



Groundwater in the coastal zone

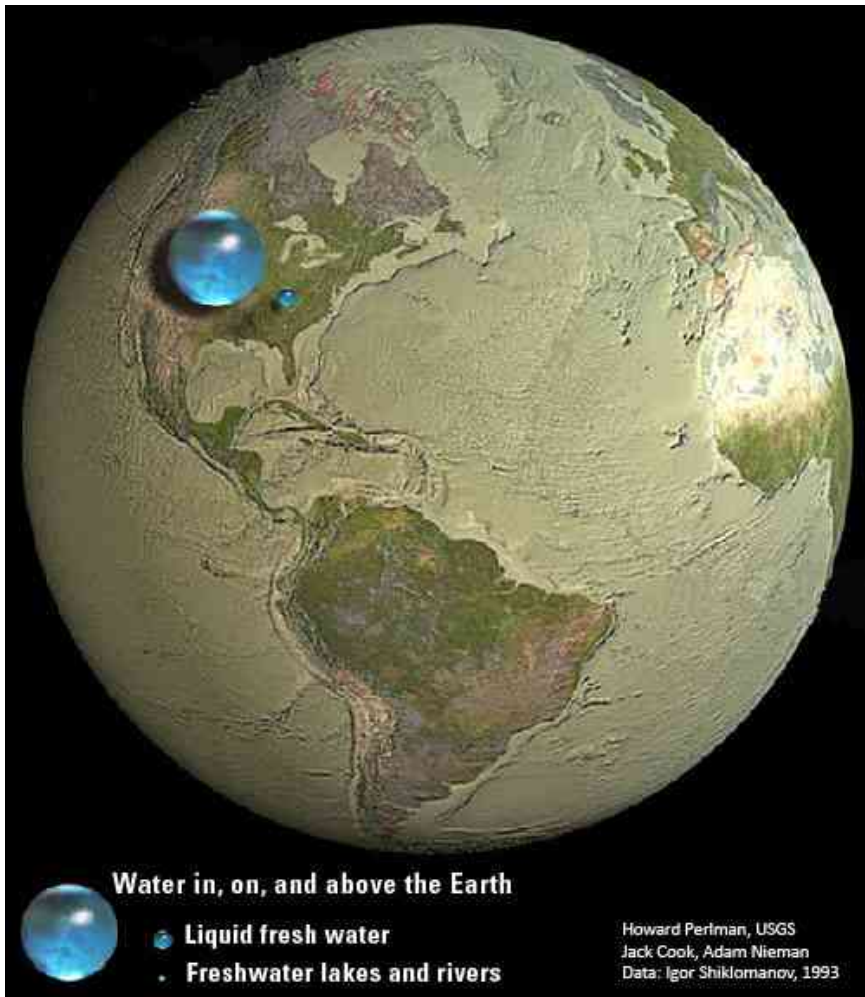
Vulnerability of groundwater systems to flooding events

Gualbert Oude Essink
Deltares & Utrecht University
gualbert.oudeessink@deltares.nl

More information:
freshsalt.deltares.nl
zoetzout.deltares.nl
20160302 GEO4-4425



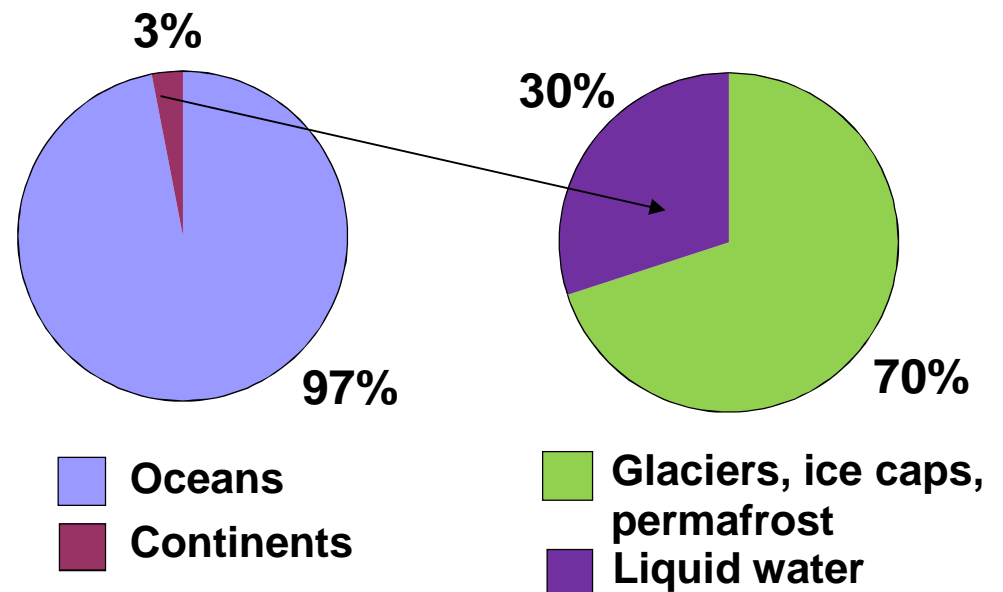
Volumes of water on Earth: a scarce product



Water in/on/above Earth

Liquid fresh water

Freshwater lakes rivers



Source: Perlman, USGS; Shiklomanov, 1993

Groundwater in the future

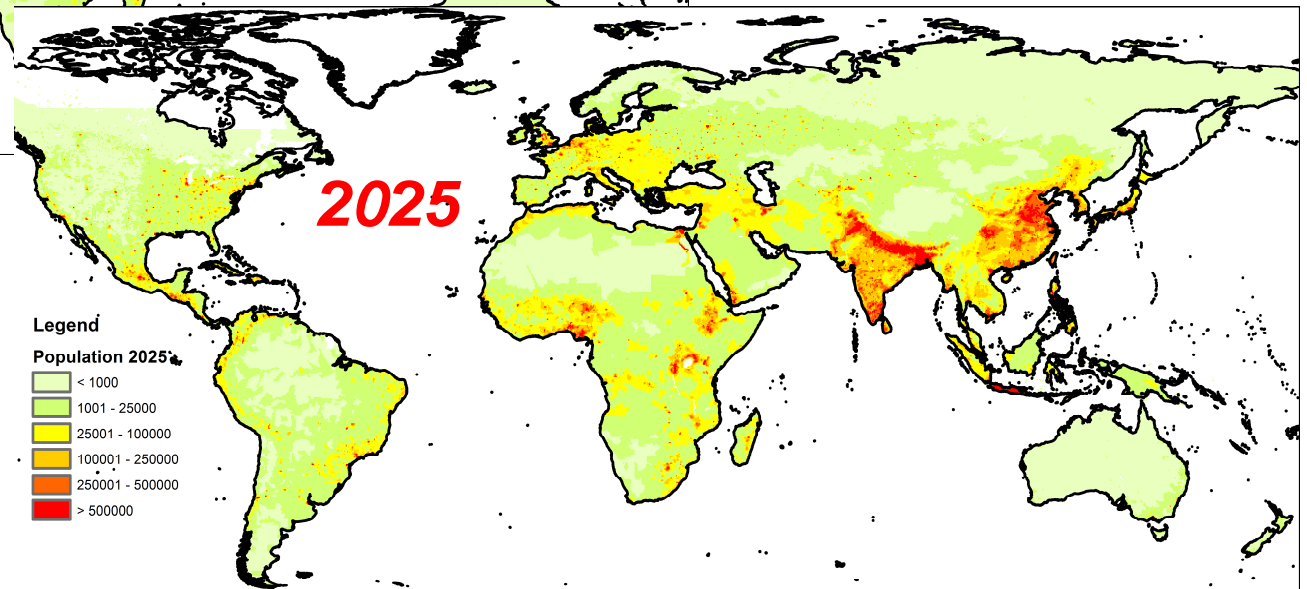
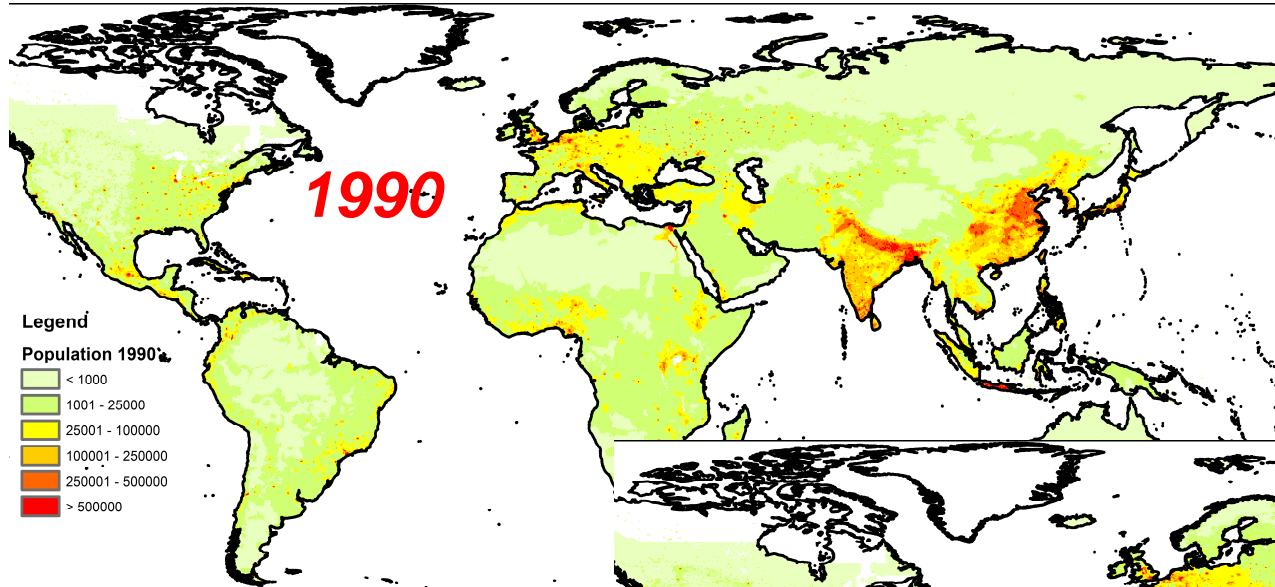
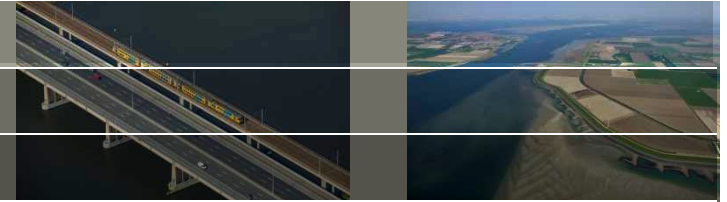


We have to cope with...

- Development energy use/production (heat-cold)
- Climate change
- Land subsidence
- Groundwater extractions
- Development spatial land use
- **Politics, Policy & Watermanagement**

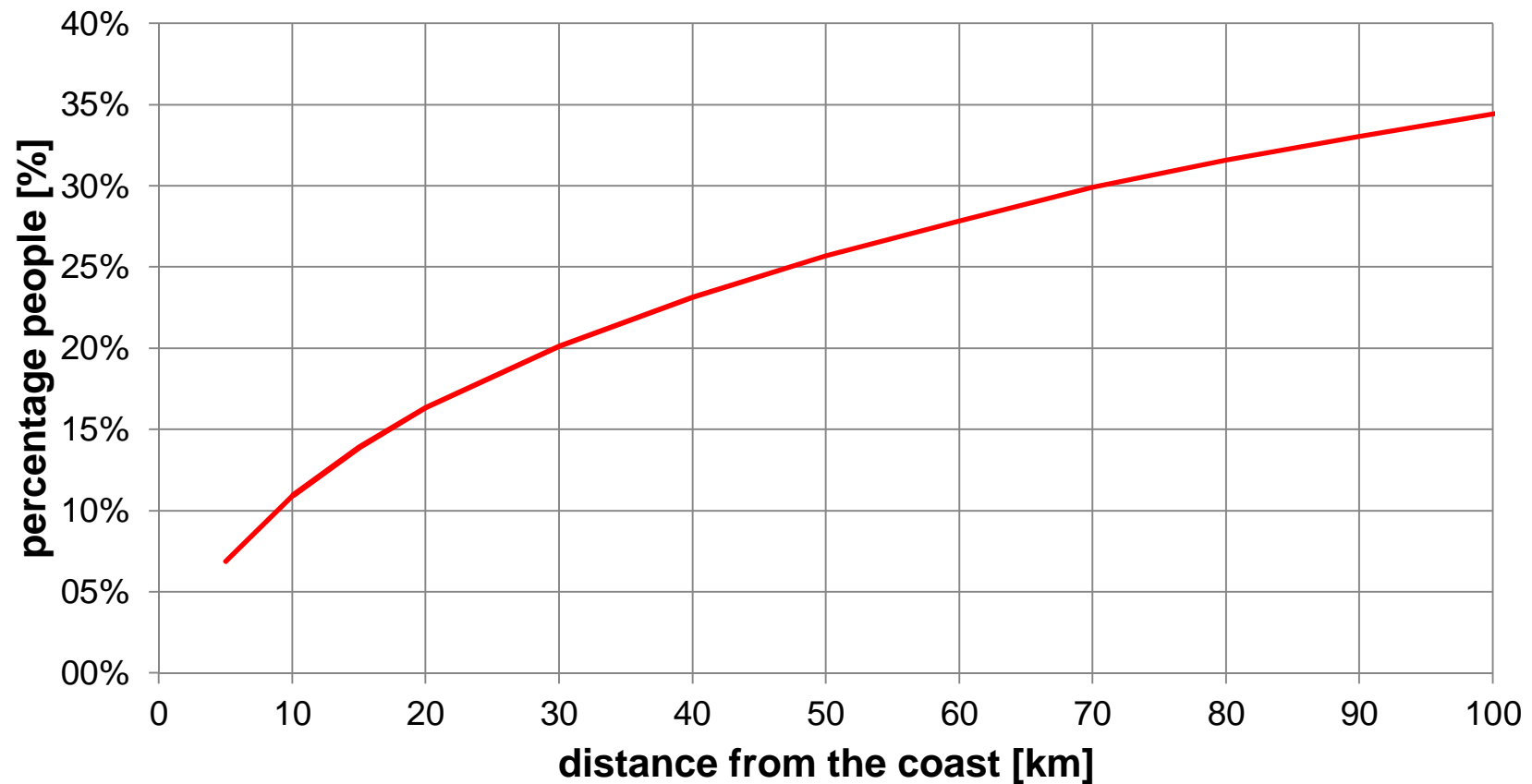
Direct anthropogenic influence on groundwater is more important than climate effect

Population growth 1990-2025

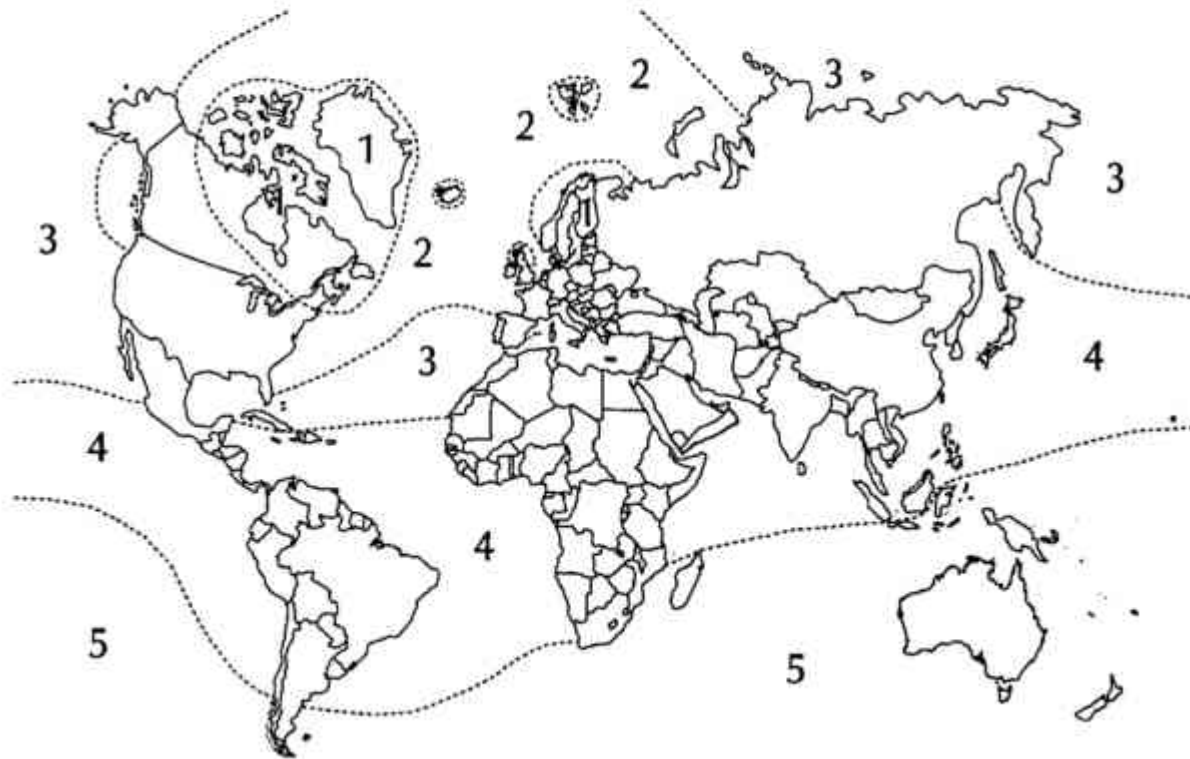
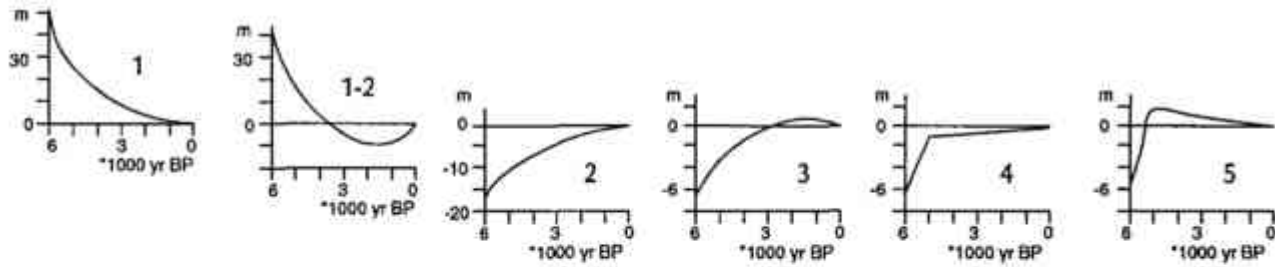


1/3 world population lives within 100km of the coast

Based on data SRTM, world coastline data and world population



Regional distribution of Holocene Sea-level Changes

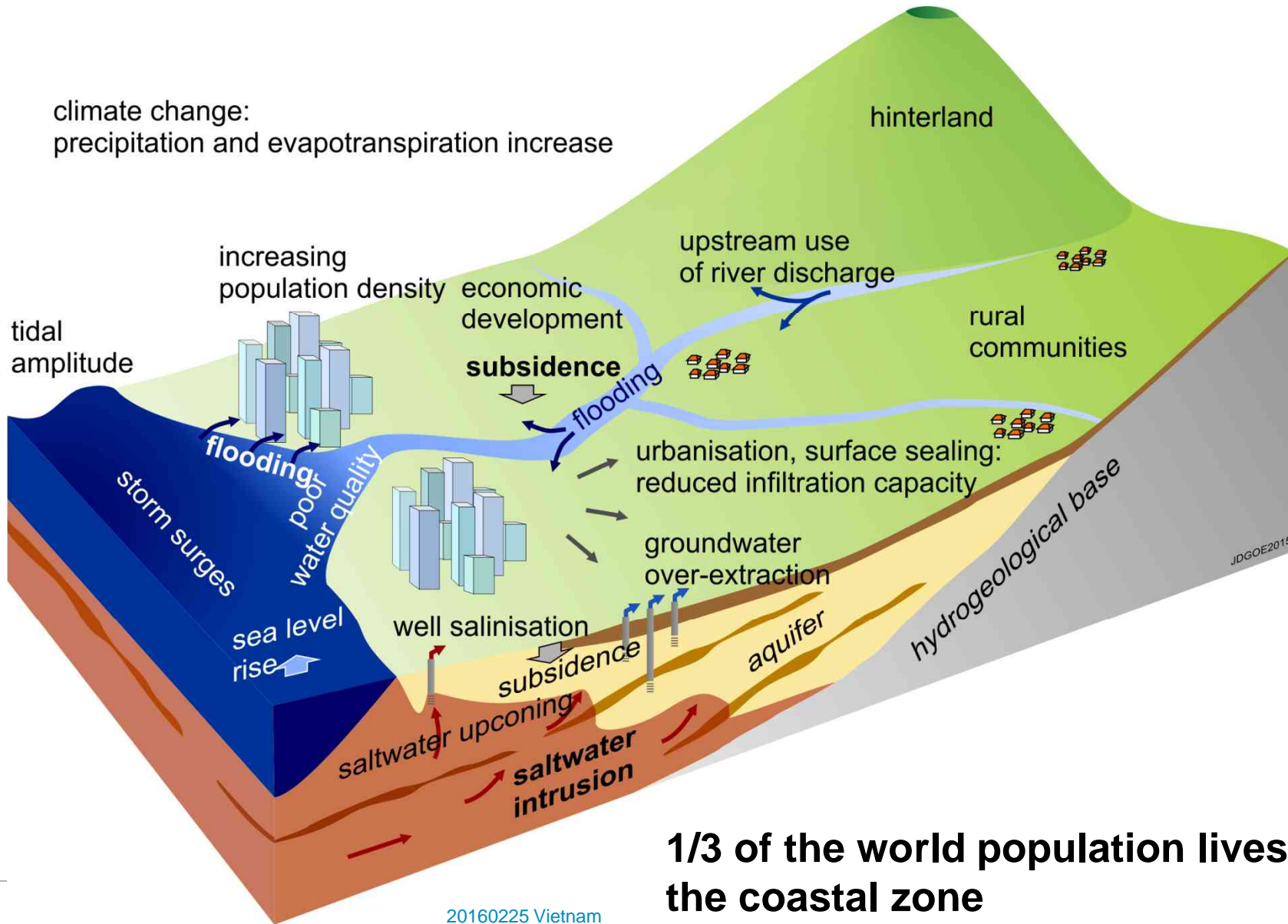
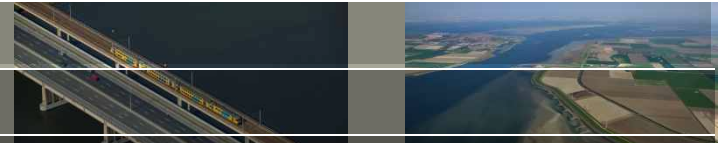


Source: Pirazzoli, P.A. & Pluet, J., 1991. *World Atlas of Holocene Sea-level Changes*. Elsevier Oceanography Series, Vol. 58

02-Mar-16

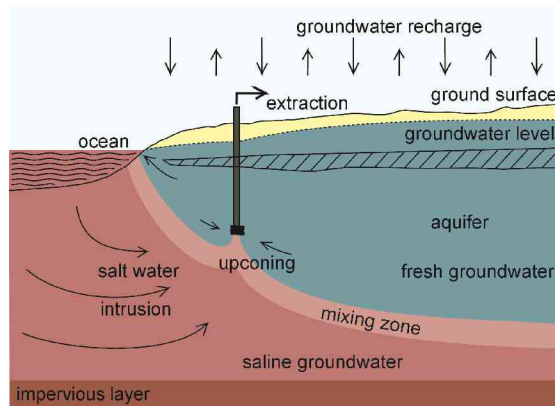
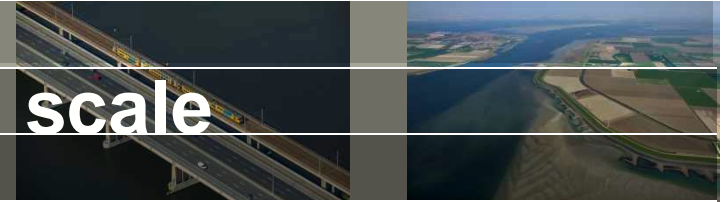
Threats to deltas worldwide:

subsidence, salinisation, depletion, sealing, sea level rise, CC

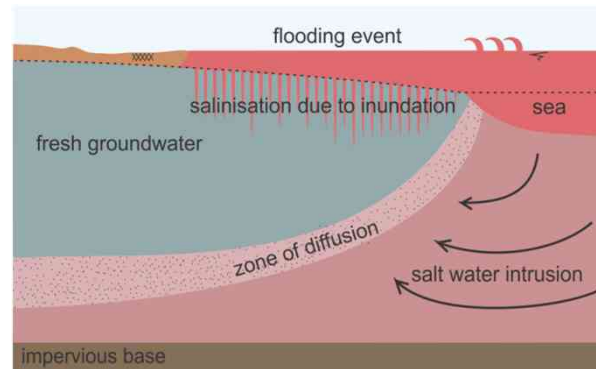


1/3 of the world population lives in the coastal zone

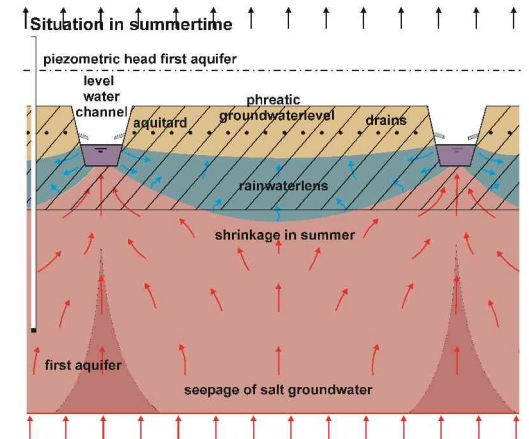
Salinisation processes at local scale



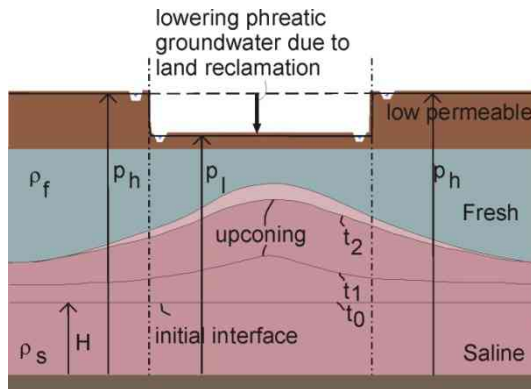
Salt water intrusion groundwater



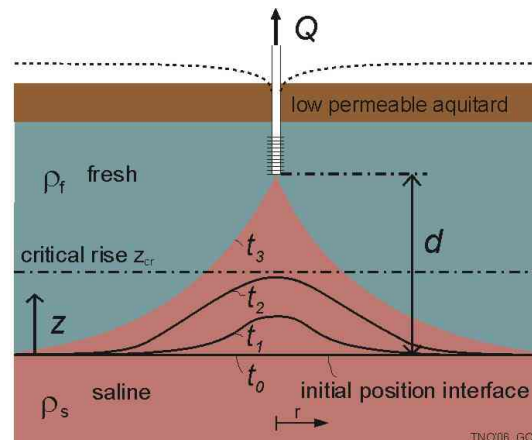
Inundation saline seawater



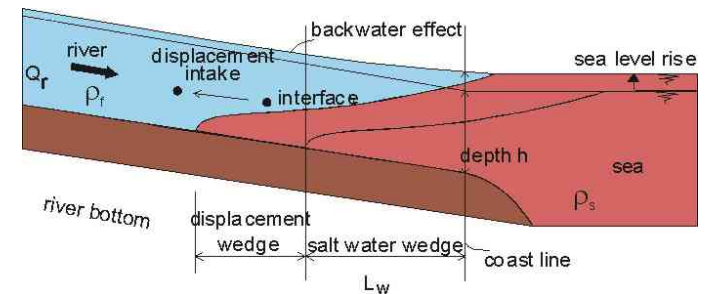
Shallow rainwaterlens



Upconing low-lying area

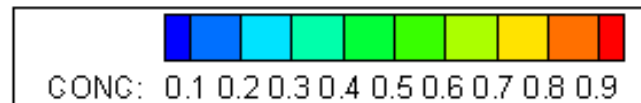
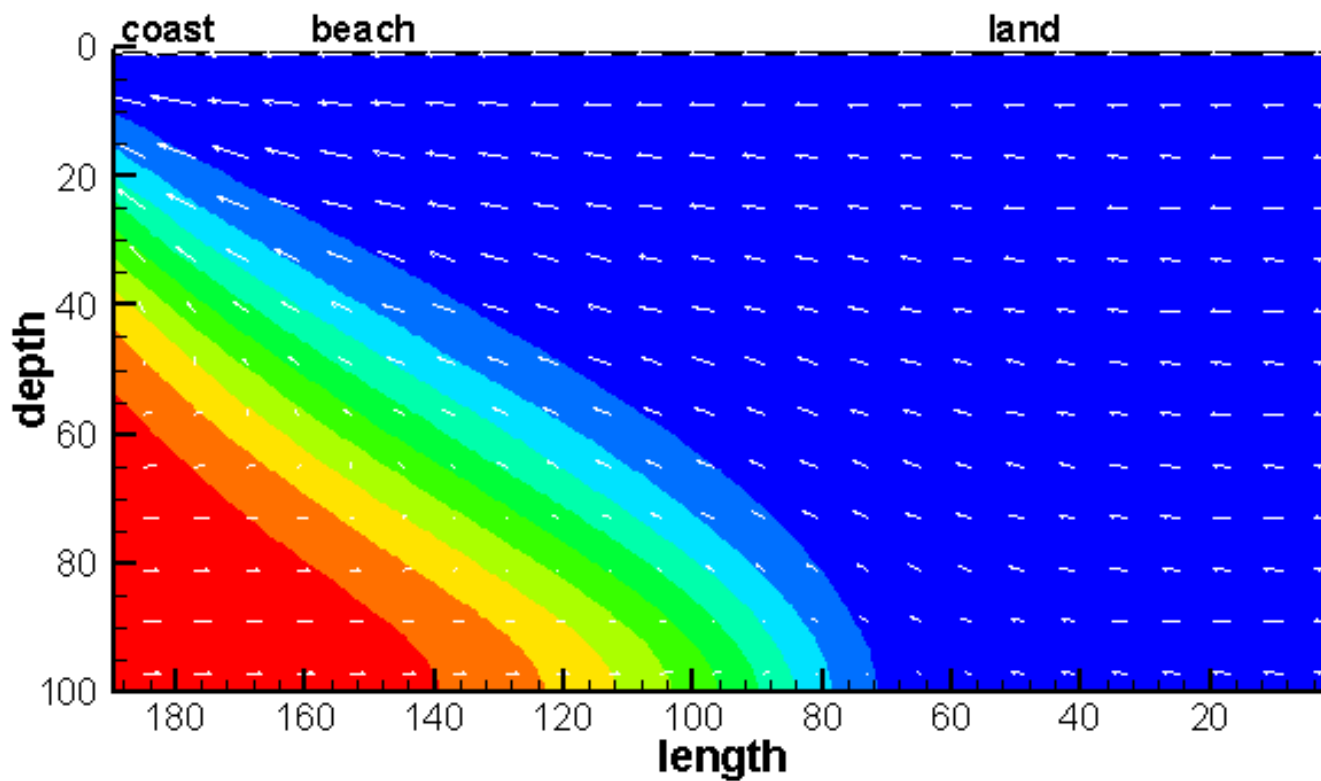


Upconing extraction



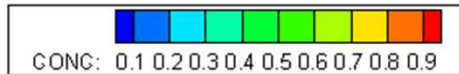
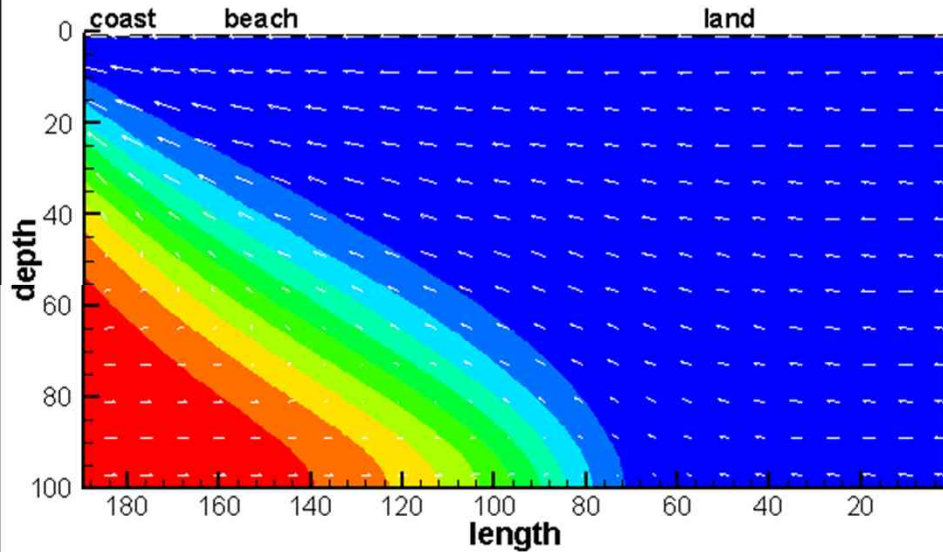
Salt water intrusion surface water

Impact of sea level rise on a coastal groundwater system: a conceptual model of saltwater intrusion



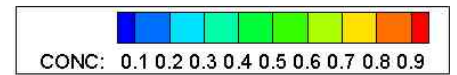
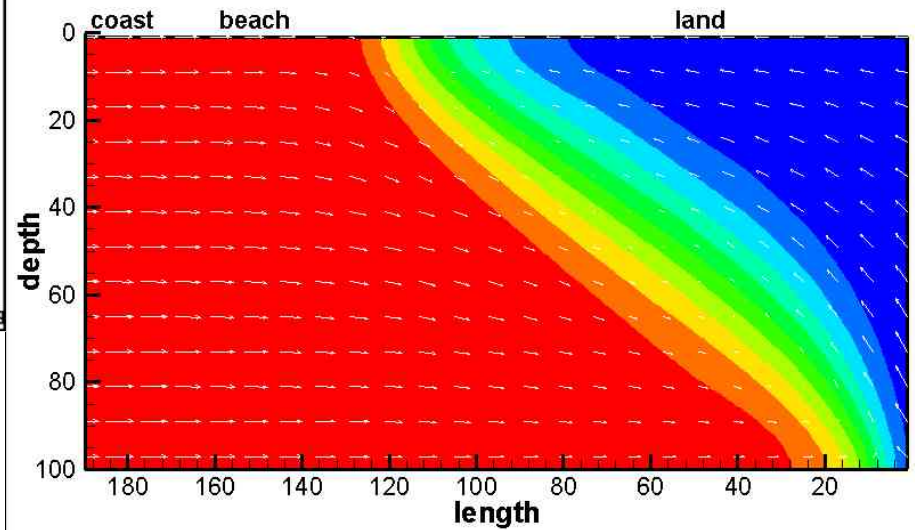
Sea level rise and salt water intrusion

Impact of sea level rise on a coastal groundwater system:
a conceptual model of saltwater intrusion



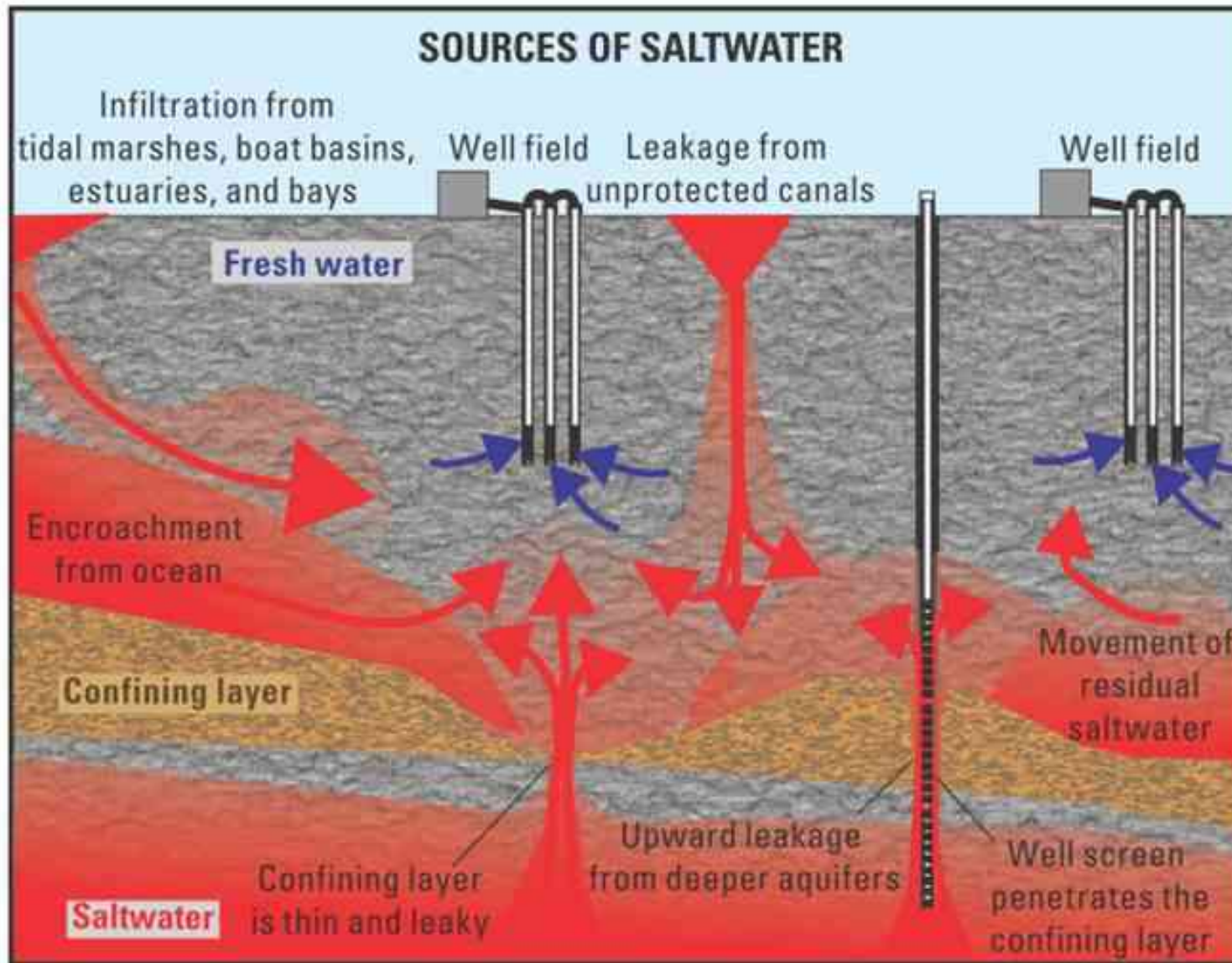
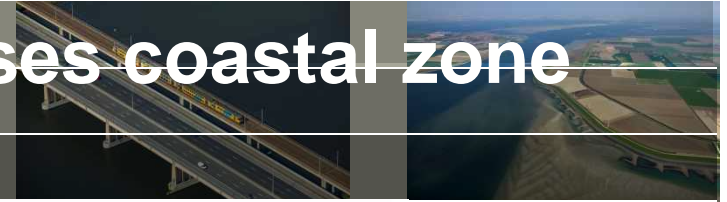
GOE, 2009

Impact of sea level rise on a coastal groundwater system:
a conceptual model of saltwater intrusion



GOE, 2009

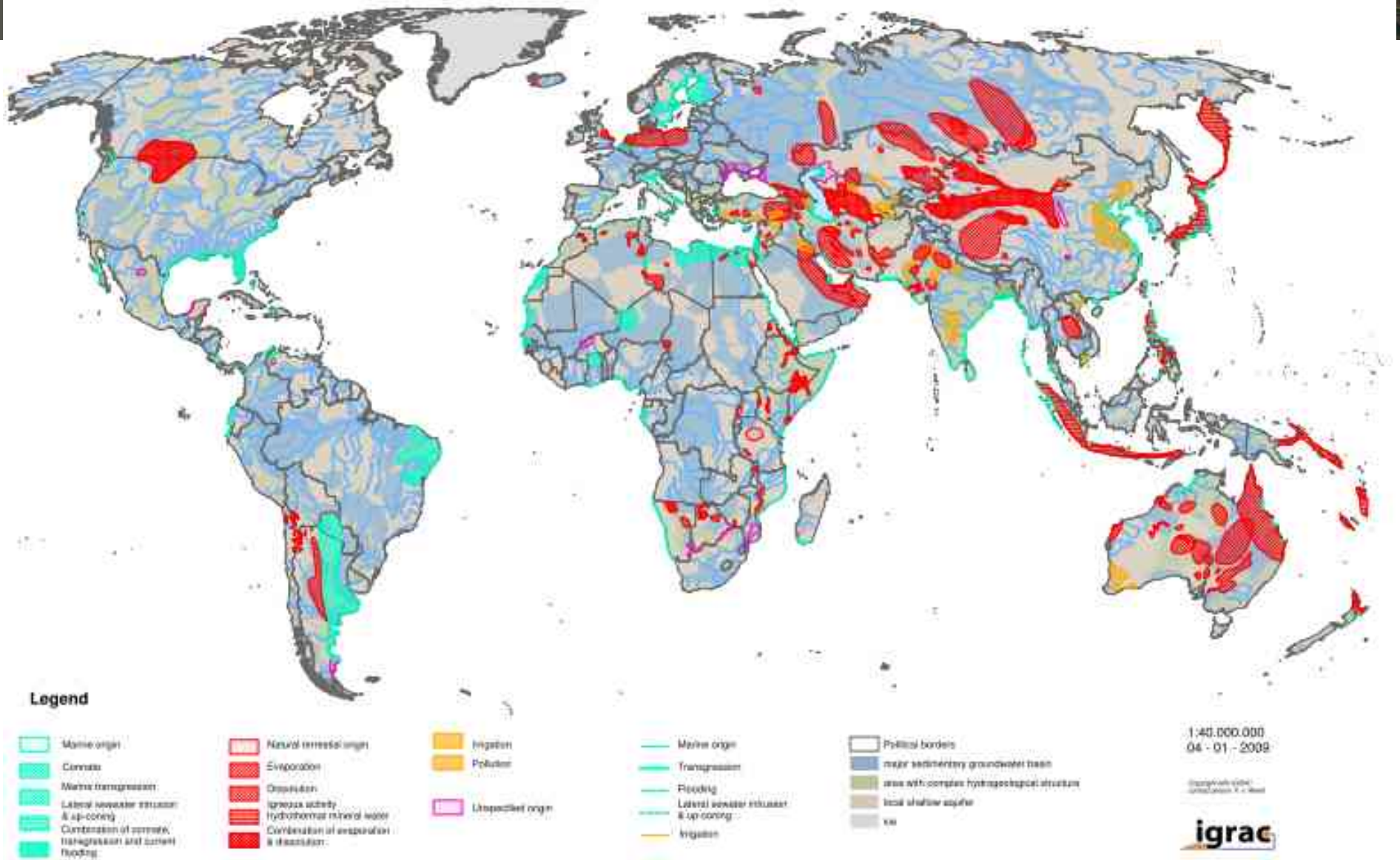
Combining salinization processes coastal zone

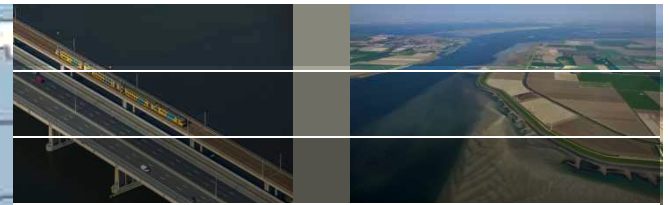


02-Mar-16


Prinos, 2014


Regions with brackish and saline groundwater at shallow and intermediate depths







S. les


 Marine origin

 Connate

 Marine transgression


 Lateral seawater intrusion & up-coning

 Combination of connate, transgression and current flooding

 Natural terrestrial origin

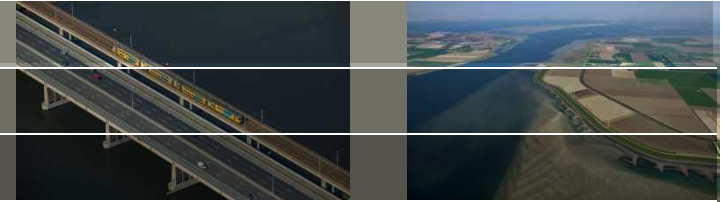
 Evaporation

 Dissolution

 Igneous activity hydrothermal mineral water

 Combination of evaporation & dissolution

Salt in water is a problem



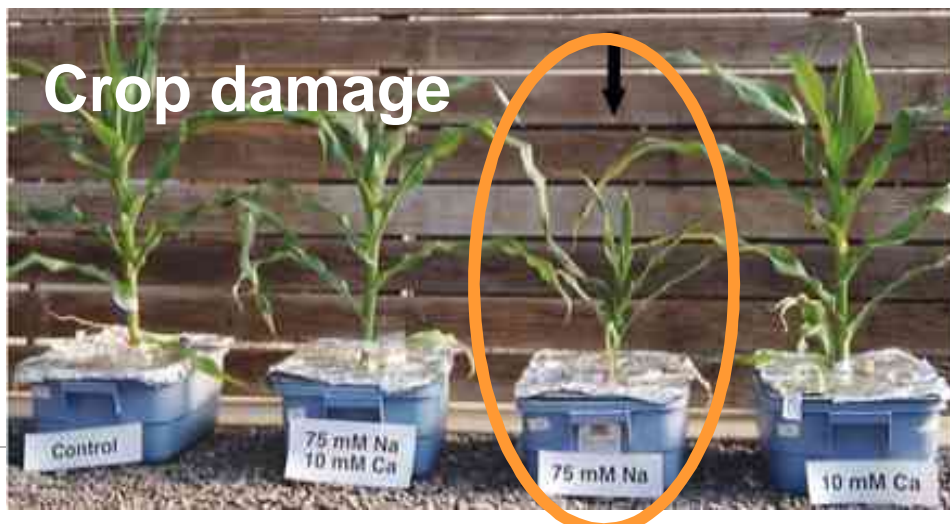
long term health
effect



salty water

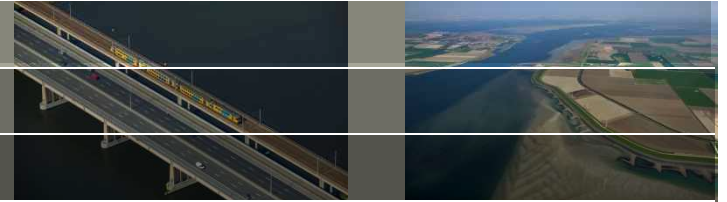
freshwater

Crop damage



Vulnerable nature

Zout in water is een probleem



-drinkwater:

- smaak (100-300 mg Cl-/l)
- lange termijn effect op gezondheid
- normering: EC & WHO=150 mg Cl-/l (vee=1500 mg Cl-/l)

-industrie:

- corrosie pijpleidingen
- bereiding voedsel

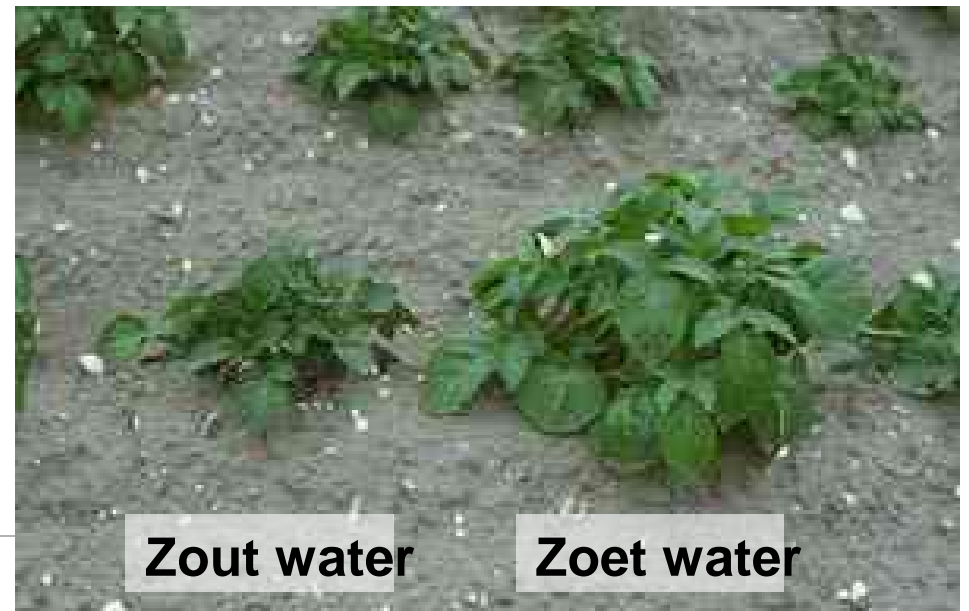
-irrigatie/landbouw:

- gewas productie
- zout schade, bijv. vanaf

Gras ≥ 3606 mg Cl-/l

Granen ≥ 4801 mg Cl-/l

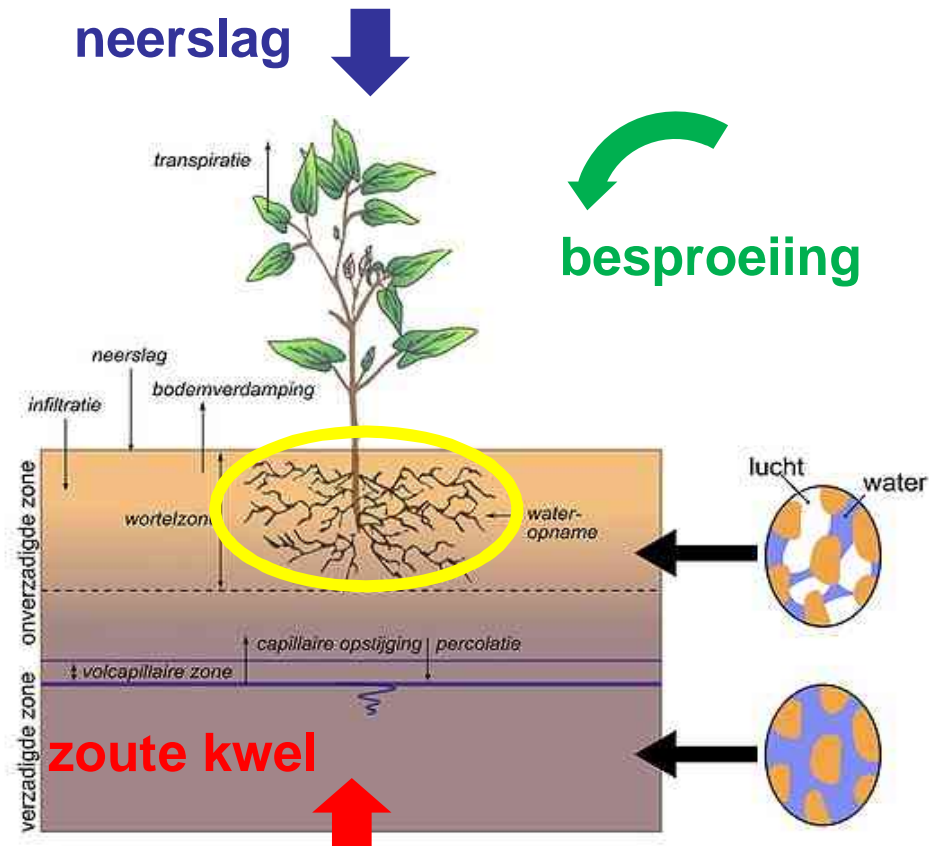
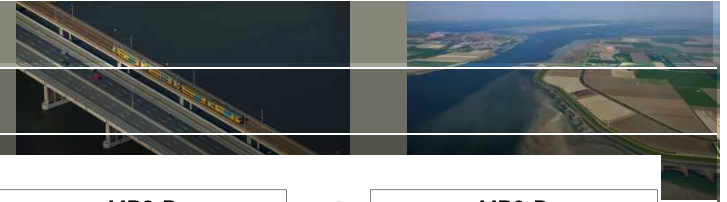
Aardappelen ≥ 756 mg Cl-/l



Zout water

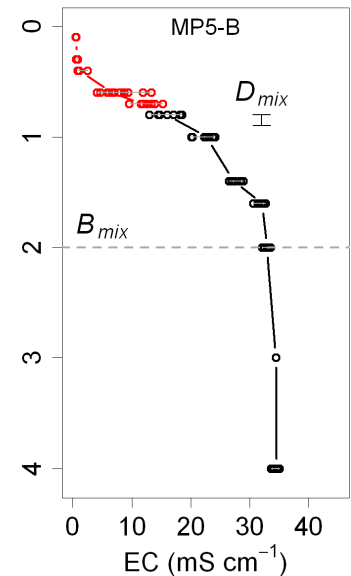
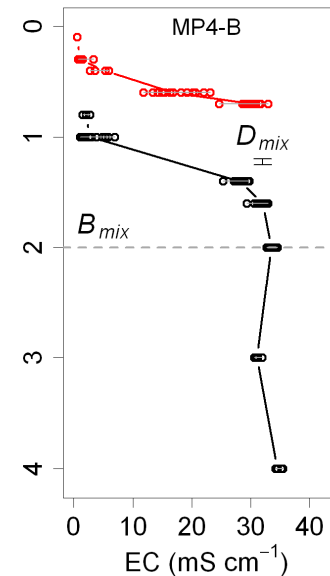
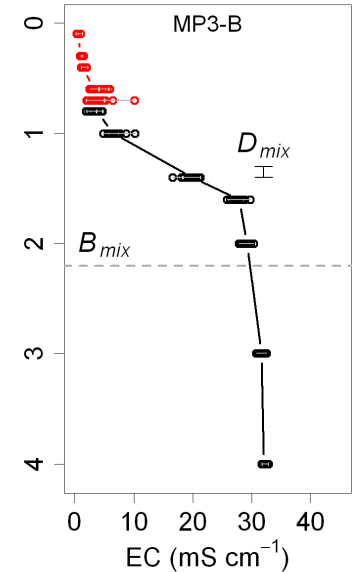
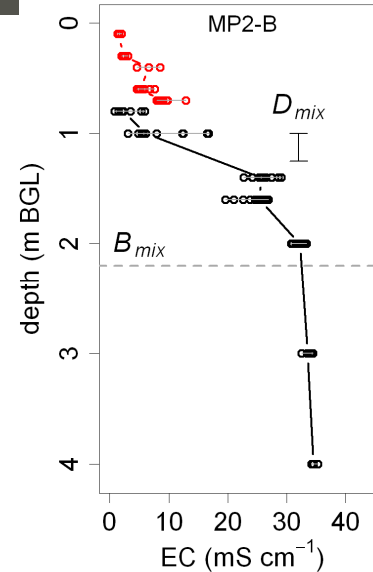
Zoet water

Zouttolerantie gewassen



Belangrijke parameters:
Chloride concentratie bij wortelzone
Landgebruik
Gevoeligheid gewassen

Jan van Scorel 20140121



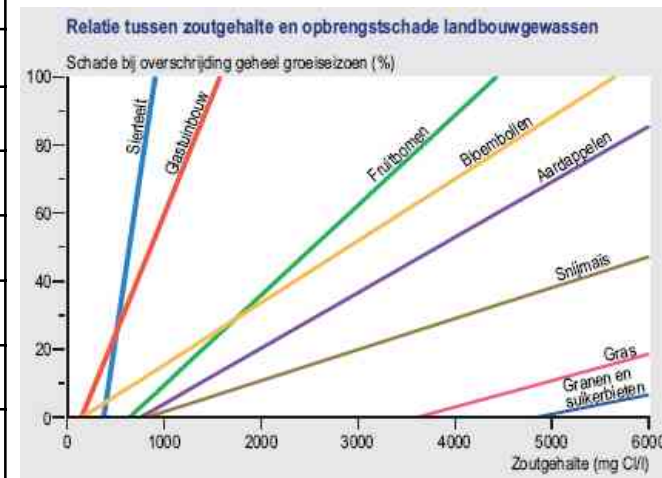
Gevolgen verzilting: zoutschade aan gewassen bij wortelzone

Belangrijke parameters:

- Chloride concentratie bij wortelzone
- Landgebruik
- Gevoeligheid gewassen

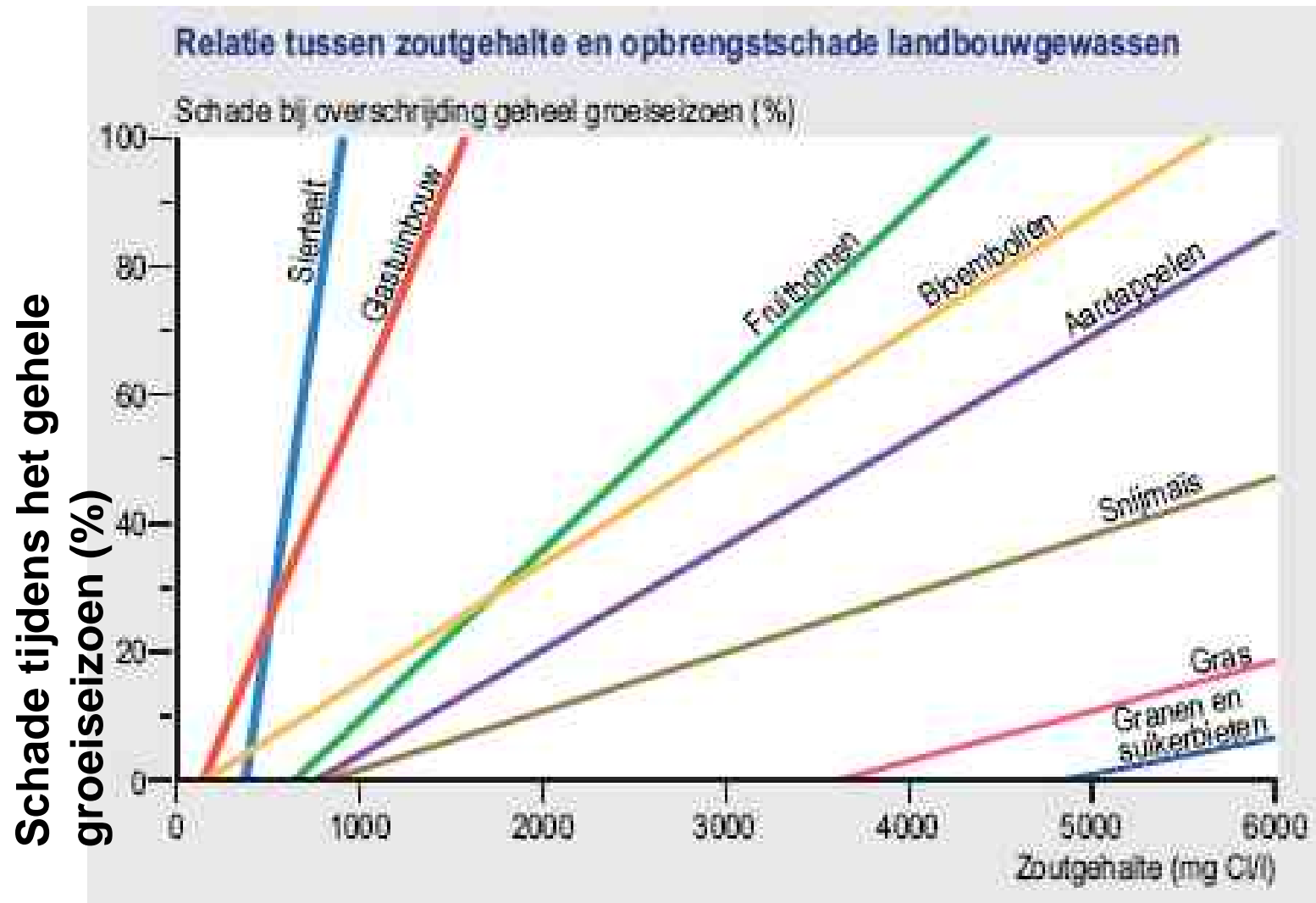
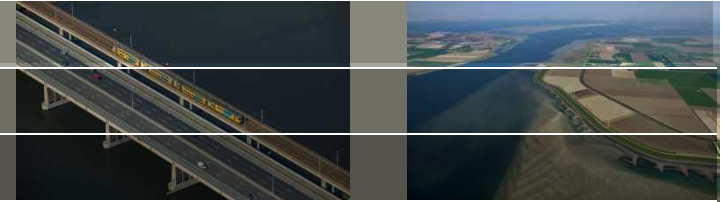
Landgebruik	Drempelwaarde wortelzone (mg Cl-/l)	Helling wortelzone (-)	Gewasopbrengst prijspeil 2050 (Euro/ha)
gras	3606	0.0078	1080
aardappelen	756	0.0163	4240
bieten	4831	0.0057	2640
granen	4831	0.0058	880
glastuinbouw	1337	0.0141	17850
boomgaard	642	0.0264	11900
bollen	153	0.0182	26000

Bron: Roest et al., 2003 en Haskoning



Bron: MNP, 2005

Zoutschade gewassen



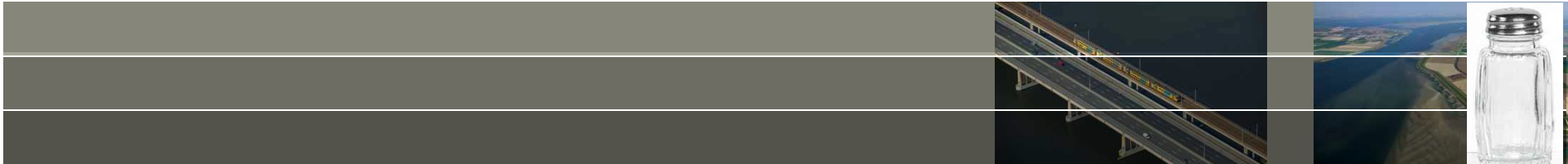
Definition of fresh and saline groundwater

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	



In 1 liter ocean: about 35 gr salt





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



Deltares



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

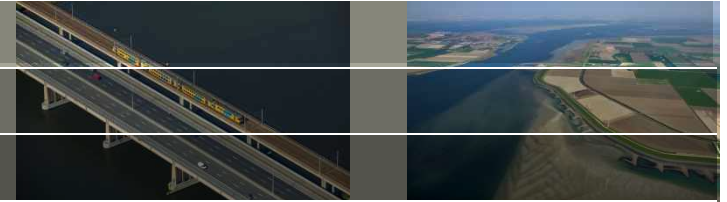




Rice can grow well in water with a salt content less than about 2.0 gr salt in 1 liter water



Sea level rise: +2 m



Nederland



Myanmar, Ayeyarwady



<http://flood.firetree.net>

Nile delta, Egypt



To get an idea about the effect on deltaic areas worldwide, just check the Dutch situation

Mississippi, USA



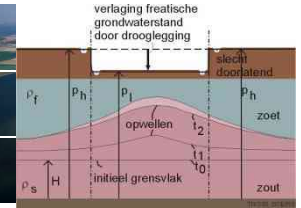
Bangladesh



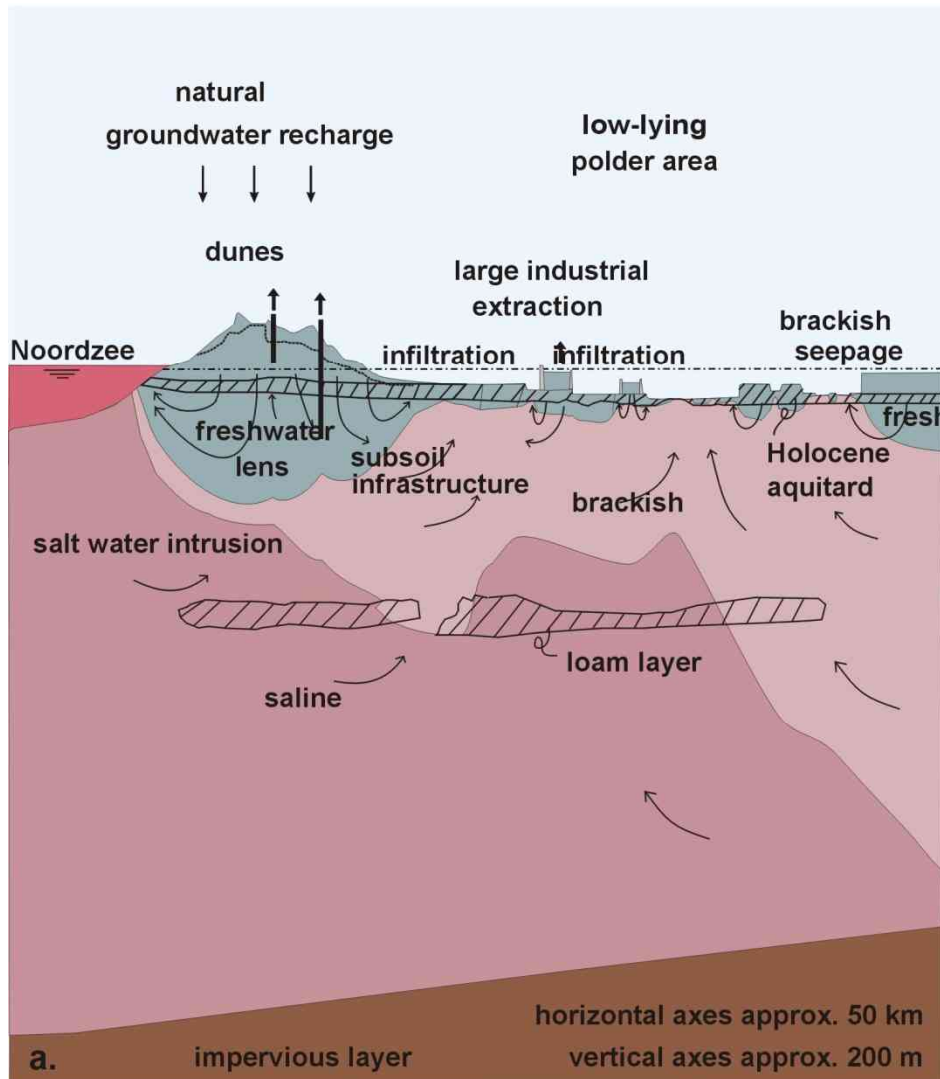
Mekong delta



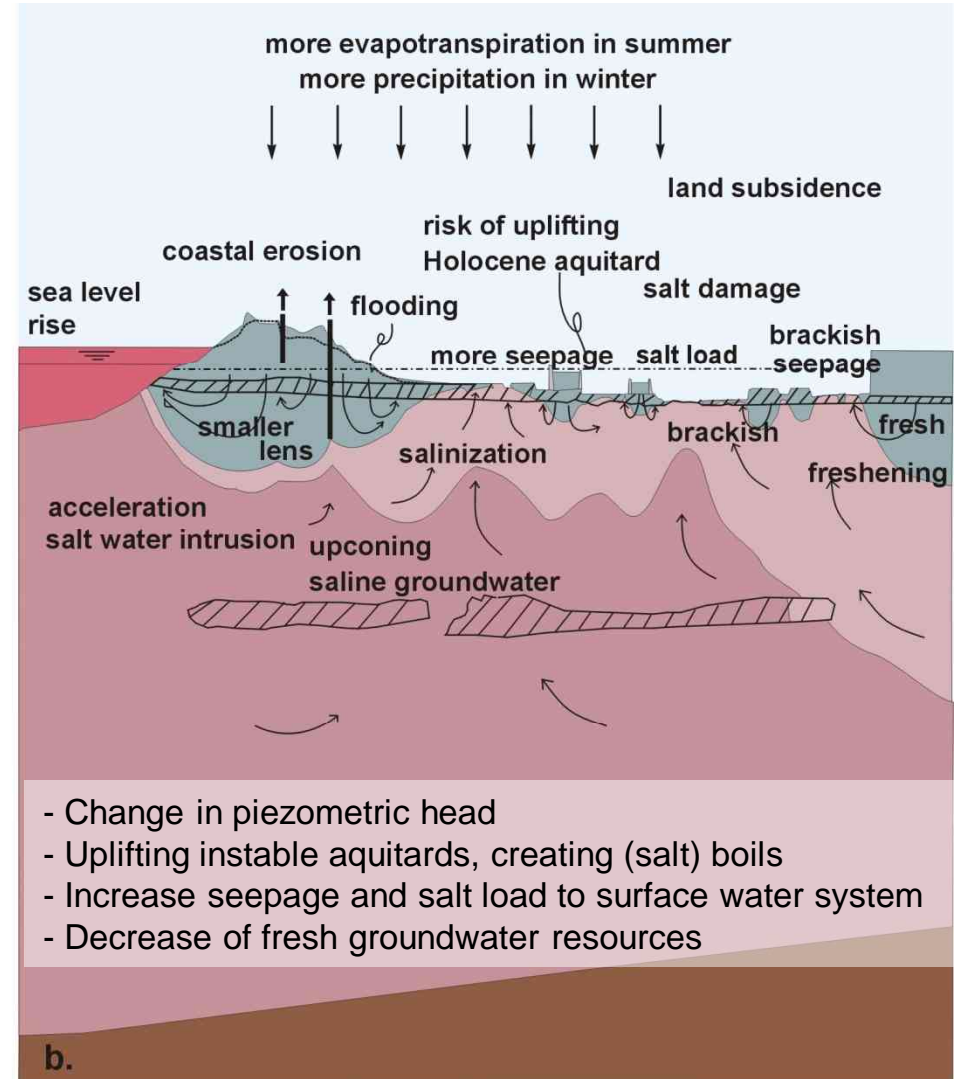
The (Dutch) groundwater system under stress



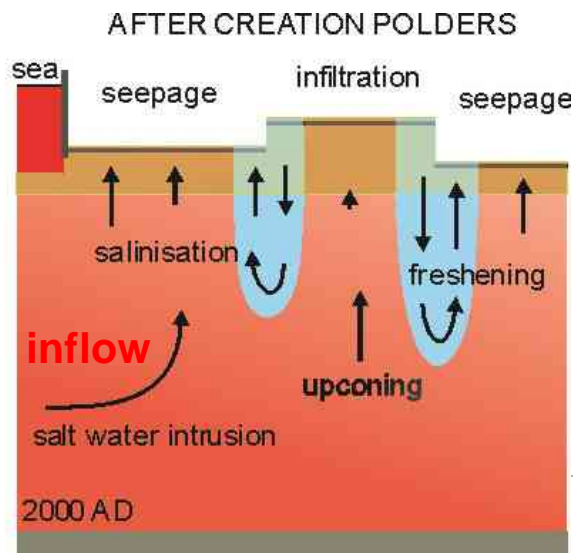
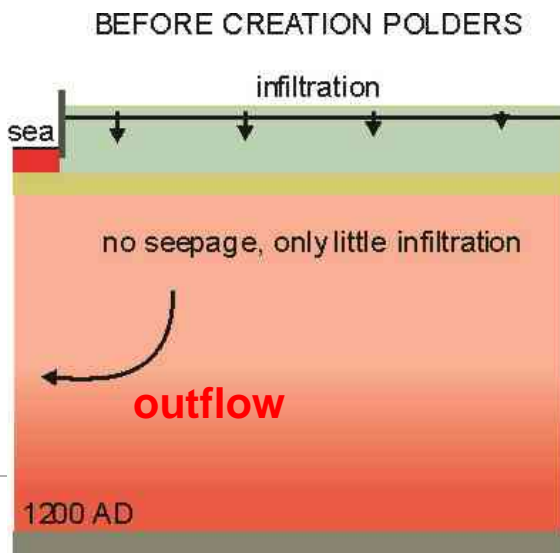
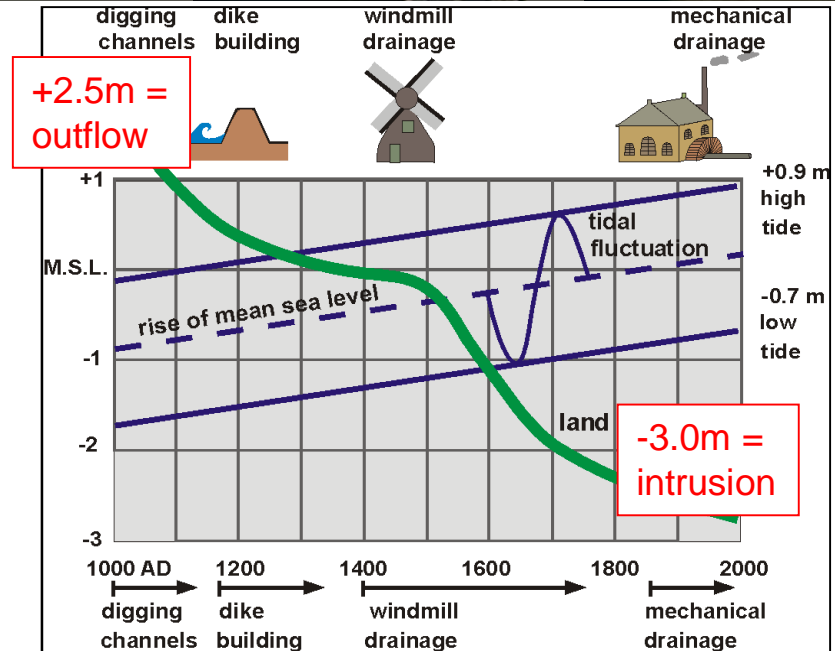
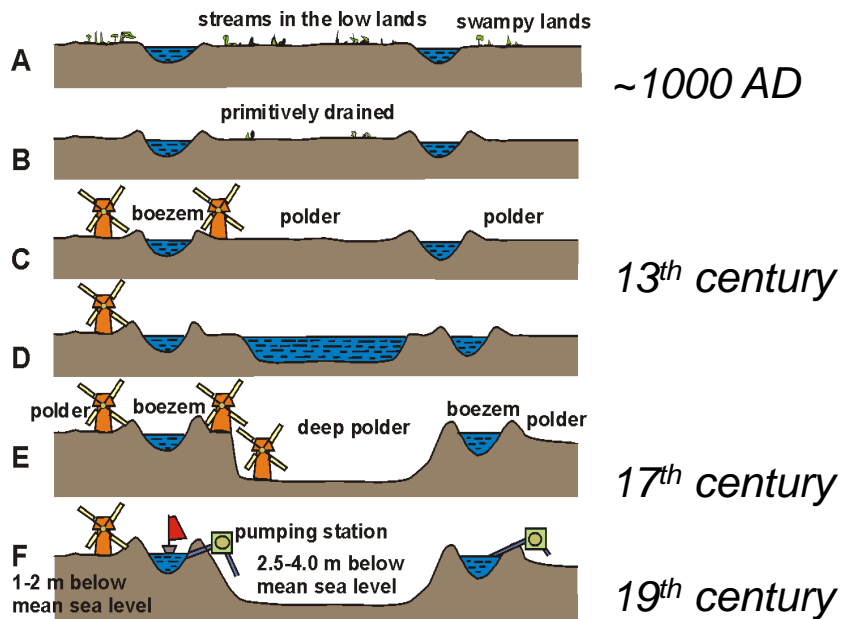
Present processes



Future changes



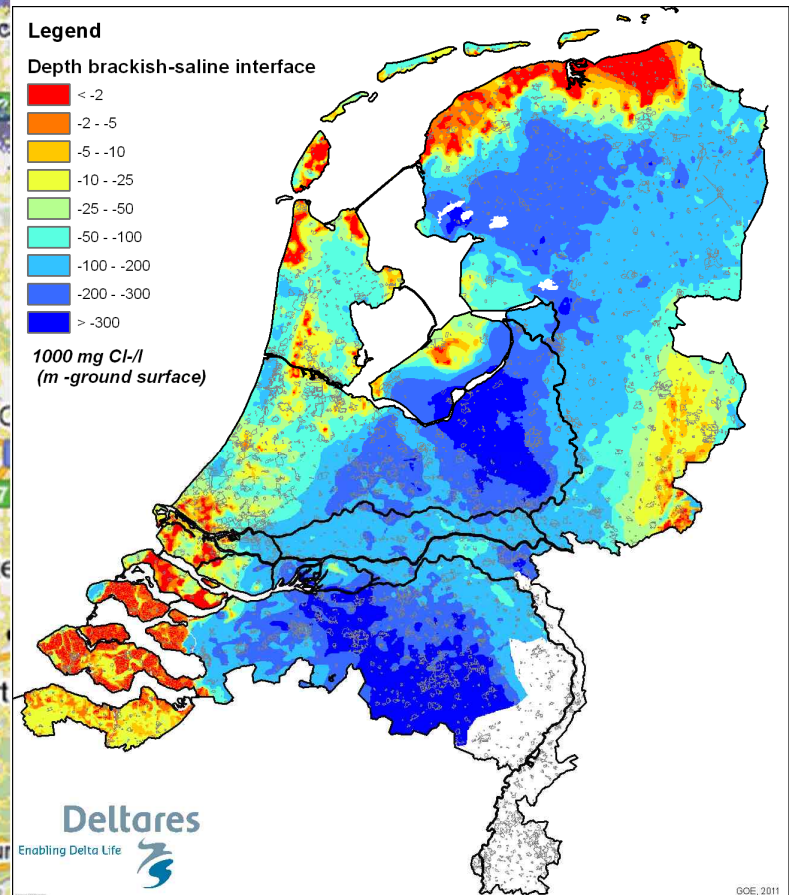
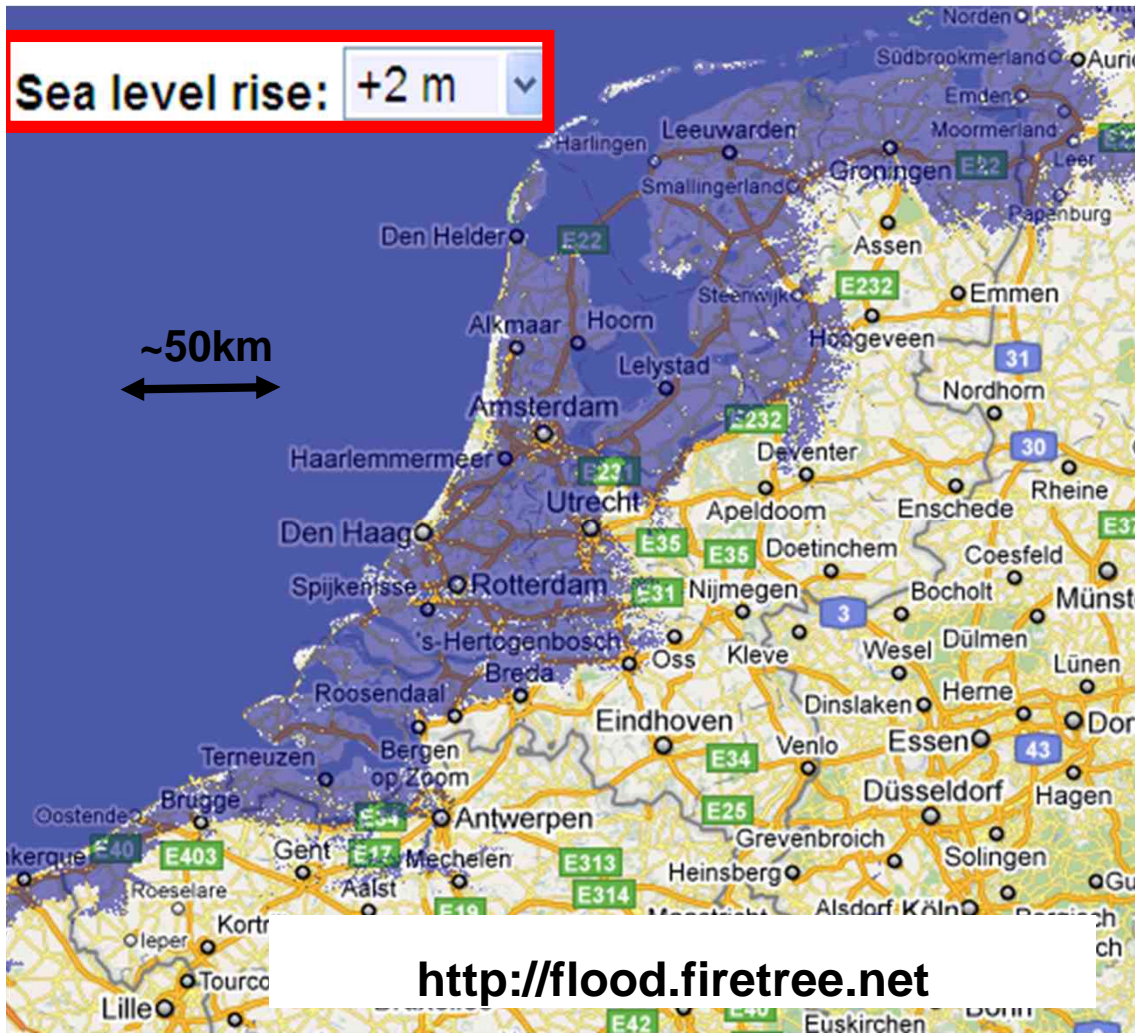
From fresh water outflow to salt water inflow



Ground surface

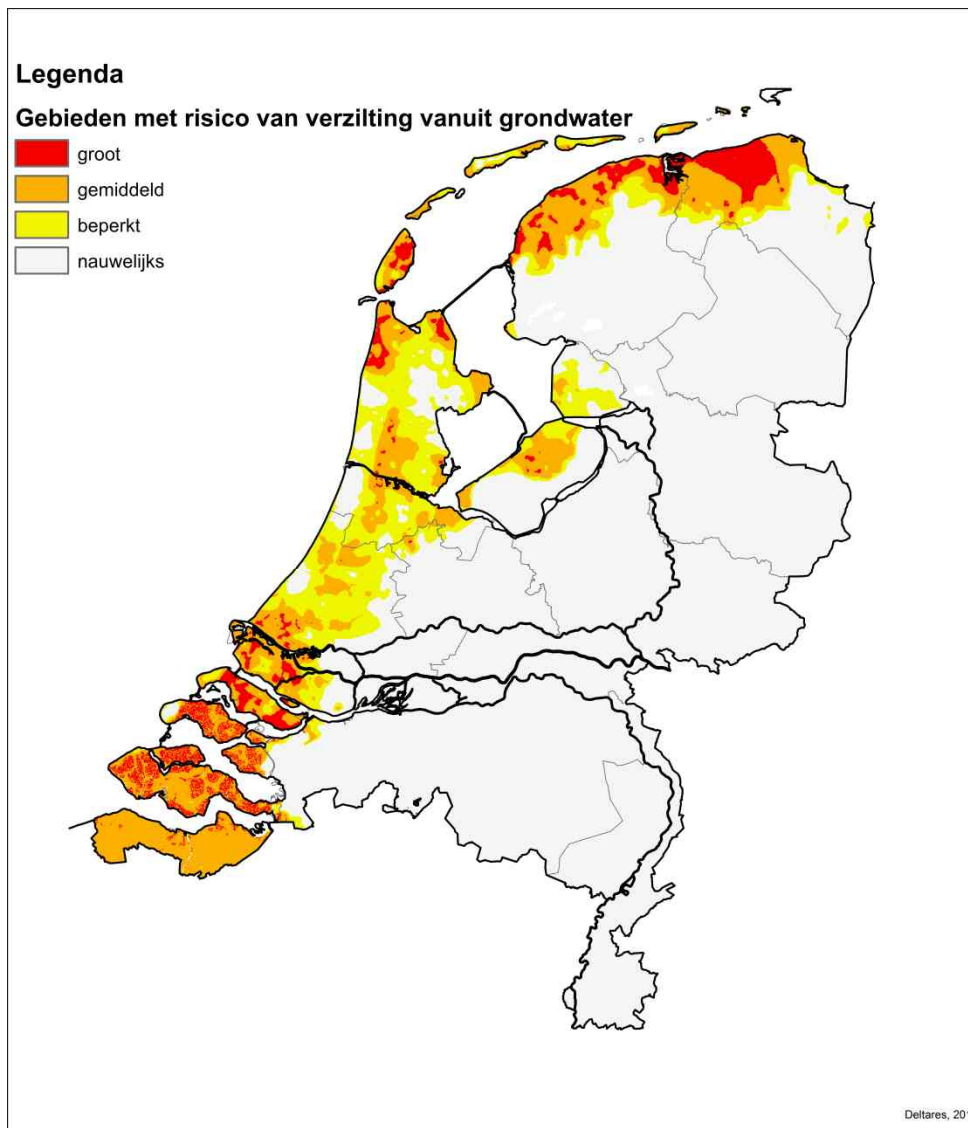
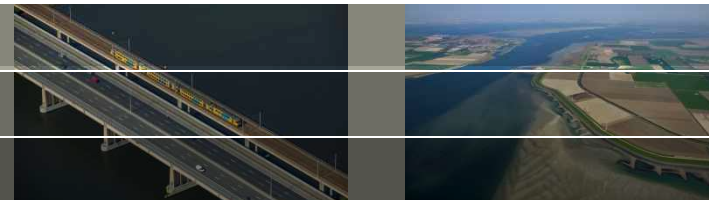
Historical subsidence of the ground surface in Holland

The Netherlands: low-lying lands and saline groundwater

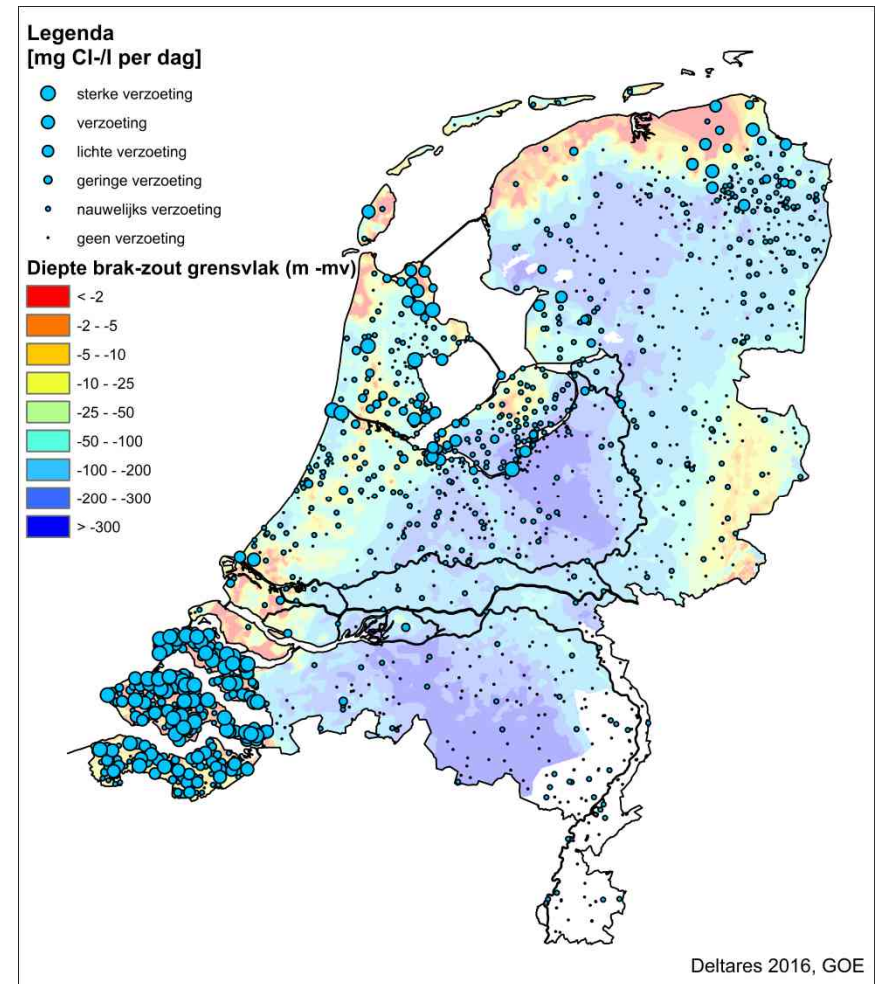
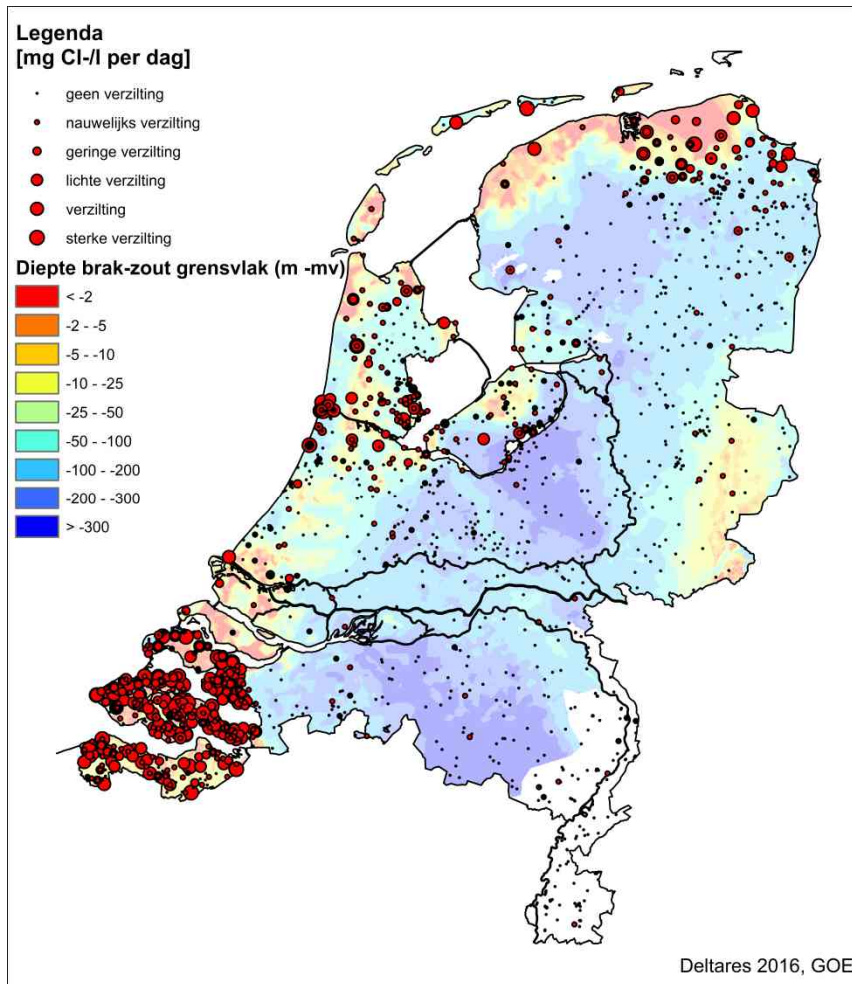


<http://flood.firetree.net>

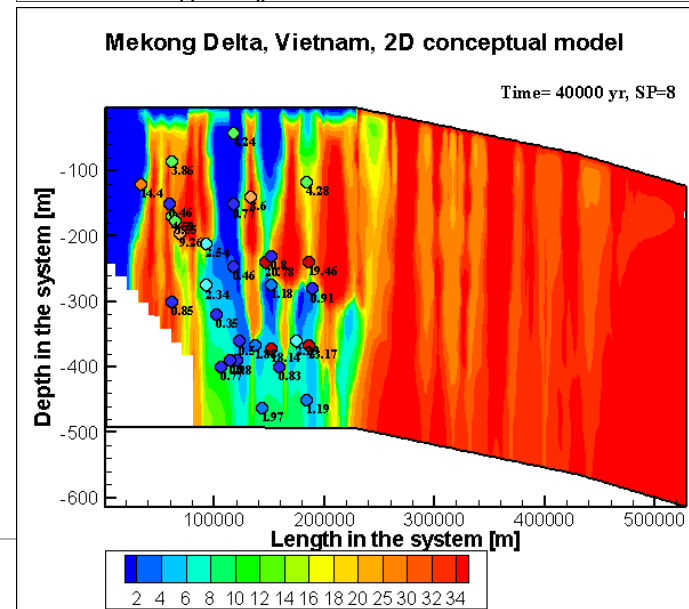
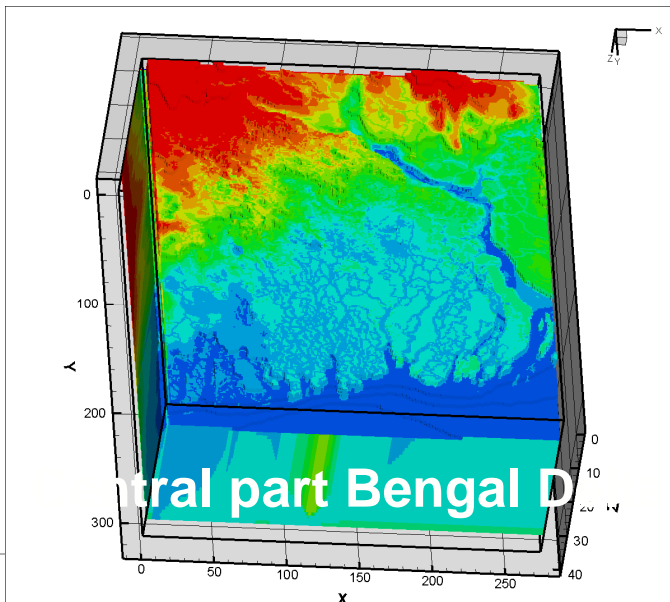
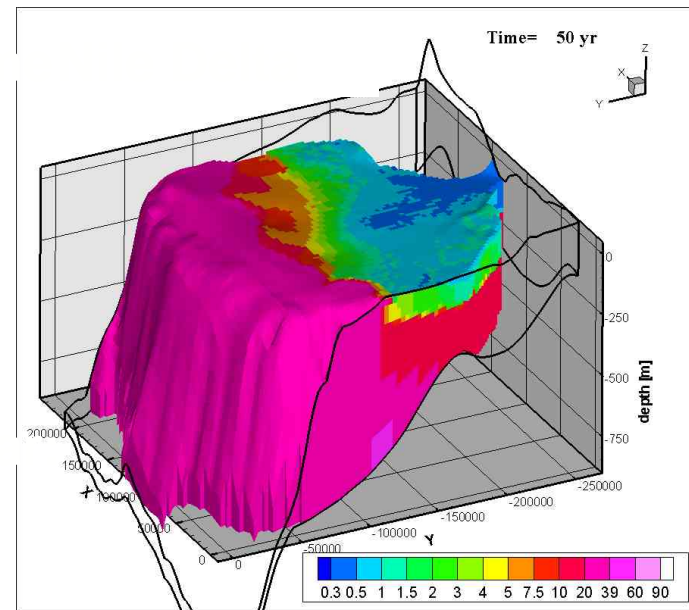
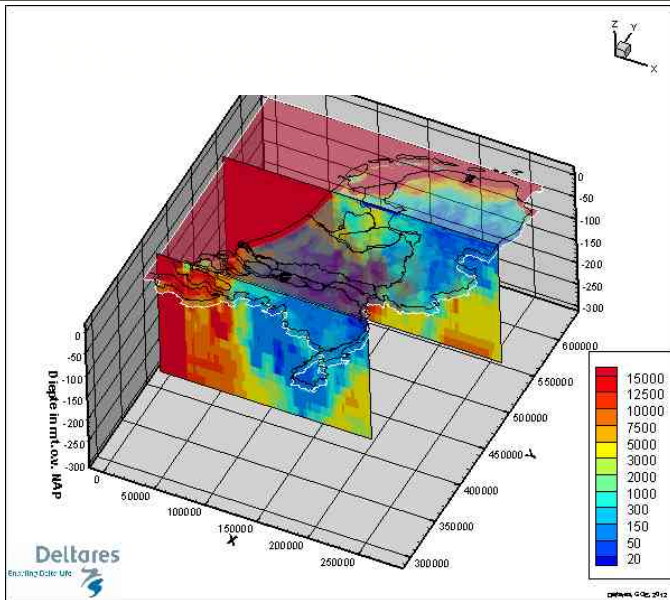
Risicogebieden verzilting



Verziltig/verzoeting grondwater: metingen

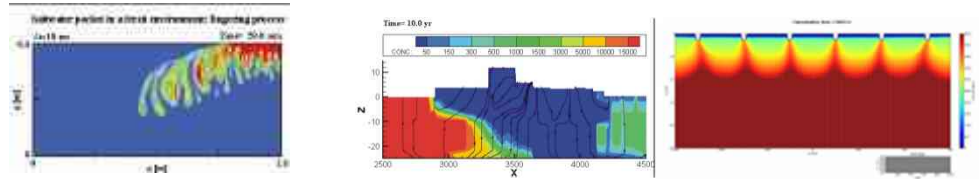


Numerical models groundwater coastal zone

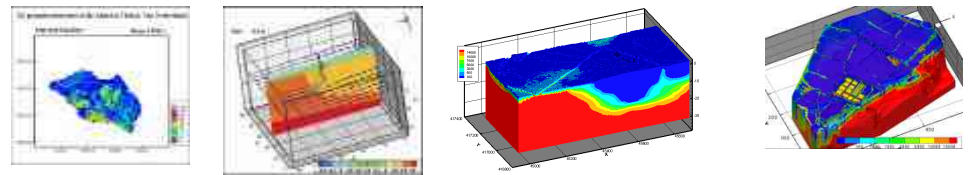


Different model cell sizes to consider several phenomena

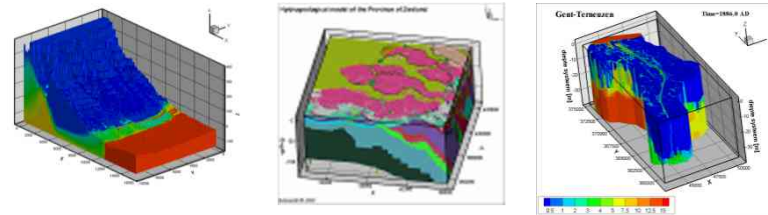
Sub-local: fingering, salty sand boils
Sri Lanka (Tsunami 2004), Zandmotor
cell size=1cm-1m



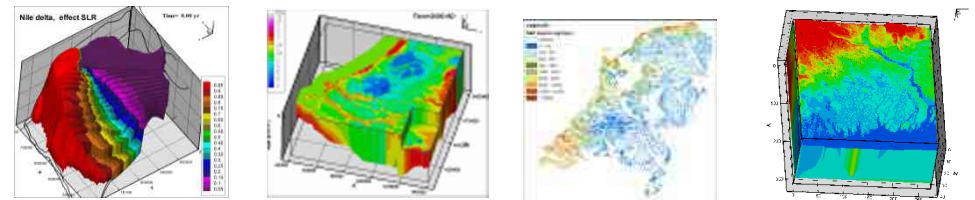
Local: rainwater lenses, heat-cold
Tholen, Schouwen-Duiveland
cell size=5-25m



