Fresh groundwater in the coastal zone

Vulnerability of groundwater systems to flooding events

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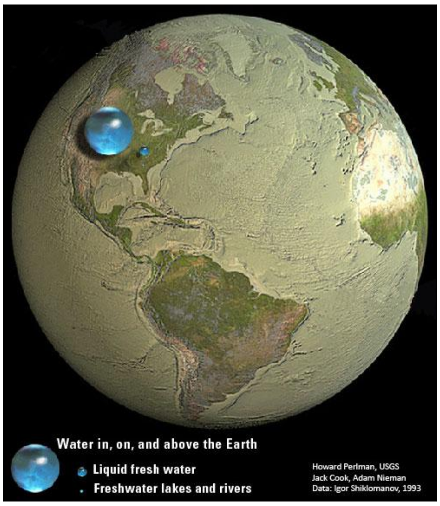
More information:
freshsalt.deltares.nl
zoetzout.deltares.nl

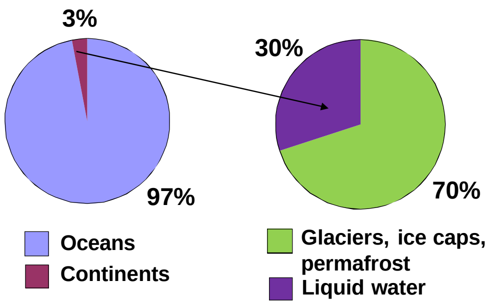
Volumes of water on Earth: a scarce product



Water in/on/above Earth

Liquid fresh water

Freshwater lakes rivers



Source: Perlman, USGS; Shiklomanov, 1993

Fresh groundwater resources in delta's seriously under stress

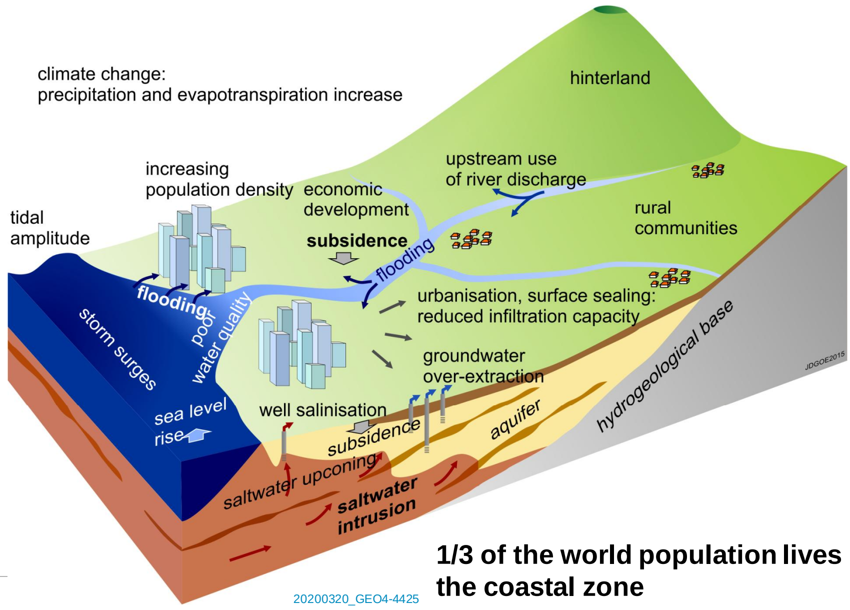
Every year, about 2 million people worldwide die from diarrhea, caused by bad drinking water quality; this is more than people dying from flooding events

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)

