Fresh groundwater in the coastal zone

Vulnerability of groundwater systems to flooding events

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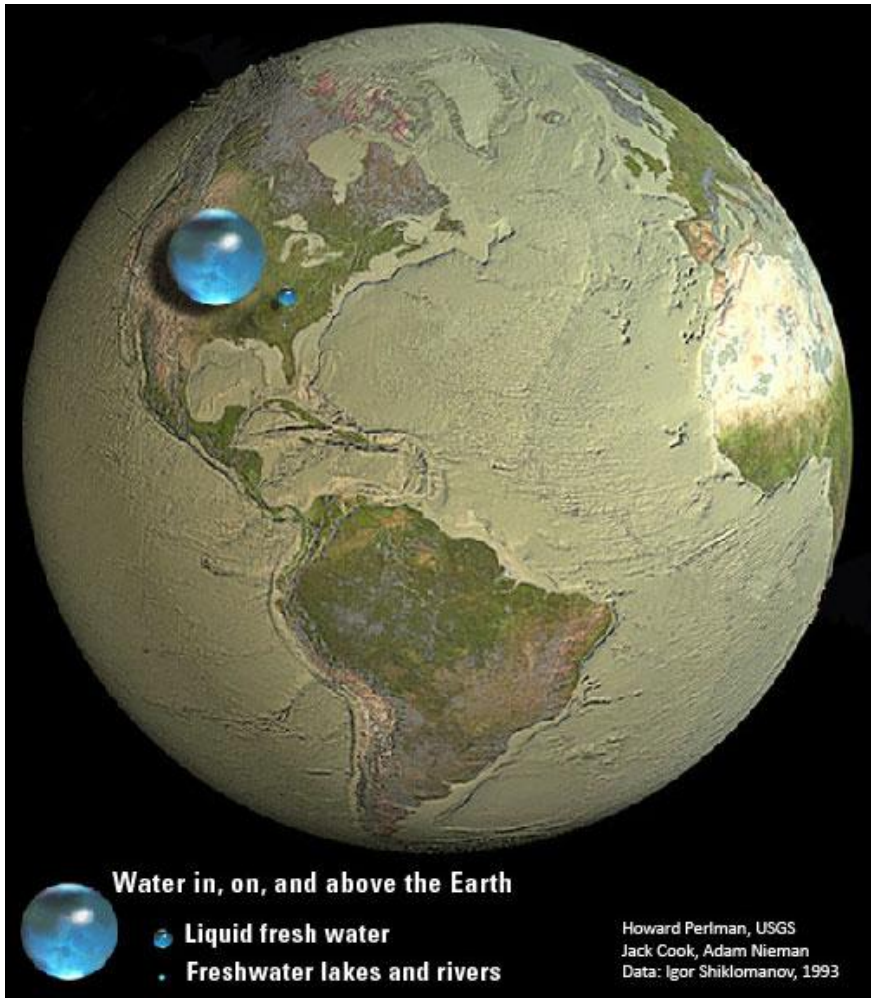
freshsalt.deltares.nl
zoetzout.deltares.nl

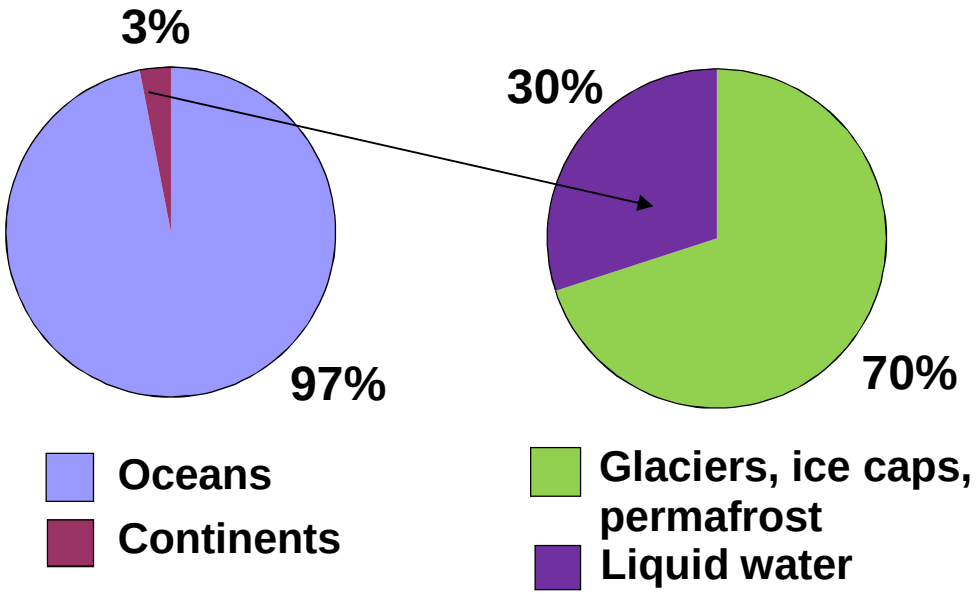
Volumes of water on Earth: a scarce product



Water in/on/above Earth

Liquid fresh water

Freshwater lakes rivers



Source: Perlman, USGS; Shiklomanov, 1993

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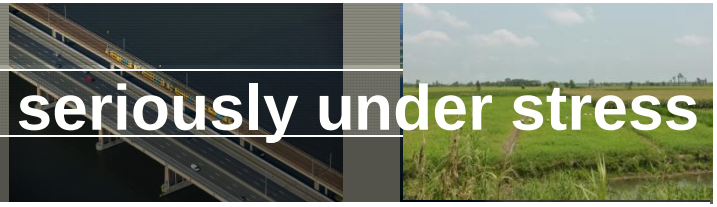
Fresh groundwater resources in delta's seriously under stress



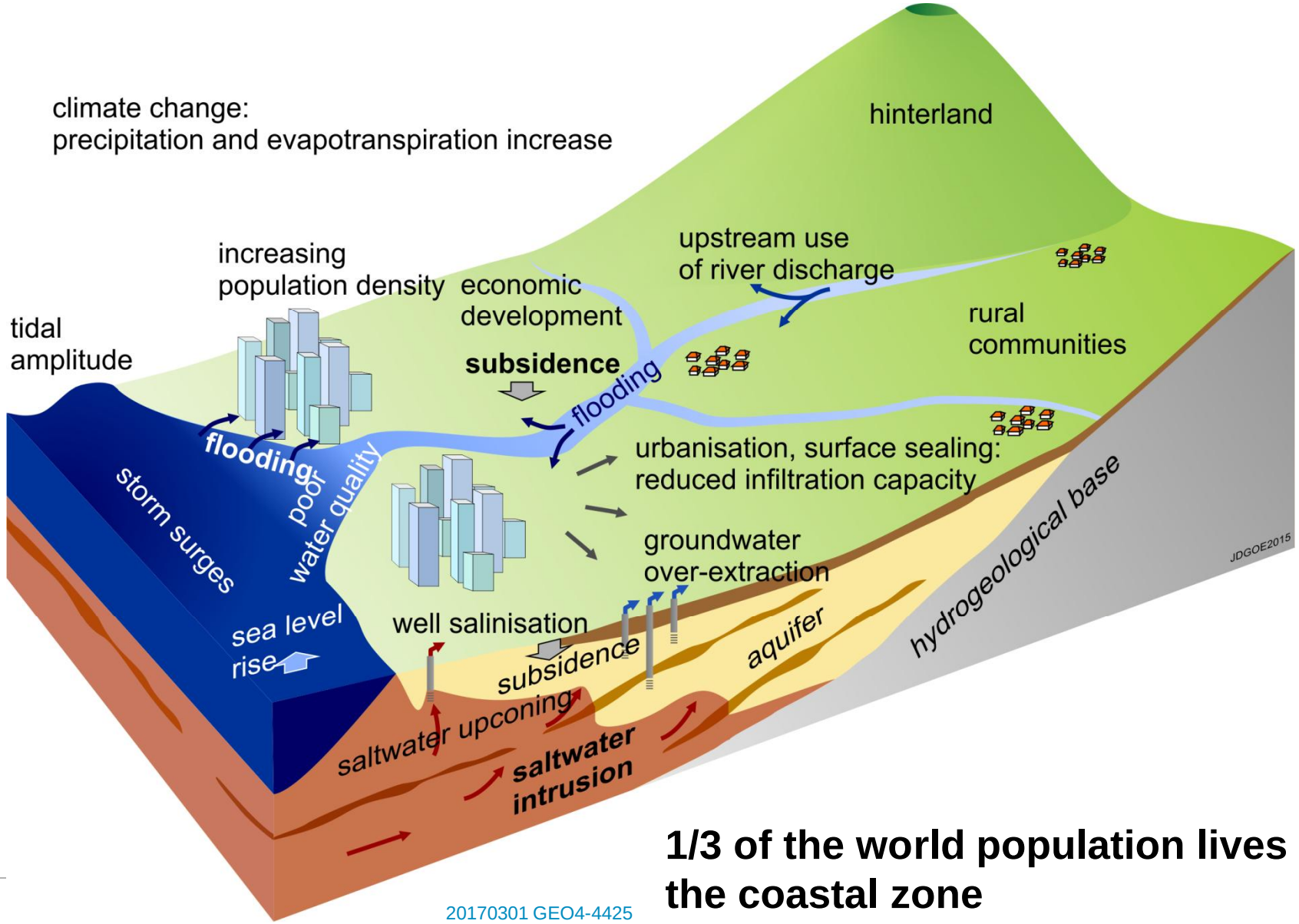
Every year, about 2 million people worldwide die from diarrhea, caused by bad drinking water quality; this is more than people dying from flooding events

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

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

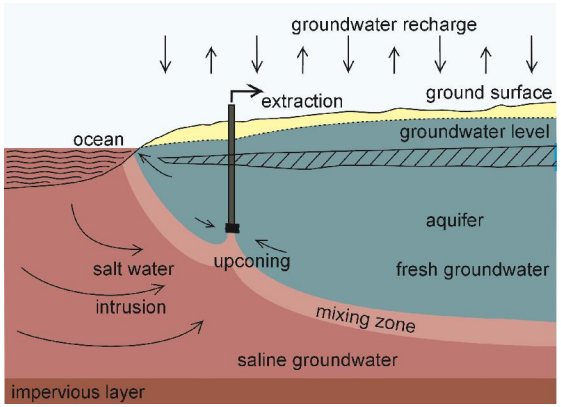
- Climate change and sea-level rise
- Increasing quantities groundwater extractions
- Land subsidence
- Politics, Policy & Watermanagement, affecting land use

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

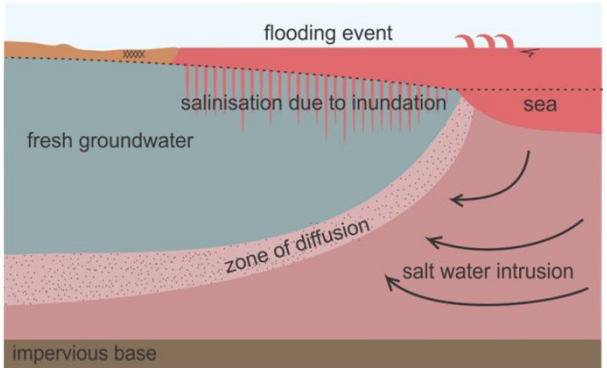


1/3 of the world population lives in the coastal zone

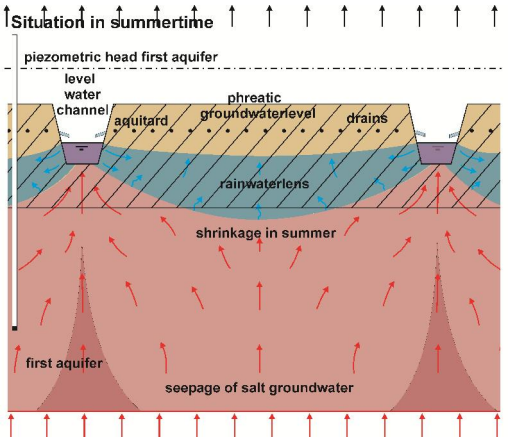
Salinisation processes at local scale



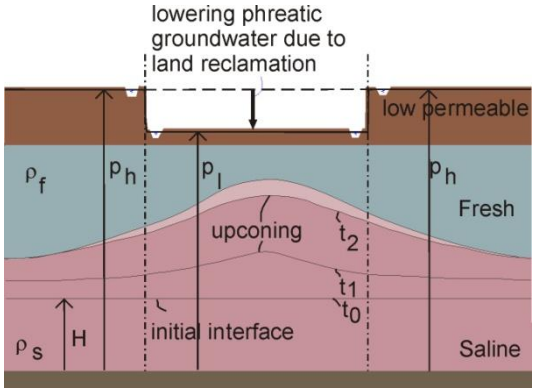
Salt water intrusion groundwater



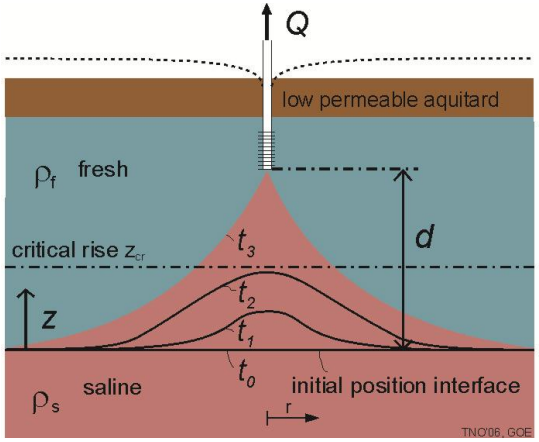
Inundation saline seawater



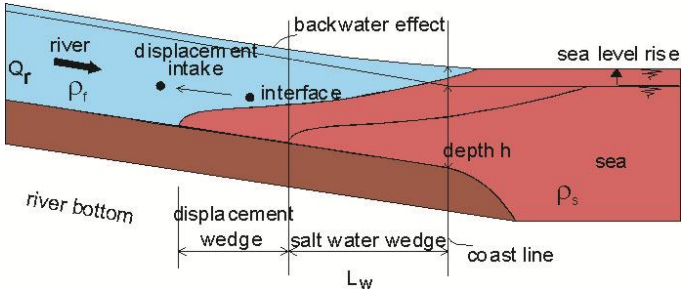
Shallow rainwaterlens



Upconing low-lying area



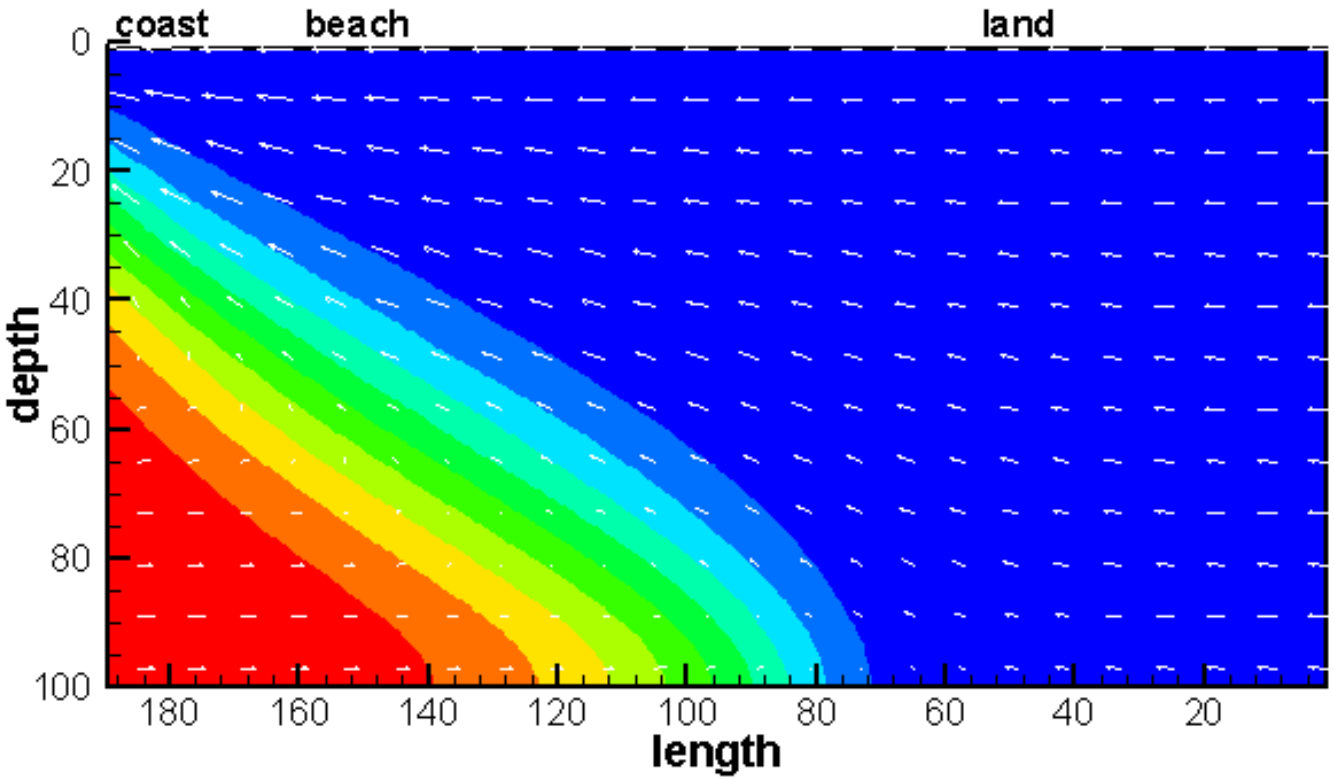
Upconing extraction



Salt water intrusion surface water

Impact of sea level rise on a coastal groundwater system:

a conceptual model of saltwater intrusion



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Enabling Delta Life

GOE, 2009

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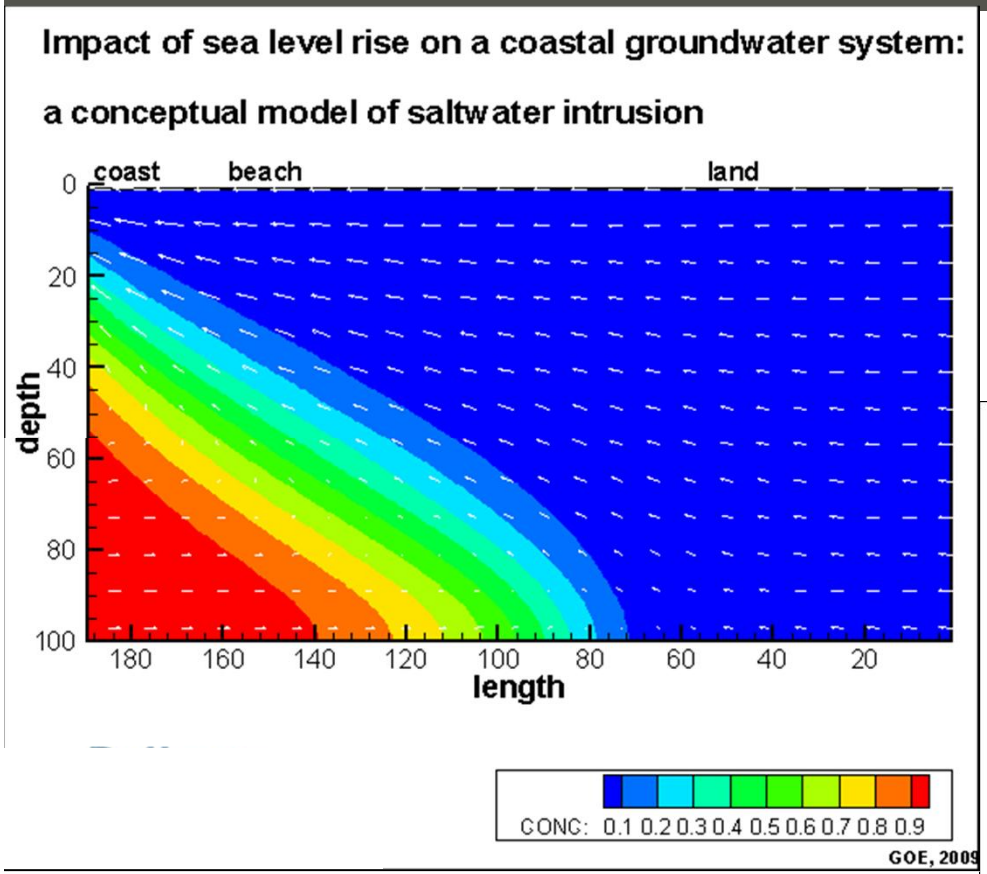
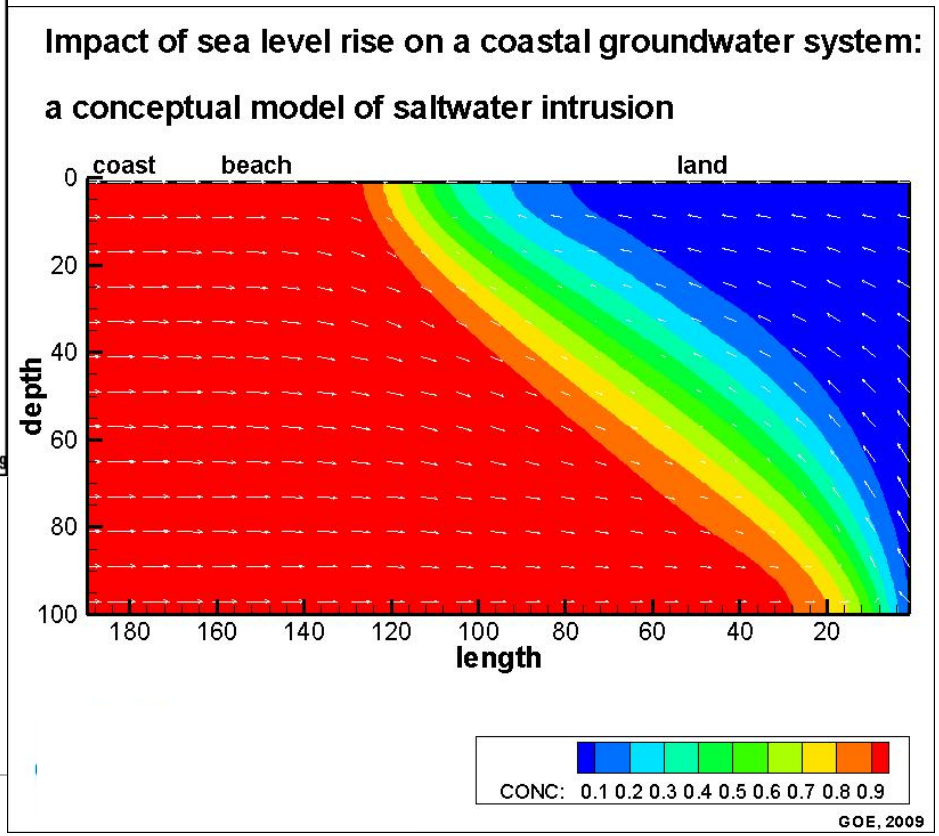
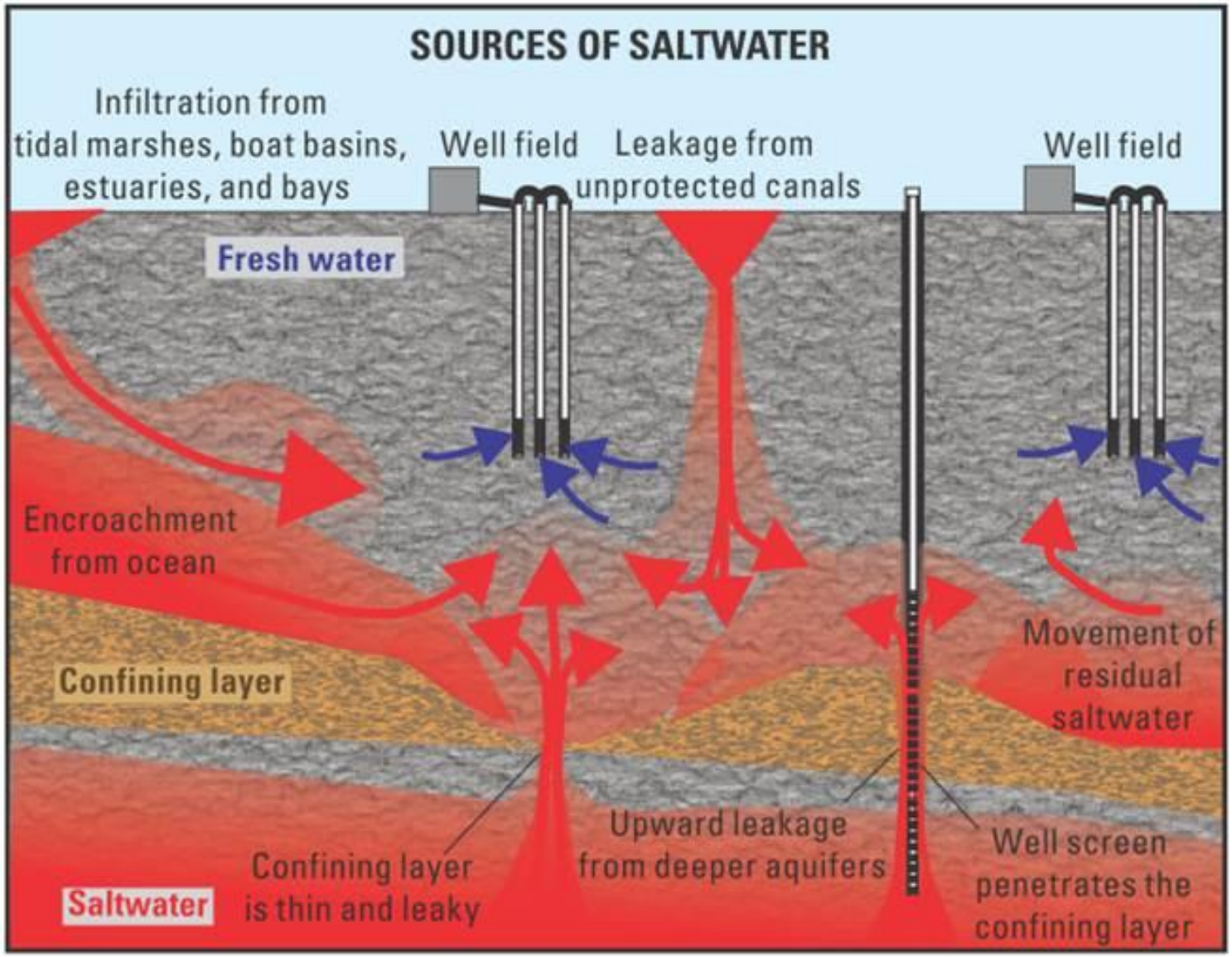
Sea level rise and salt water intrusion



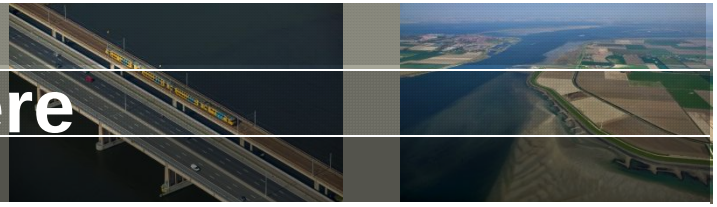


Combining salinization processes coastal zone



Prinos, 2014

Stress 1: there is salt everywhere



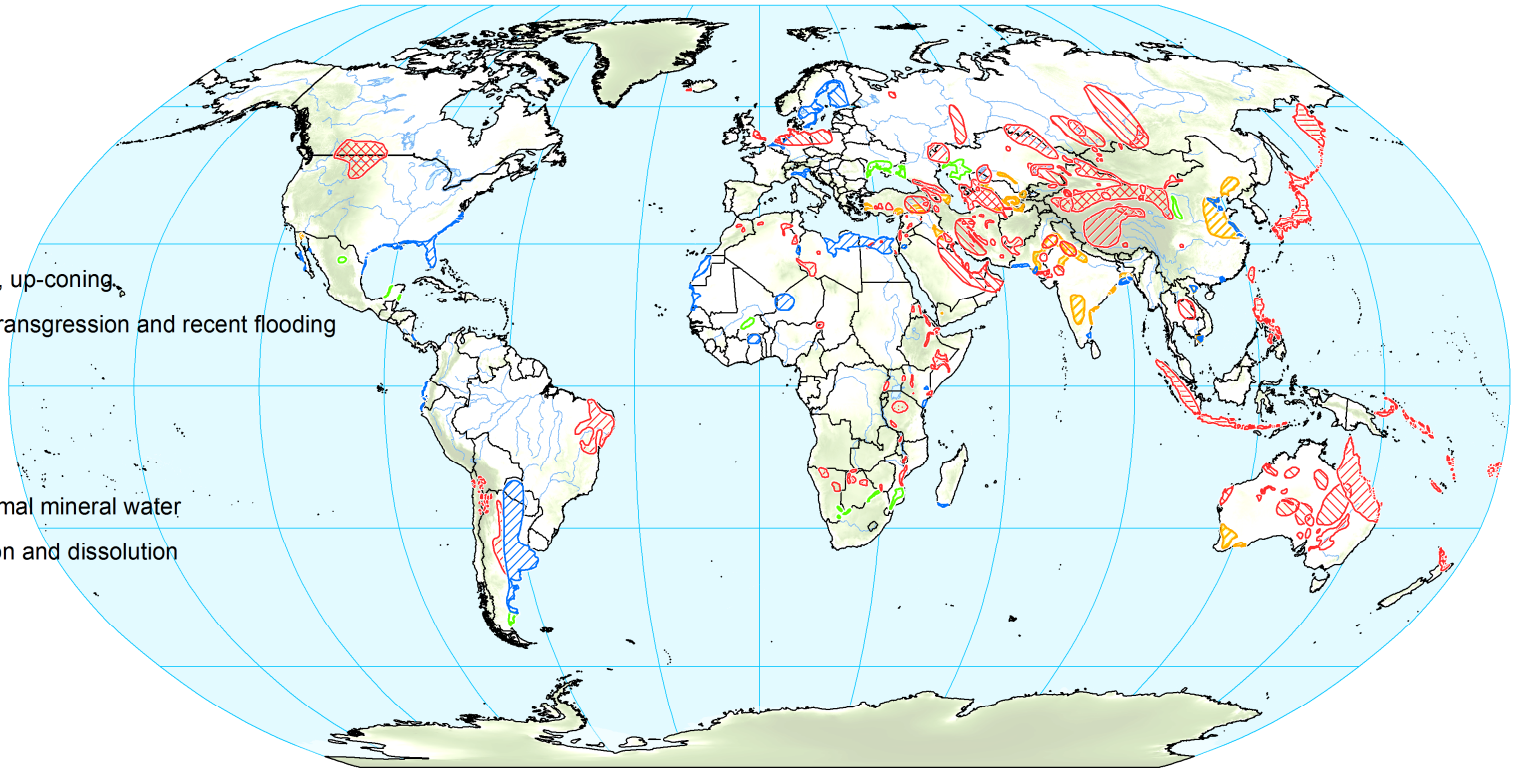
Saline Groundwater of the World

Legend

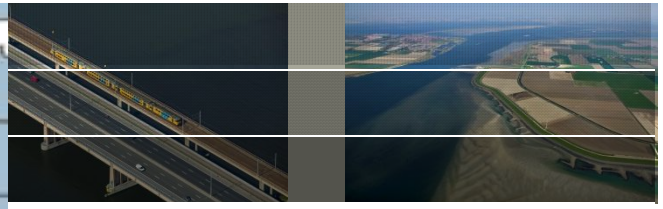
Groundwater_Salinity

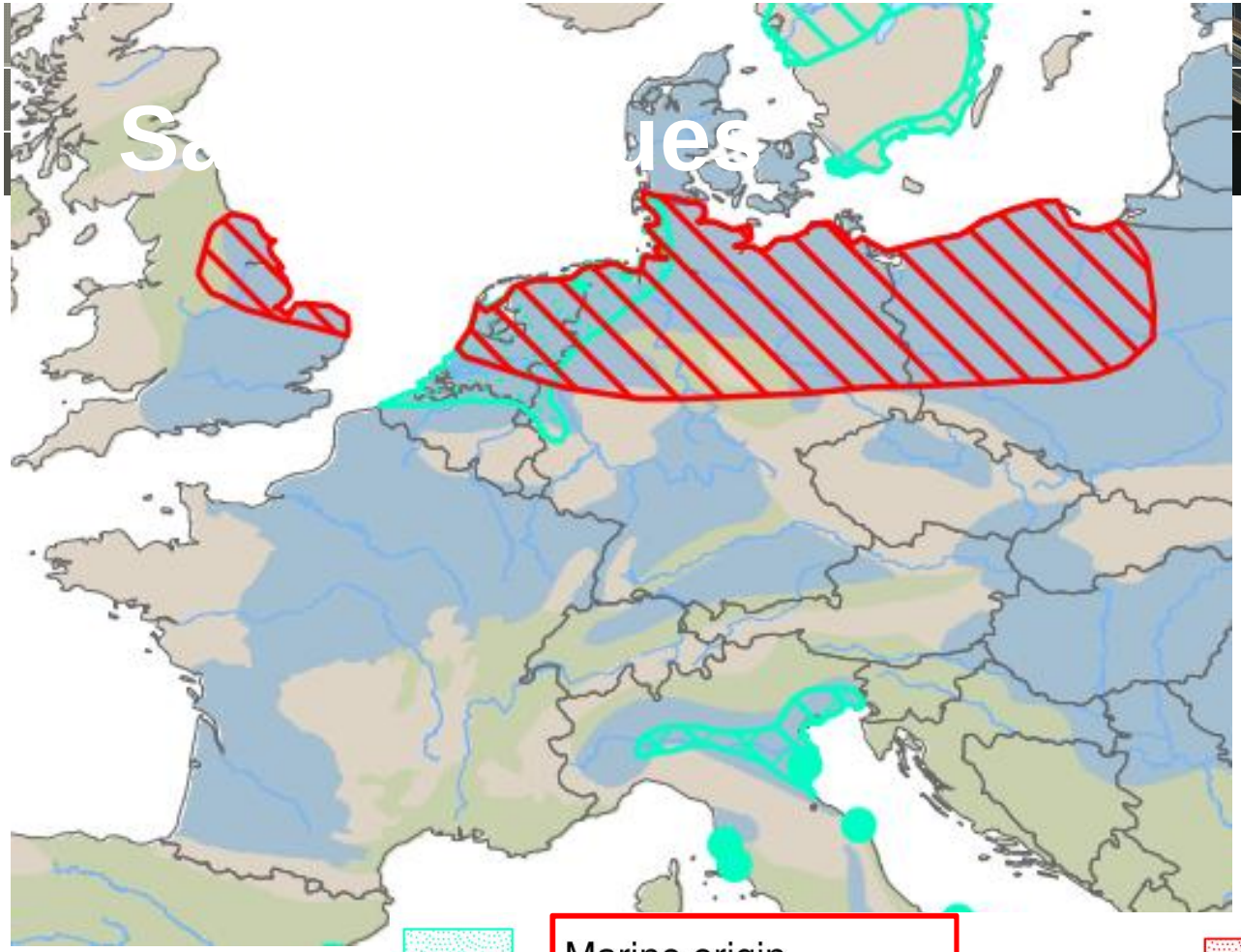
Genetic Category

- A0 Marine origin
- A1 Connate
- A2 Marine transgression
- A4 Lateral seawater intrusion, up-coning
- A7 Combination of connate, transgression and recent flooding
- B0 Natural terrestrial origin
- B1 Evaporation
- B2 Dissolution
- B4 Igneous activity hydrothermal mineral water
- B5 Combination of evaporation and dissolution
- C1 Irrigation
- C2 Pollution
- D0 Unspecified origin



Sa ues





Marine origin

Connate

Marine transgression

Lateral seawater intrusion & up-coning

Combination of connate, transgression and current flooding

Natural terrestial origin

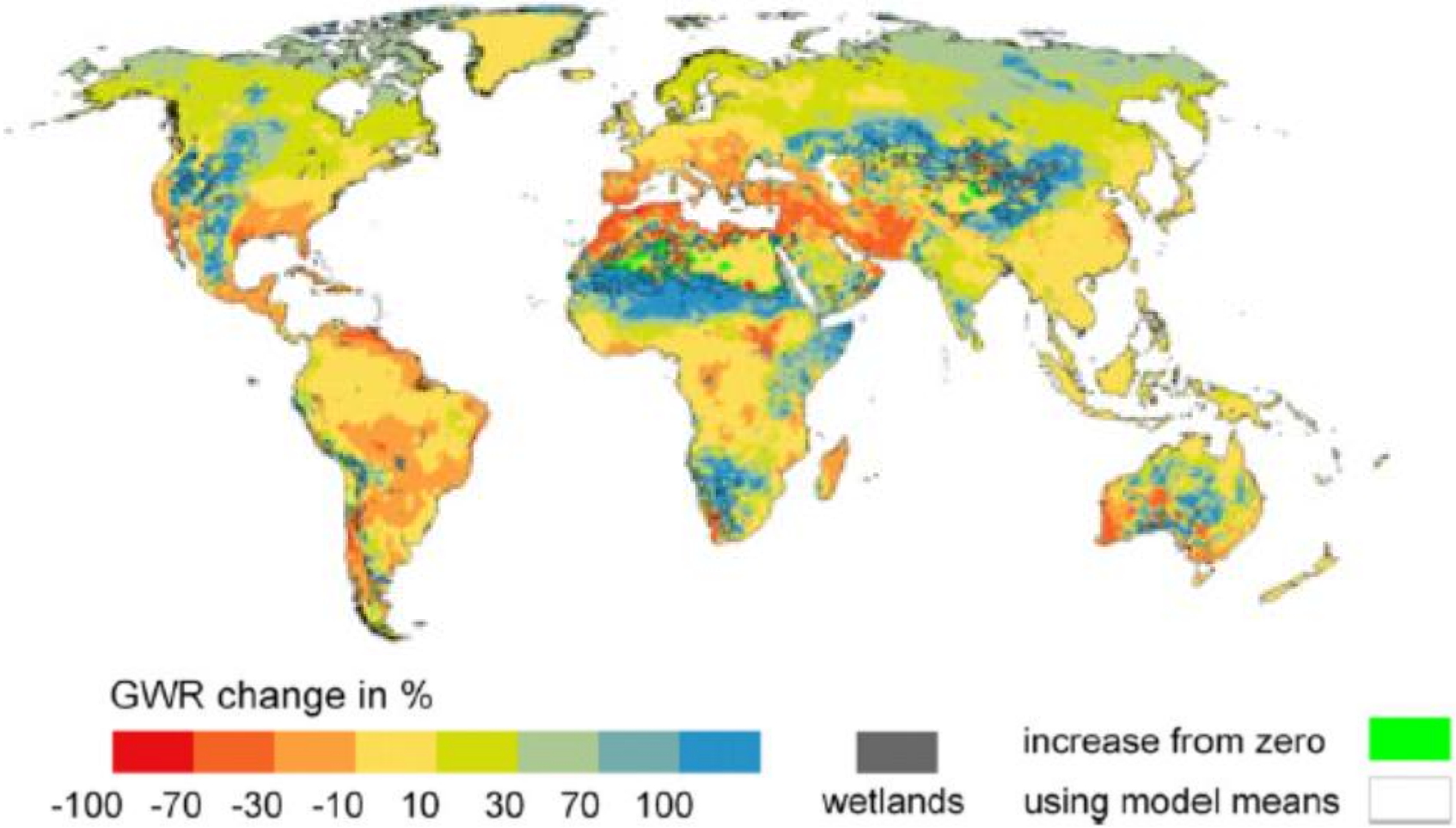
Evaporation

Dissolution

Igneous activity hydrothermal mineral water

Combination of evaporation & dissolution

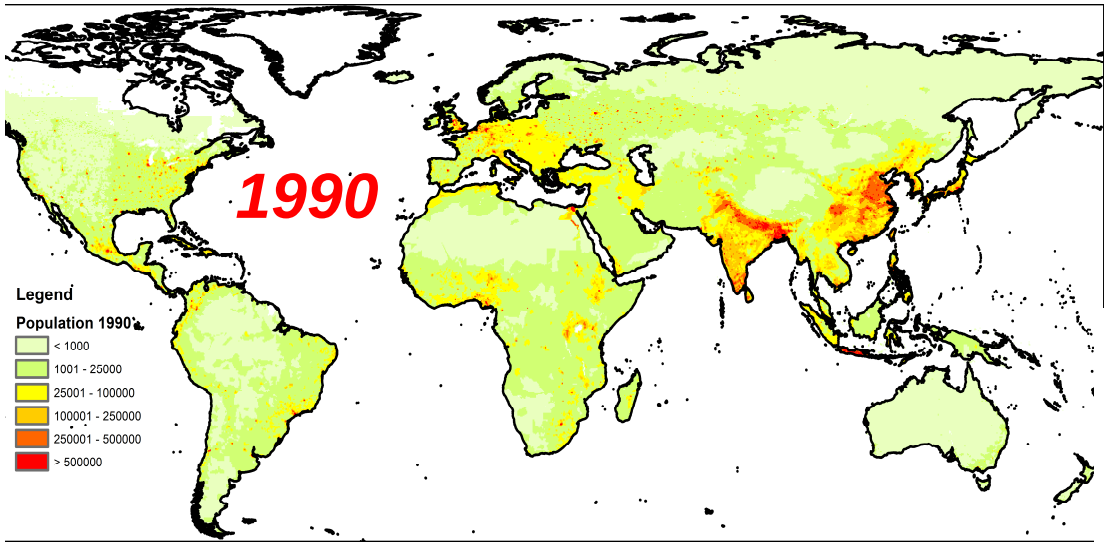
Stress 2: Change in groundwater recharge by end of century

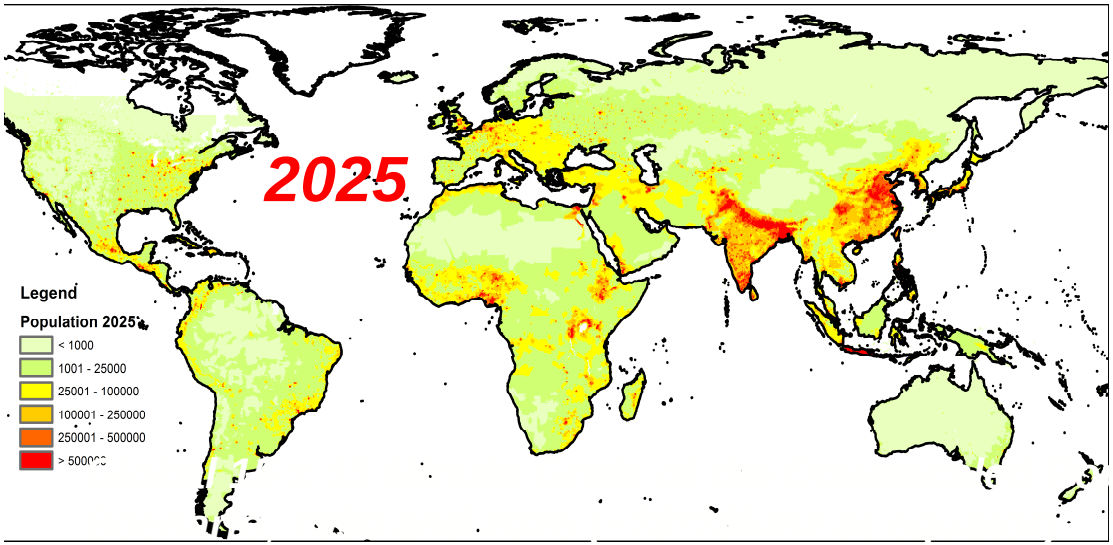


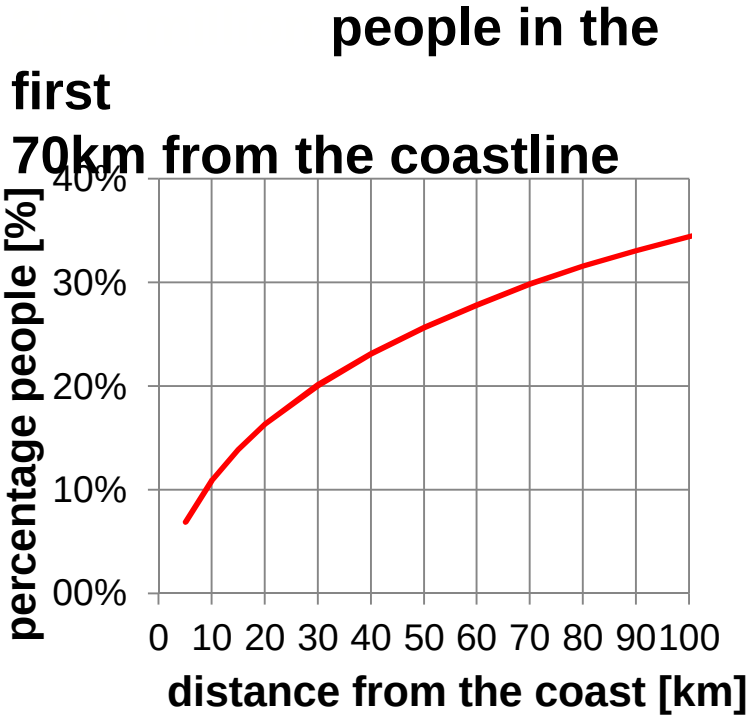
Projected percent changes of groundwater recharge by the end of this century with respect to present (1971–2000)
WaterGAP model with five different GCMs for RCP8.5

Portmann et al, 2013, ERL
From: Wada

Stress 3: Population growth 1990-2025, needing water







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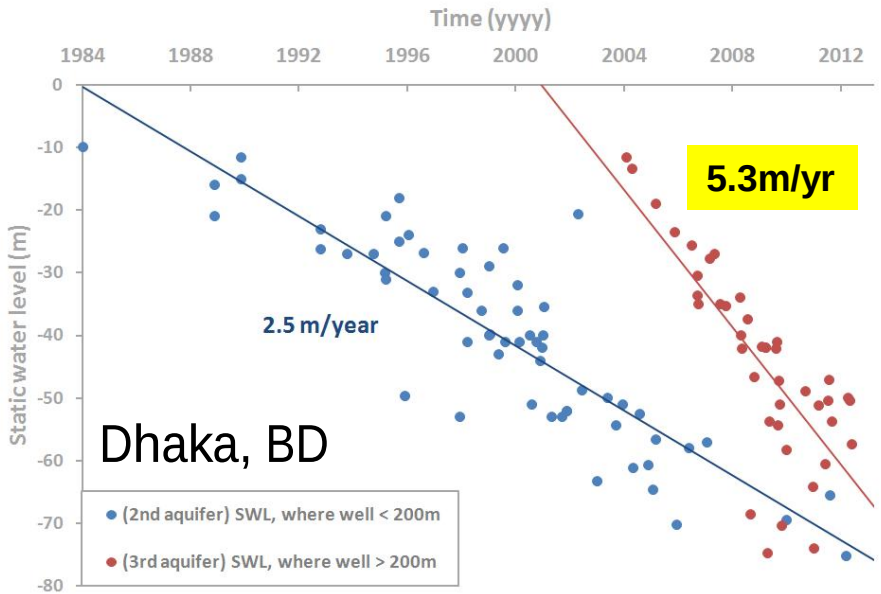
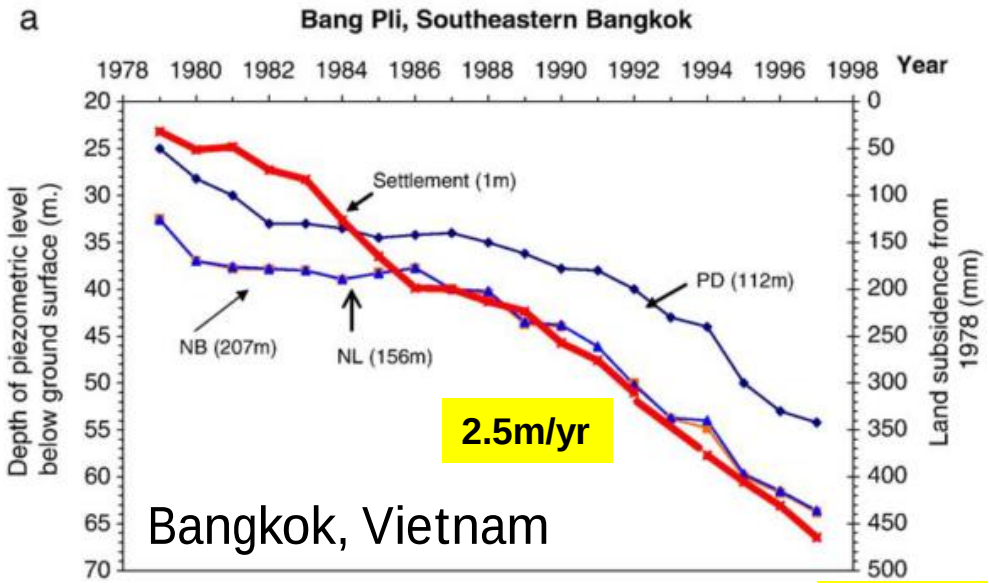
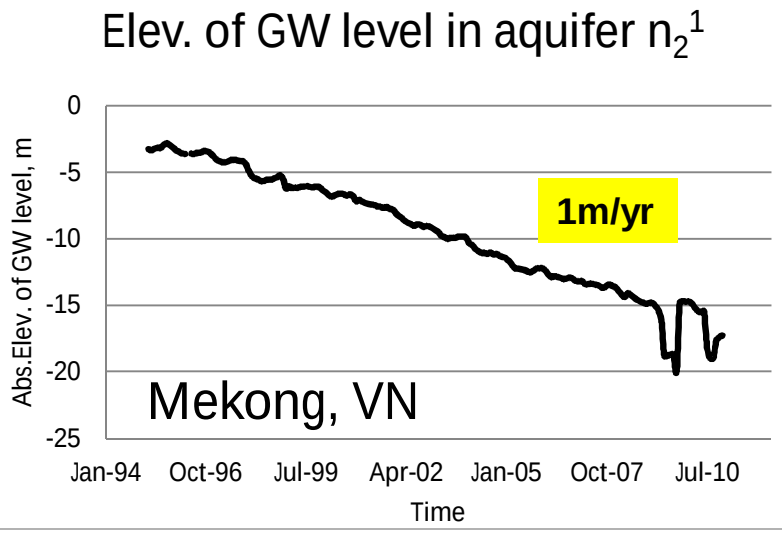
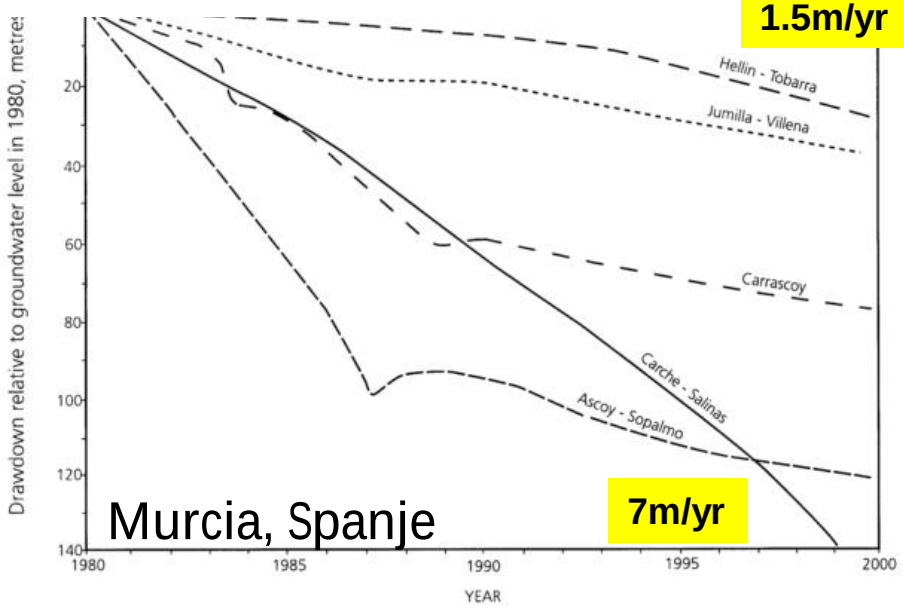
Stress 4: Serious overexploitation coastal aquifers worldwide