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



National: fresh groundwater resources
Nile Delta, BD, Zuid-Holland
cell size=250m-3km



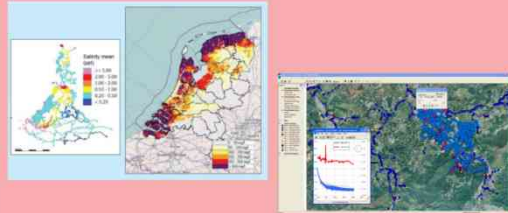
Goal:
To take largest cell size possible to accurately
model relevant salinisation processes

Modelling tools: iMOD Open Source

Flexible Mesh/SOBEK

major features:

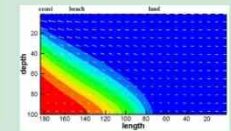
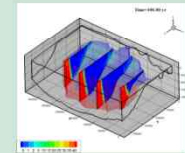
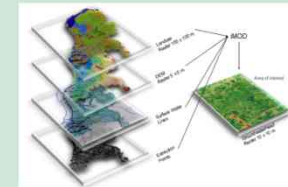
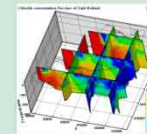
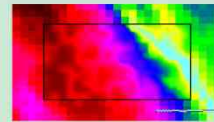
- salt water intrusion & surface water quality
- 1D network or 2D horizontal grid
- powerful hydrodynamic simulation engine
- complex flows & water related processes
- dispersion coefficient calibrated with field data & model results from DELFT3D
- also flood forecasting



iMOD-SEAWAT

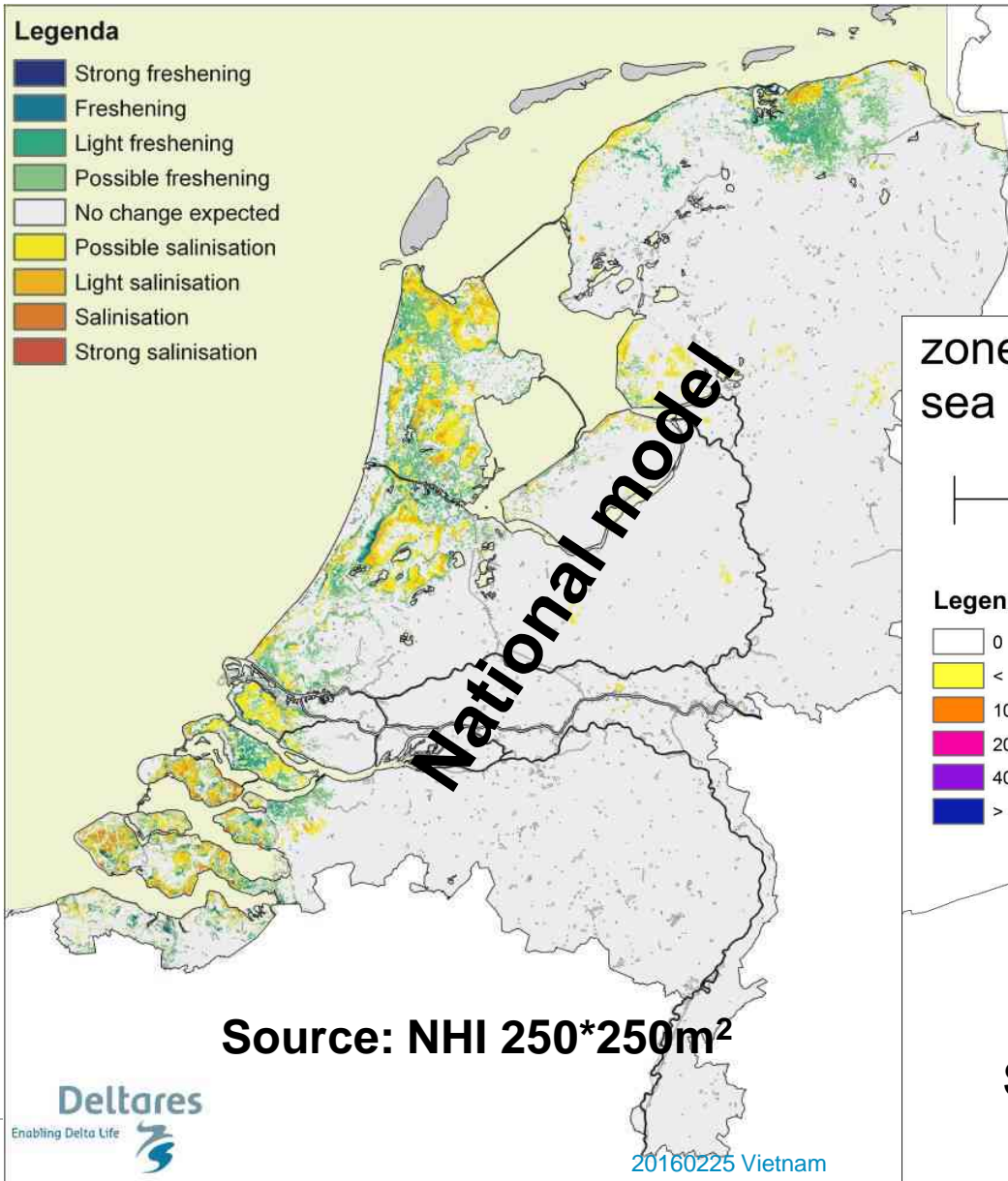
major features:

- SEAWAT in iMOD setting
- cores are **MODFLOW** and **MT3D**
- 3D variable-density
- salt water intrusion and heat transport
- easy to use graphical user interface
- interactive geologic schematisation
- supports participative processes
- compatible with other models & codes
- handles large data volumes
- creates and runs scenario's

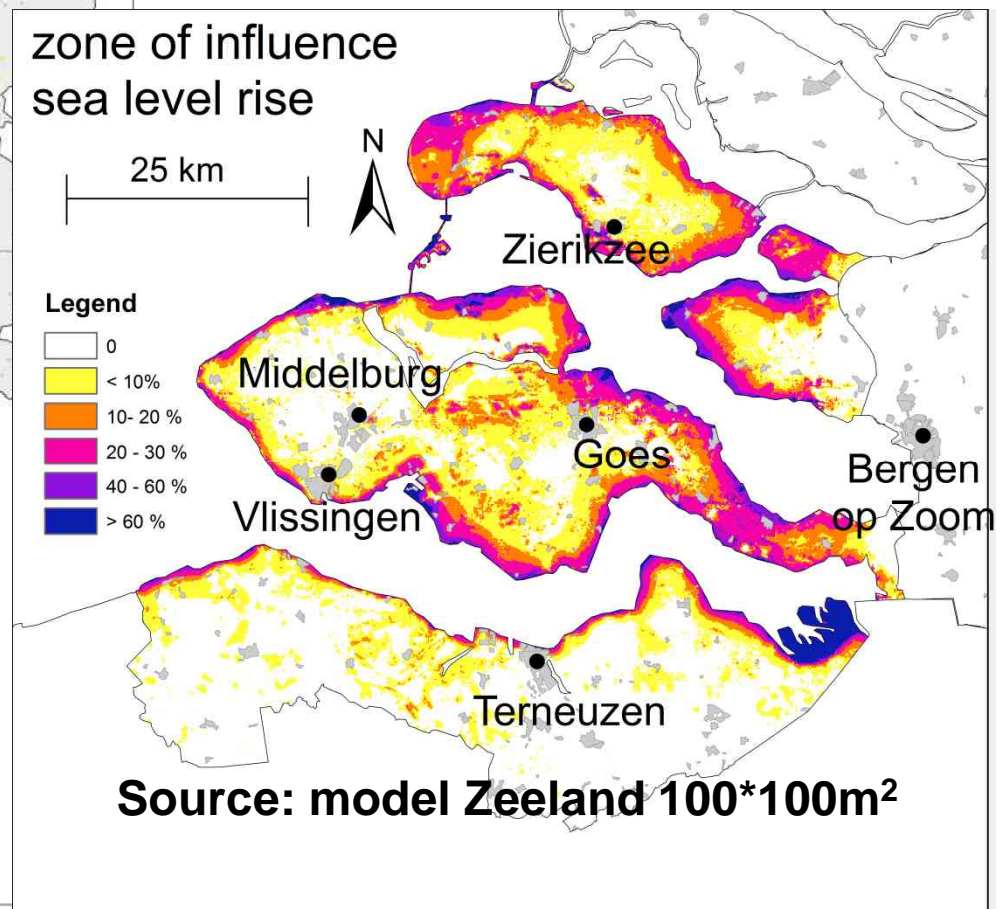


<http://oss.deltares.nl/web/imod>

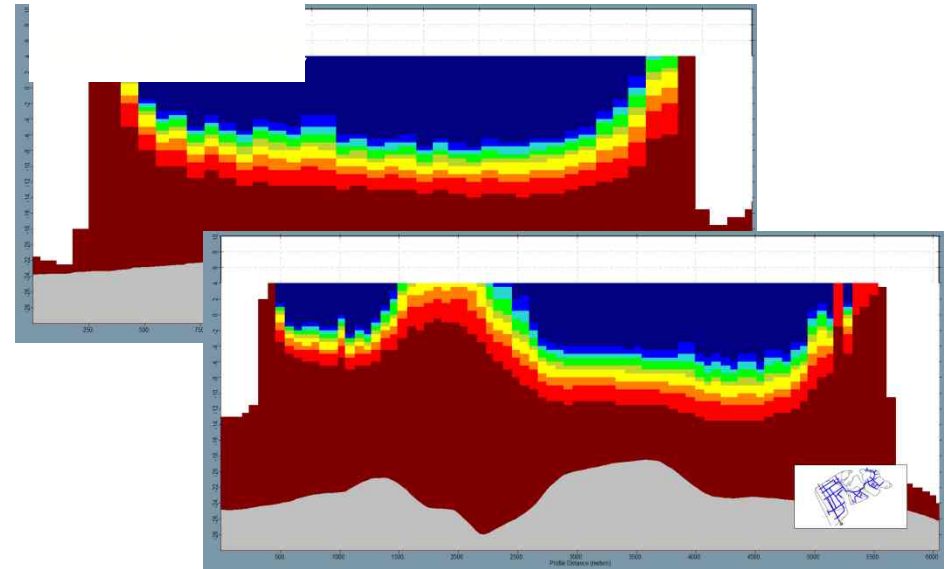
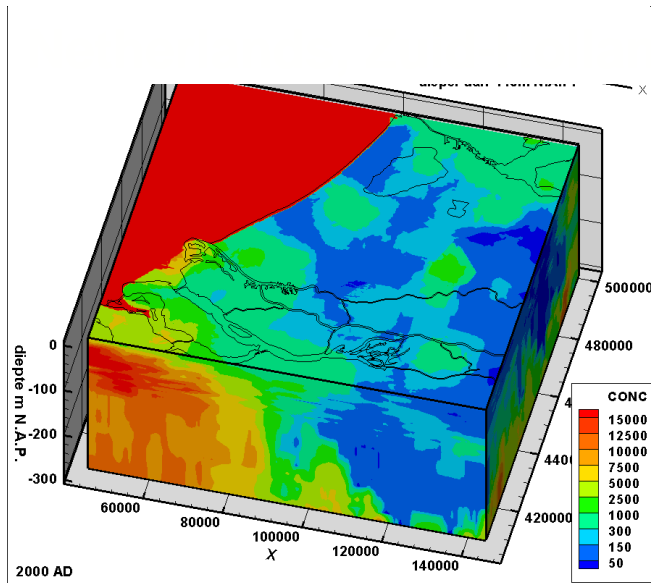
Salinisation & freshening under Climate & Global stress



Regional model



3D Regional coastal groundwater model studies



Modelling:

- variable-density groundwater flow, coupled solute transport

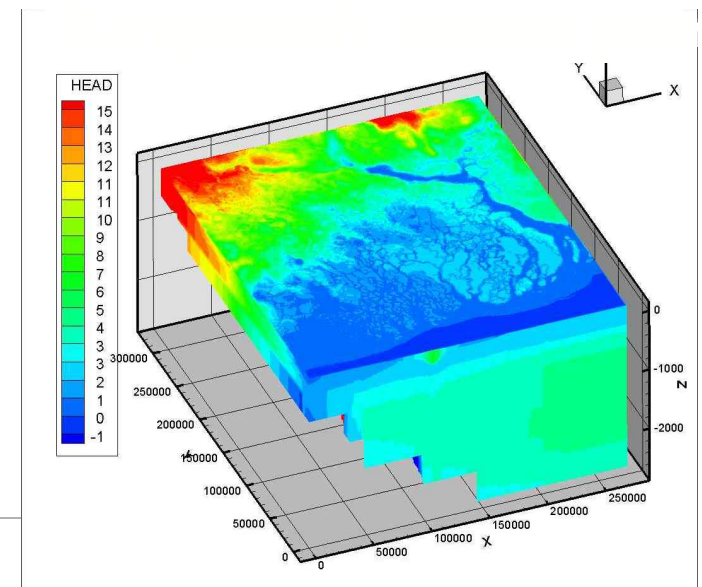
Simulating effects of:

- autonomous processes (change extraction rates)
- sea level rise, changing recharge pattern
- land subsidence

Quantifying:

- hydraulic head
- saline seepage / infiltration
- fresh groundwater resources

20160225 Vietnam



Interaction fresh-saline groundwater-surface water

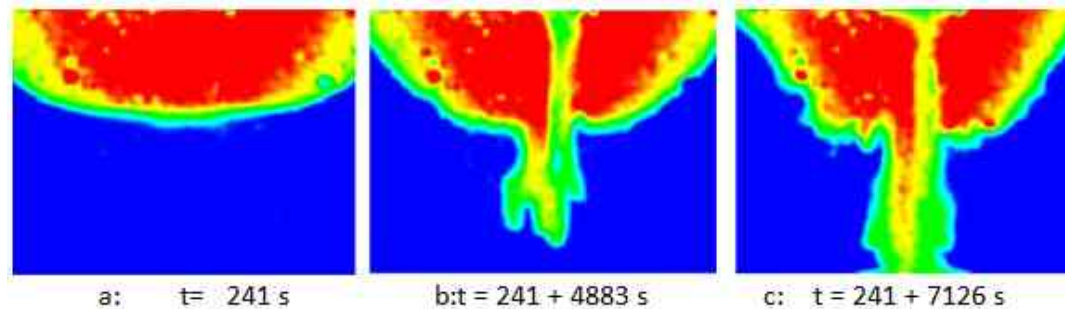
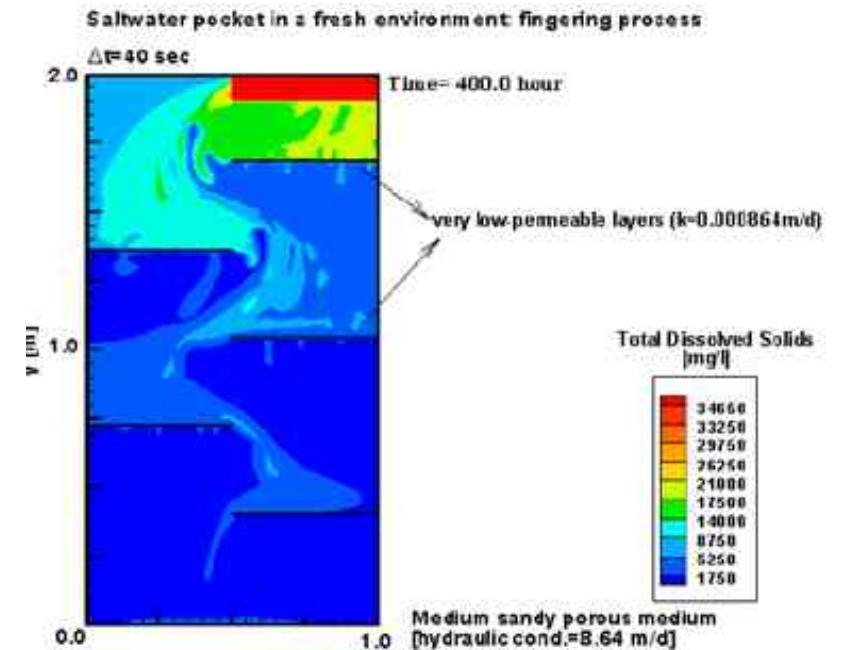
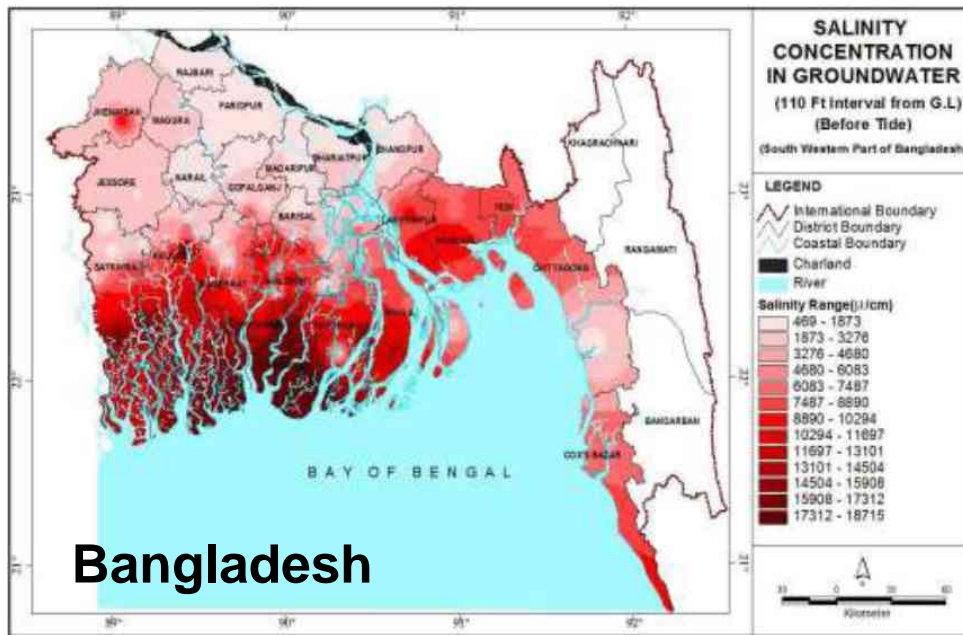
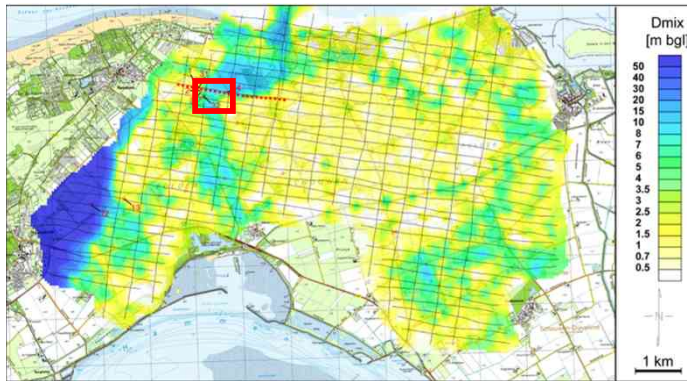


Figure 2.11. Fingering processes in a saturated porous medium (red = salt; blue = fresh).
(Johannsen *et al*, 2006)

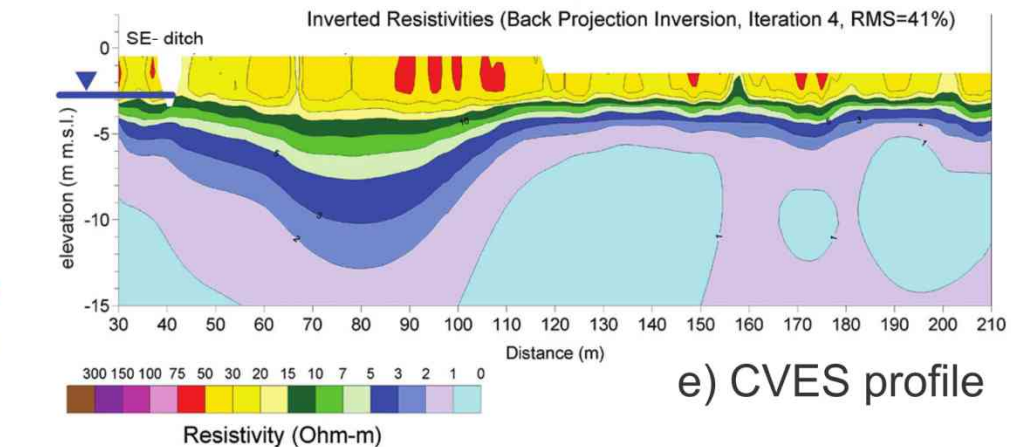
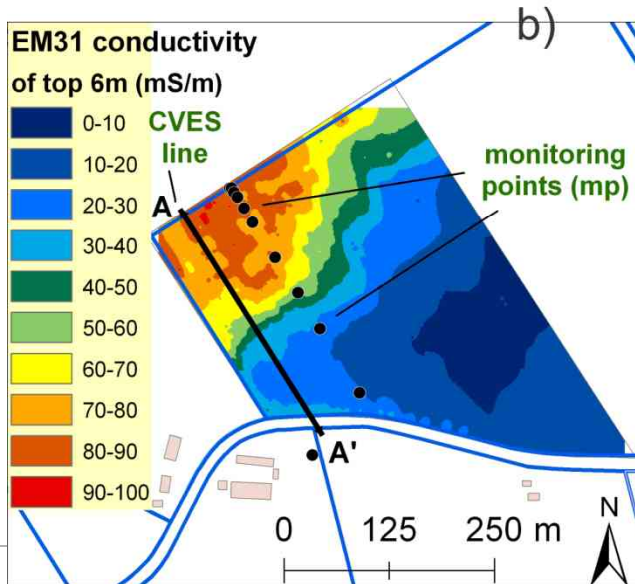
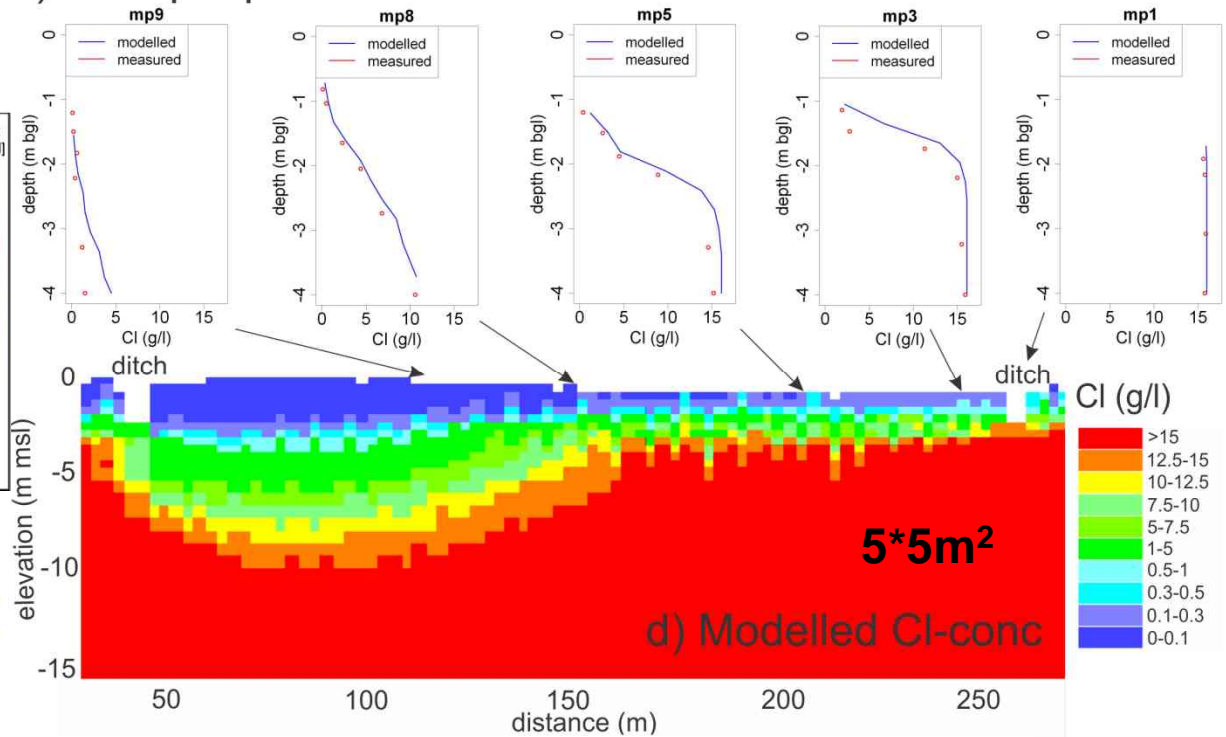
Comparison monitoring data with model results



a) Airborne EM

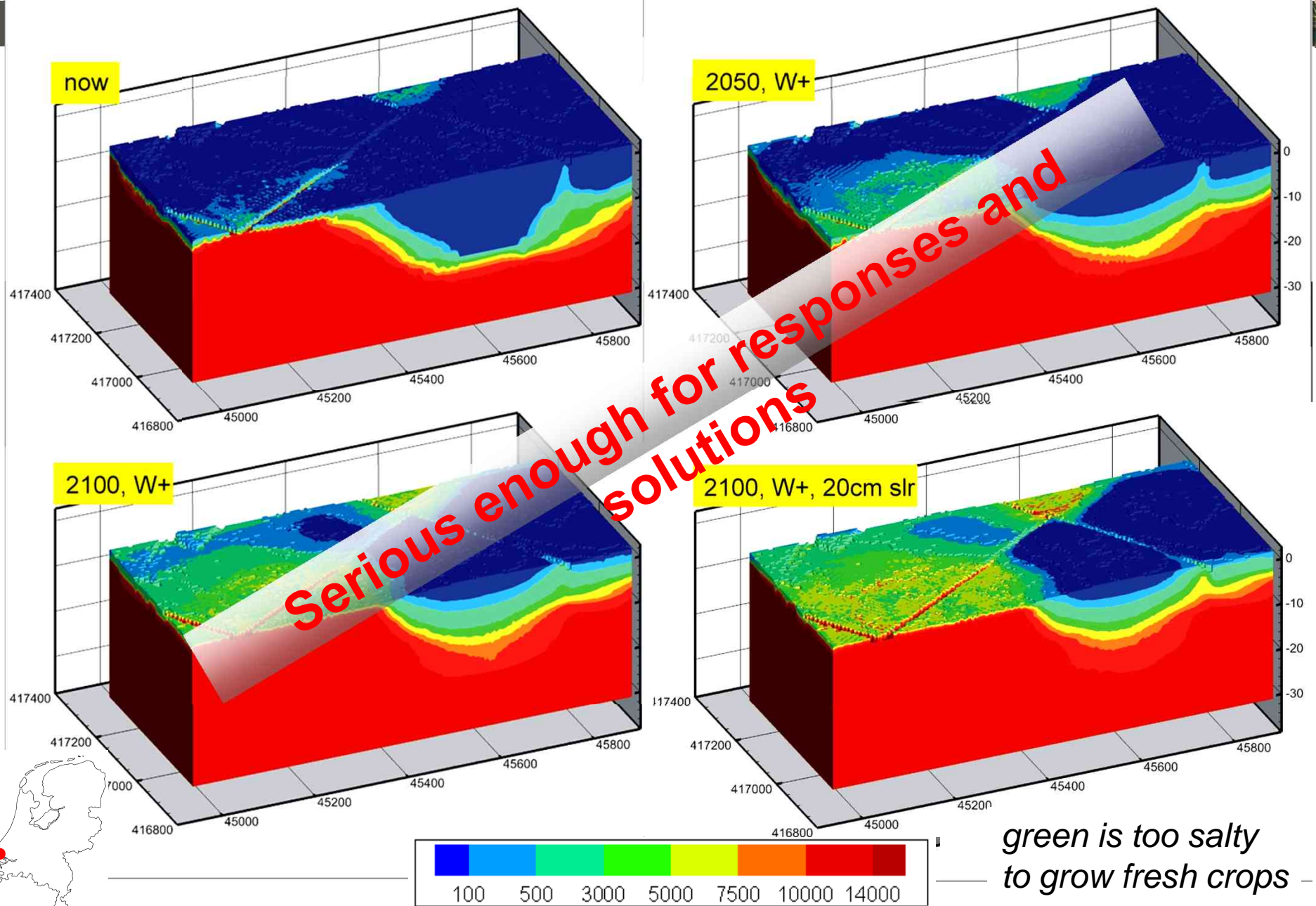


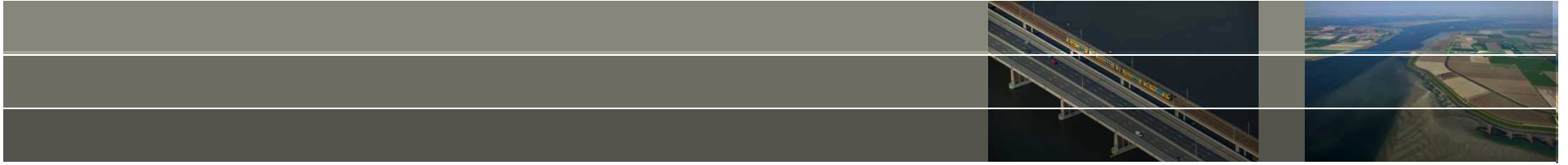
c) CI-depth profiles



e) CVES profile

Modelled Cl-concentration: different CC scenarios



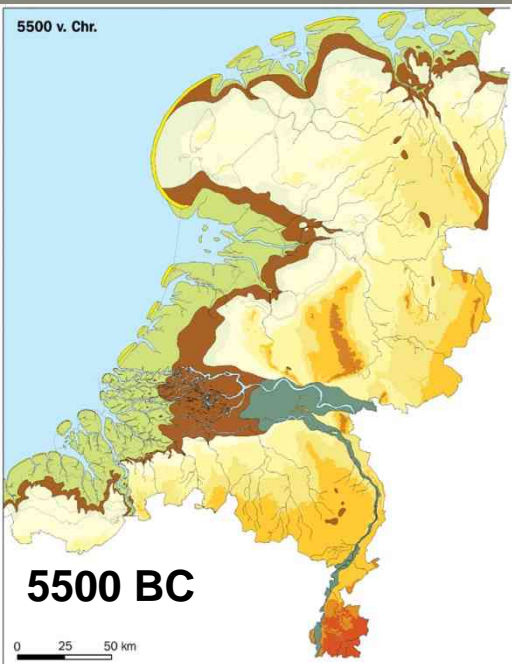


Palaeo-hydrogeographical modelling

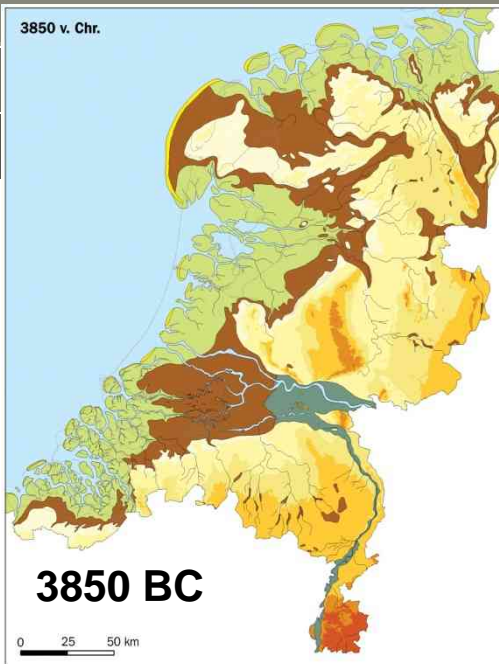


**CAN WE PREDICT THE
PRESENT SALT DISTRIBUTION
IN GROUNDWATER?**

5500 v. Chr.



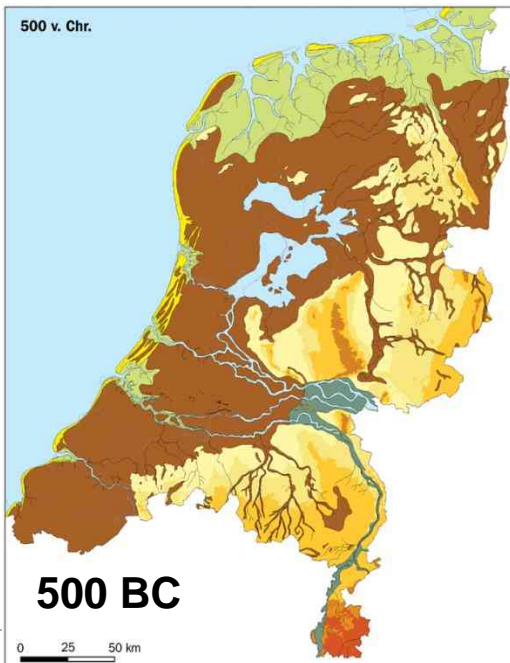
3850 v. Chr.



2750 v. Chr.



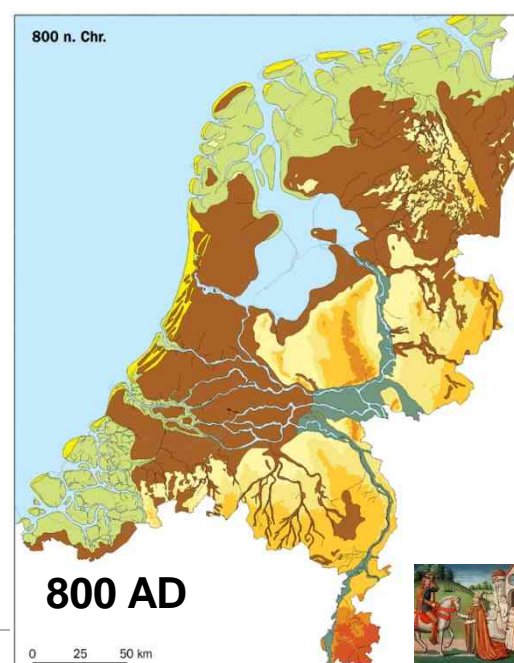
500 v. Chr.



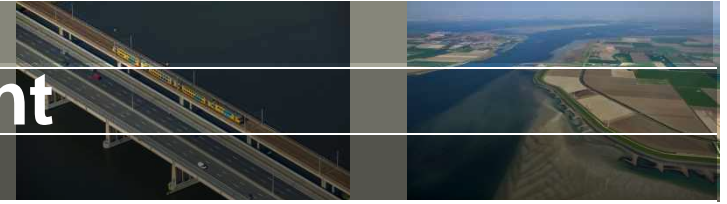
50 n. Chr.



800 n. Chr.



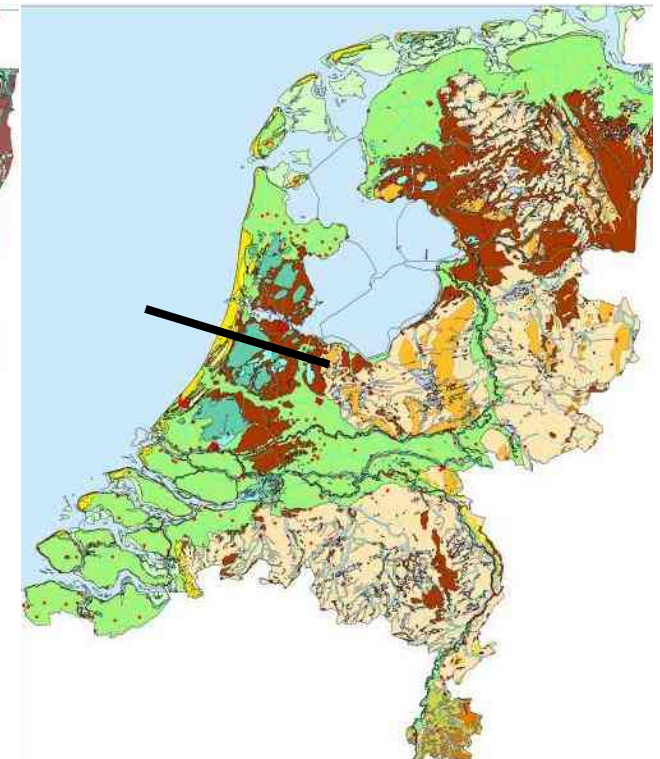
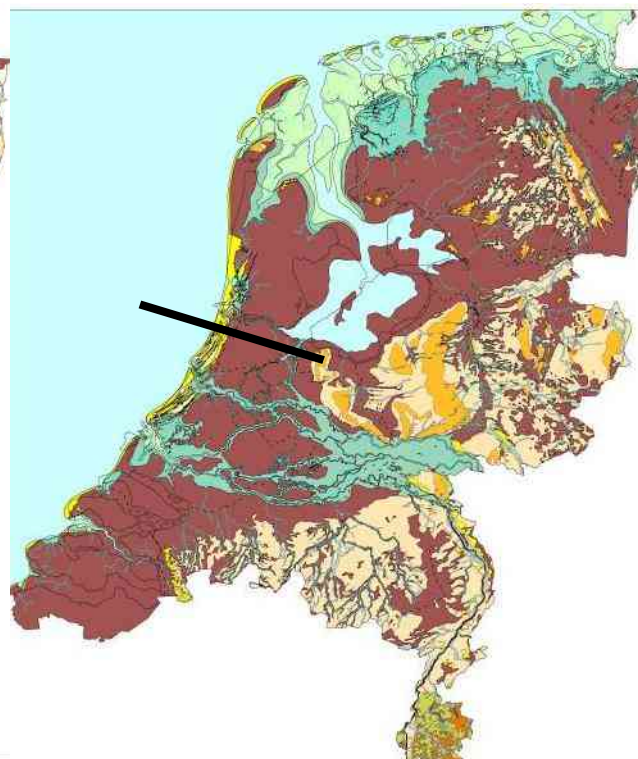
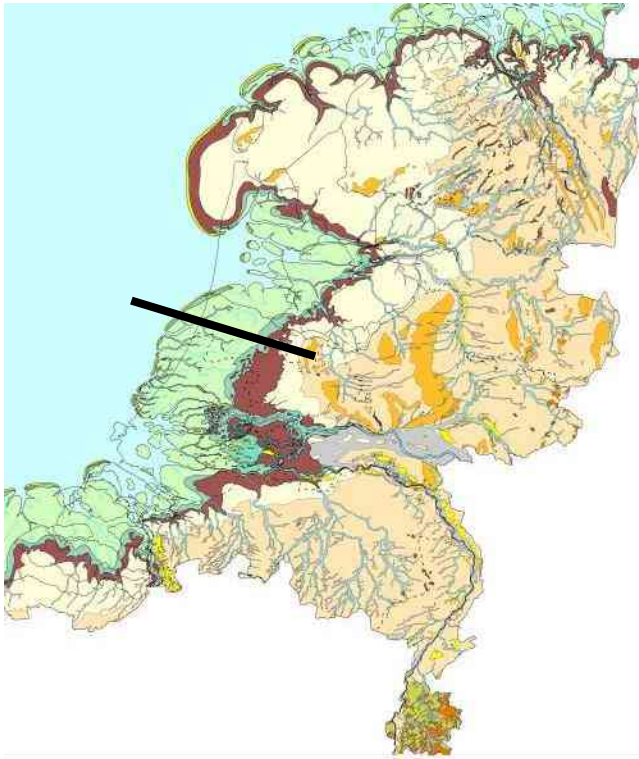
Palaeogeographical development



5500 BC

100 AD

1850 AD



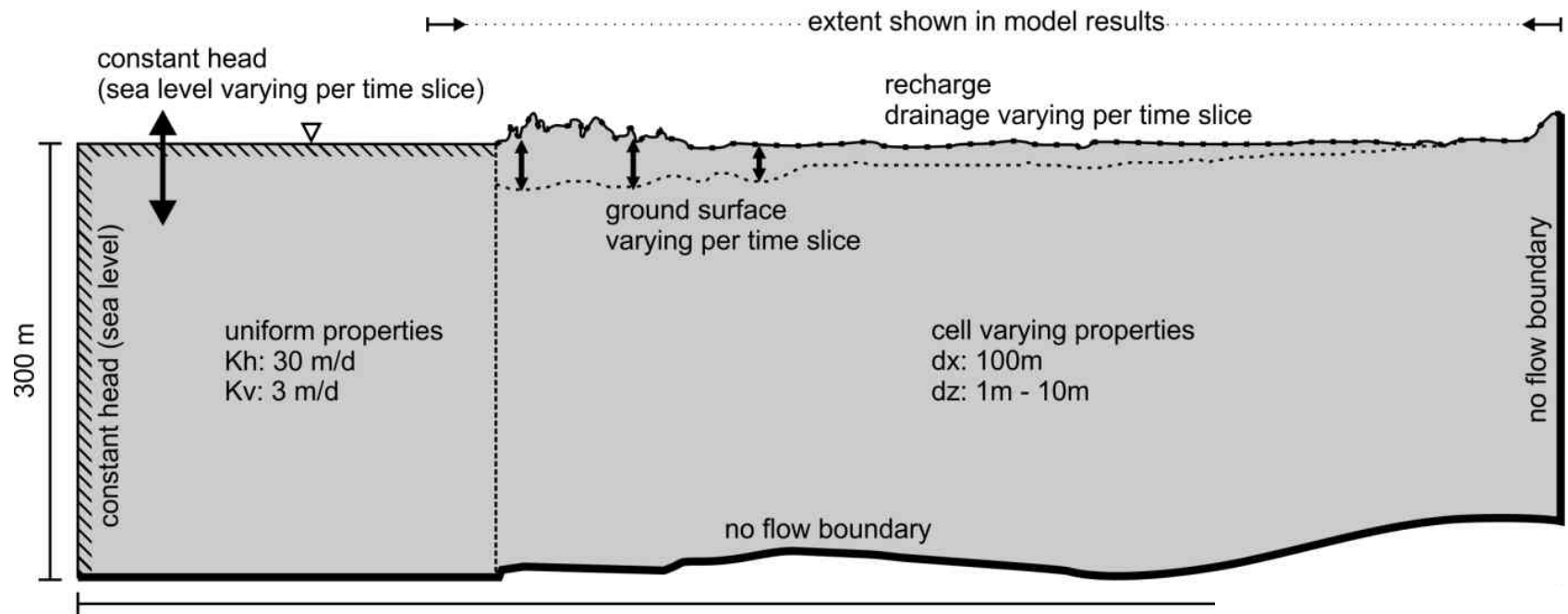
Maximal transgression

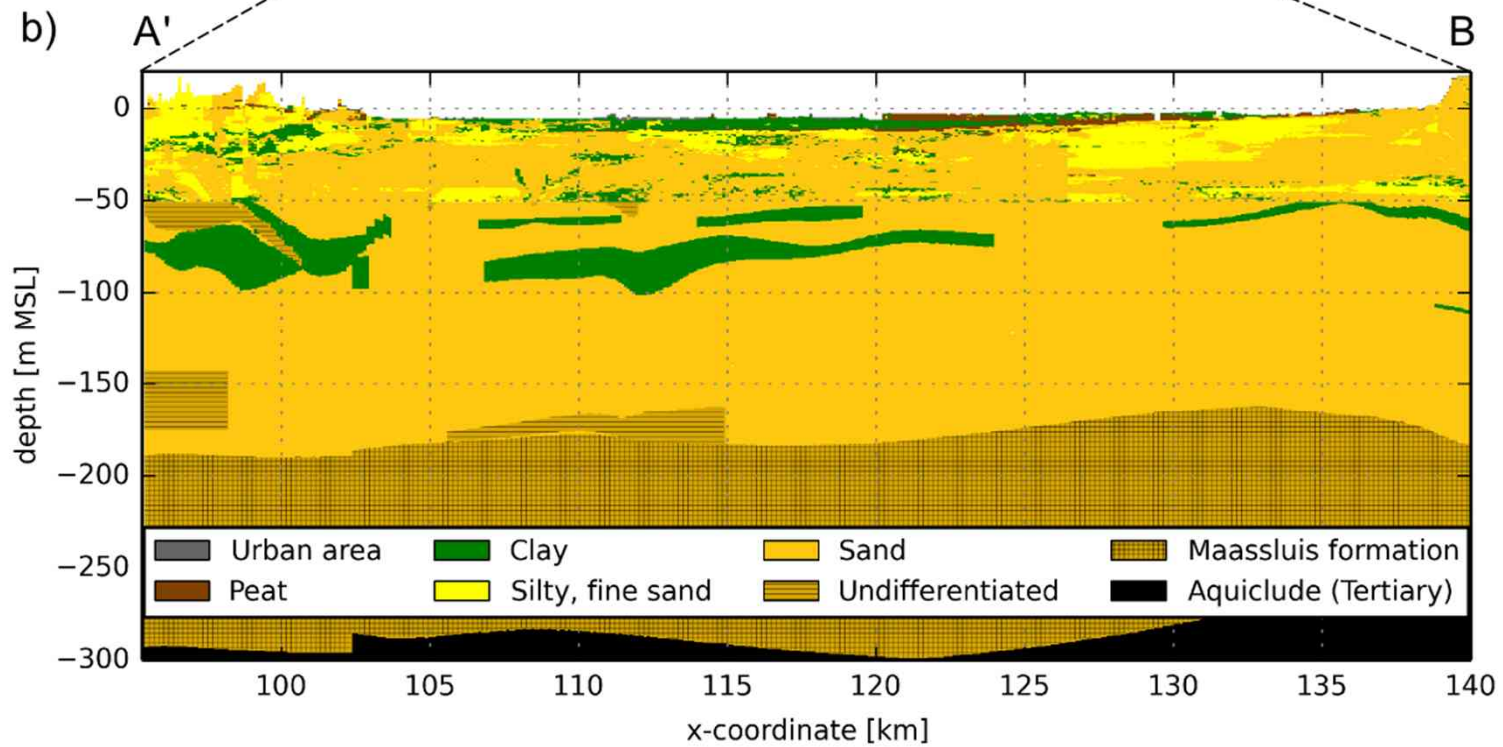
Peat development

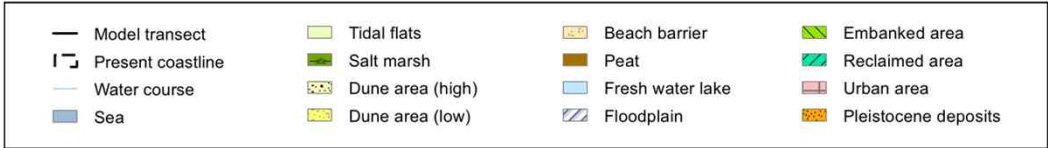
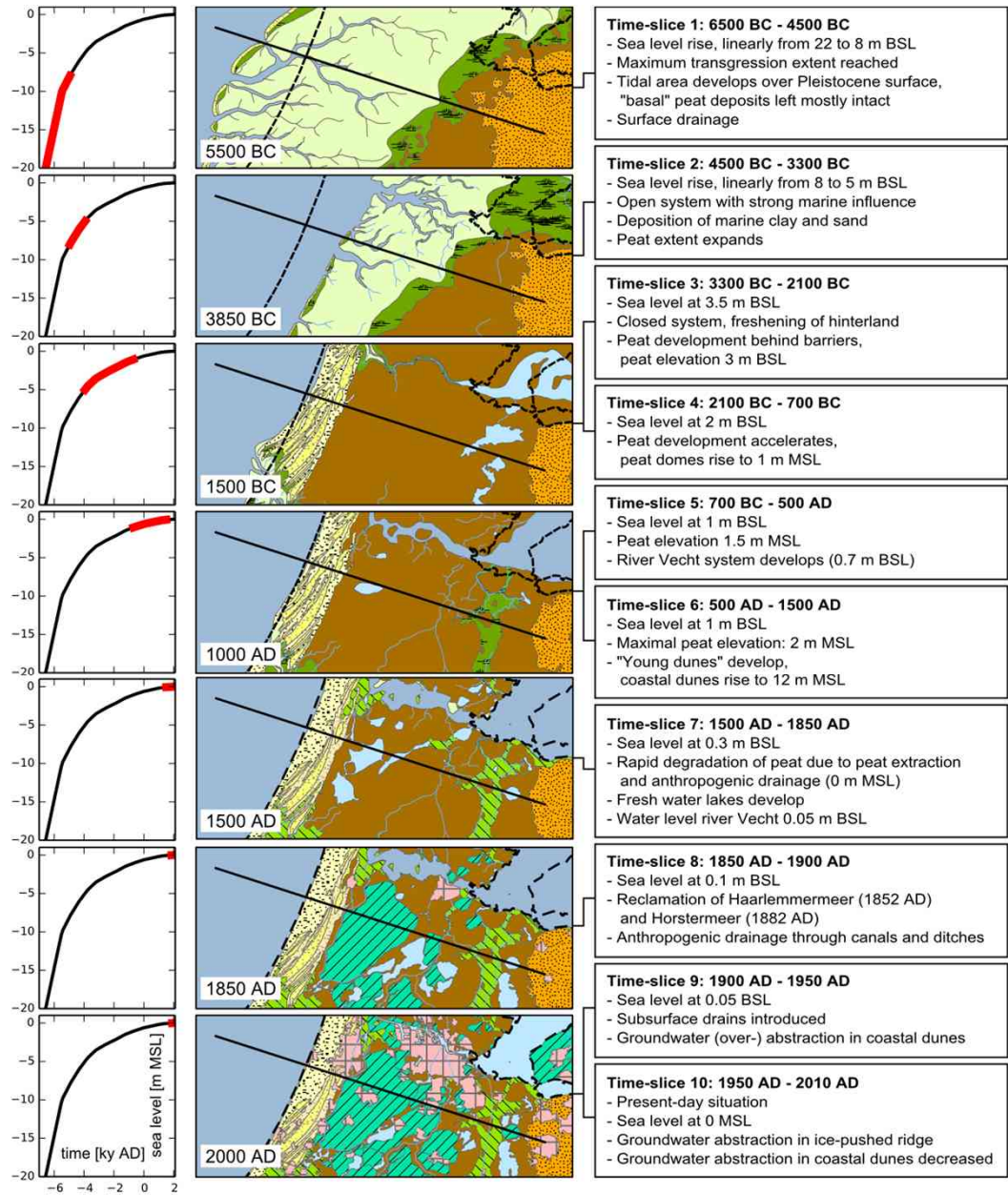
Reclaimed land, polder