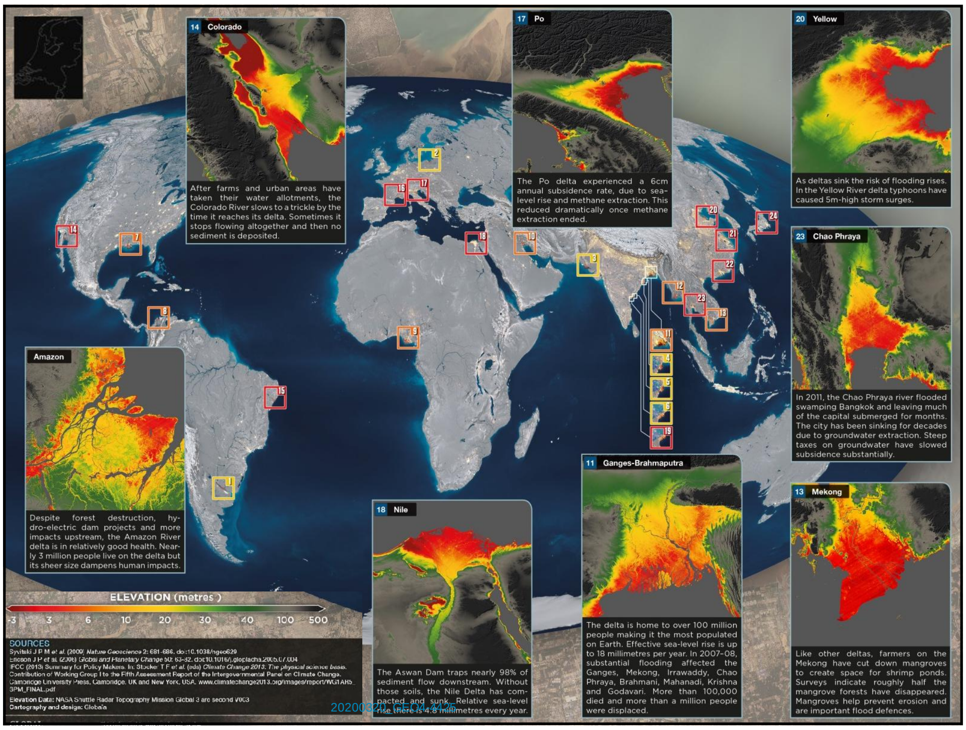
In the future, delta's have to cope which…:

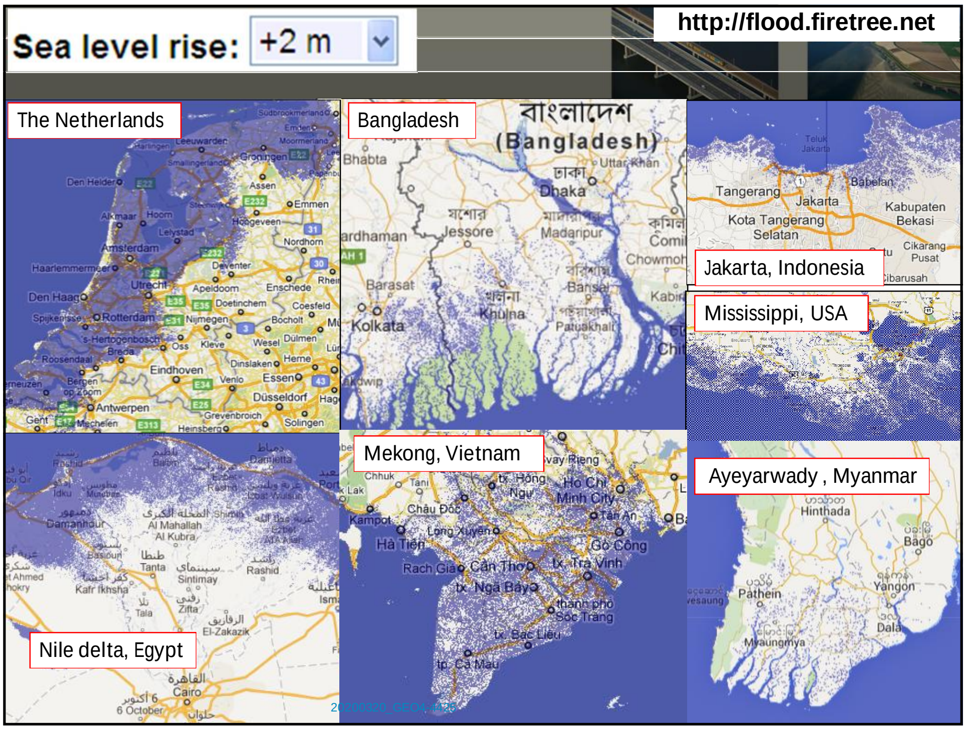
- Climate change and sea-level rise
- Increasing quantities groundwater extractions
- Land subsidence
- Politics, Policy & Watermanagement, affecting land use

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

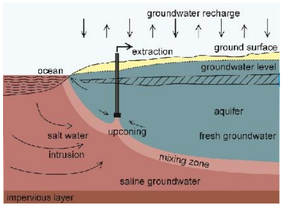


1/3 of the world population lives in the coastal zone

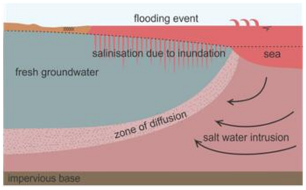

14 Colorado
17 Po
20 Yellow
23 Chao Phraya
Amazon
18 Nile
11 Ganges-Brahmaputra
13 Mekong
ELEVATION (metres)
SOURCES


Sea level rise: +2 m
http://flood.firetree.net
The Netherlands
Bangladesh
Jakarta, Indonesia
Mississippi, USA
Mekong, Vietnam
Ayeyarwady , Myanmar
Nile delta, Egypt

