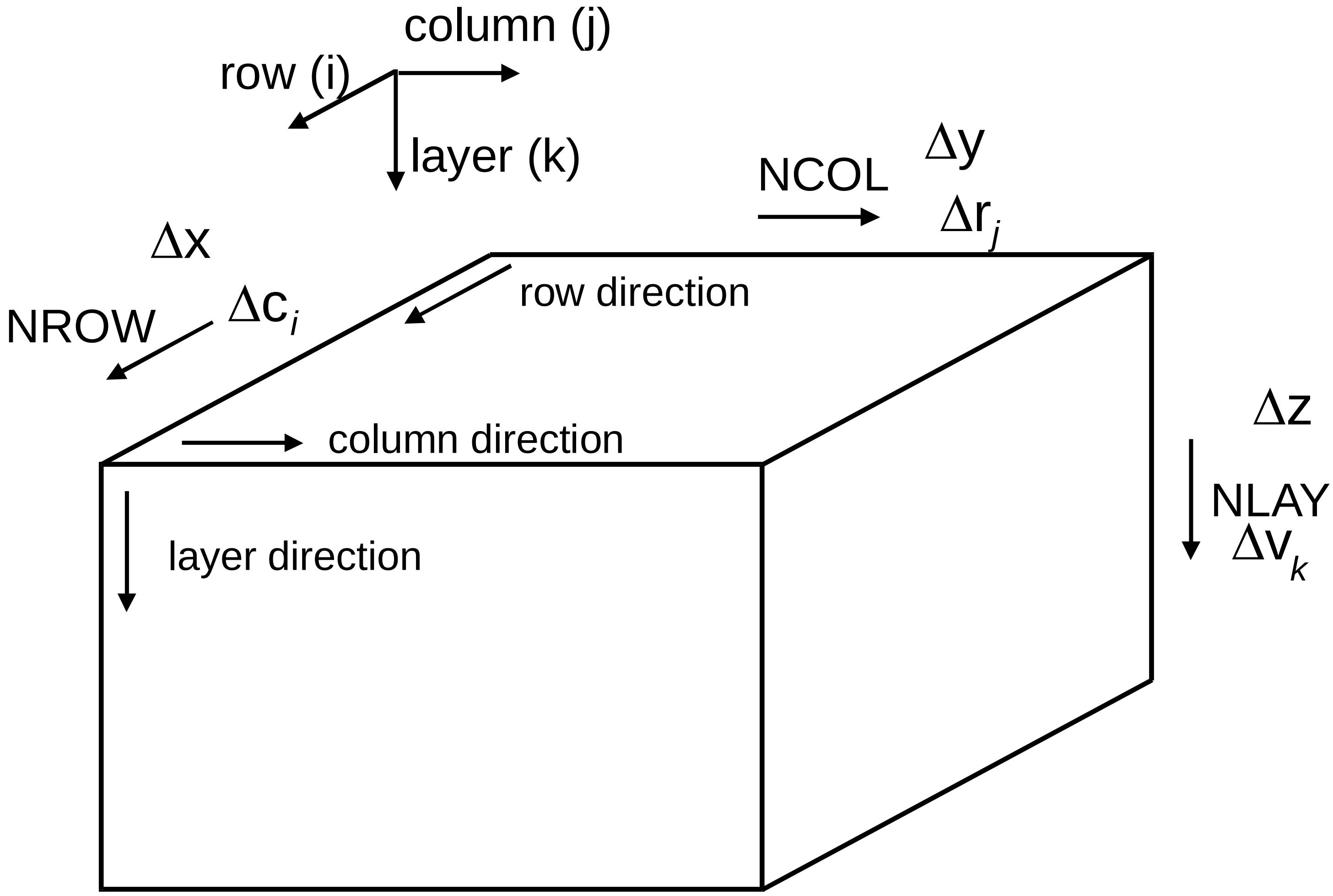
MOCDENS3D is based on MODFLOW

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

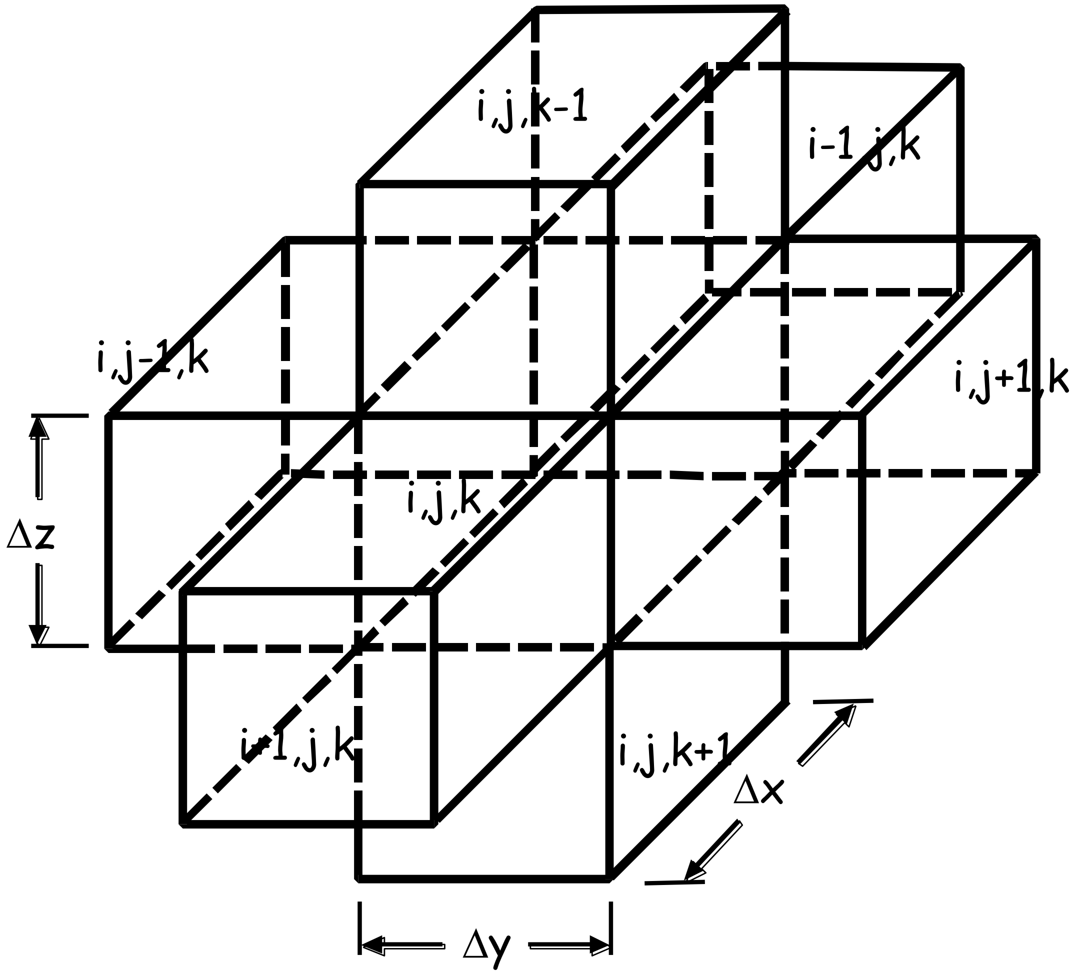
(M.G. McDonald & A.W. Harbaugh, from 1983 on)

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

Nomenclature MODFLOW element [i,j,k]



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



Continuity equation (I)

In - Out = Storage

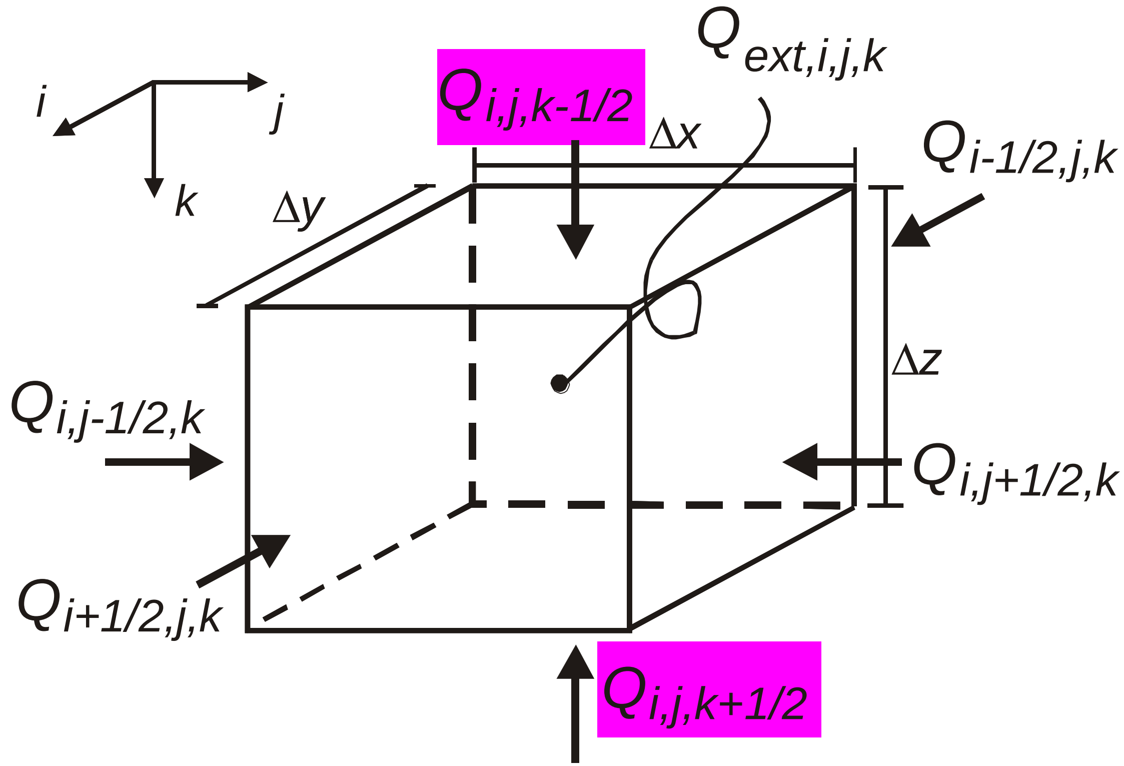
$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial \phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial \phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial \phi}{\partial z}\right)-W=S_s\frac{\partial \phi}{\partial t}$$

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

Continuity equation (II)