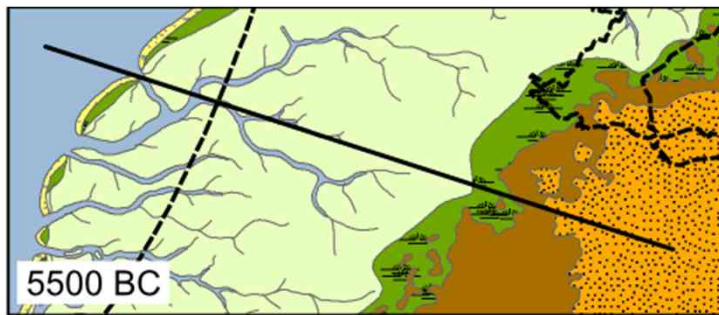
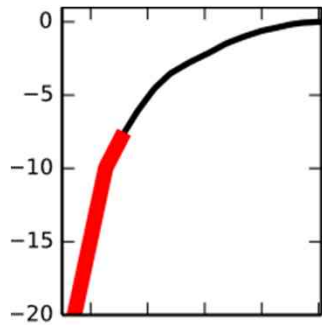
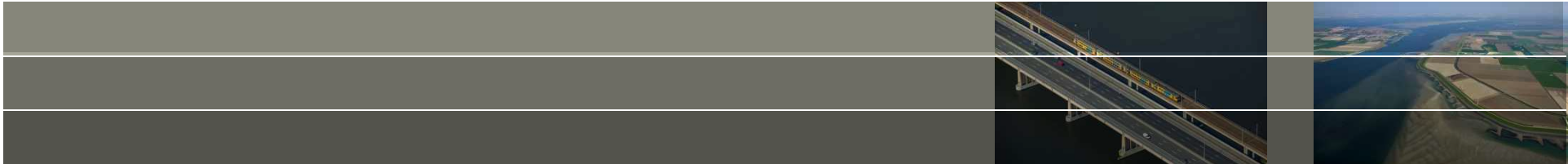
Occurrence of salt under the polder Haarlemmermeer

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



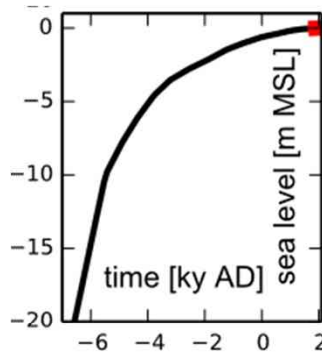






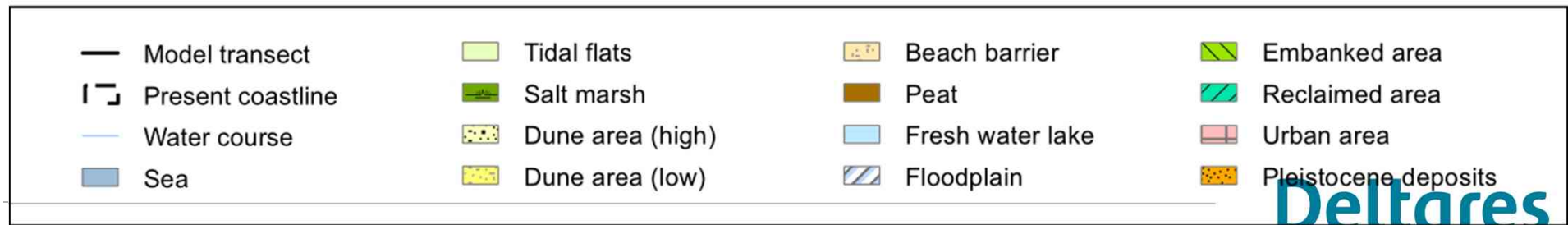
Time-slice 1: 6500 BC - 4500 BC

- 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 10: 1950 AD - 2010 AD

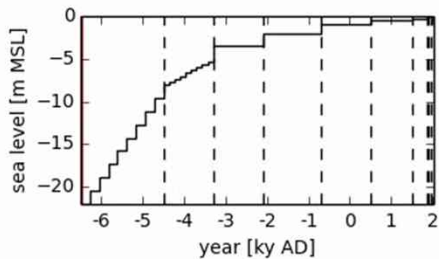
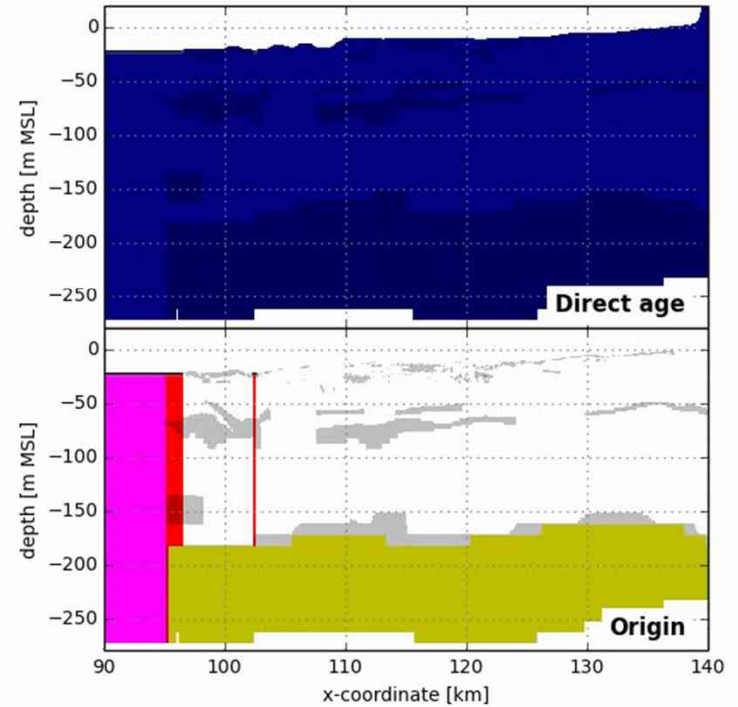
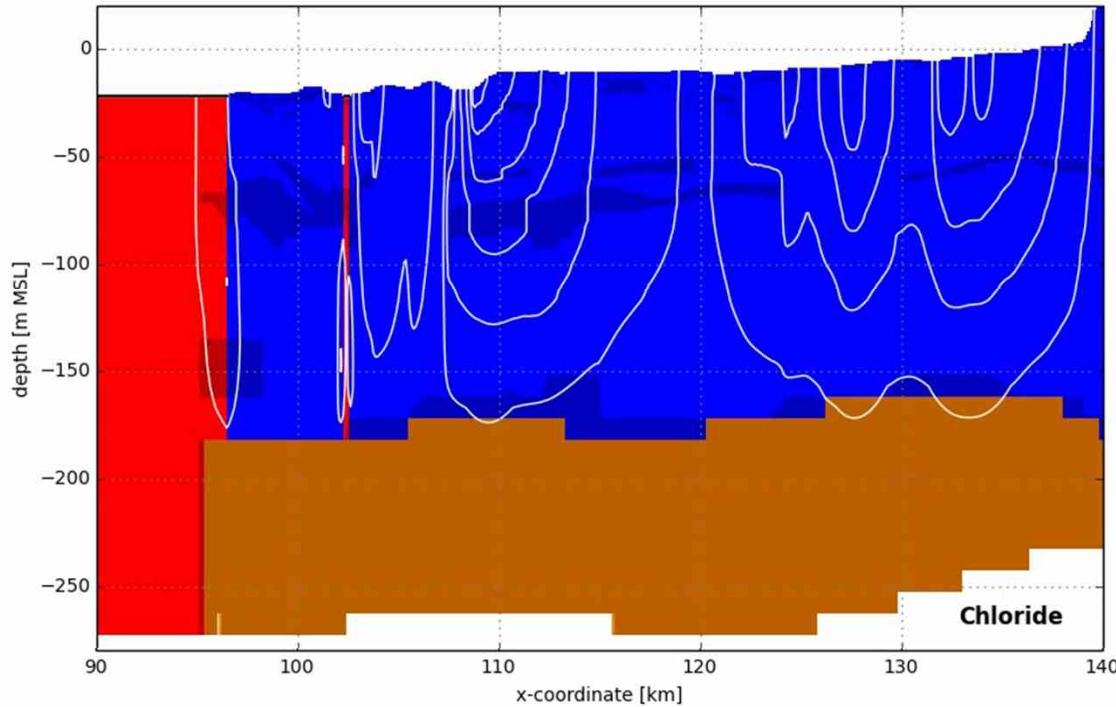
- Present-day situation
- Sea level at 0 MSL
- Groundwater abstraction in ice-pushed ridge
- Groundwater abstraction in coastal dunes decreased



Development saline groundwater in the Holocene

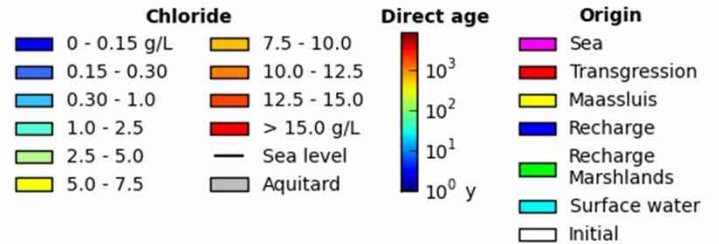
Supplementary information to Delsman et al., 2014. Palaeo-modelling of coastal salt water intrusion during the Holocene: an application to the Netherlands.

Model time: 6500 BC



Timeslice 1: 6500 BC - 4500 BC

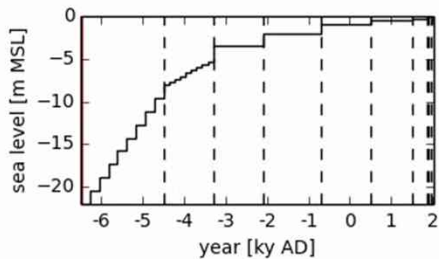
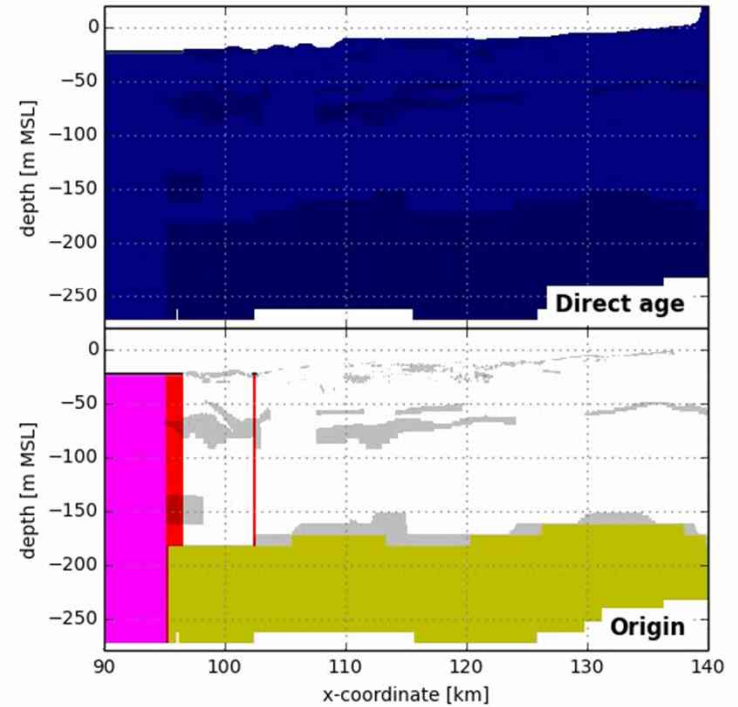
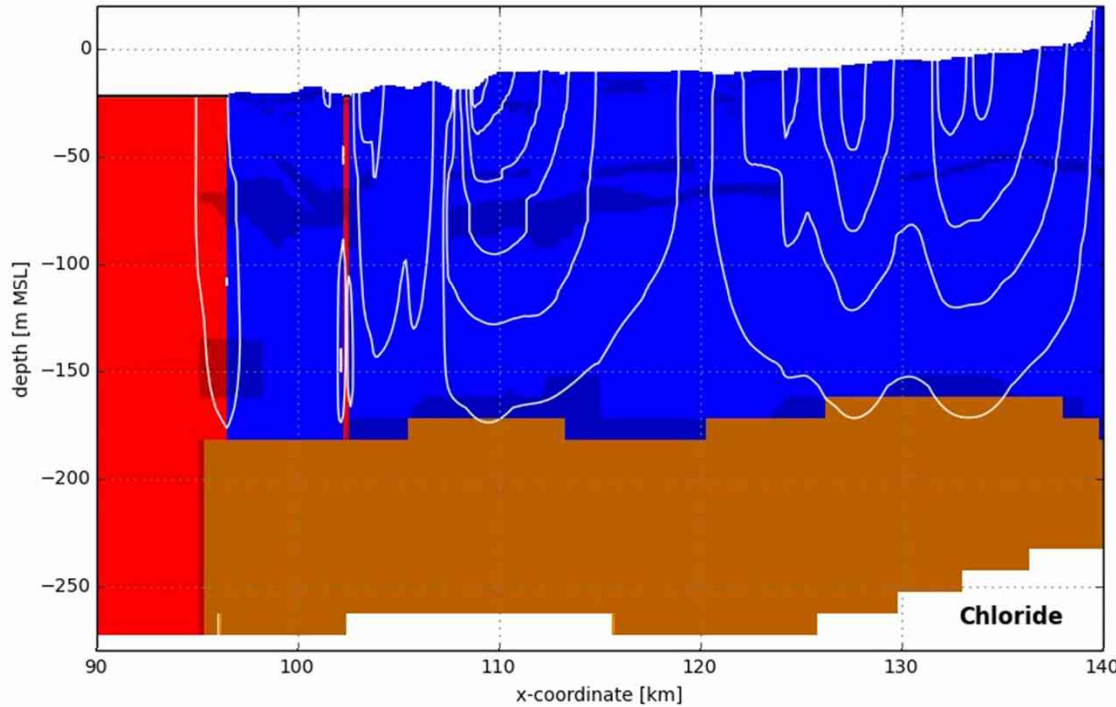
- Sea level rise, linearly from 22 to 8 m BSL
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- Surface drainage



Development saline groundwater in the Holocene

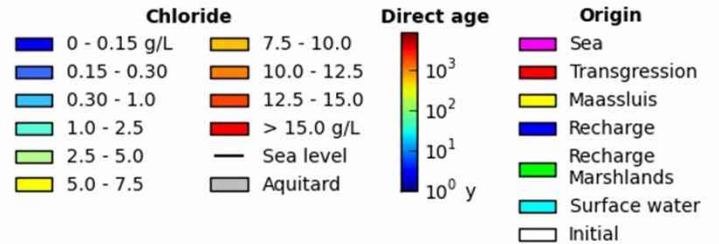
Supplementary information to Delsman et al., 2014. Palaeo-modelling of coastal salt water intrusion during the Holocene: an application to the Netherlands.

Model time: 6500 BC

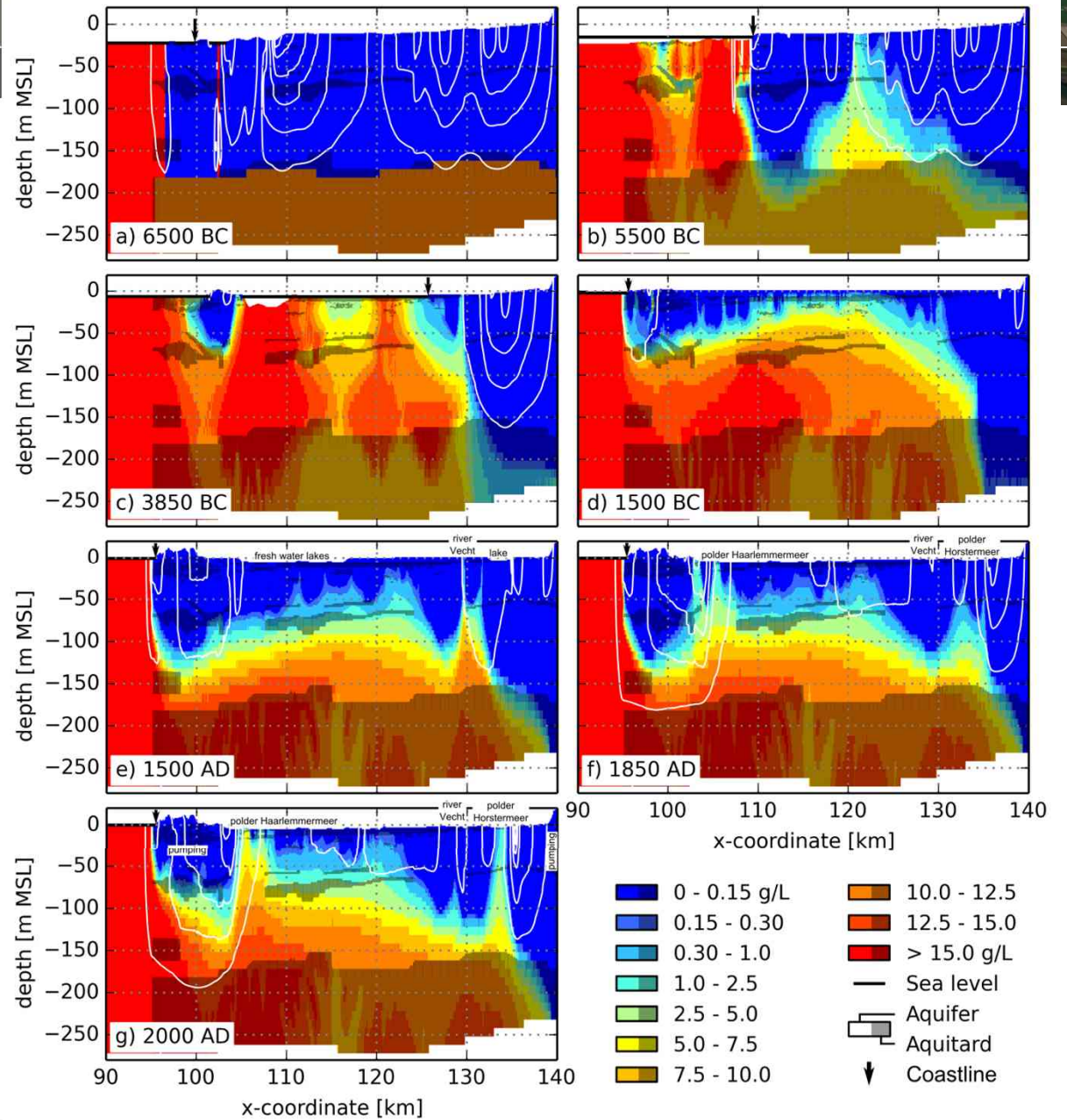
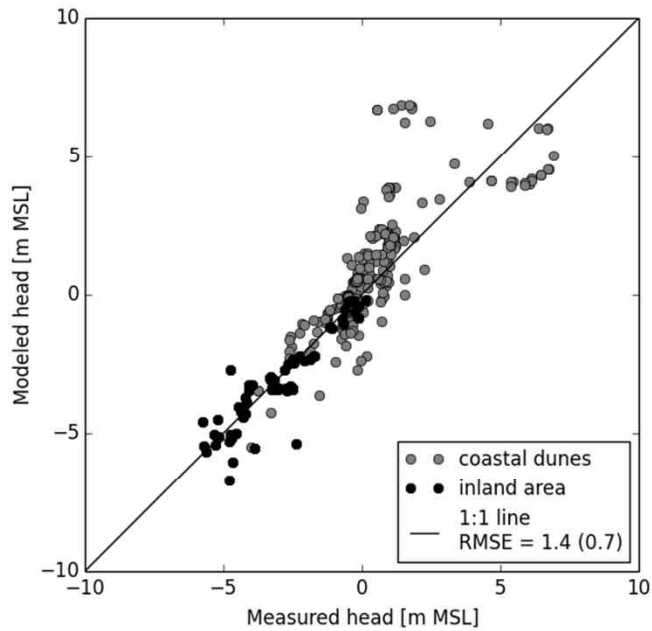


Timeslice 1: 6500 BC - 4500 BC

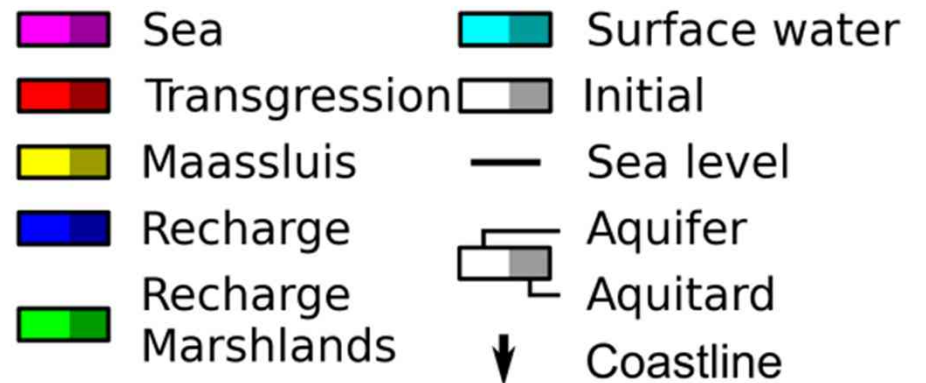
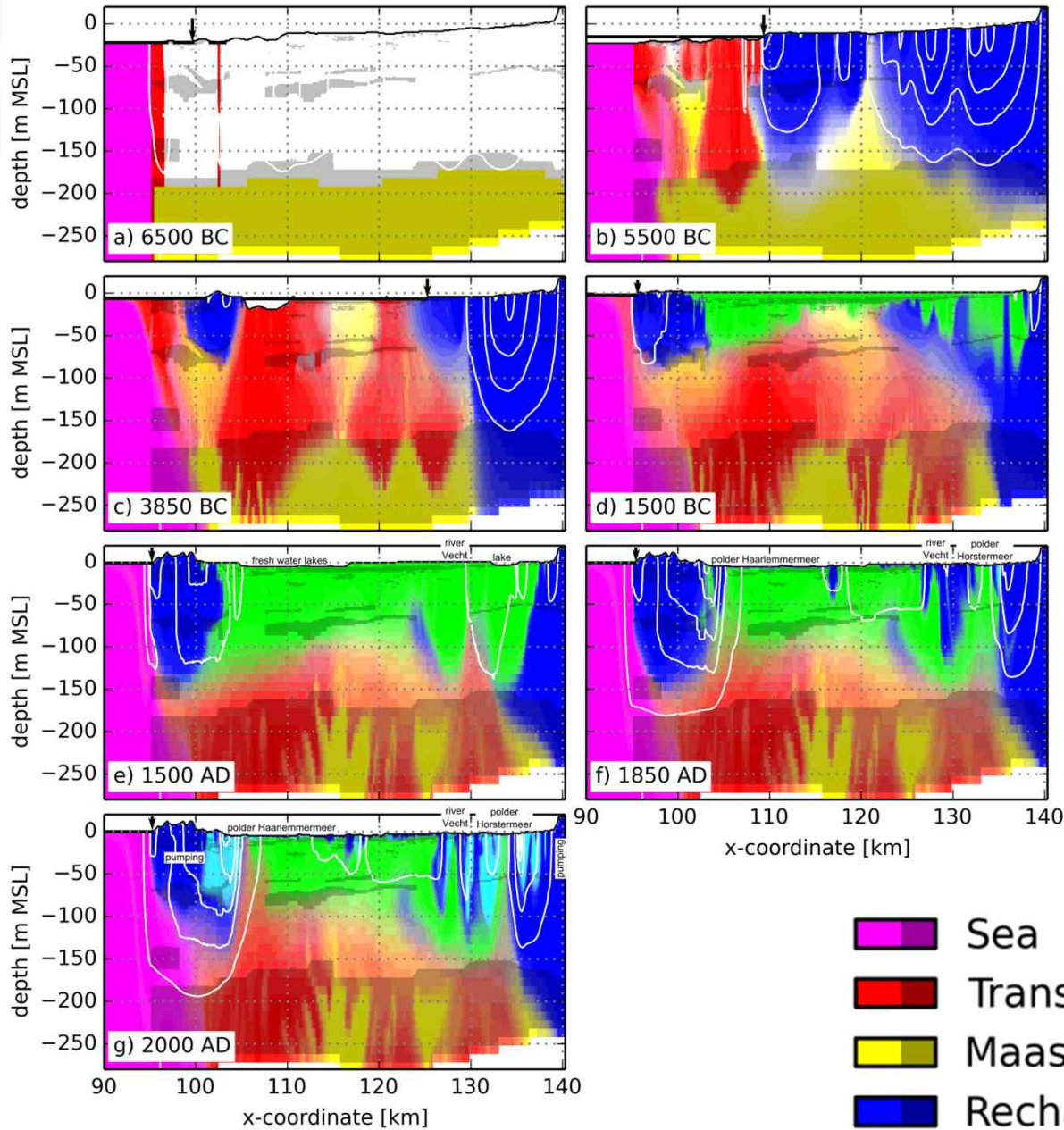
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage



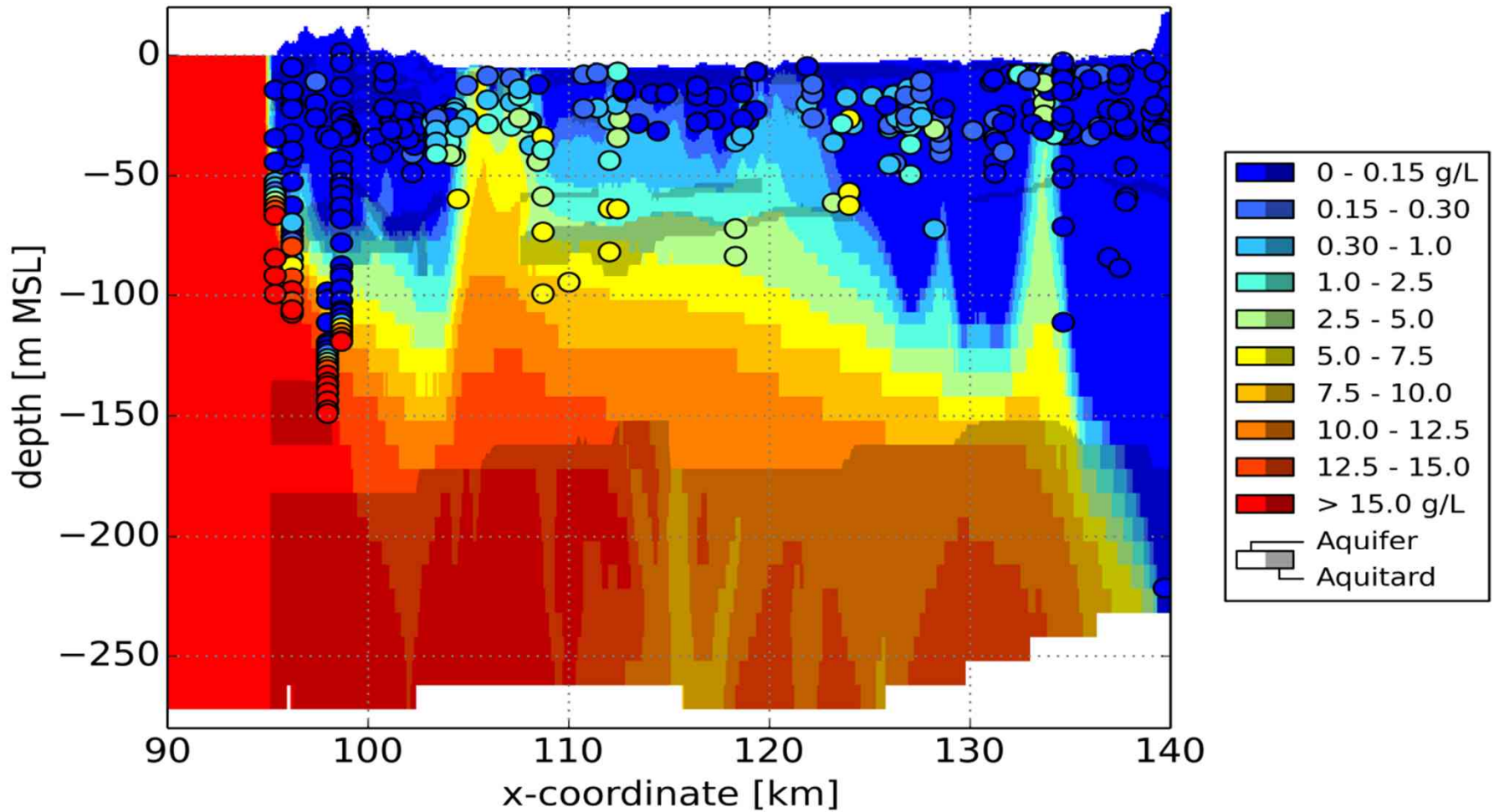
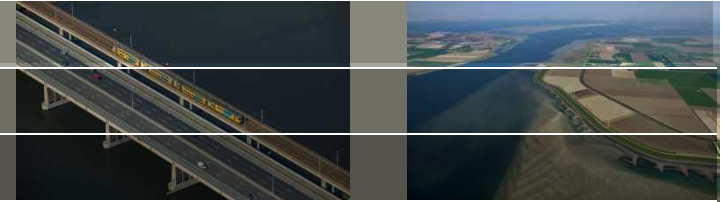
Model versus measurements

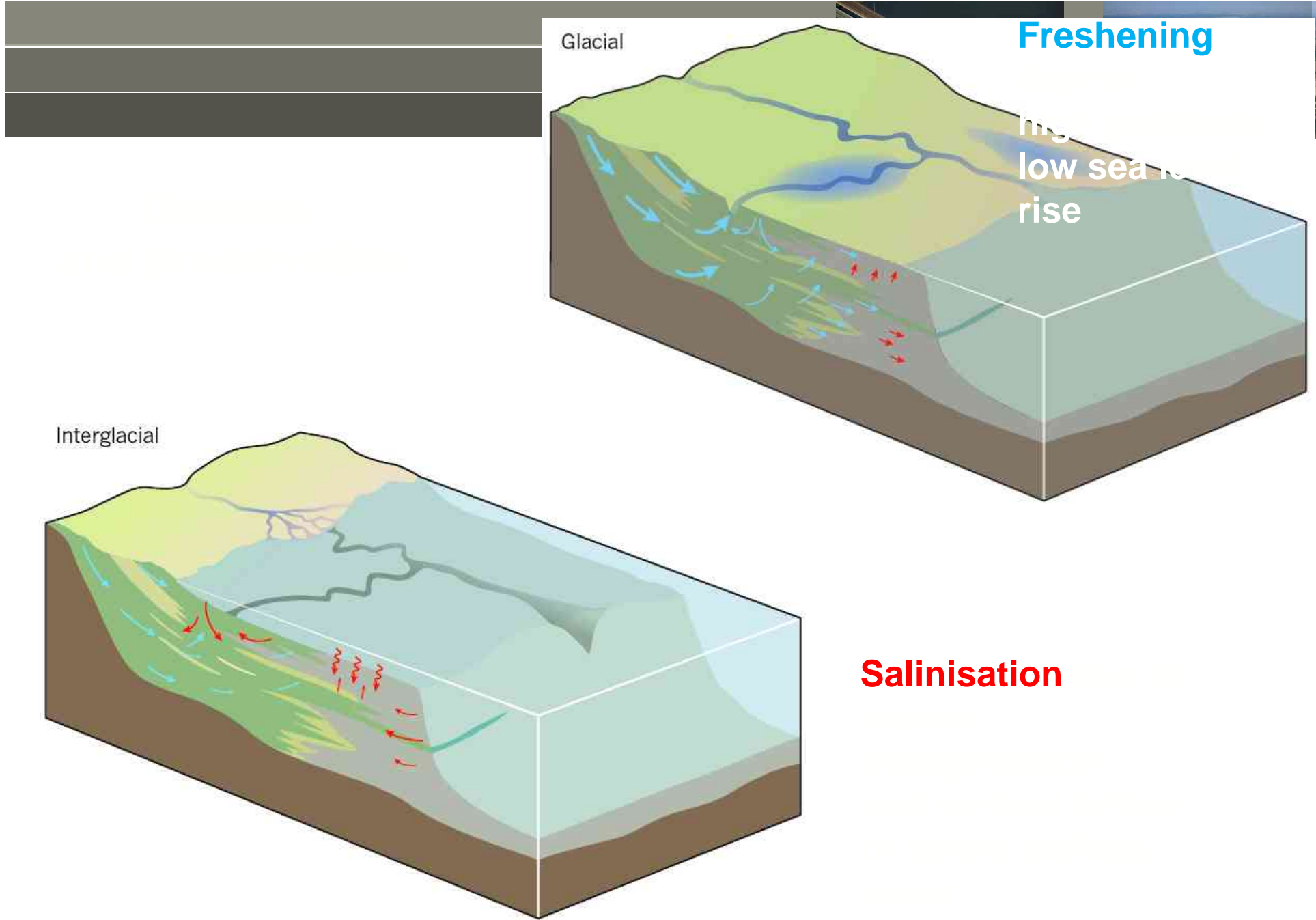


Origin source



Model versus measurements

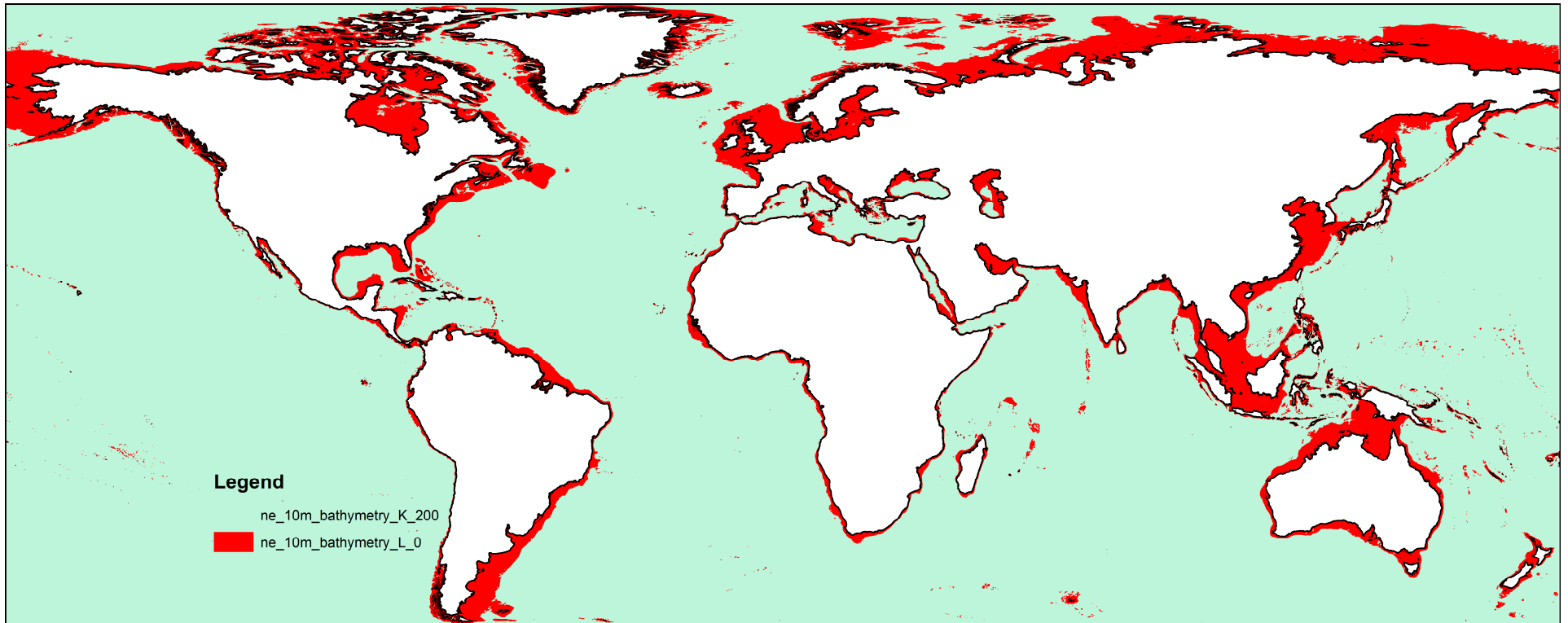




World map of topography and bathymetry showing known occurrences of fresh and brackish offshore

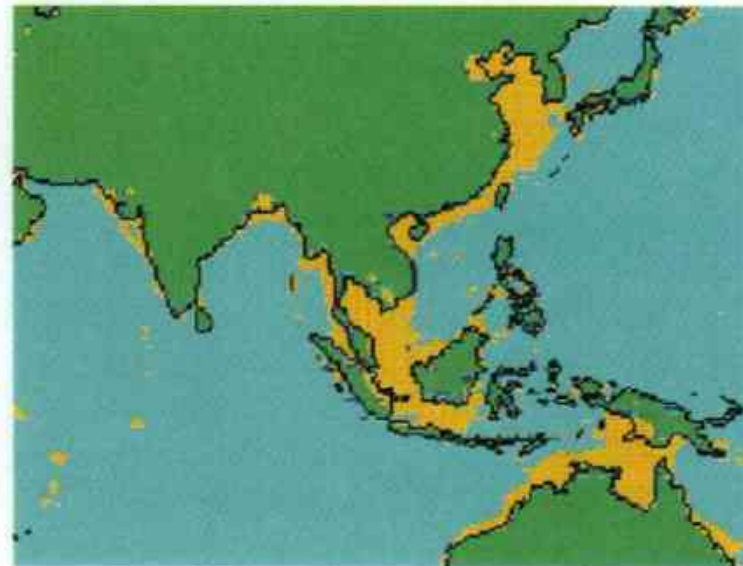
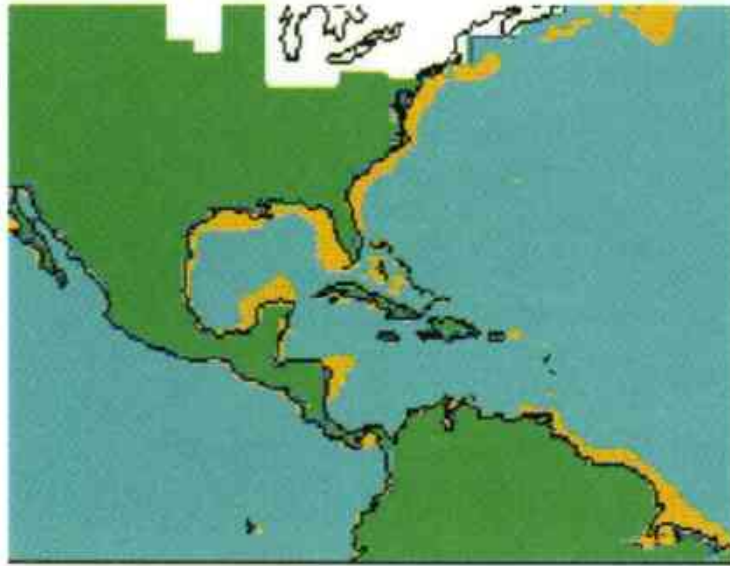
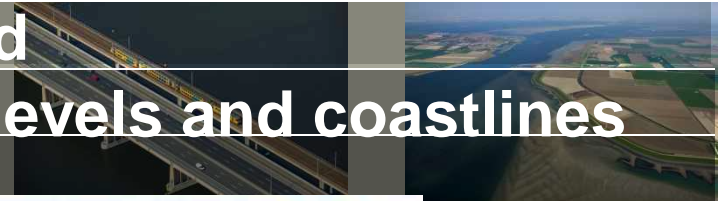


Possible locations of offshore (submarine) groundwater

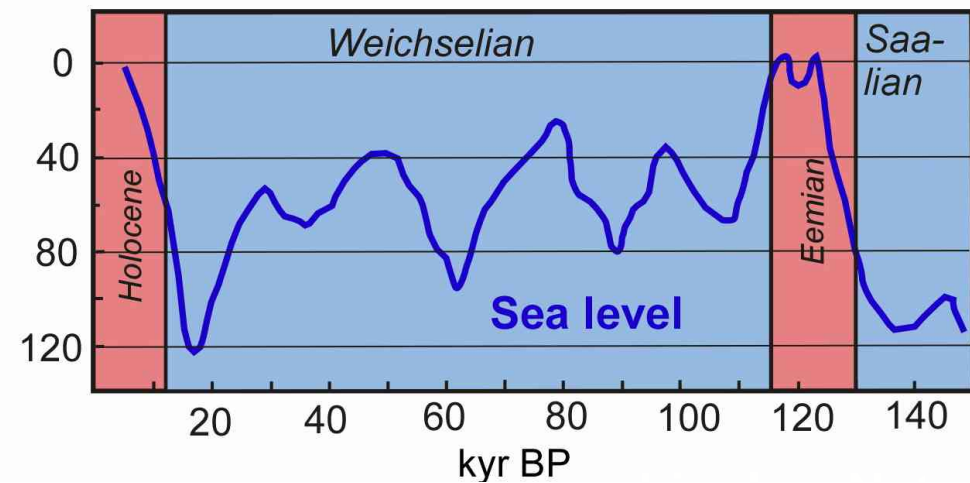
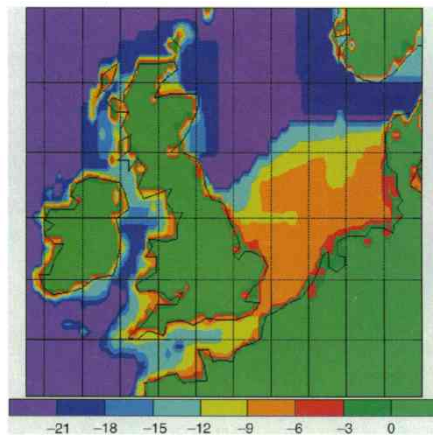


Coastal zone cases around the world

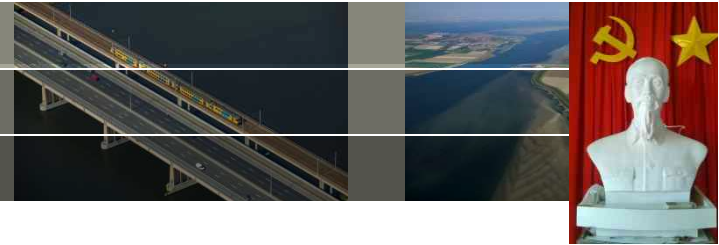
Occurrence related to dynamic sea-levels and coastlines



Peltier, *Science*, 1994



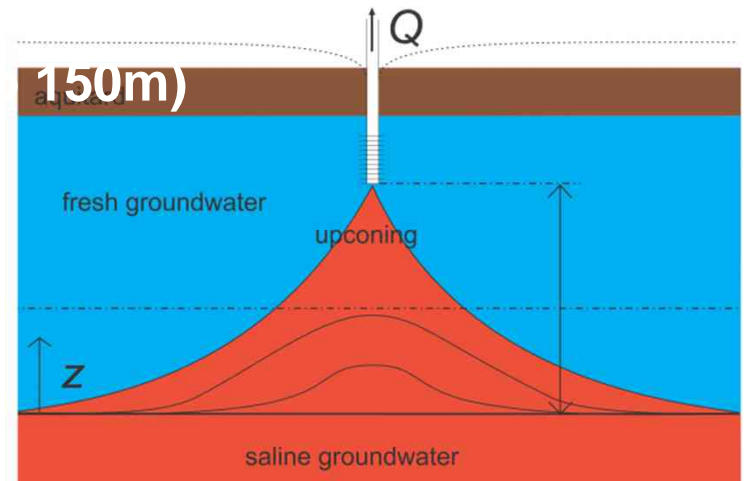
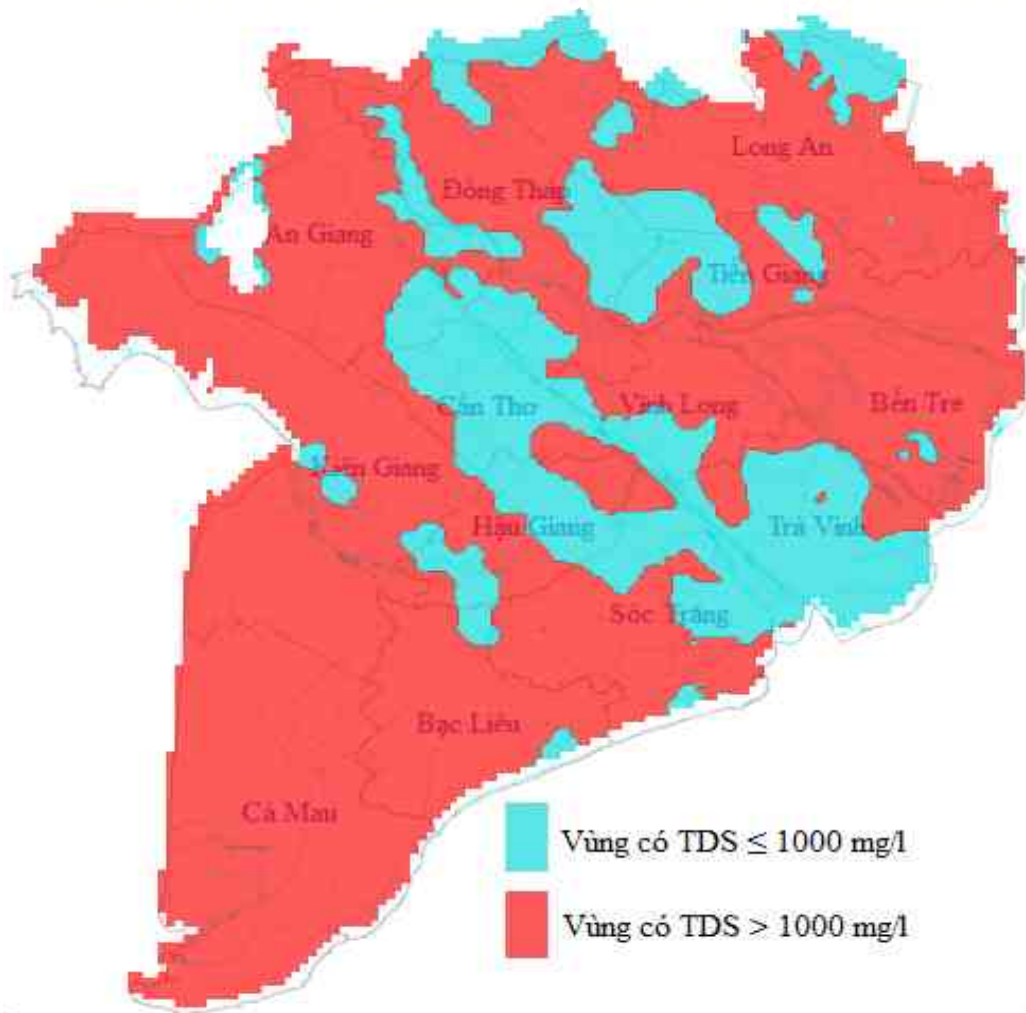
Vietnam, Mekong Delta



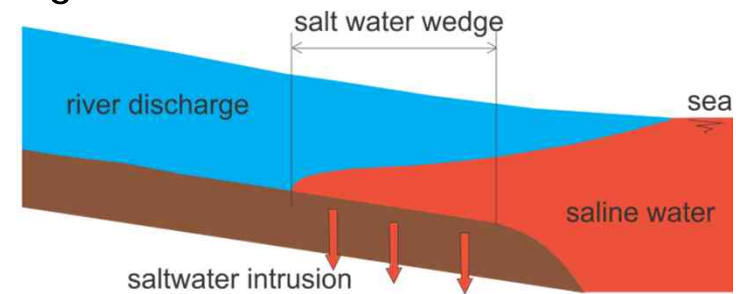
Aquaculture (shrimp farms) need an enormous quantity of fresh groundwater