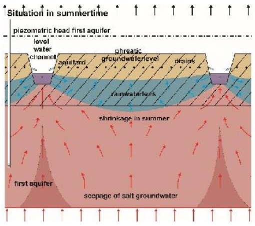
Salinisation processes at local scale



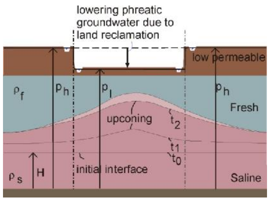
Salt water intrusion groundwater



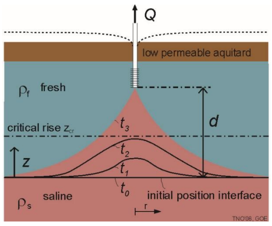
Inundation saline seawater



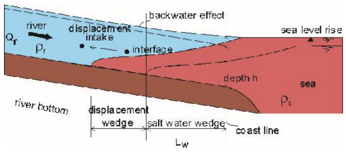
Shallow rainwaterlens



Upconing low-lying area



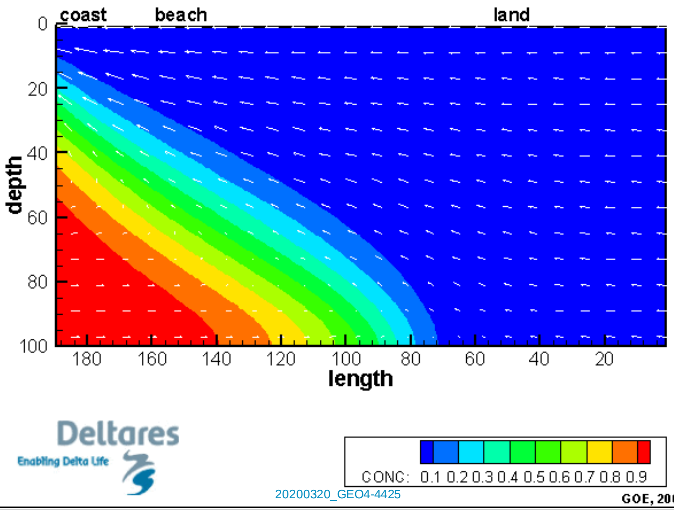
Upconing extraction



Salt water intrusion surface water

Impact of sea level rise on a coastal groundwater system:

a conceptual model of saltwater intrusion



GOE, 2009

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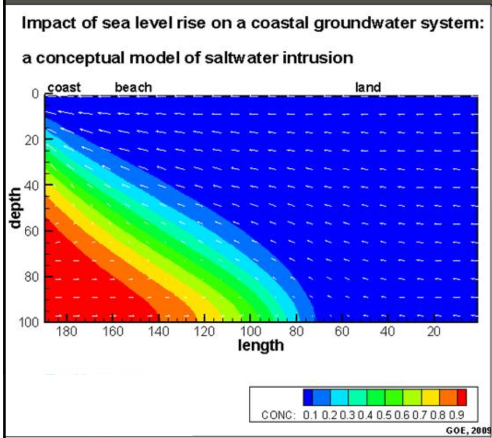
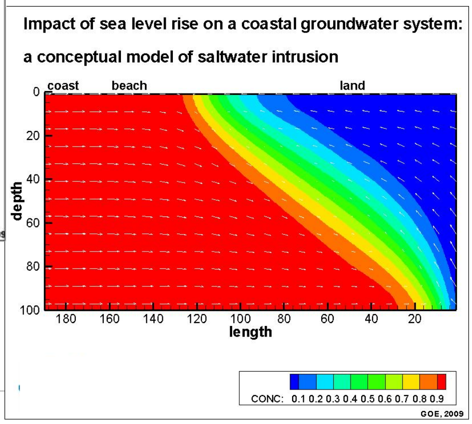
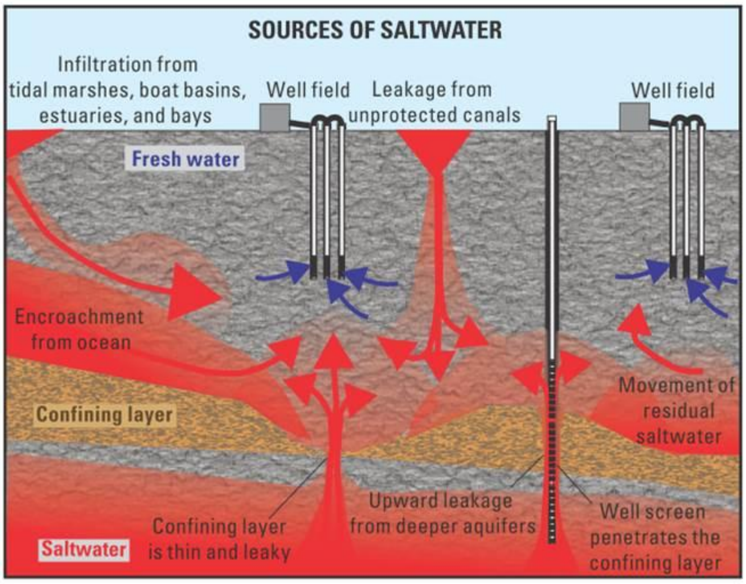
Sea level rise and salt water intrusion