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

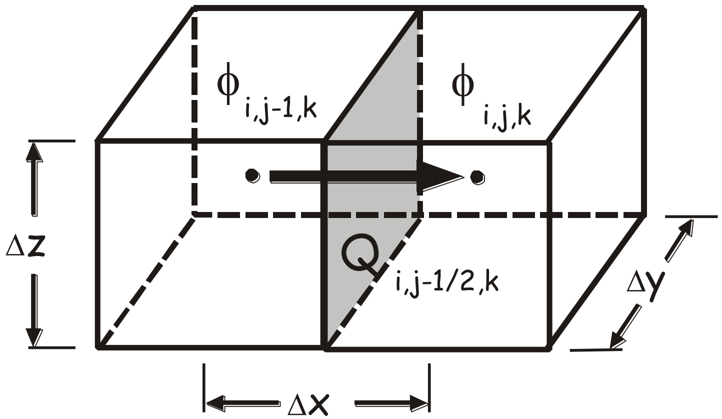
In = positive



$$Q_{i,j-1/2,k} + Q_{i,j+1/2,k} + Q_{i-1/2,j,k} + Q_{i+1/2,j,k} + Q_{i,j,k-1/2} + Q_{i,j,k+1/2} + Q_{ext,i,j,k}$$

$$= SS_{i,j,k} \frac{\phi^{t}_{i,j,k} - \phi^{t+\Delta t}_{i,j,k}}{\Delta t} \Delta V$$

Flow equation (Darcy's Law)



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

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

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

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

Density dependent vertical flow equation

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

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

$$Q_z = surface * q_z$$

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

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

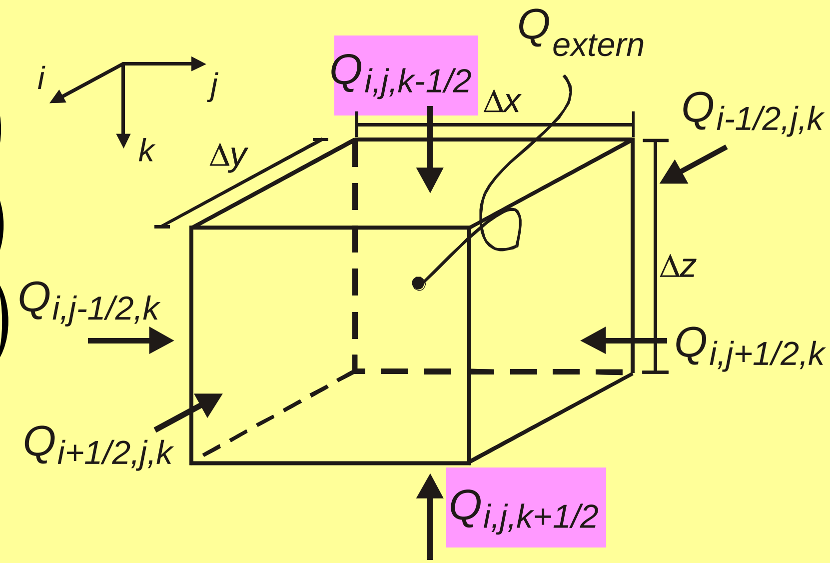
$$Q_{i,j,k-1/2} = CV_{i,j,k-1/2}\left(\phi_{f,i,j,k-1} - \phi_{f,i,j,k} + BUOY_{i,j,k-1/2}\Delta z\right)$$

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

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

Density dependent groundwater flow equation

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



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

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

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

Takes into account all external sources

Rewriting the term:

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

Thé variable density groundwater flow equation

$$Q_{i,j-1/2,k} + Q_{i,j+1/2,k} + Q_{i-1/2,j,k} + Q_{i+1/2,j,k} + Q_{i,j,k-1/2} + Q_{i,j,k+1/2} + Q_{ext,i,j,k}$$

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

and:

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

gives:

$$CV_{i,j,k-1/2} \phi^{t+\Delta t}_{f,i,j,k-1} + CC_{i-1/2,j,k} \phi^{t+\Delta t}_{f,i-1,j,k} + CR_{i,j-1/2,k} \phi^{t+\Delta t}_{f,i,j-1,k}$$

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

$$+ CR_{i,j+1/2,k} \phi^{t+\Delta t}_{f,i,j+1,k} + CC_{i+1/2,j,k} \phi^{t+\Delta t}_{f,i+1,j,k} + CV_{i,j,k+1/2} \phi^{t+\Delta t}_{f,i,j,k+1} = RHS_{i,j,k}$$

with :

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

$$RHS_{i,j,k} = -Q'_{i,j,k} - SC1_{i,j,k} \phi^{t}_{f,i,j,k} / (\Delta t)$$

$$- CV_{i,j,k-1/2} BUOY_{i,j,k-1/2} \Delta v_{k-1/2} + CV_{i,j,k+1/2} BUOY_{i,j,k+1/2} \Delta v_{k+1/2}$$

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

Equation of state

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

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

or

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

Method of Characteristics (MOC)

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

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

Lagrangian approach:

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

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

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

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

The Peclet number stands for the ratio between advection and dispersion

Procedure of MOC: advective transport by particle tracking

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

Steps in MOC-procedure

1. Determine concentration gradients at old timestep k-1

2. Move particles to model advective transport

3. Concentration of particles to concentration in element node

4. Determine concentration gradients on new timestep k*

5. Determine concentration in element node after advective, dispersive/source transport on timestep k

Konikow and Bredehoeft, 1978

Causes of errors in MOC-procedure

1. Concentration gradients

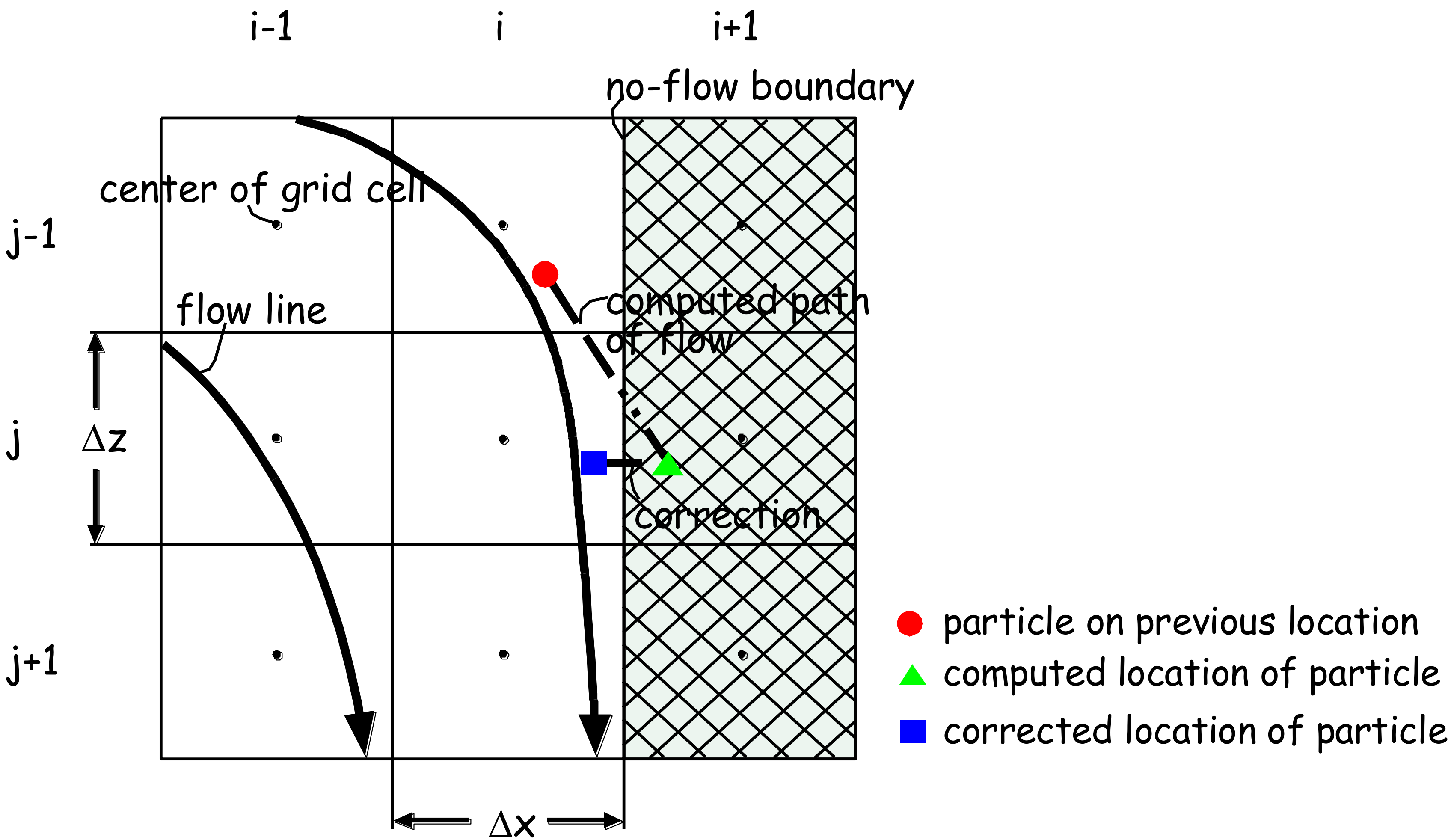
2. Average from particles to node element, and visa versa

3. Concentration of sources/sinks to entire element

4. Empty elements

5. No-flow boundary: reflection in boundary

Reflection in boundary



Numerical dispersion problem (I)

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

Peclet number $Pe \leq 2 \text{ to } 4$

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

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

Numerical dispersion problem (II)

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

$$\Delta x \leq 2\alpha_L \text{ to } 4\alpha_L$$

where α_L = longitudinal dispersivity [L]

What does that mean?