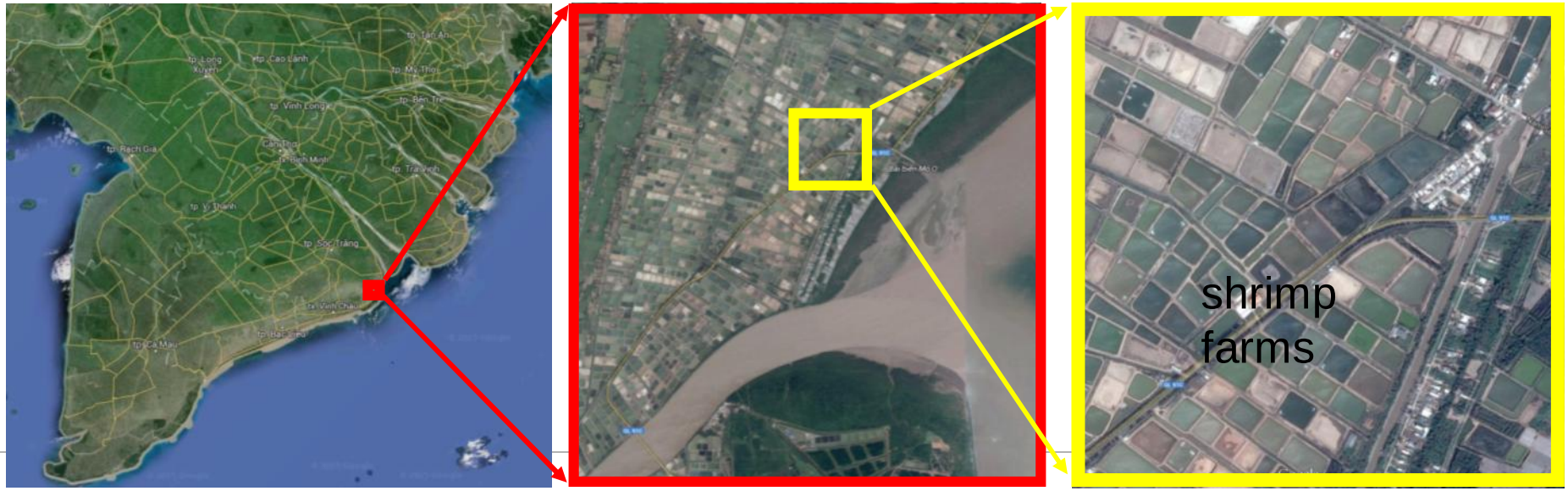




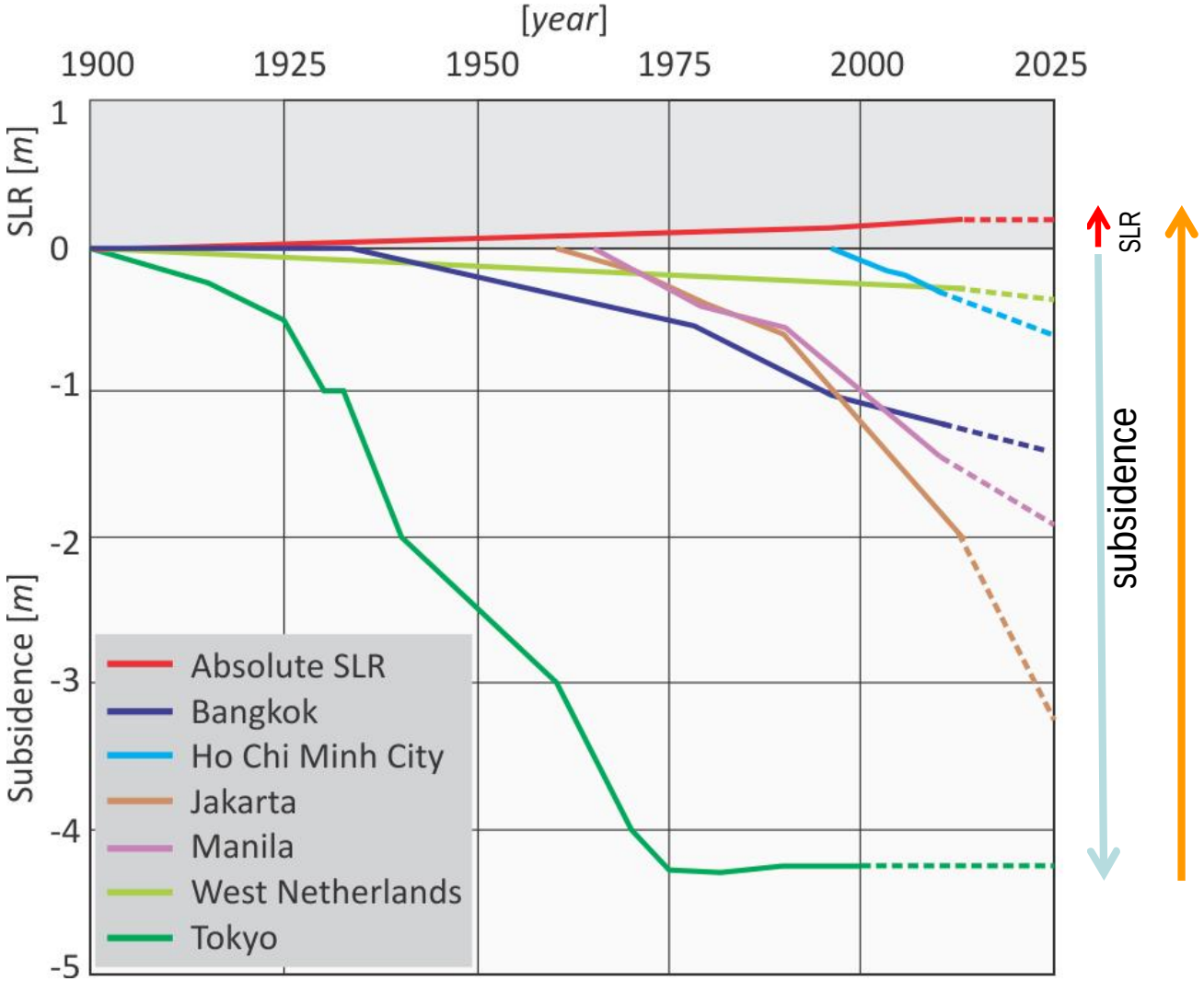


Groundwater overexploitation in Mekong Delta

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



Stress 5: Land subsidence in some major coastal cities



Relative SLR Tokyo is 4.5 m

Subsidence issues are underestimated

Land subsidence San Joachim Valley, CA, USA

9 m since 1930s

San Francisco

Los Angeles

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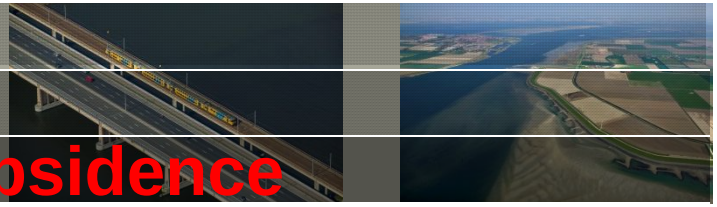
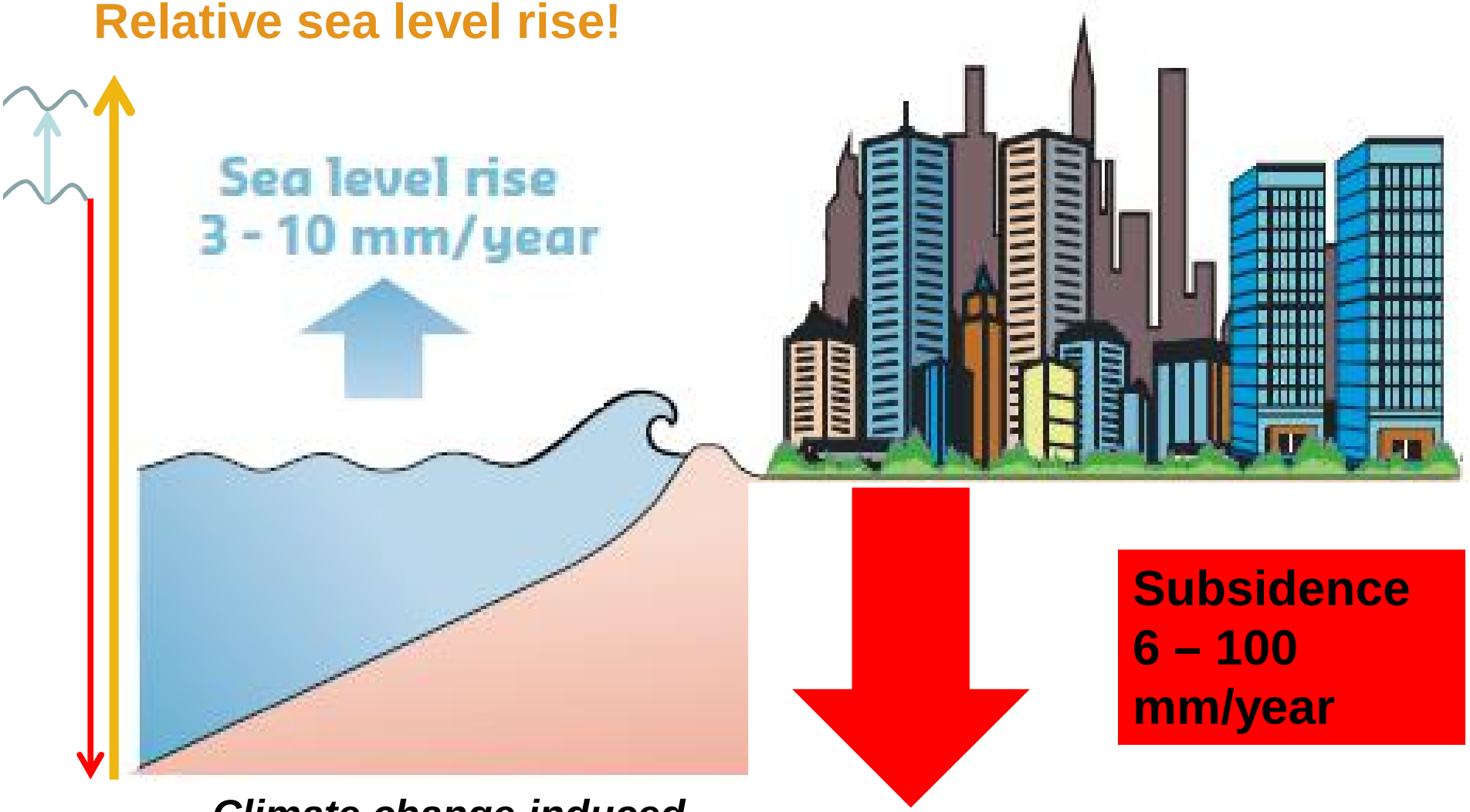
Sinking delta cities

Absolute Sea Level Rise *versus* Subsidence

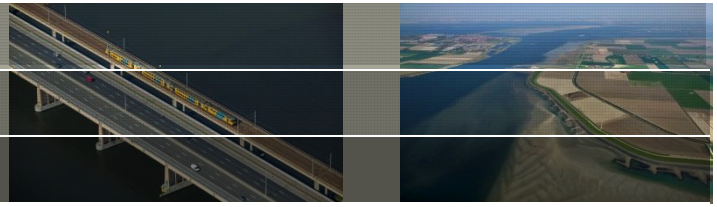


Relative sea level rise!



Climate change induced

Land subsidence



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

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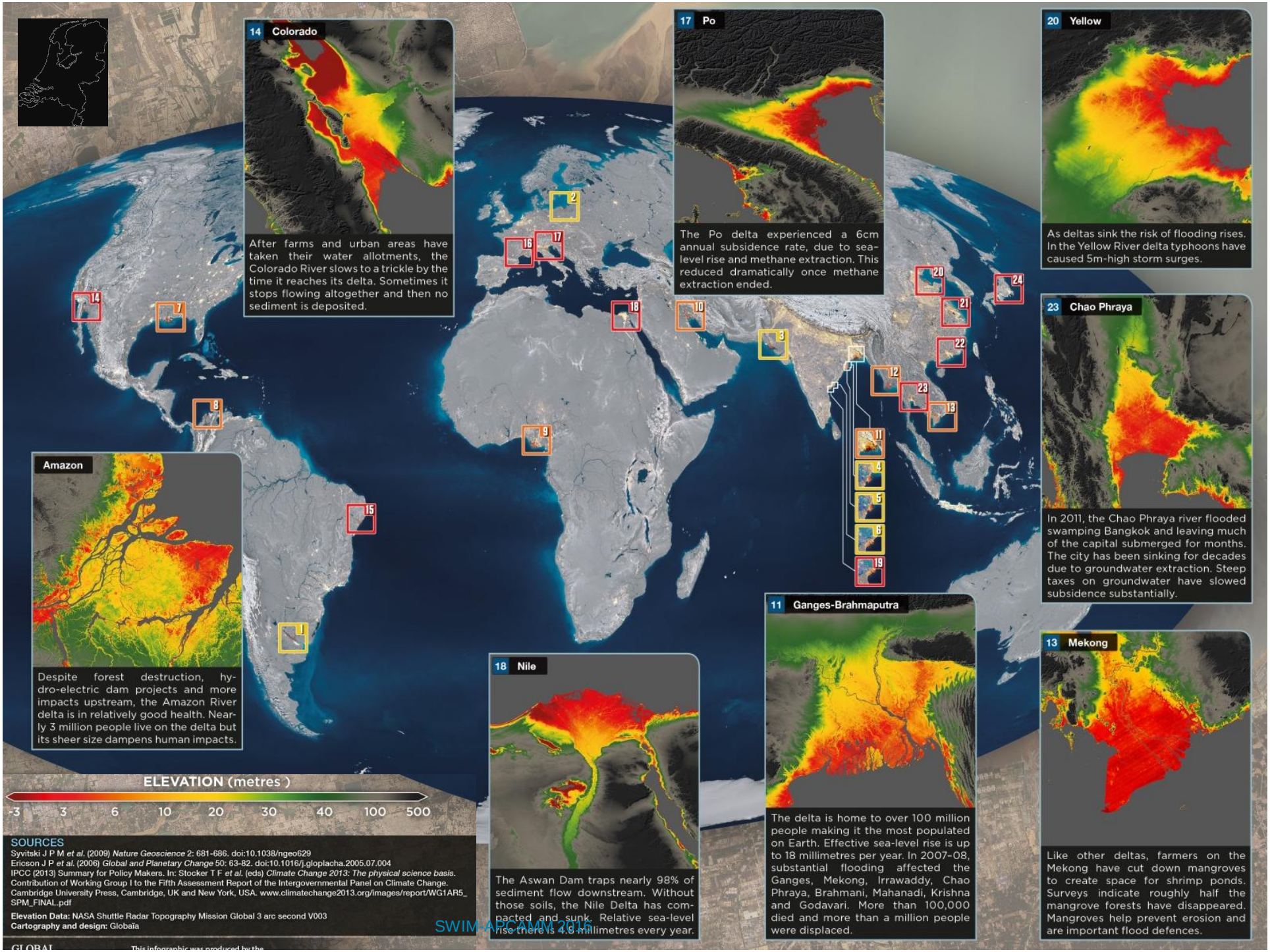
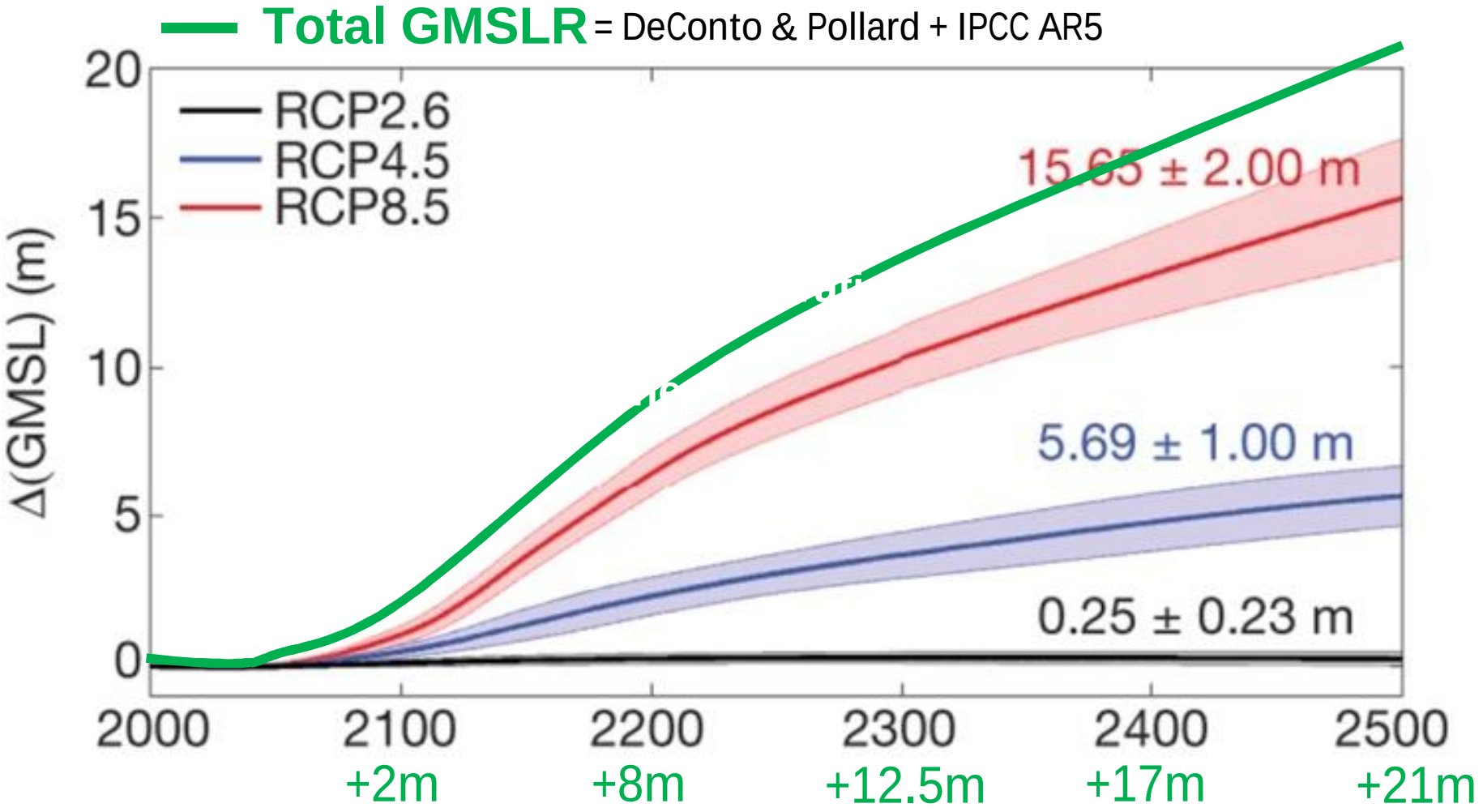
Sea level rise: +2 m

http://flood.firetree.net

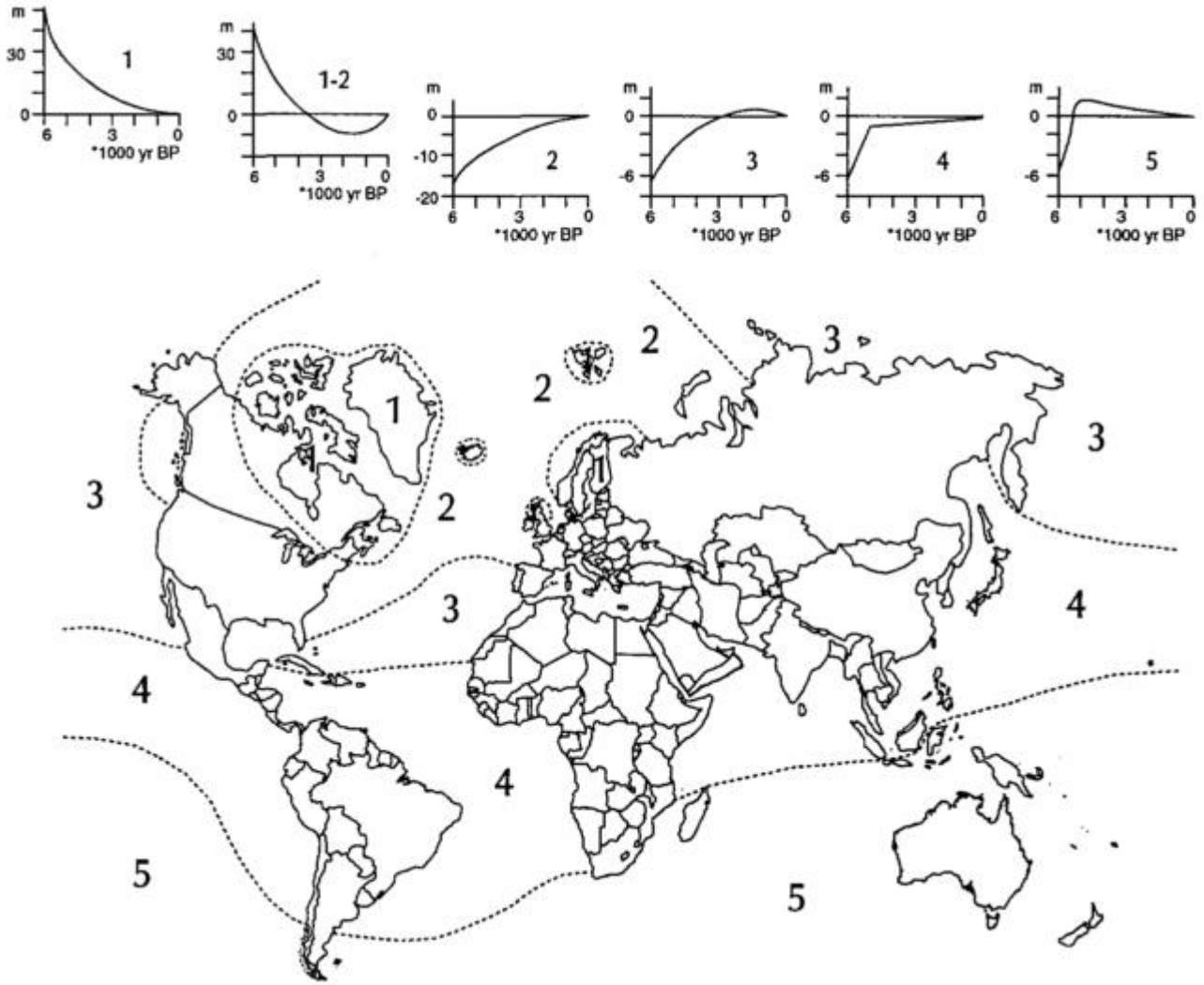


Stress 6: Global Mean Sea Level Rise (GMSL)



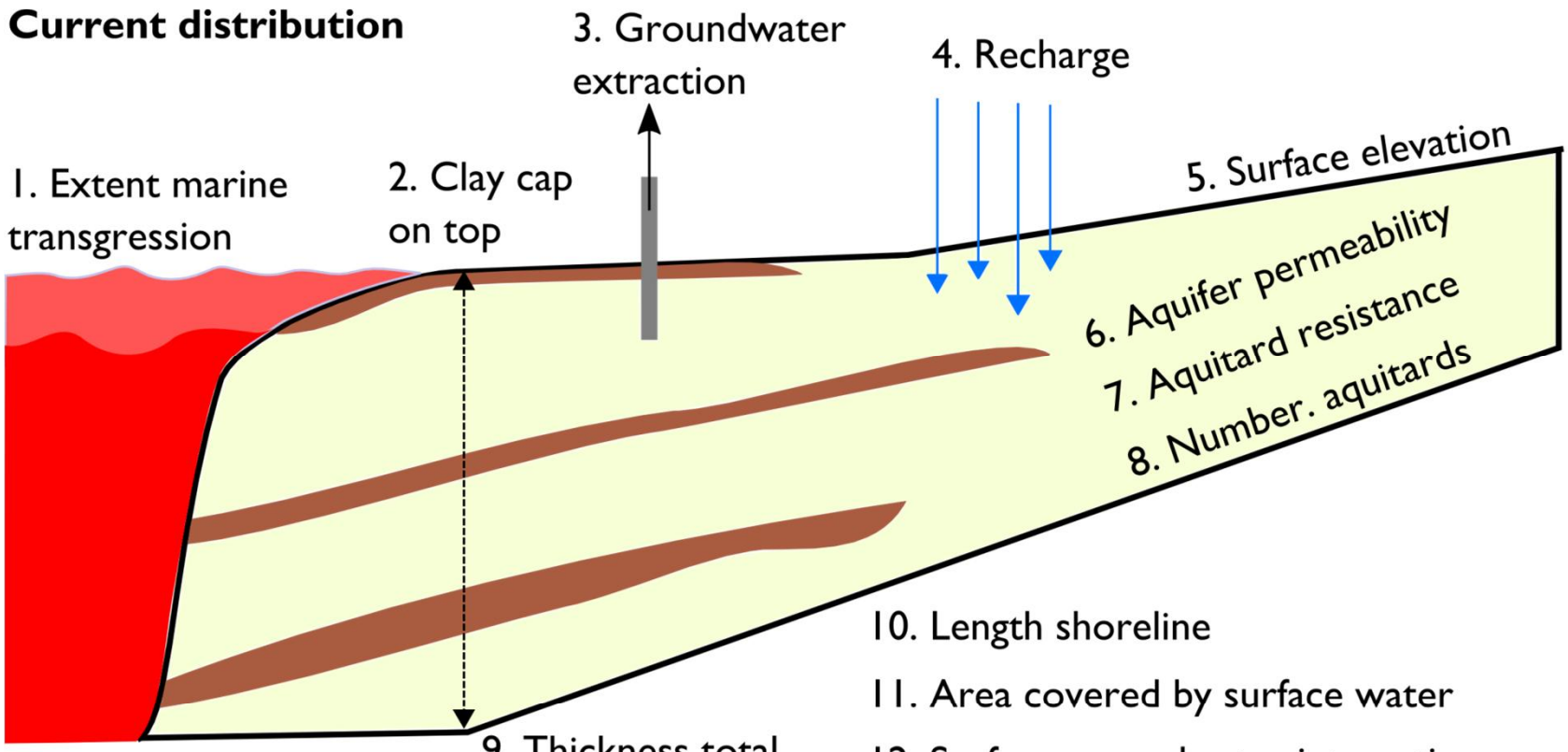
DeConto *and Pollard. 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591–597 (2016) doi:10.1038/nature17145*

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

Factors determining fresh groundwater resources delta's



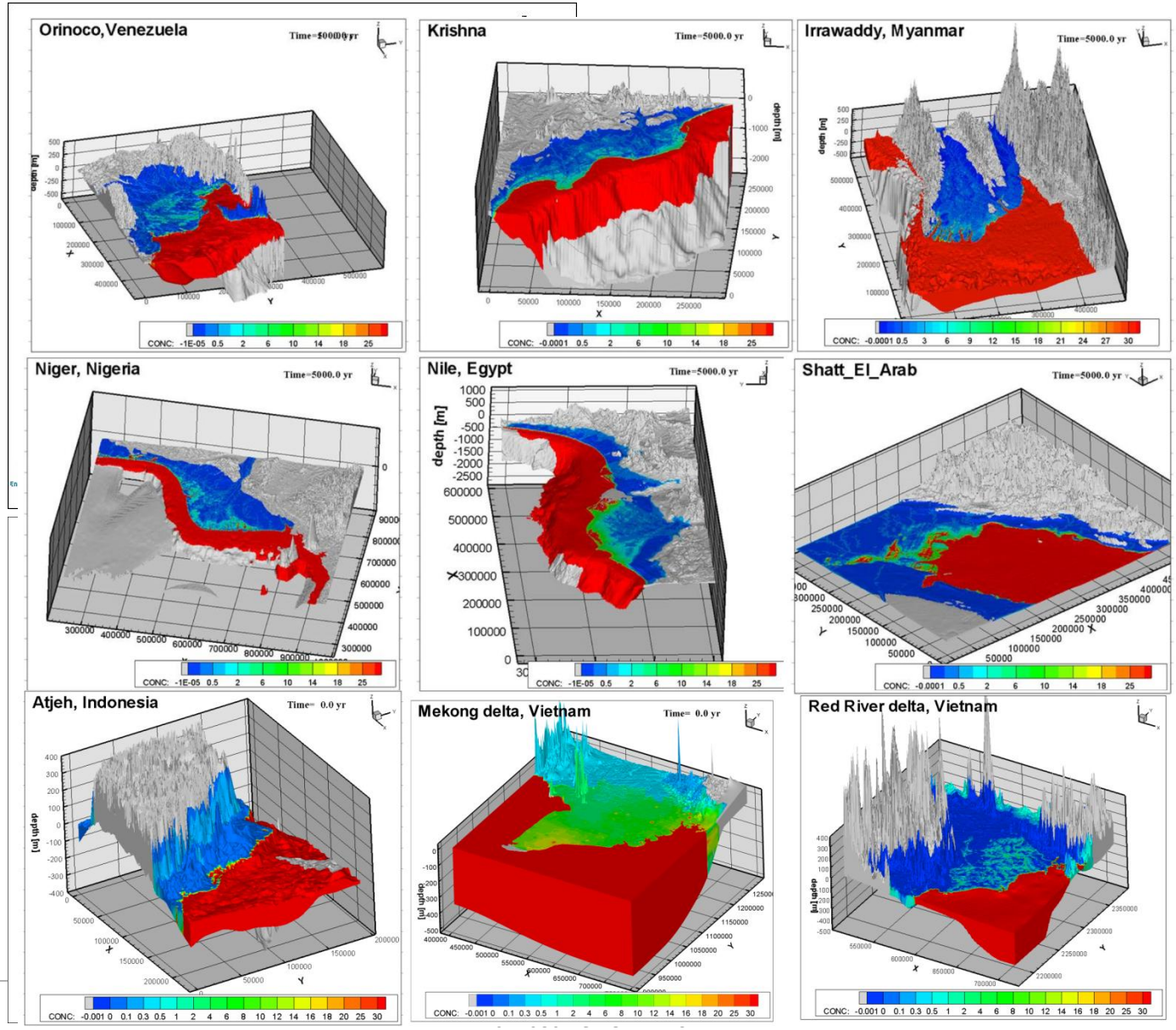
10. Length shoreline
11. Area covered by surface water
12. Surface-groundwater interaction
13. Extent salt water intrusion surface water
14 Bathymetry

Future Distribution

15. Sea-level rise
16. Land subsidence
17. Changing meteorological conditions

See presentation D. Zamrsky at SWIM
See poster J. Van Engelen at SWI

Numerical 3D models groundwater coastal zone



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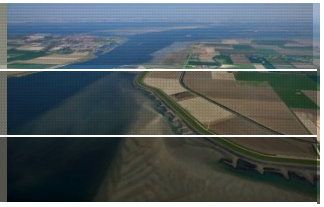
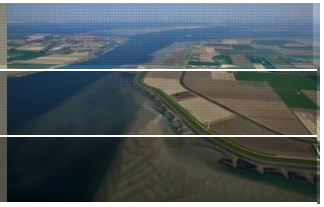
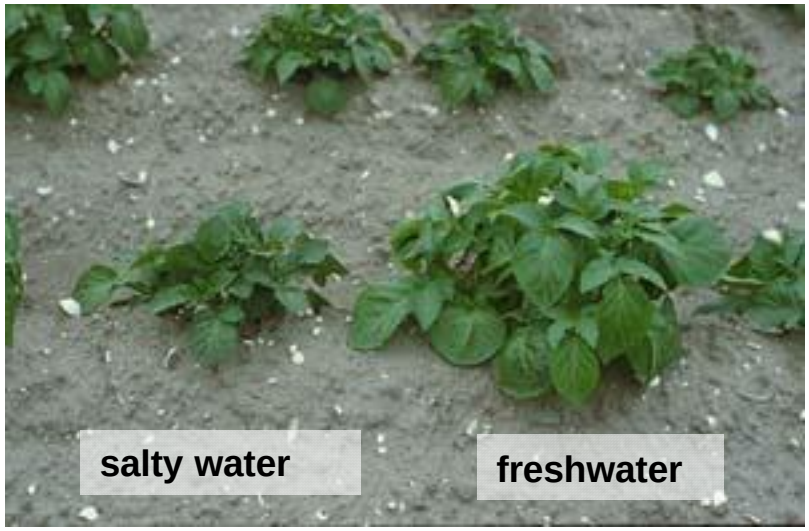
Comparing the four deltas

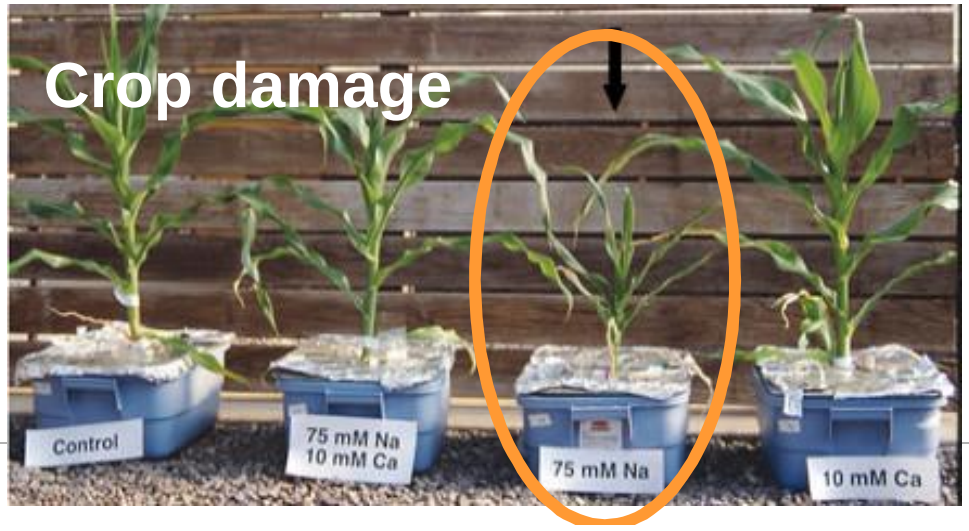


	Mekong Vietnam	Nile Egypt	Ganges-Brahma-putra, Kulna area, Bangladesh	Rhine-Meuse Netherlands
Responsible institutes data collection	DWRPIS Division for Water Resources Planning and Investigation for the South of Viet Nam	RIGW Research Institute for Groundwater	DPHE Department of Public Health Engineering BWBD: B.Wat.Dev.Board BADC: B.Agri.Dev.Coor.	TNO Geological Survey of The Netherlands
Data availability salinity	Large amount	Very limited	Pretty limited	Large amount
Stresses, next to salinisation, SLR, CC	Overexploitation, Subsidence	Overexploitation	Overexploitation, Subsidence, Arsenic	Subsidence
People + increase million	17 Increase 1.1%/yr	40 Increase 2.25%/yr	163 Increase 1.2 %/yr	16 Increase 0.3%/yr
Extraction billion m^3/yr (=1km^3/yr)	0.75, increase	4, big increase ->8	~2.5	1, stable
Estimated fresh GW volume 10^9 m^3	~750	450	>10000, but contaminated with Arsenic	1000
Depletion factor (volume/extraction)	~1000, but very limited recharge thus probably mining	~100 thus mining, limited recharge	>>1000, but Arsenic in it	~1000, no mining and clean surface water alternative
Replenishment?	limited, thick clay layer	yes, indirect via irrigation canals	yes, large amount; small scale only drinking water	yes, large amounts

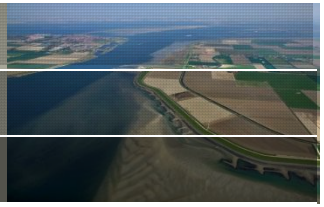
Salt in water is a problem







Salt in water is a problem



-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:

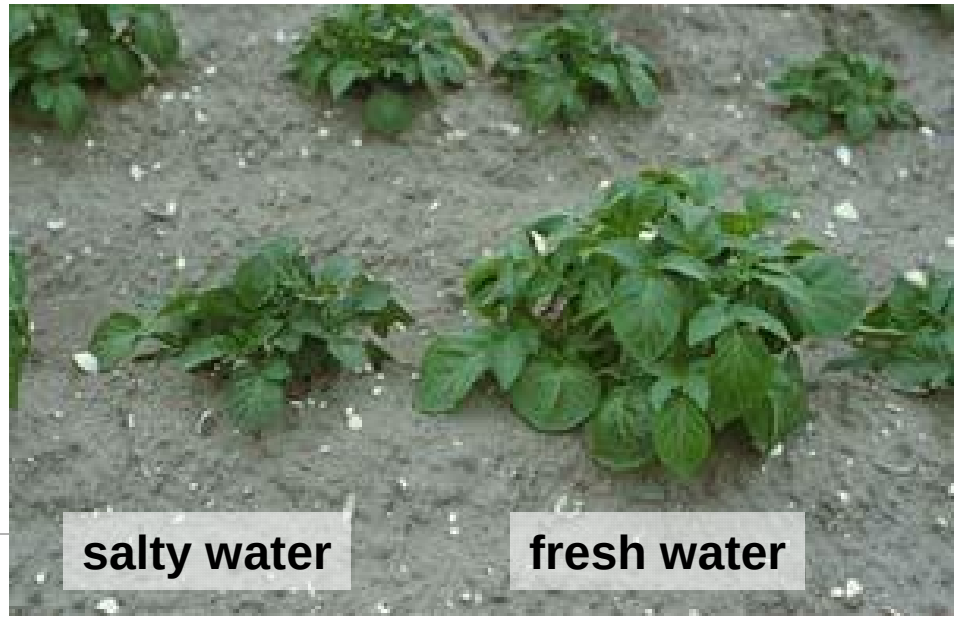
- corrosion pipes
- preparation food

-irrigation/agriculture:

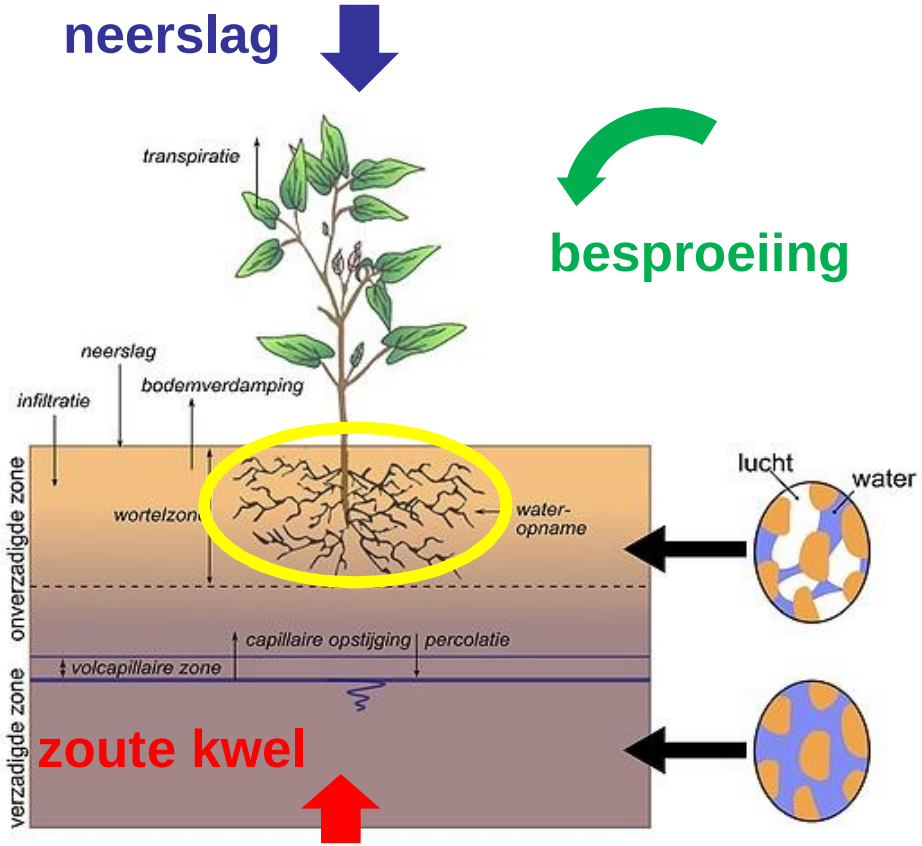
- production crops
- salt damage

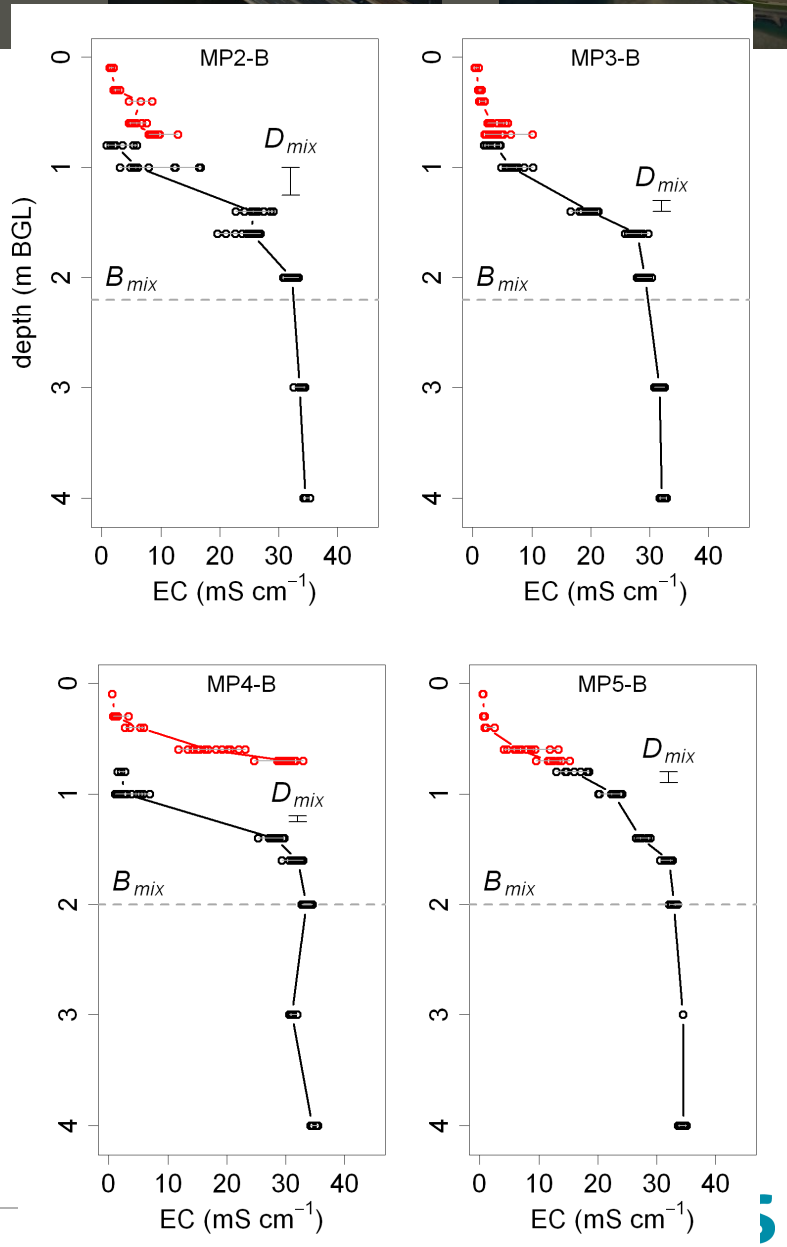
Grass ≥ 3606 mg Cl-/l
Cereals ≥ 4801 mg Cl-/l
Potatoes ≥ 756 mg Cl-/l

Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad



Zouttolerantie gewassen

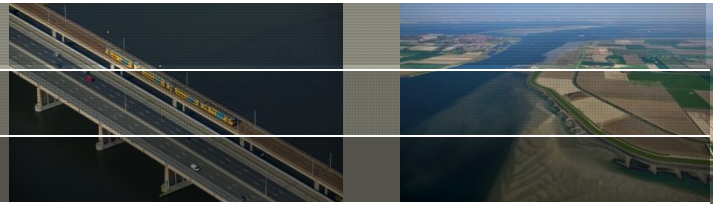




Belangrijke parameters:

- **Chloride concentratie bij wortelzone**
- **Landgebruik**
- **Gevoeligheid gewassen**

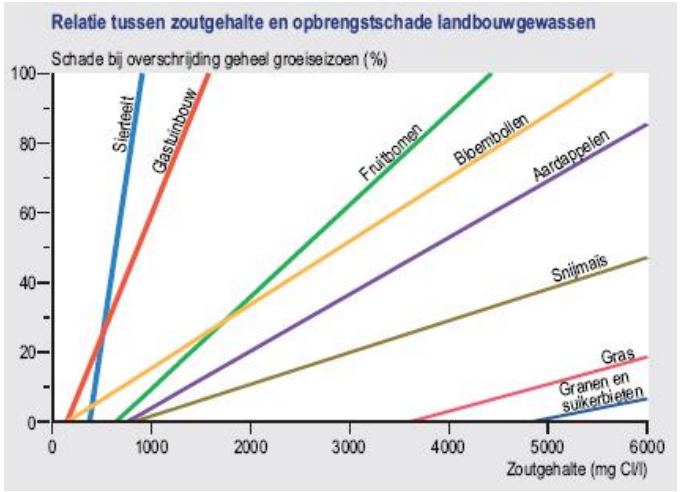
Salt damage to crops



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: MNP, 2005

Source: Roest et al., 2003 en Haskoning

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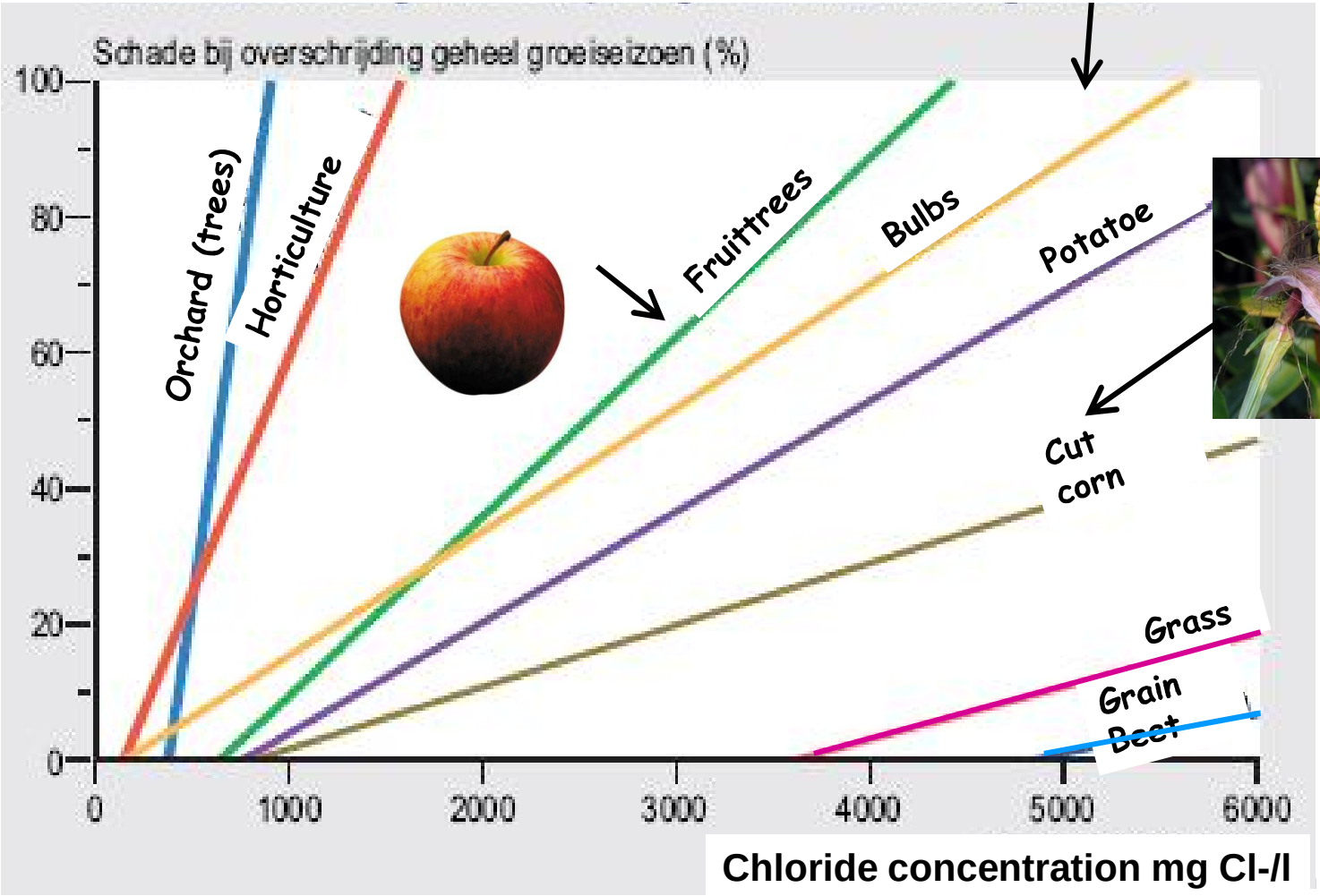
Salt damage to crops

Relation between salt concentration and damage to crops

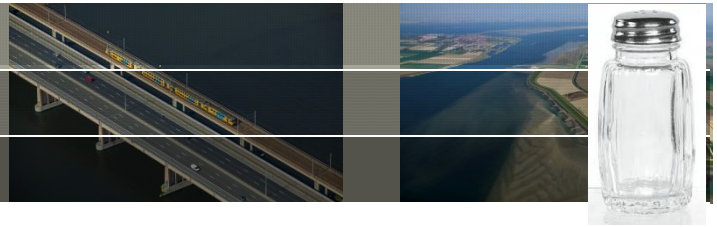


Source: MNP, 2005

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	

Deltares

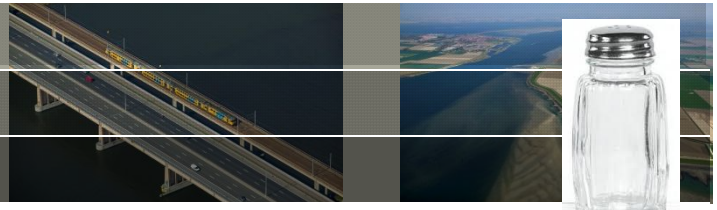


In 1 liter ocean: about 35 gr salt

Deltares

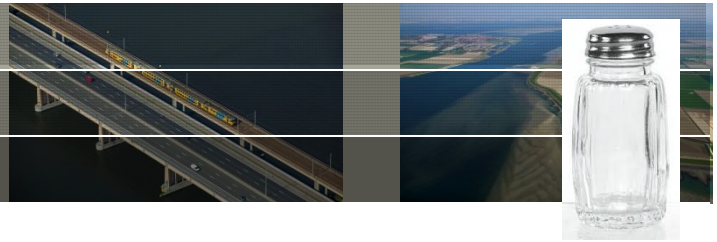
In 1 liter Dead Sea water (Jordan) : about 280 gr salt