Combining salinization processes coastal zone



Prinos, 2014

In 1 liter ocean: about 35 gr salt

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

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

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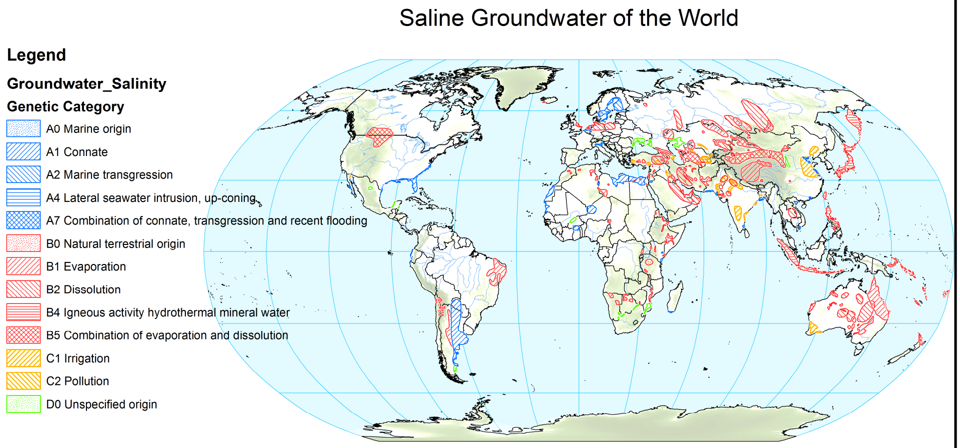
Rice can grow well in water with a salt content less than about 2.0 gr salt in 1 liter water

Stress 1: there is salt everywhere



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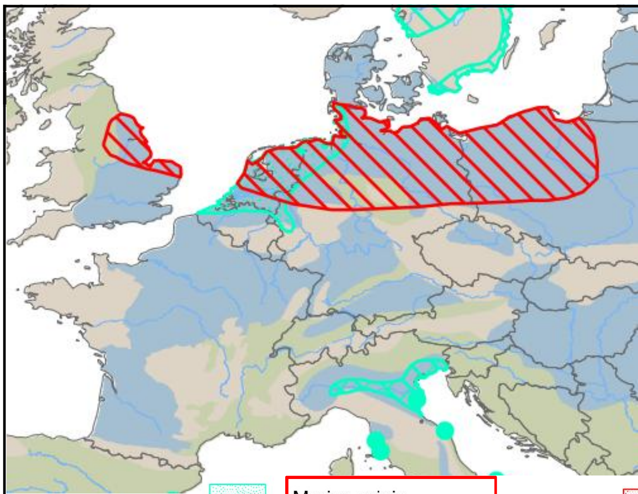