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

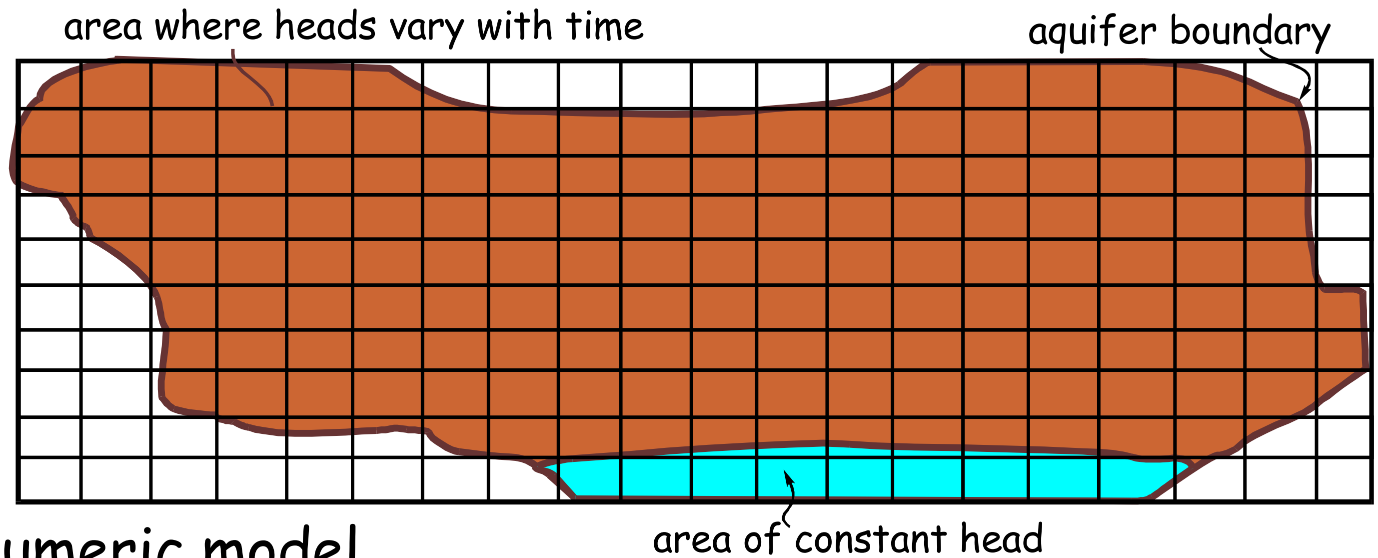
Numerical dispersion problem (III)

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

MODFLOW

Boundary conditions in MODFLOW (I)

Example of a system with three types of boundary conditions



Numeric model

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

Boundary conditions in MODFLOW (II)

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

Packages in MODFLOW

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

1. Well package

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

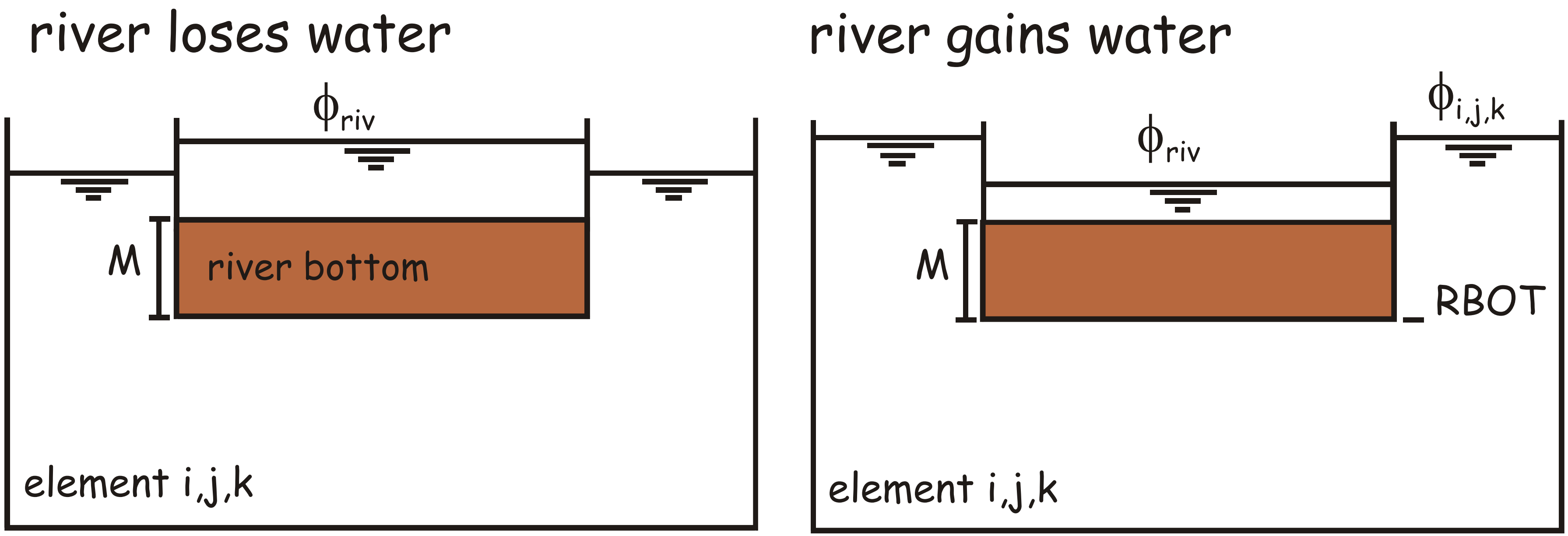
Example: an extraction of 10 m^3 per day should be inserted in an element as:

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

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

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

2. River package (I)



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

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

2. River package (II)

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

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

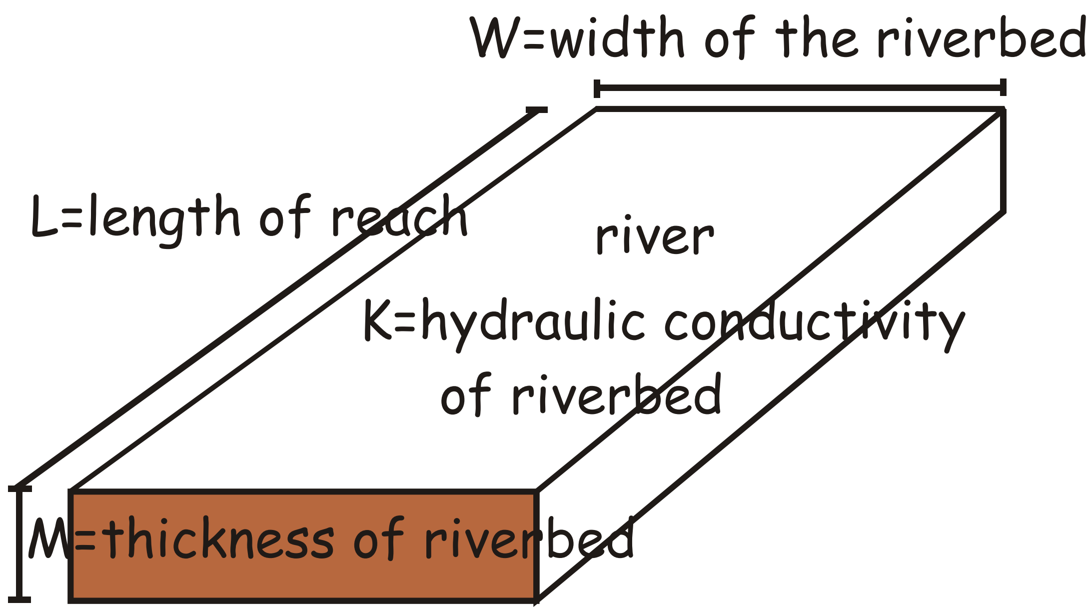
$$Q_{ext,i,j,k} = P_{i,j,k}\phi_{i,j,k}^{t+\Delta t} + Q'_{i,j,k}$$

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

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

2. River package (III)

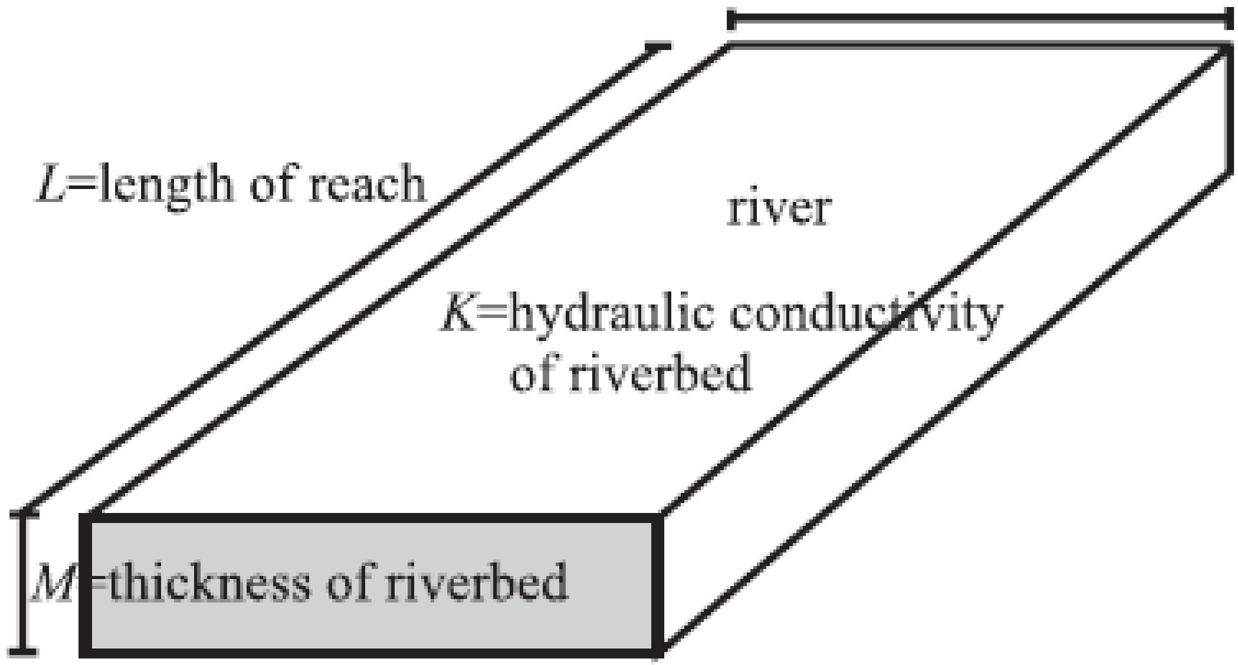
Determine the conductance of the river in one element:



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

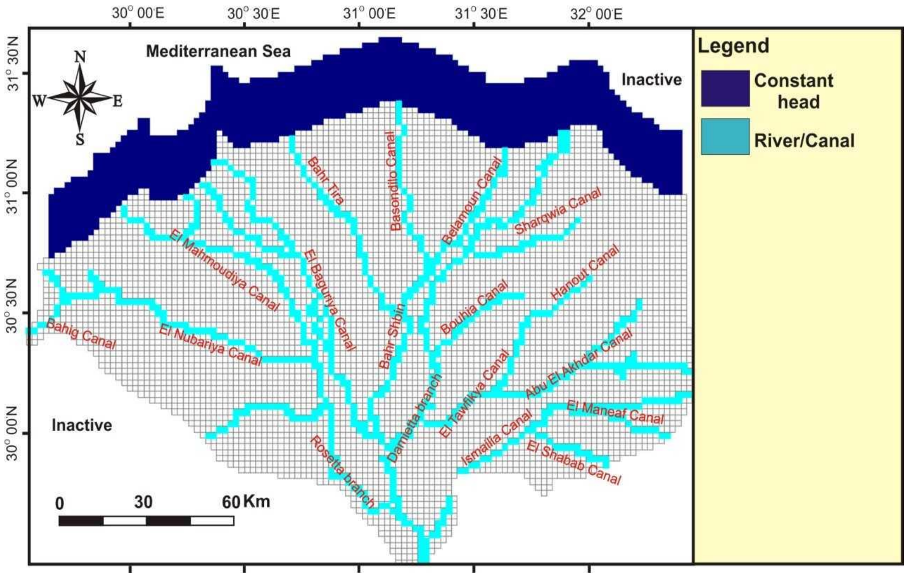
CONDUCTANCE

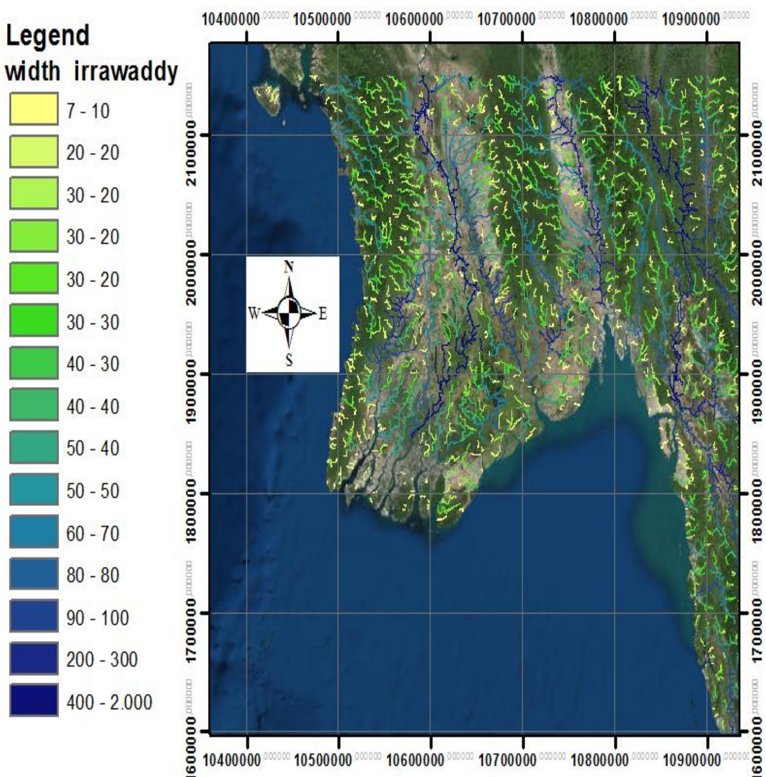
conductance of prism: $C = KLW/M$



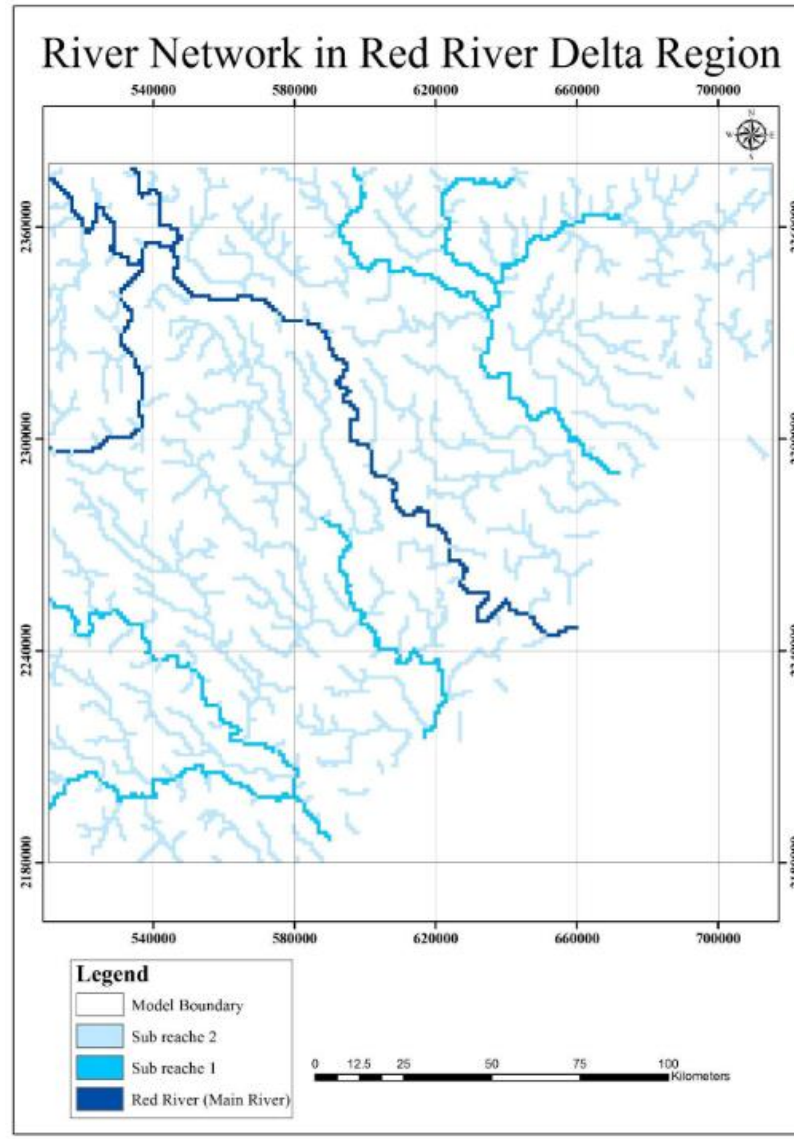
River Package: water courses

1. Location of watercourses
2. Water level; different approach per type of watercourse
3. Drainage resistance (conductance)
4. Chloride concentration surface water





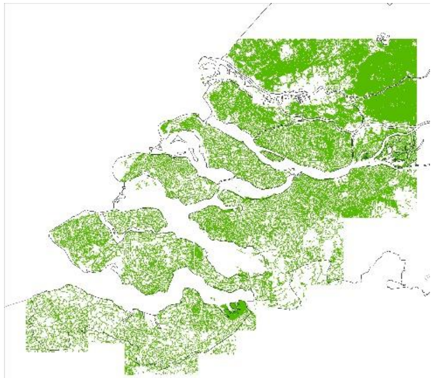
Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS)



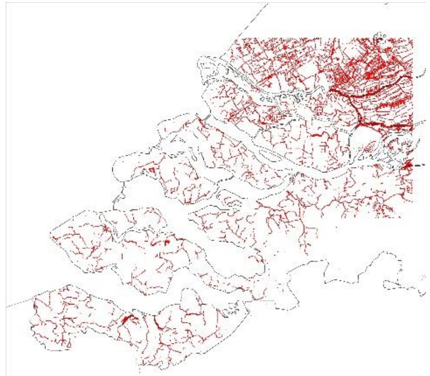
River types, model Zeeland

Watercourse type	**Type**	**Indeling Waterboard**
1	*Sloot*=ditch (top10)	Primaire waterloop / secundaire waterloop
2	*Rivier*=river (top10)	Primaire waterloop
3	*Meer*=lake (top10)	
4	*Kanaal*=canal (top10)	
5	*Greppel*=trench (top10)	Secundaire waterloop/ tertiare waterloop
6	*Zee*=sea or *binnenwater*=innersea	