Deltares



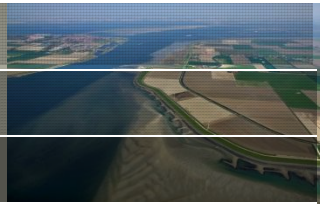
In 1 liter drinking water: about 0.6 gr salt is allowed

Deltares



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

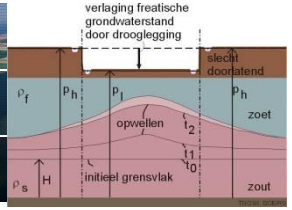
To get an idea about the effect on deltaic areas worldwide, just check the Dutch siutaion

Mississippi, USA

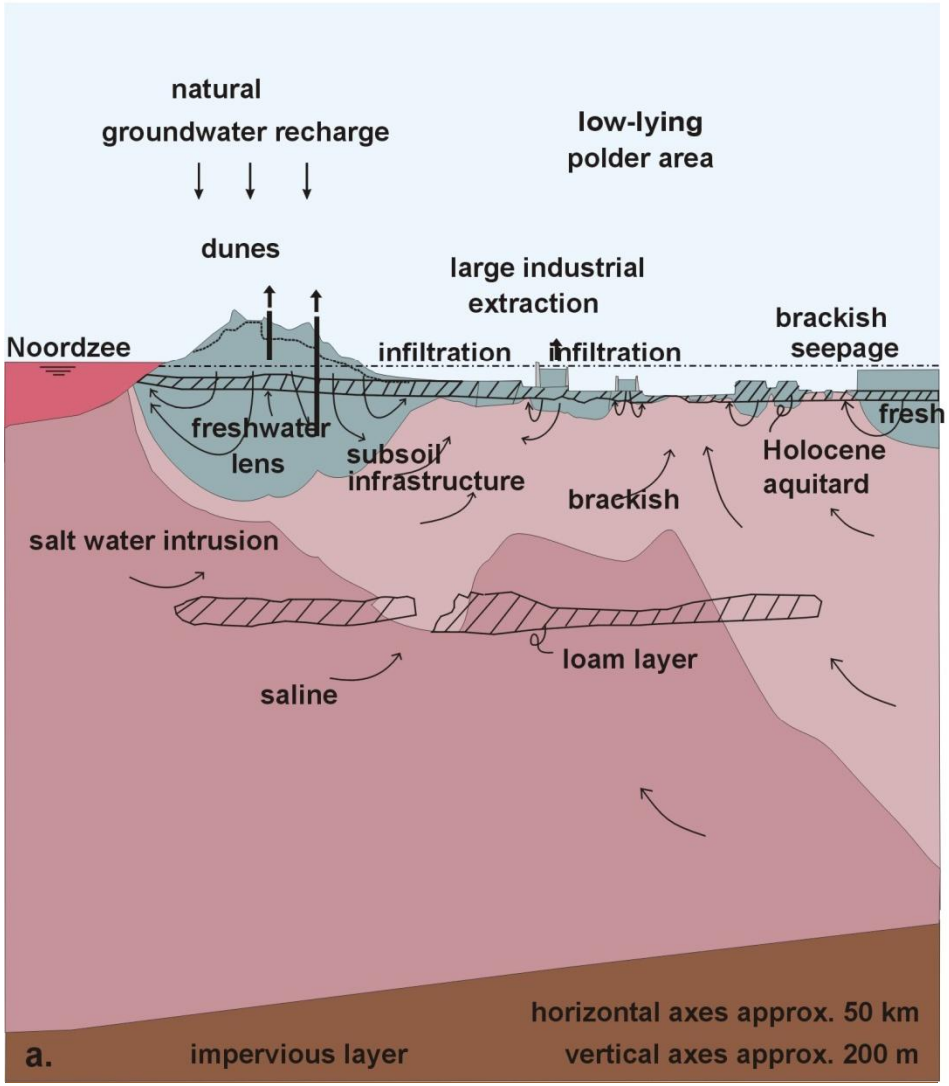
Bangladesh

Mekong delta

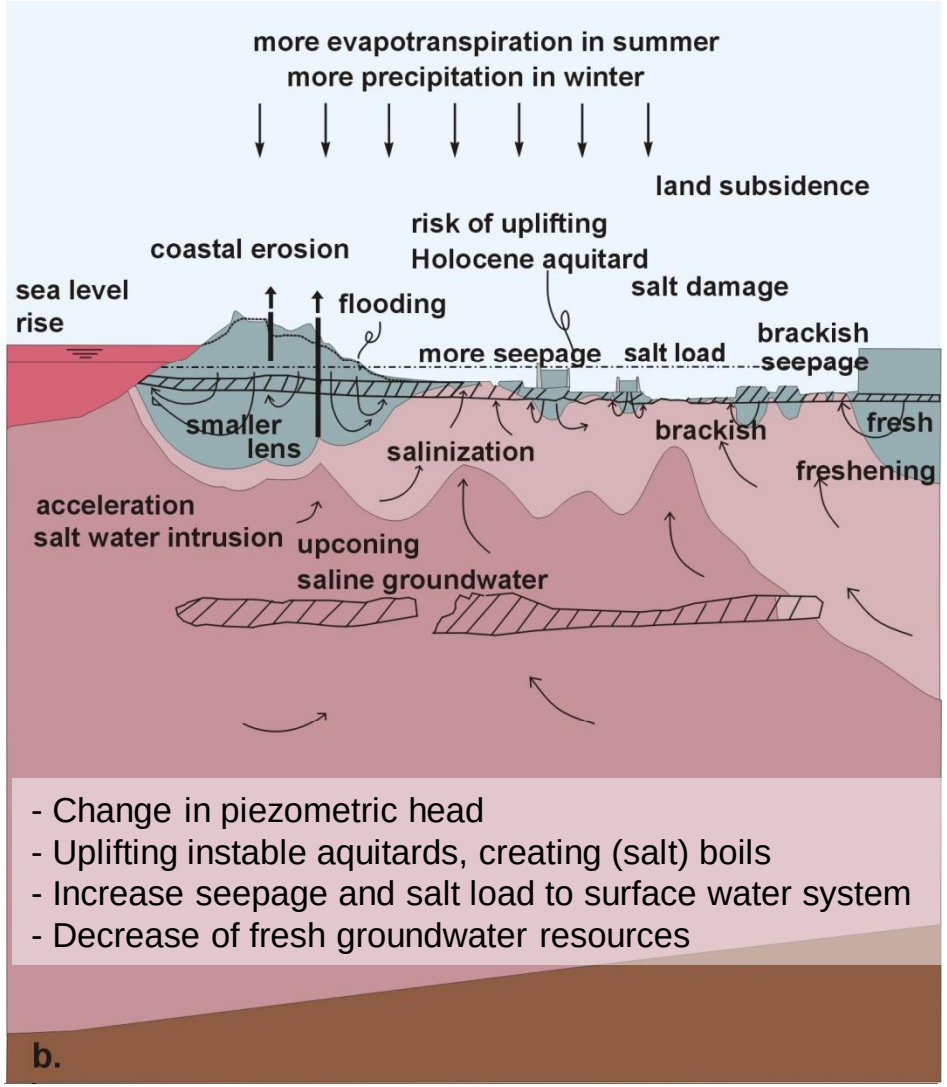
The (Dutch) groundwater system under stress



Present processes

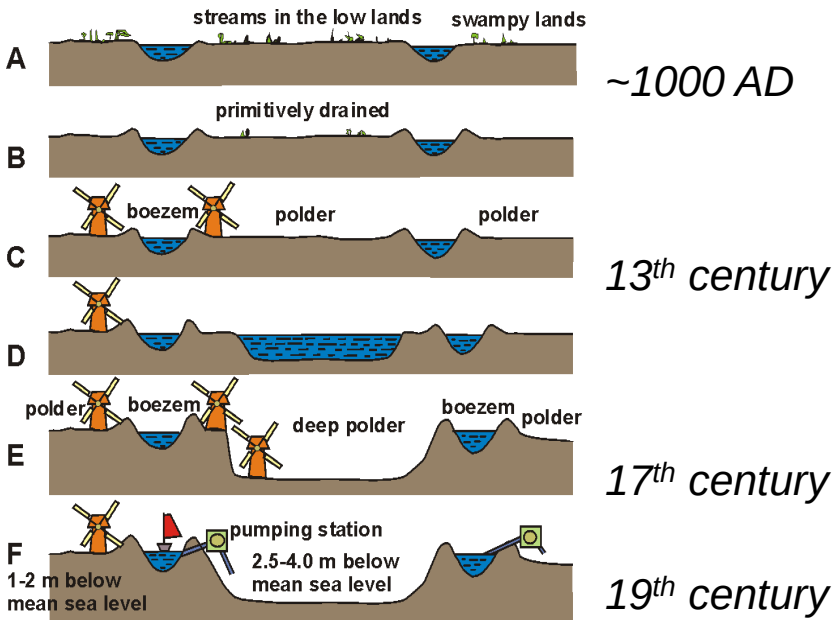


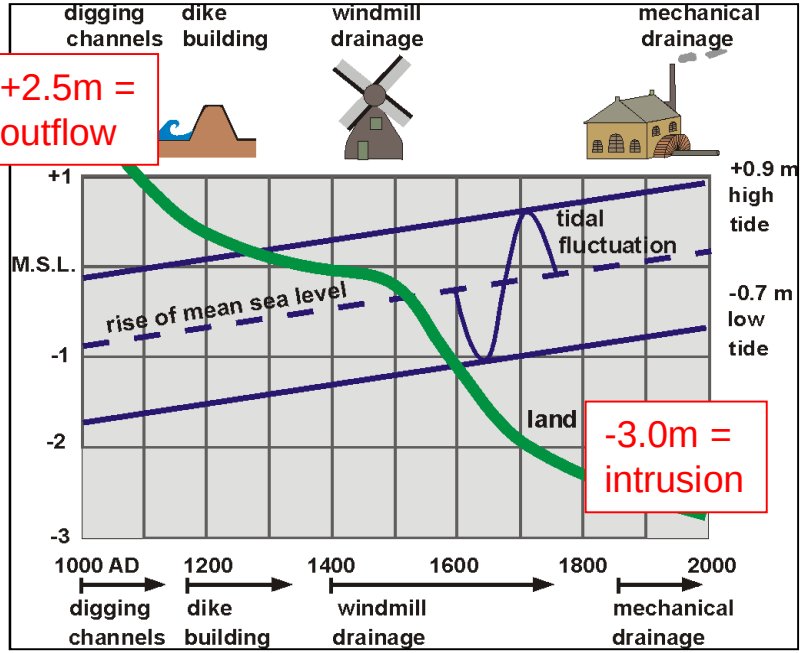
Future changes

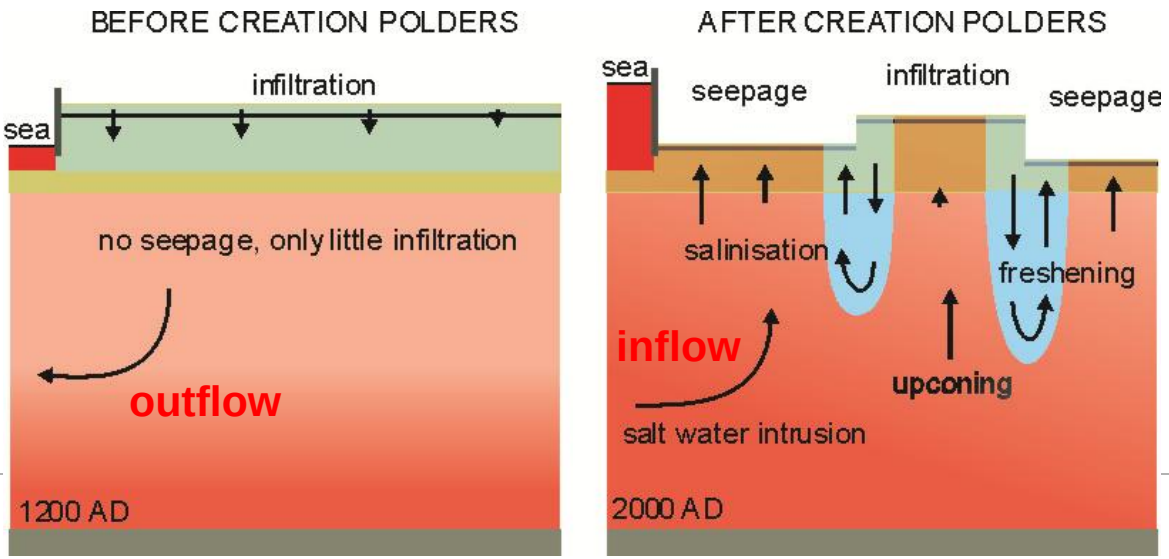


- Change in piezometric head
- Uplifting instable aquitards, creating (salt) boils
- Increase seepage and salt load to surface water system
- Decrease of fresh groundwater resources

From fresh water outflow to salt water inflow





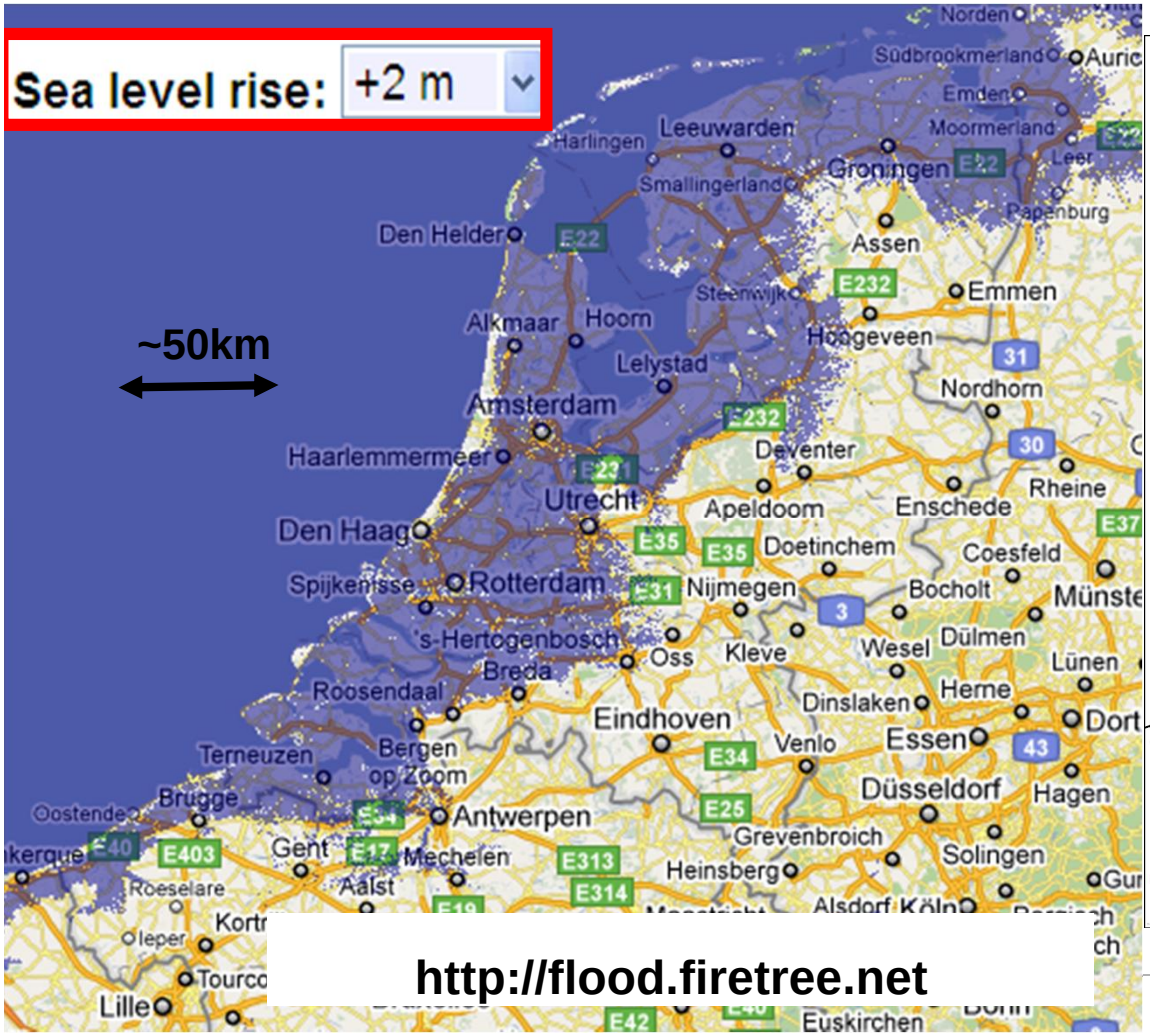


Ground surface

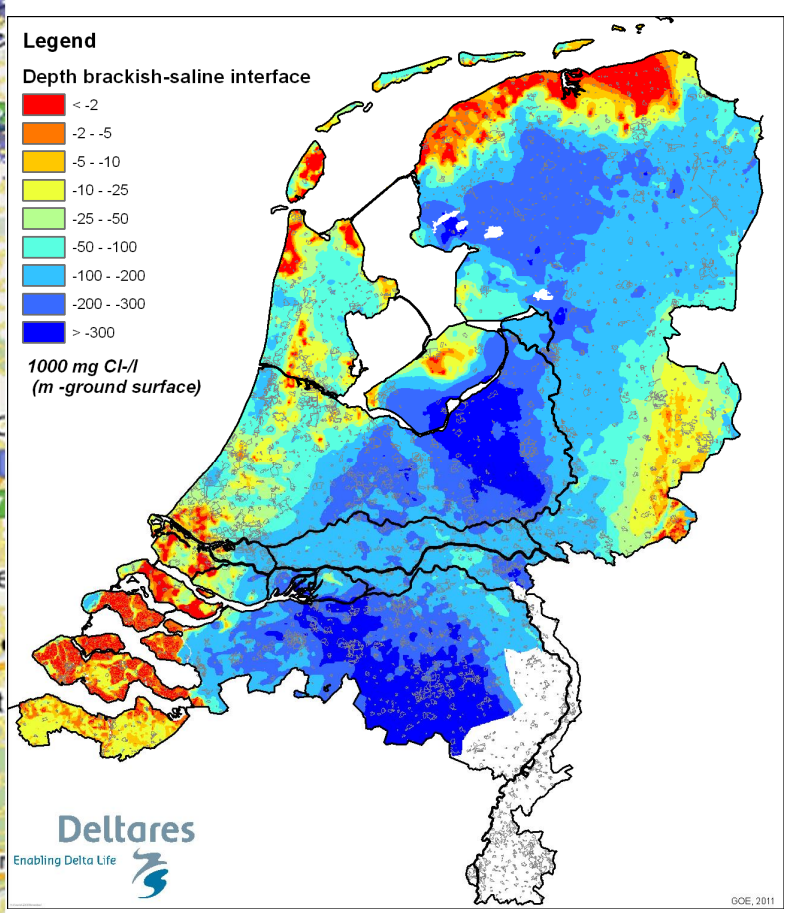
Historical subsidence of the ground surface in Holland

Deltares

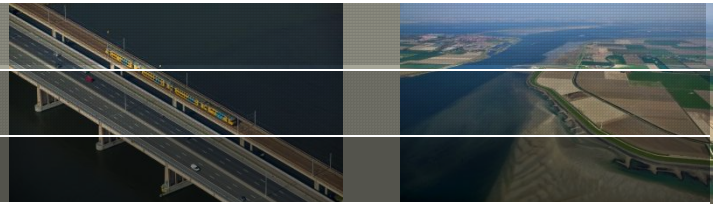
The Netherlands: low-lying lands and saline groundwater

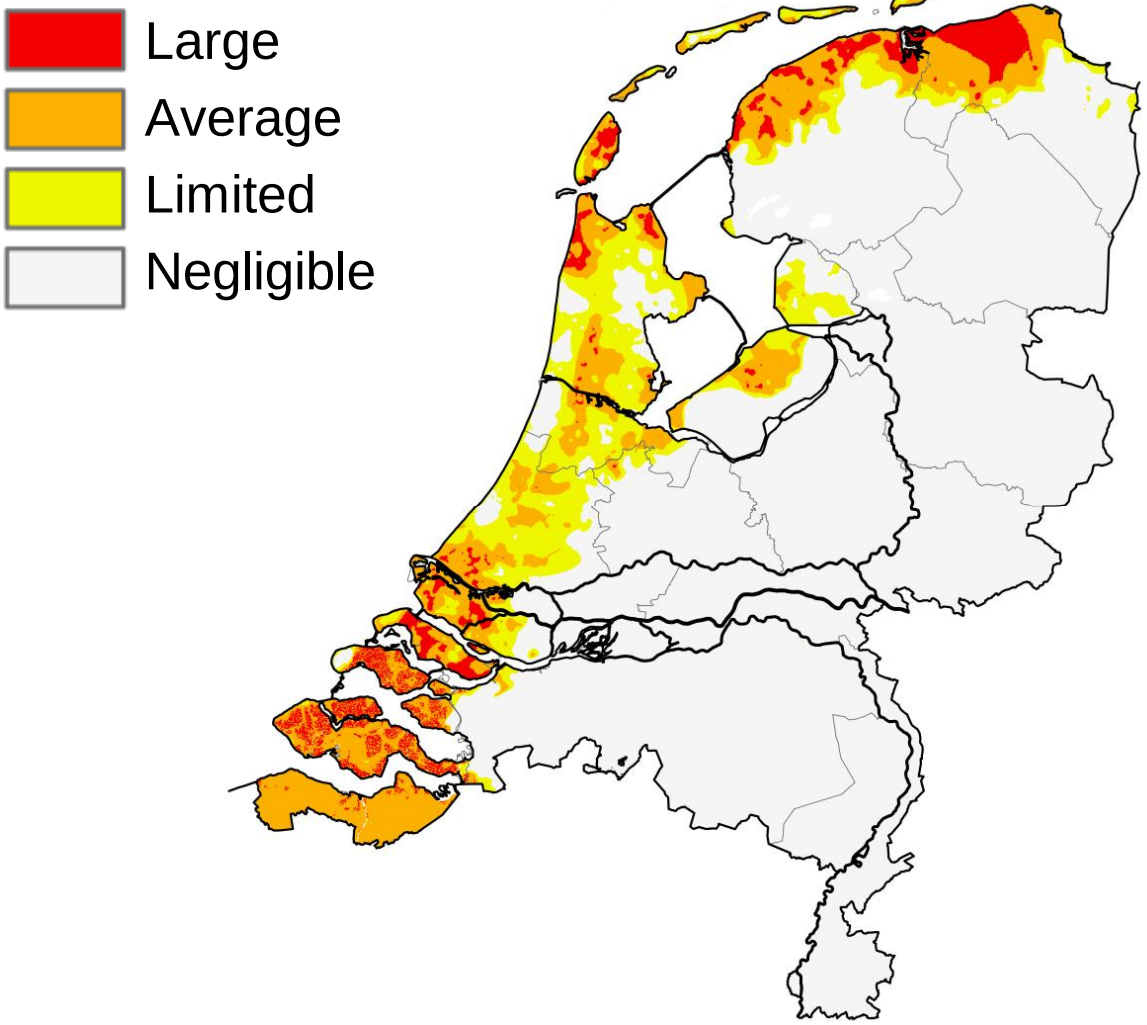


http://flood.firetree.net



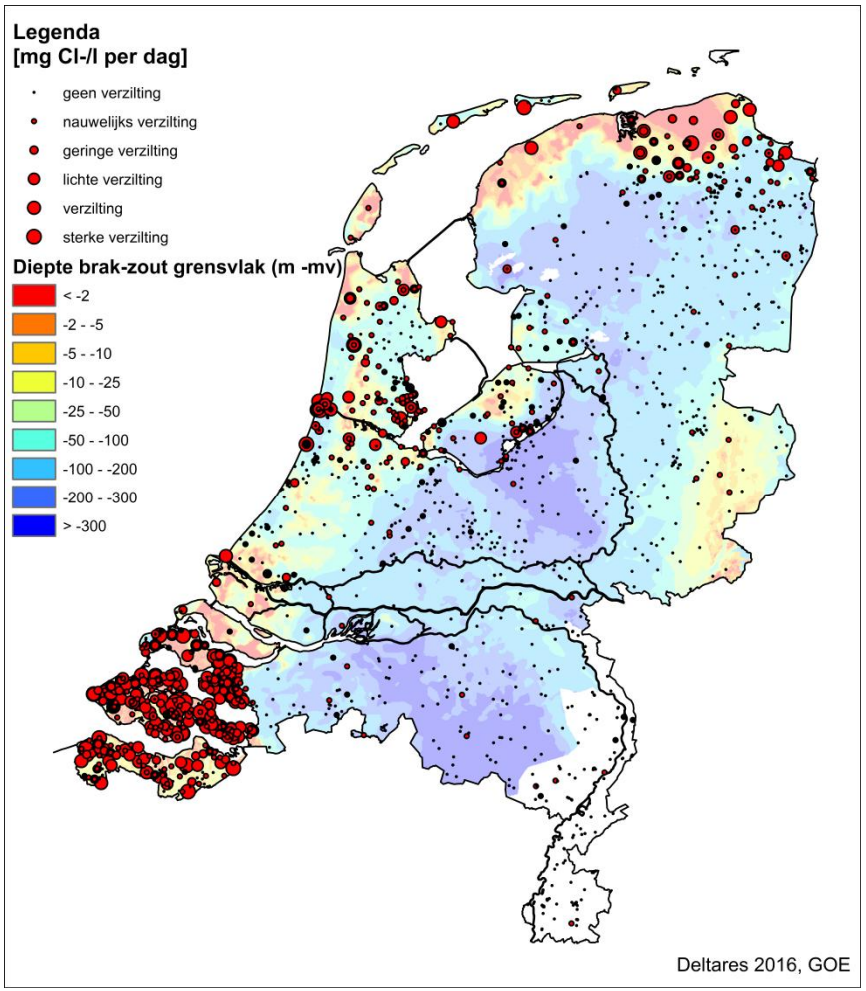
Zones of risk of salinisation

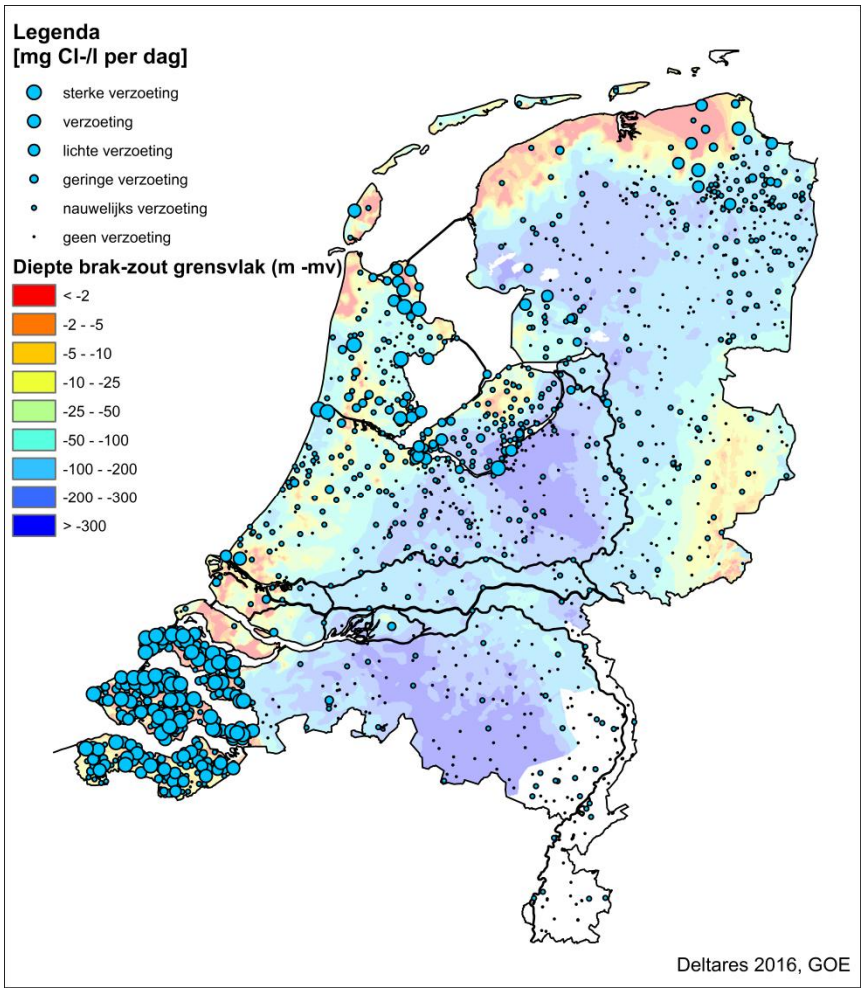


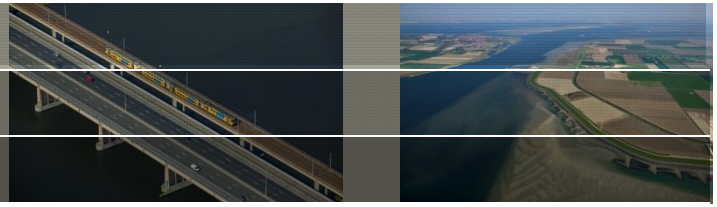


Deltares

Salinisation-freshening groundwater: measurements



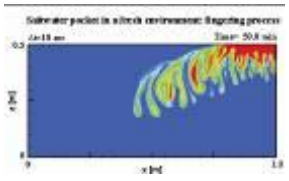
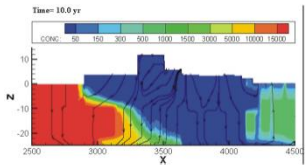
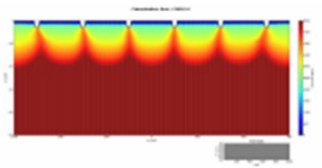




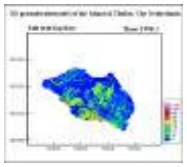
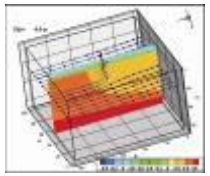
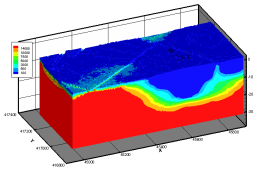
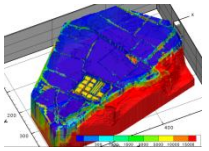
Deltares

Different model cell sizes to consider several phenomena

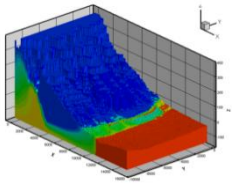
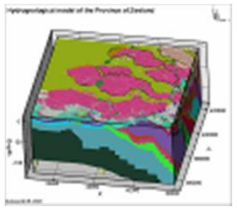
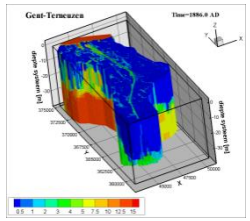
Sub-local: fingering, salty sand boils
Sri Lanka (Tsunami 2004), Zandmotor
cell size=1cm-1m

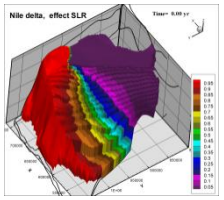
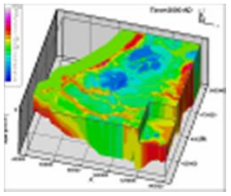
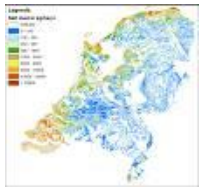
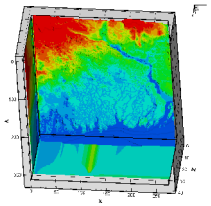
Local: rainwaterlenses, heat-cold
Tholen, Schouwen-Duiveland
cell size=5-25m

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

National: 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

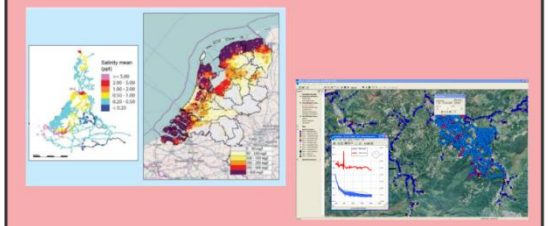
Deltares

Modelling tools: iMOD Open Source

Flexible Mesh/SOBEK

major features:

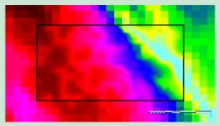
- salt water intrusion & surface water quality
- 1D network or 2D horizontal grid
- powerful hydrodynamic simulation engine
- complex flows & water related processes
- dispersion coëfficiënt calibrated with field data & model results from DELFT3D
- also flood forecasting

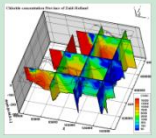


iMOD-SEAWAT

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

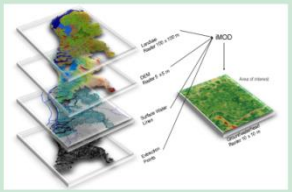


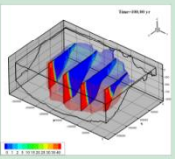


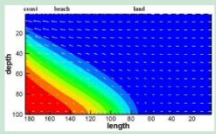
SUB-CR (subsidence)

major features:

- core is **MODFLOW**
- includes slow subsidence (creep)
- saturated and unsaturated zone



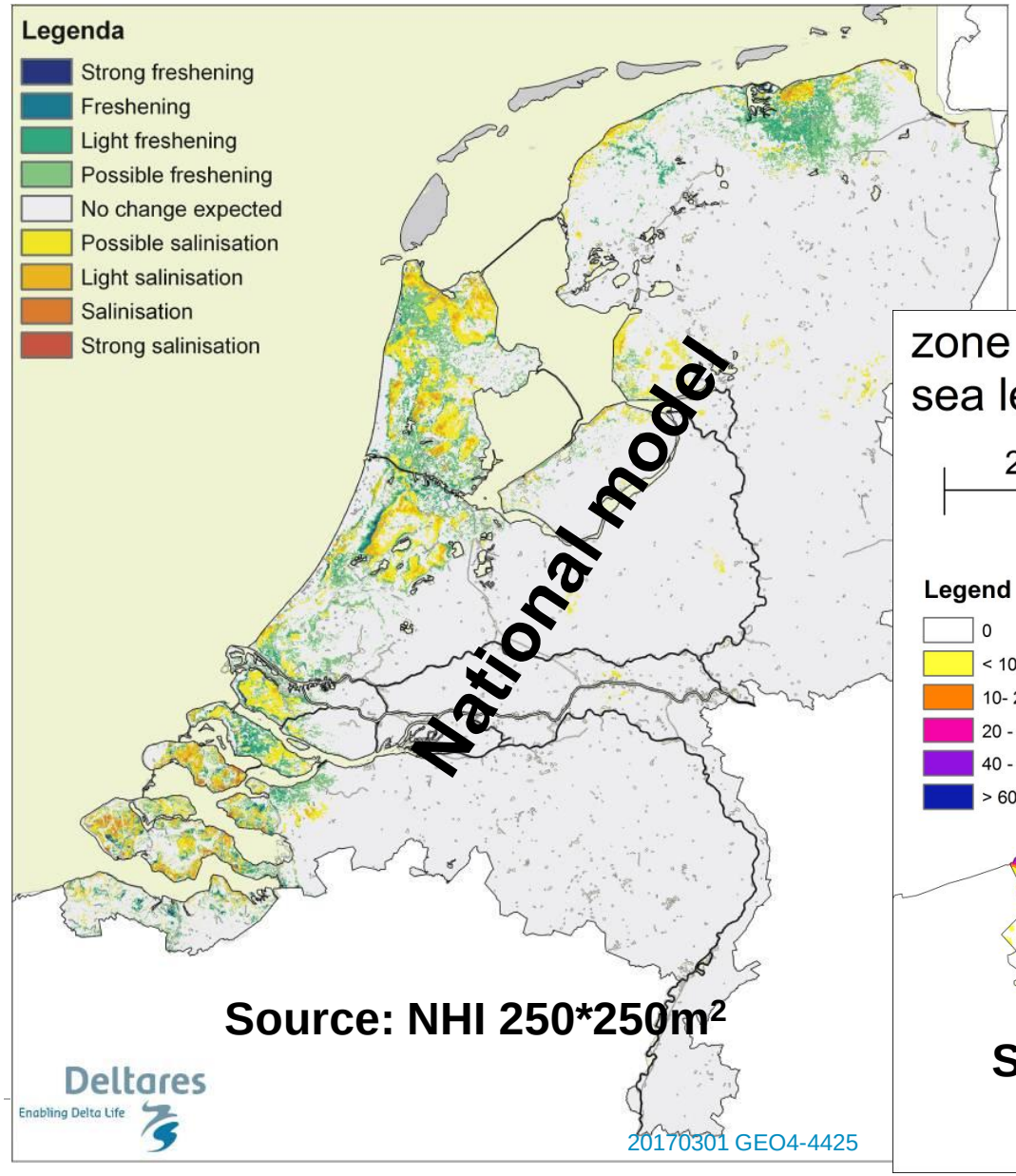




http://oss.deltares.nl/web/imod

Deltares

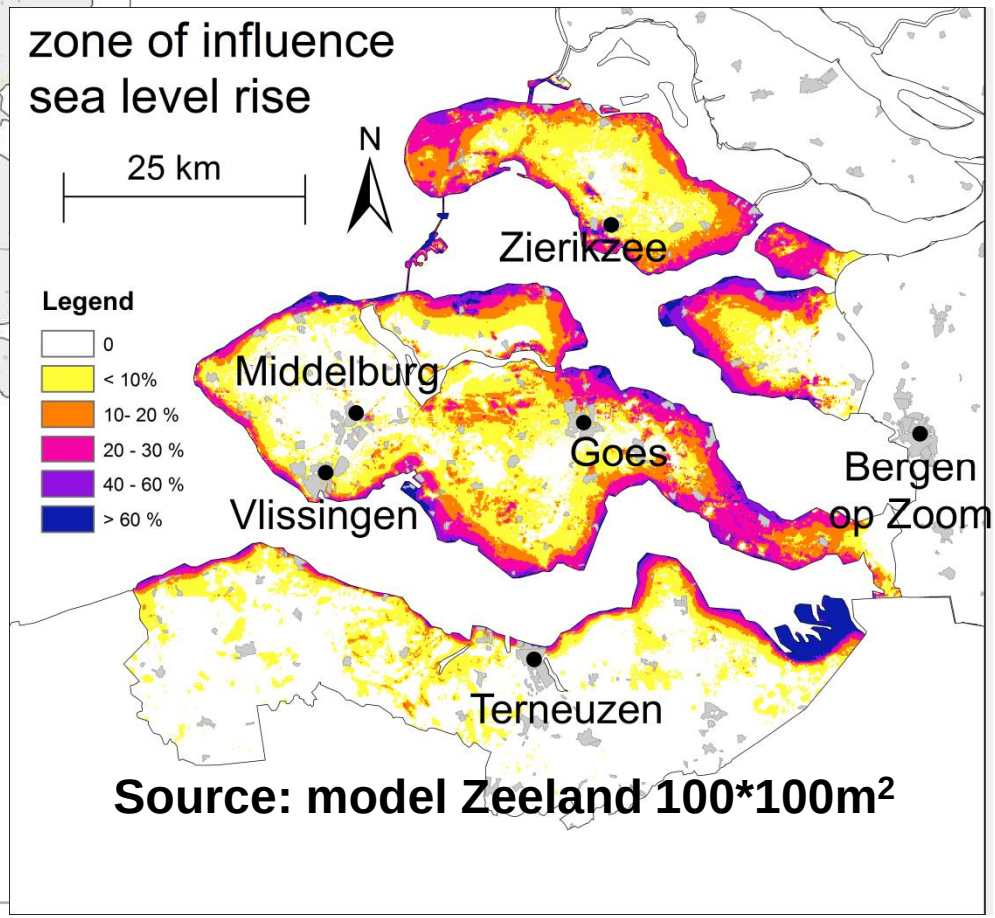
Salinisation & freshening under Climate & Global stress



Source: NHI 250*250m²

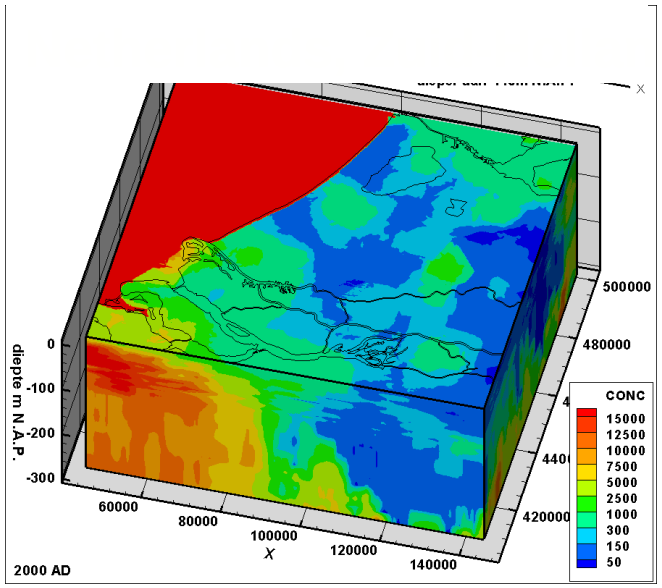
Deltares
Enabling Delta Life

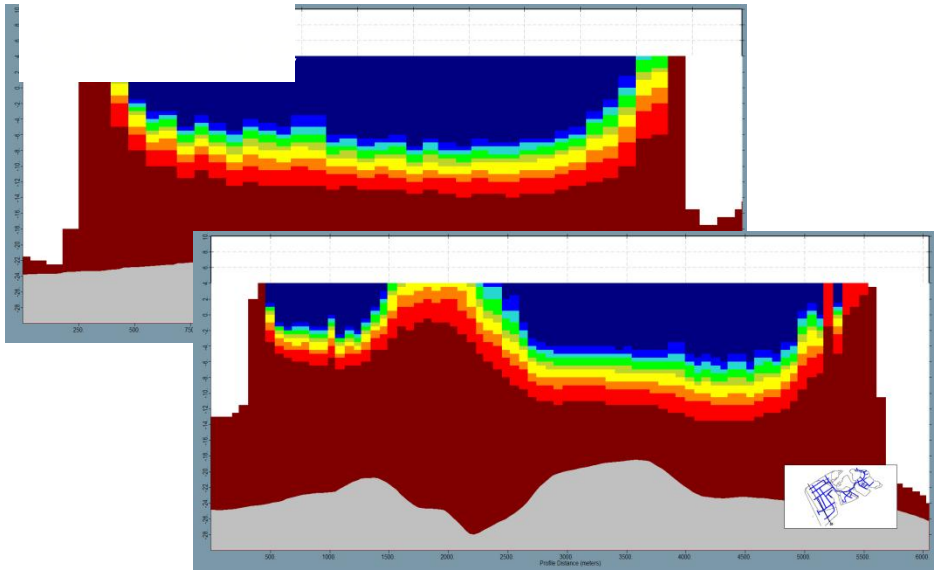
Regional model



Source: model Zeeland 100*100m²

3D Regional coastal groundwater model studies





Modelling:

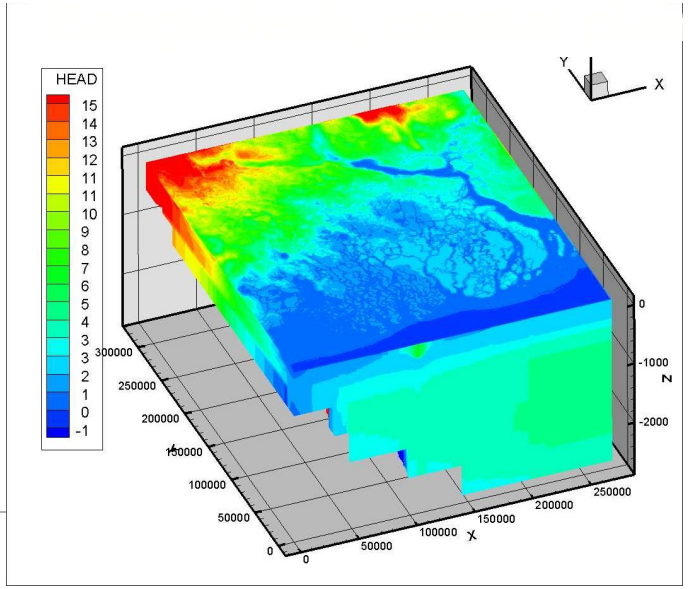
- **variable-density groundwater flow, coupled solute transport**

Simulating effects of:

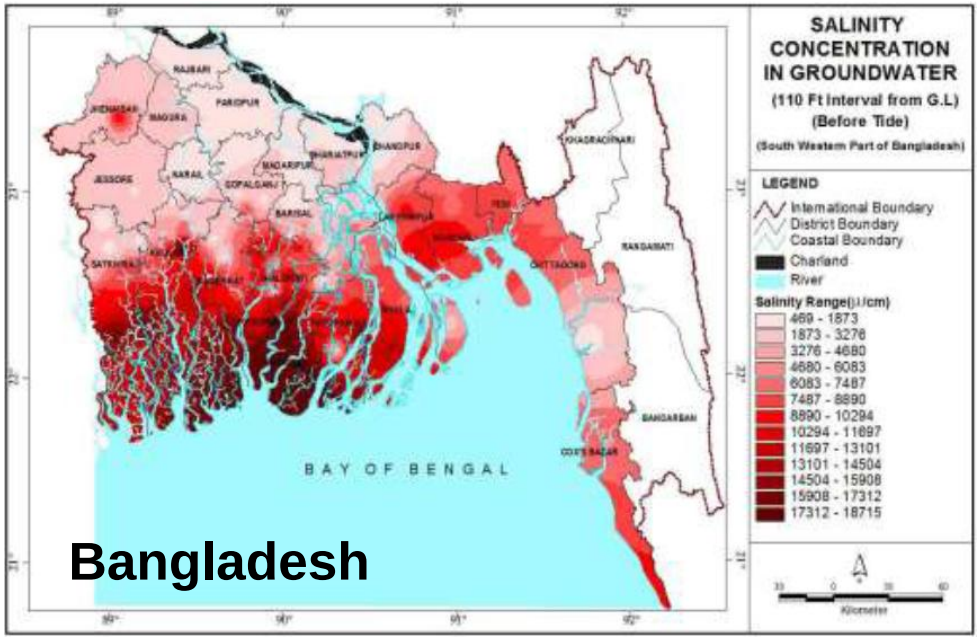
- **autonomous processes (change extraction rates)**
- **sea level rise, changing recharge pattern**
- **land subsidence**

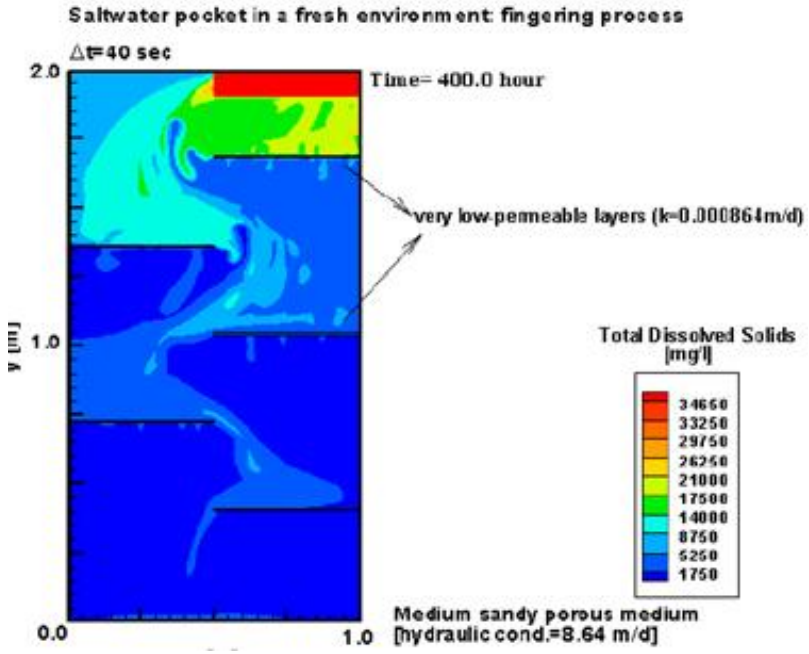
Quantifying:

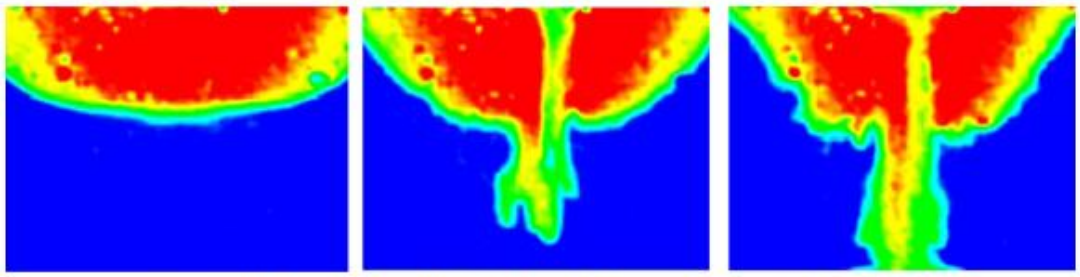
- **hydraulic head**
- **saline seepage / infiltration**
- **fresh groundwater resources**



Interaction fresh-saline groundwater-surface water







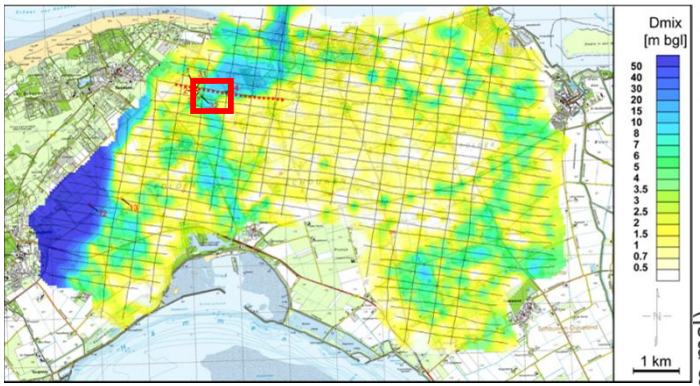
a: t= 241 s b:t = 241 + 4883 s c: t = 241 + 7126 s