Fresh-saline groundwater in the Mekong delta

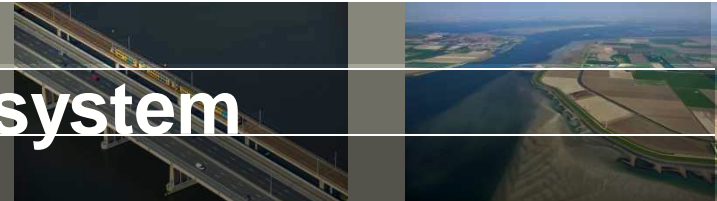


Upconing under groundwater extraction

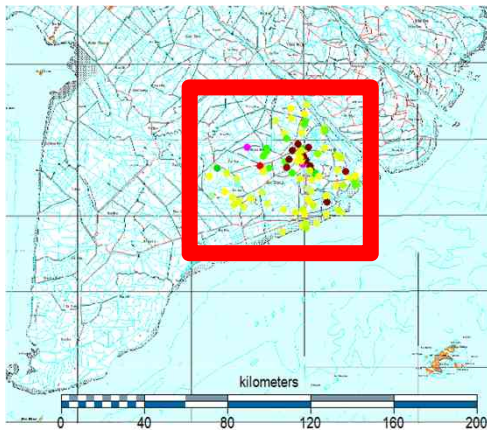


Salt water intrusion surface water (and groundwater)

Understand the groundwater system

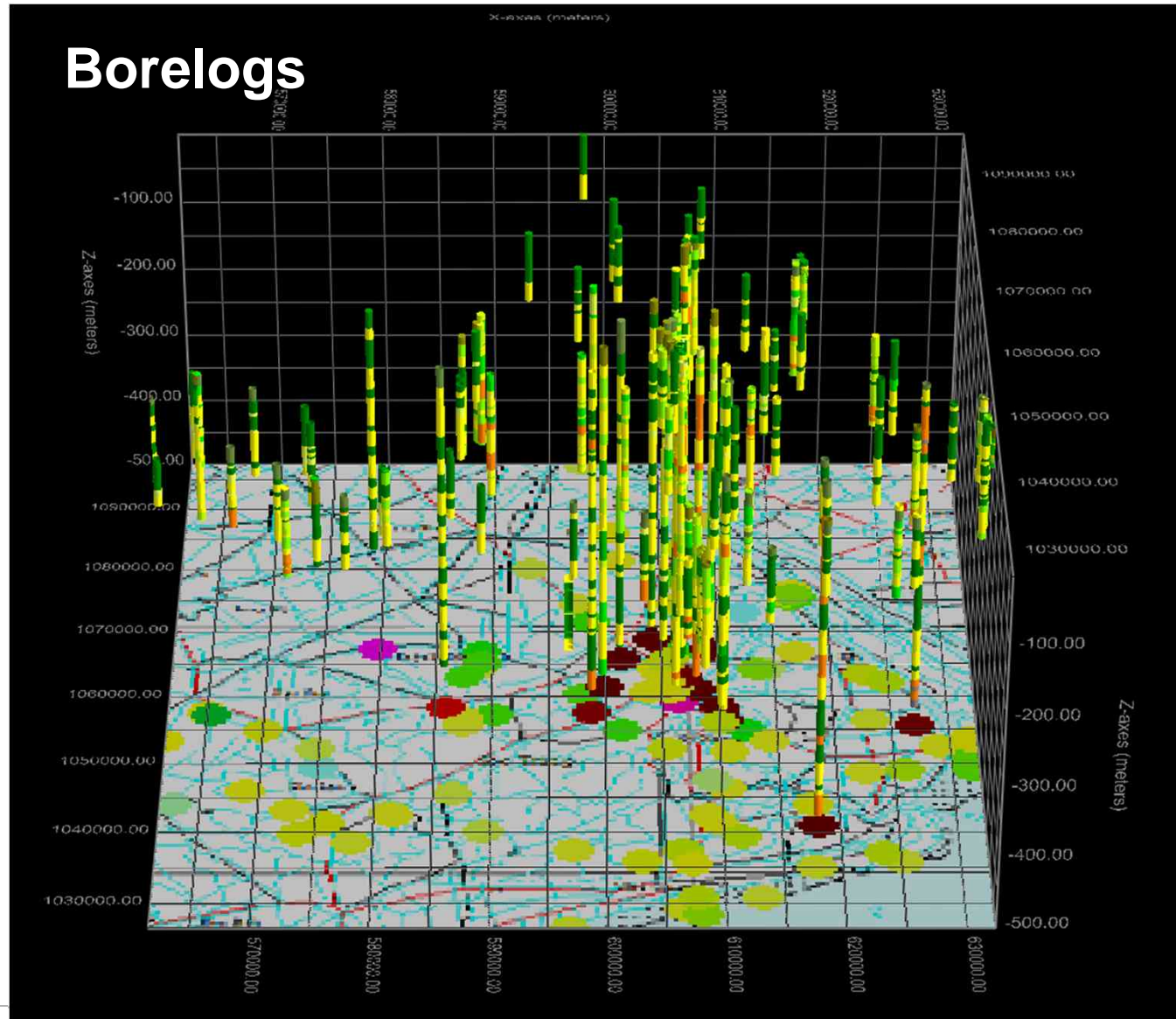


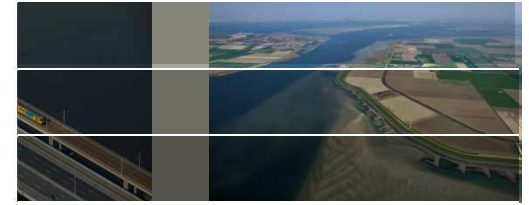
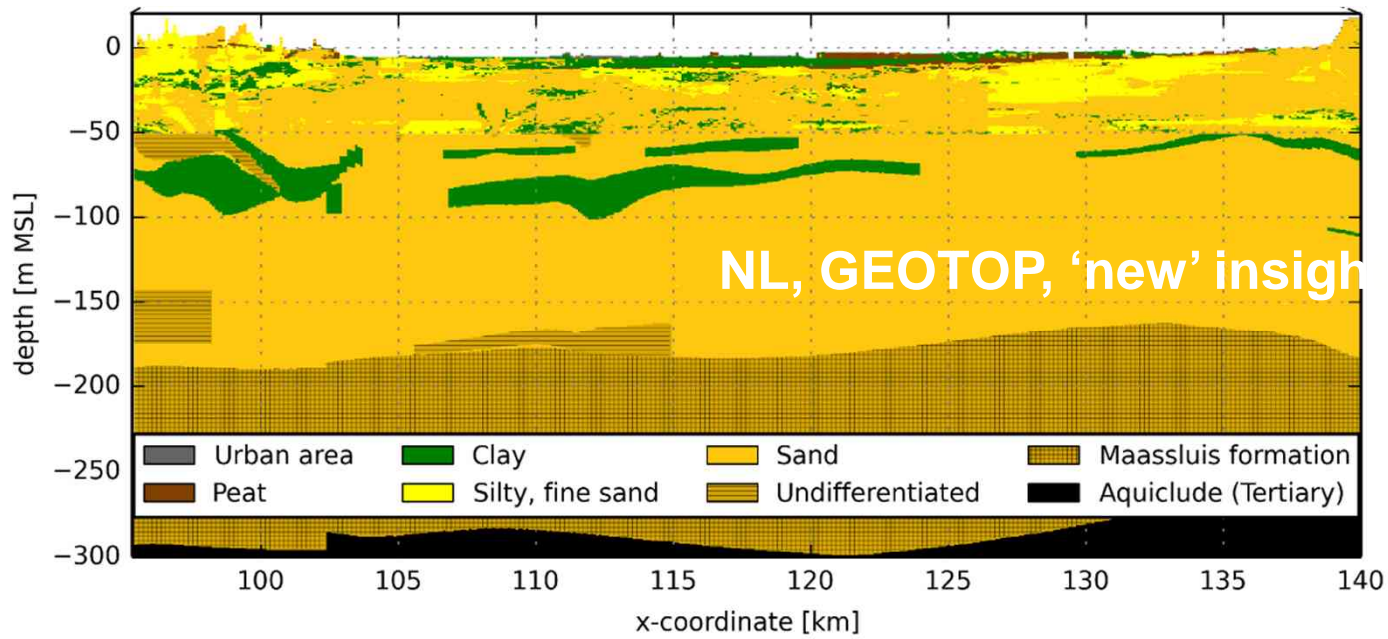
Borelogs



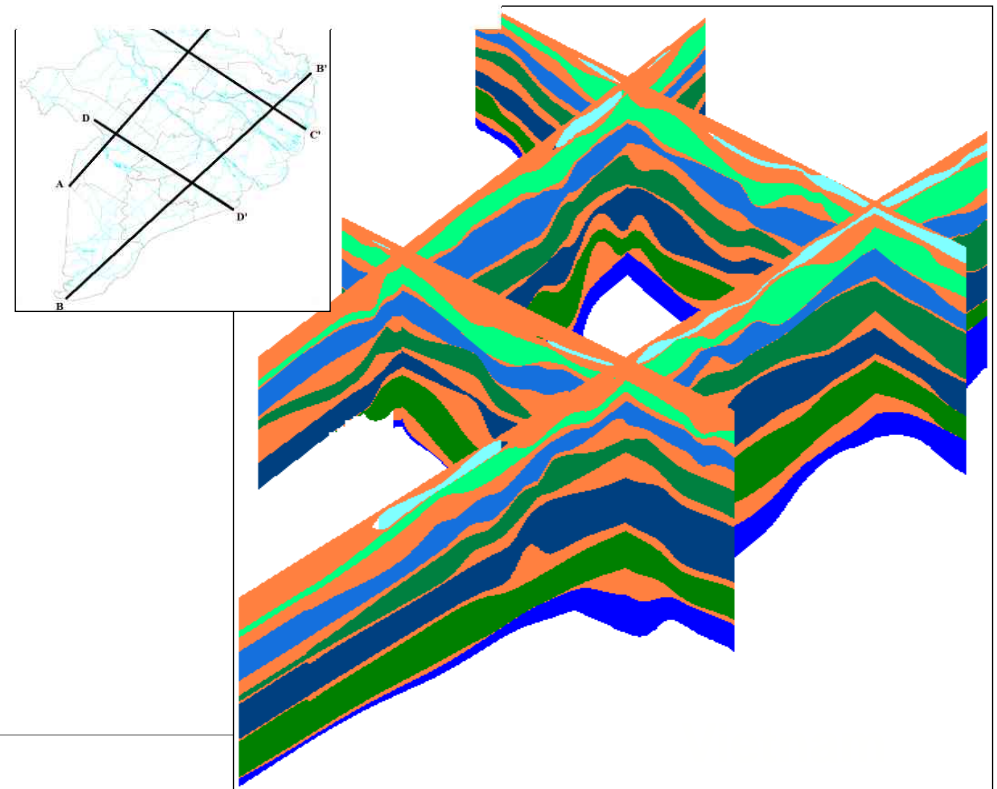
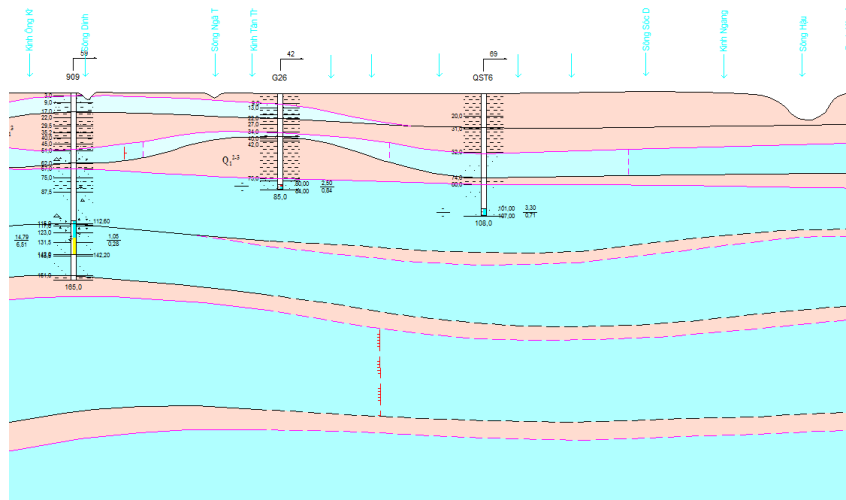
Legend for Boreholes

Label	Clr	Description	Width
S	Dark Green	Clay	1.00
SB	Medium Green	Silty_clay	1.00
BS	Bright Green	Clayey_silt	1.00
B	Light Green	Silt	1.00
BC	Yellow-Green	Sandy_silt	1.00
CB	Yellow	Silty_sand	1.00
C	Orange	Sand	1.00
CS	Light Orange	Gravel&Sand	1.00
M	Olive Green	Mud	1.00
MS	Dark Olive Green	Muddy_clay	1.00

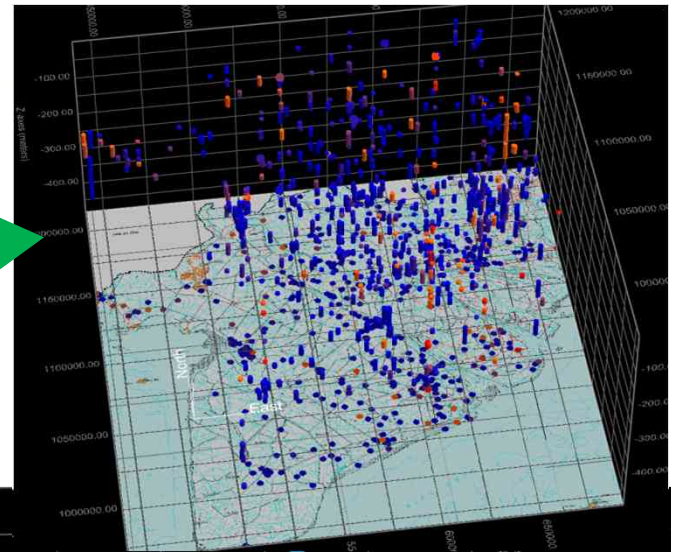
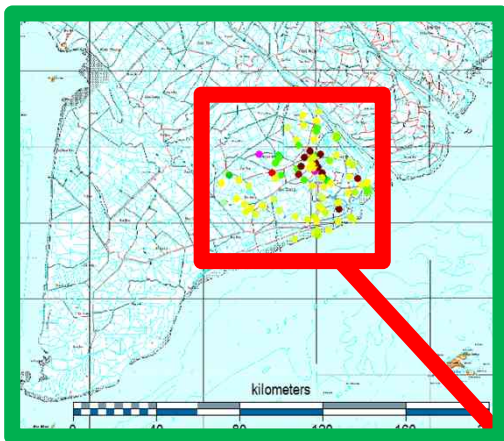




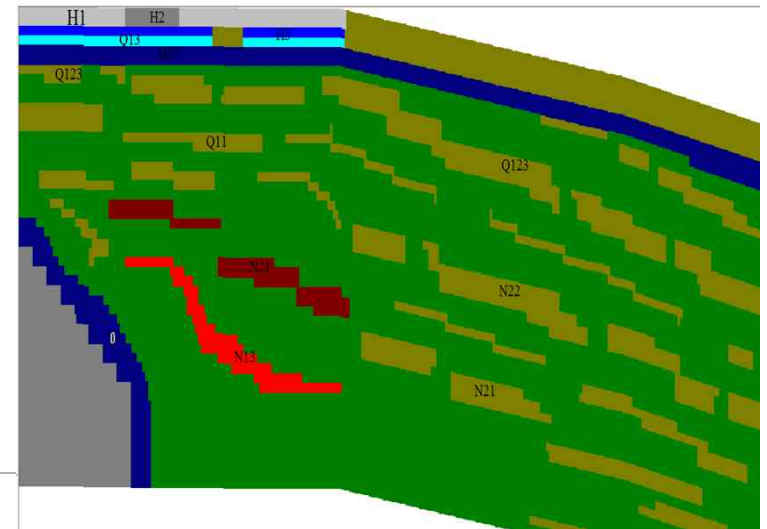
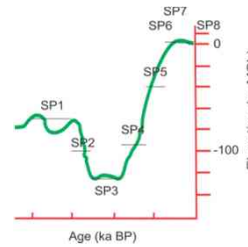
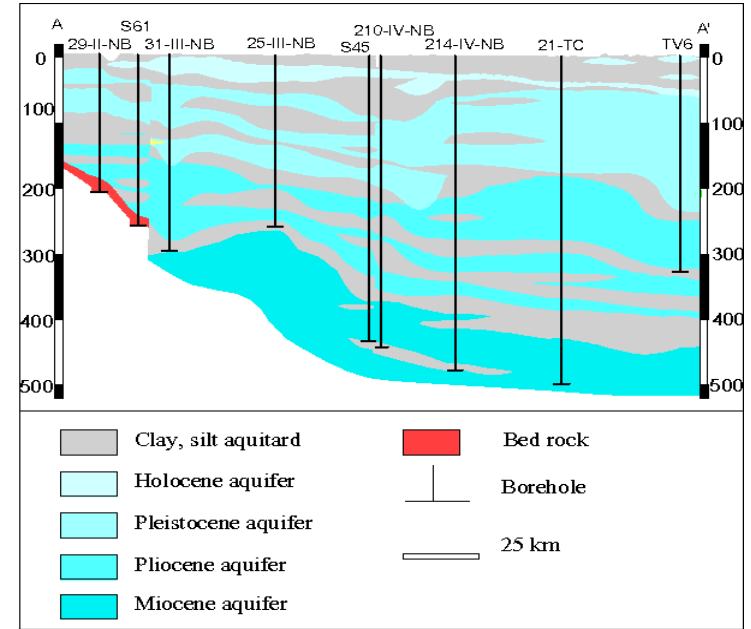
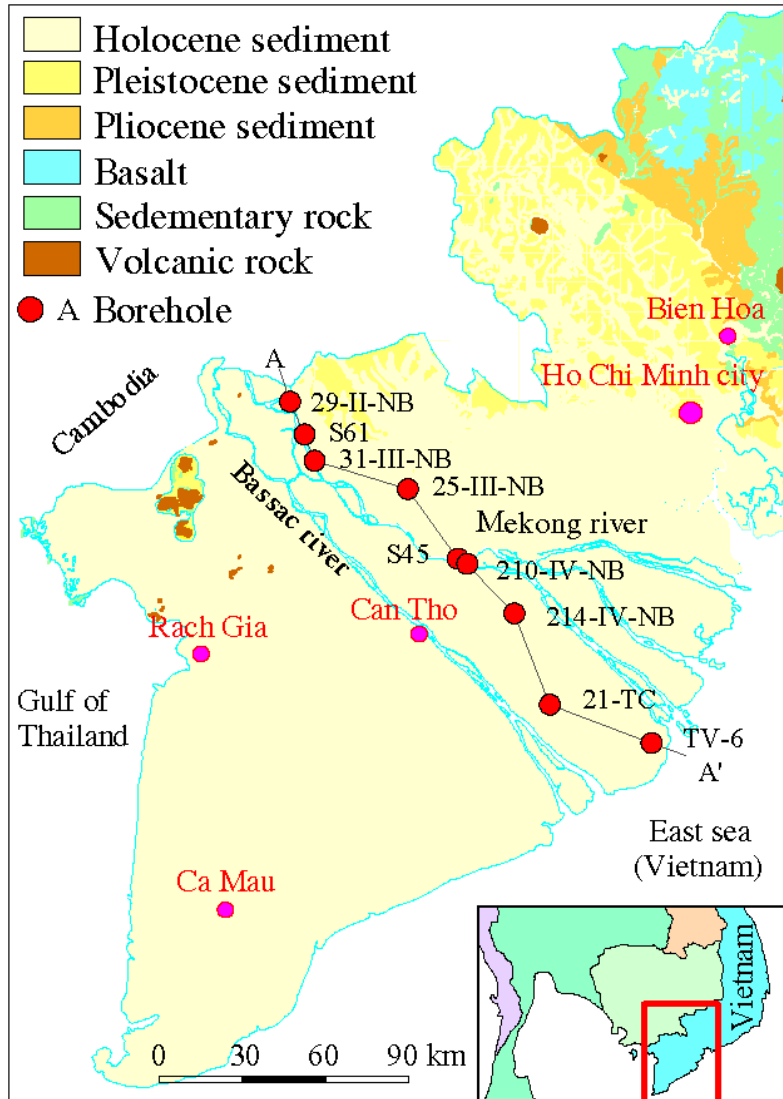
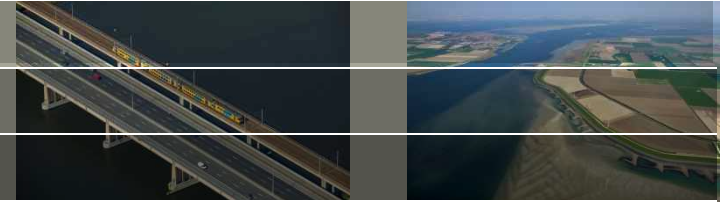
How is the geology?



Understand the groundwater system



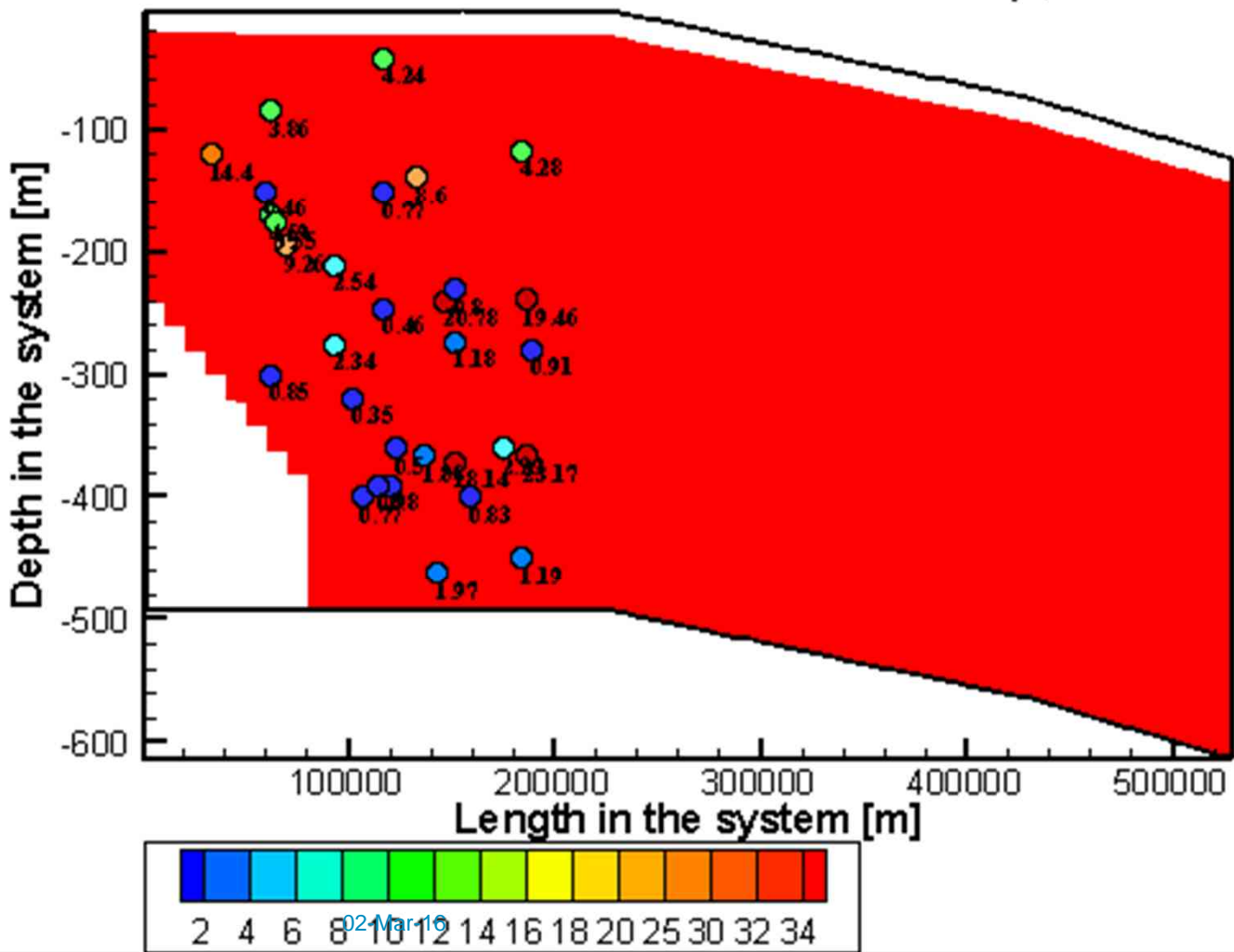
2D profile model



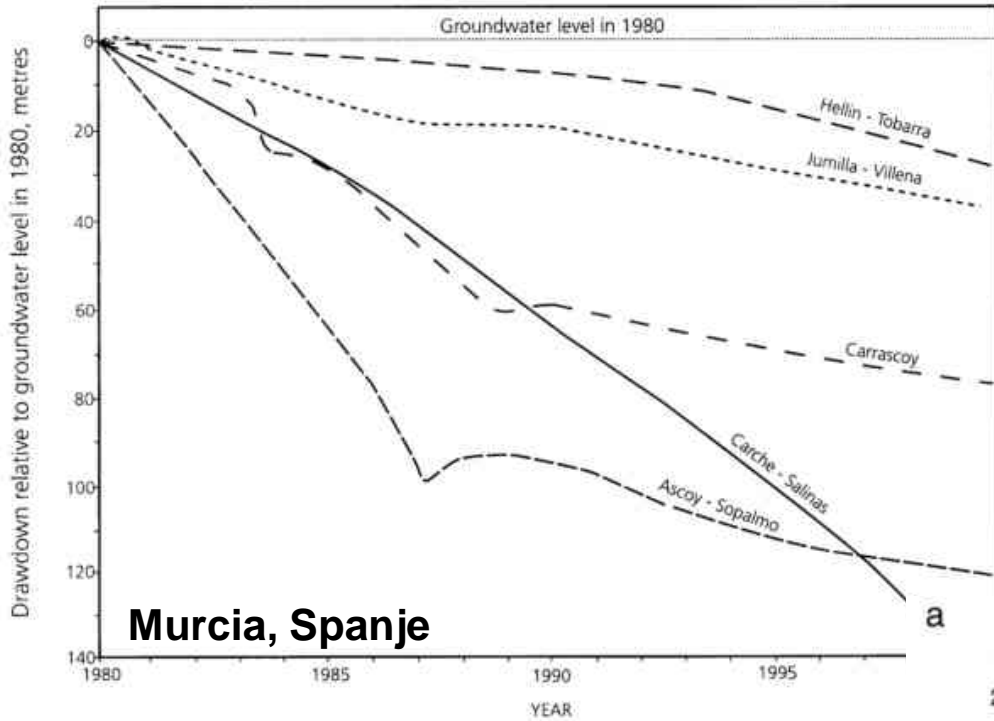


Mekong Delta, Vietnam, 2D conceptual model

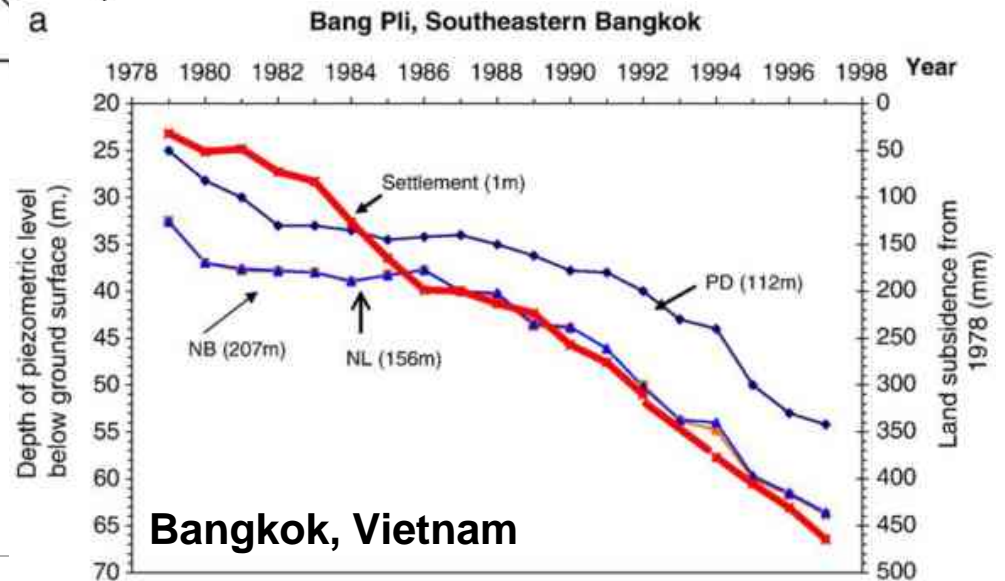
Time = 0 yr, SP=1



Serious overexploitation aquifers worldwide

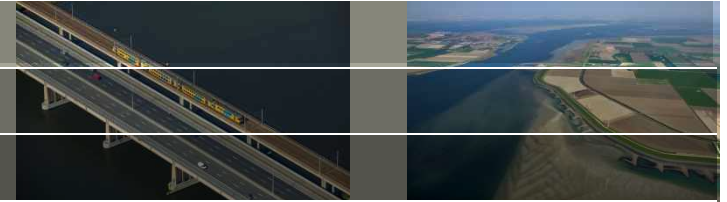


Murcia, Spanje



Bangkok, Vietnam

Sinking delta cities



Sea level rise
3 - 10 mm/year

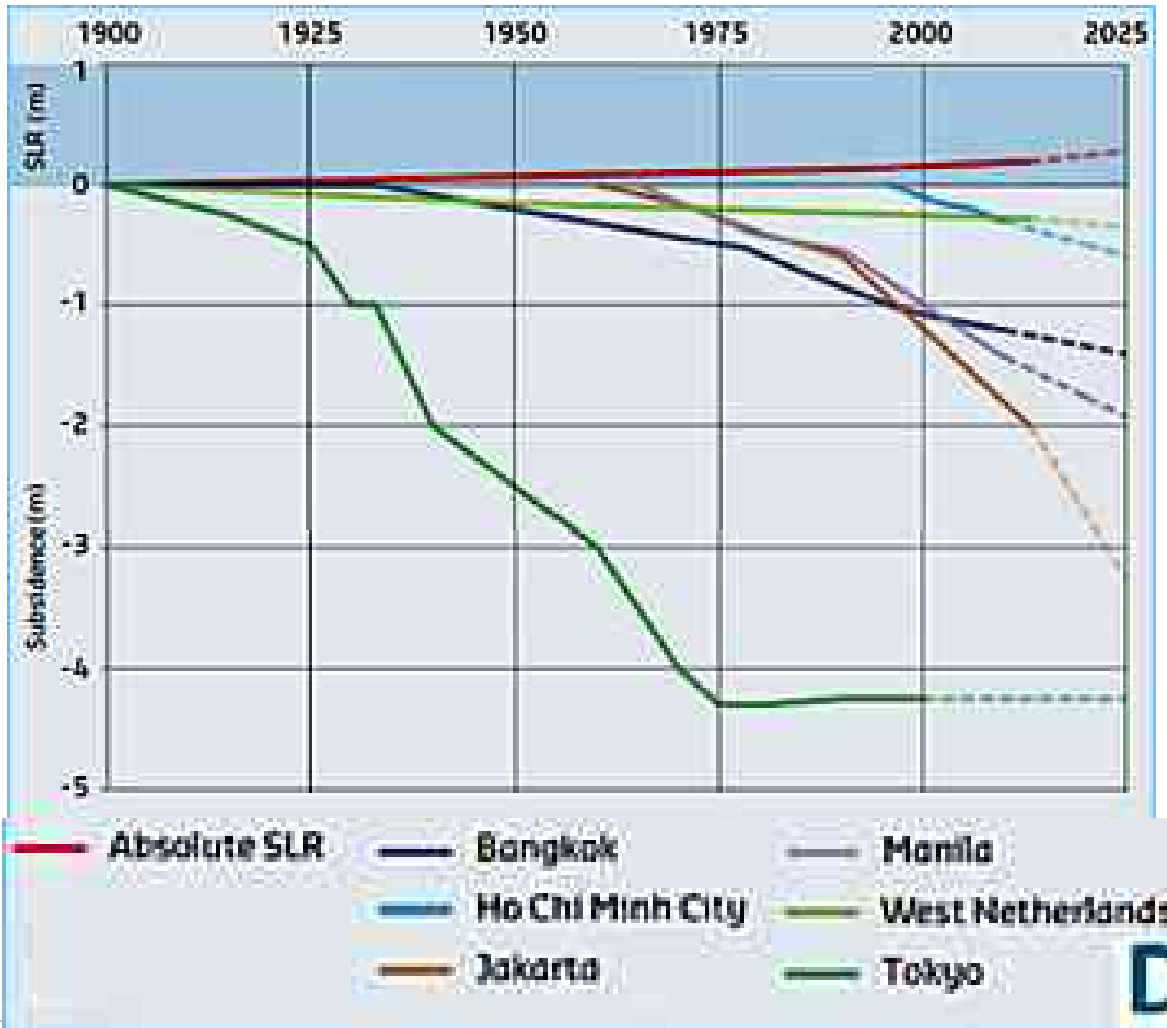


Subsidence
6 - 100 mm/year



Examples of some major coastal cities

The subsidence issue is underestimated



↑ SLR
↓ subsidence

RSL Tokyo
4,5 m!



Land subsidence San Joachim Valley, CA, USA



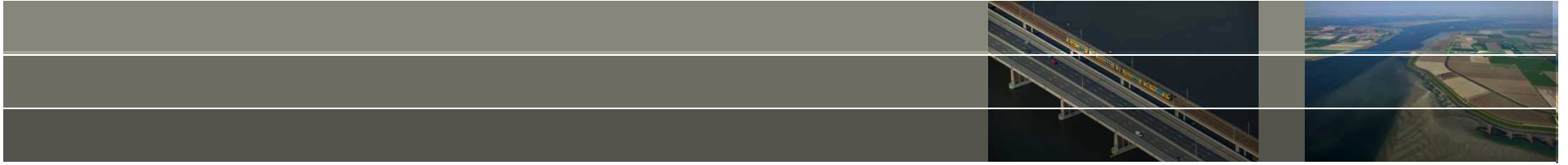
9 m since 1930s

San Francisco



Los Angeles

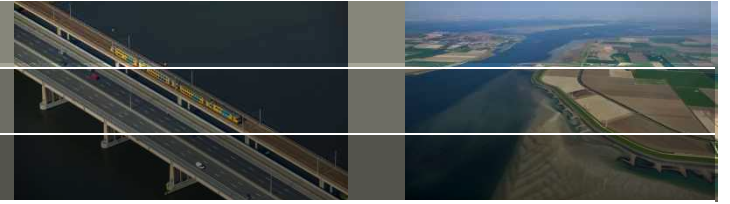
Deltares



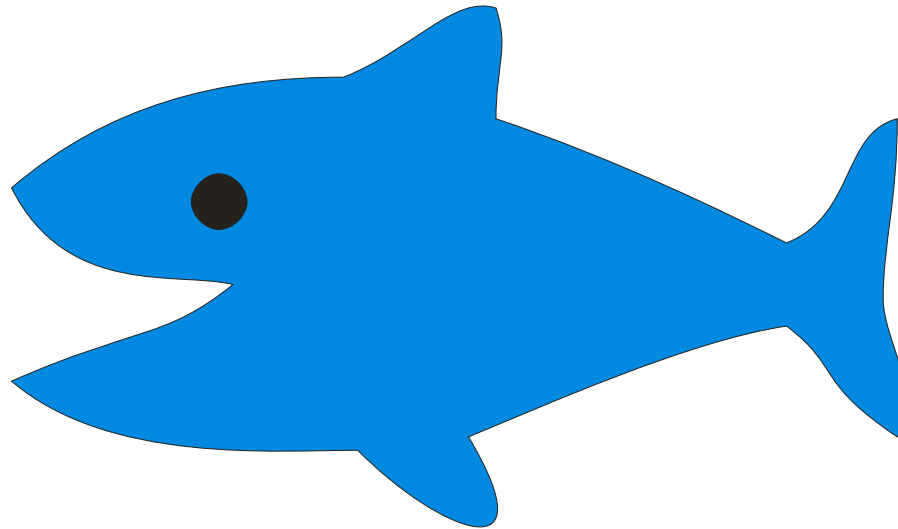
Base idea

Many local solutions for fresh groundwater supply can have regional impact

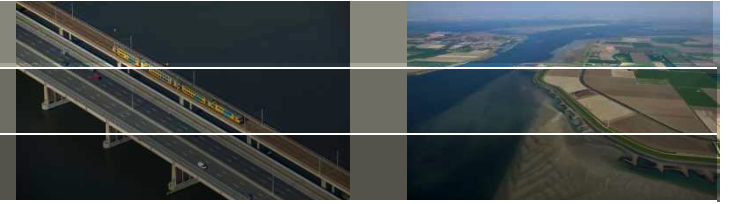
Starring



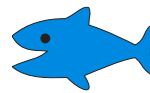
solution fresh groundwater supply



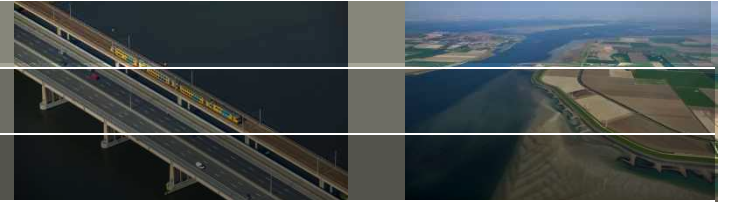
Starring



Local solution fresh groundwater supply



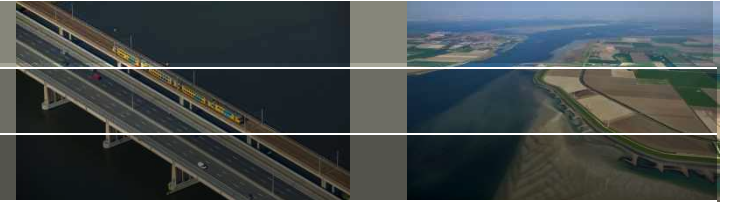
Starring



climate and global change

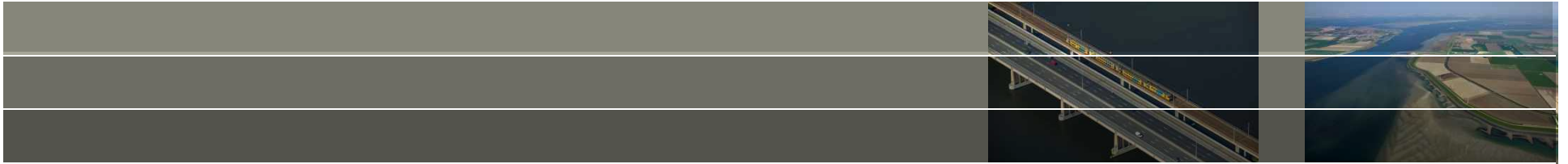


Starring

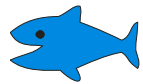


climate and global change



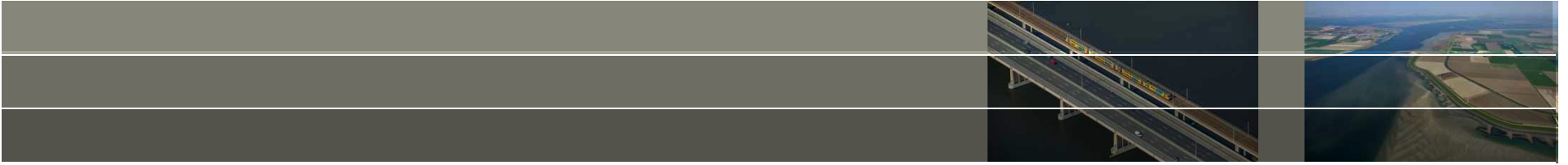


Local solution fresh
groundwater supply



climate and global change



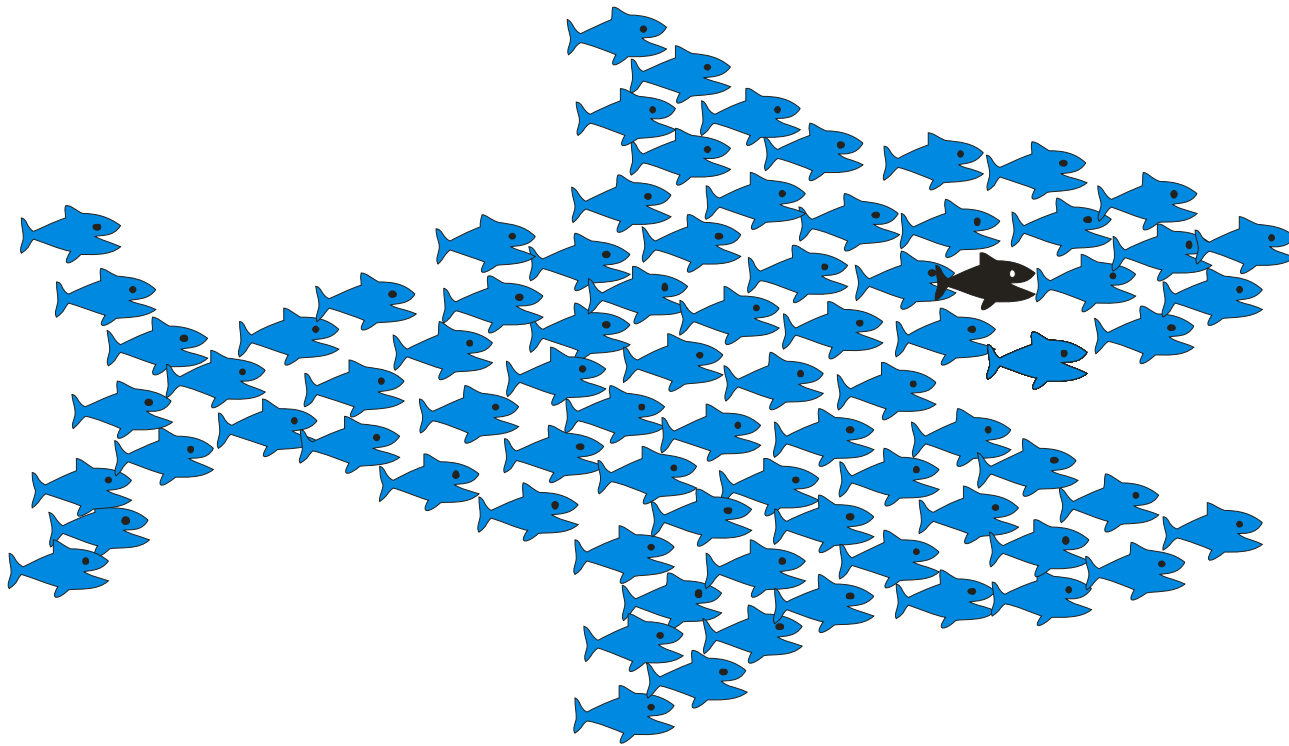


What should be the response?