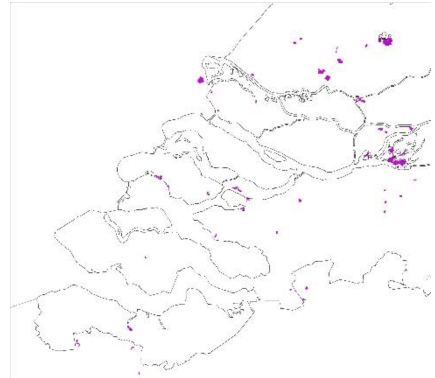
River types, model Zeeland



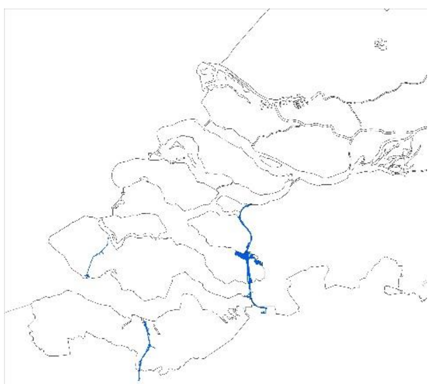
Waterloop type 1: sloot



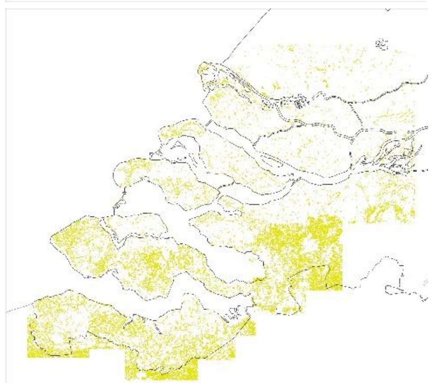
Waterloop type 2: rivier



Waterloop type 3: meer



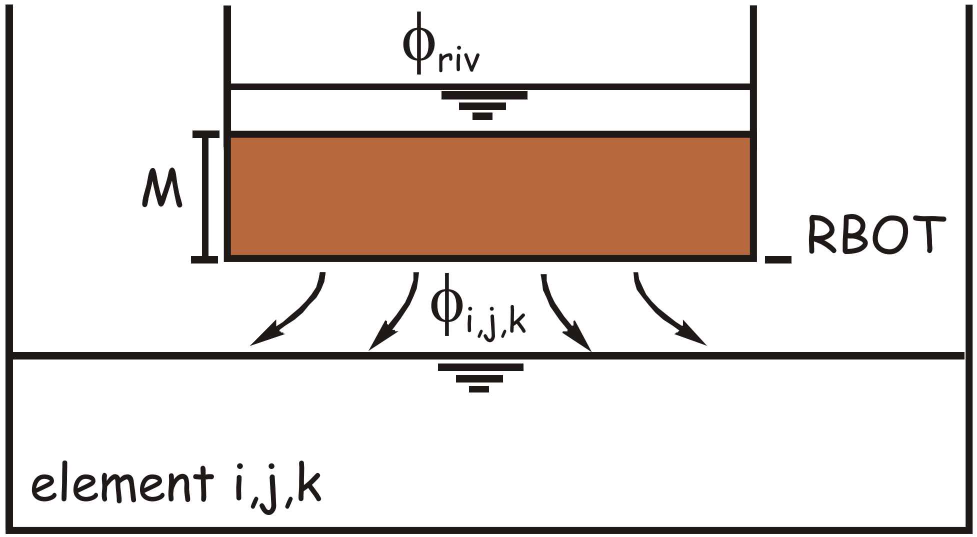
Waterloop type 4: kanaal



Waterloop type 5: greppel

Waterloop type 6:
binnenwater en zee

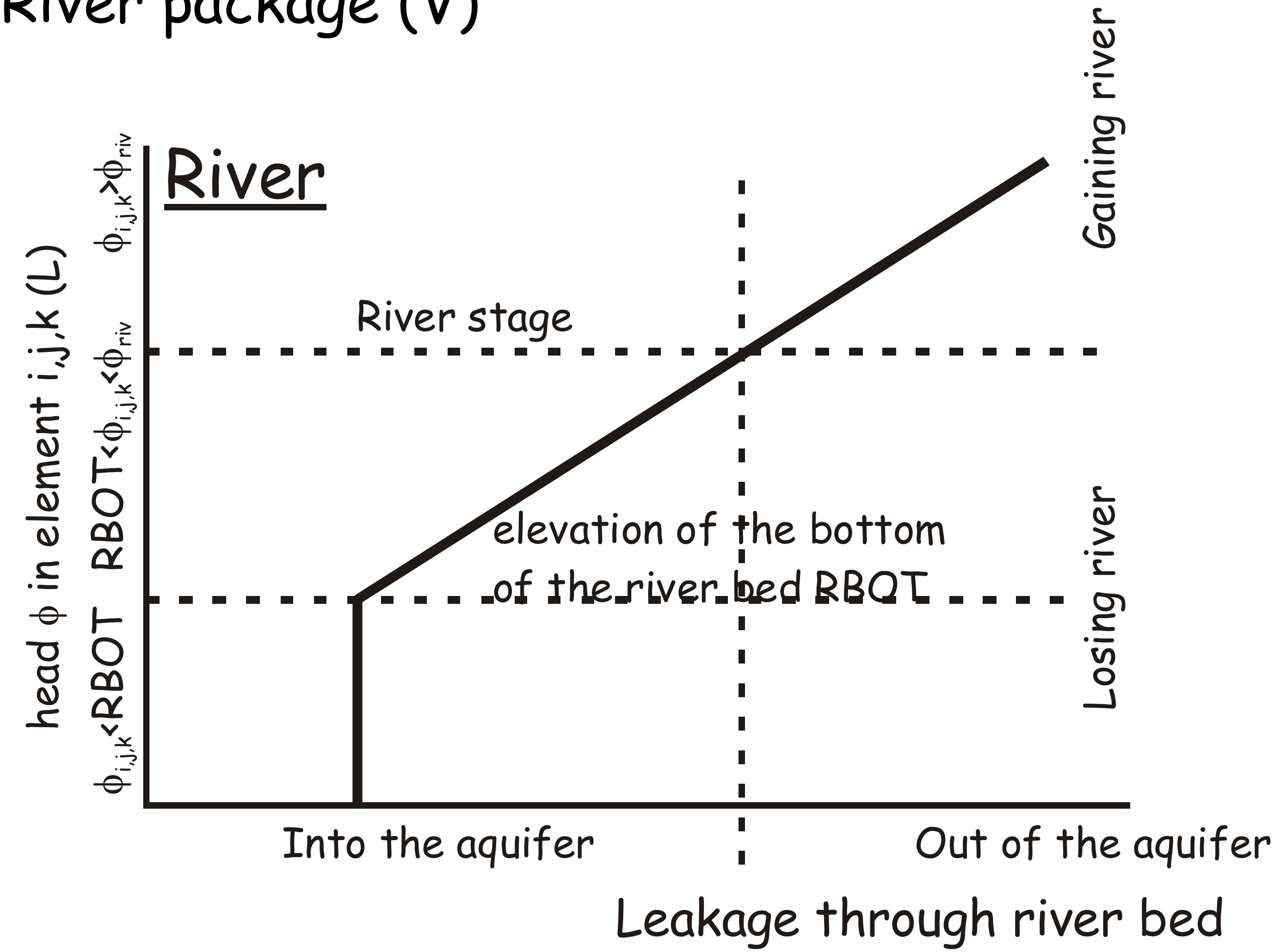
2. River package (IV)
Leakage to the groundwater system



Special case:

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

2. River package (V)



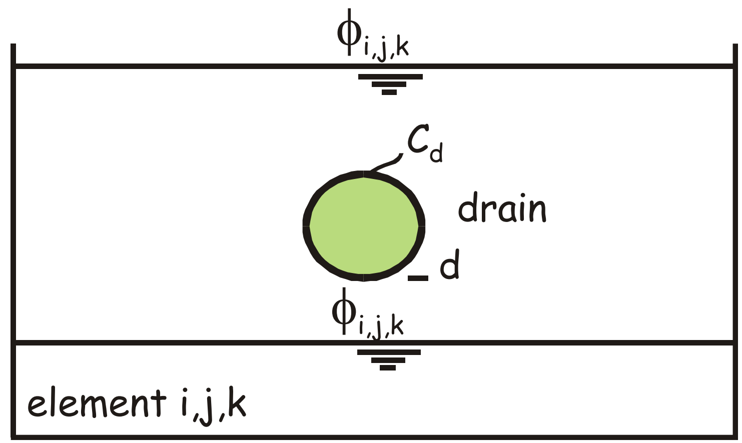
3. Recharge package

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

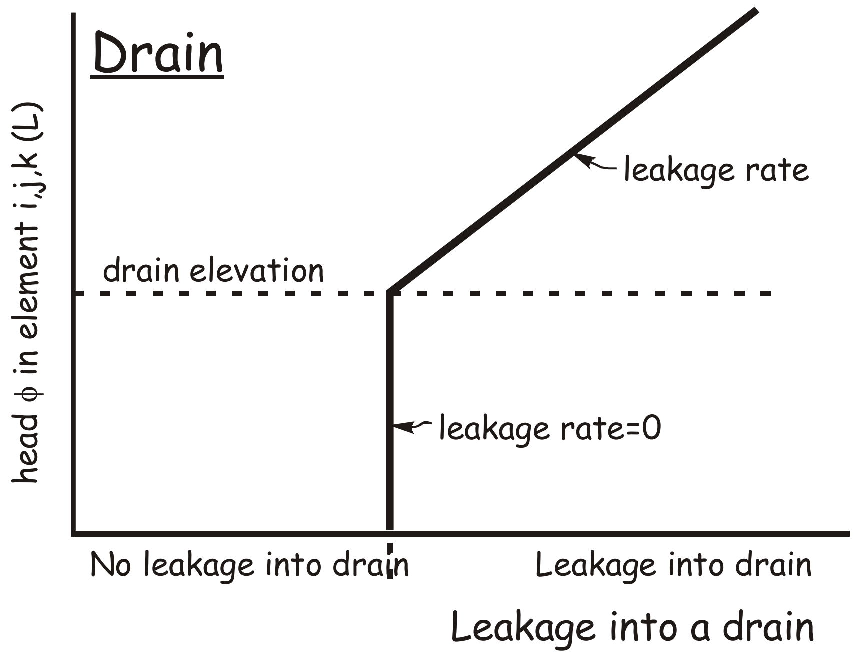
4. Drain package

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

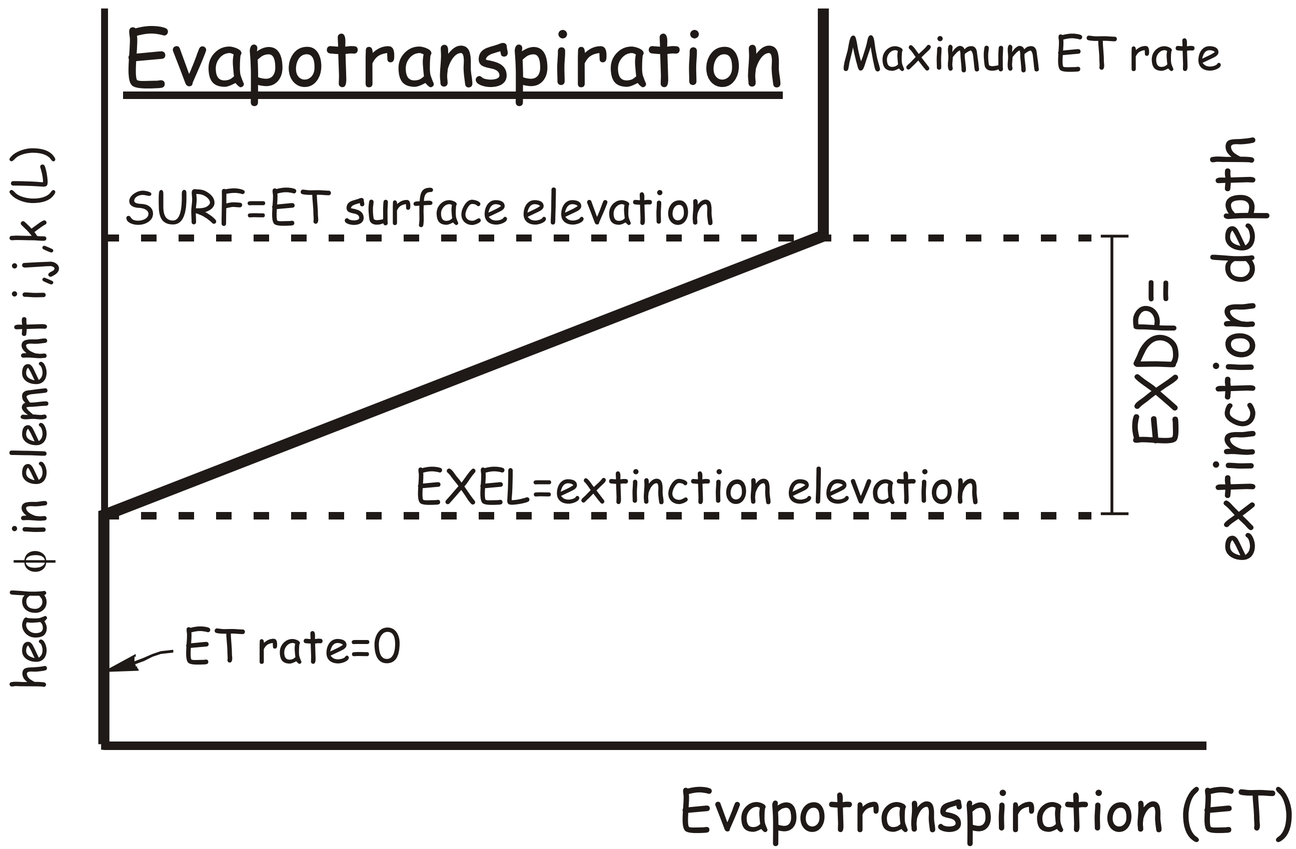
Special case:



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

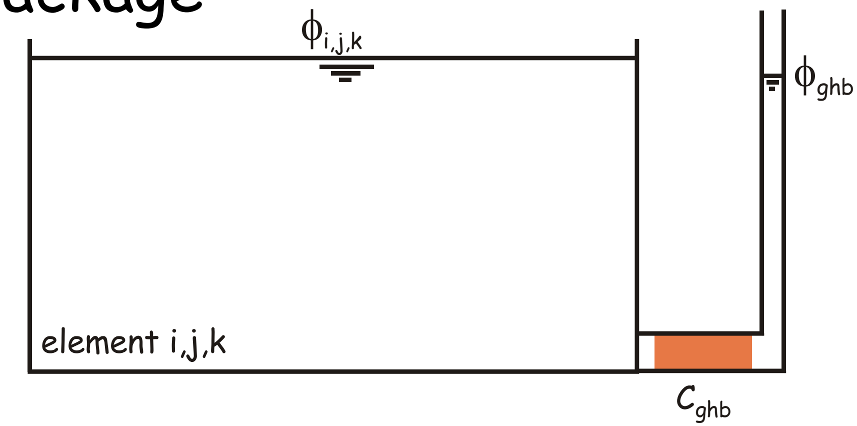


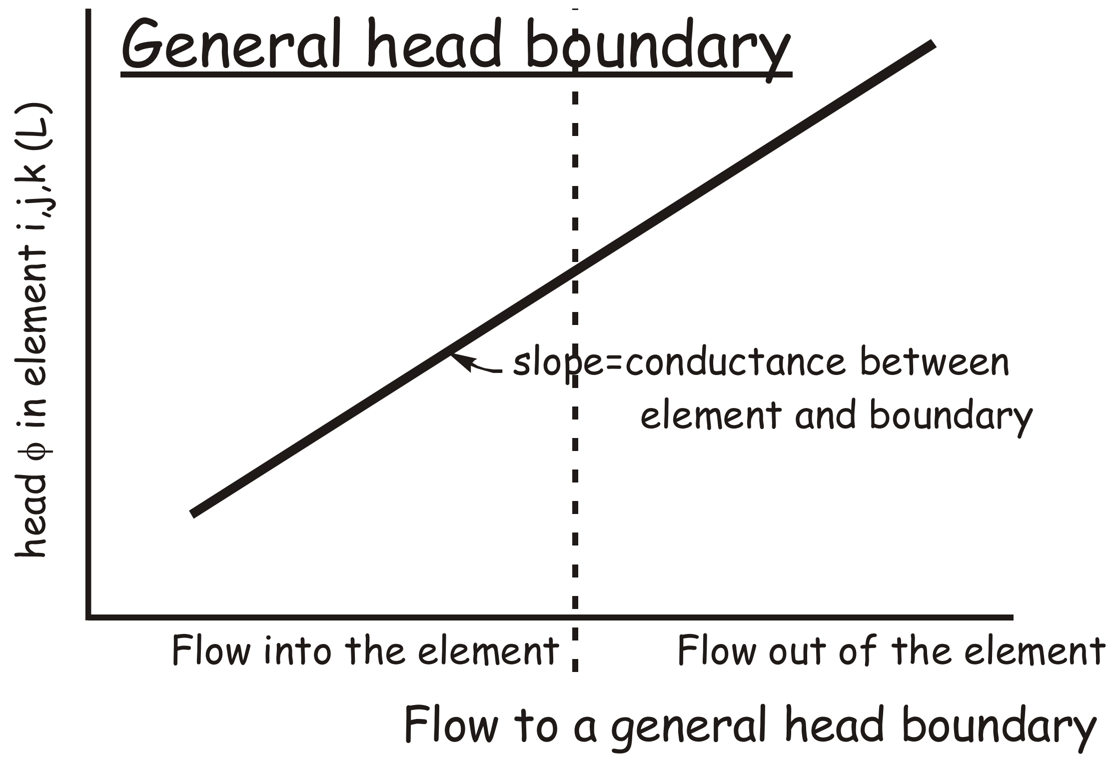
5. Evapotranspiration package



6. General head boundary package

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

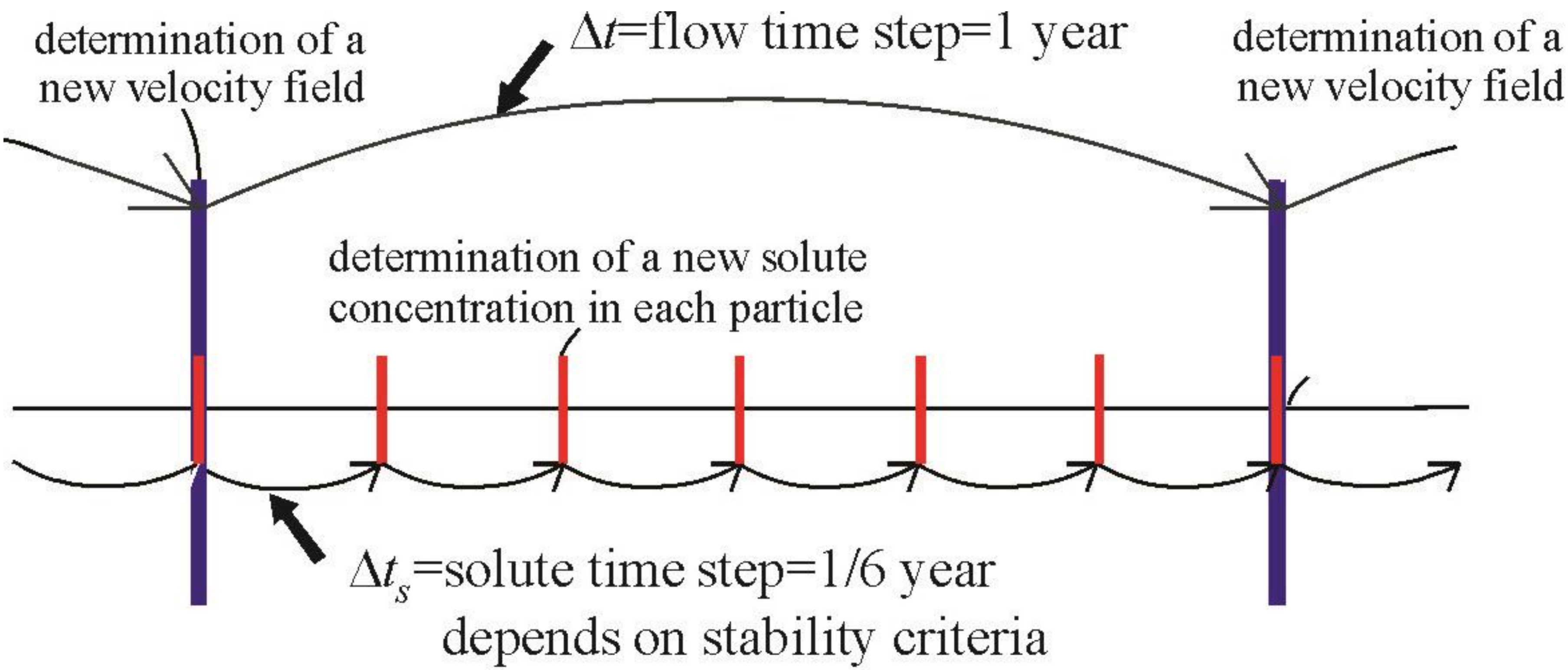




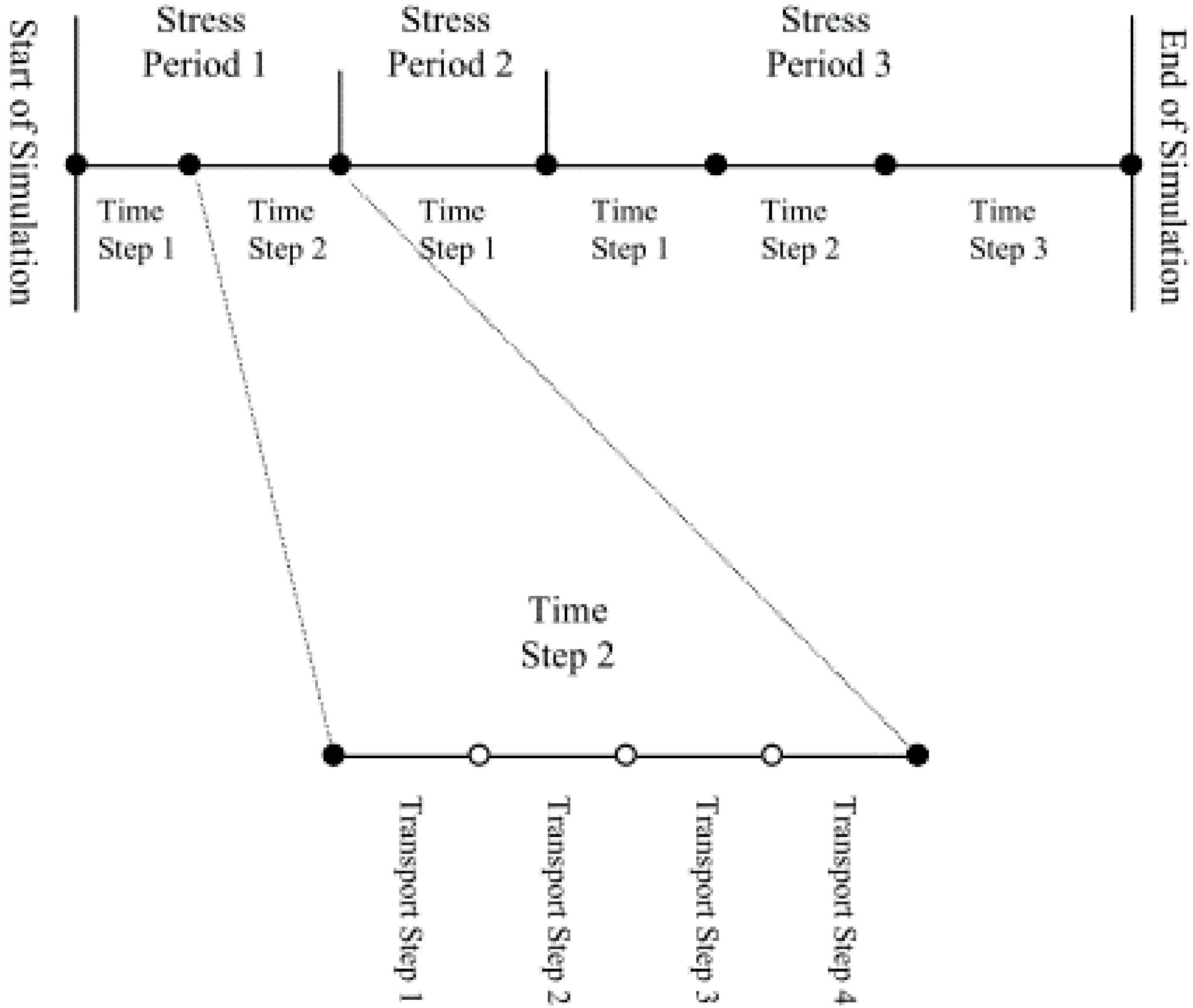
Time indication MODFLOW

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

Flow time step and solute time step