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

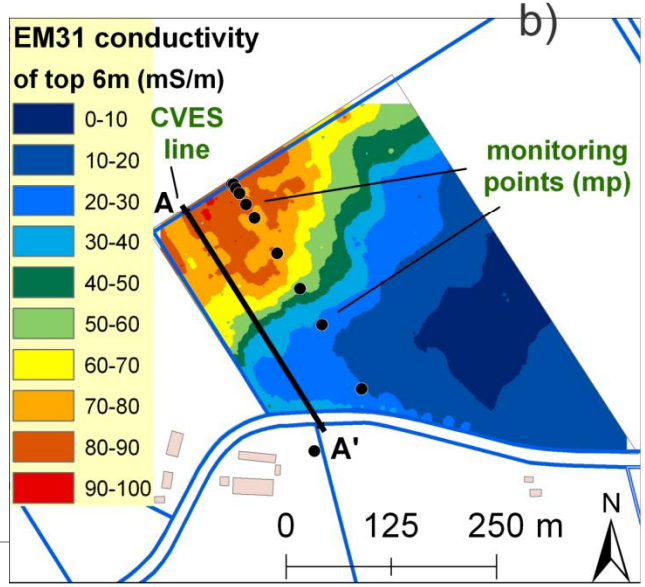
Deltares

Comparison monitoring data with model results

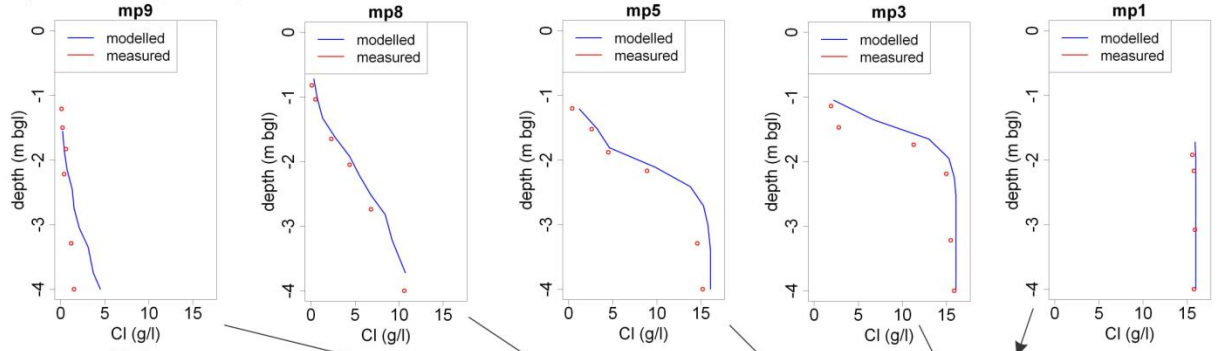
a) Airborne EM

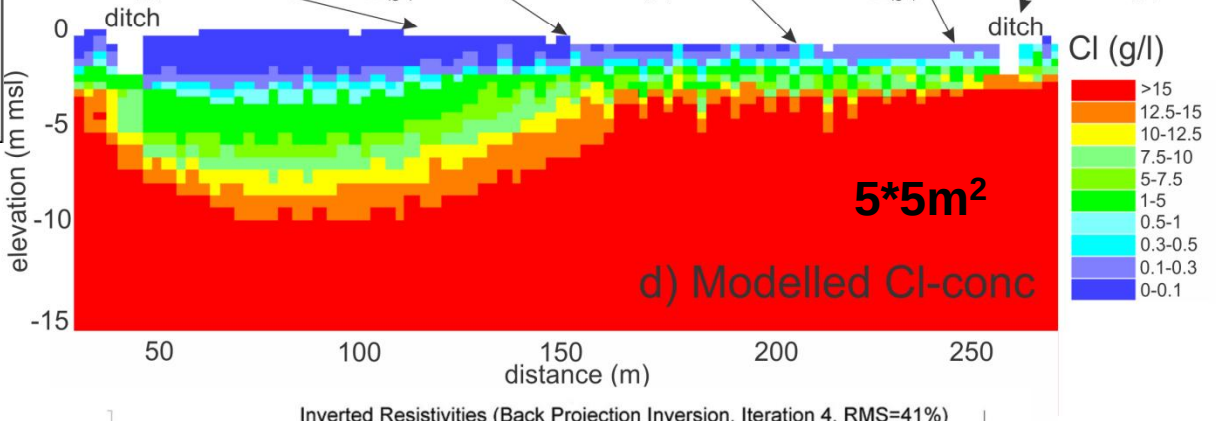


b)

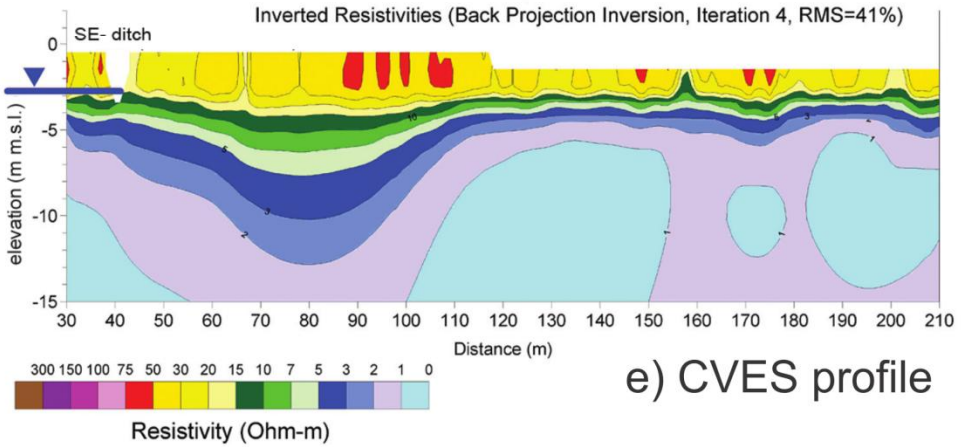


c) Cl-depth profiles



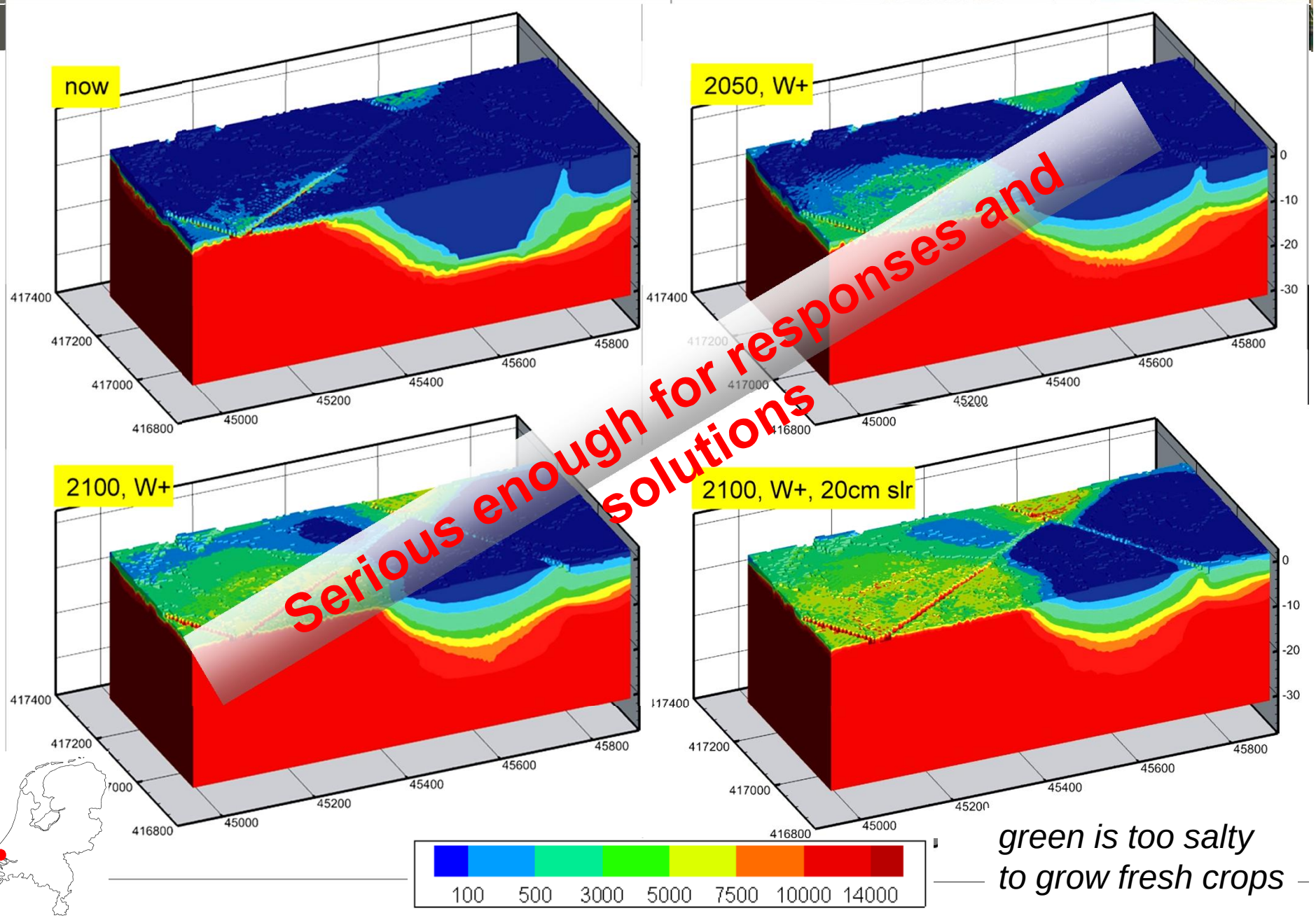


d) Modelled Cl-conc

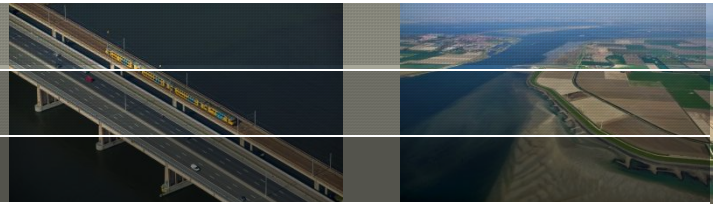


e) CVES profile

Modelled Cl-concentration: different CC scenarios

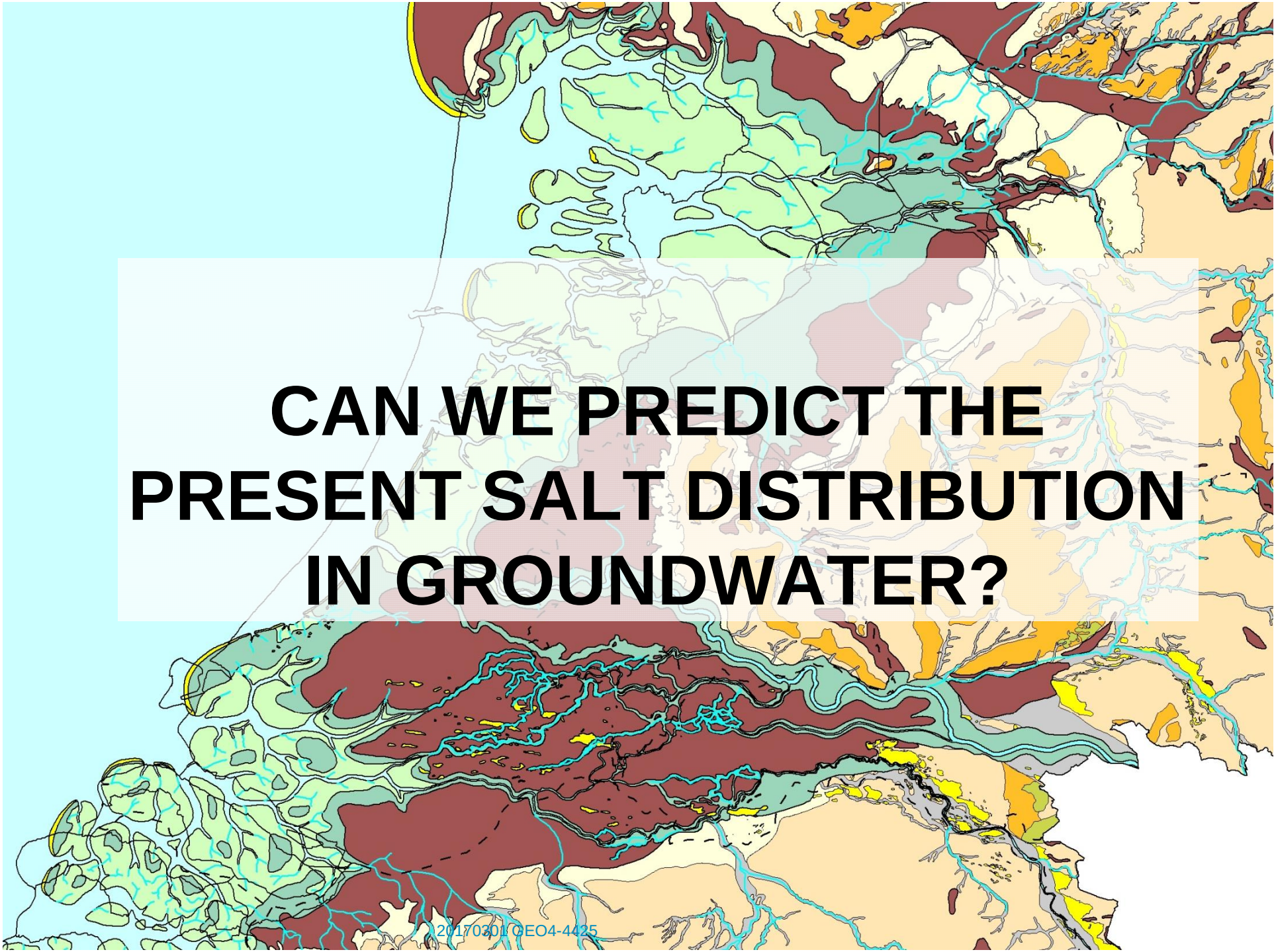


green is too salty to grow fresh crops

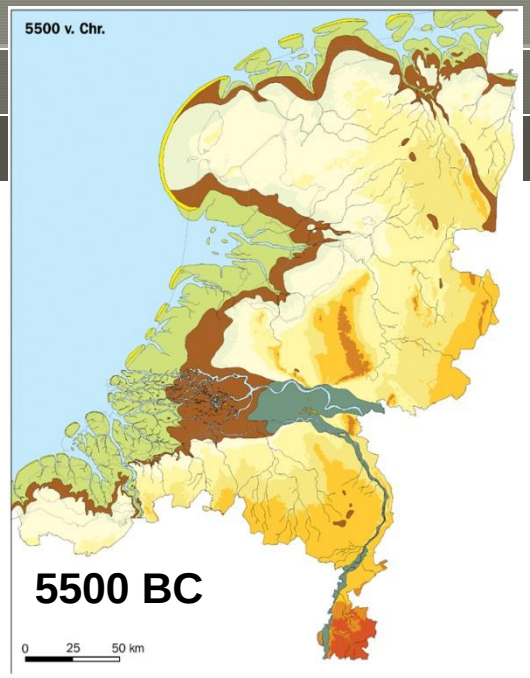


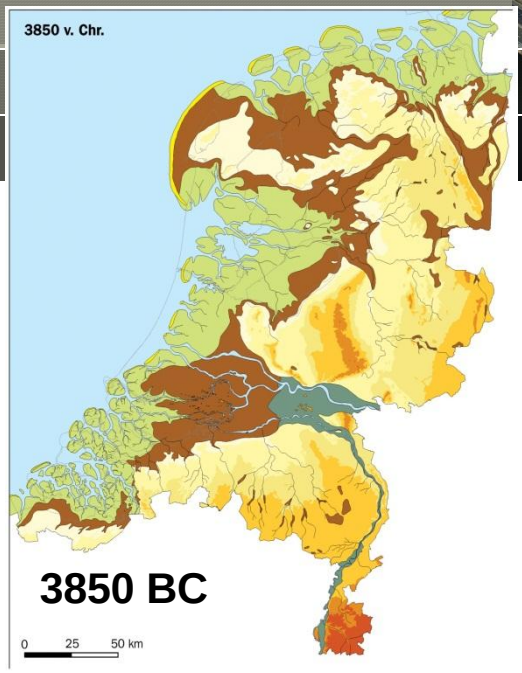
Palaeo-hydrogeographical modelling

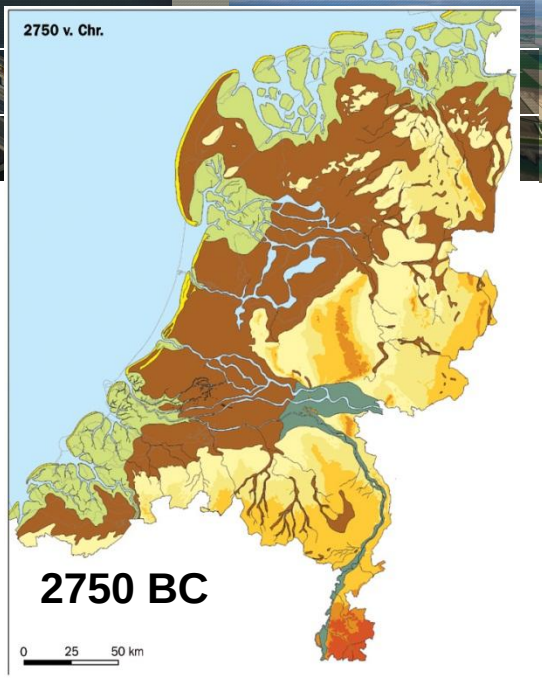
Delsman et al., HESS, 20

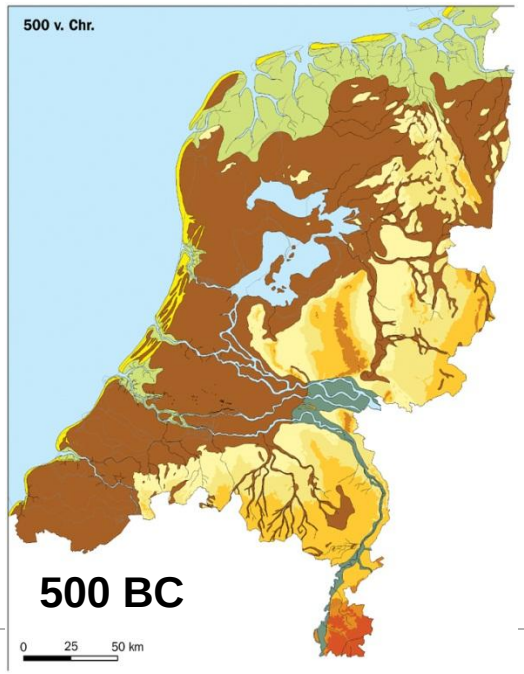


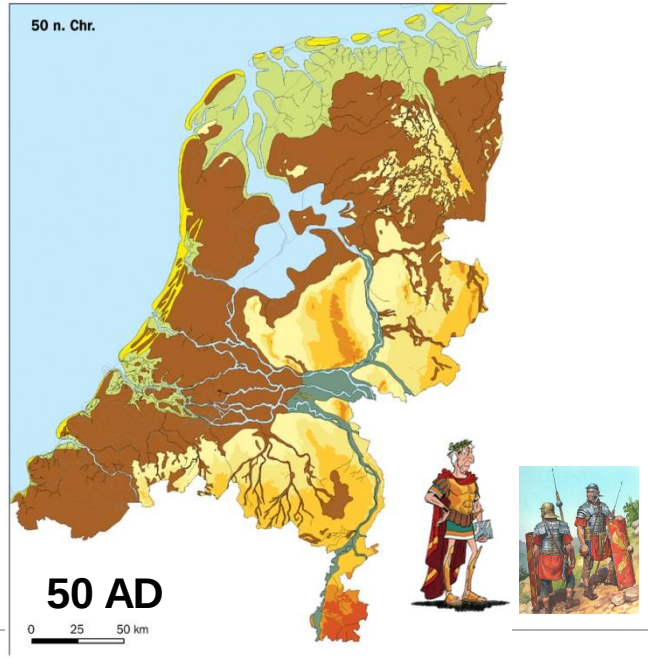
CAN WE PREDICT THE PRESENT SALT DISTRIBUTION IN GROUNDWATER?

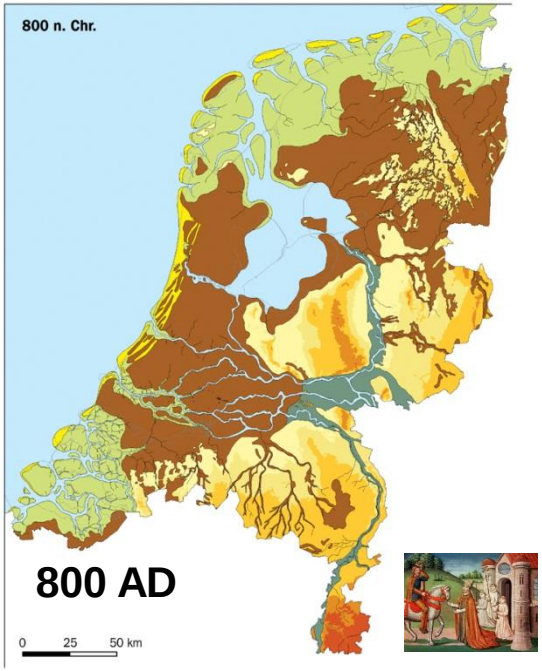

5500 v. Chr.
5500 BC
0 25 50 km


3850 v. Chr.
3850 BC
0 25 50 km

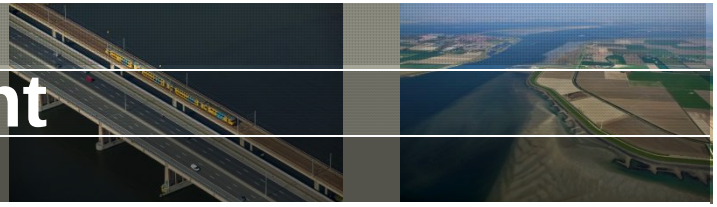

2750 v. Chr.
2750 BC
0 25 50 km


500 v. Chr.
500 BC
0 25 50 km

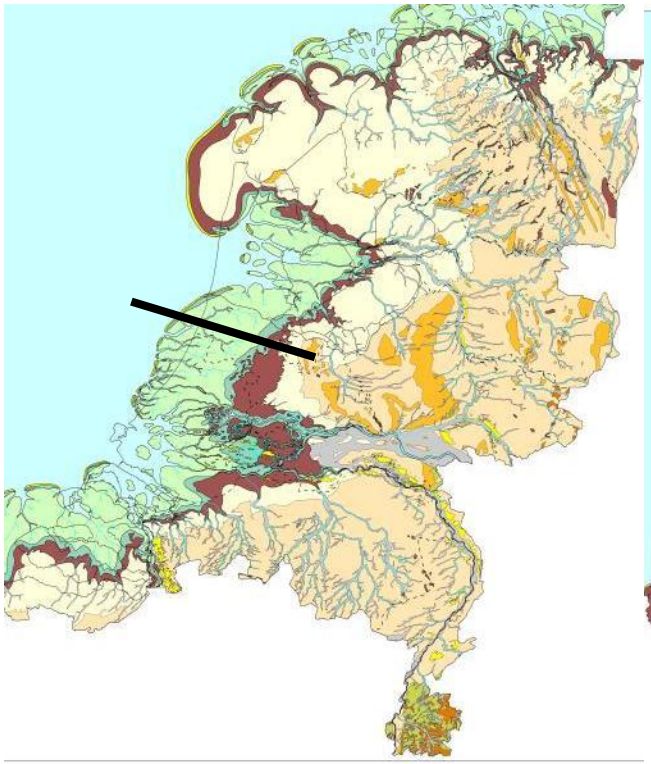

50 n. Chr.
50 AD
0 25 50 km


800 n. Chr.
800 AD
0 25 50 km

Palaeogeographical development

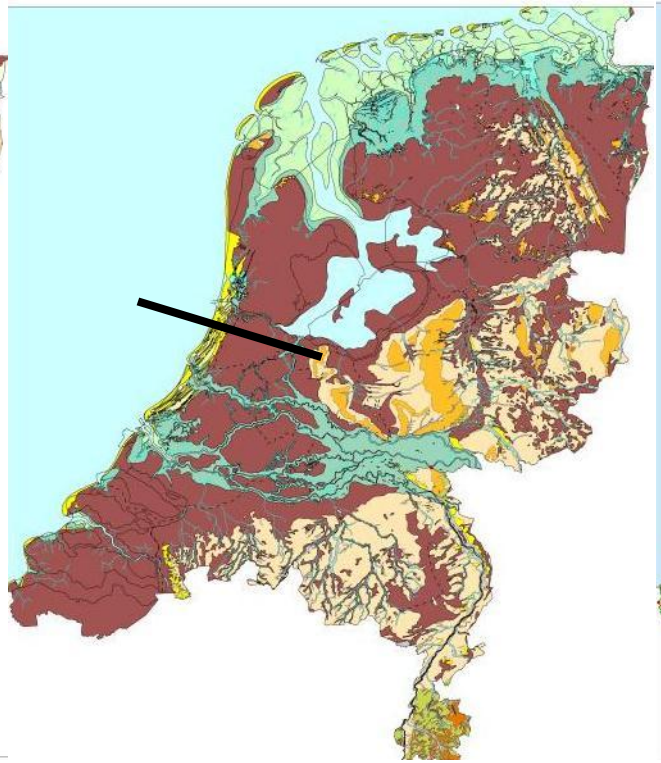


5500 BC



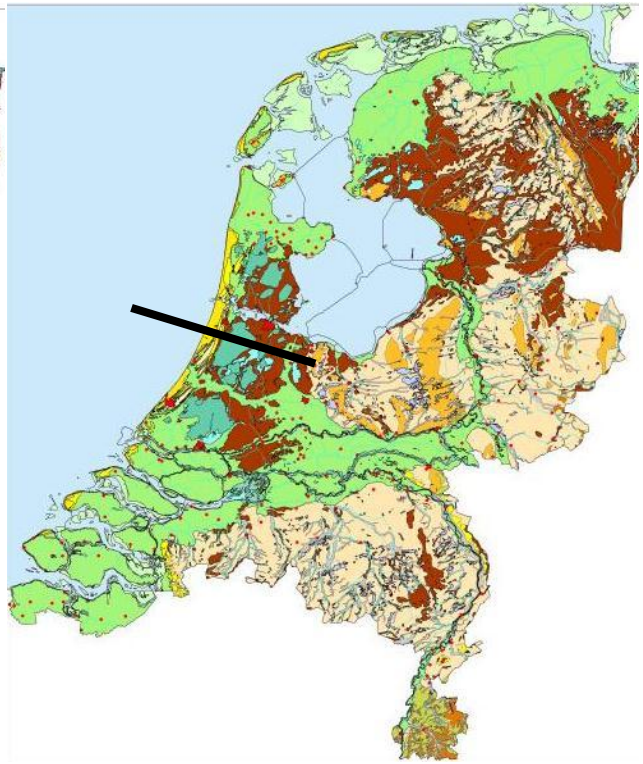
Maximal transgression

100 AD



Peat development

1850 AD



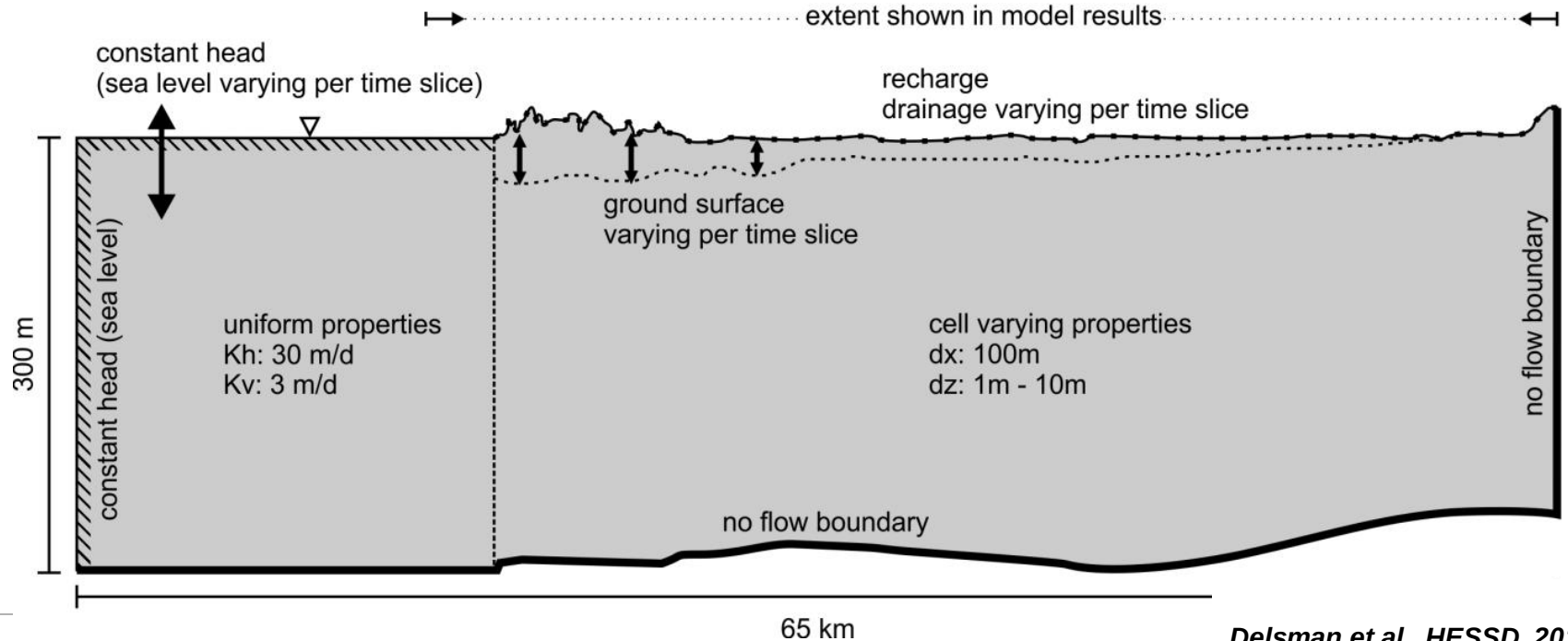
Reclaimed land, polder

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

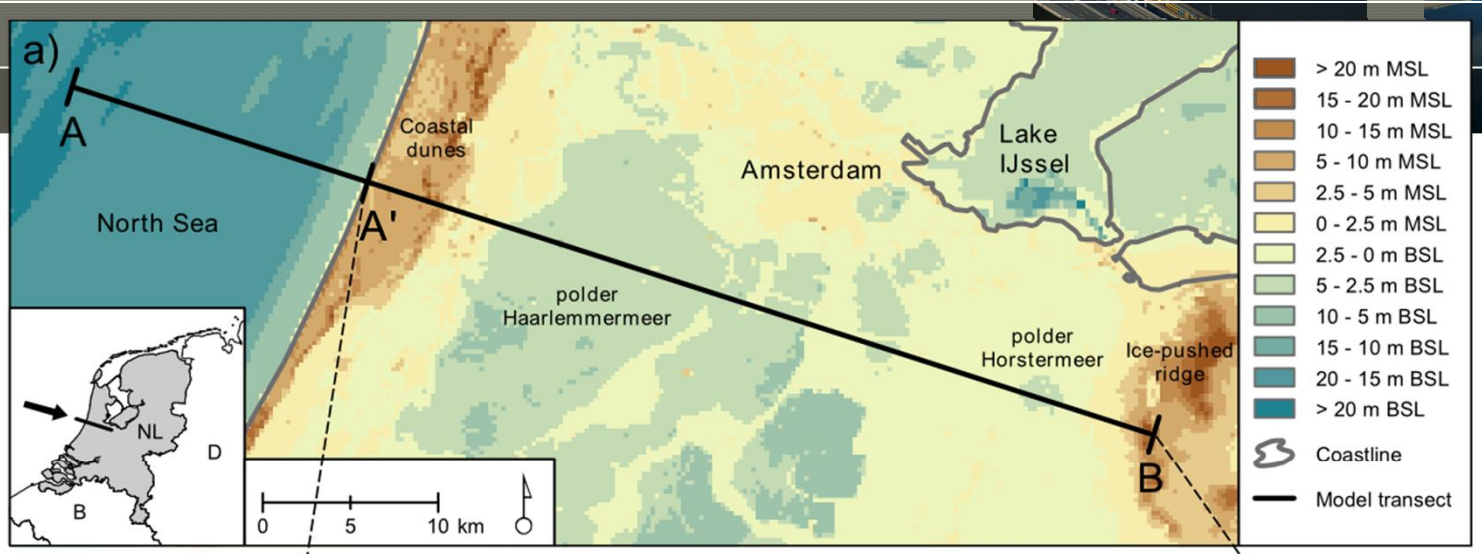
Deltares

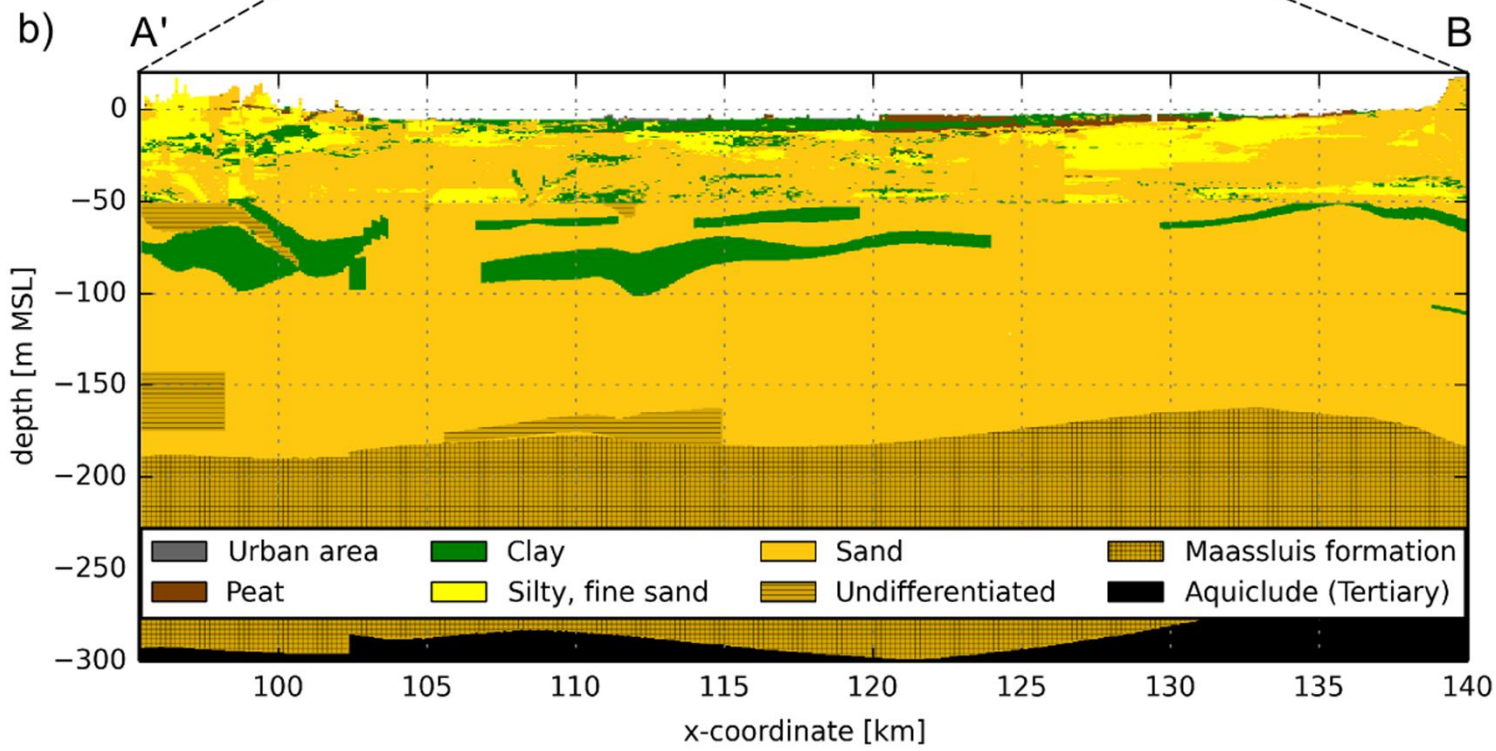
Occurrence of salt under the polder Haarlemmermeer

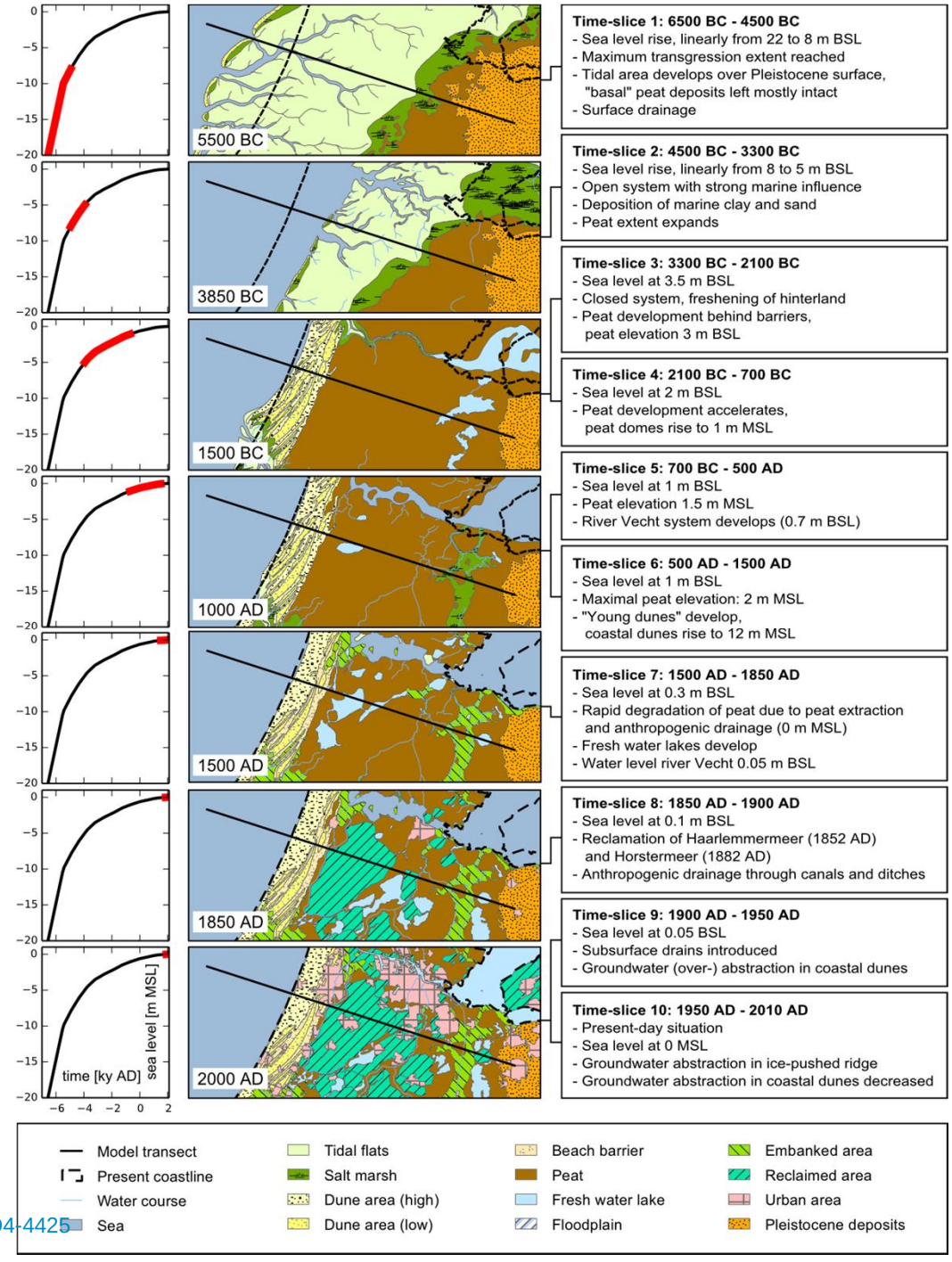
- Model profile Zandvoort - Hoofddorp – Hilversum
- Palaeogeographical development (Vos et al, 2011)
- 6500 BC - 2010 AD
- marine transgression
- Peat development, peat degradation, drainage, reclamation

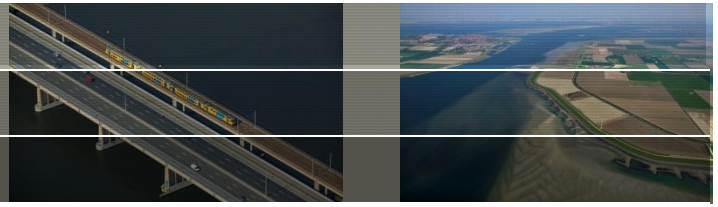


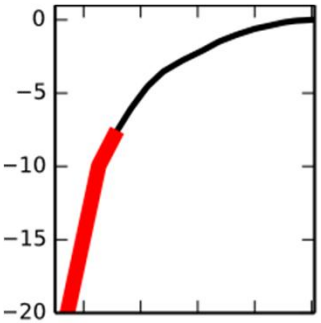
Delsman et al., HESSD, 2013

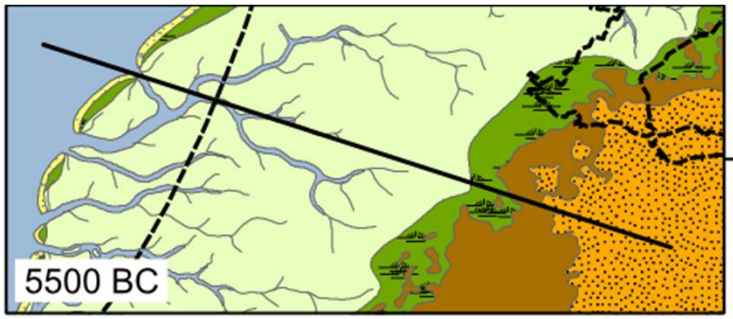

a)
A
A'
B
North Sea
Coastal dunes
Amsterdam
Lake IJssel
polder Haarlemmermeer
polder Horstermeer
Ice-pushed ridge
NL
D
B
0
5
10 km
> 20 m MSL
15 - 20 m MSL
10 - 15 m MSL
5 - 10 m MSL
2.5 - 5 m MSL
0 - 2.5 m MSL
2.5 - 0 m BSL
5 - 2.5 m BSL
10 - 5 m BSL
15 - 10 m BSL
20 - 15 m BSL
> 20 m BSL
Coastline
Model transect


b)
A'
B
depth [m MSL]
0
−50
−100
−150
−200
−250
−300
100
105
110
115
120
125
130
135
140
x-coordinate [km]
Urban area
Peat
Clay
Silty, fine sand
Sand
Undifferentiated
Maassluis formation
Aquiclude (Tertiary)

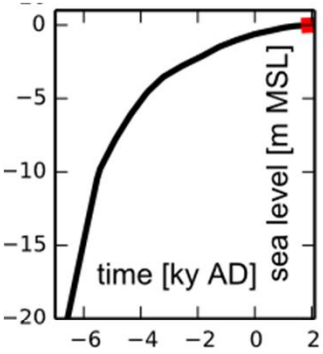


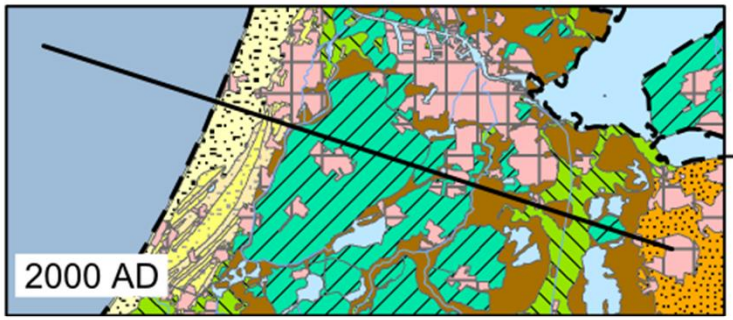






Time-slice 1: 6500 BC - 4500 BC
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage



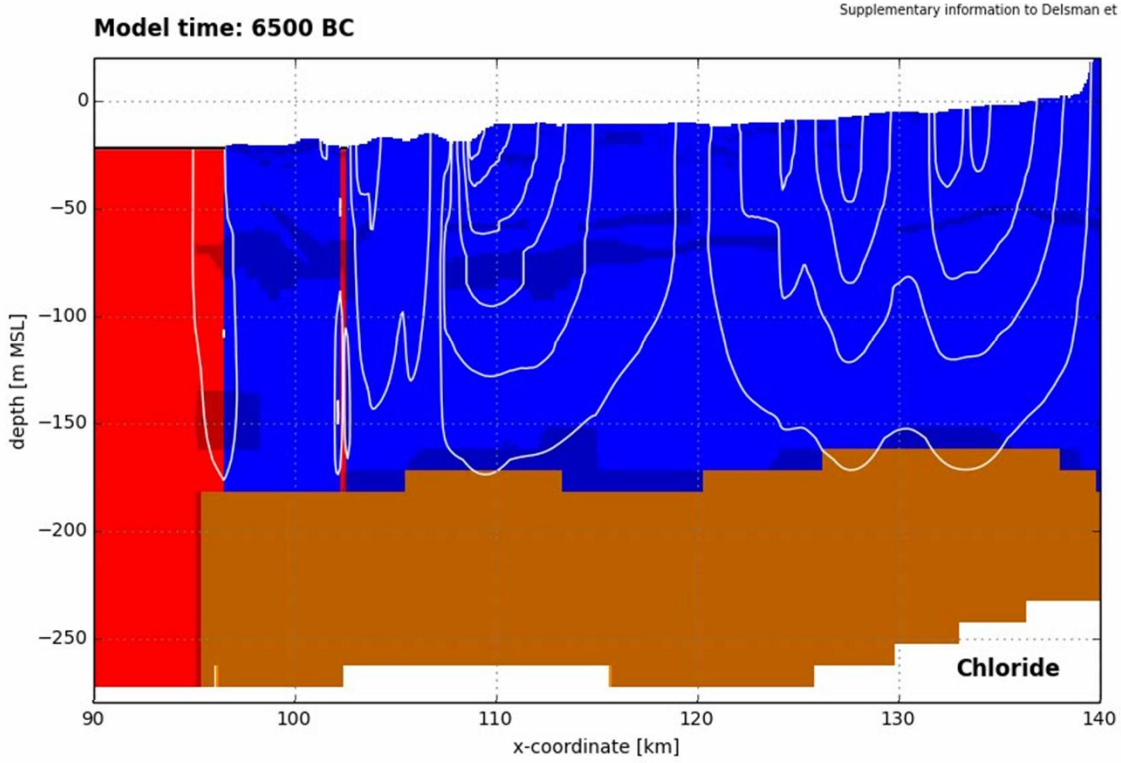


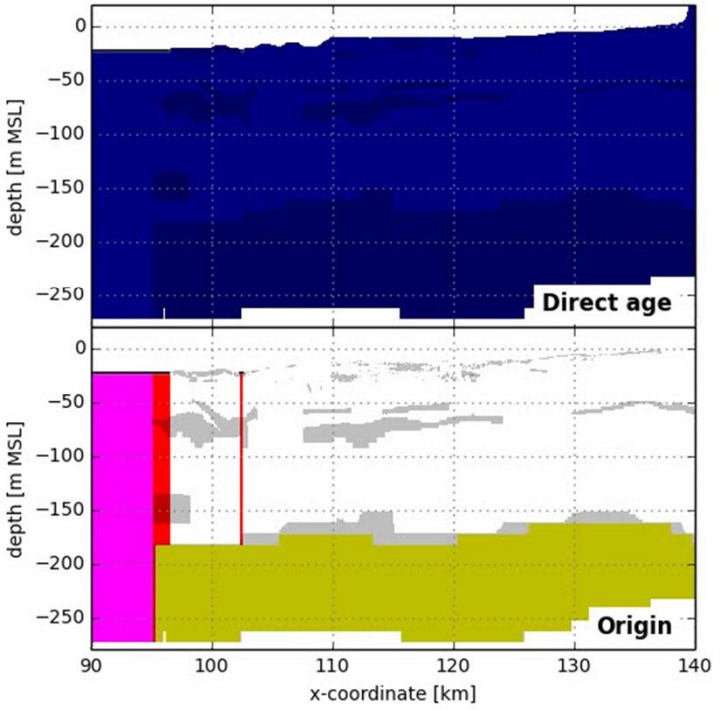
Time-slice 10: 1950 AD - 2010 AD
- Present-day situation
- Sea level at 0 MSL
- Groundwater abstraction in ice-pushed ridge
- Groundwater abstraction in coastal dunes decreased

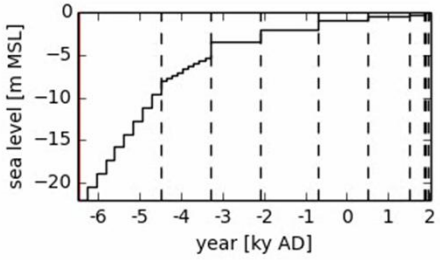
Model transect
Present coastline
Water course
Sea
Tidal flats
Salt marsh
Dune area (high)
Dune area (low)
Beach barrier
Peat
Fresh water lake
Floodplain
Embanked area
Reclaimed area
Urban area
Pleistocene deposits