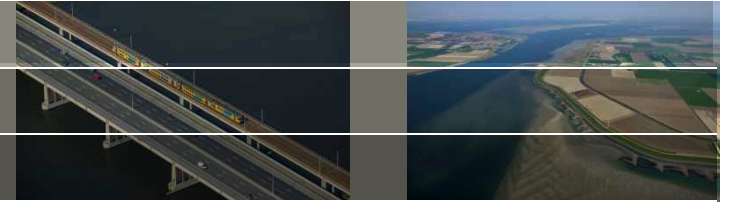
Many local solutions fresh groundwater supply

climate and global change

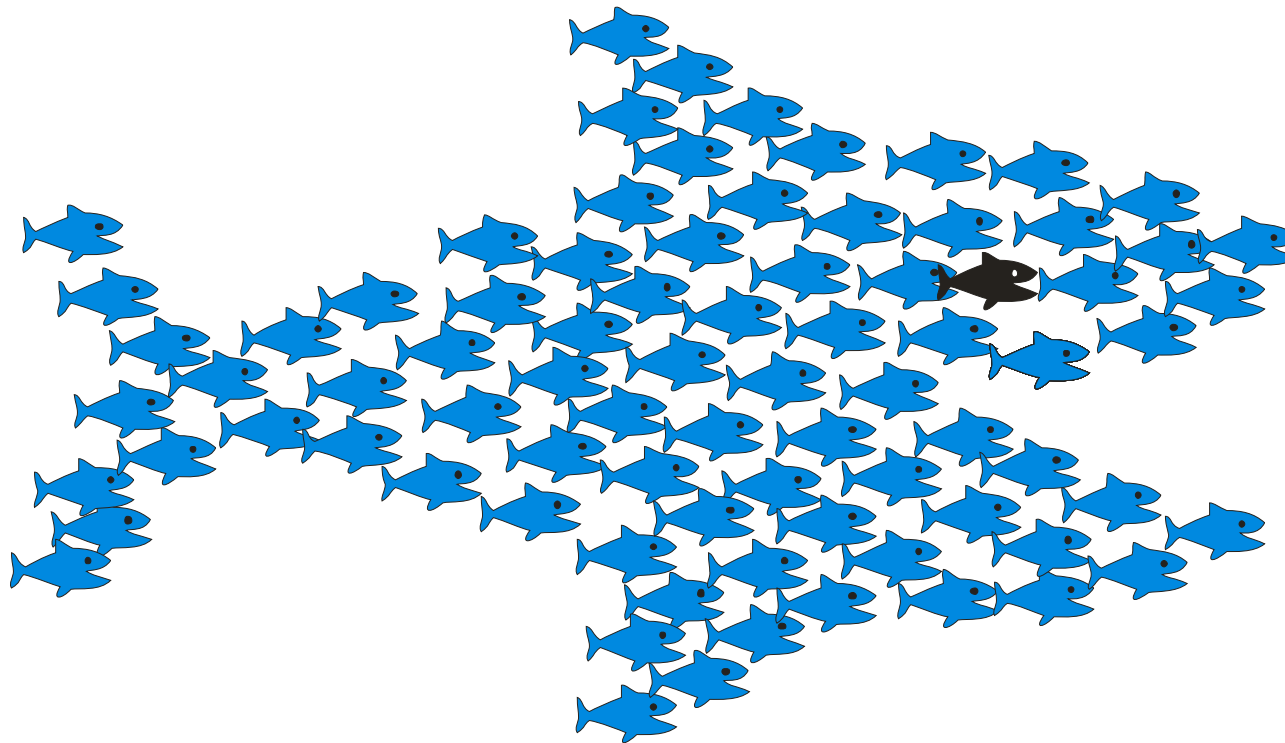


Many local solutions for fresh groundwater supply can have regional impact

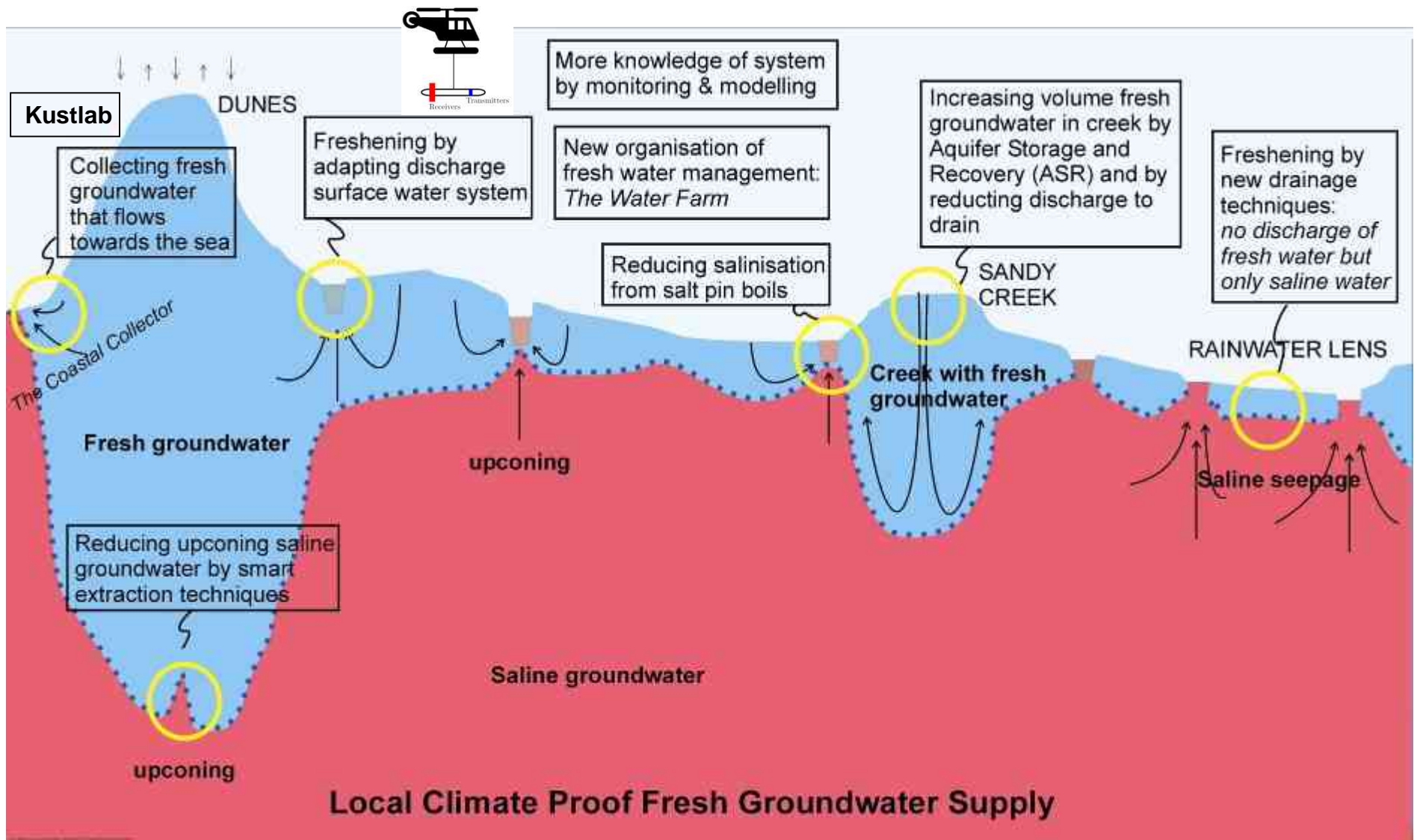
Key activities



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

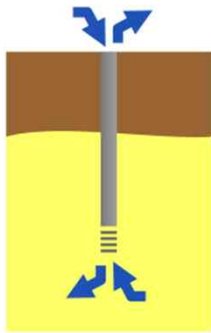


Local climate proof fresh water supply

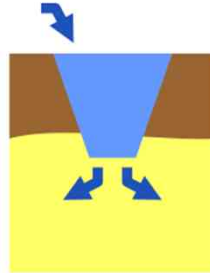


Aquifer Storage and Recovery / Managed Aquifer Recharge

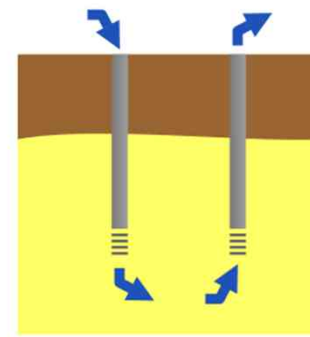
Aquifer storage and recovery (ASR)



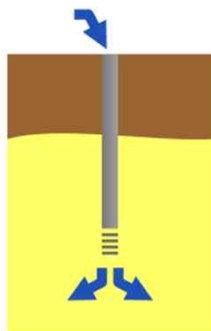
Infiltration ponds, galleries



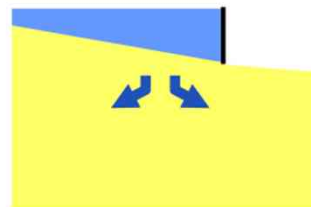
Aquifer storage, transport and recovery (ASTR)



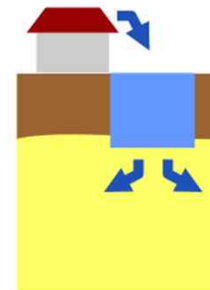
Dry wells



Recharge weirs, releases
Runoff harvesting



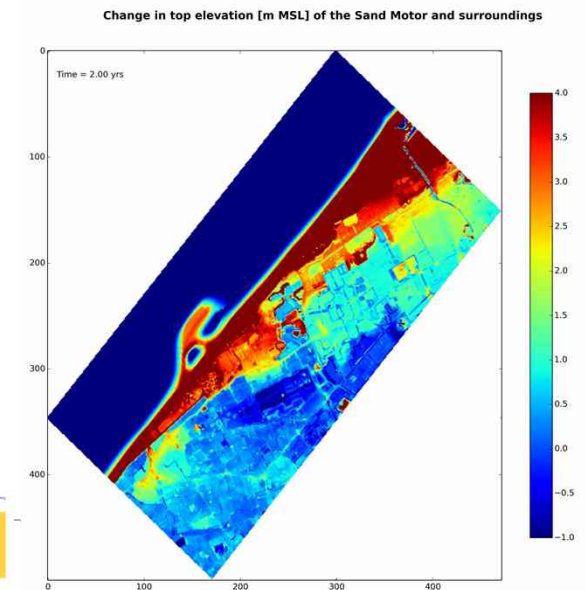
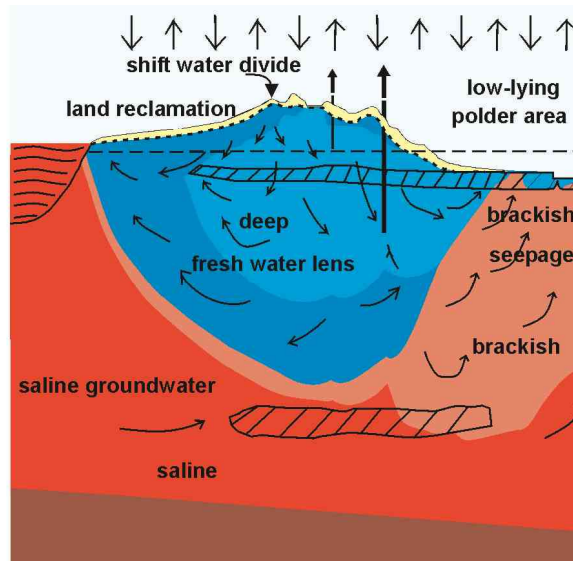
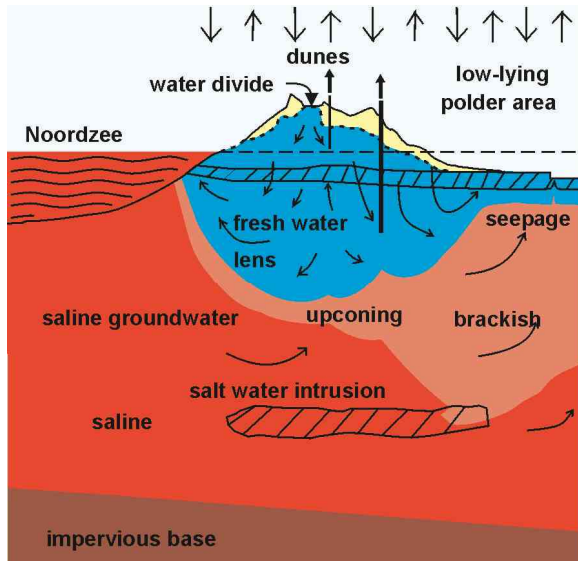
Rainwater harvesting



Increase strategic freshwater reservoirs in the coastal zone



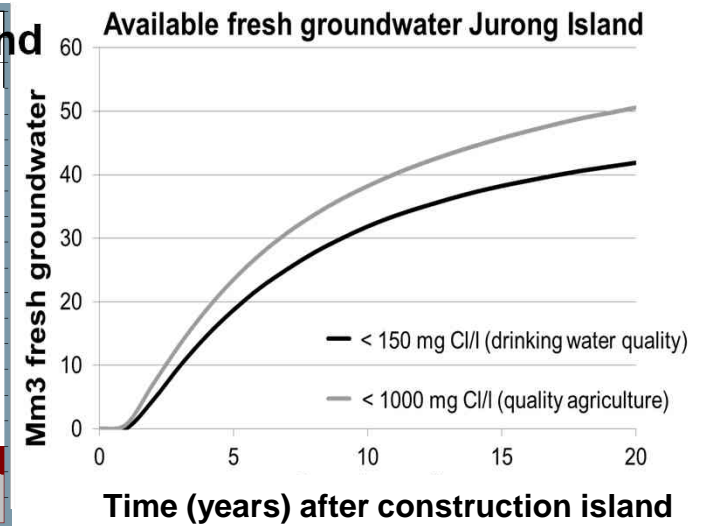
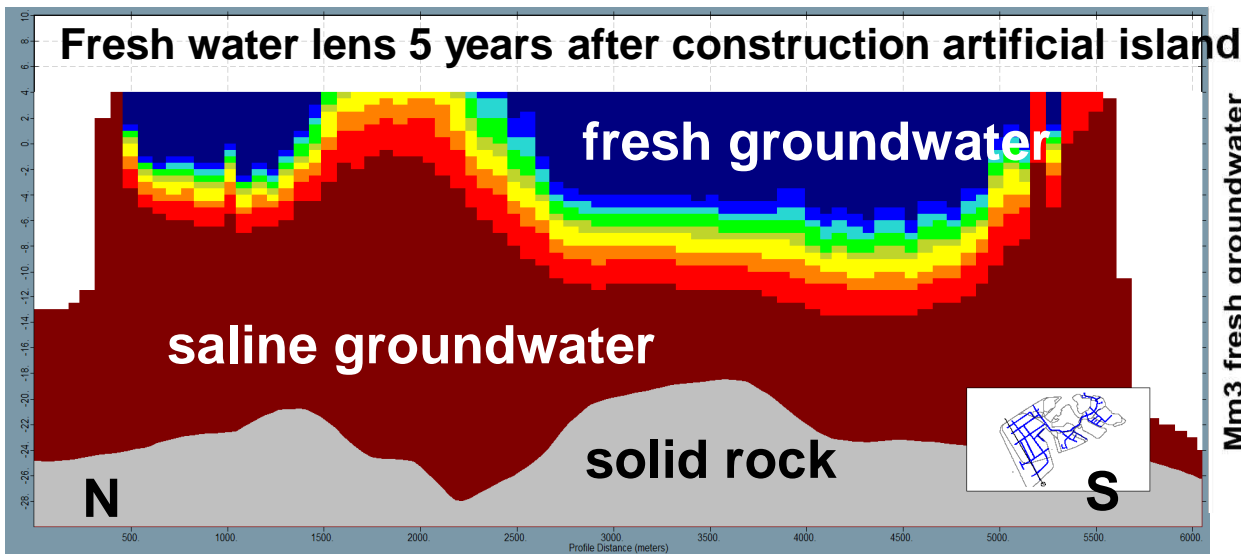
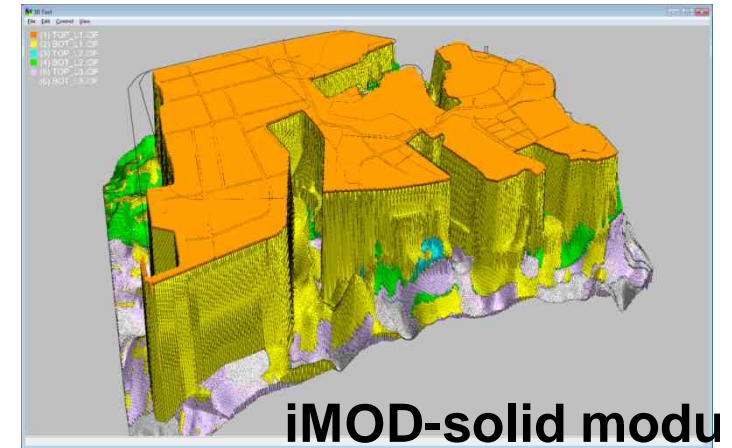
NatureCoast, Building with Nature, De Zandmotor



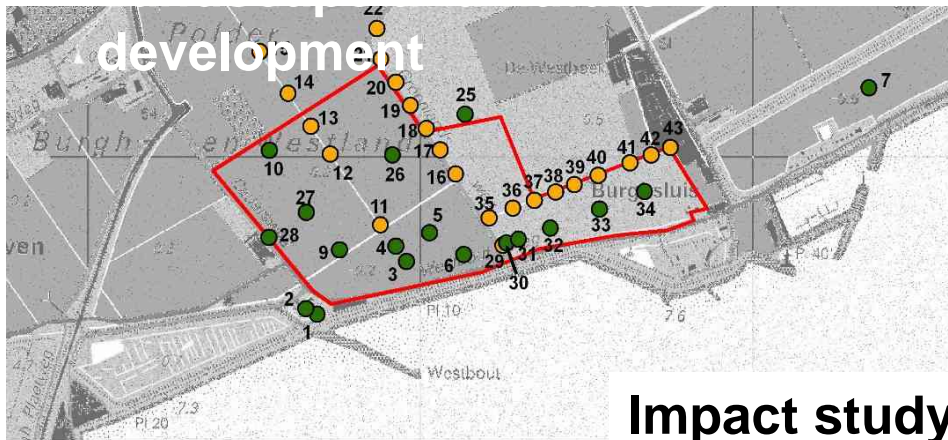
Development of the Sand Motor



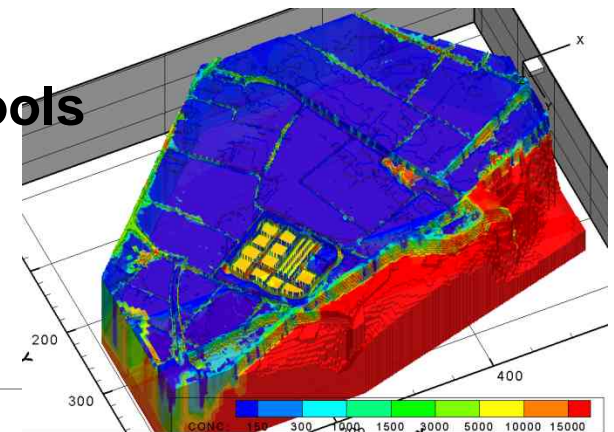
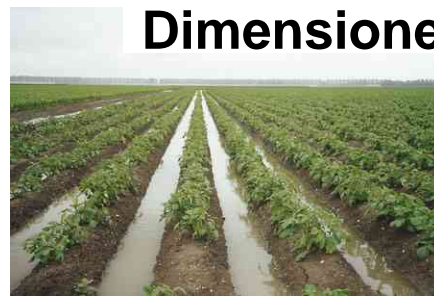
Local model: iMOD-SEAWAT Jurong Island Singapore



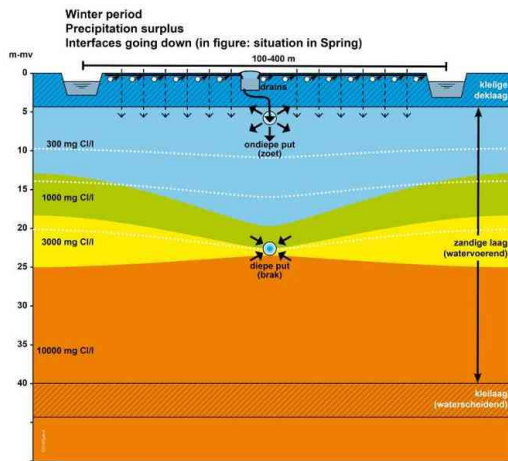
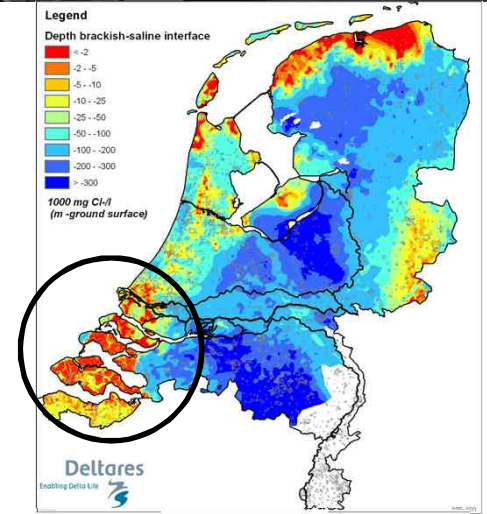
The Coastal Laboratory: aquaculture on fertile land



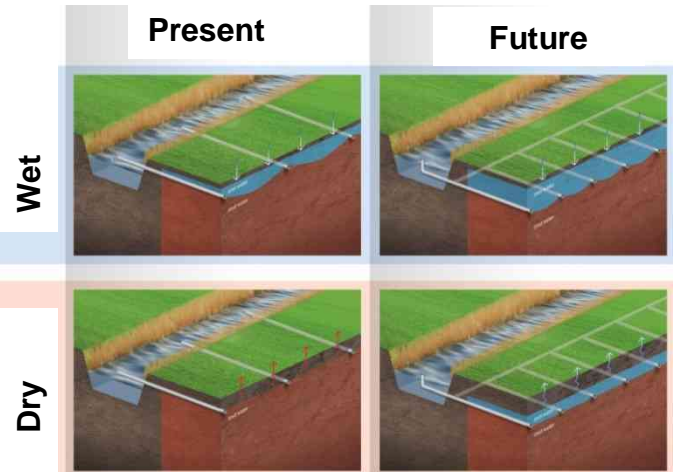
Impact study
Monitoring
Dimensioning saline pools



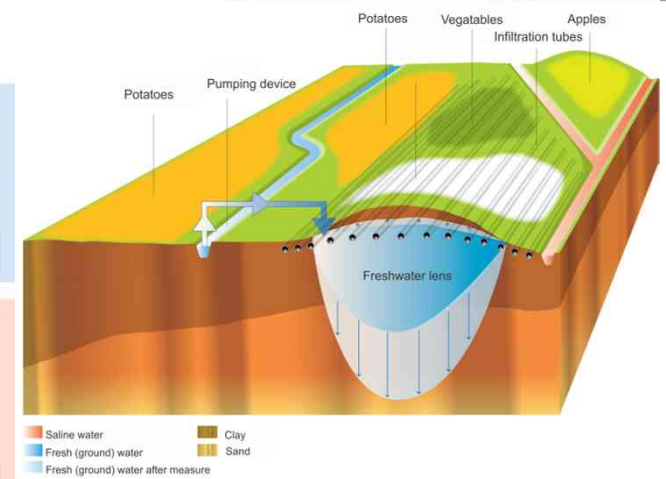
GO-FRESH: Local measures to increase fresh water supply



The Freshmaker
Injection fresh water and extraction saline



Drains2Buffer
Smart deep drainage protects thin freshwater lens



Creek Ridge Infiltration Tunnel
Elevation ground water level by infiltration surface

GO-FRESH: Startign up 3 local fresh water supply pilots

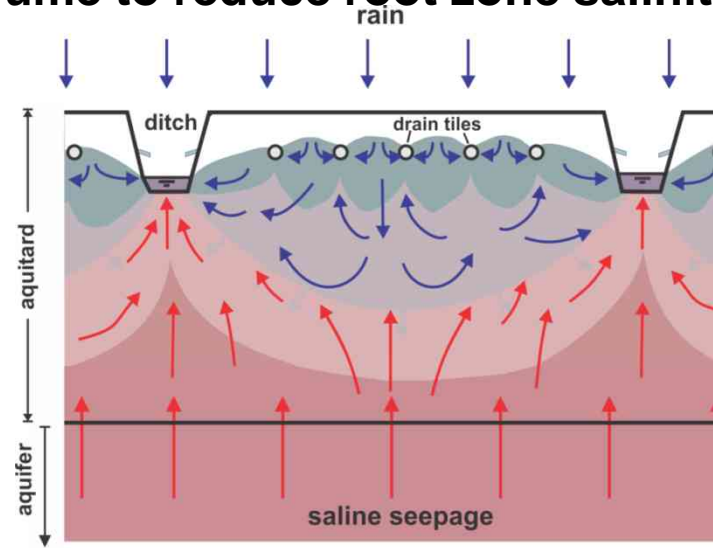
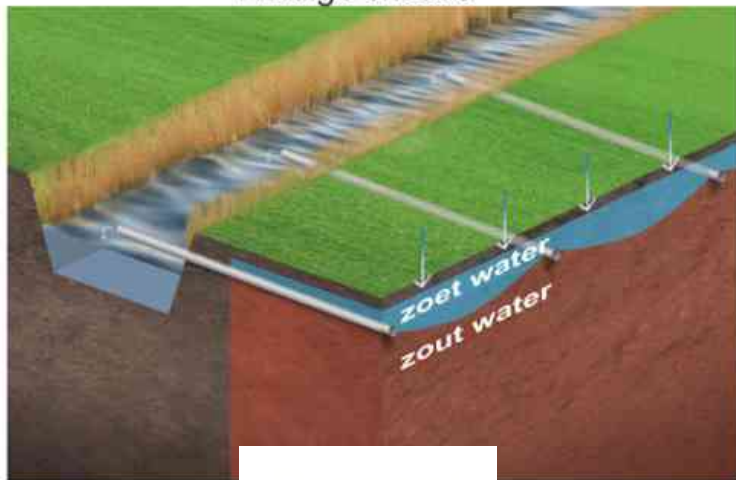


Drains2Buffer

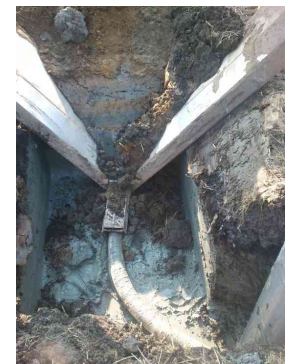
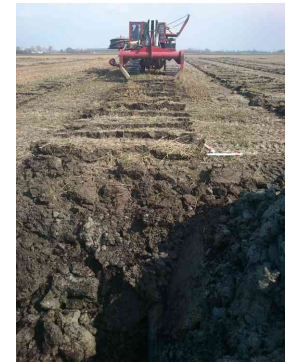
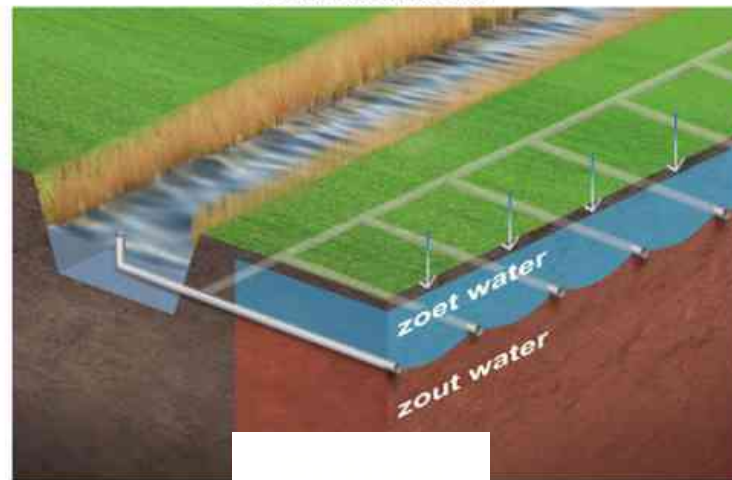
Increase rainwater lens volume to reduce root zone salinity



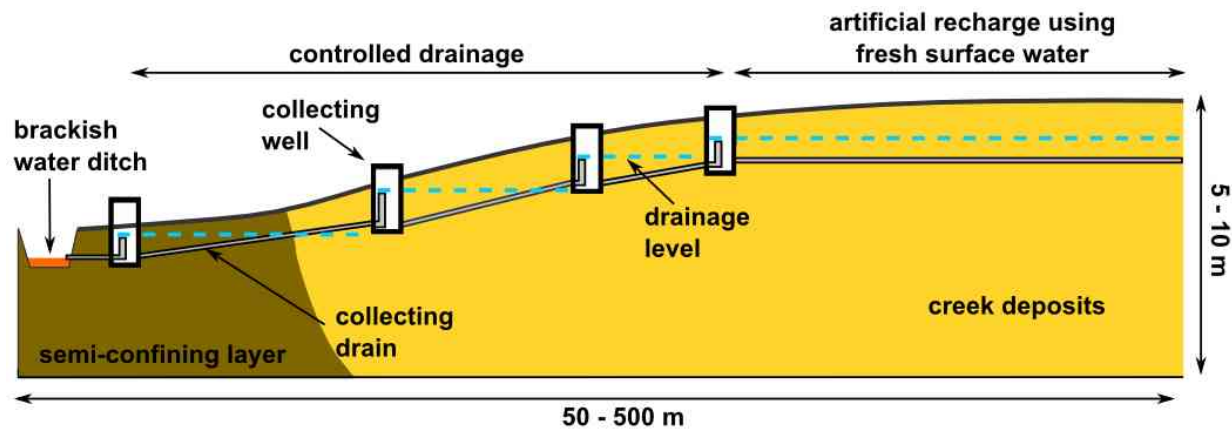
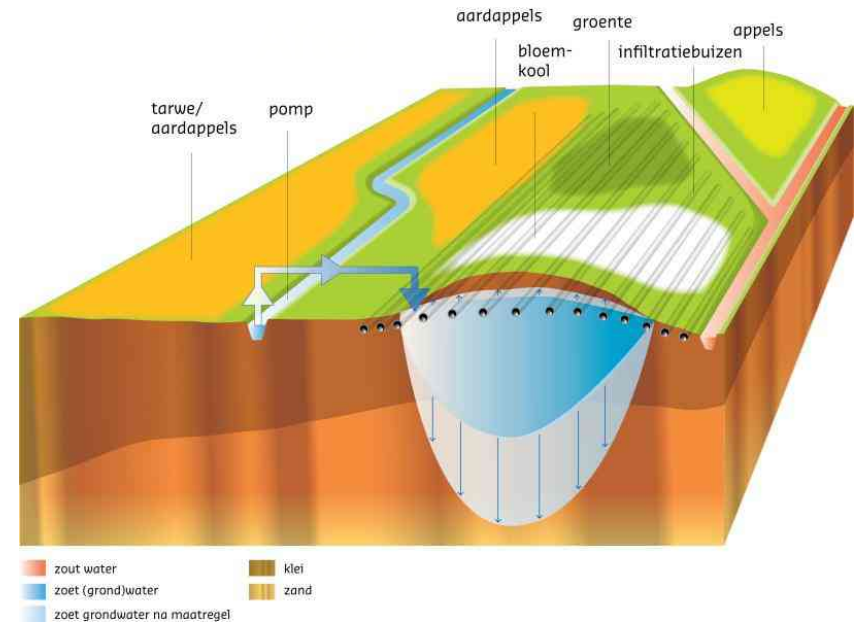
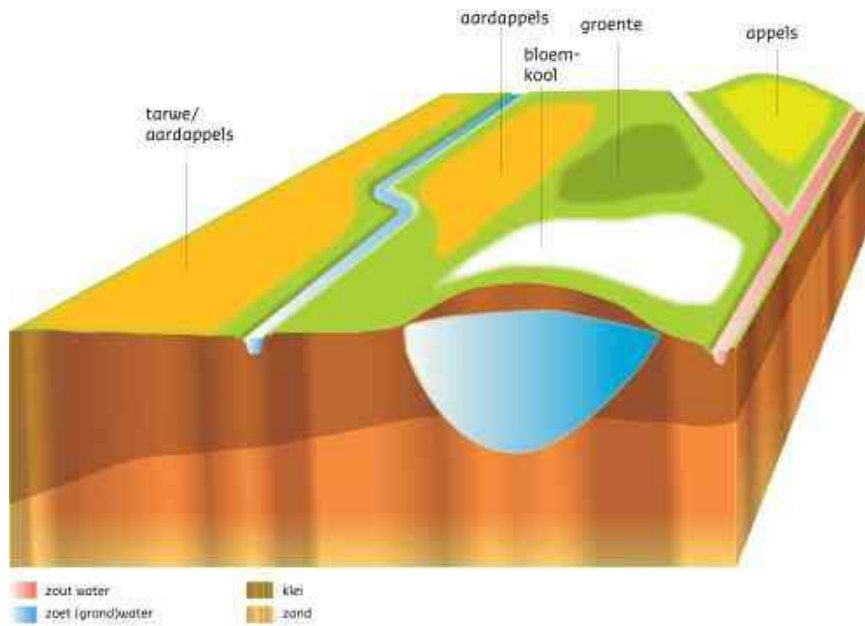
Huidige situatie



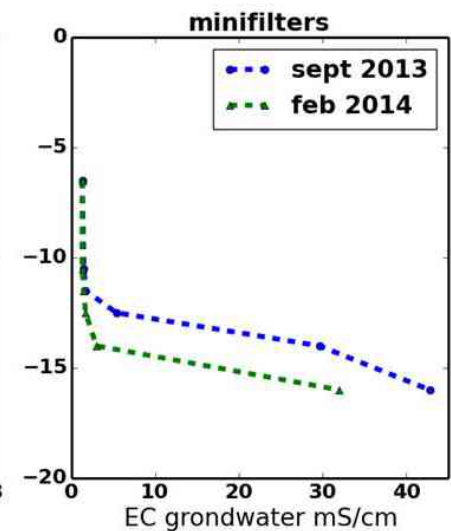
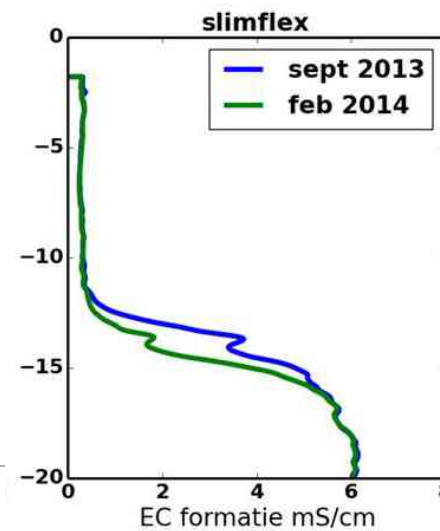
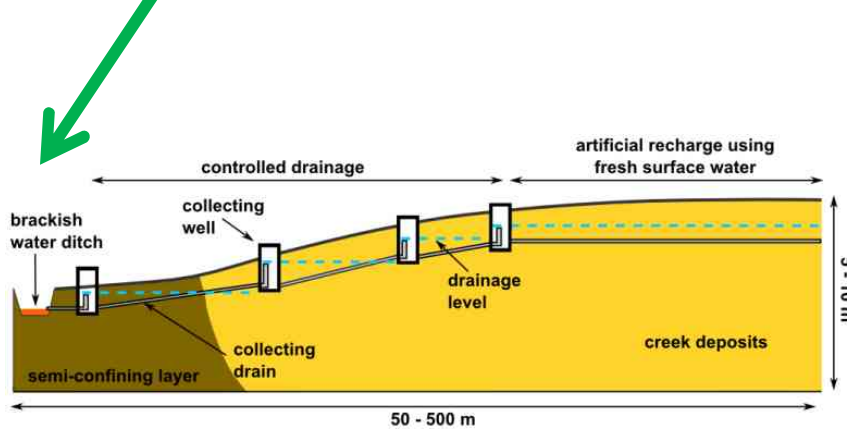
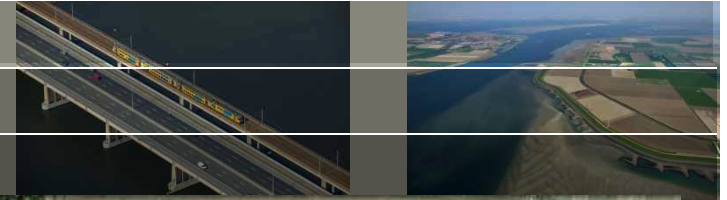
Nieuwe situatie



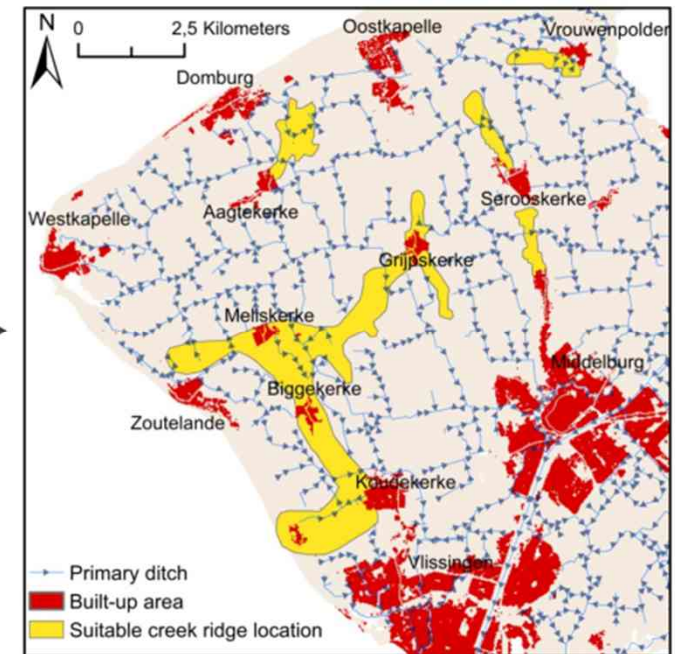
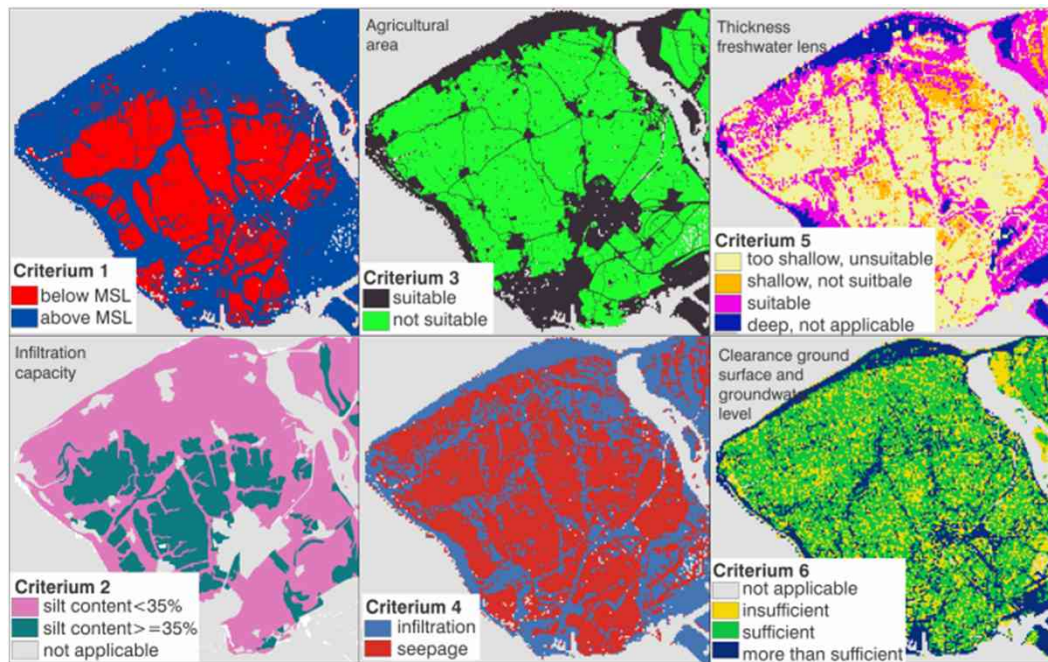
Increase of freshwater lens by active infiltration fresh surface water: pilot GO-FRESH (Pauw et al., 2015)



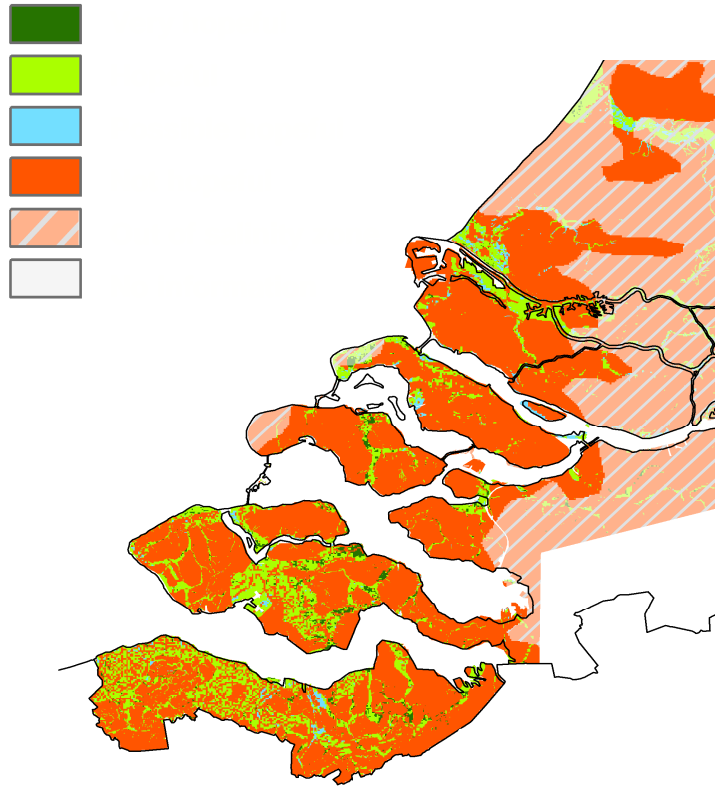
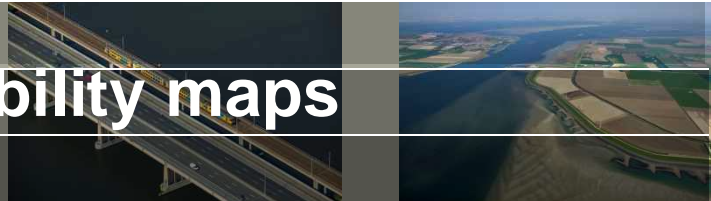
Pilot Creek ridge infiltration



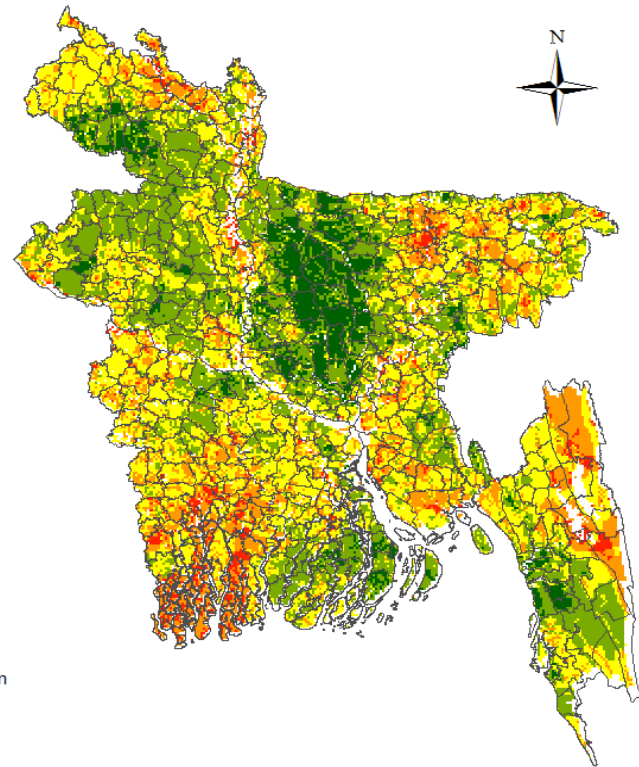
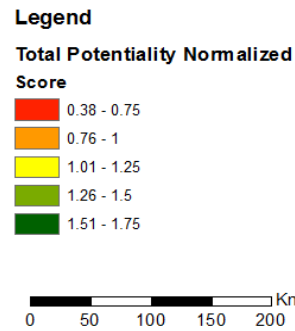
Up-scaling: potential and vulnerability maps at different scales

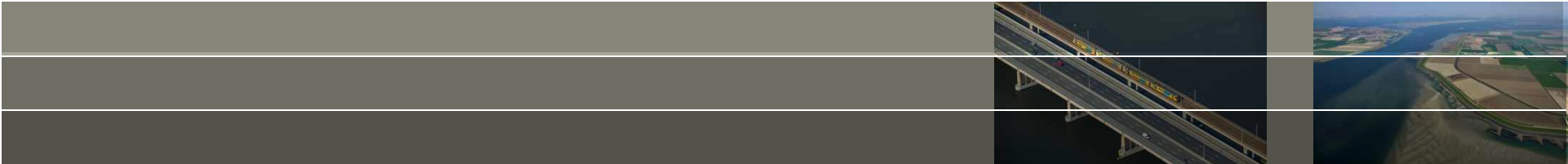


Up-scaling: potential and vulnerability maps at different scales



Creek Ridge Infiltration







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

**or other flooding events*

Daniel Zamrsky^{1,2}, Marta Faneca Sánchez¹, **Gu Oude Essink**^{1,3}
Subsurface and Groundwater Systems
Deltares, The Netherlands
freshsalt.deltares.nl

2



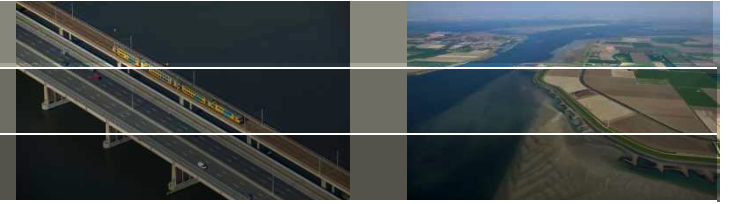
3



Universiteit Utrecht

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

Sense of Urgency

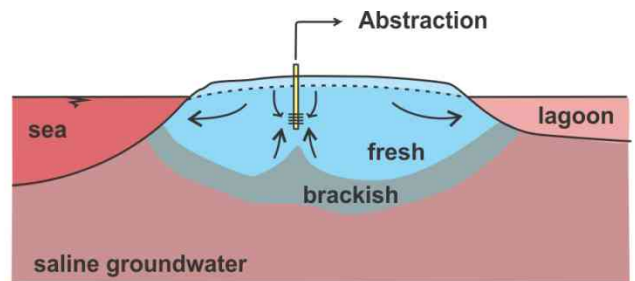


Every year, about 2 million people worldwide die from diarrhea, caused by bad drinking water quality

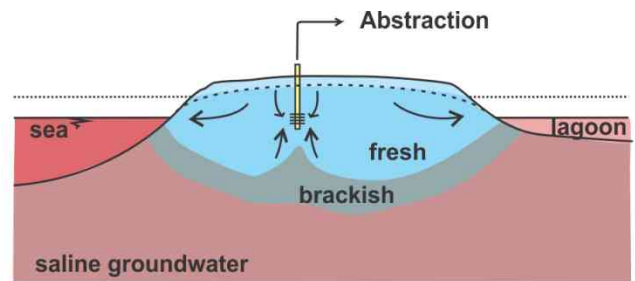
Groundwater is an important source of drinking water in underdeveloped countries, due to its high quality and relatively easy-to-access quantity (now 30% and increasing)

What will happen when a disaster like a tsunami hits a coastal area?

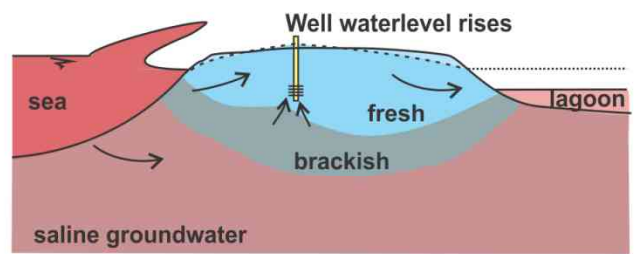
Salinization of fresh groundwater by tsunami inundations might lead to a temporal stop of groundwater extractions in affected areas



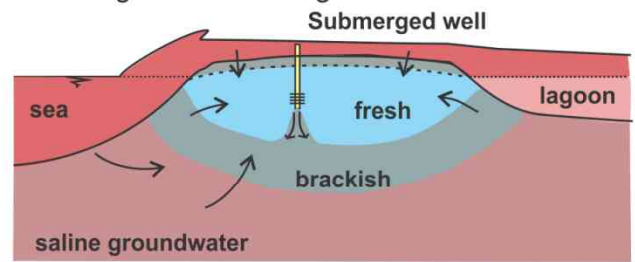
1. Before Tsunami



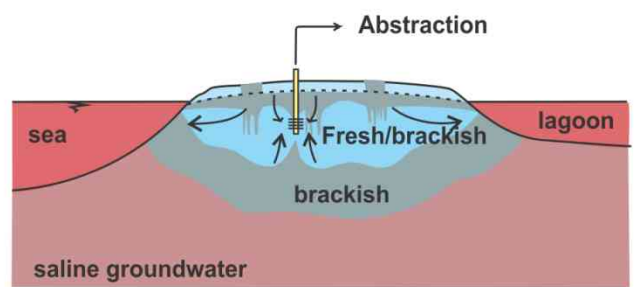
2. Just before Tsunami:
Lowering of sea- and lagoonwater level



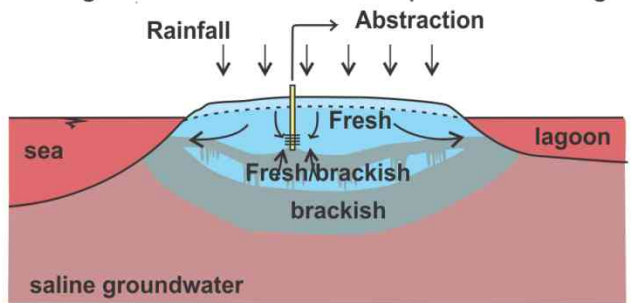
3. Just before Tsunami:
Subsurface pressure wave precedes surface wave



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



5. After Tsunami
Freshwater mixed with brackish water



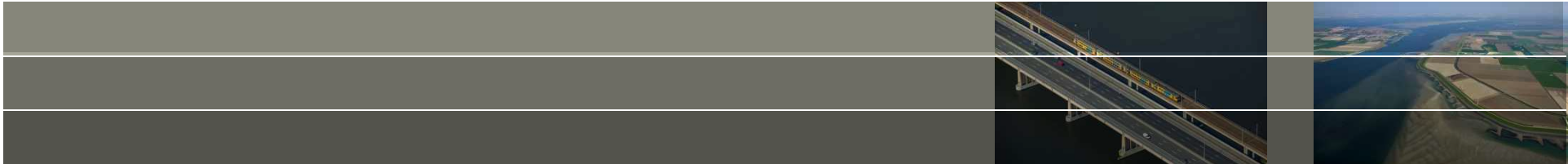
6. After Tsunami
Recharge by rainfall replaces brackish water

<http://svho-support.nl/index/images/new6.jpg>

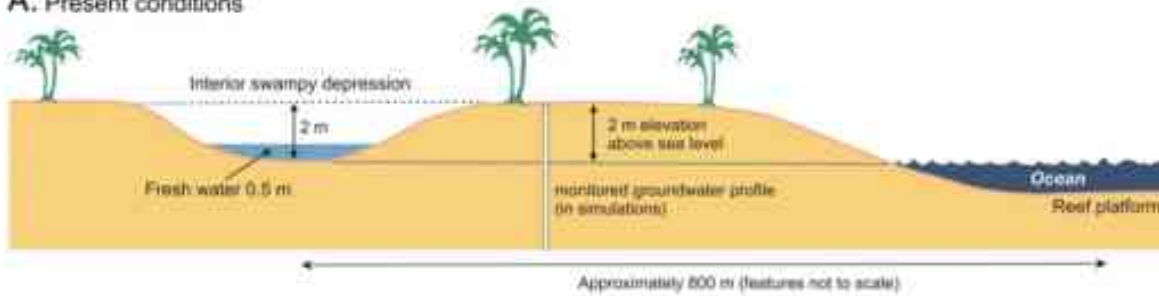
<http://svho-support.nl/index/images/new27.jpg>

<http://svho-support.nl/index/images/new32.jpg>

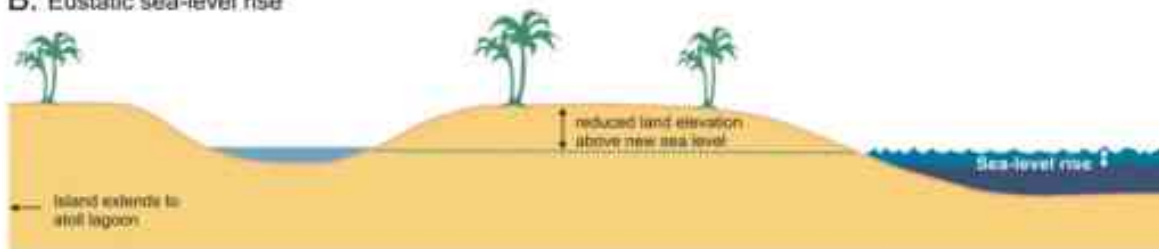




A. Present conditions



B. Eustatic sea-level rise



C. Cyclone washover after eustatic SLR



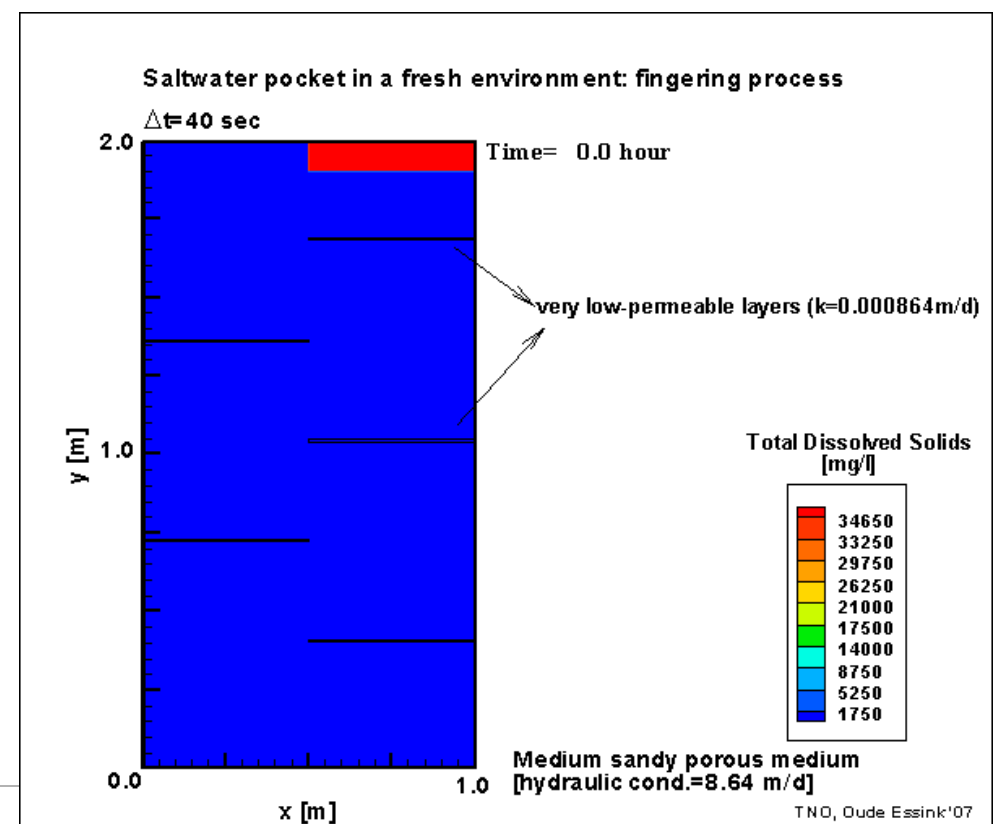
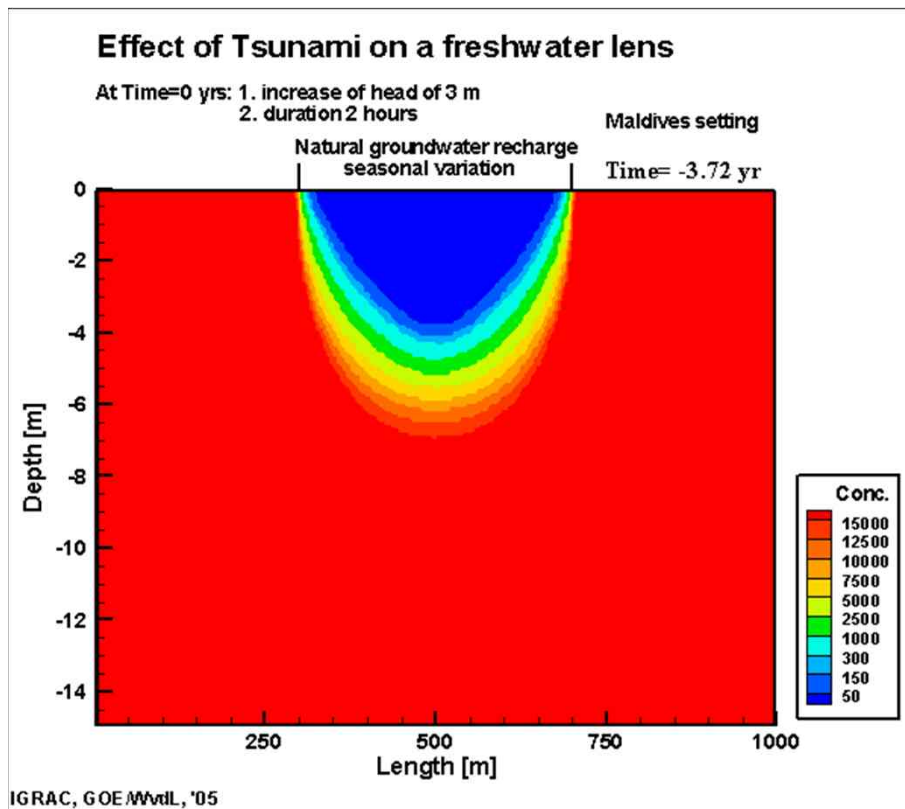
D. Cyclone washover with accompanying temporary SLR



Salinisation processes of fresh groundwater reserves

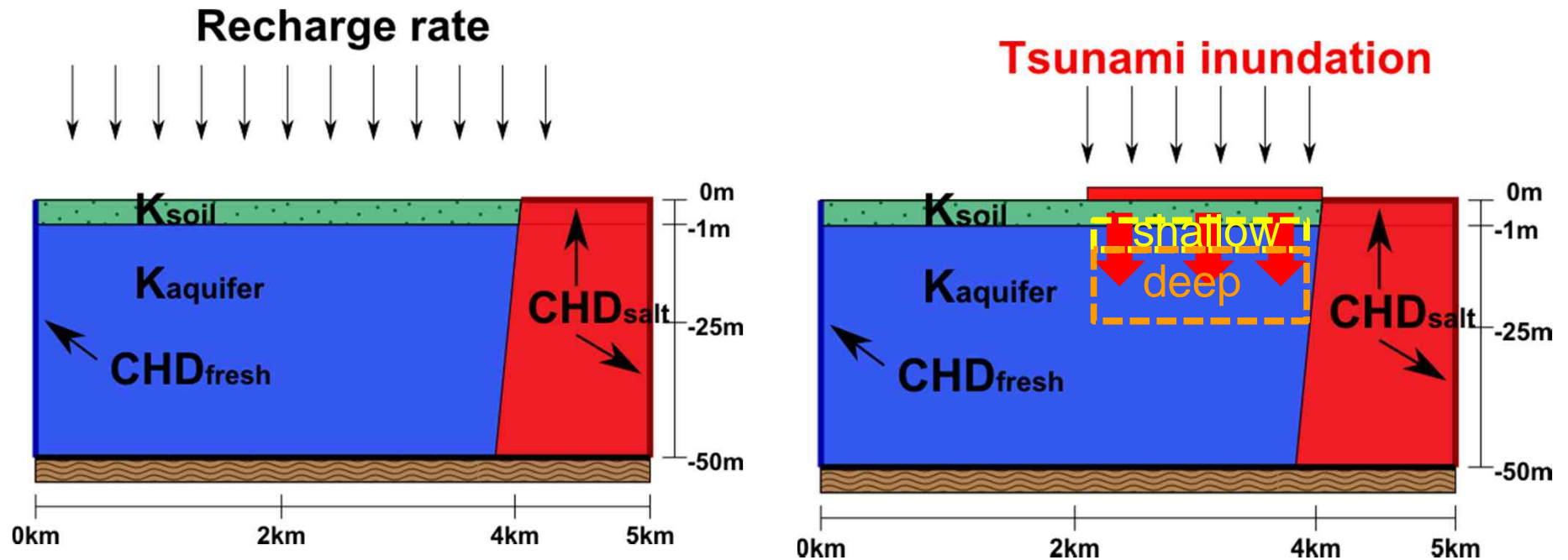
Impression of relevant salinisation processes in coastal aquifers:

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



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?