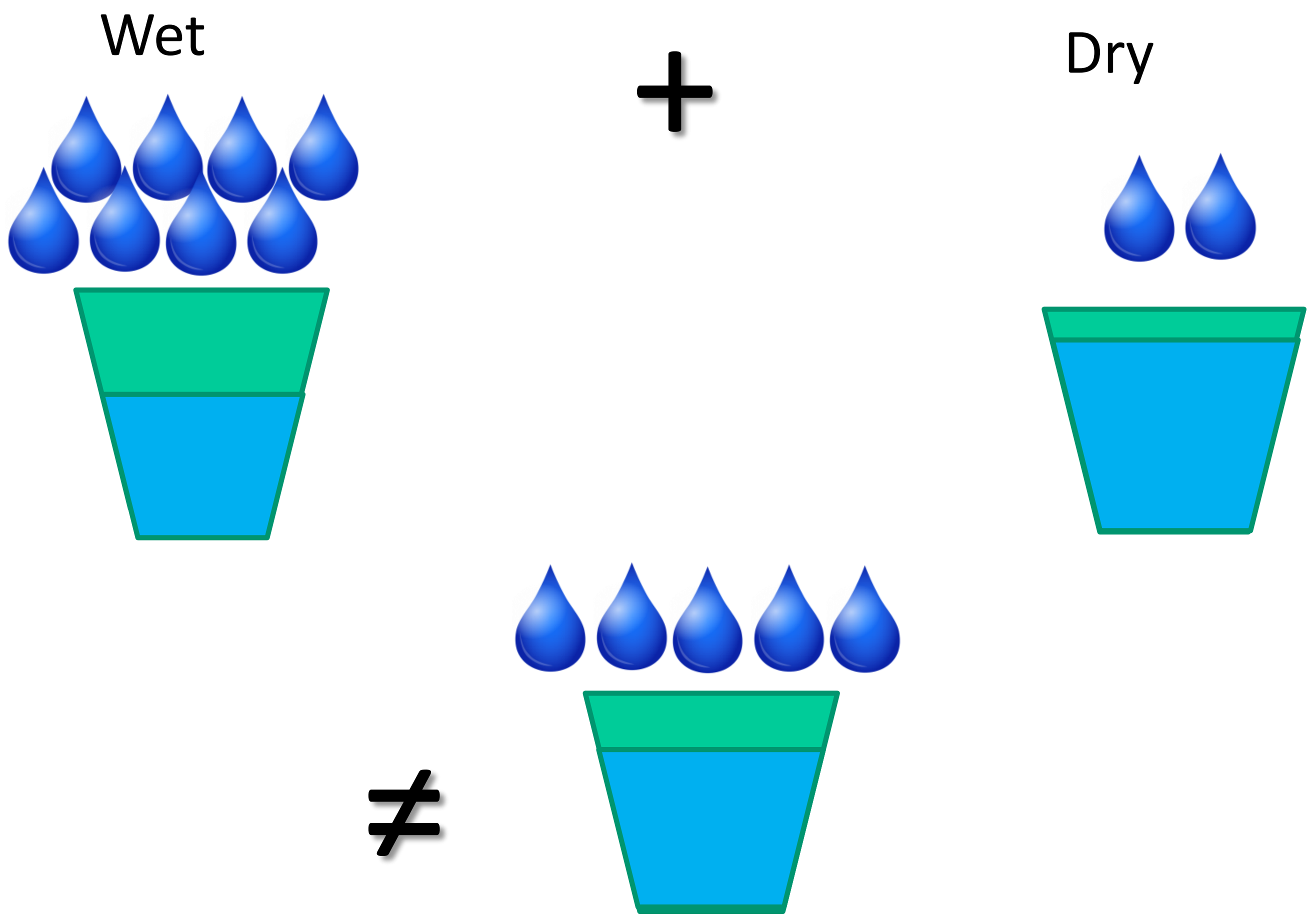


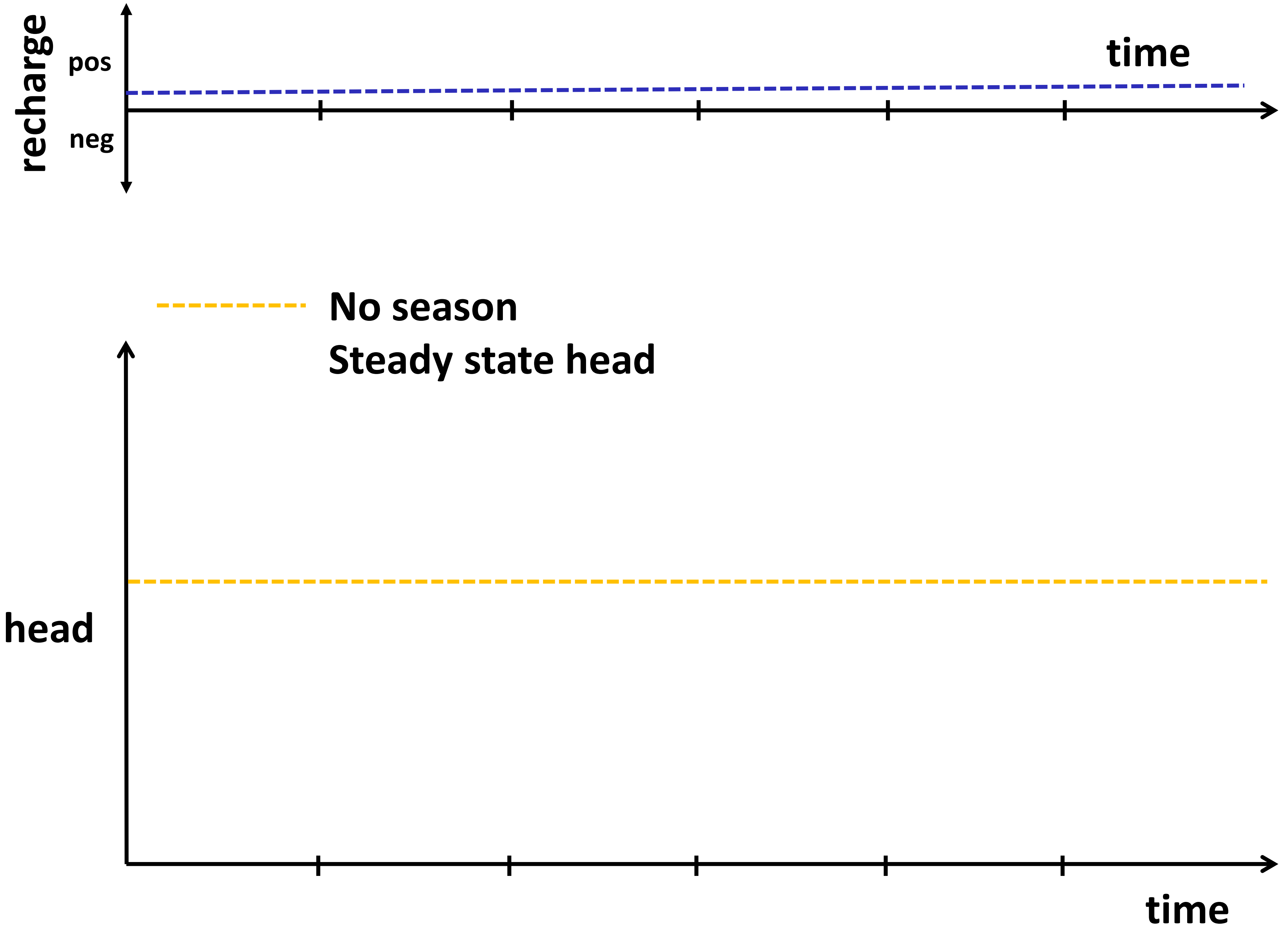
* velocity field remains constant during 1 year
* solute concentration changes during each solute time step

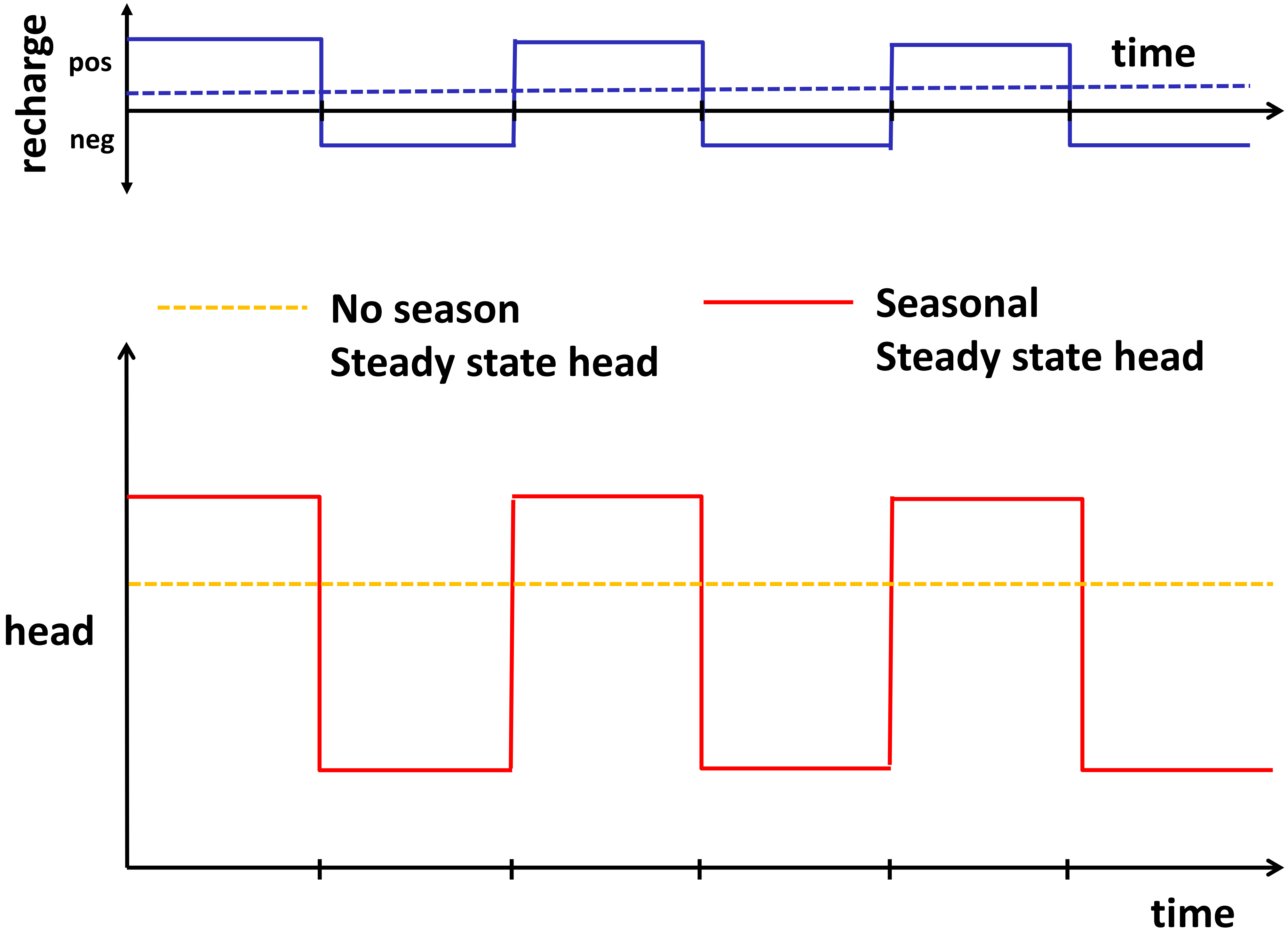


Start of Simulation
Stress Period 1
Stress Period 2
Stress Period 3
End of Simulation
Time Step 1
Time Step 2
Time Step 1
Time Step 1
Time Step 2
Time Step 3
Time Step 2
Transport Step 1
Transport Step 2
Transport Step 3
Transport Step 4