Development saline groundwater in the Holocene

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

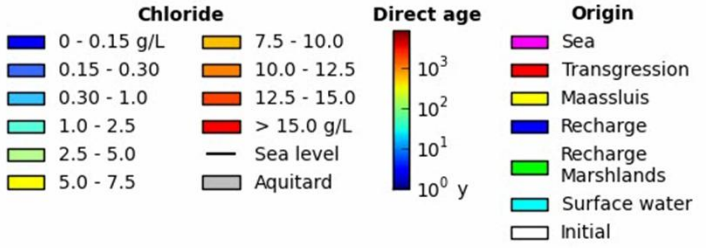






Timeslice 1: 6500 BC - 4500 BC

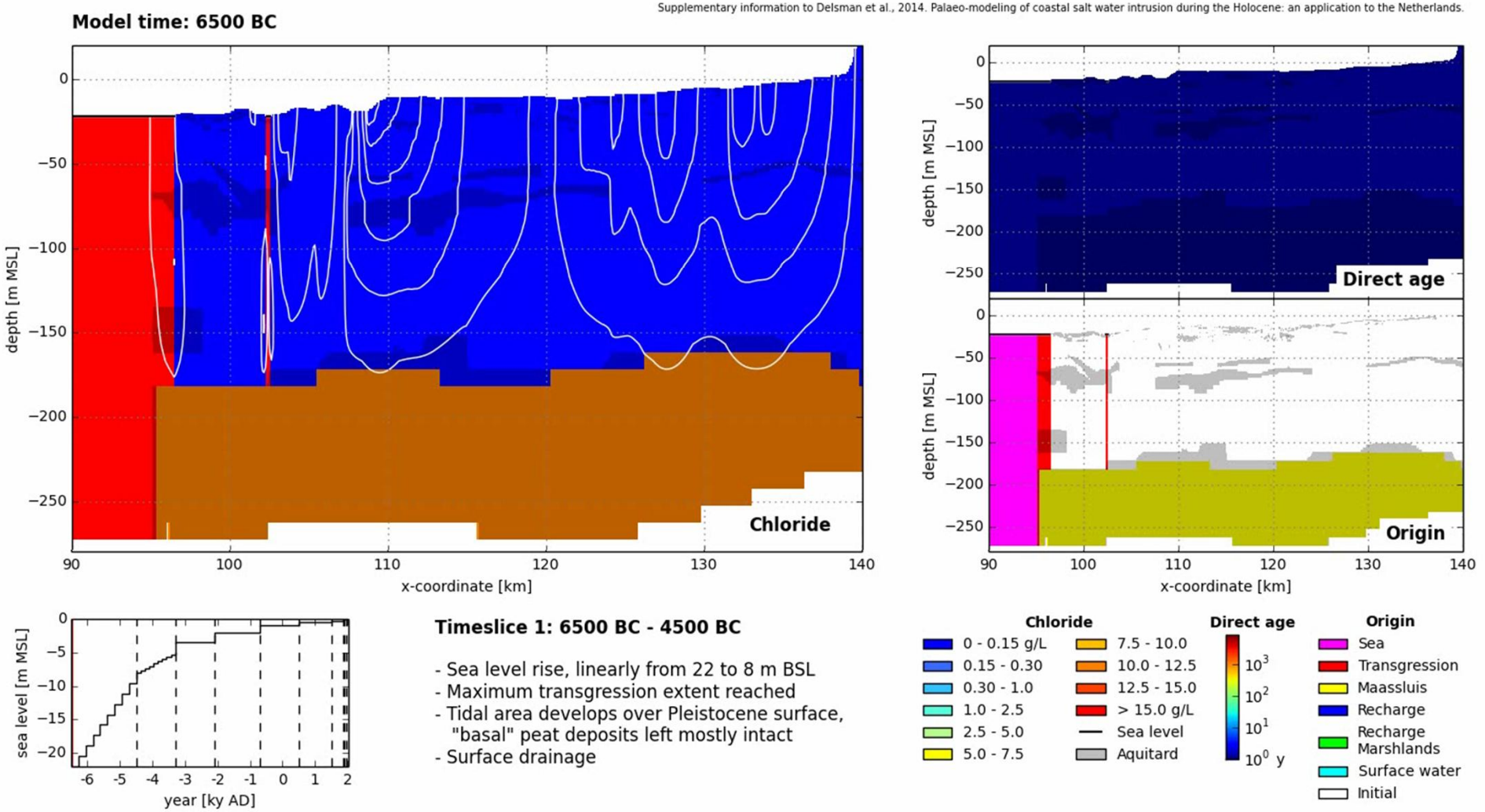
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage



Delsman et al., HESS, 201

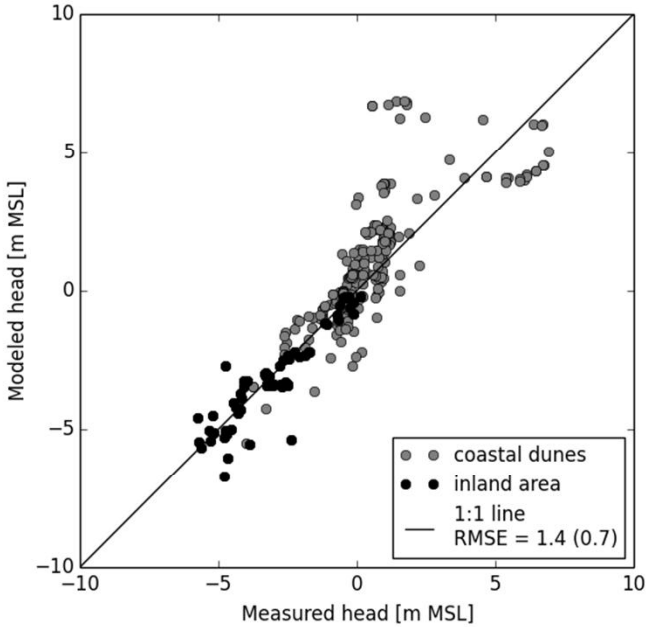
Development saline groundwater in the Holocene

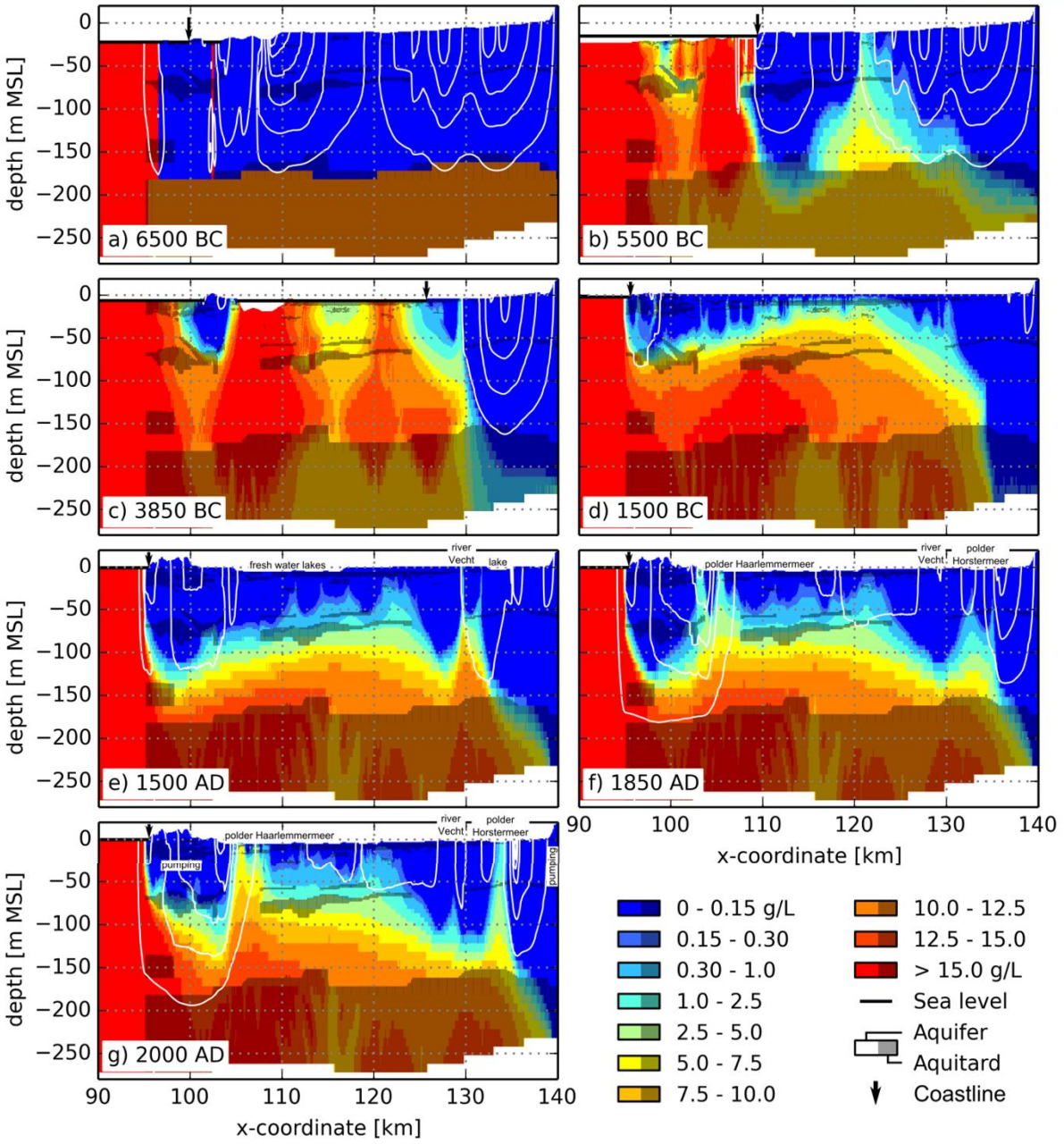
Supplementary information to Delsman et al., 2014. Palaeo-modeling of coastal salt water intrusion during the Holocene: an application to the Netherlands.



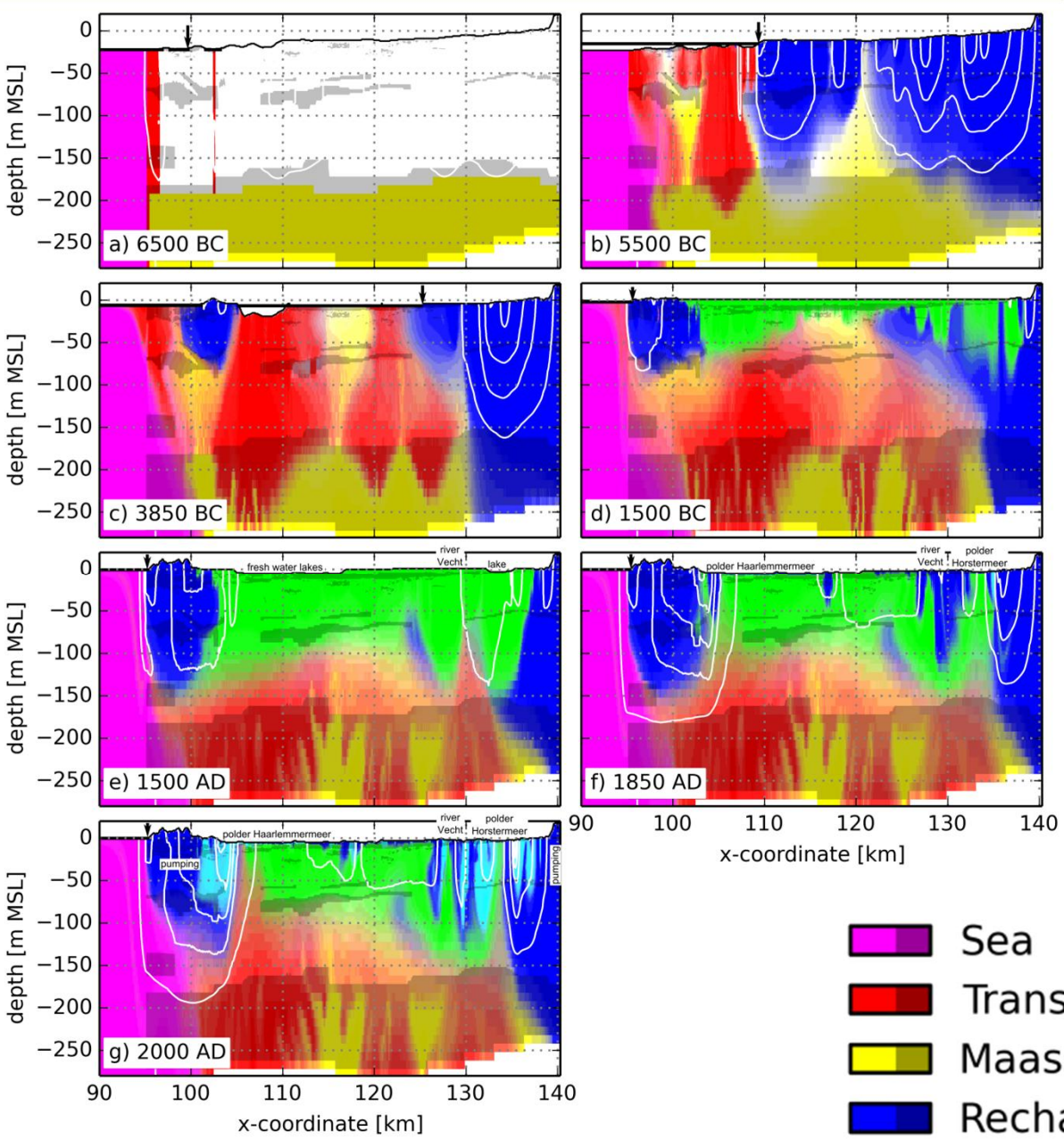
Delsman et al., HESS, 201

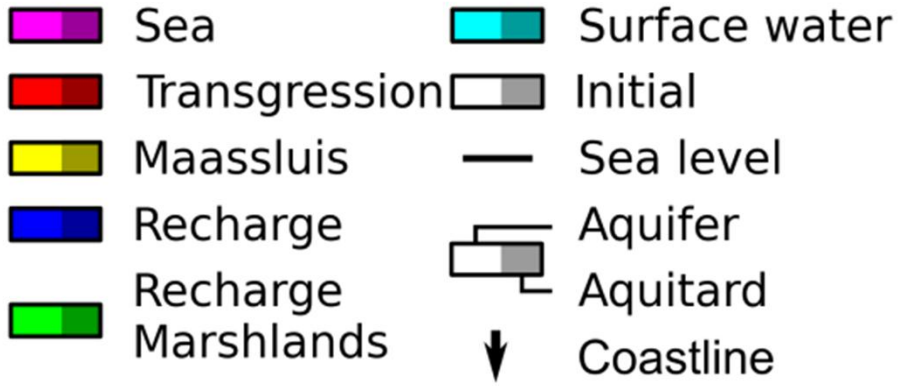
Model versus measurements



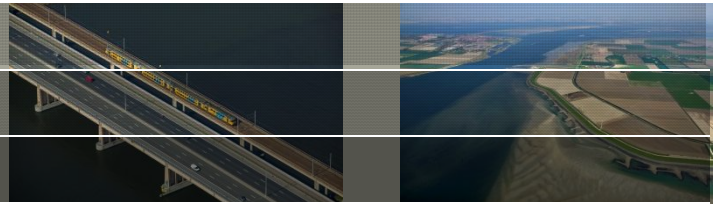


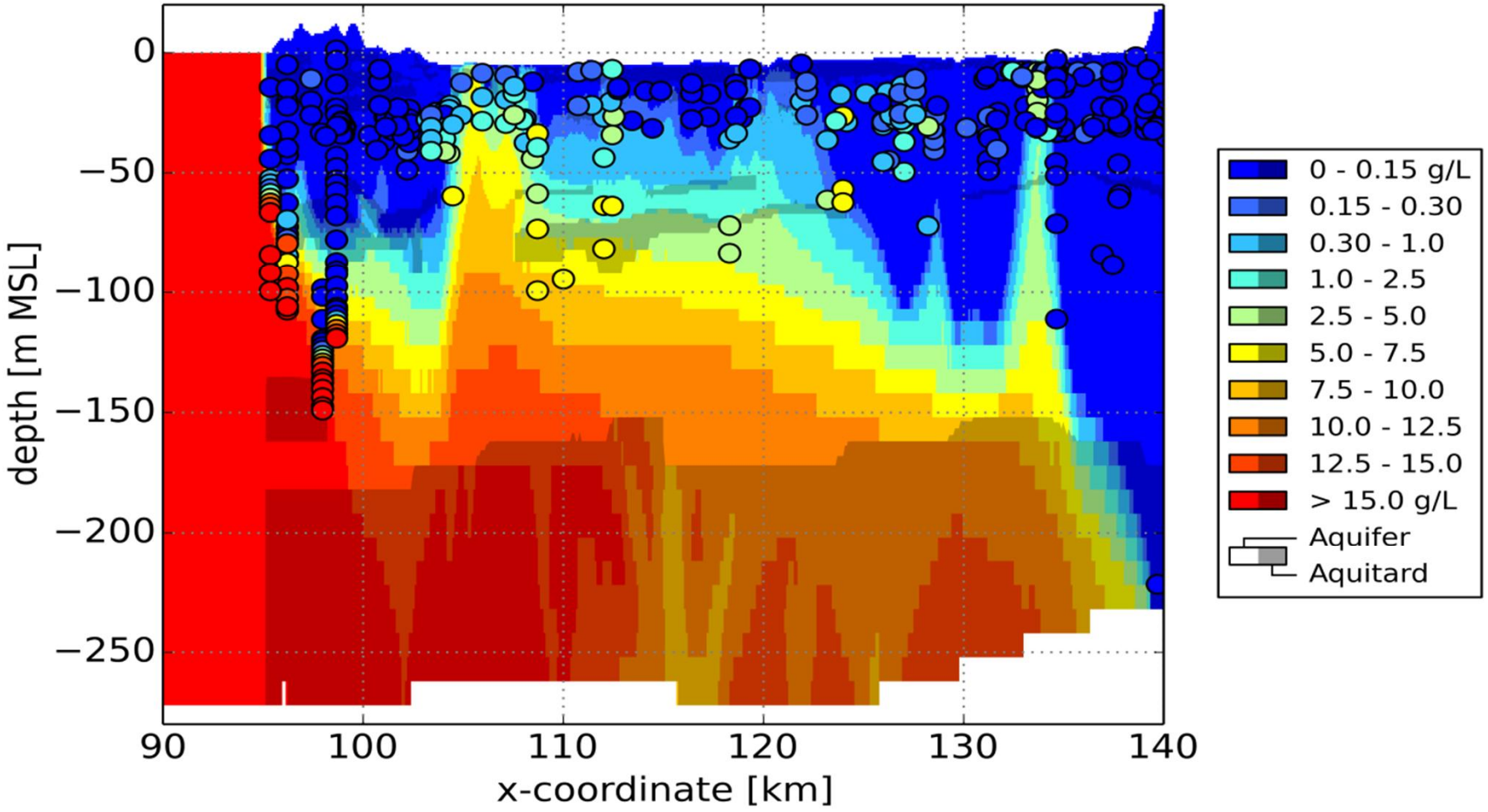
Origin source



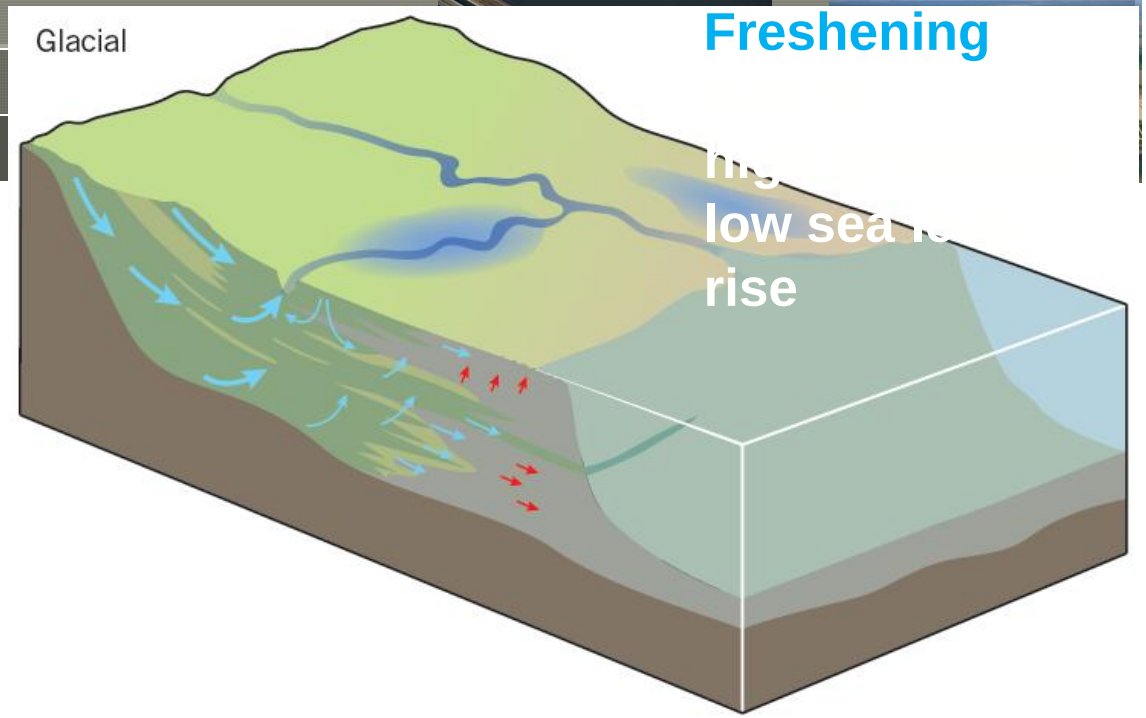


Model versus measurements



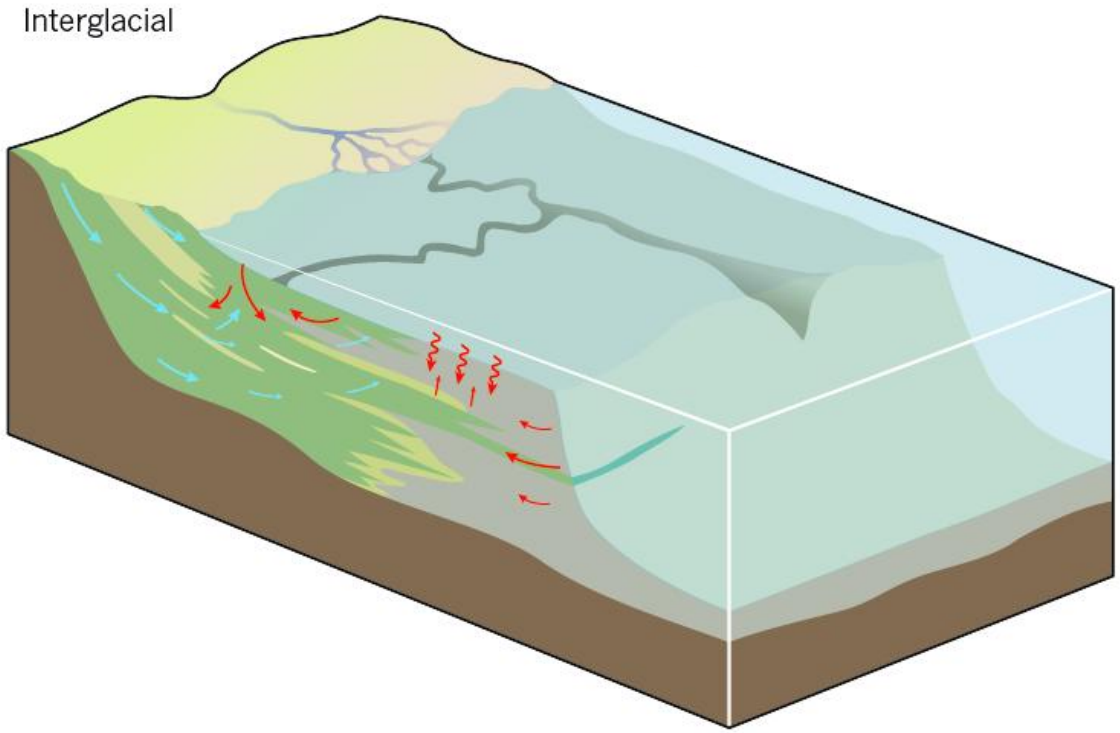


Deltares



Freshening

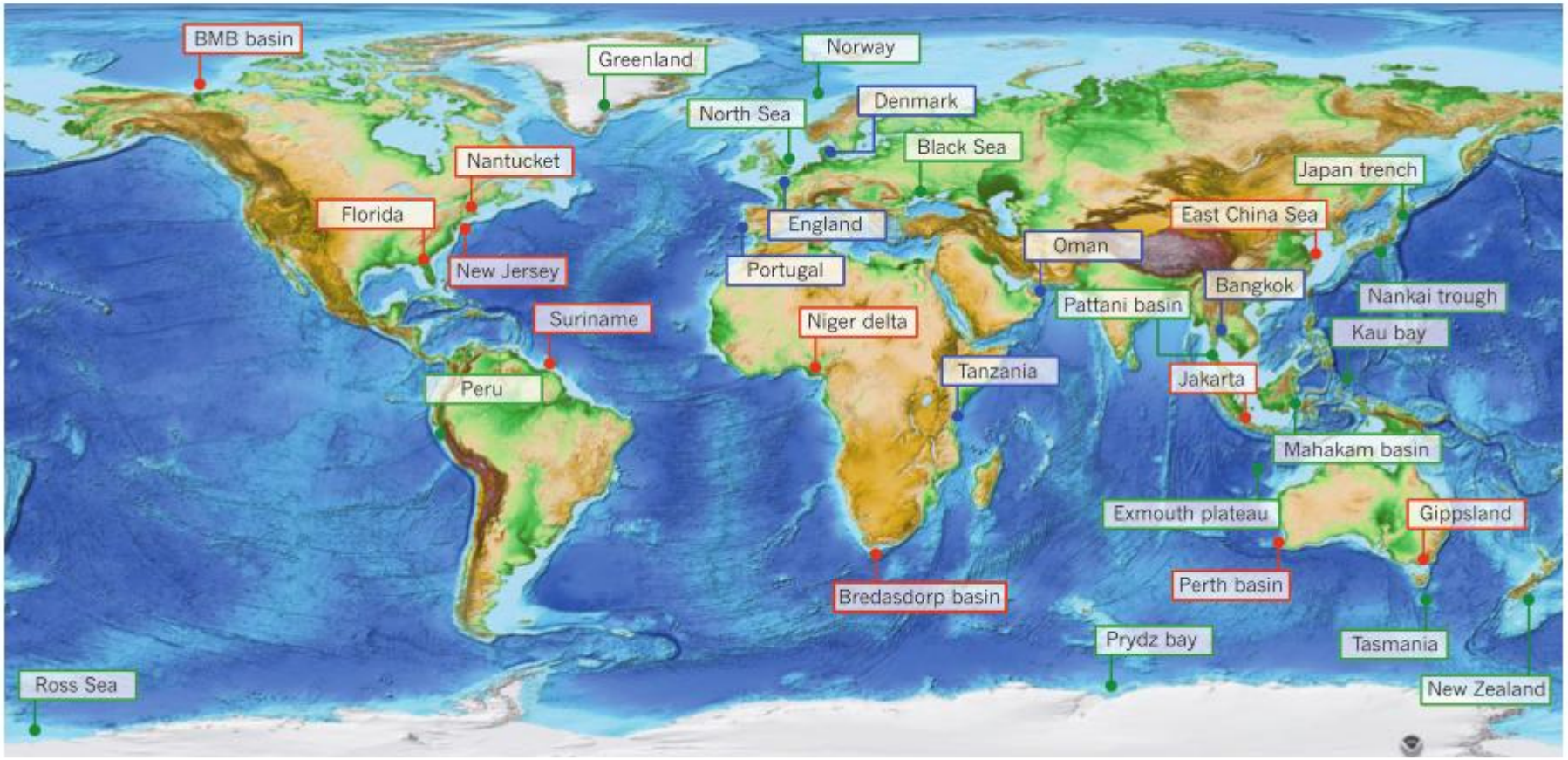
low sea le
rise



Salinisation

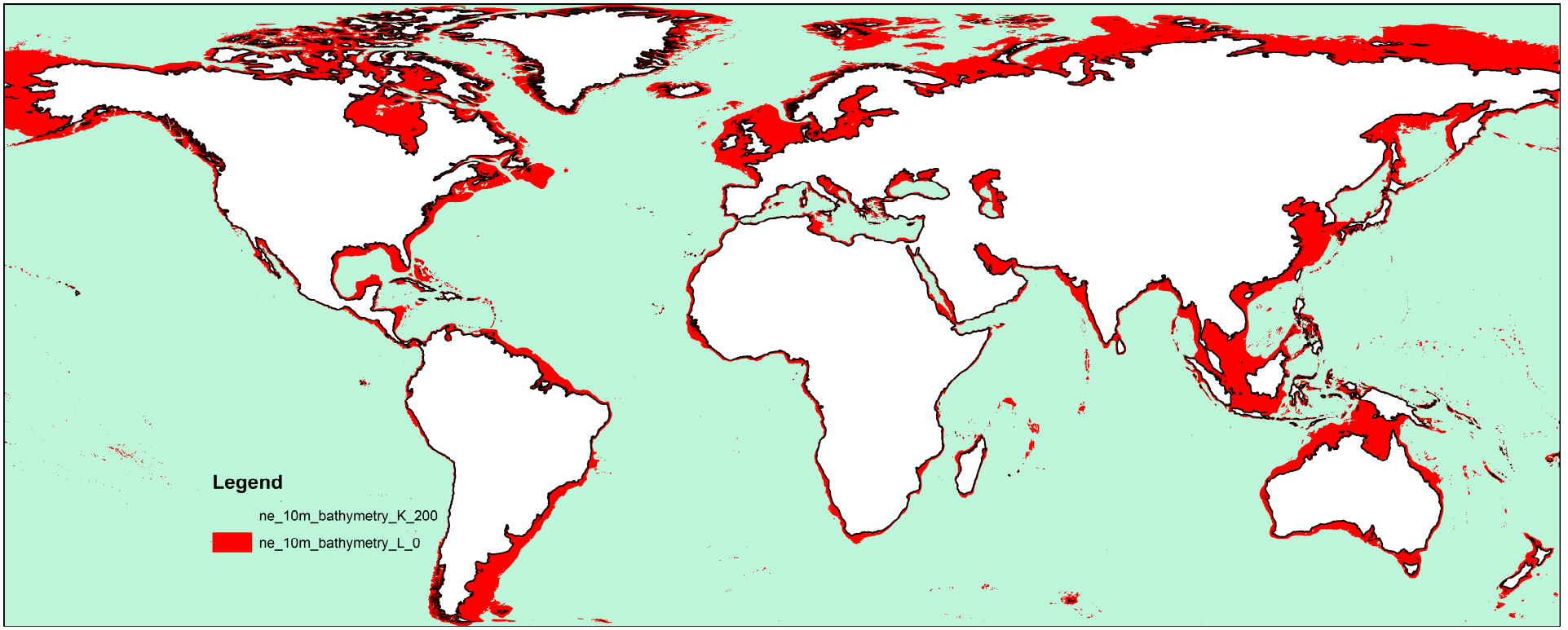
Source: Nature, 2013

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



Deltares

Possible locations of offshore (submarine) groundwater



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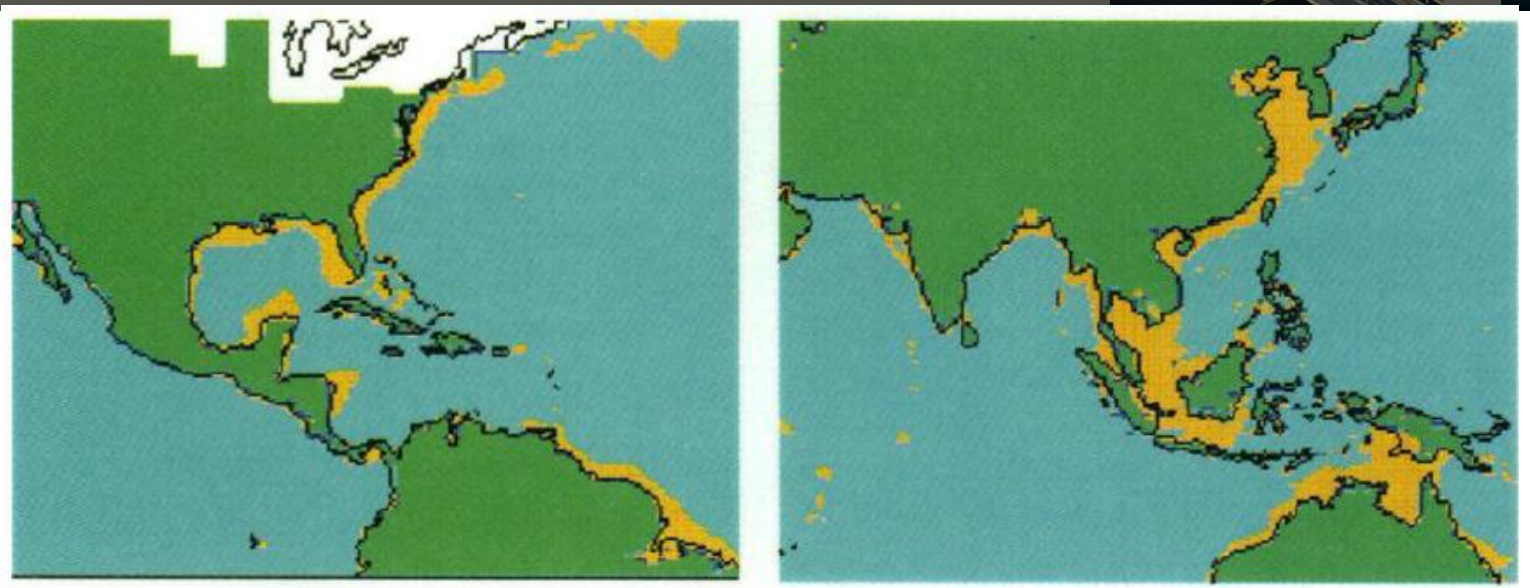
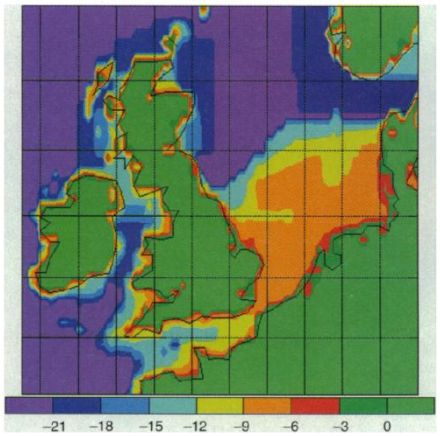
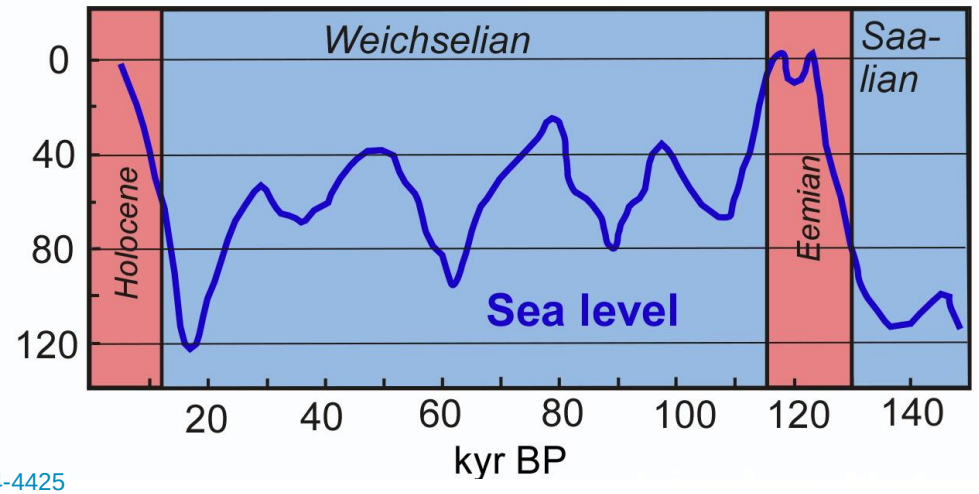
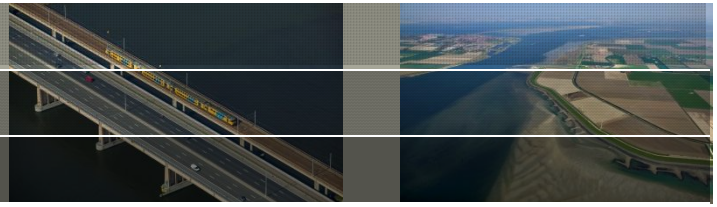
Coastal zone cases around the world
Occurrence related to dynamic sea-levels and coastlines



Peltier, *Science*, 1994







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Enabling Delta Life

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

**or other flooding events*

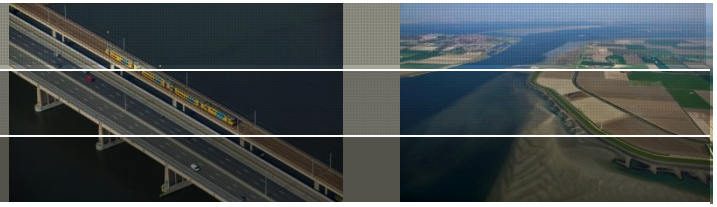
Daniel Zamrsky[1,2], Marta Faneca Sànchez[1], **Gu Oude Essink**[1,3]
Subsurface and Groundwater Systems
Deltares, The Netherlands
freshsalt.deltares.nl

2 WAGENINGEN UR

3 Universiteit Utrecht

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

Sense of Urgency

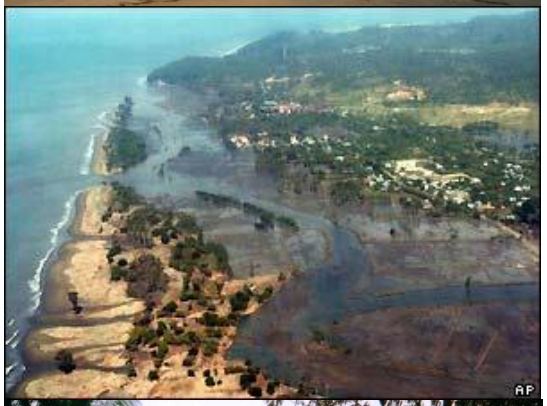


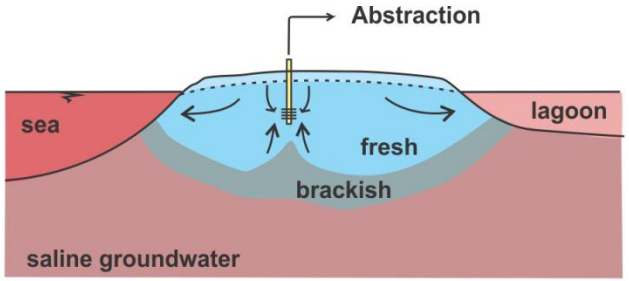
Every year, about 2 million people worldwide die from diarrhea, caused by bad drinking water quality

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)

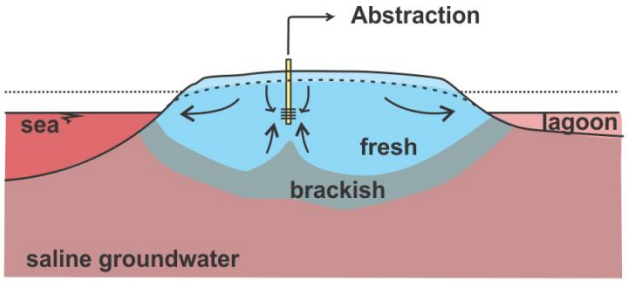
What will happen when a disaster like a tsunami hits a coastal area?

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

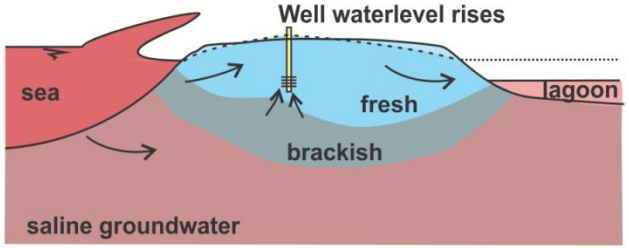




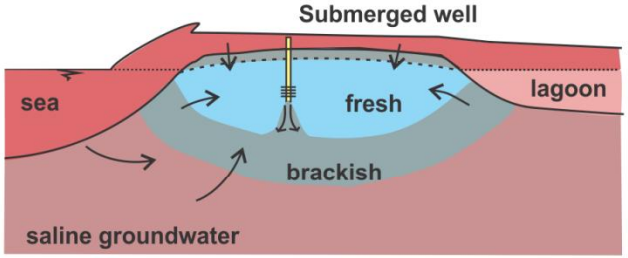
1. Before Tsunami



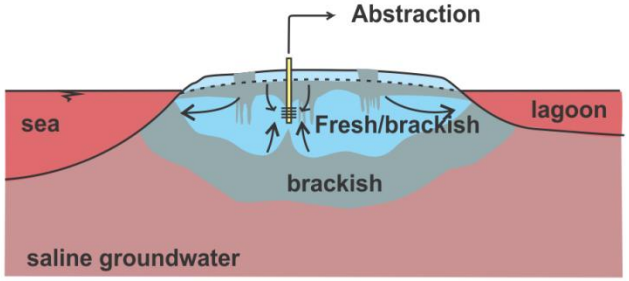
2. Just before Tsunami:
Lowering of sea- and lagoonwater level



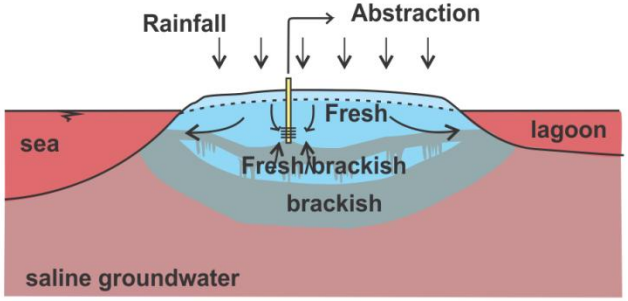
3. Just before Tsunami:
Subsurface pressure wave precedes surface wave



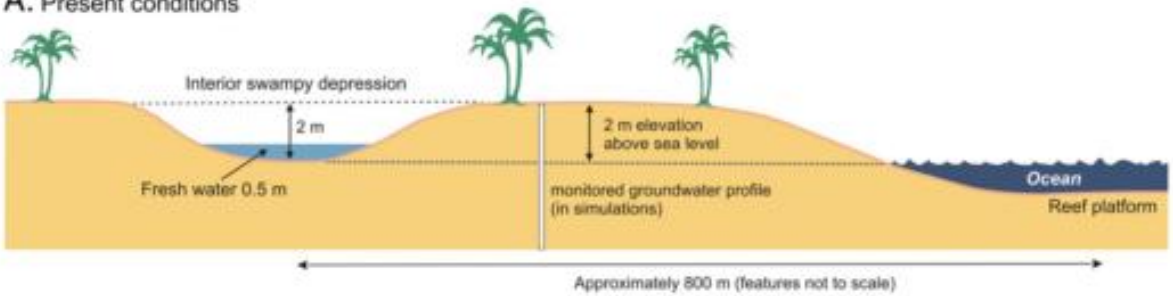
4. During Tsunami: Flooding of island,
mixing of water due to sudden pressure changes

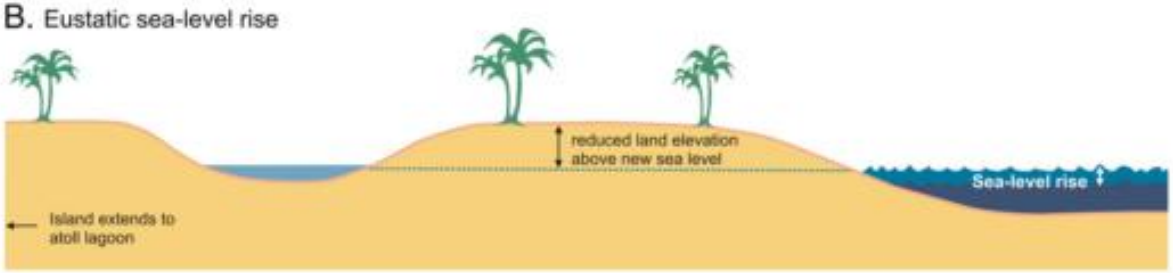


5. After Tsunami
Freshwater mixed with brackish water



6. After Tsunami
Recharge by rainfall replaces brackish water


A. Present conditions
Interior swampy depression
2 m
Fresh water 0.5 m
2 m elevation
above sea level
monitored groundwater profile
(in simulations)
Ocean
Reef platform
Approximately 800 m (features not to scale)


B. Eustatic sea-level rise
reduced land elevation
above new sea level
Sea-level rise
Island extends to
atoll lagoon


C. Cyclone washover after eustatic SLR
Cyclone-driven waves
Seawater
inundation by
wave washover
Ocean

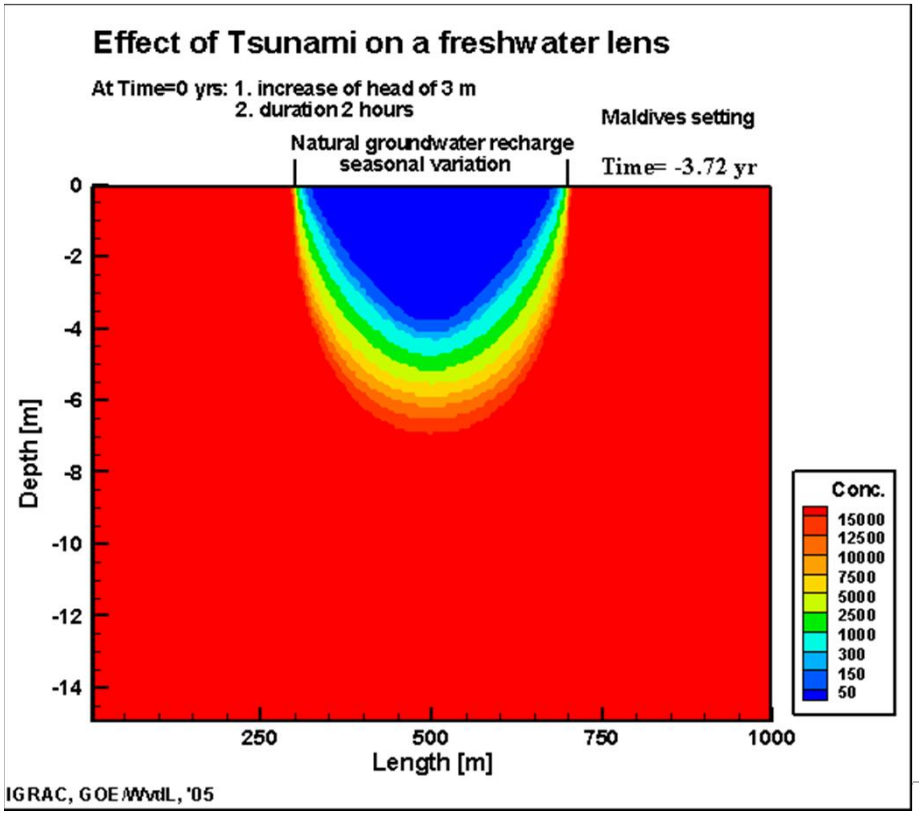

D. Cyclone washover with accompanying temporary SLR
Cyclone-driven waves
additional temporary
sea level-rise
severe inundation:
wave washover with storm surge

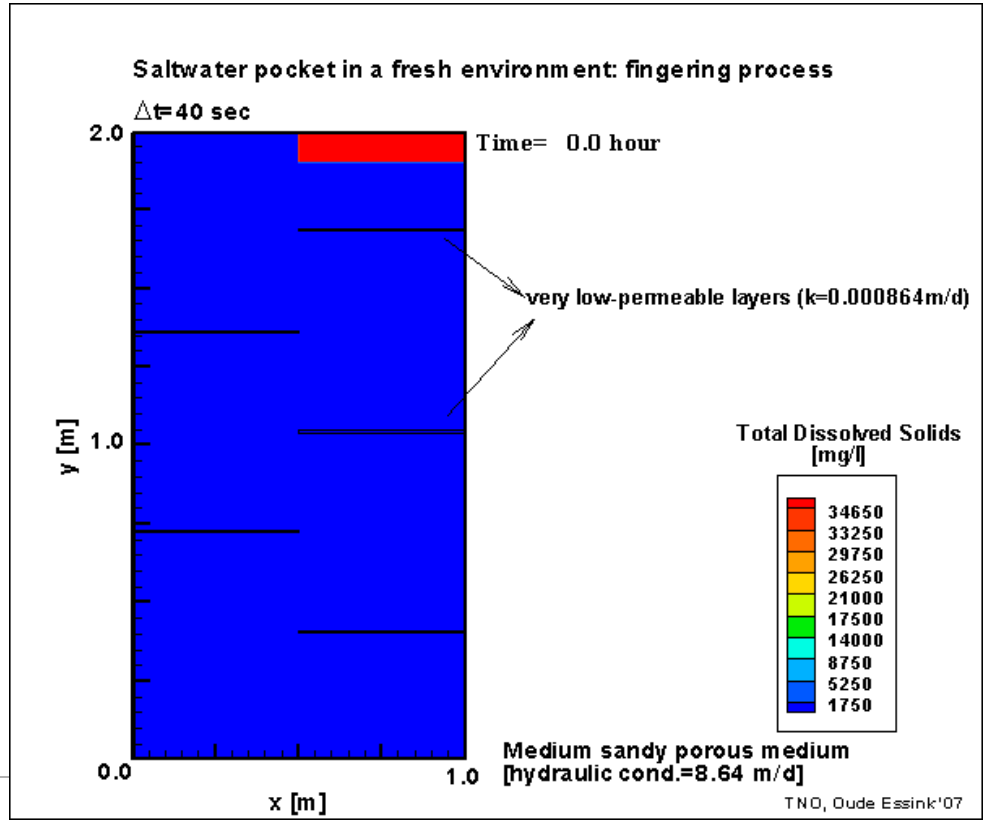
Deltares

Salinisation processes of fresh groundwater reserves

Impression of relevant salinisation processes in coastal aquifers:

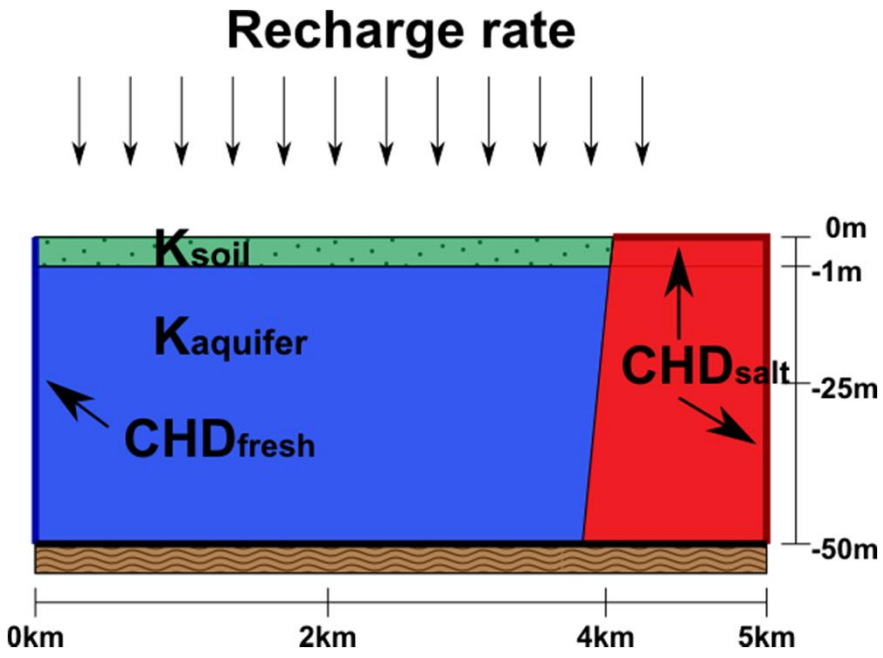
- Contamination freshwater lens after sea water flooding
- Saline fingering processes in the subsoil

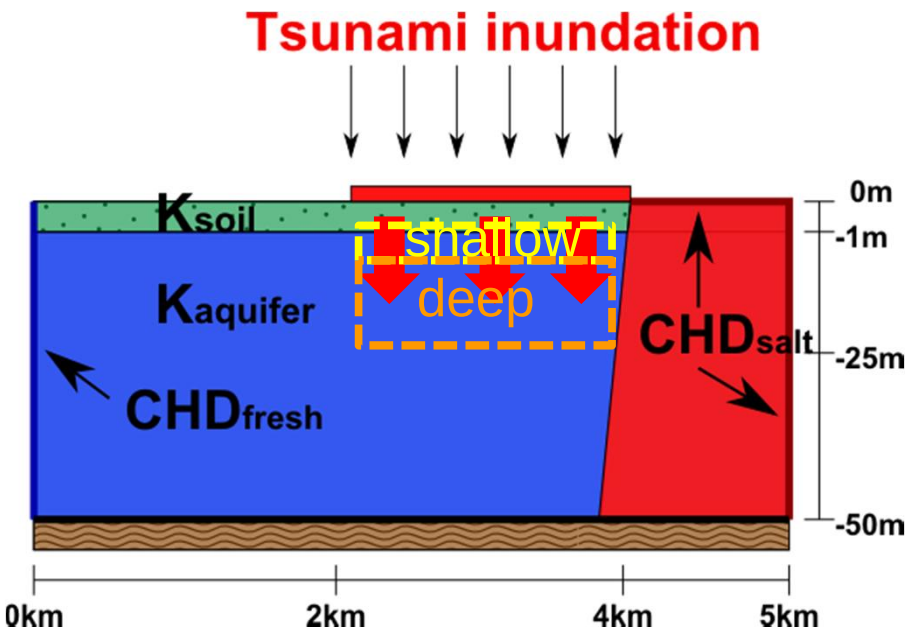




Concept 2D modelling variable-density groundwater flow and coupled salt transport

Normal system

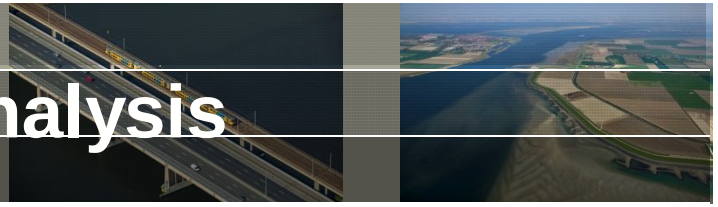




- Focus on coastal *deep* and *shallow* fresh groundwater resources
- How long does it takes before the groundwater system is fresh again, available for groundwater extractions?