Using global datasets in the analysis

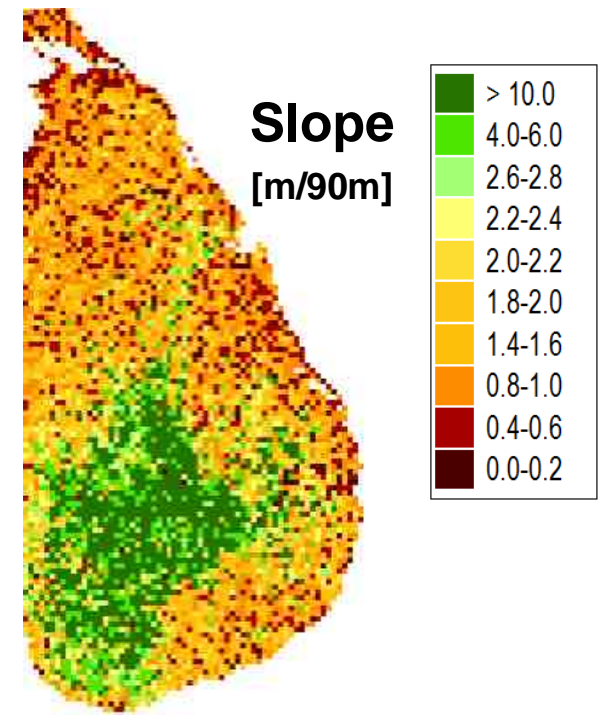
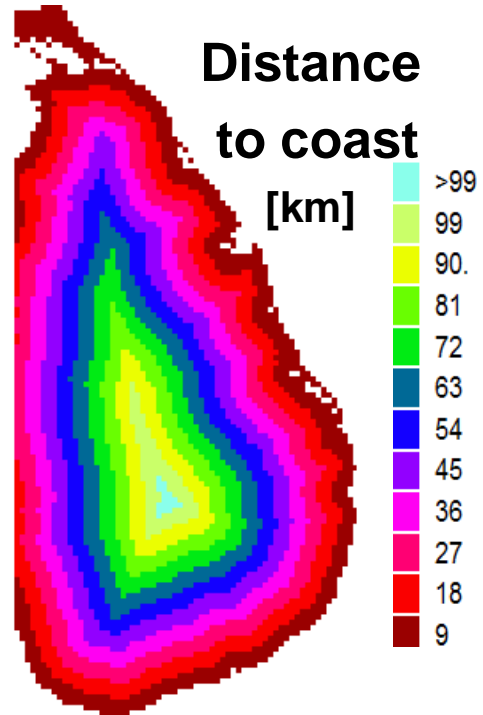
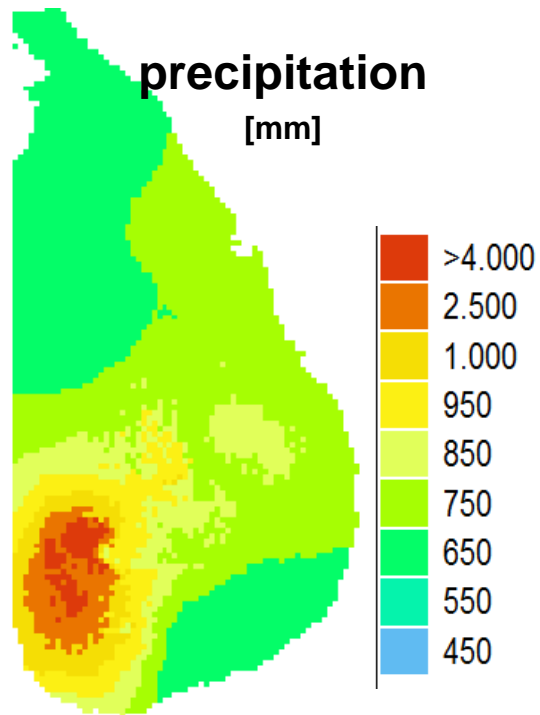
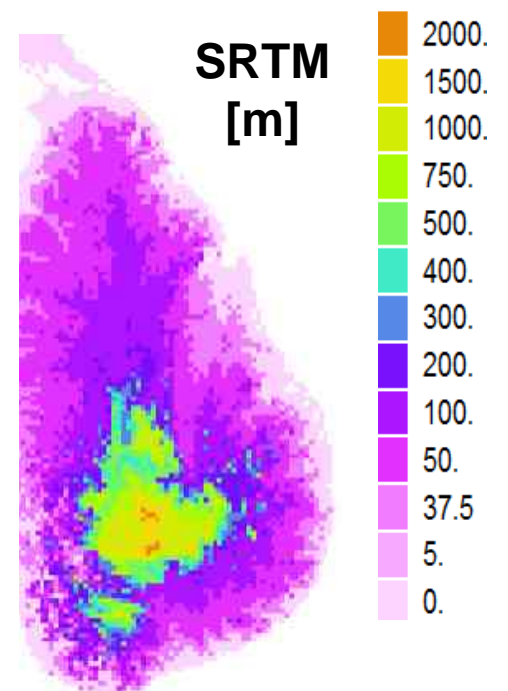
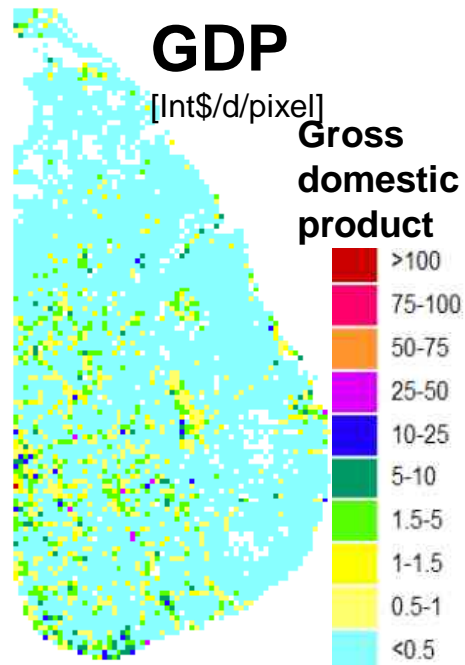
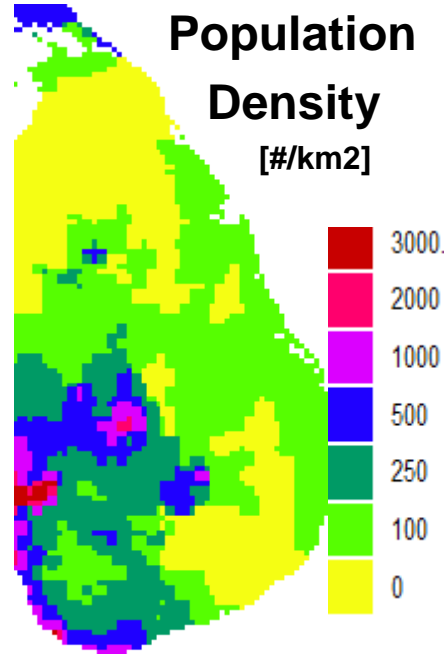
- **SRTM – DEM of the world**

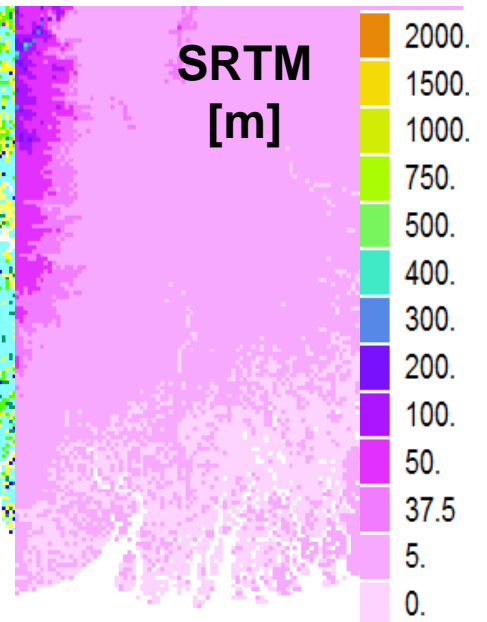
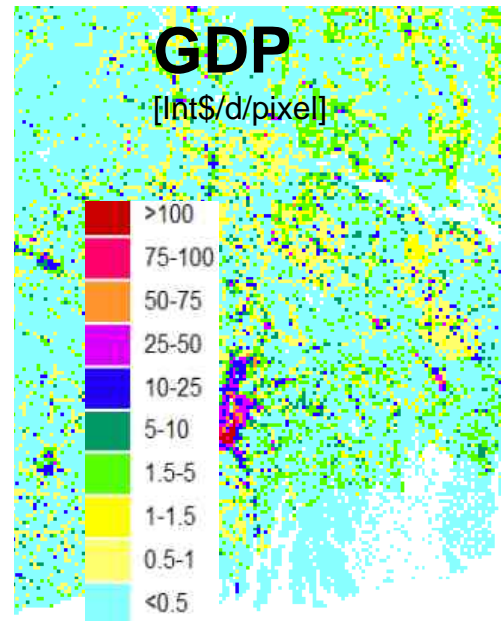
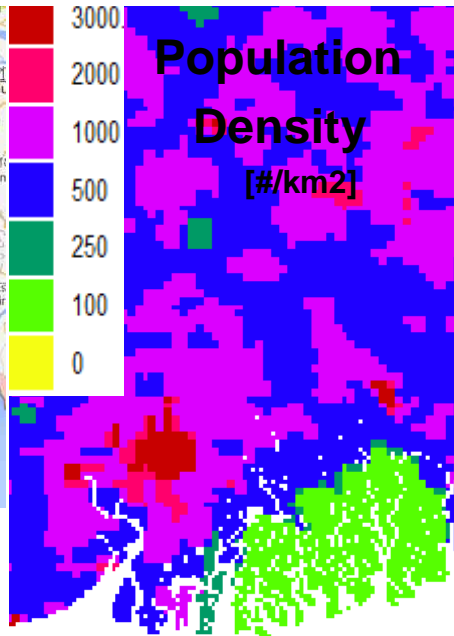
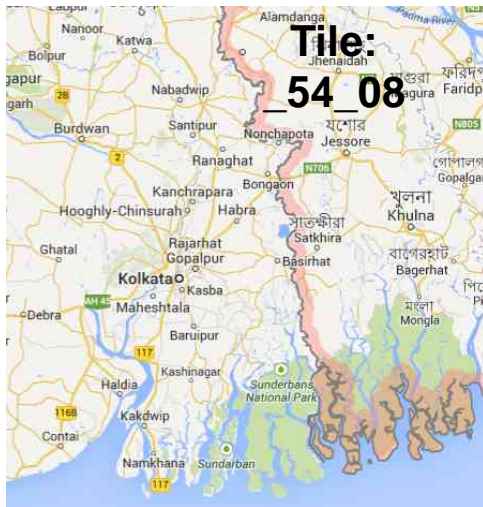
- Used to create:
 - *Slope*
 - *Distance to coast*

- **Resampling**

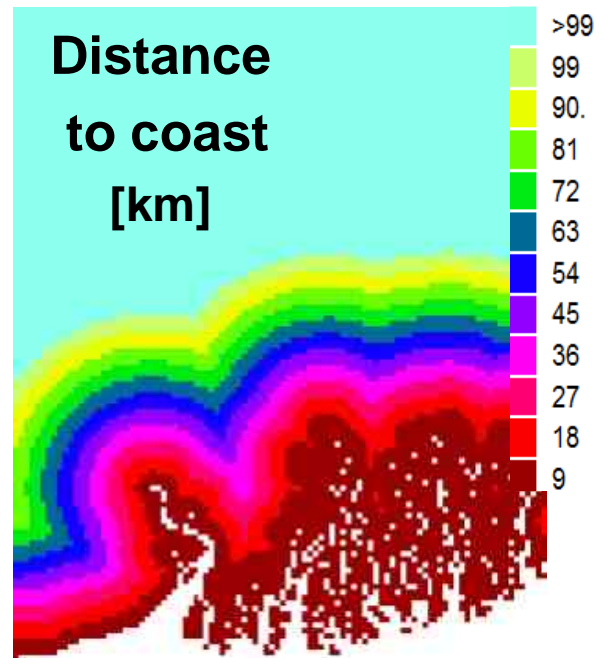
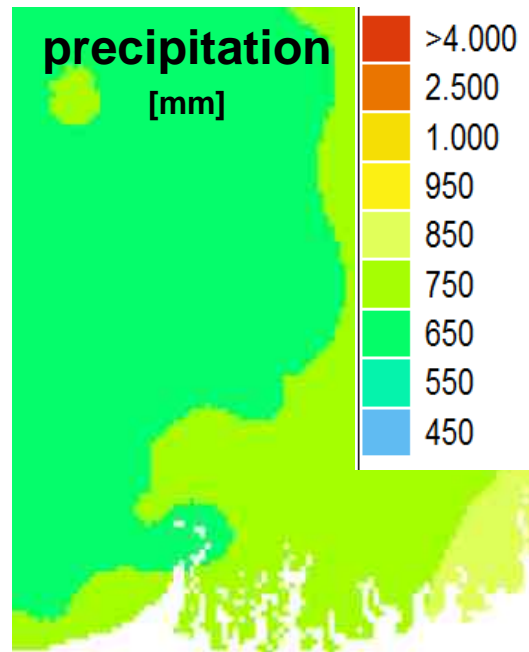
- Different resolution of other original datasets (e.g. population density)

Name	Type	Resolution
<i>SRTM</i>	raster	90 m
<i>Population density</i>	raster	≈ 4.6 km
<i>Land use</i>	raster	300 m
<i>Soil map</i>	raster	≈ 1 km
<i>Precipitation</i>	raster	≈ 1 km
<i>Tsunami occurrence</i>	point shape file	-
<i>Bathymetry</i>	raster	≈ 1 km
<i>GDP</i>	raster	≈ 1 km

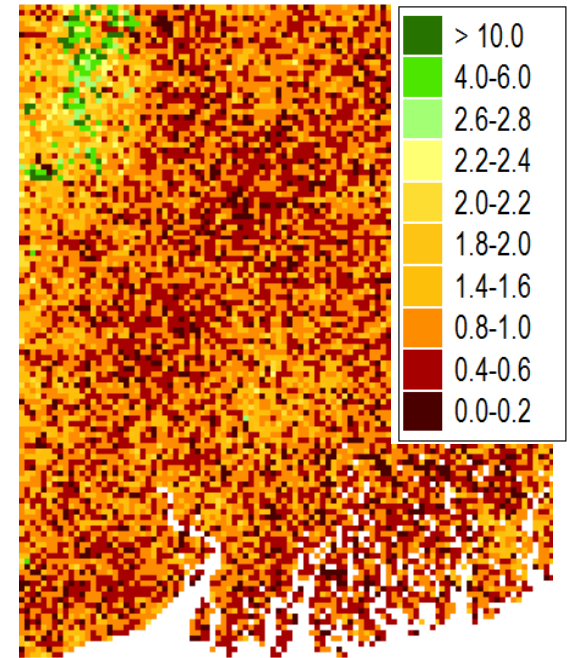




Bangladesh



Slope [m/90m]



Methodology Vulnerability Tsunami Index

- Combine topography, tsunami risk and socio-economic factors (poverty)
- Topographical vulnerability index: *Elevation*, *Slope*, *Distance to coast*
- Determine simple equation and ranges of values
 - Literature review (e.g. regional studies Indonesia)
 - Tsunami inundation extents and affected areas in history

Elevation ID_{elev}

Slope ID_{slope}

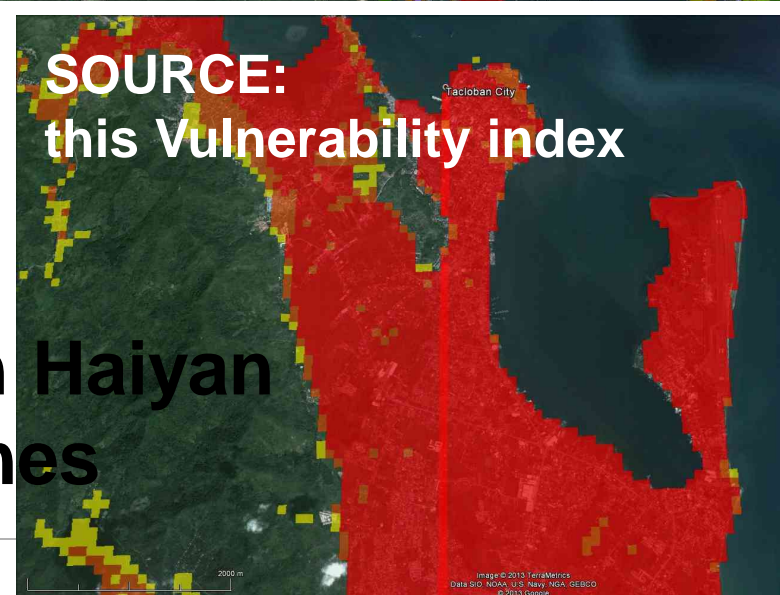
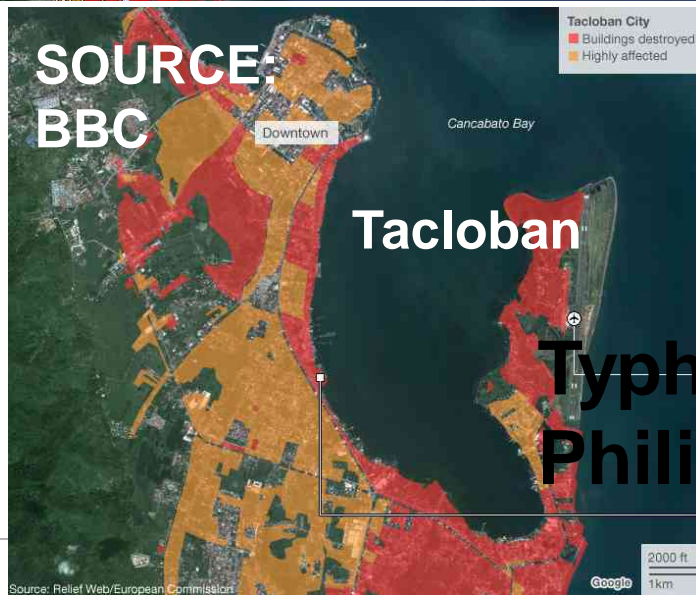
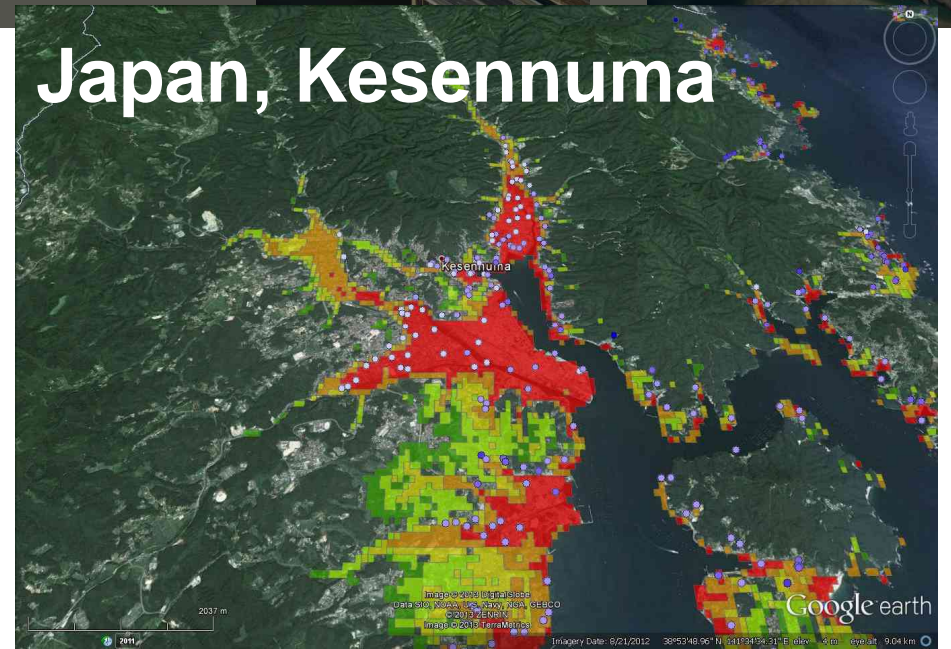
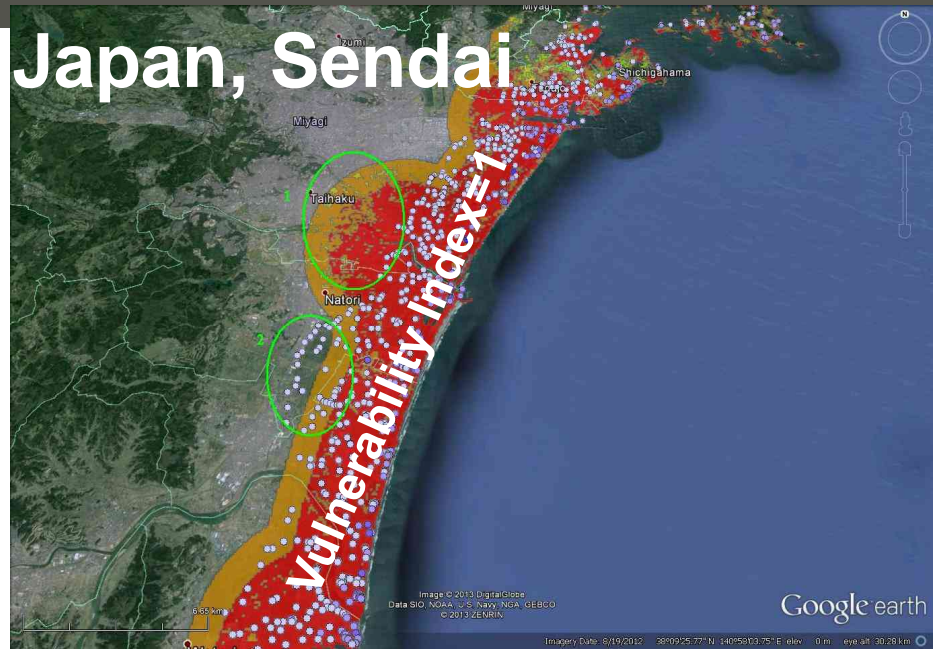
Distance to coast ID_{dist}

$$vulnerability\ index = 4 * ID_{elev} + ID_{dist} + ID_{slope}$$

<i>Final index</i>	Variable ID values and ranges					
	1	2	3	4	5	30
Variable / ID						
Topographical elevation (m above sea level)	min - 8	8 - 16	16 - 24	24 - 32	32 - 40	> 40
Topographical slope (°)	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	> 5
Distance to coast (pixels)	0 - 7	7 - 15	15 - 25	25 - 40	40 - 55	> 55
Distance to coast (m)	0 - 540	540 - 1350	1350 - 2250	2250 - 3600	3600 - 4950	> 4950

Vulnerability level	Sum of IDs	Vuln. ID
Very high	6 - 9	1
High	10 - 14	2
Medium	15 - 19	3
Low	20 - 24	4
Very low	25 - 29	5
None	> 30	6

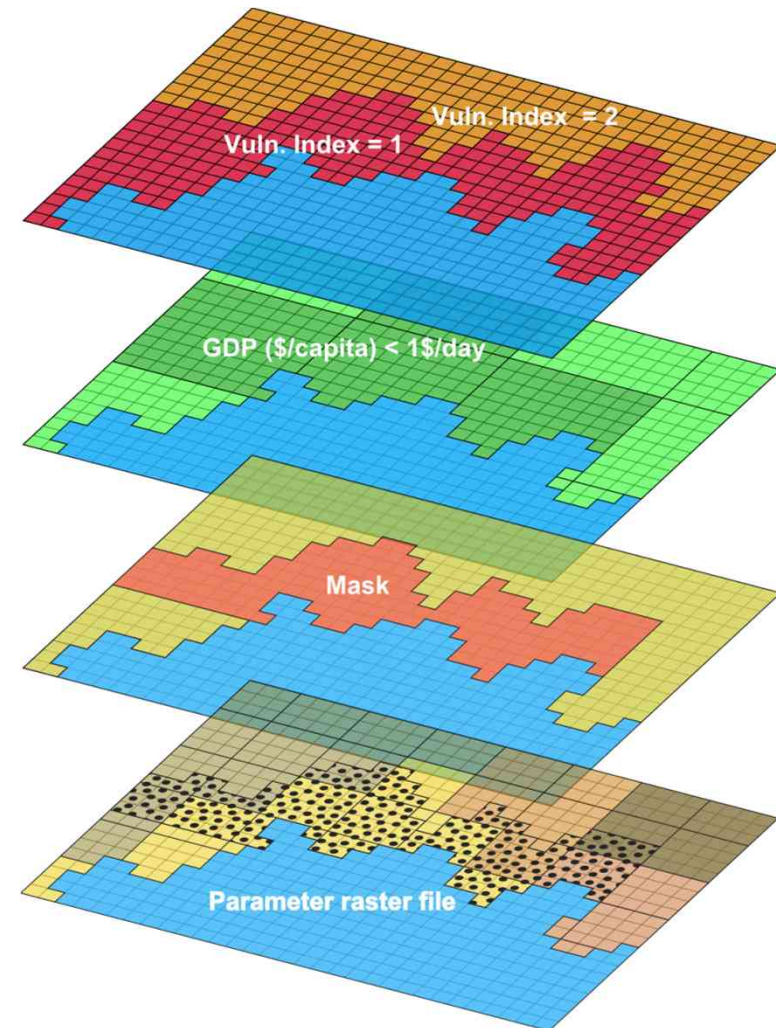
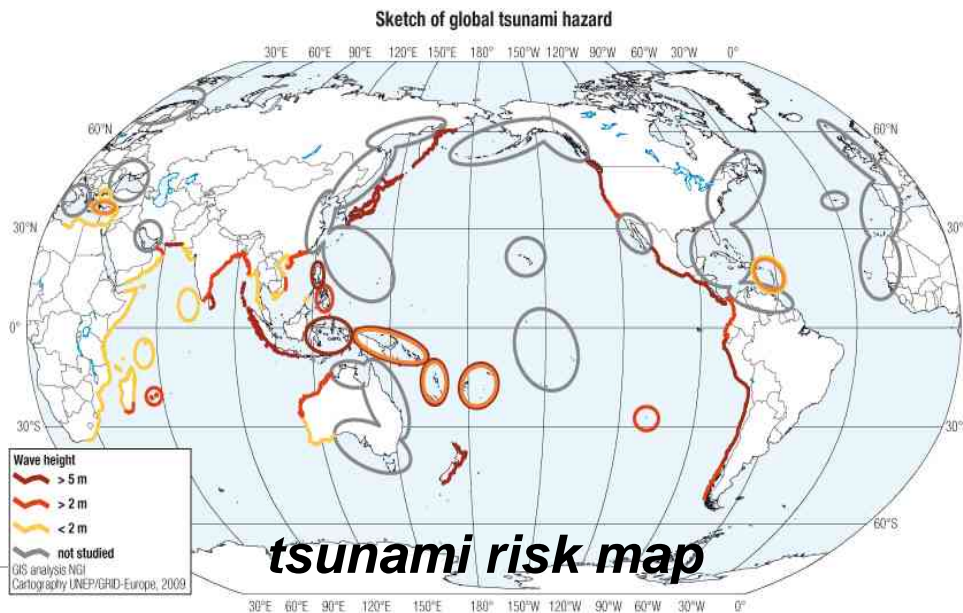
Vulnerability Tsunami index example

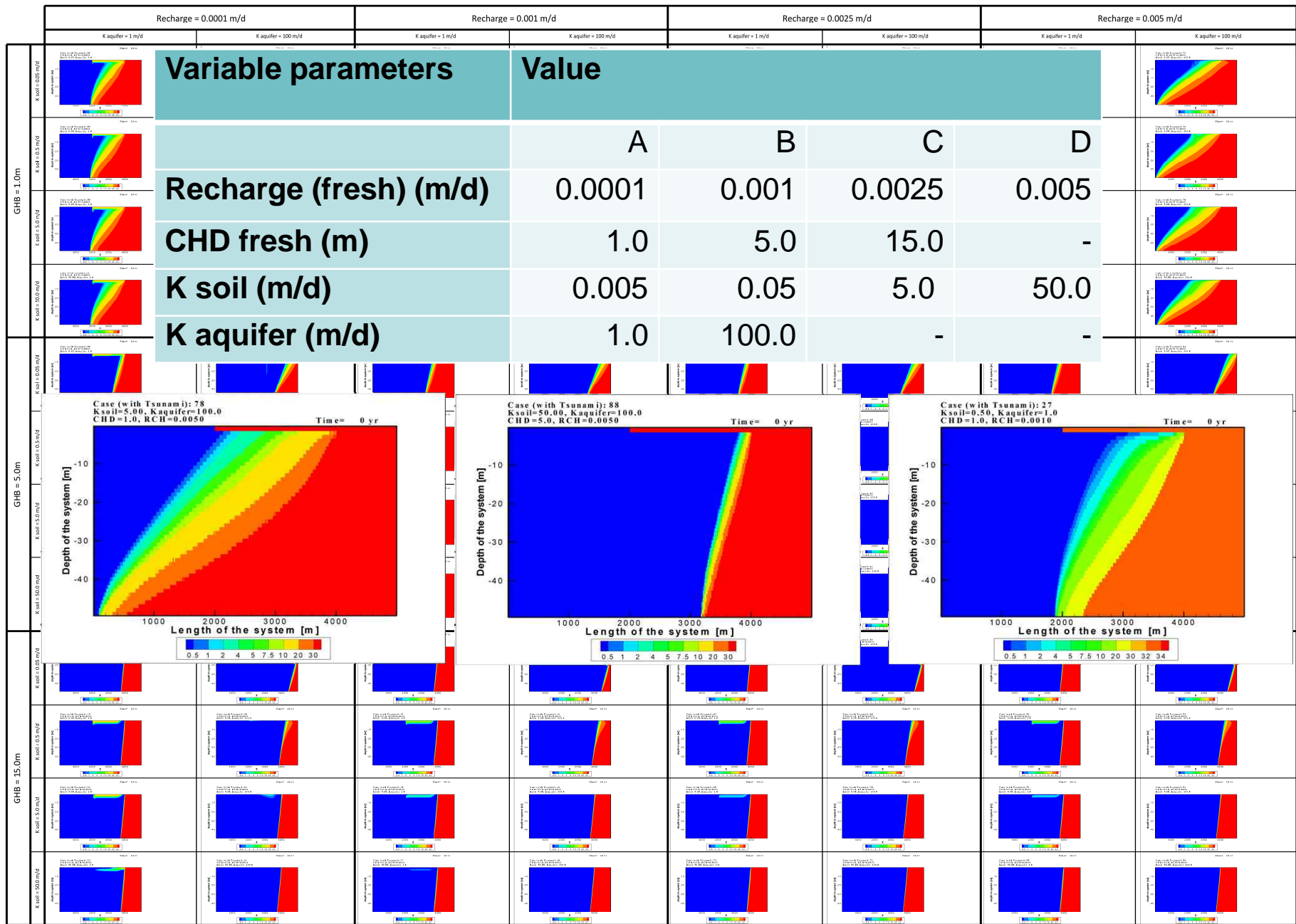


Socio-economic factor and parameter values statistics

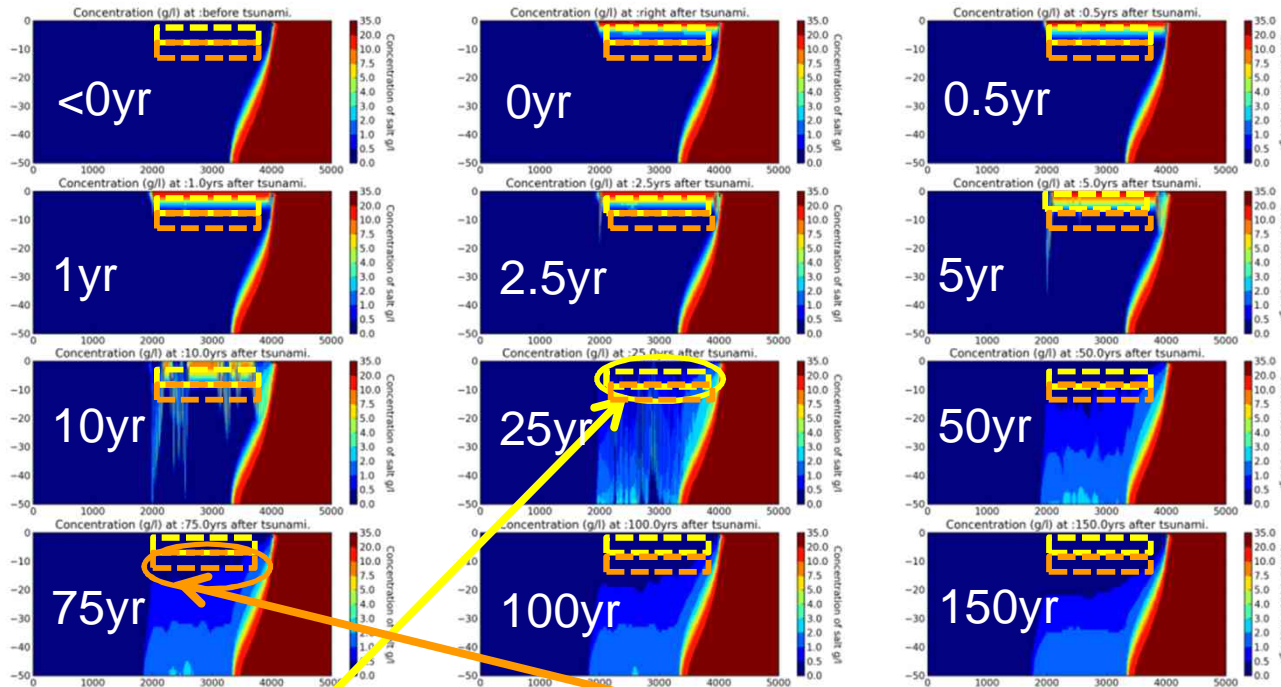
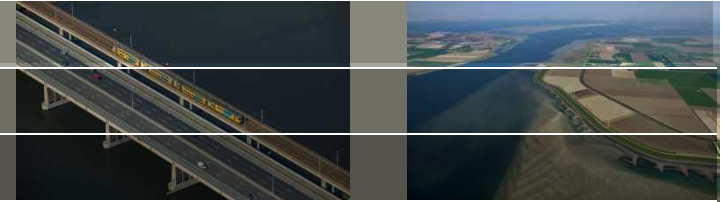
- **Focus on poor areas (1\$/day per capita)**
 - Combining the pop. density and GDP datasets
- **Parameter statistics for chosen areas**
 - Soil types
 - Precipitation
 - Population density

Input to model (total # simulations : 96)

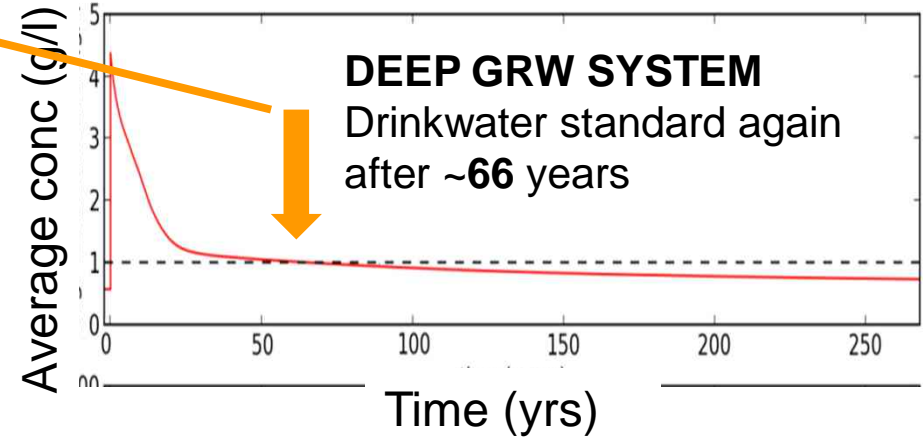
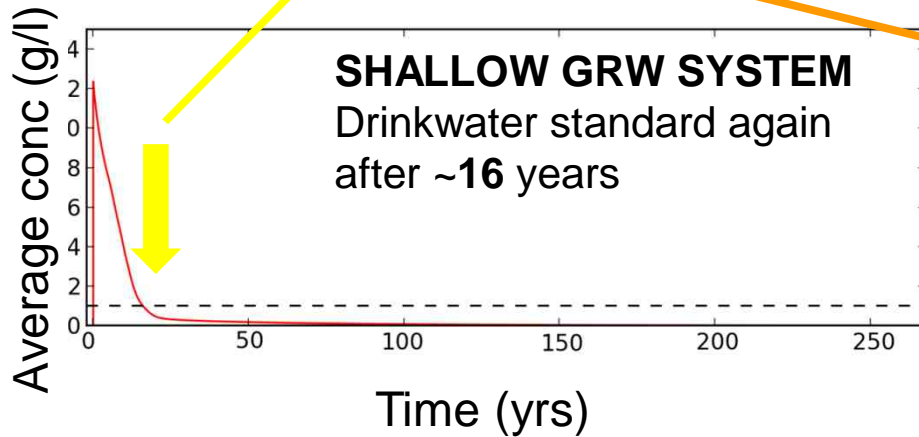




Results of one case



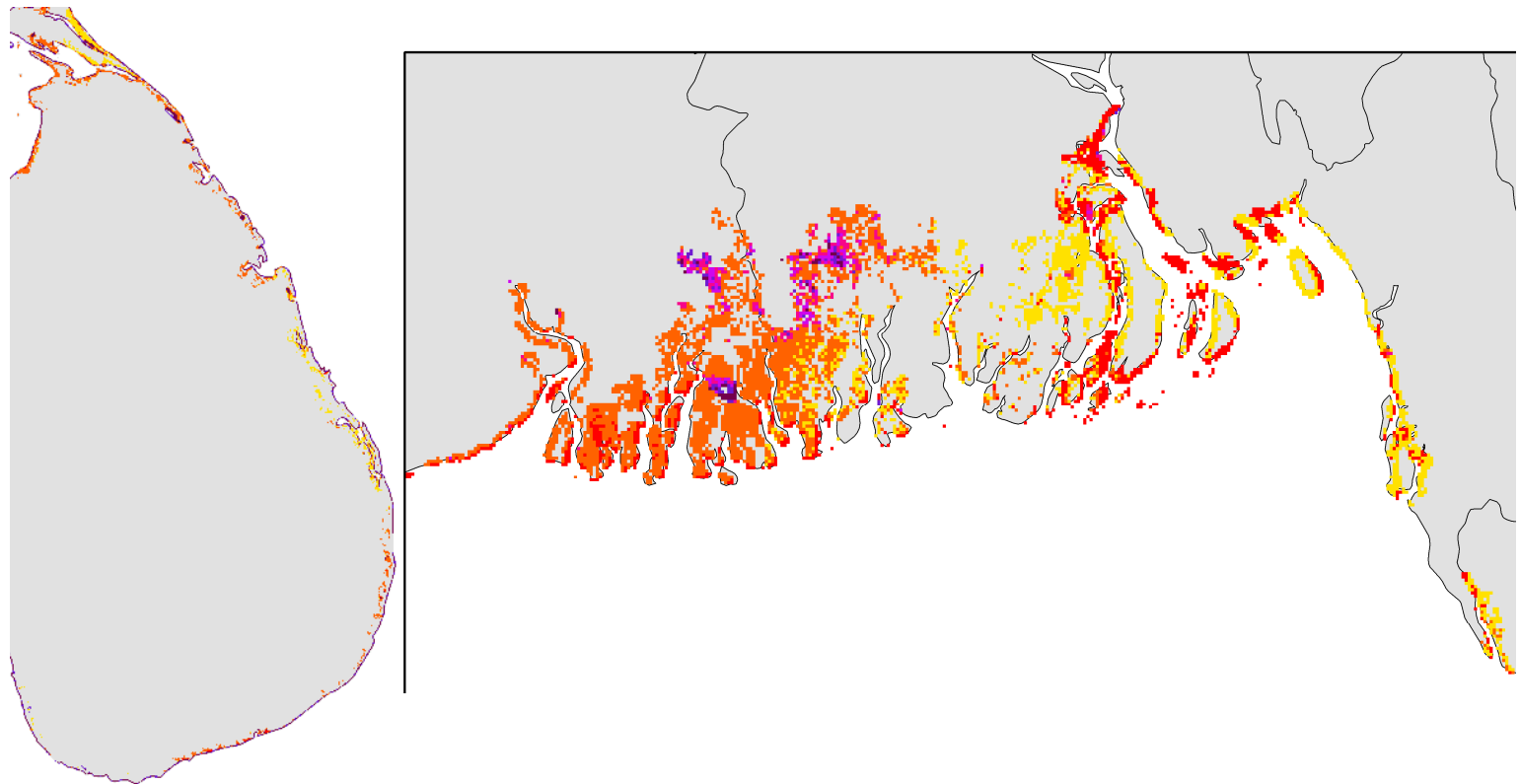
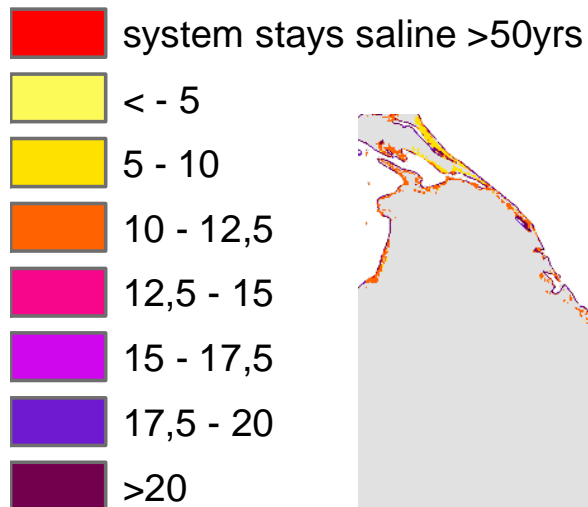
Salt water fingers intrude the groundwater system the coming tens of years

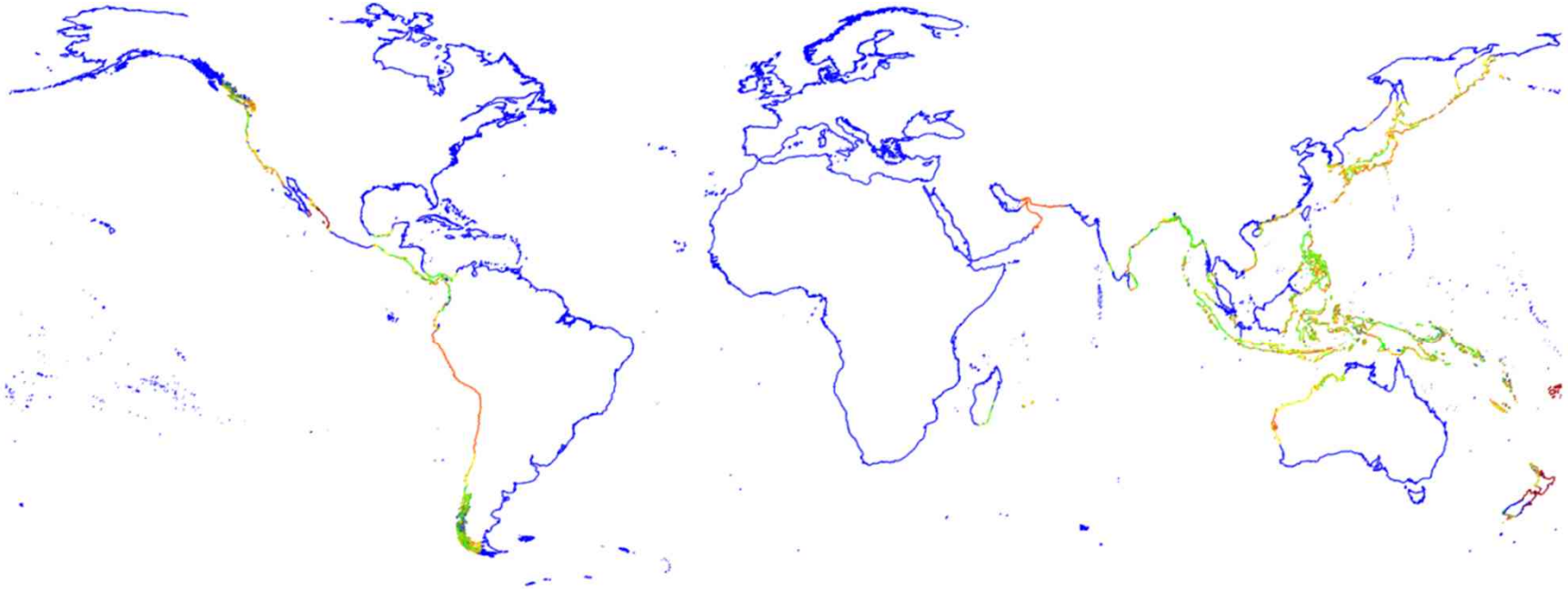


Back to the Map!