Acknowledge non-stationarity

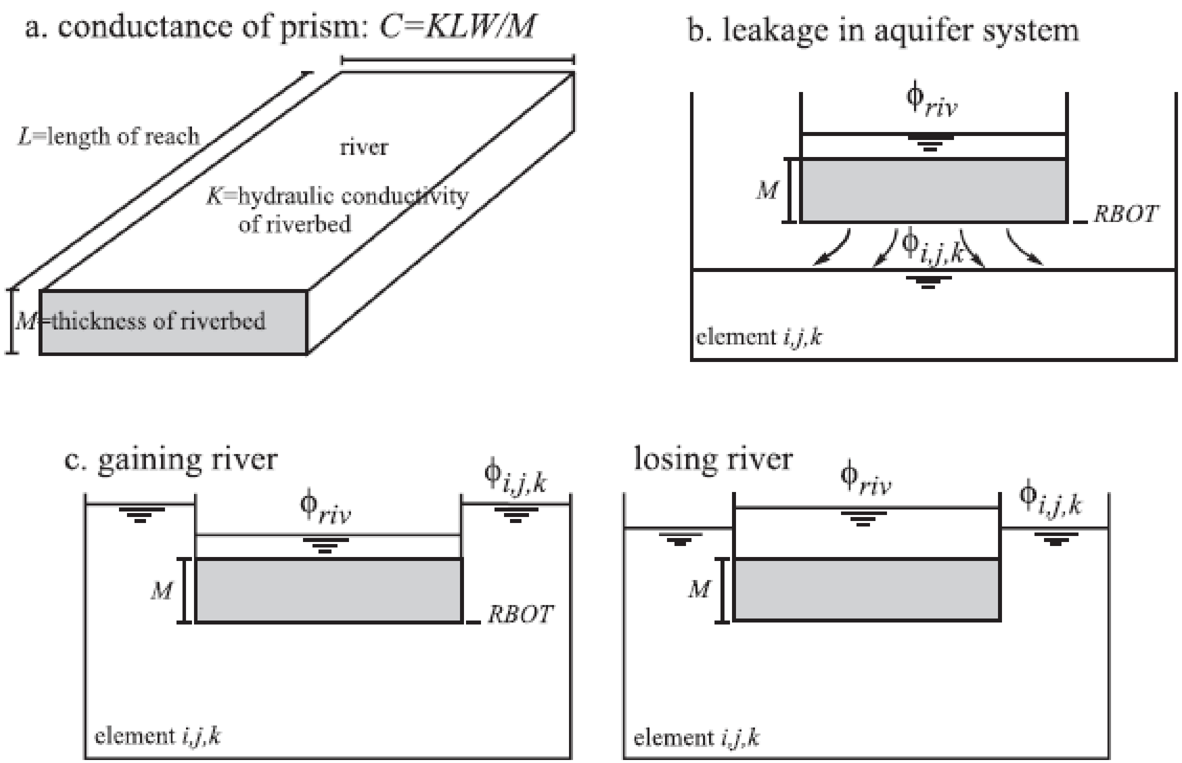


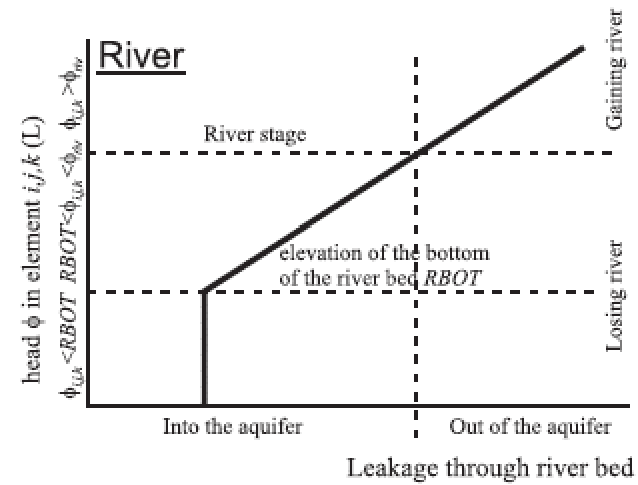

recharge
pos
neg
time
No season
Steady state head
head
time

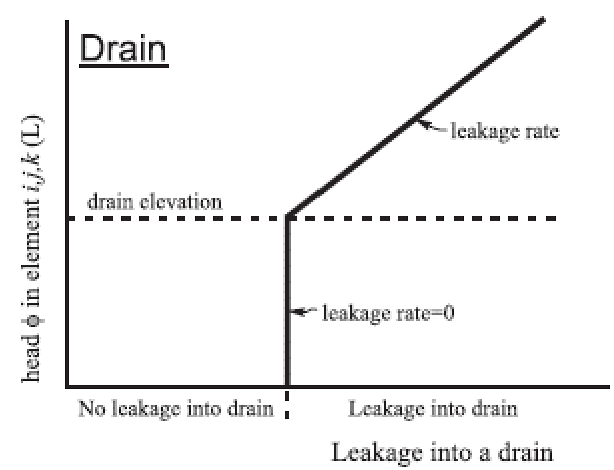

recharge
pos
neg
time
No season
Steady state head
Seasonal
Steady state head
head
time

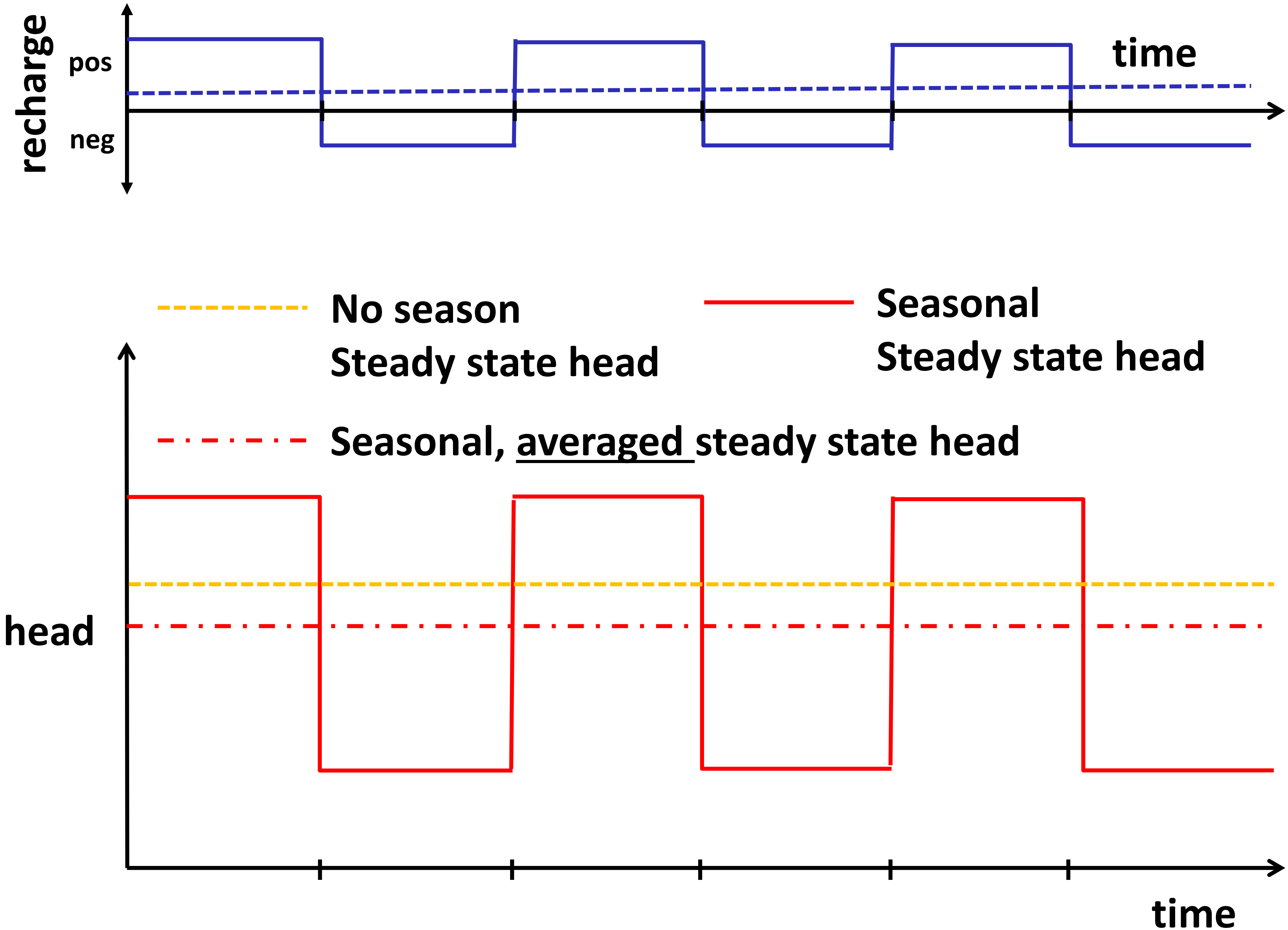
Non-linearity discharge systems, e.g. rivers

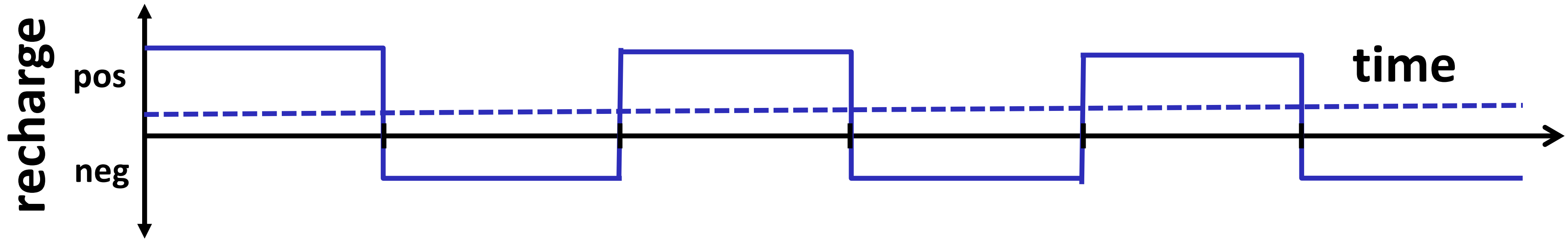
During high recharge fluxes, more water is discharged, and head is less high








recharge
pos
neg
time
No season
Steady state head
Seasonal
Steady state head
Seasonal, averaged steady state head
head
time



Extra issue: with smaller effective velocities, hydrodynamic disp. is smaller too