Deltares

Using global datasets in the analysis

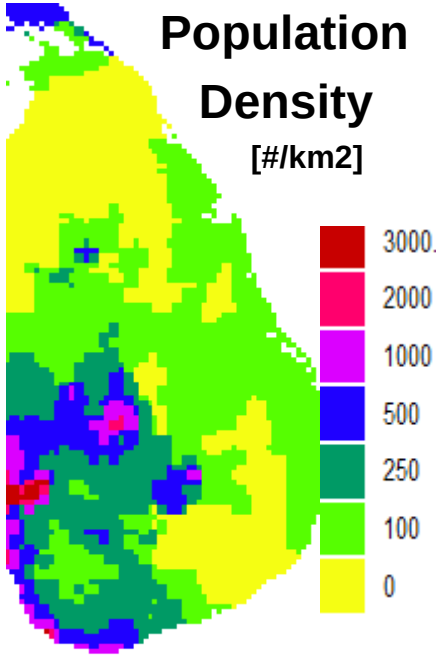


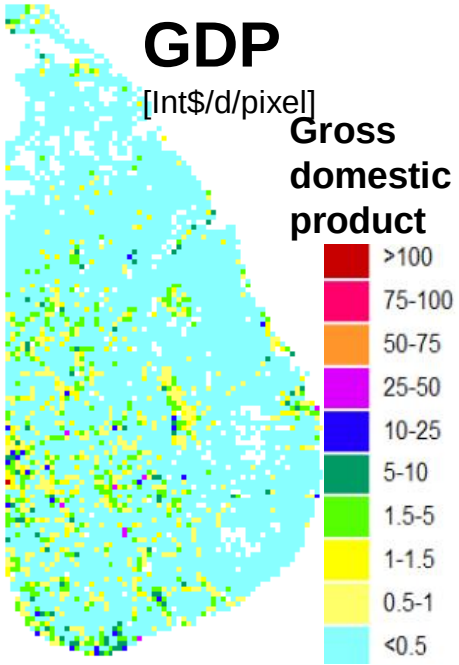
- **SRTM – DEM of the world**
  - Used to create:
    - *Slope*
    - *Distance to coast*
- **Resampling**
  - Different resolution of other original datasets (e.g. population density)

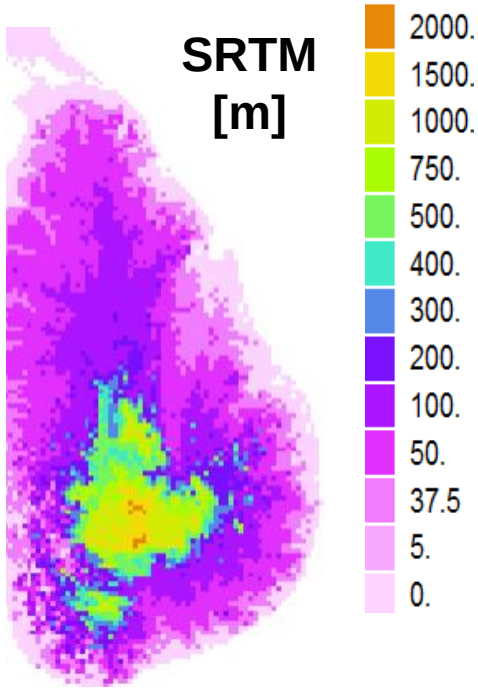
Name	Type	Resolution
SRTM	raster	90 m
Population density	raster	≈ 4.6 km
Land use	raster	300 m
Soil map	raster	≈ 1 km
Precipitation	raster	≈ 1 km
Tsunami occurrence	point shape file	-
Bathymetry	raster	≈ 1 km
GDP	raster	≈ 1 km

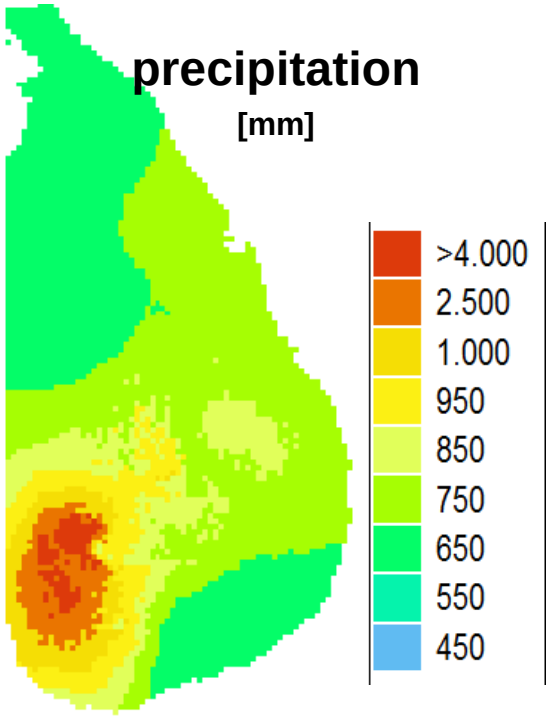
Deltares

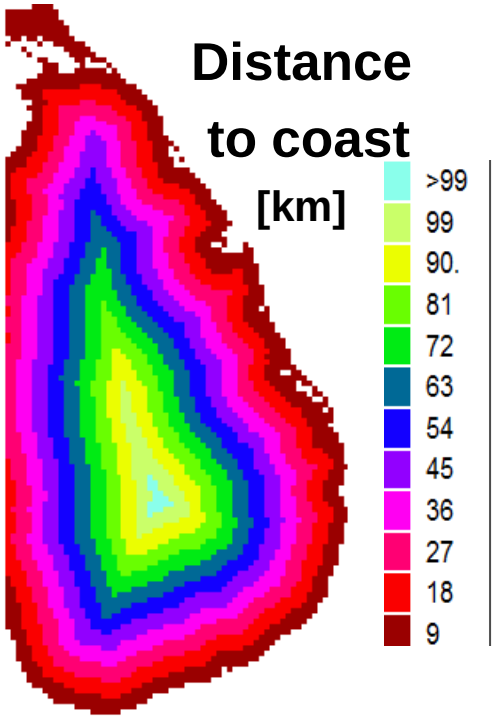

Tile:
_53_11
Jaffna
Kilinochchi
Vavuniya
Kuchchaveli
Hamillewa
Trincomale
Anuradhapura
Megaswewa
Batticalo
Sri Lanka
Negombo
Kandy
Gampaha
Nuwara
Eliya
Malabe
Moratuwa
Yala National
Park
Galle
Tangalla
Matara

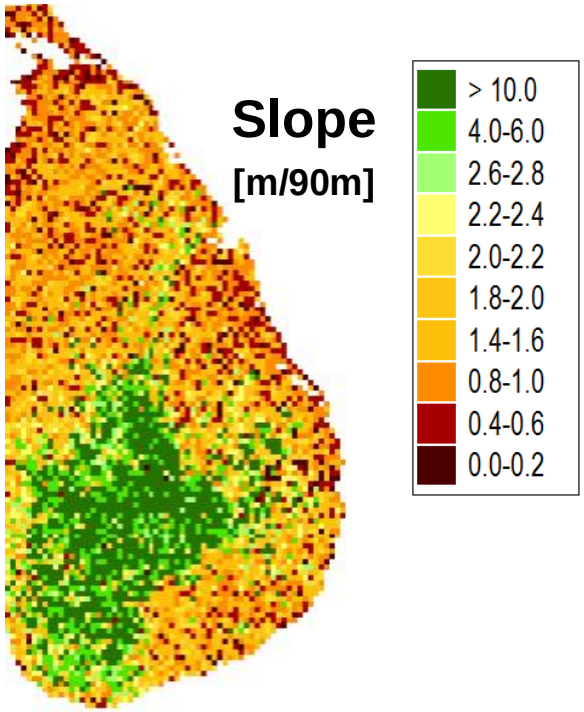

Population
Density
[#/km2]
3000.
2000
1000
500
250
100
0

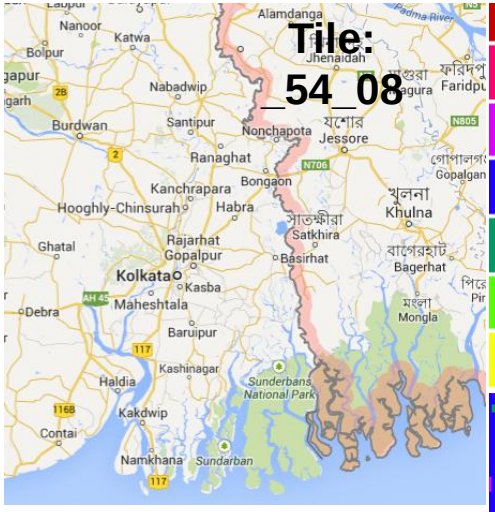

GDP
[Int$/d/pixel]
Gross
domestic
product
>100
75-100
50-75
25-50
10-25
5-10
1.5-5
1-1.5
0.5-1
<0.5

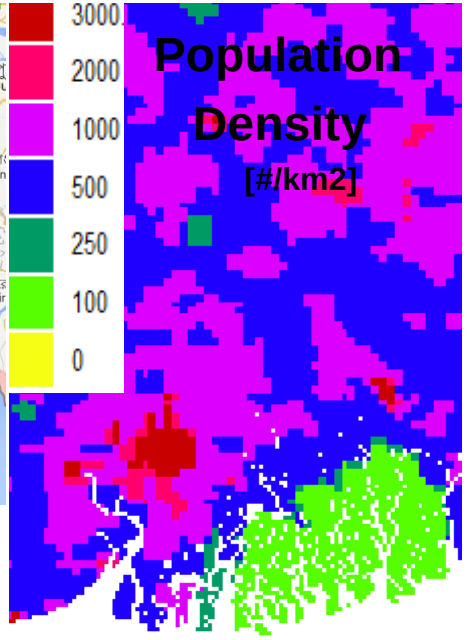

SRTM
[m]
2000.
1500.
1000.
750.
500.
400.
300.
200.
100.
50.
37.5
5.
0.

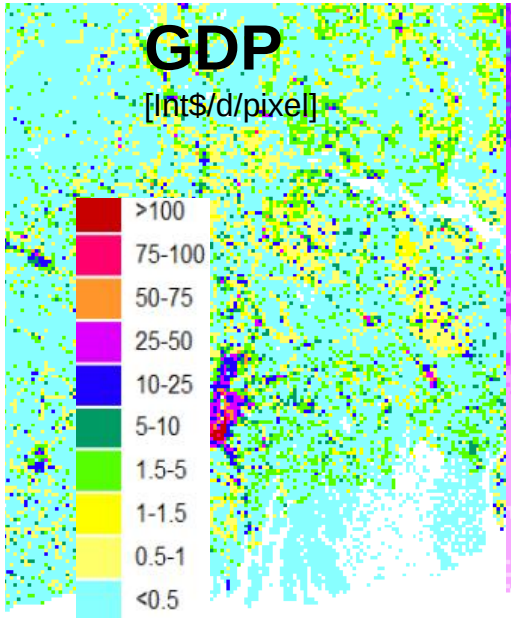

precipitation
[mm]
>4.000
2.500
1.000
950
850
750
650
550
450

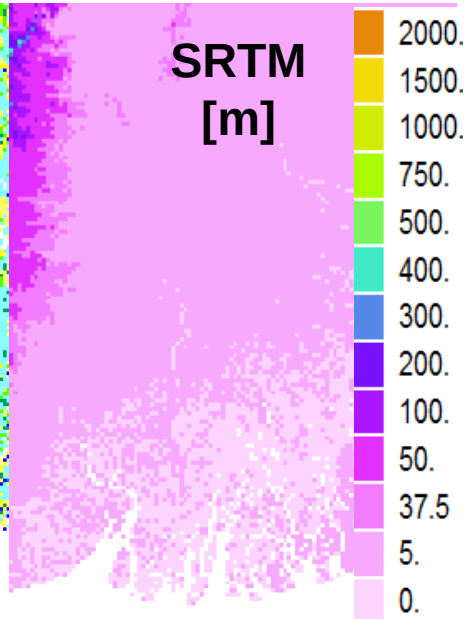

Distance
to coast
[km]
>99
99
90.
81
72
63
54
45
36
27
18
9


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

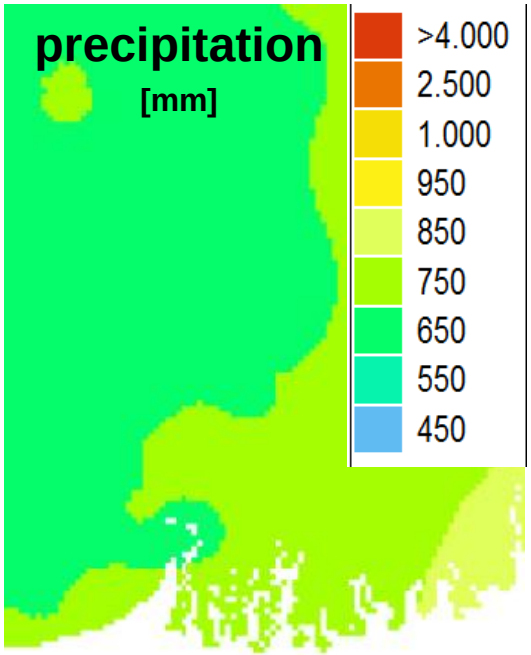


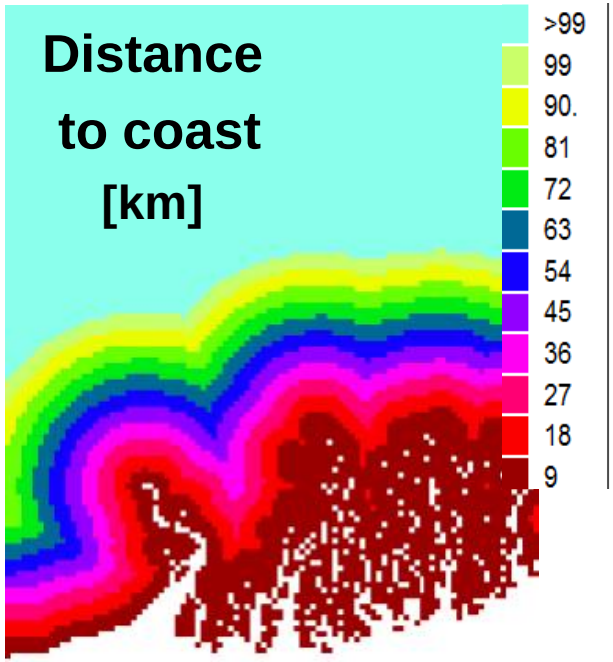




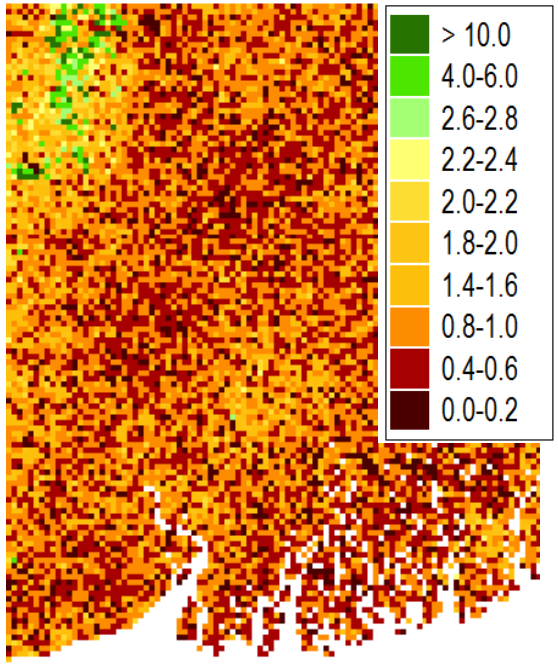


Bangladesh





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**

$Elevation \quad ID_{elev}$

$Slope \quad ID_{slope}$

$Distance\ to\ coast \quad ID_{dist}$

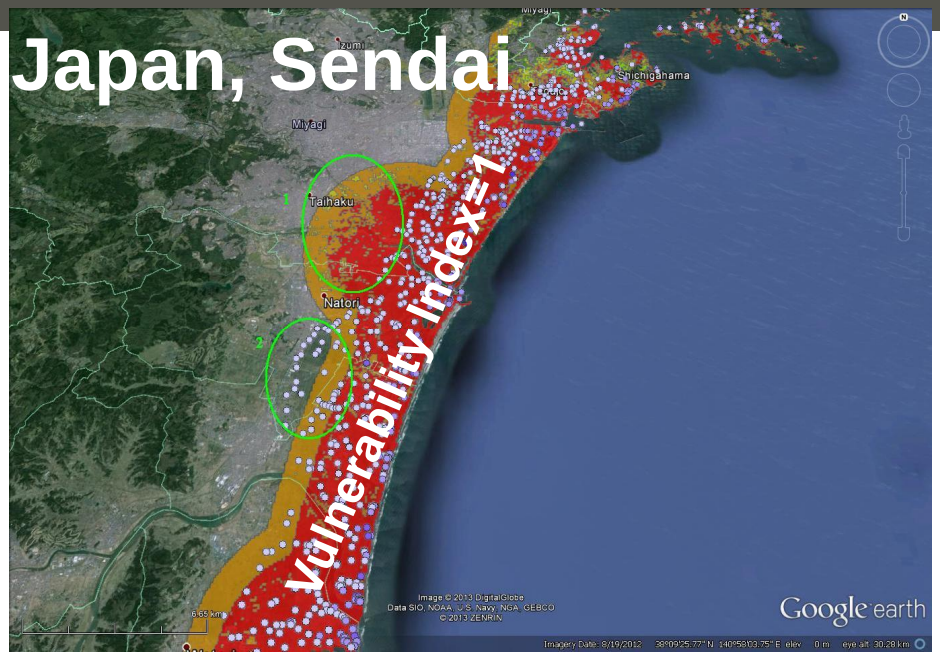
$$vulnerability\ index = 4 * ID_{elev} + ID_{dist} + ID_{slope}$$

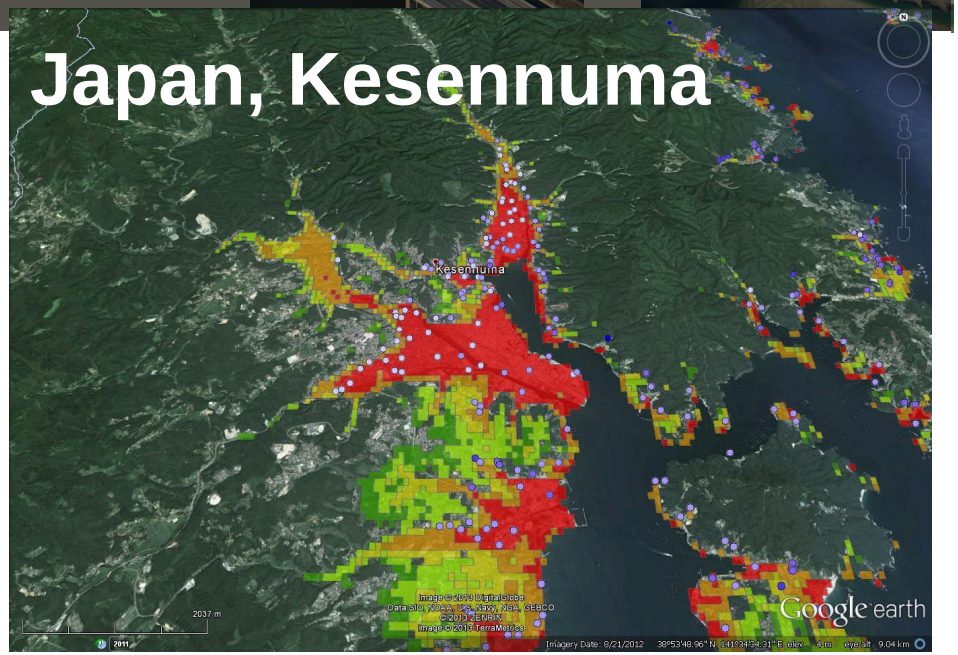
Final index	Variable ID values and ranges					
Variable / ID	1	2	3	4	5	30
Topographical elevation (m above sea level)	min - 8	8 - 16	16 - 24	24 - 32	32 - 40	> 40
Topographical slope (°)	0 - 1	1 - 2	2 - 3	3 - 4	4 -5	> 5
Distance to coast (pixels)	0 - 7	7 - 15	15 - 25	25 - 40	40 - 55	> 55
Distance to coast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

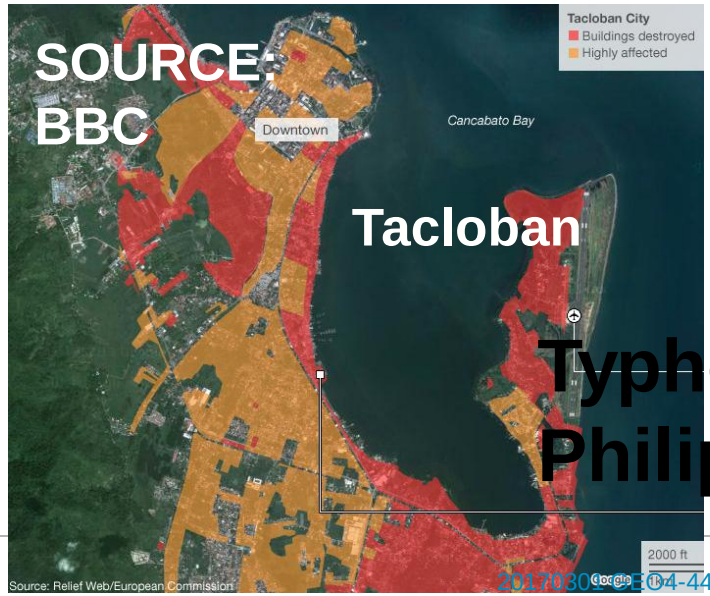
Vulnerability level	Sum of IDs	Vuln. ID
Very high	6 - 9	1
High	10 - 14	2
Medium	15 - 19	3
Low	20 - 24	4
Very low	25 - 29	5
None	> 30	6

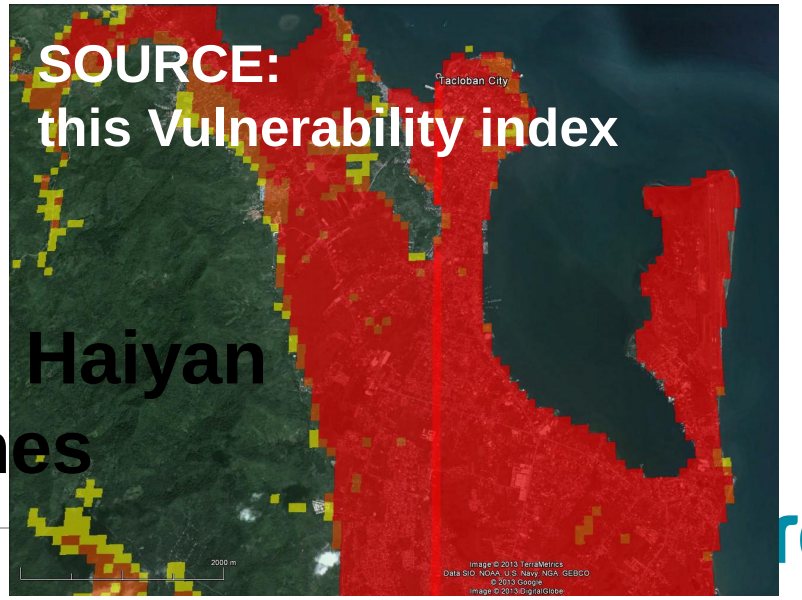
Deltares

Vulnerability Tsunami index example







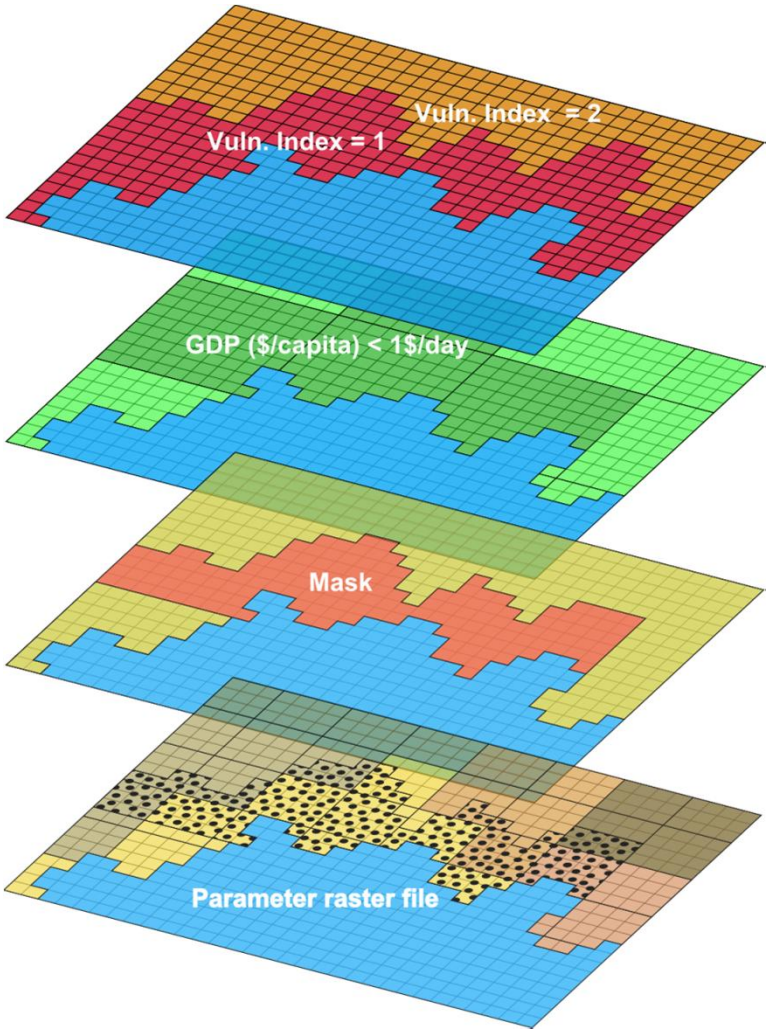


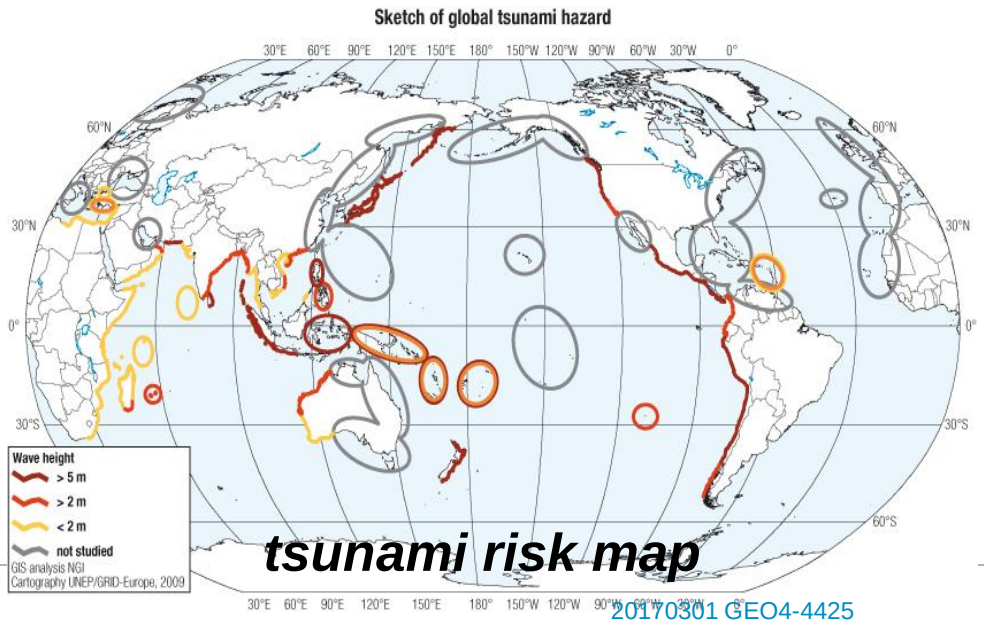
Typhoon Haiyan
Philippines

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)

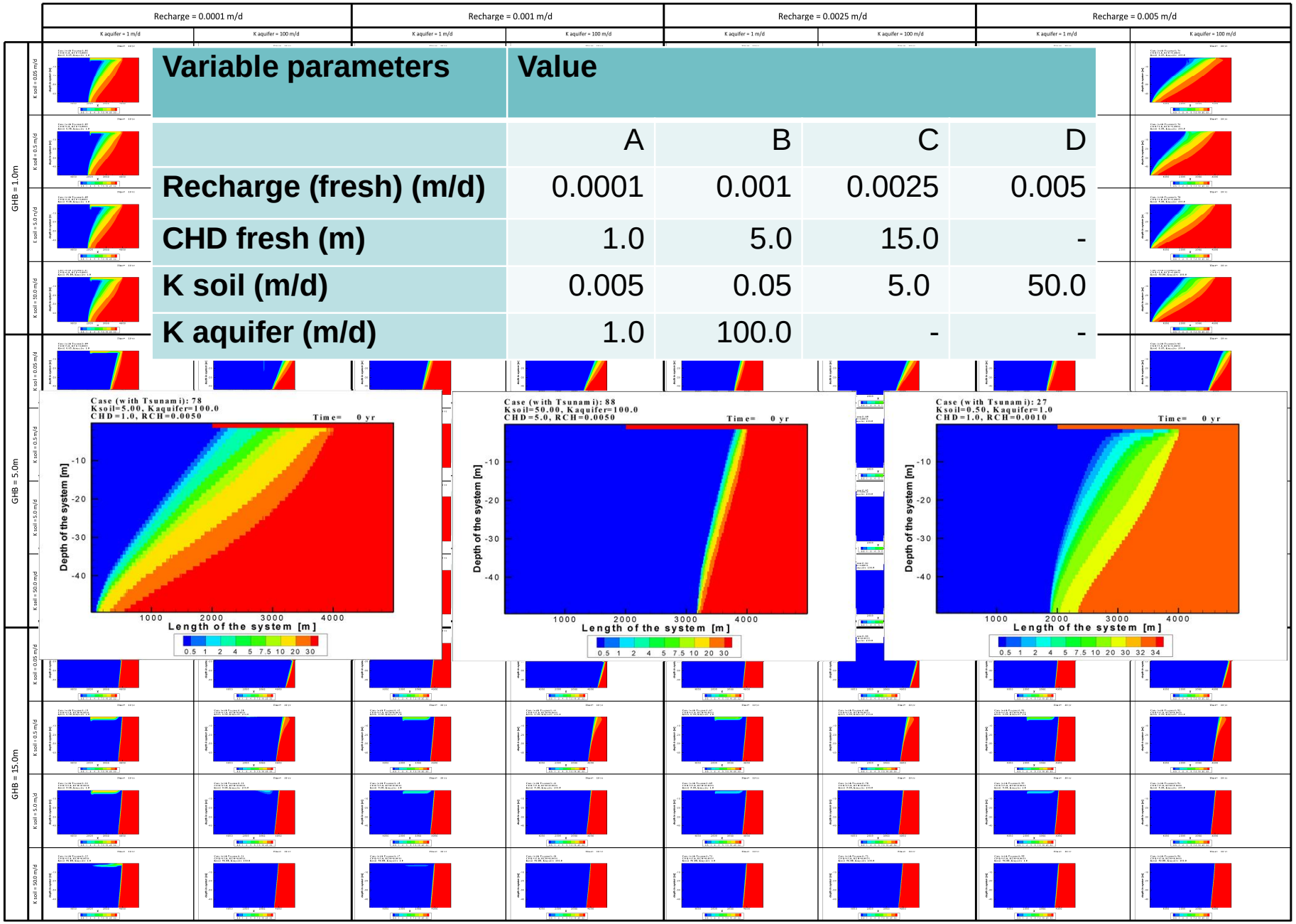




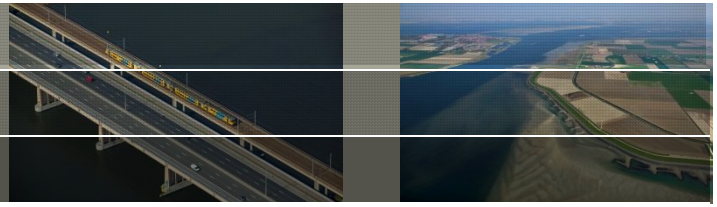
tsunami risk map

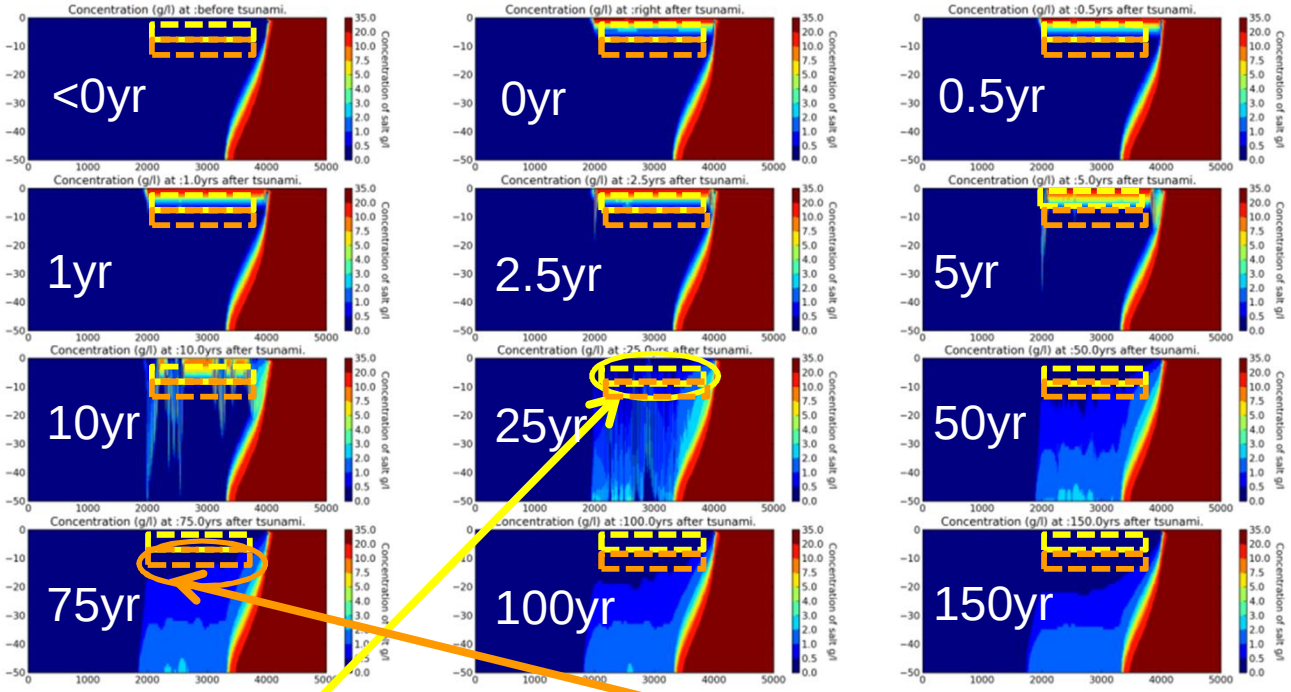
Deltares

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	-	-

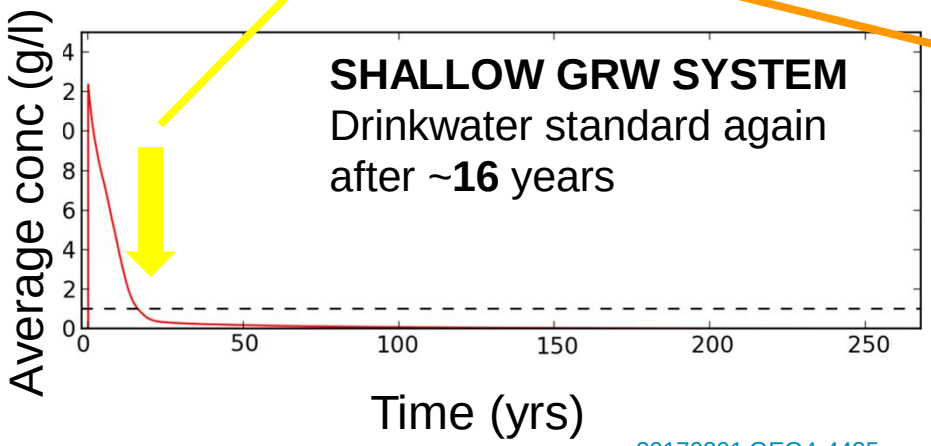


Results of one case

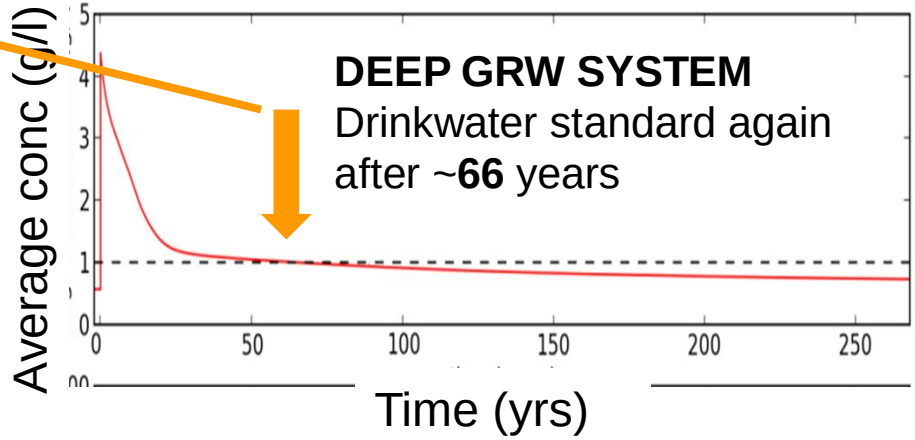




Salt water fingers intrude the groundwater system the coming tens of years



SHALLOW GRW SYSTEM
Drinkwater standard again after ~**16** years

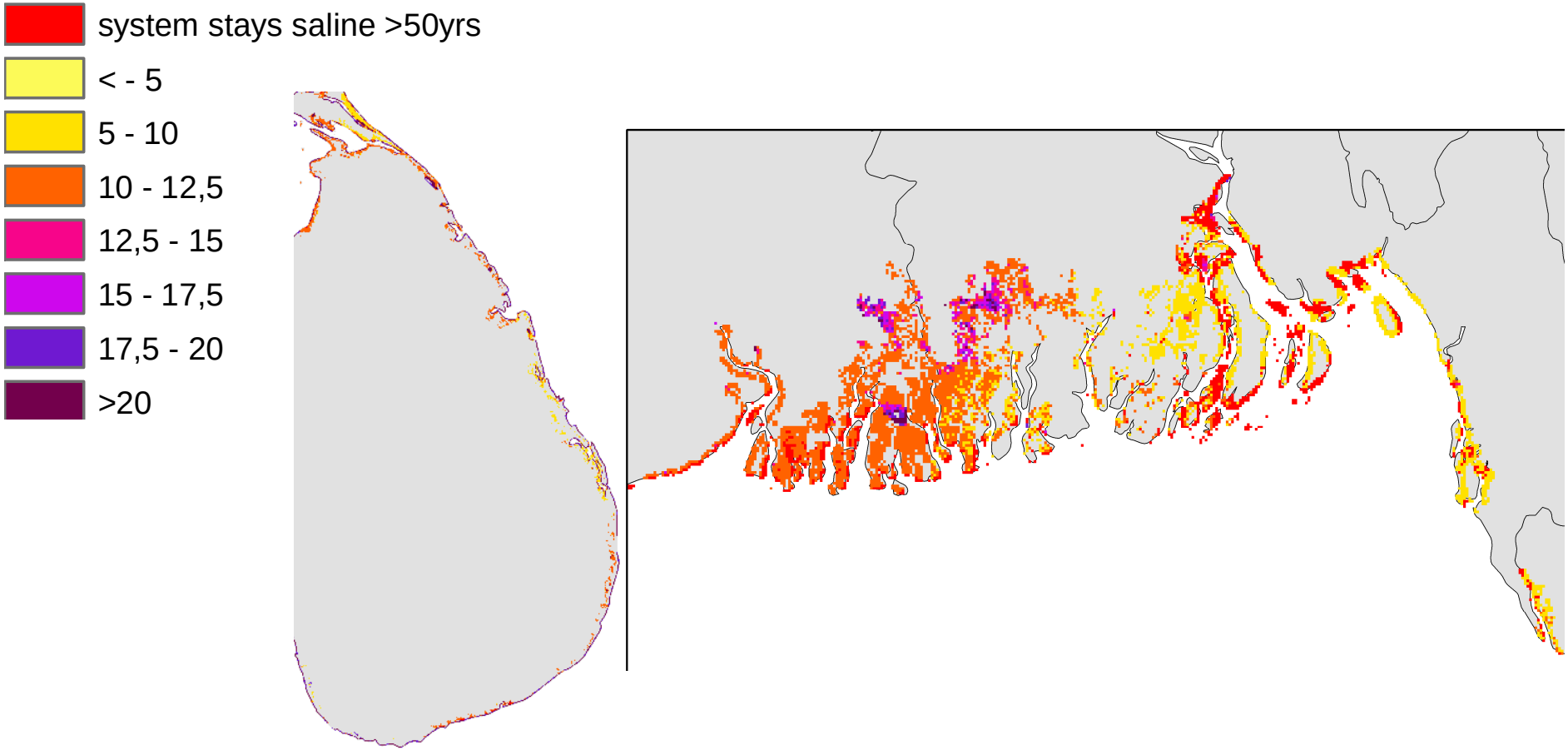


DEEP GRW SYSTEM
Drinkwater standard again after ~**66** years

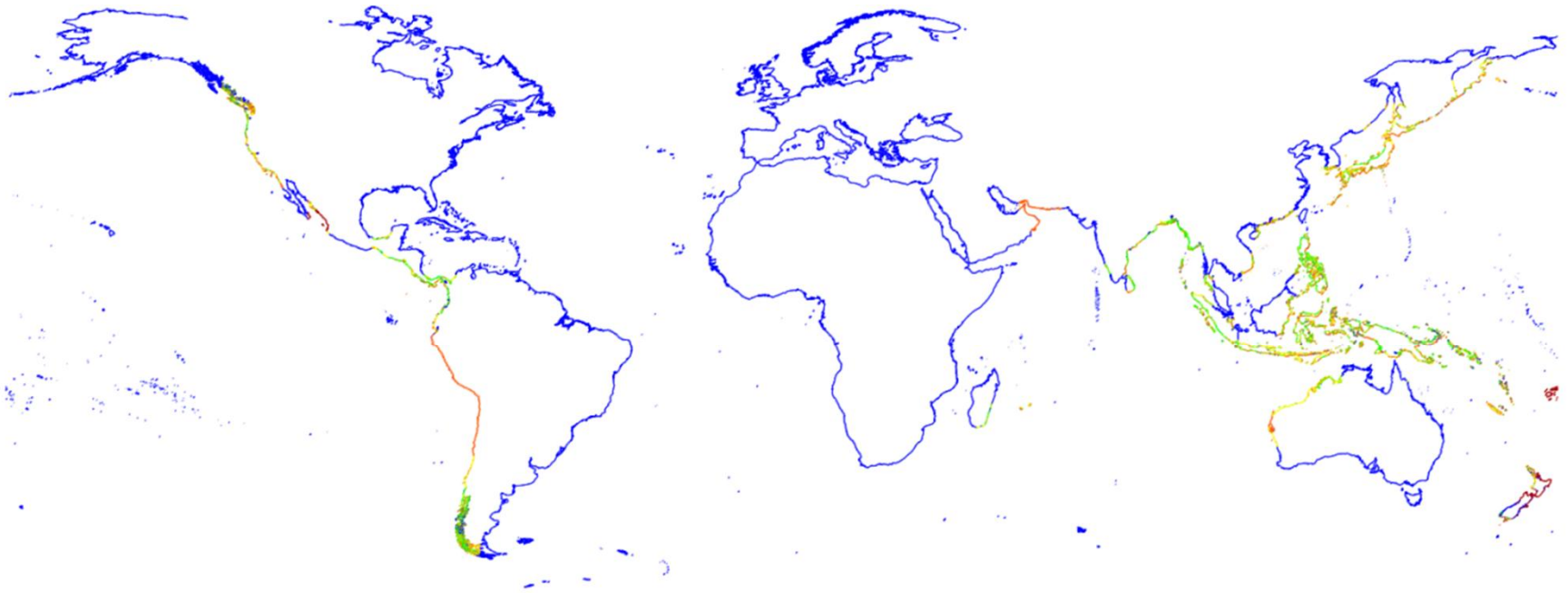
Back to the Map!