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

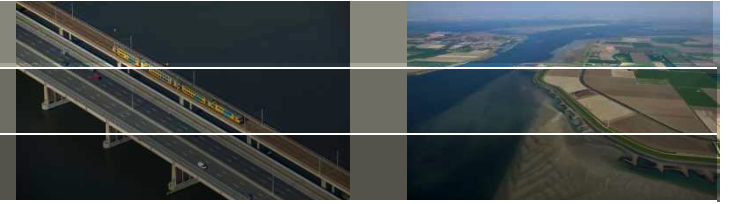
Legend Time (yrs) before the shallow coastal groundwater system is fresh enough again for drinking water extraction





Vulnerability of groundwater aquifers to tsunami effects, evaluated as time (yrs.) necessary for aquifer to reach 95% fresh-water distribution of pre-tsunami state, indicating drinking water availability using groundwater resources in coastal zones after flooding disasters

Concluding



On approach

- Assessing vulnerability index on global scale is possible with free accessible datasets and tools
- Methodology is tested in some regional studies and shows good fit with tsunami run-up measurements

On fresh water resources:

- After a tsunami, groundwater in the coastal zone may stay salty and not drinkable for many years

We want to:

- test approach in one specific regional area, with detailed information

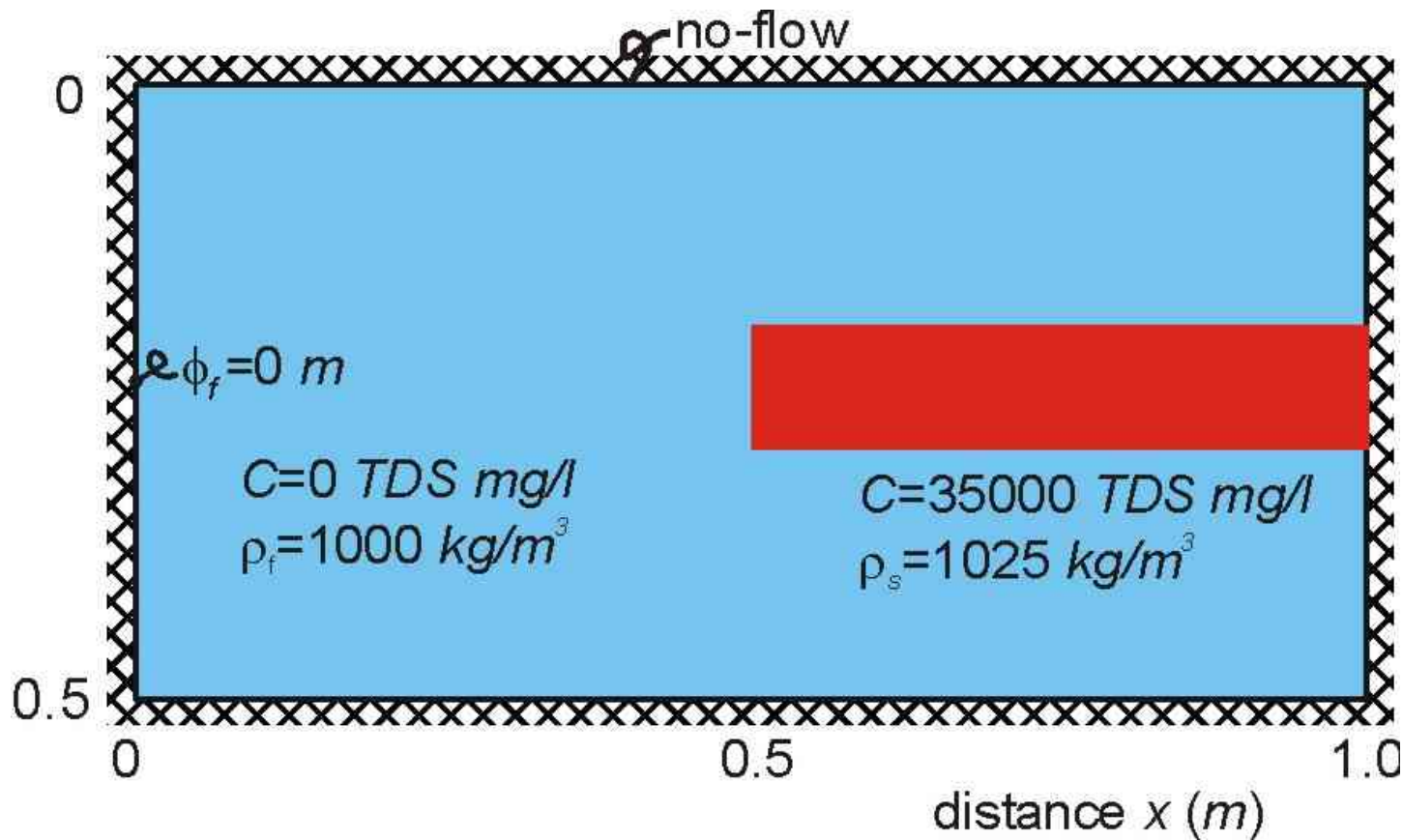
We need:

- global dataset on geology

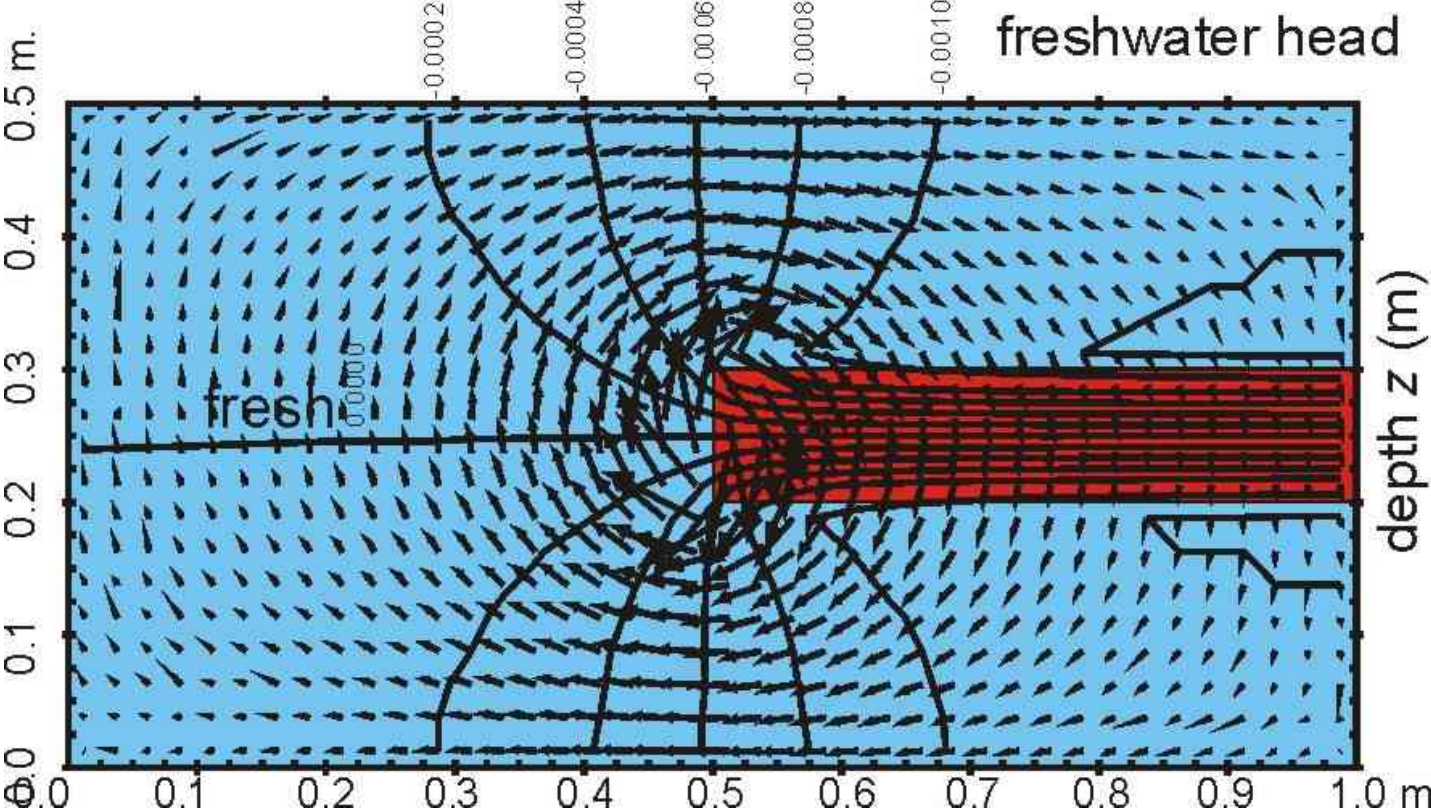
Next steps are:

- upscale to other flooding events (e.g. storm surges)
- Climate Change, Sea Level Rise, Global Change (groundwater extractions)
- 3D approach for the top 25 deltas worldwide, including land subsidence

Effect of size model cell on physical process



Effect of size model cell on physical process

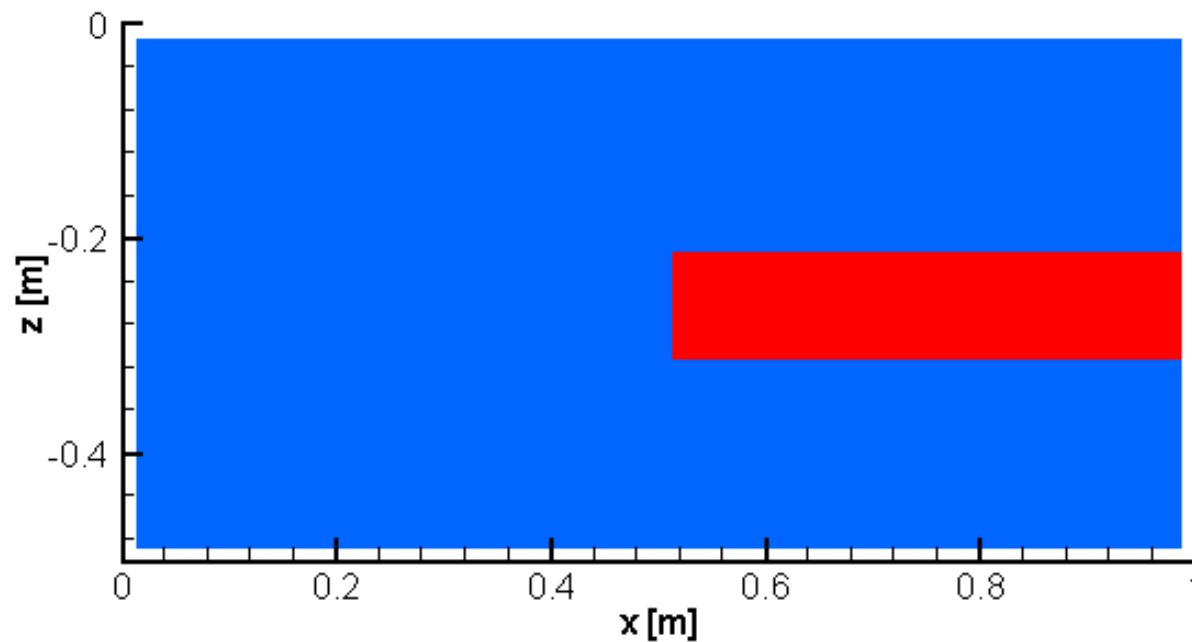


SALT WATER POCKET IN A FRESH ENVIRONMENT

Saline pocket in fresh groundwater: fingering process

40*20 cells

Time= 0 min

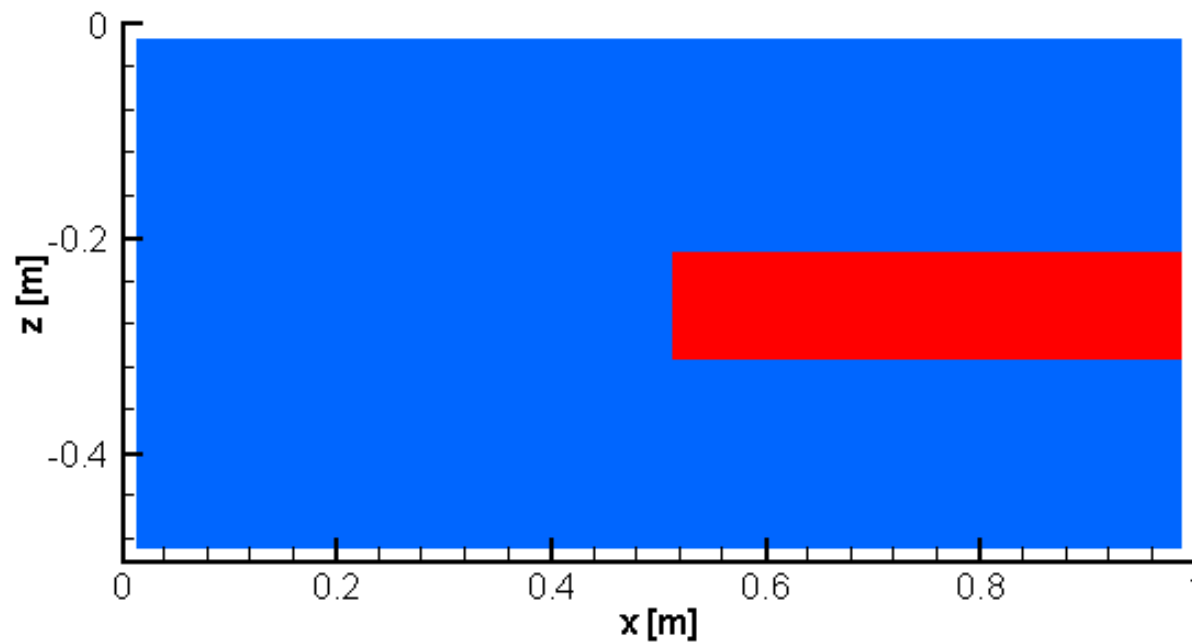


SALT WATER POCKET IN A FRESH ENVIRONMENT

Saline pocket in fresh groundwater: fingering process

40*20 cells

Time= 0 min

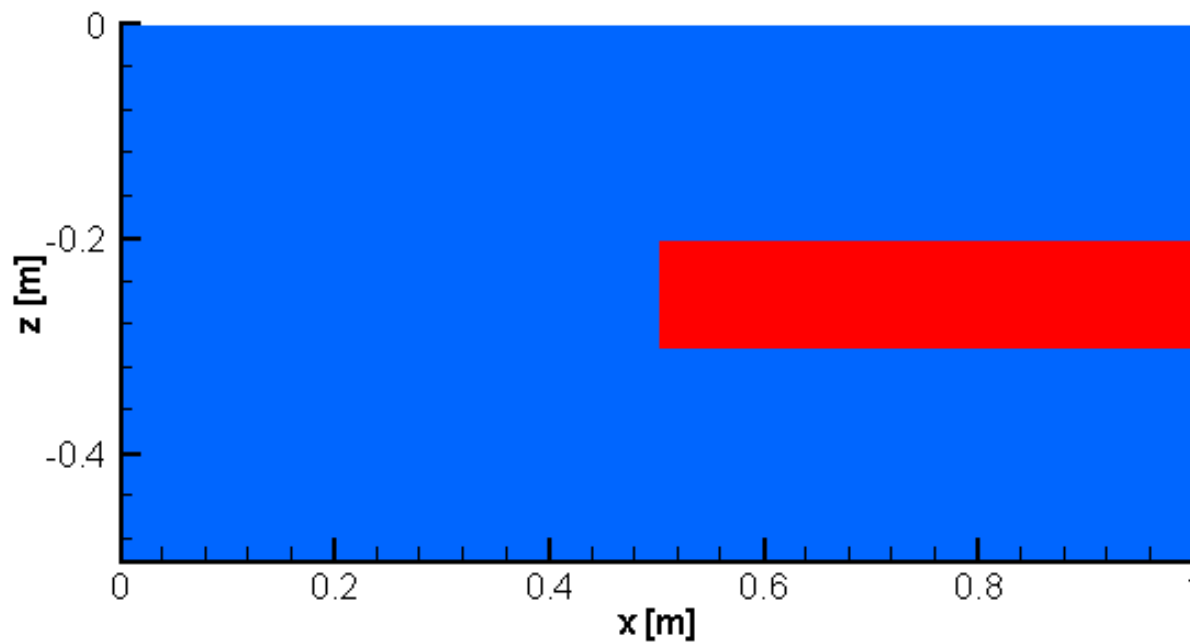


SALT WATER POCKET IN A FRESH ENVIRONMENT

Saline pocket in fresh groundwater: fingering process

320*160 cells

Time= 0 min

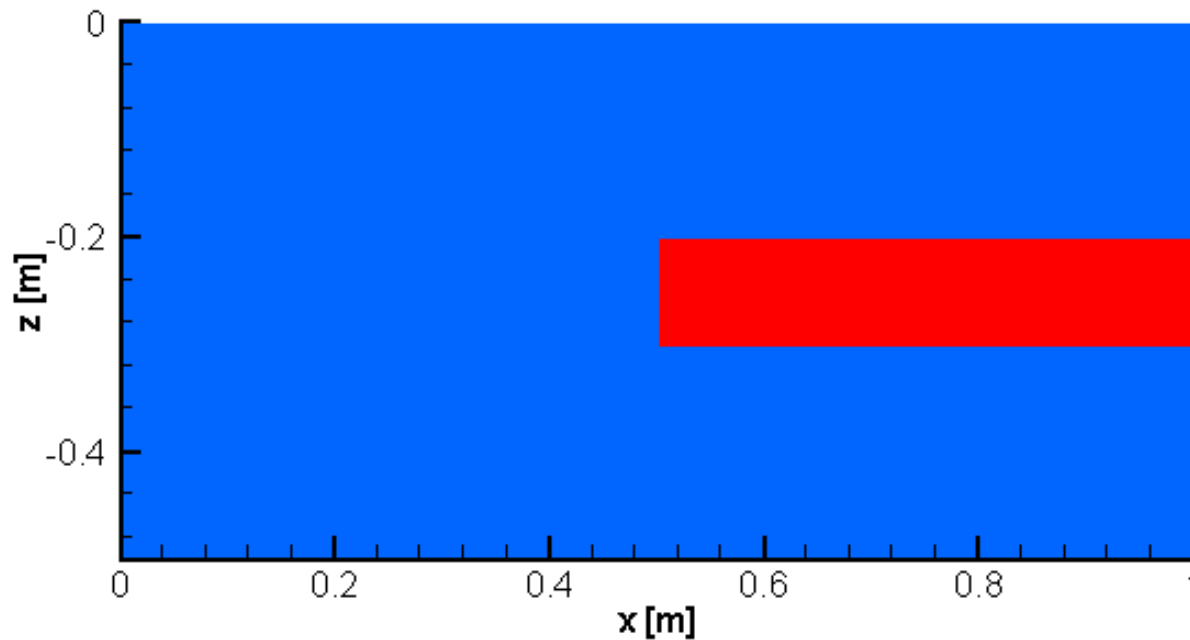


SALT WATER POCKET IN A FRESH ENVIRONMENT

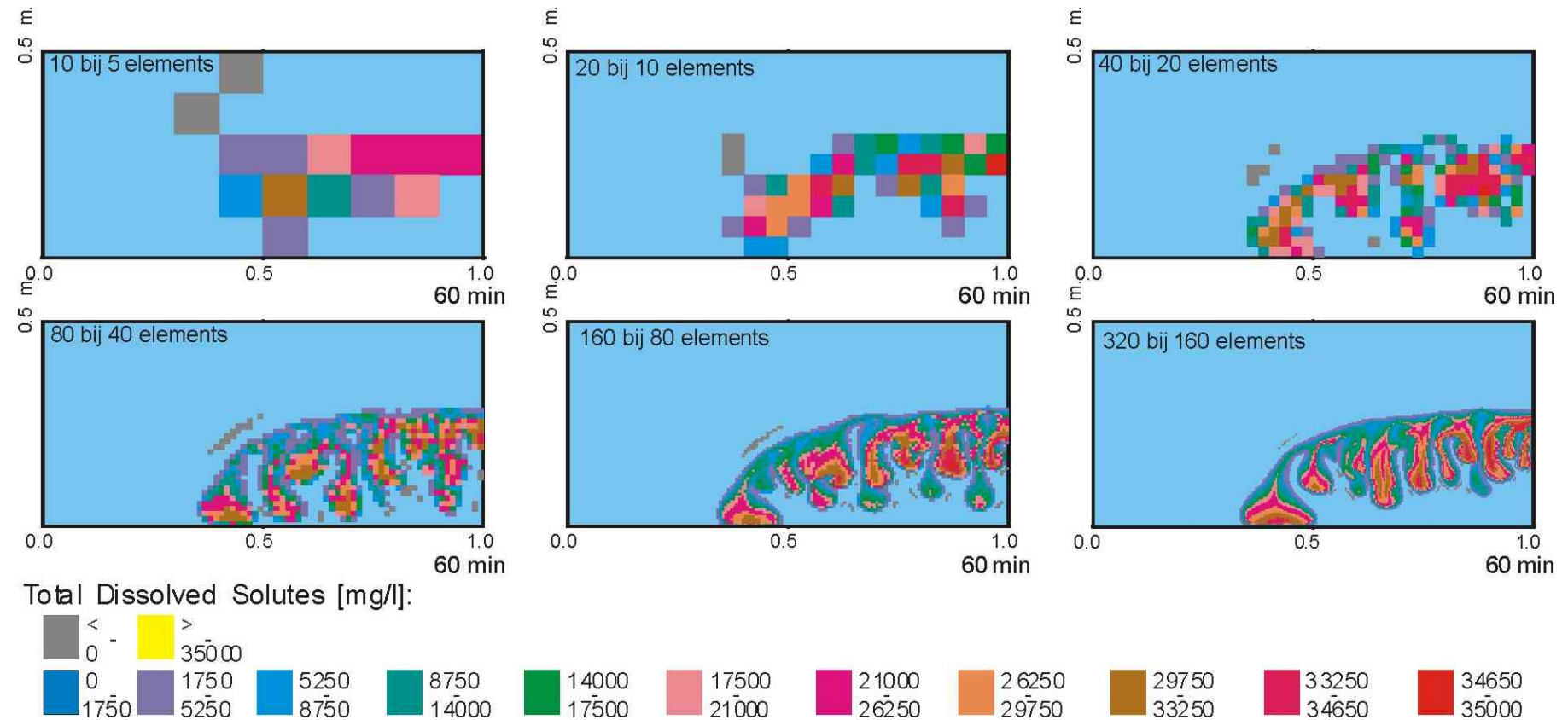
Saline pocket in fresh groundwater: fingering process

320*160 cells

Time= 0 min

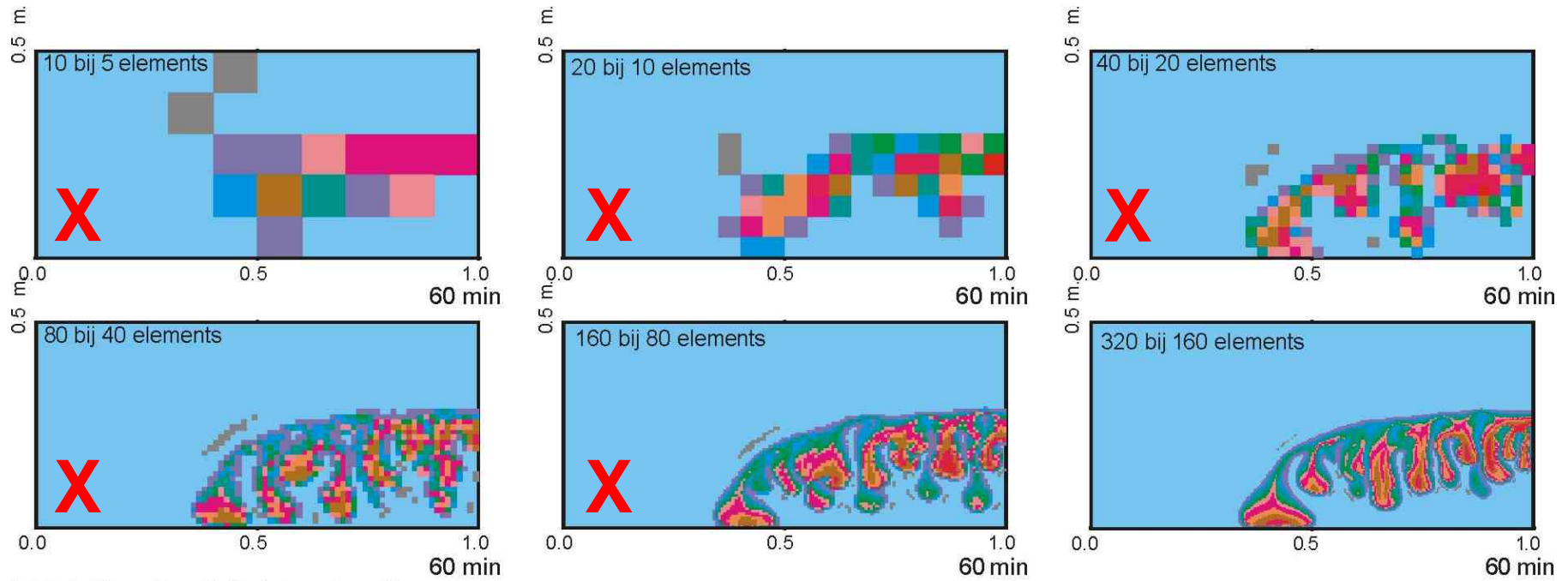


Effect of model cell size on physical process

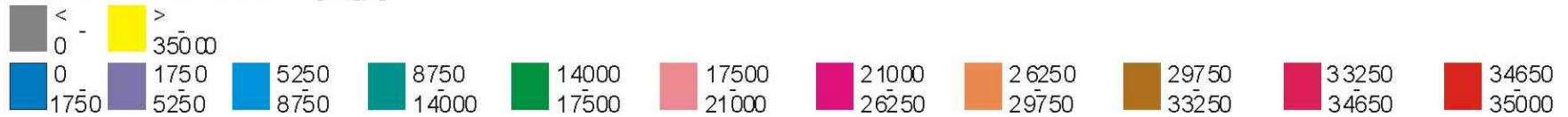


Model size cell has a **large** effect on modelling result!

Effect of size model cell on physical process

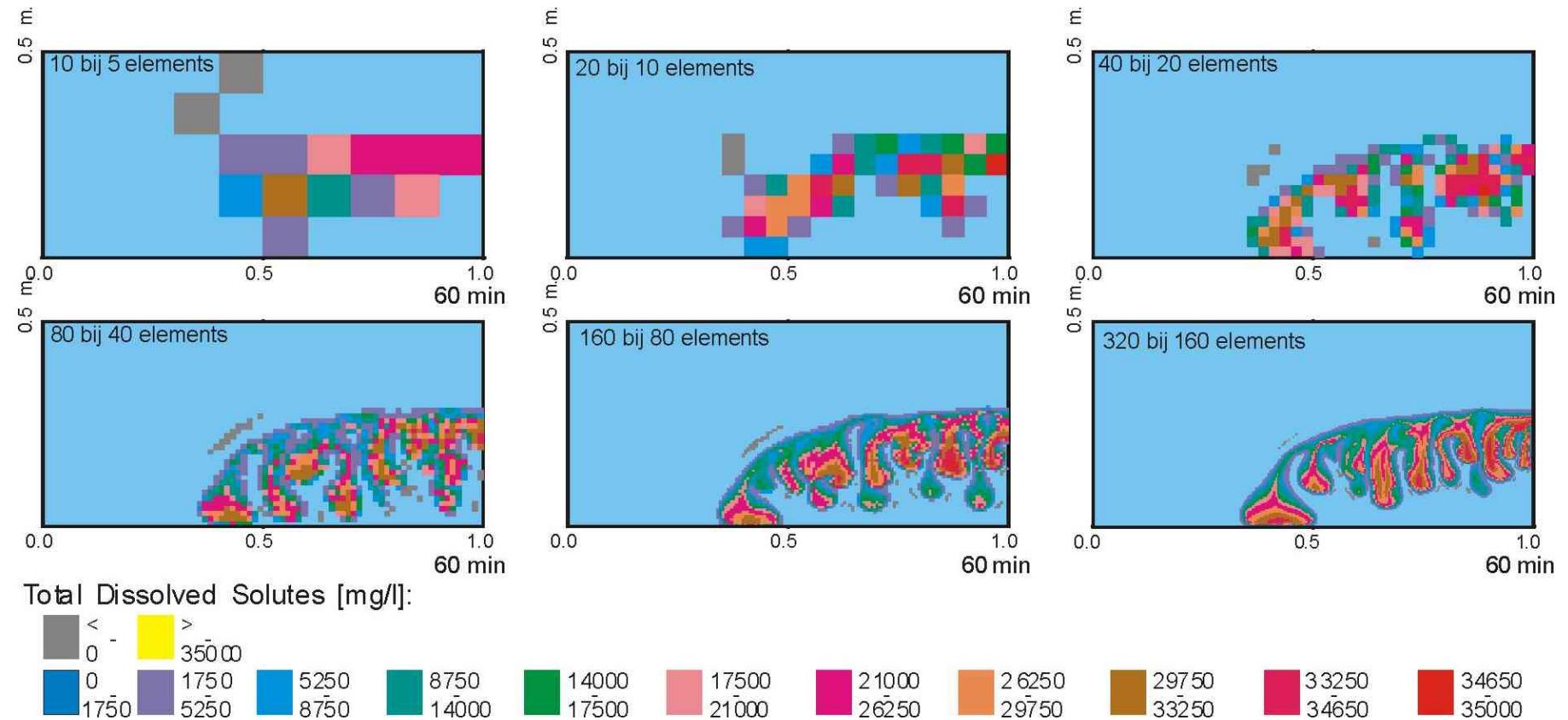


Total Dissolved Solutes [mg/l]:



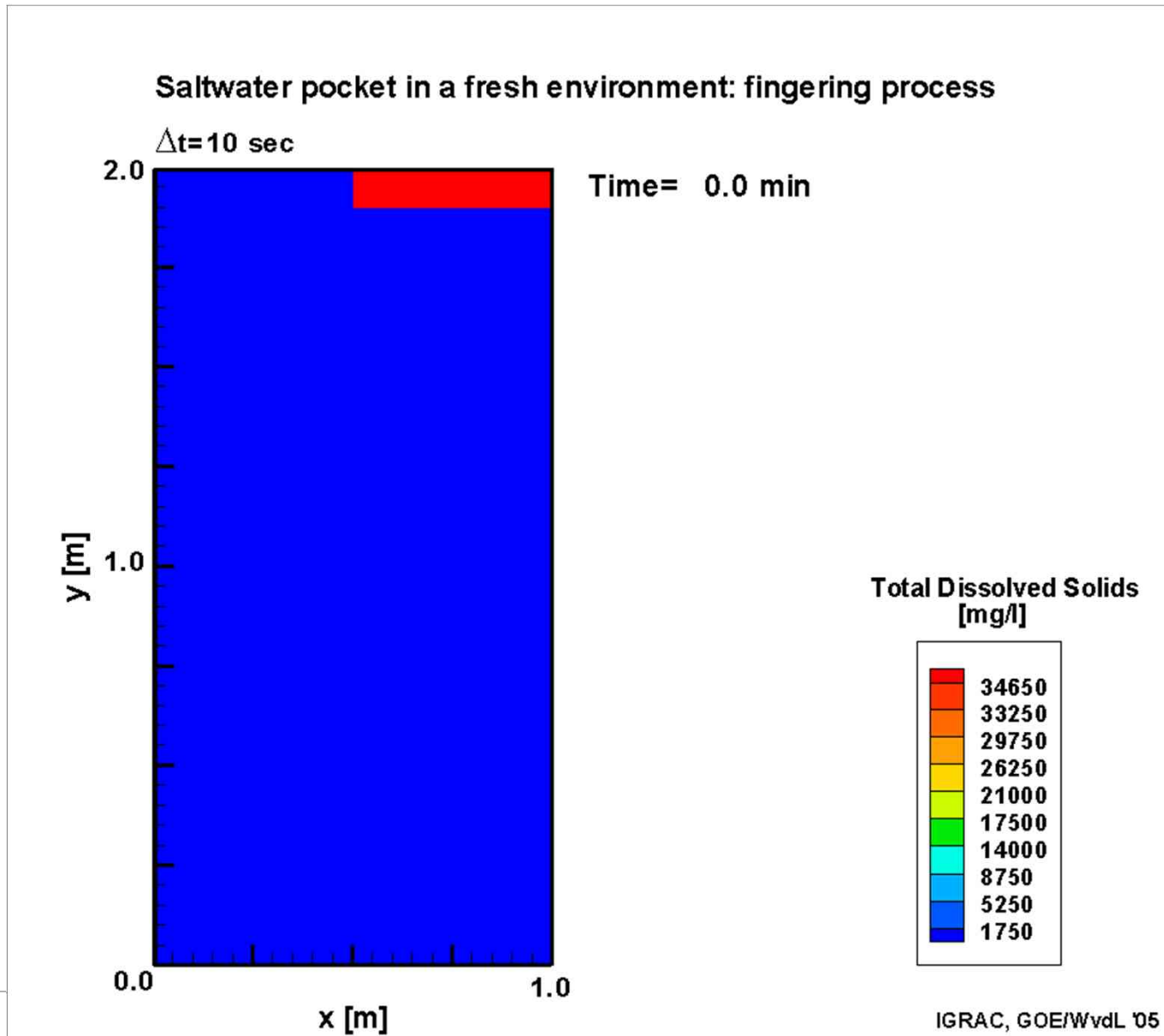
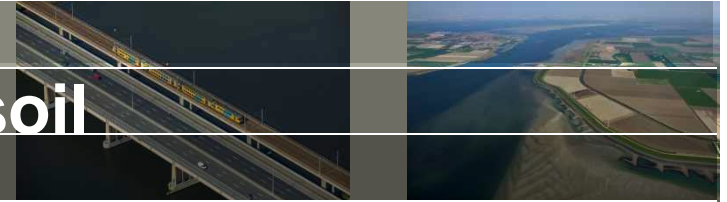
X= LOUSY models for predicting exact number of salt water fingers

Effect of size model cell on physical process

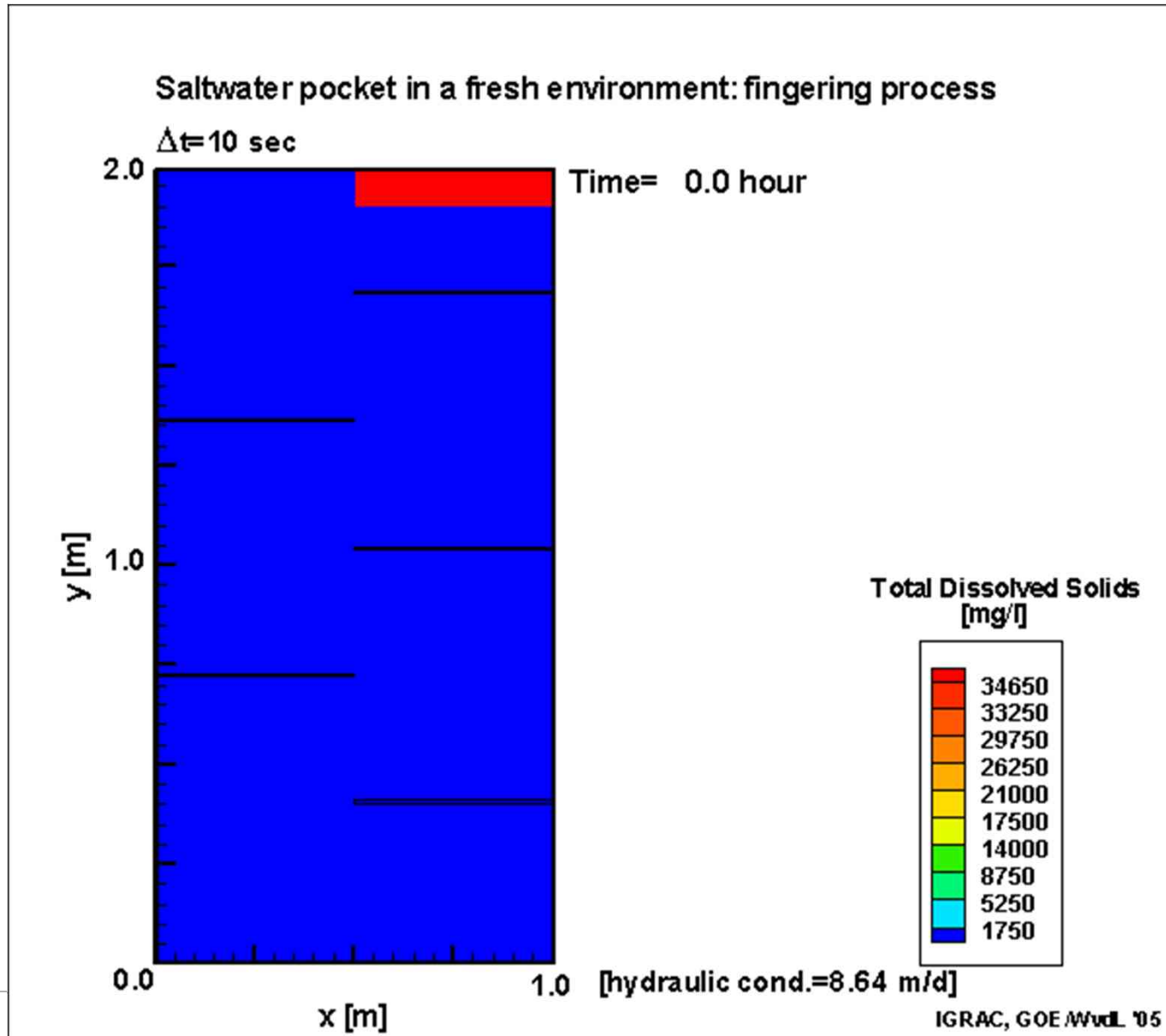
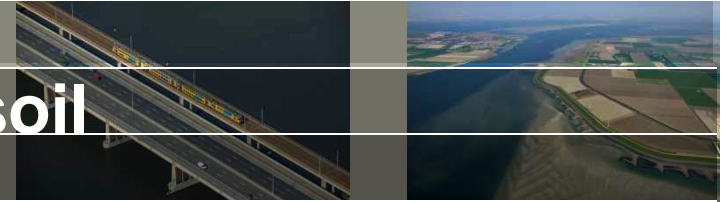


All models are GOOD for predicting moment of touching bottom (60min)!

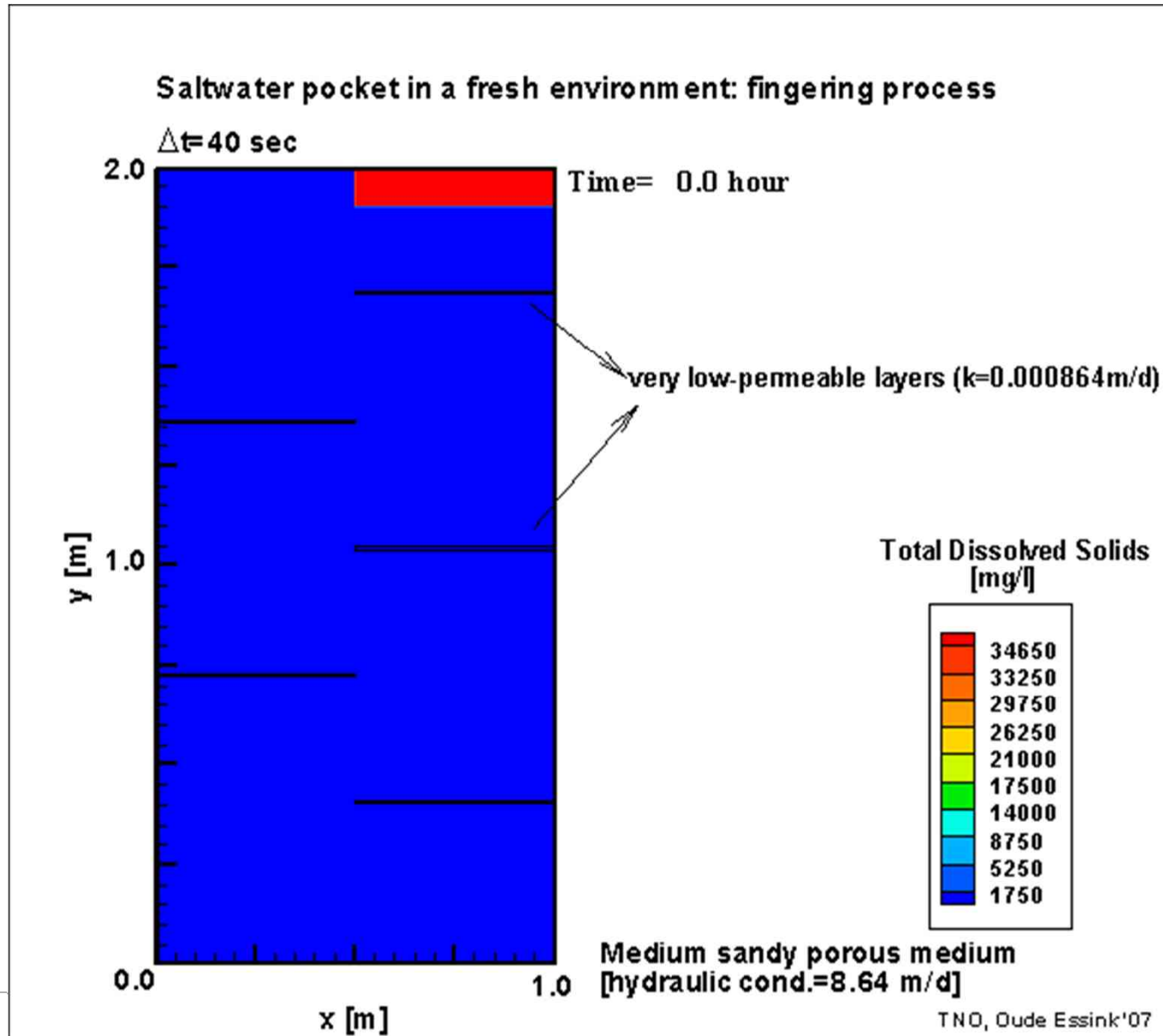
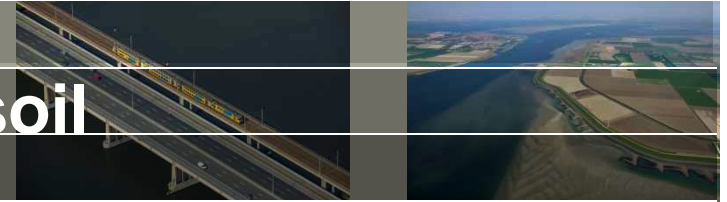
Fingering processes in the subsoil



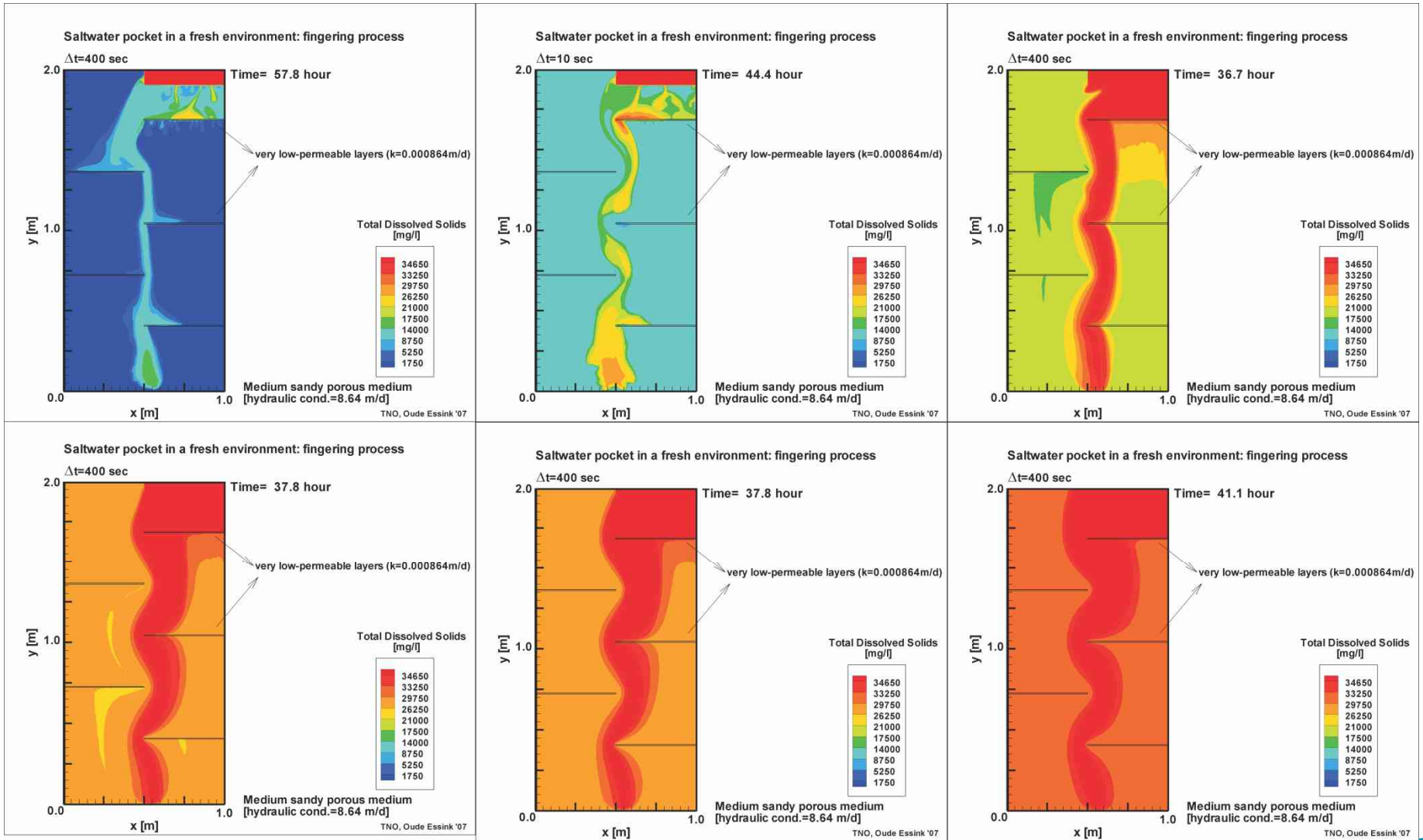
Fingering processes in the subsoil

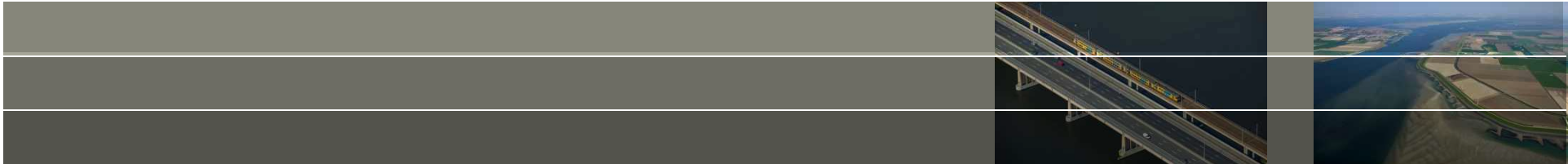


Fingering processes in the subsoil



Effect background salinity: 0, 25%, 50%, 75%, 80%, 90%





Thank you for your attention!

***More information:
freshsalt.deltares.nl***