- 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



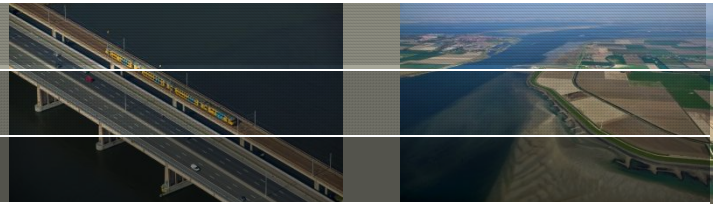
Deltares



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

Deltares

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

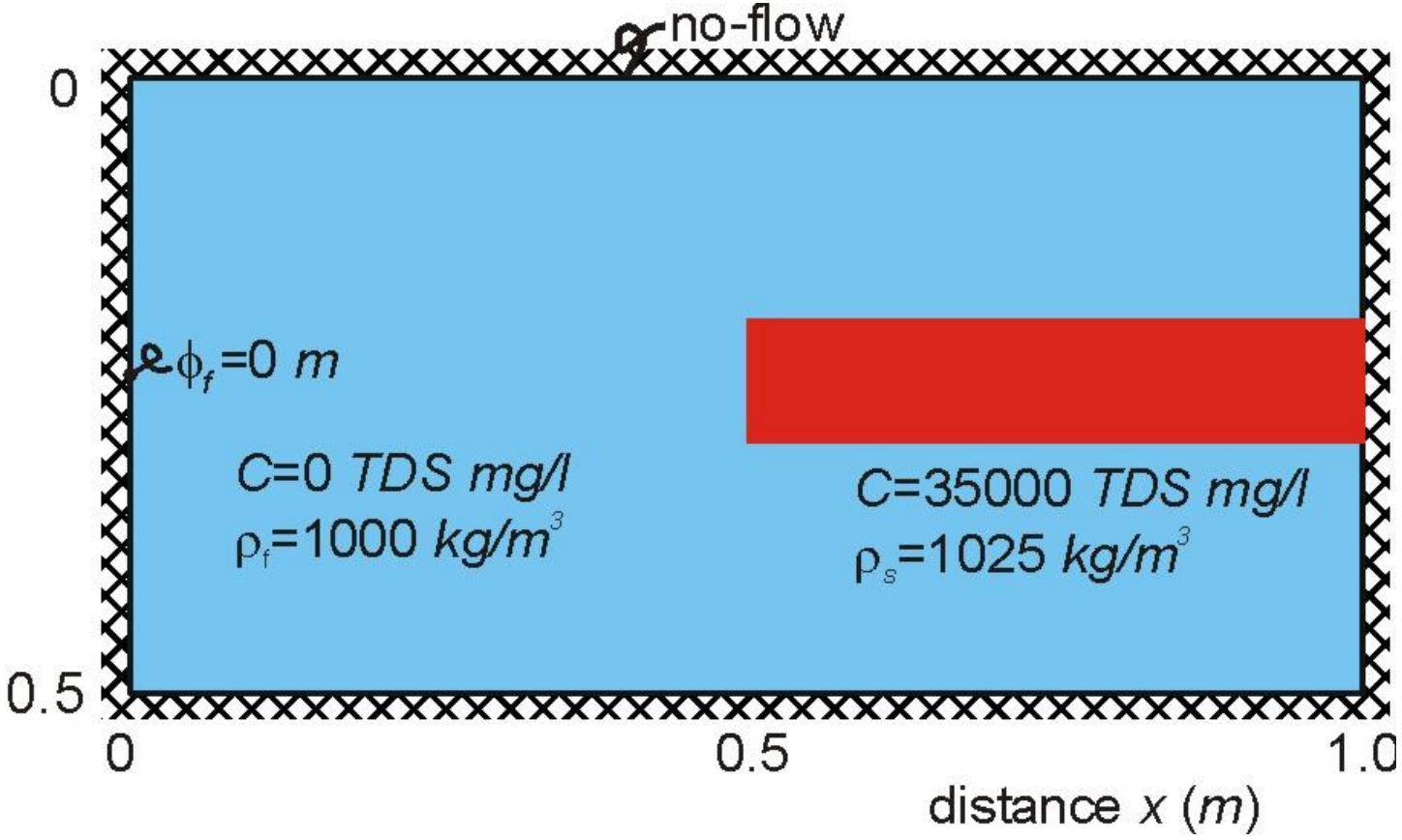
We need:

- global dataset on geology

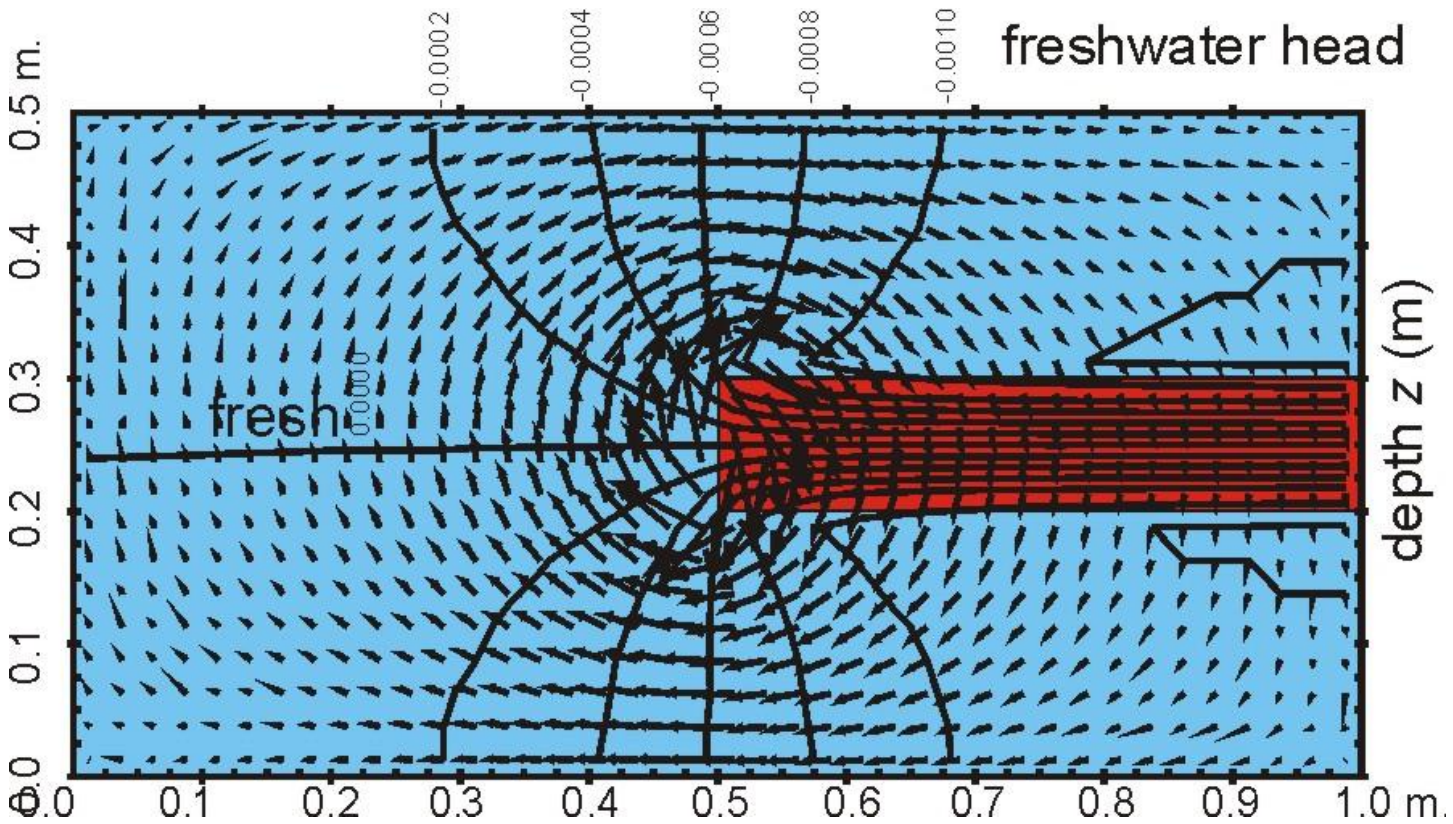
Next steps are:

- 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

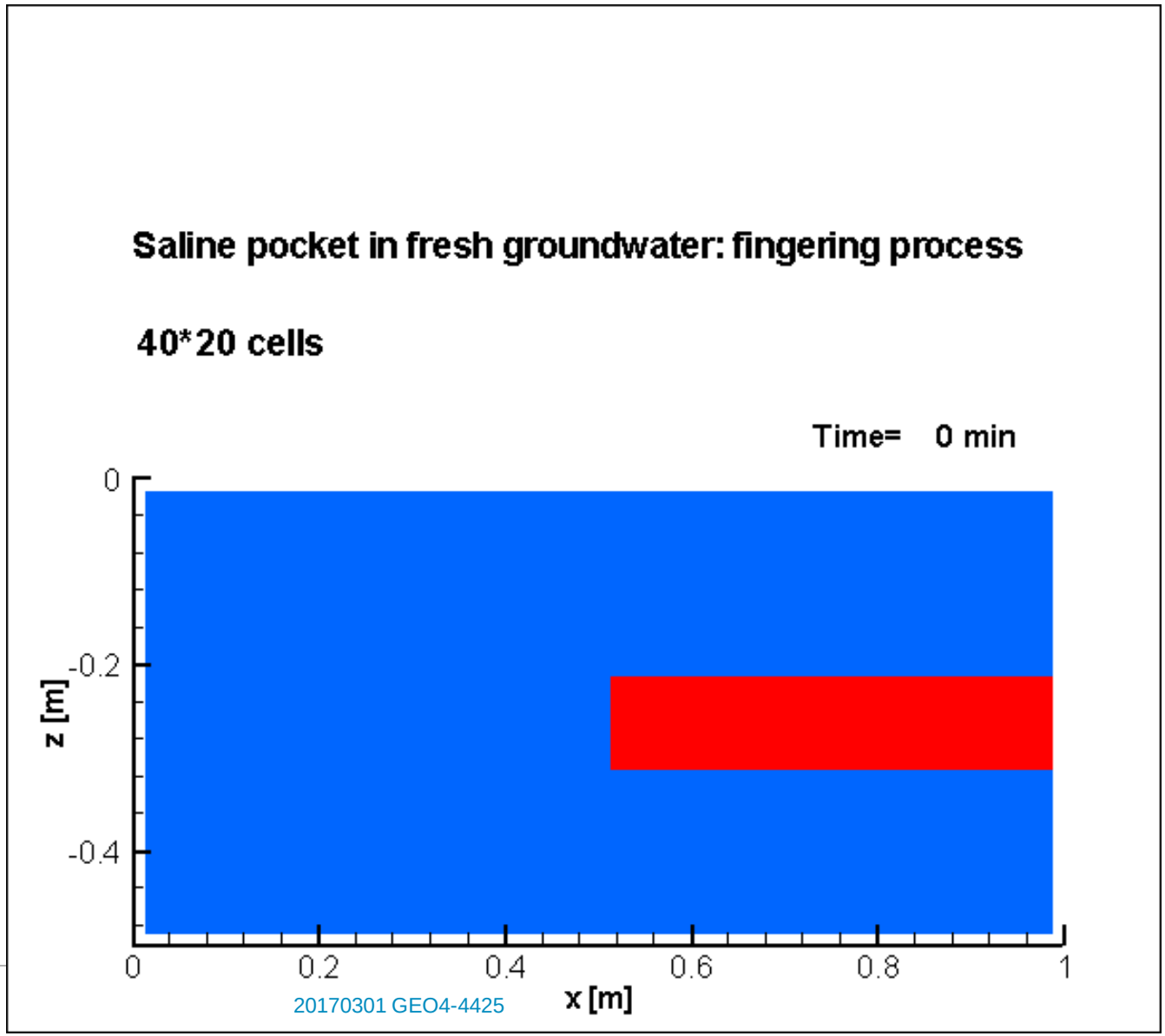
Effect of size model cell on physical process



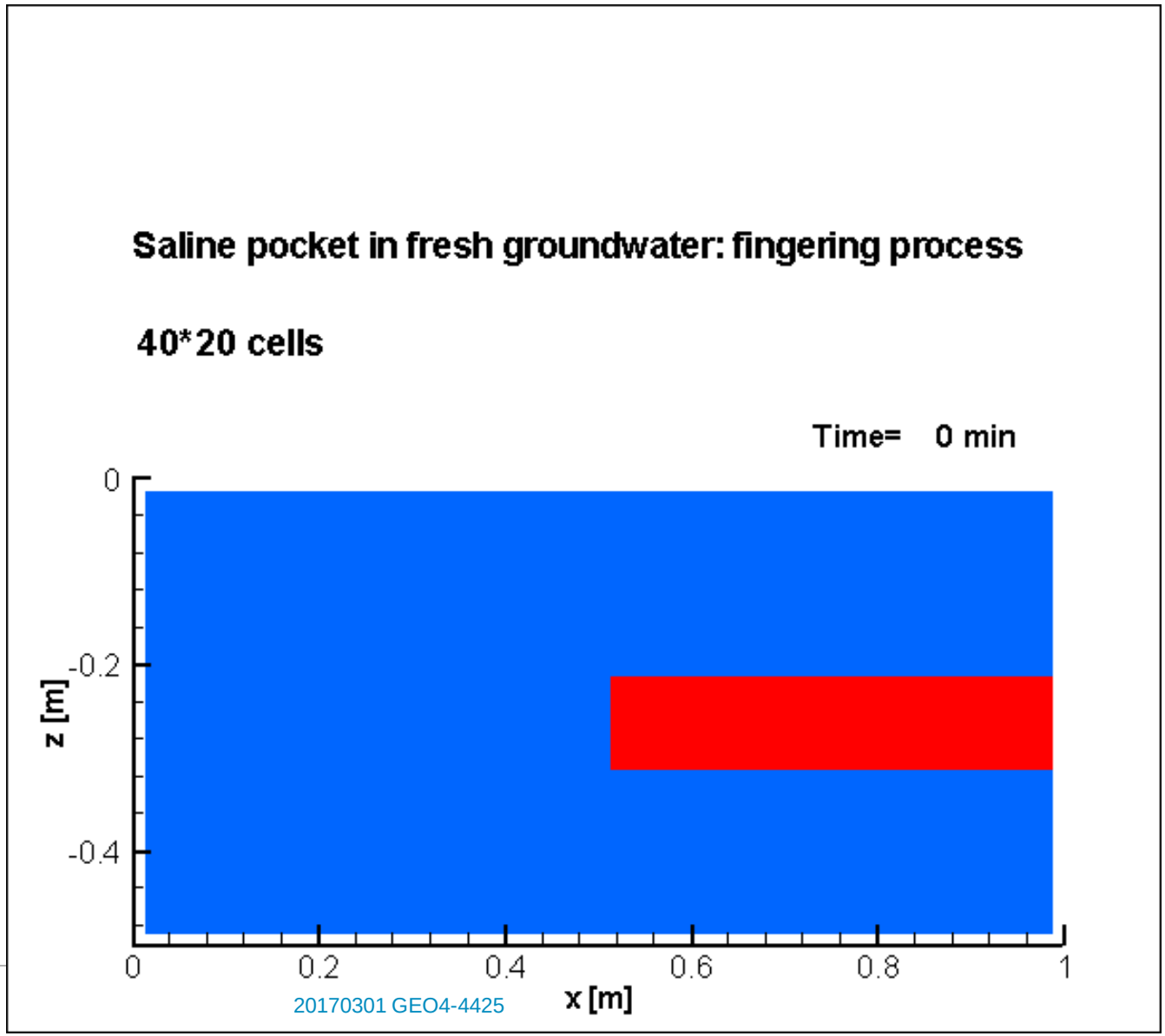
Effect of size model cell on physical process



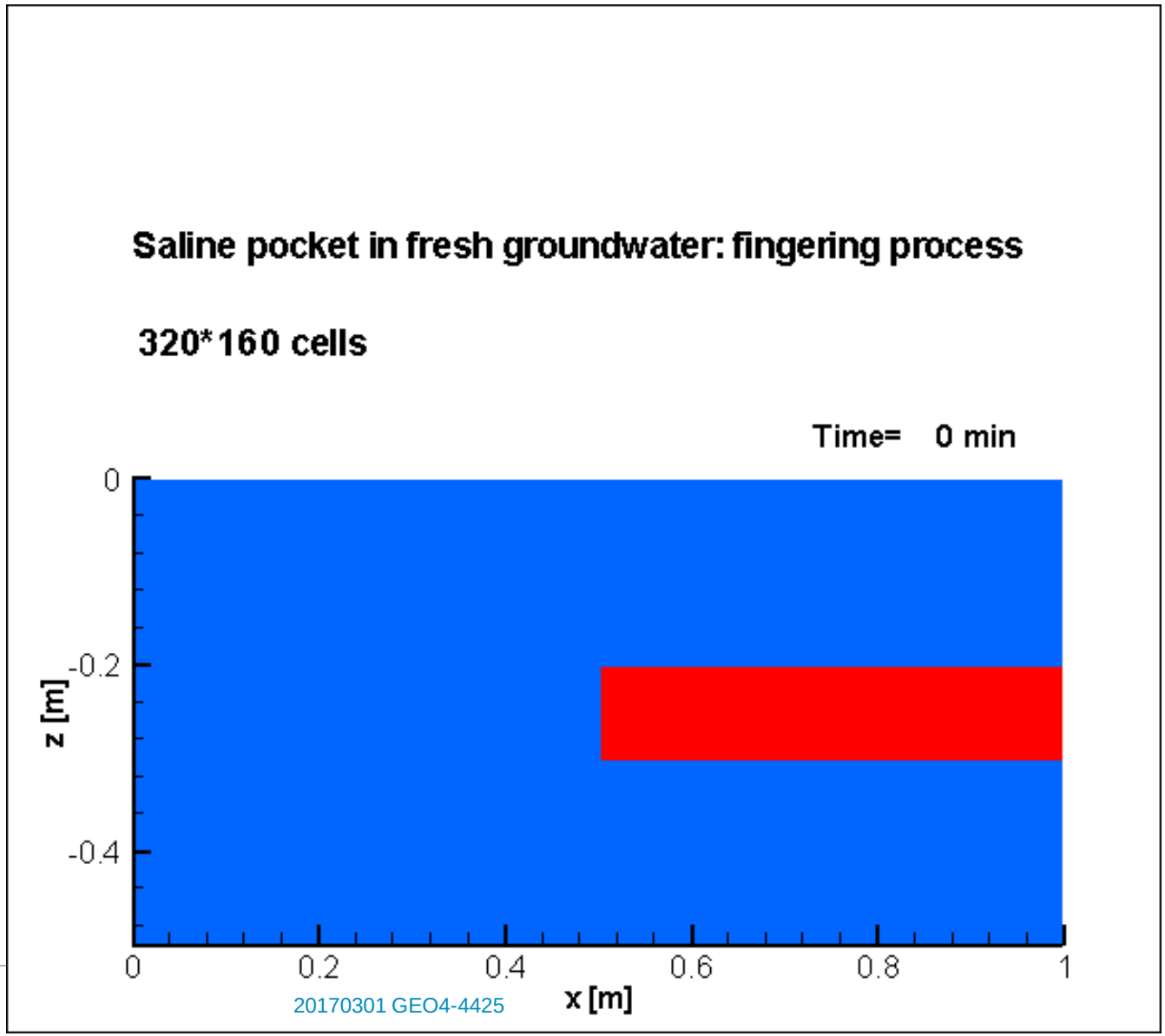
SALT WATER POCKET IN A FRESH ENVIRONMENT



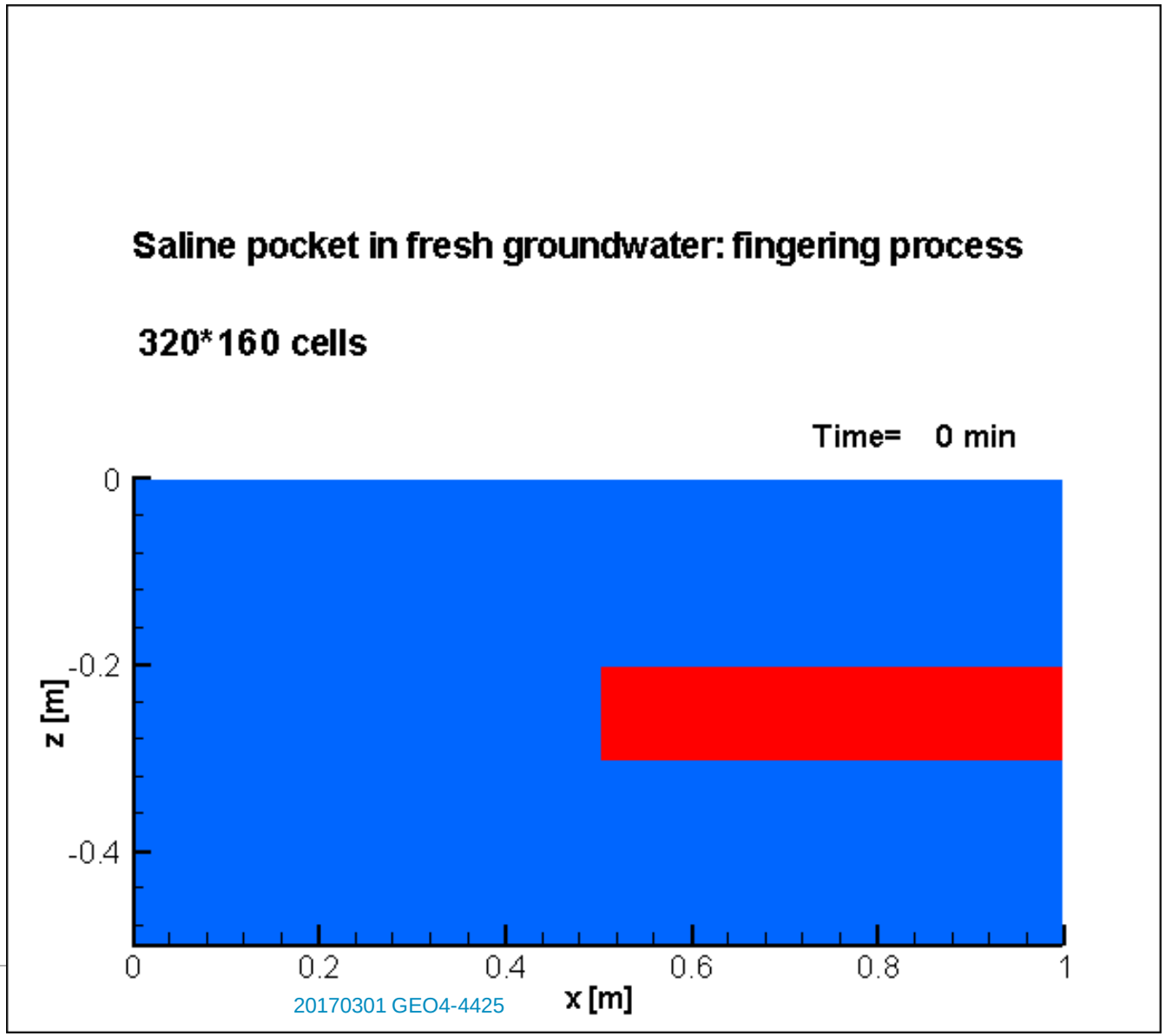
SALT WATER POCKET IN A FRESH ENVIRONMENT



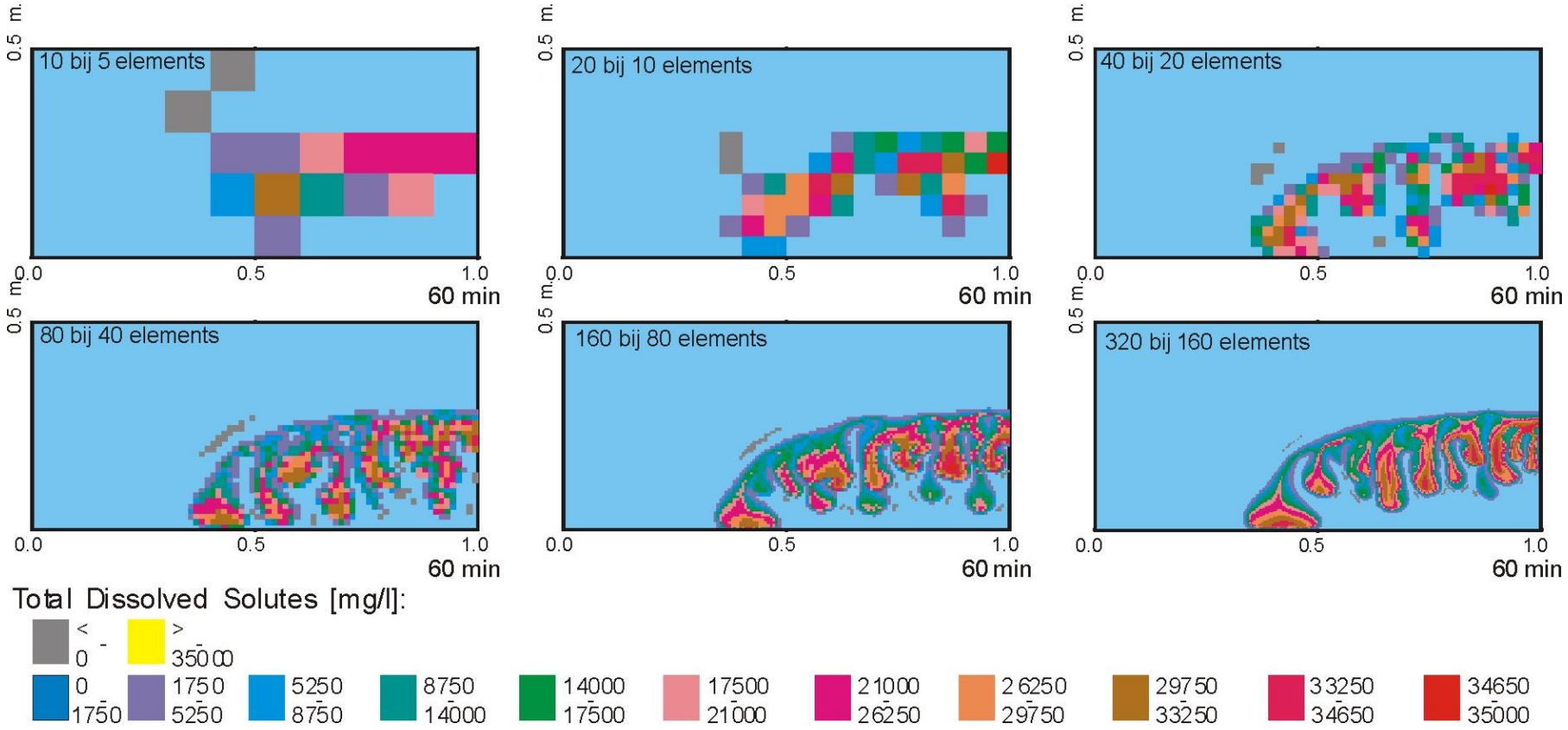
SALT WATER POCKET IN A FRESH ENVIRONMENT



SALT WATER POCKET IN A FRESH ENVIRONMENT

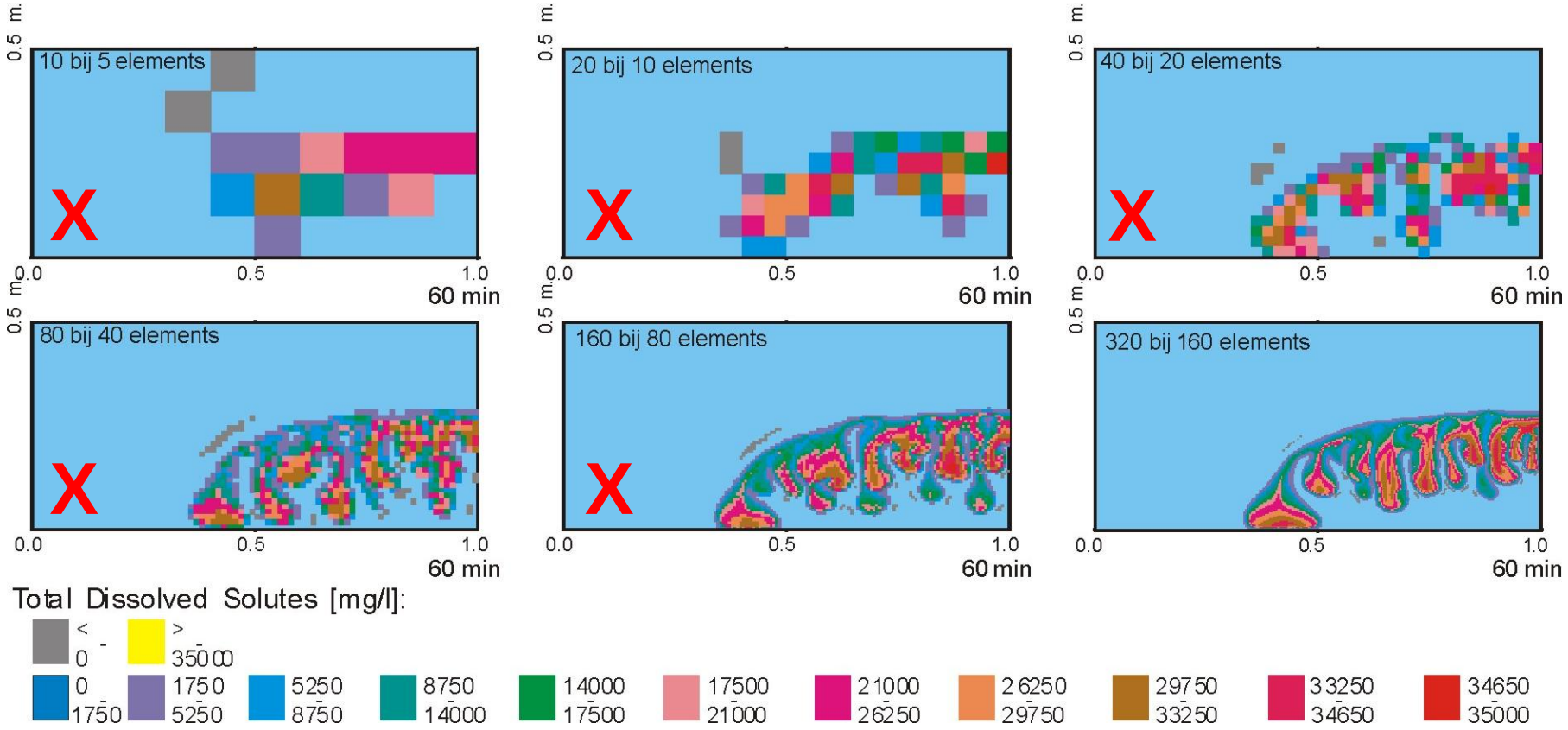


Effect of model cell size on physical process



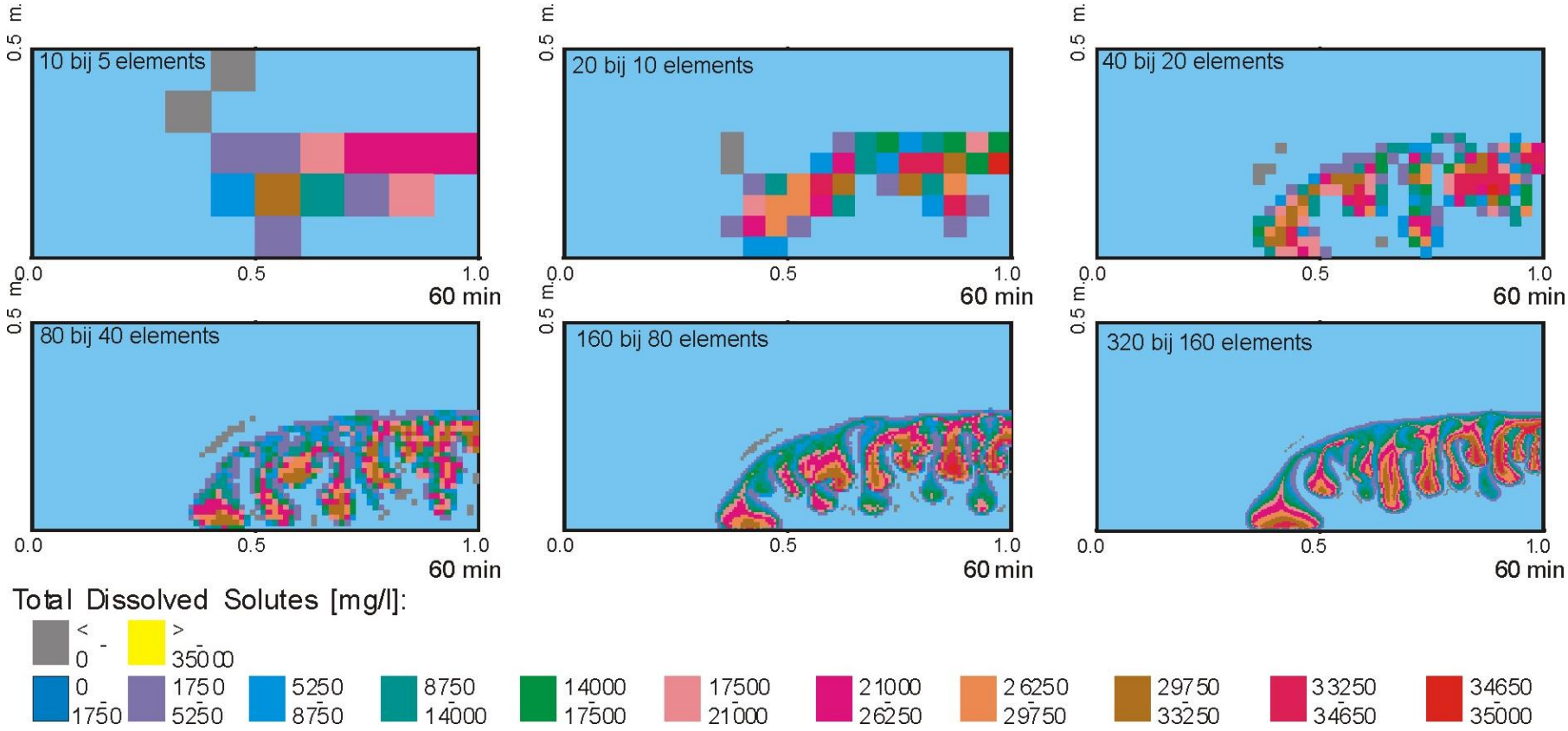
Model size cell has a **large** effect on modelling result!

Effect of size model cell on physical process



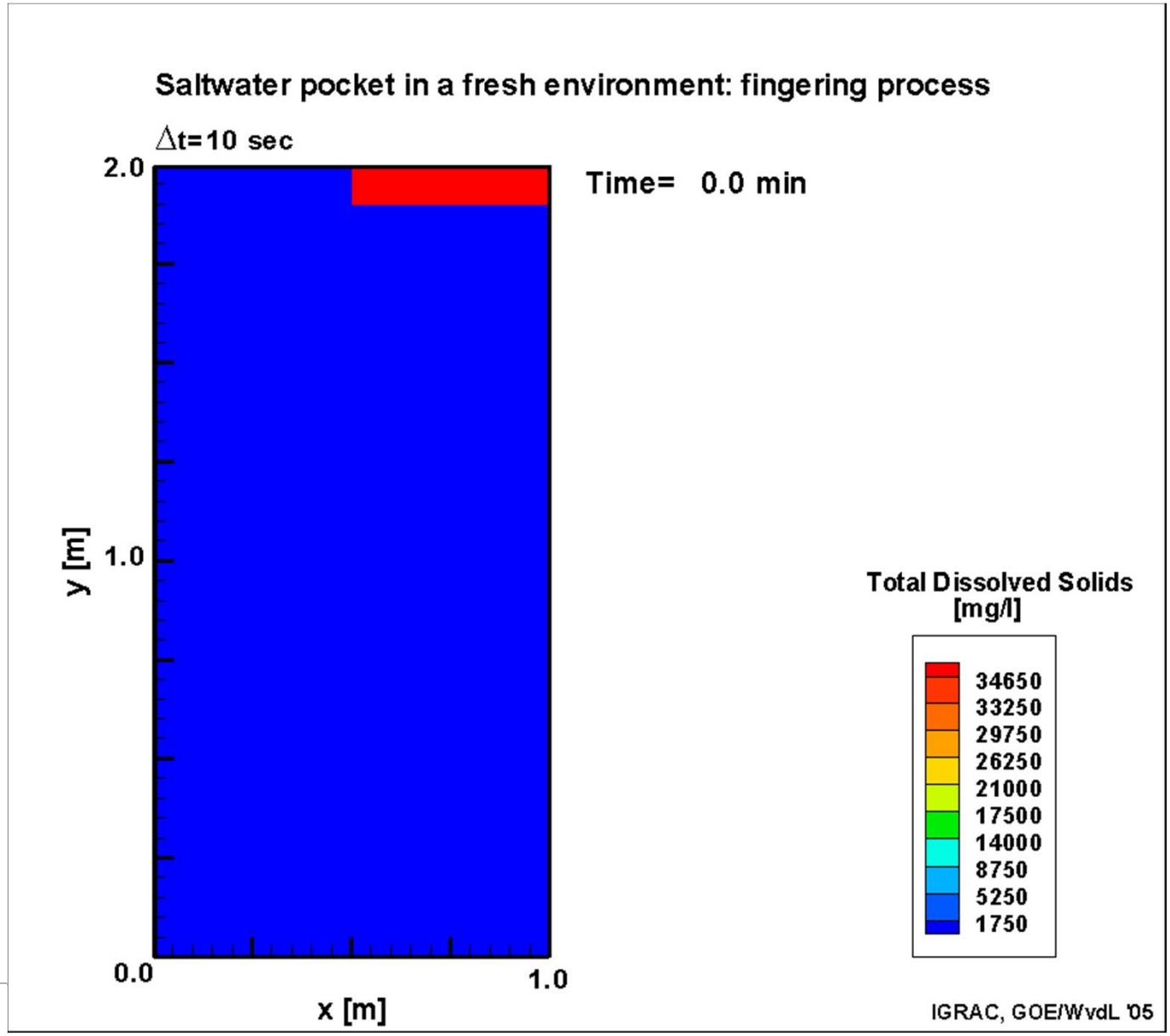
X= LOUSY models for predicting exact number of salt water fingers

Effect of size model cell on physical process



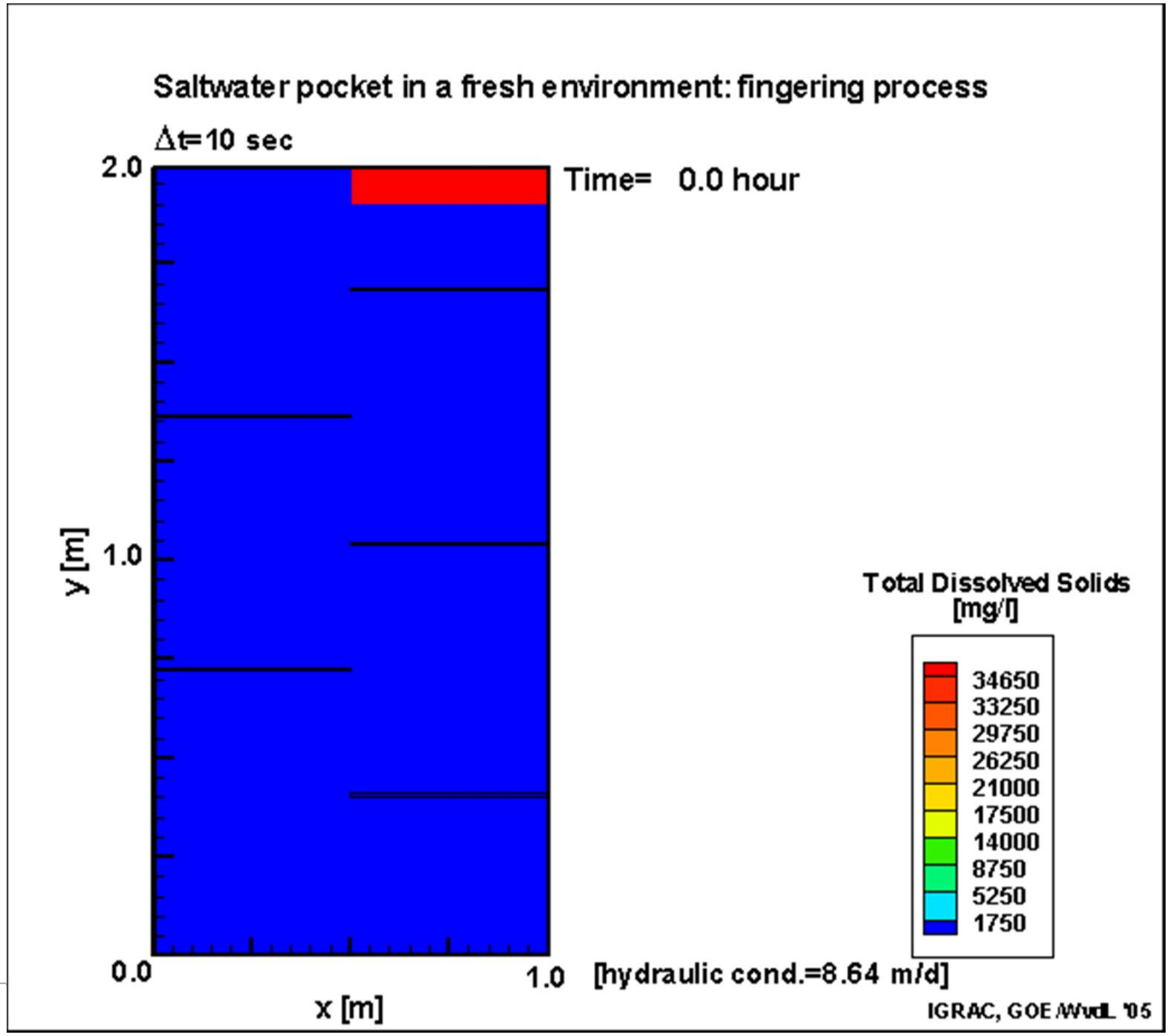
All models are GOOD for predicting moment of touching bottom (60min)!

Fingering processes in the subsoil



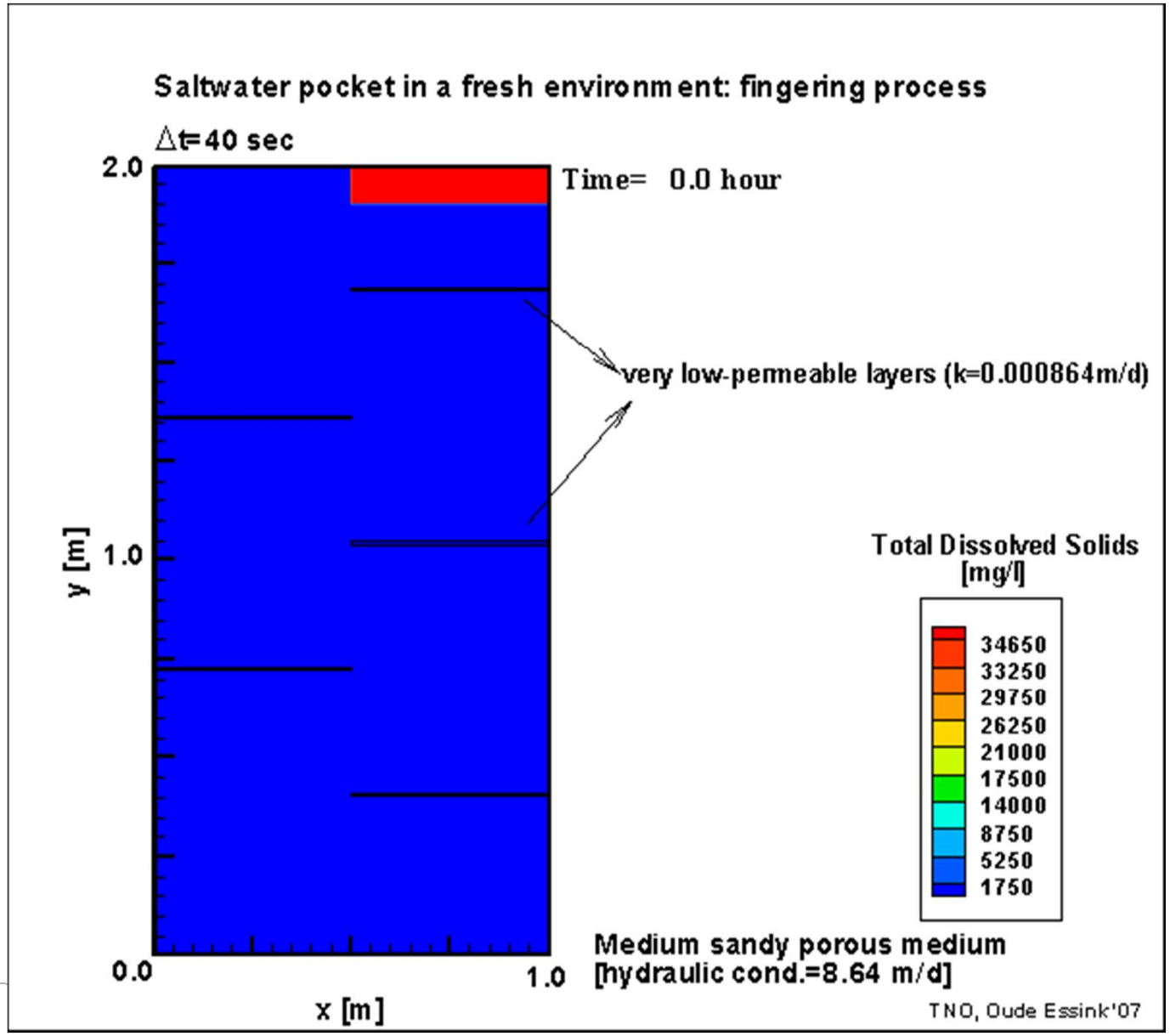
Deltares

Fingering processes in the subsoil



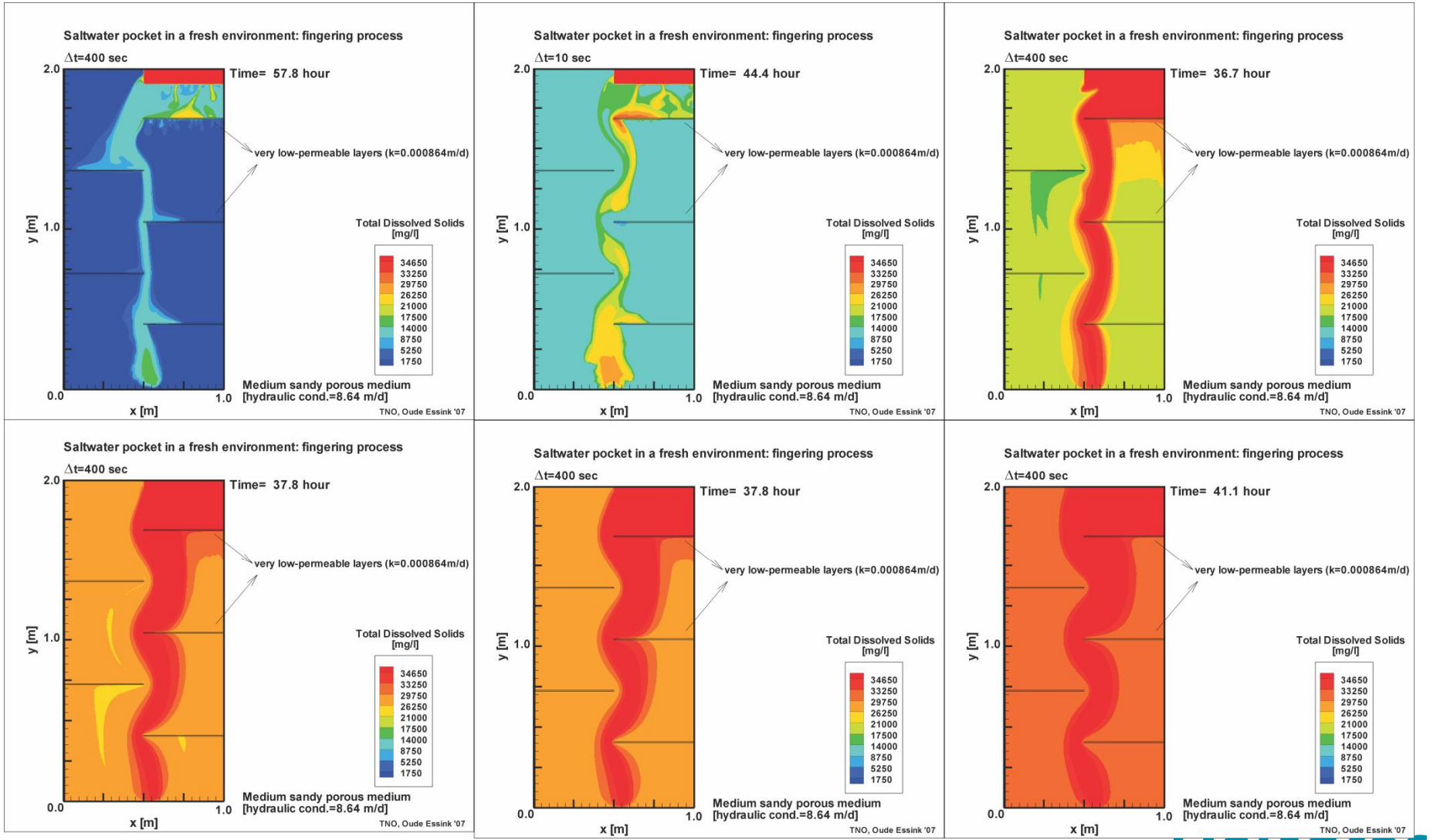
Deltares

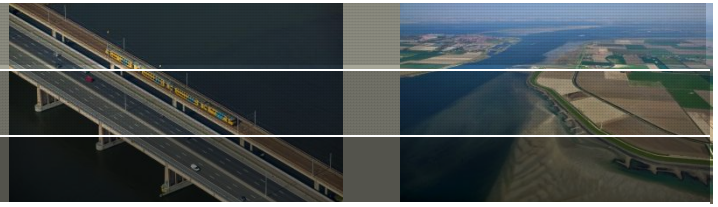
Fingering processes in the subsoil



Deltares

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



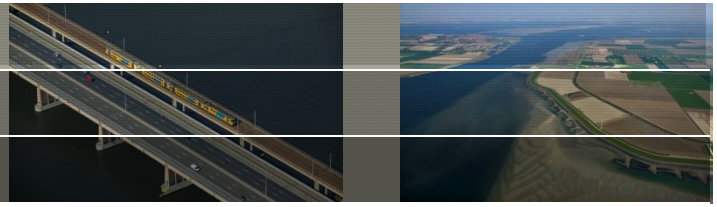


Base idea

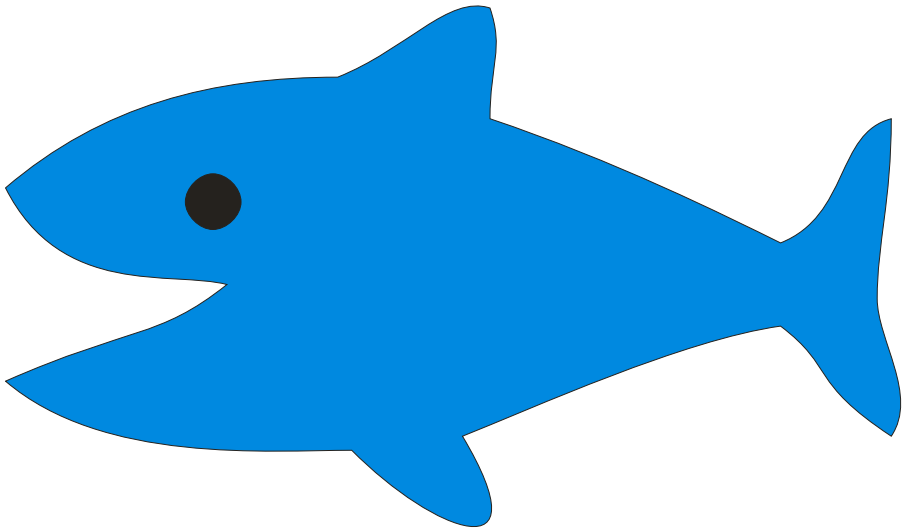
Many local solutions for fresh groundwater supply can have regional impact

Deltares

Starring

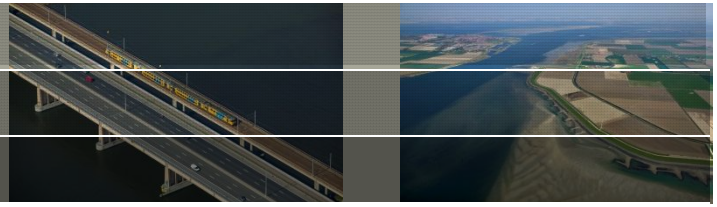


solution fresh groundwater supply

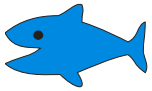


Deltares

Starring

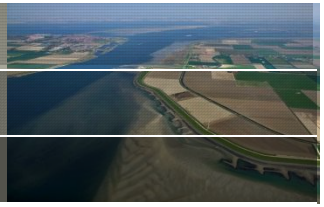


Local solution fresh groundwater supply



Deltares

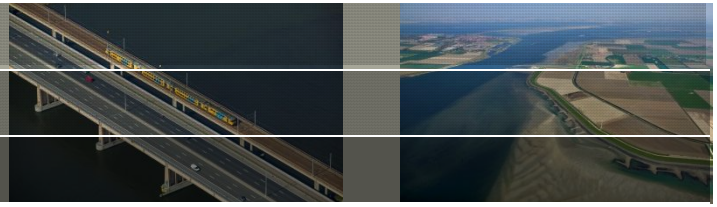
Starring



climate and global change

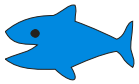
Deltares

Starring

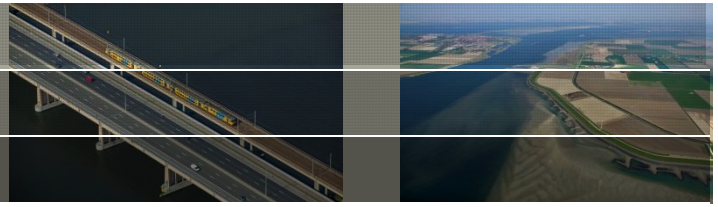


climate and global change

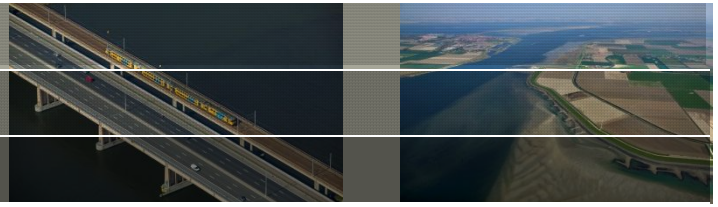
Local solution fresh groundwater supply



climate and global change

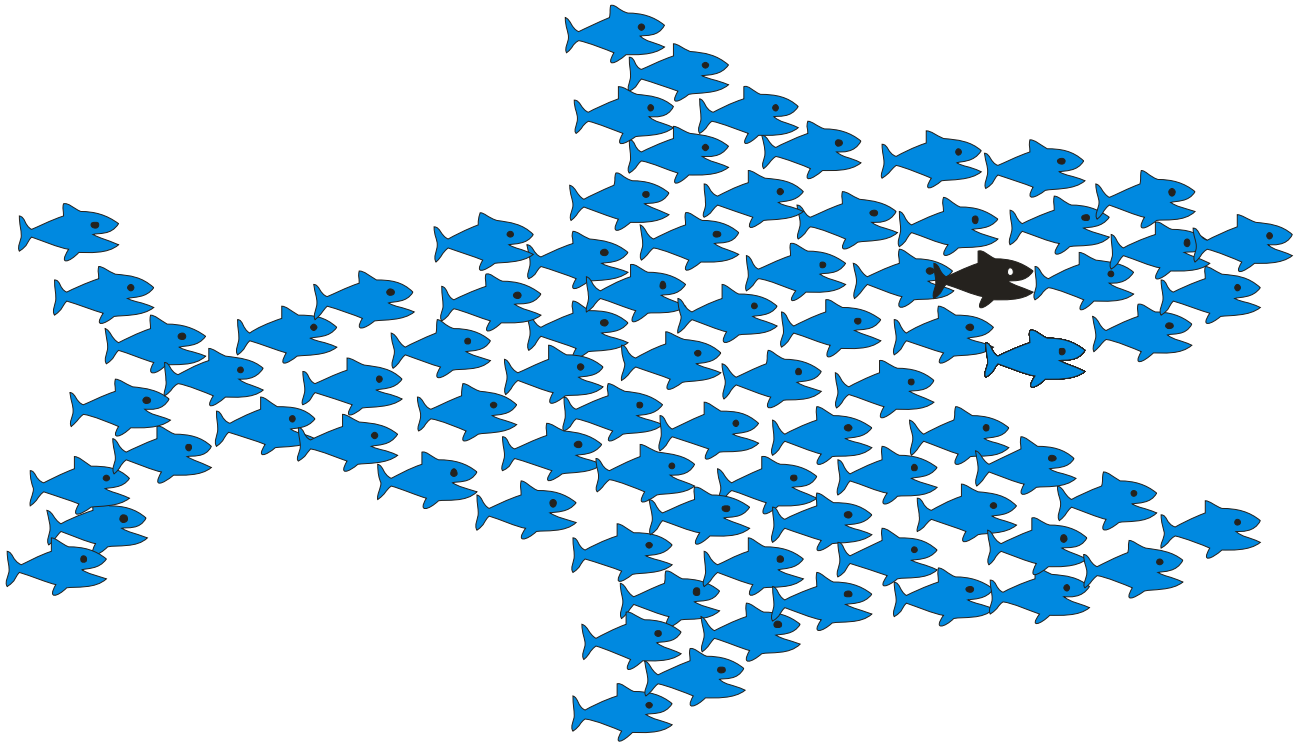


What should be the response?



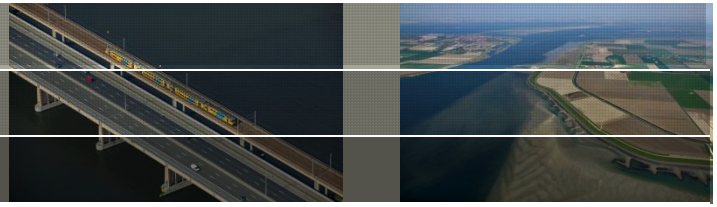
Many local solutions fresh groundwater supply

climate and global change

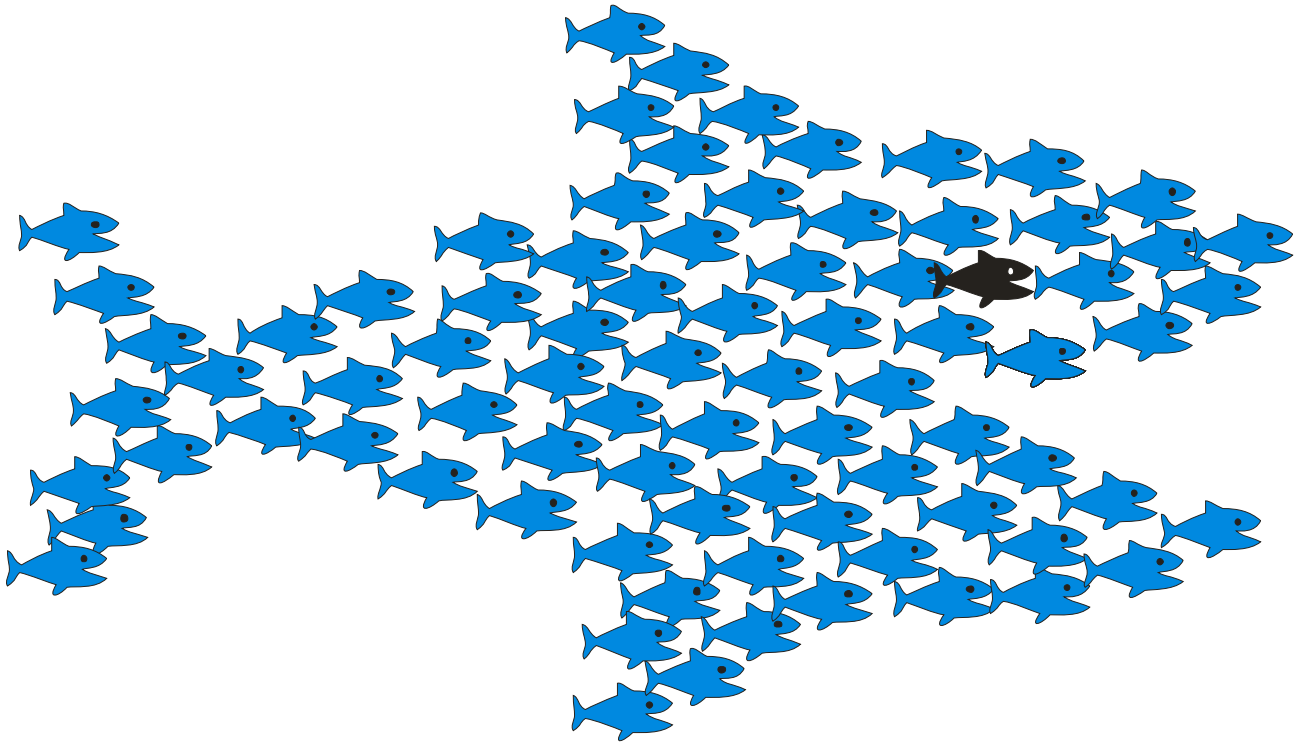


Many local solutions for fresh groundwater supply can have regional impact

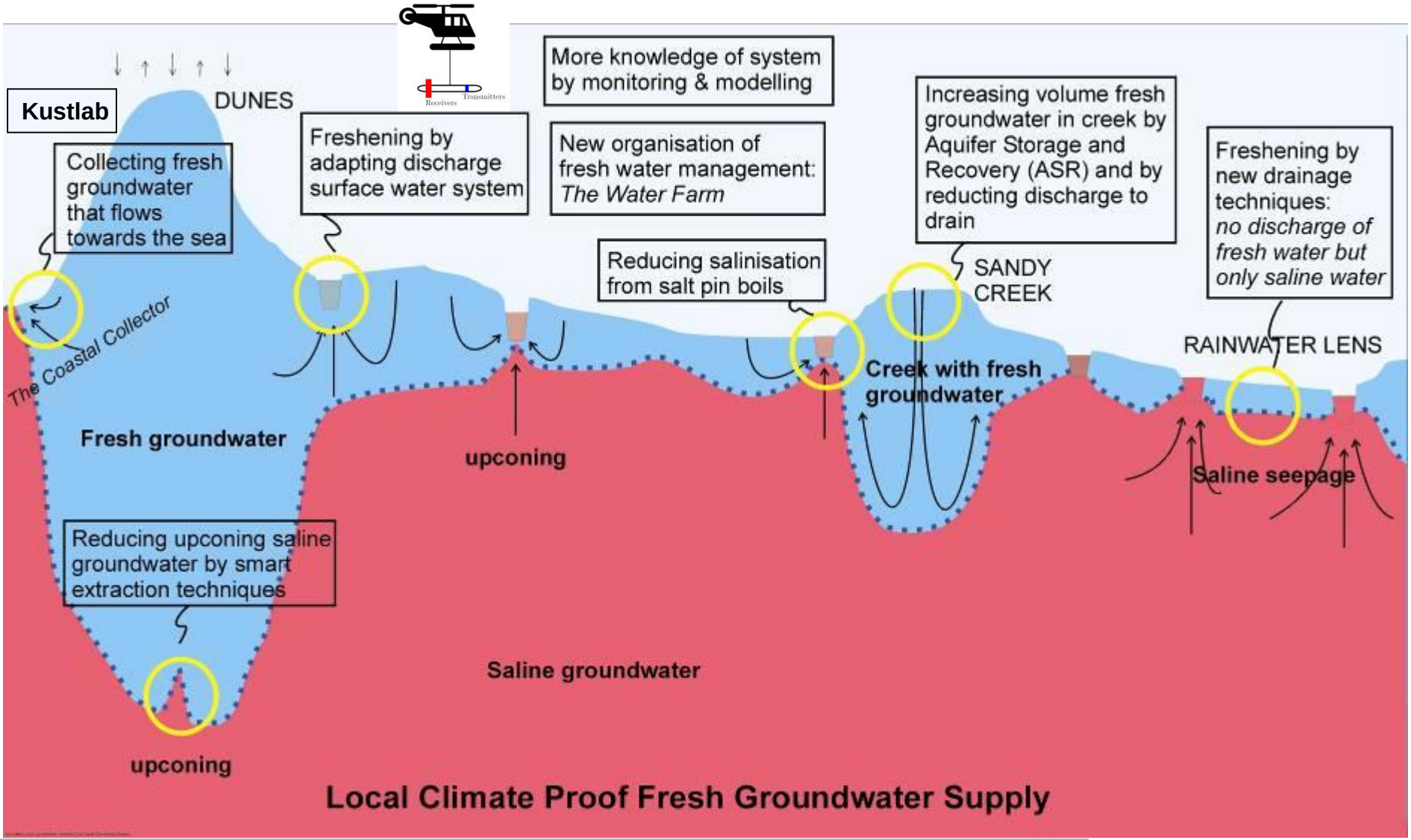
Key activities



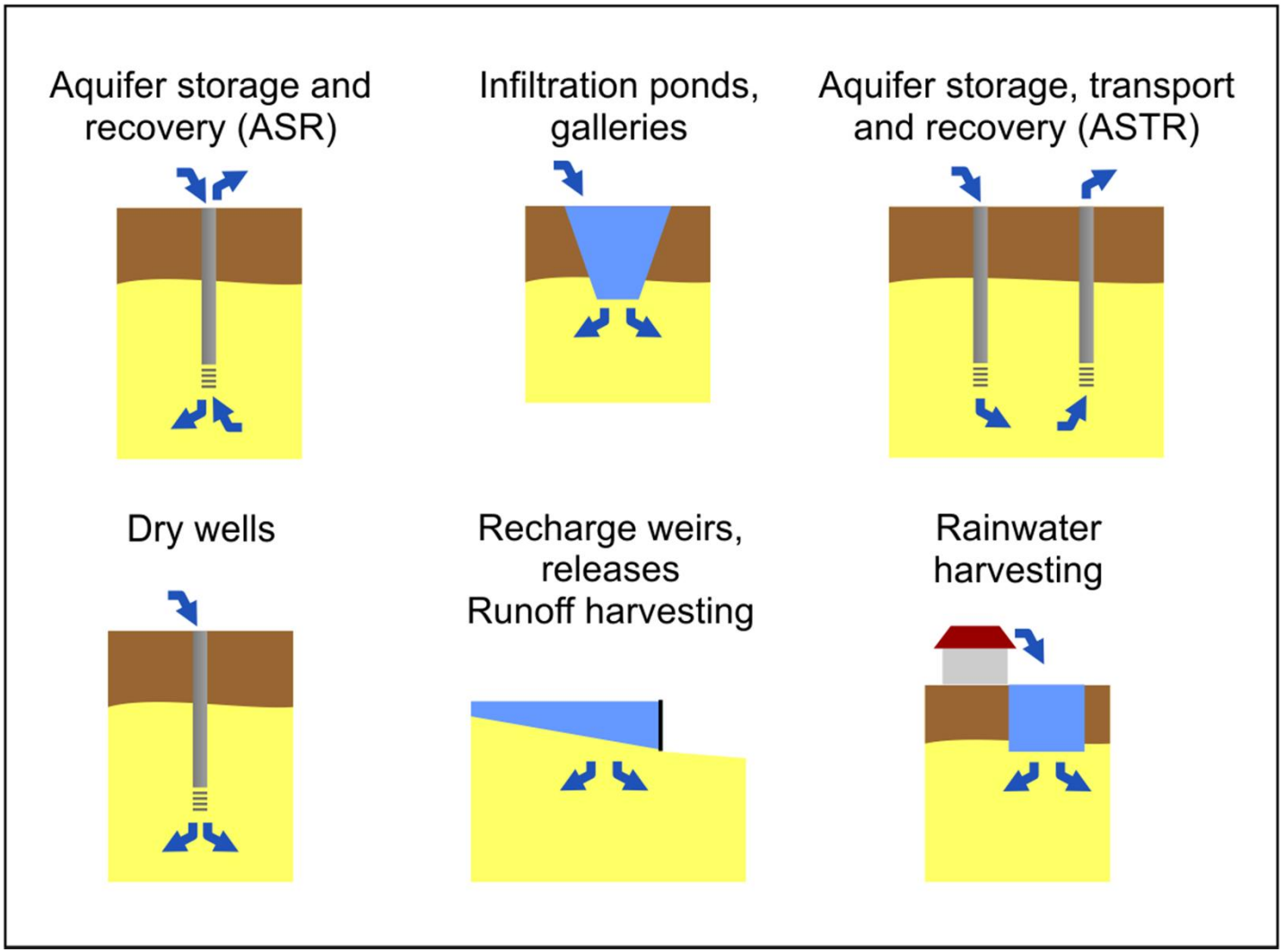
- upscaling local cases to regional strategy
- assess economical feasibility
- increase impact: communicate our showcases
- working together



Local climate proof fresh water supply



Aquifer Storage and Recovery / Managed Aquifer Recharge



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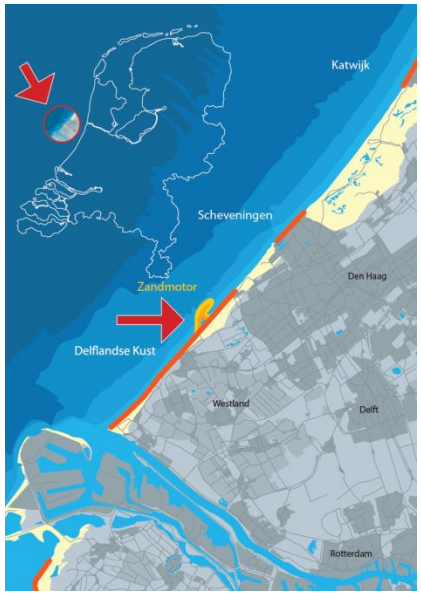
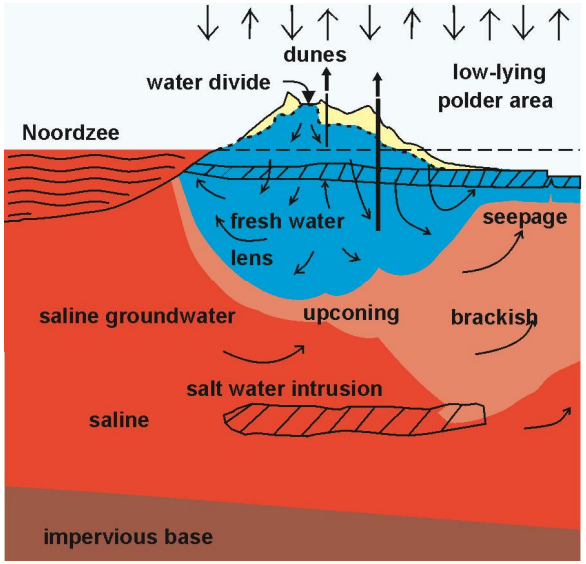
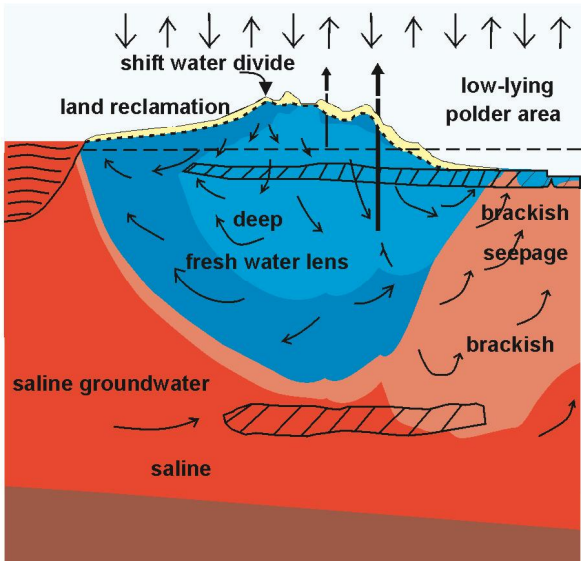
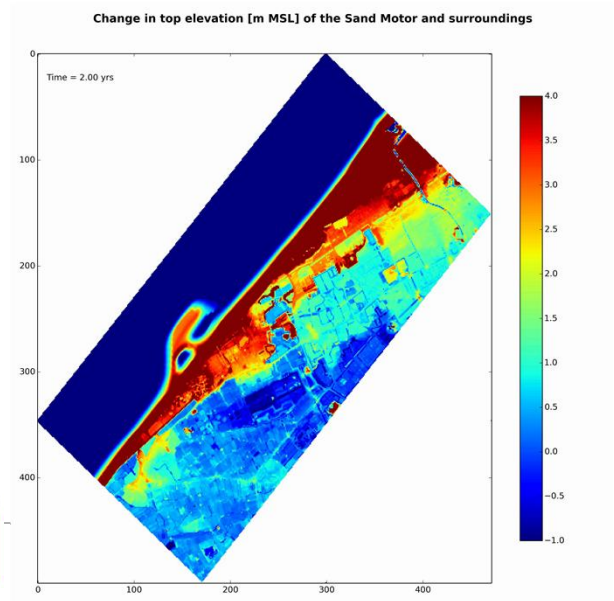
Increase strategic freshwater reservoirs in the coastral zone

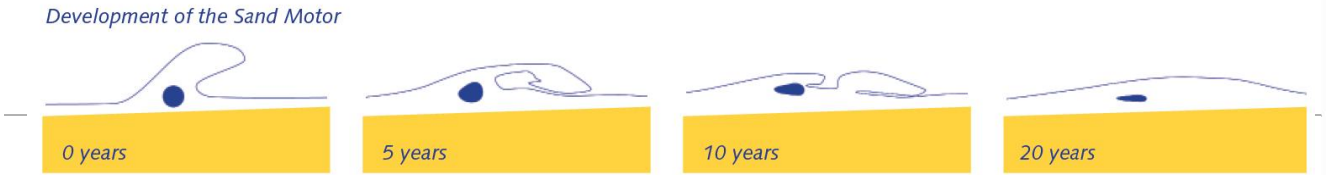


NatureCoast, Building with Nature, De Zandmotor

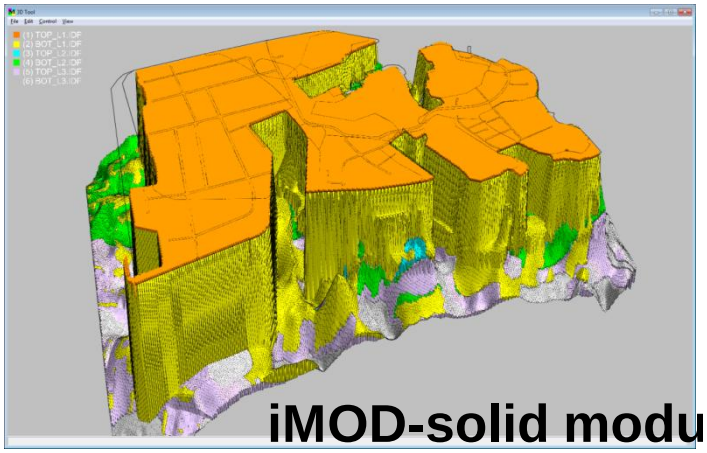


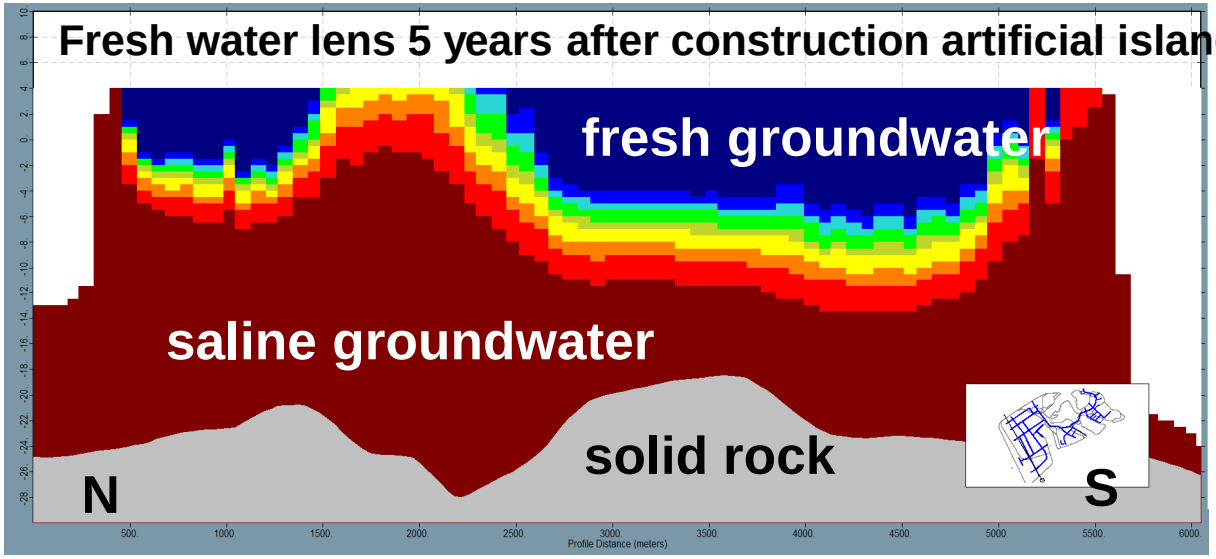


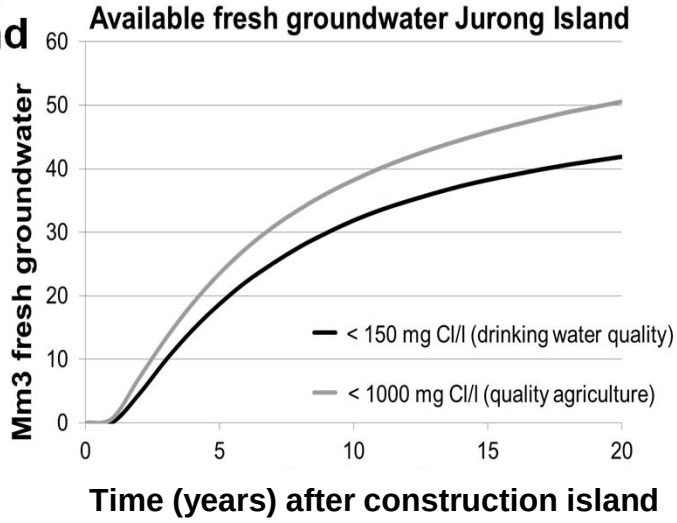




Local model: iMOD-SEAWAT Jurong Island Singapore

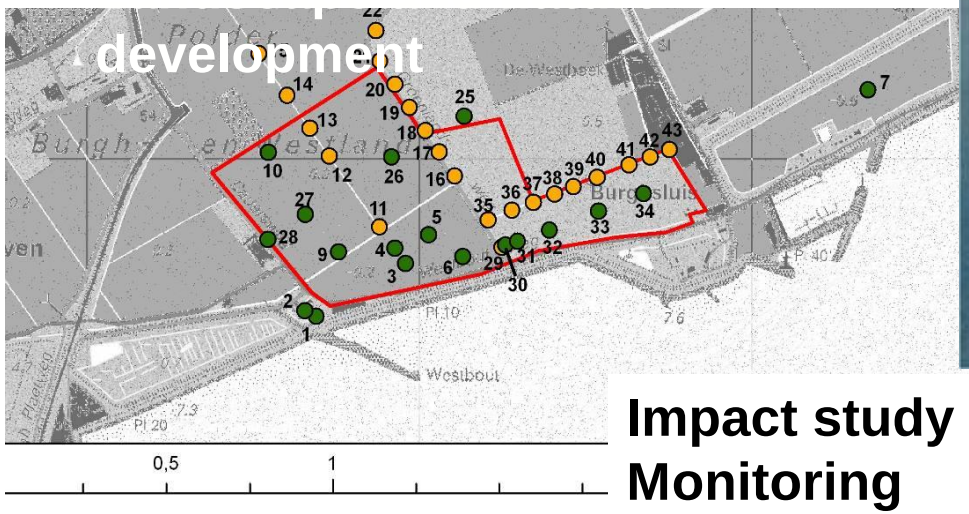




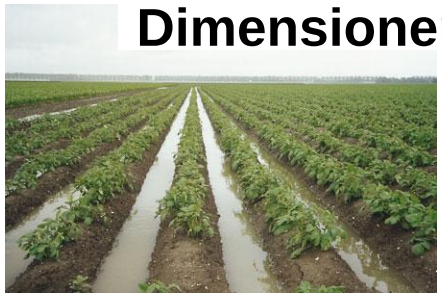


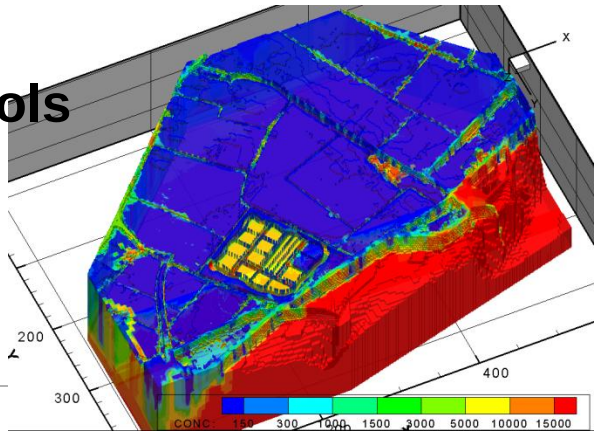
The Coastal Laboratory: aquaculture on fertile land

development

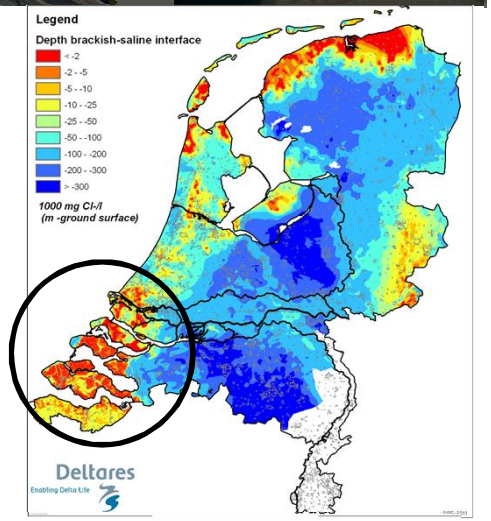


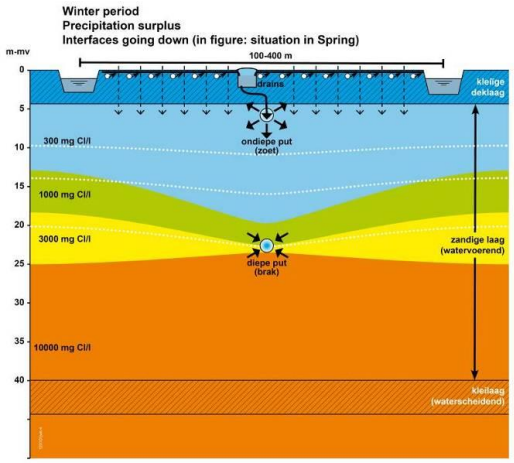
Impact study
Monitoring
Dimensionering saline pools



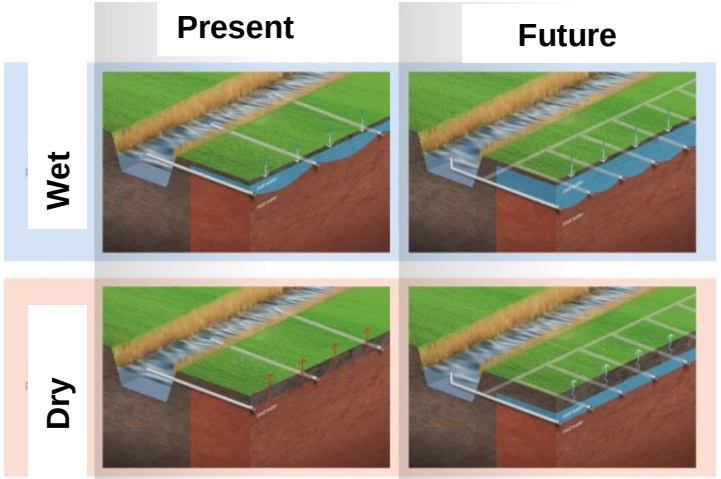


GO-FRESH: Local measures to increase fresh water supply

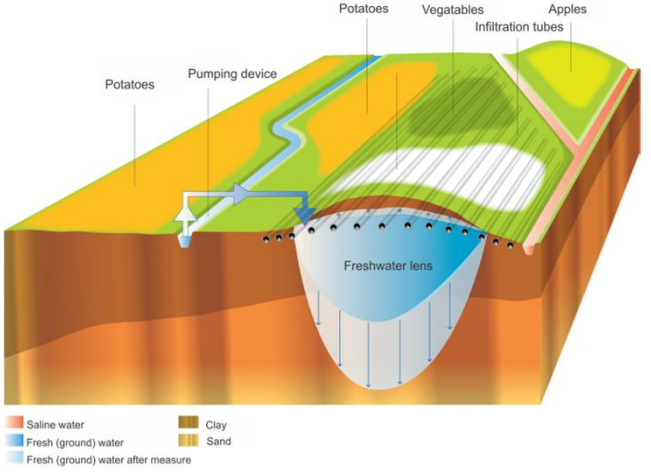




The Freshmaker
Injection fresh water and extraction saline



Drains2Buffer
Smart deep drainage protects thin freshwater lens



Creek Ridge Infiltration Te
Elevation ground water level
by infiltration surface

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

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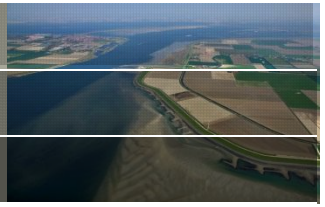
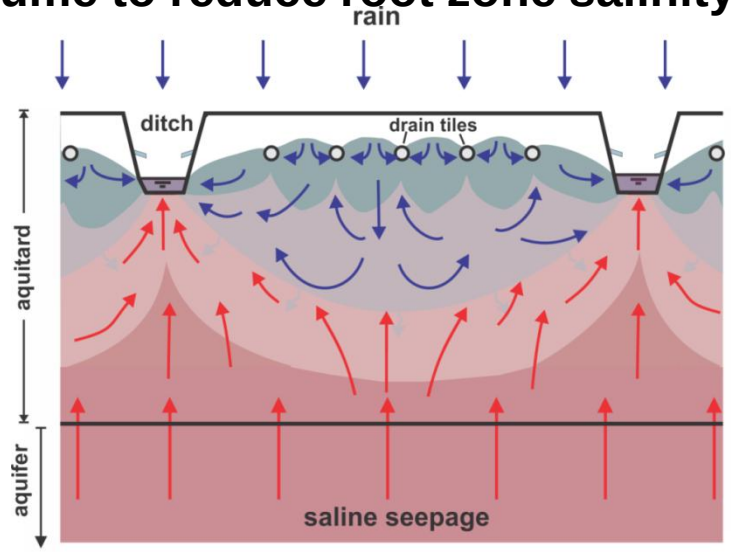
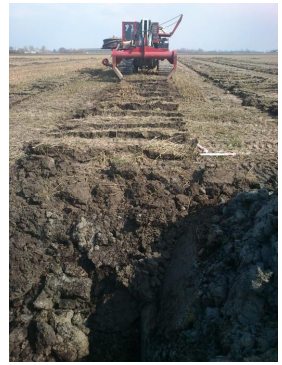
Drains2Buffer

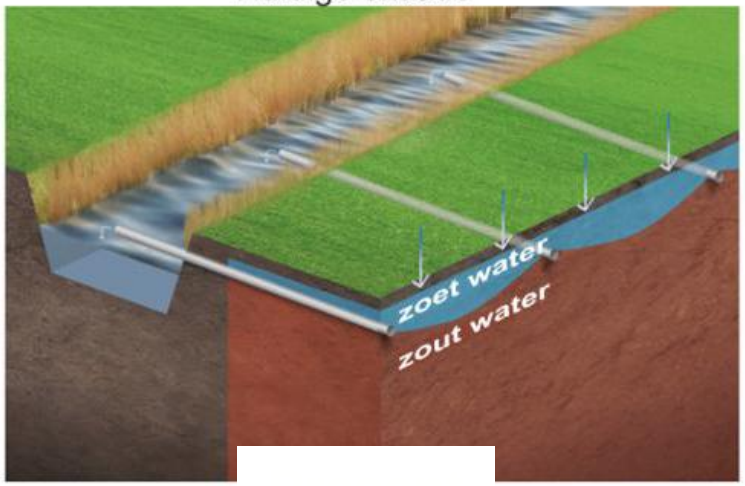


Increase rainwater lens volume to reduce root zone salinity

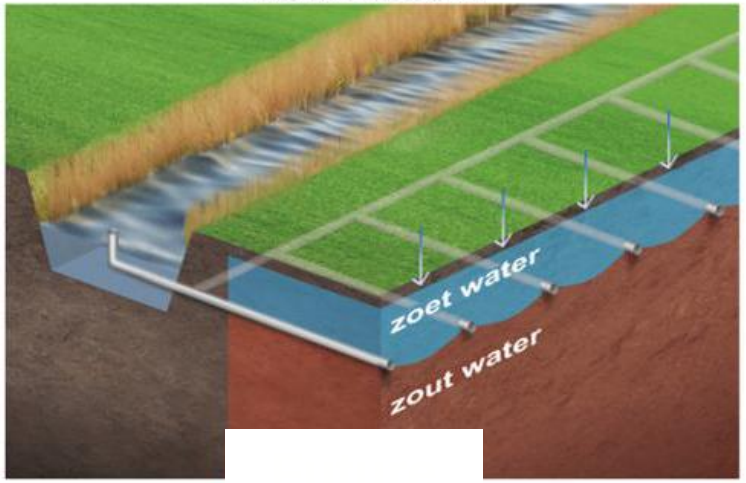




Huidige situatie

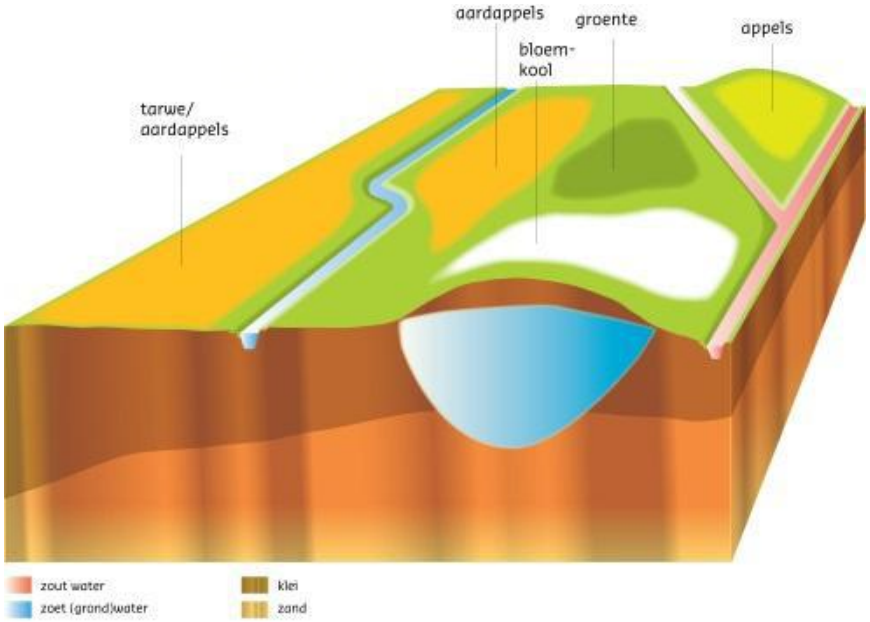


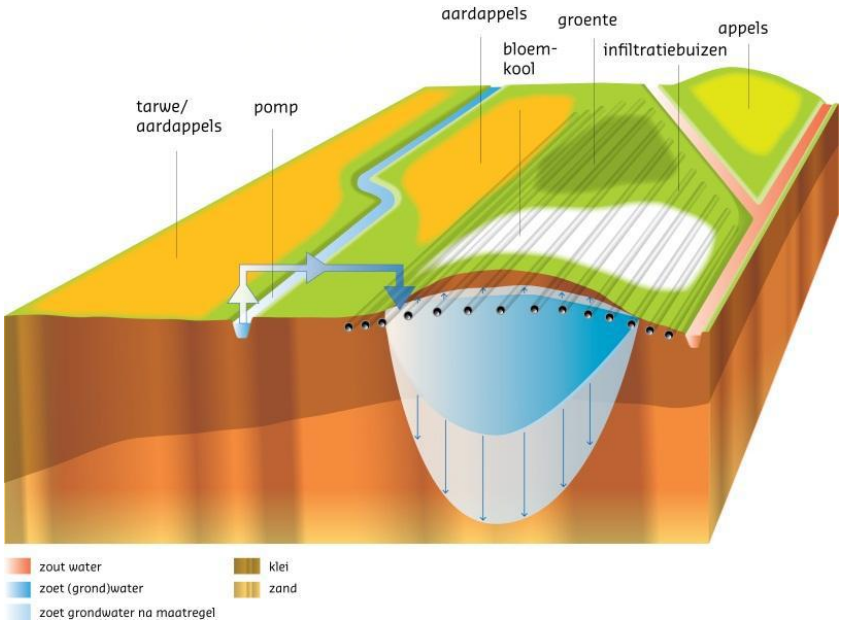
Nieuwe situatie

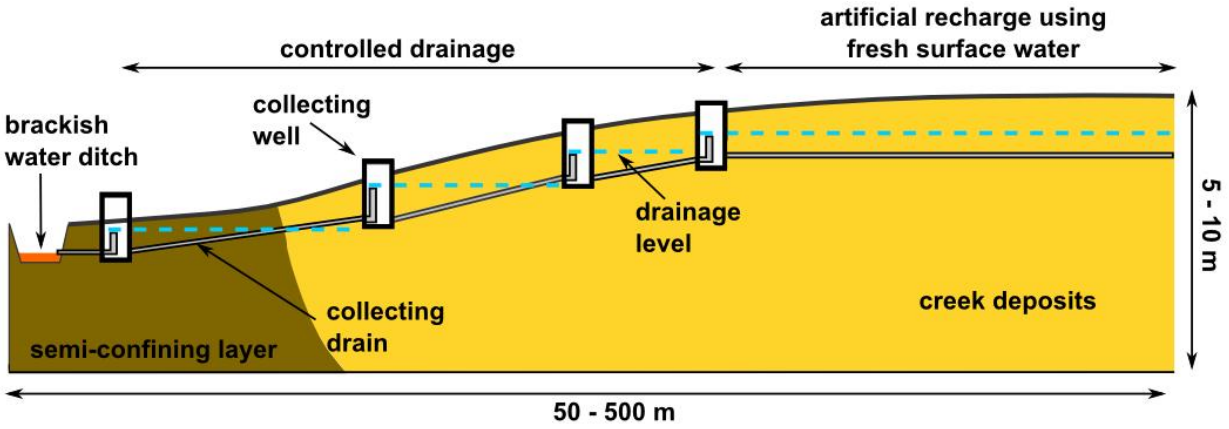


GO-FRESH

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







GO-FRESH

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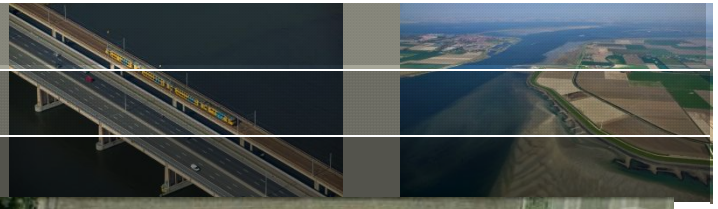
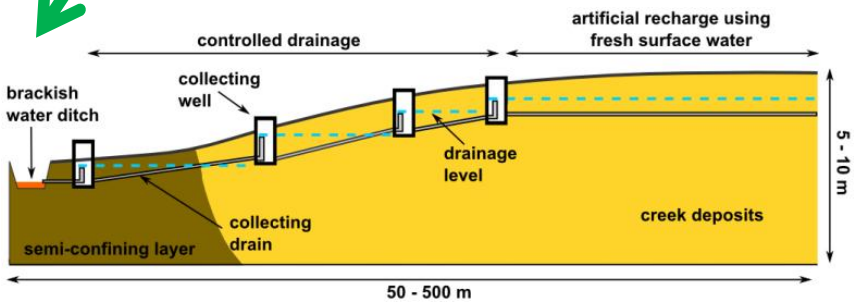
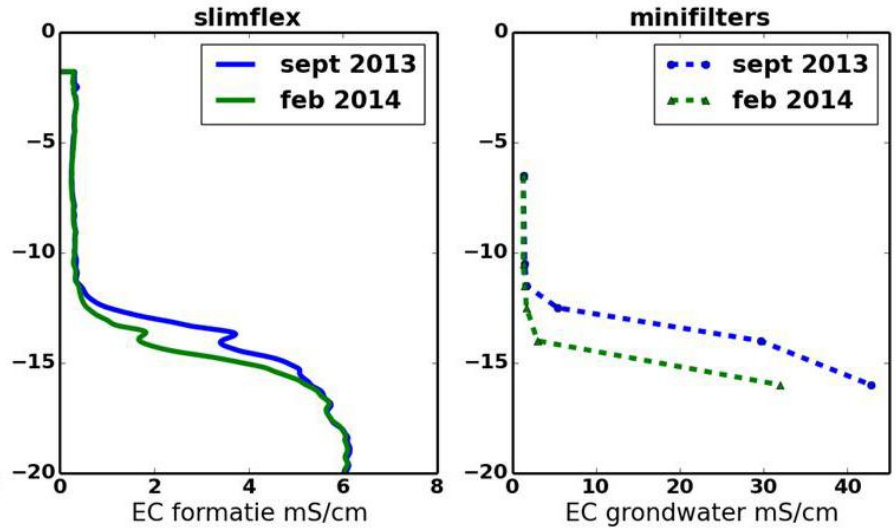
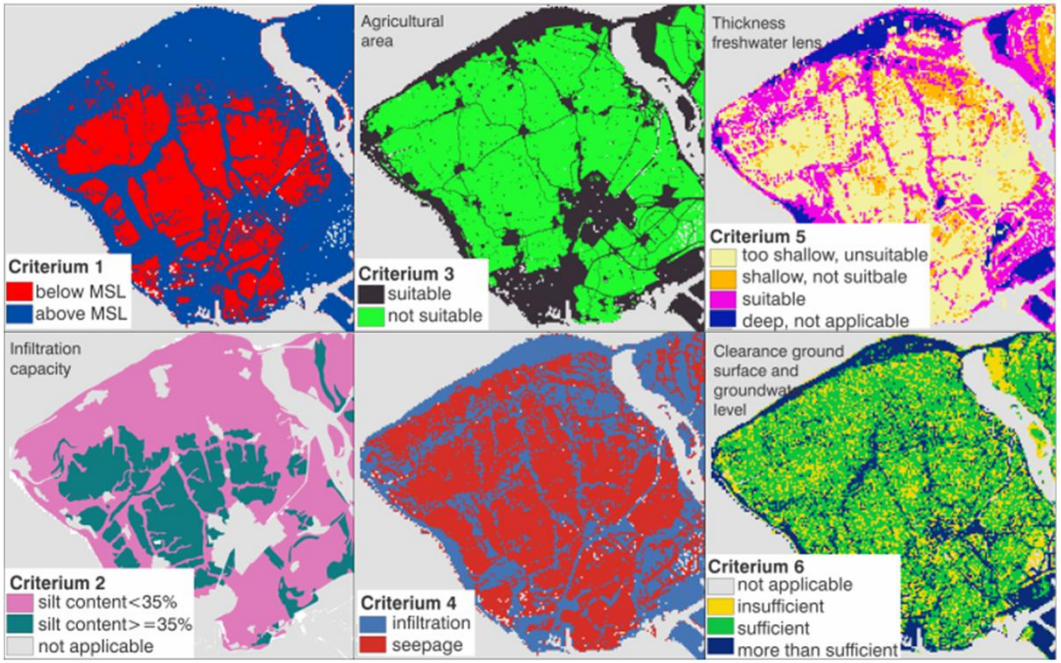
Pilot Creek ridge infiltration

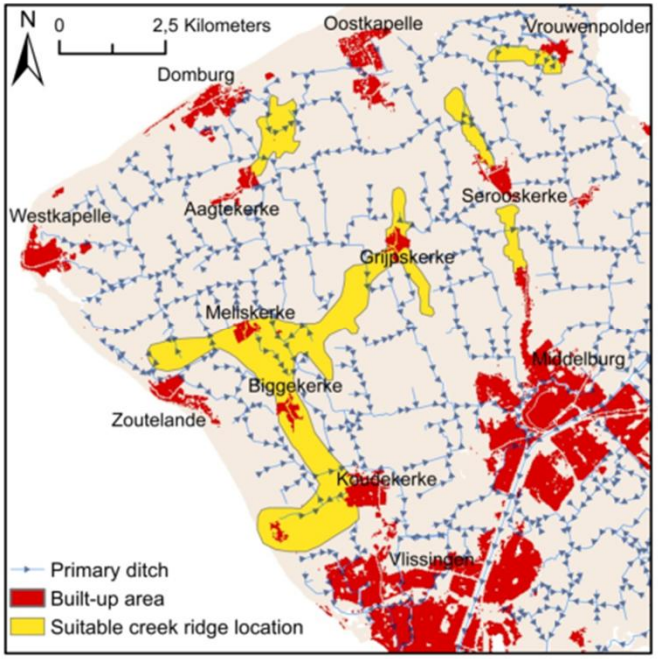






Up-scaling: potential and vulnerability maps at different scales





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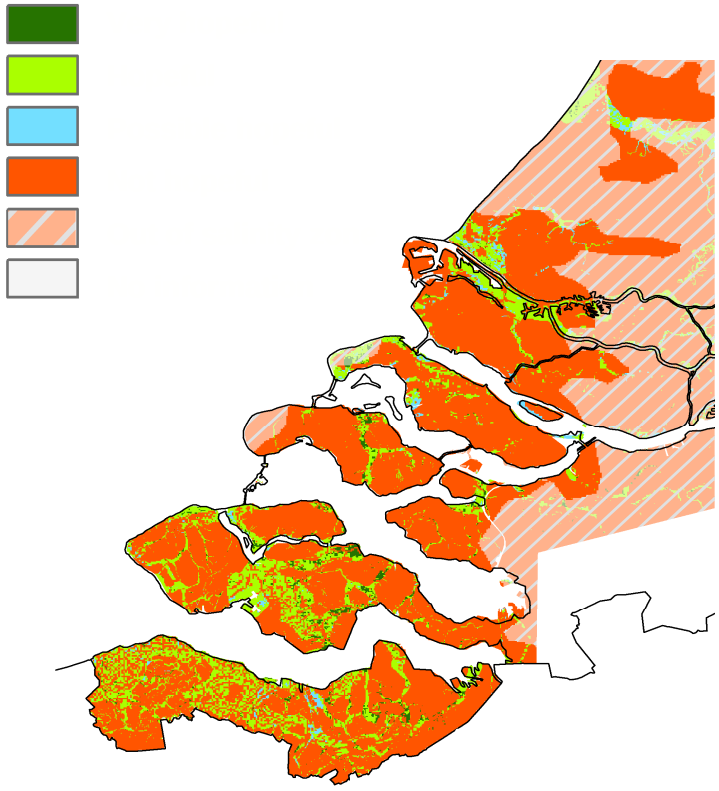
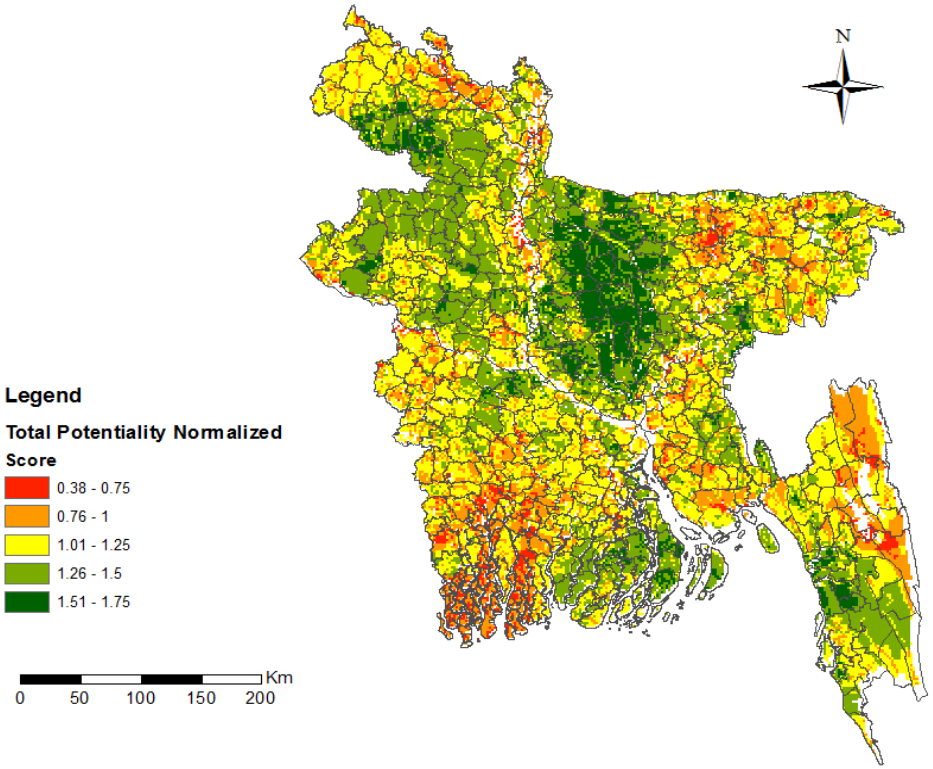
Up-scaling: potential and vulnerability maps at different scales



Creek Ridge Infiltration



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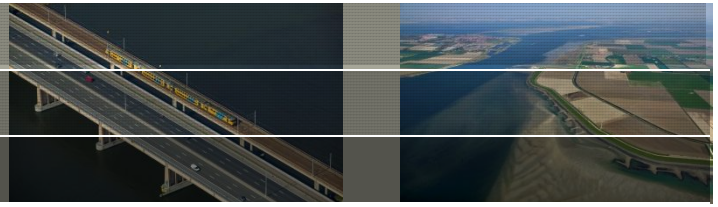

Thank you for your attention!

More information:
freshsalt.deltares.nl

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