Marine origin

Connate

Marine transgression

Lateral seawater intrusion & up-coning

Combination of connate, transgression and current flooding

Natural terrestrial origin

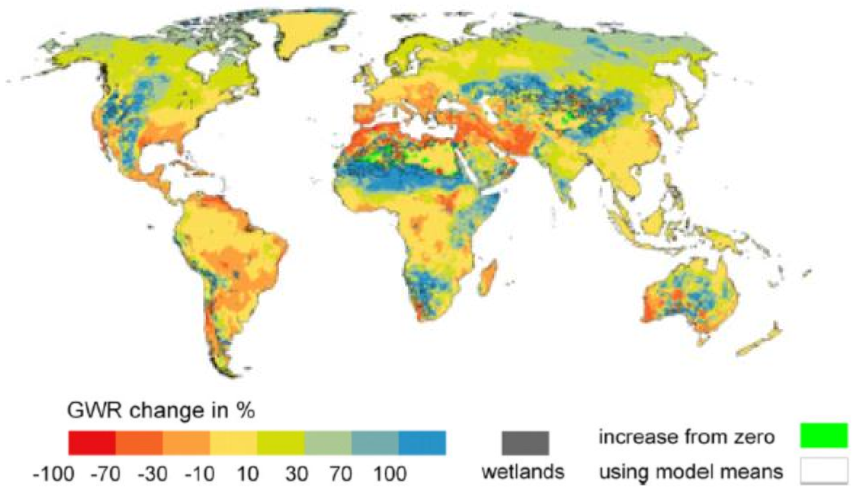
Evaporation

Dissolution

Igneous activity hydrothermal mineral water

Combination of evaporation & dissolution

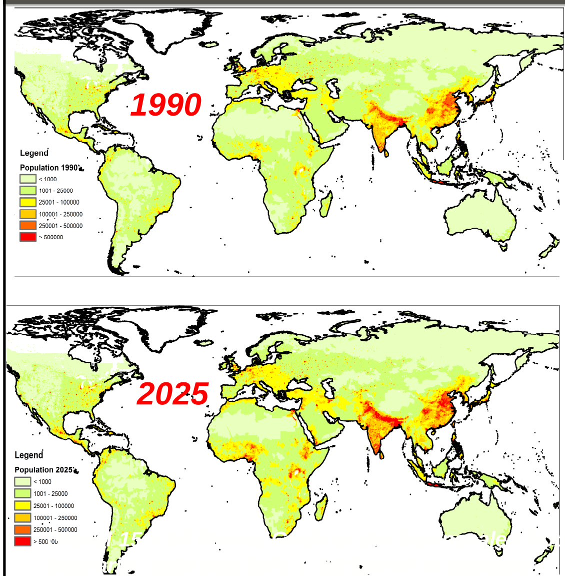
Stress 2: Change in groundwater recharge by end of century

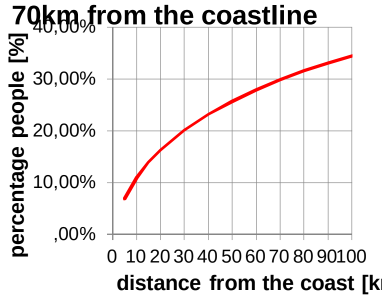


Projected percent changes of groundwater recharge by the end of this century with respect to present (1971–2000)
WaterGAP model with five different GCMs for RCP8.5

Portmann et al, 2013, ERL
From: Wada

Stress 3: Population growth 1990-2025, needing water





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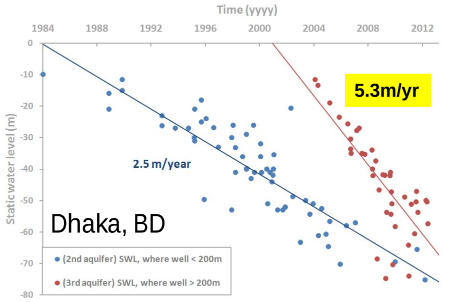
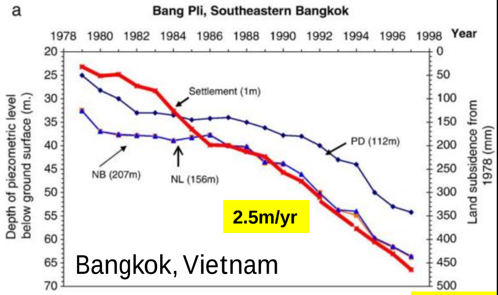
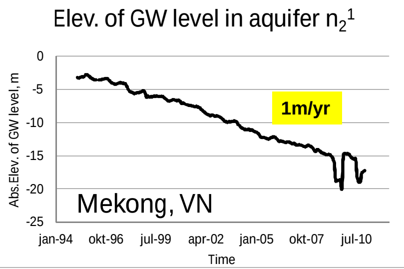
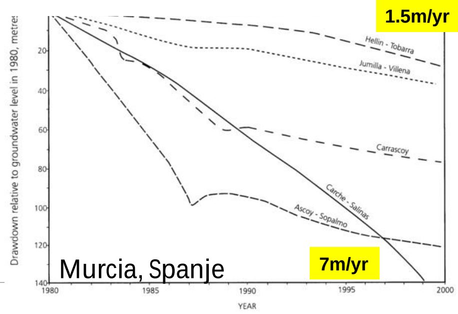
Stress 4: Serious overexploitation coastal aquifers worldwide









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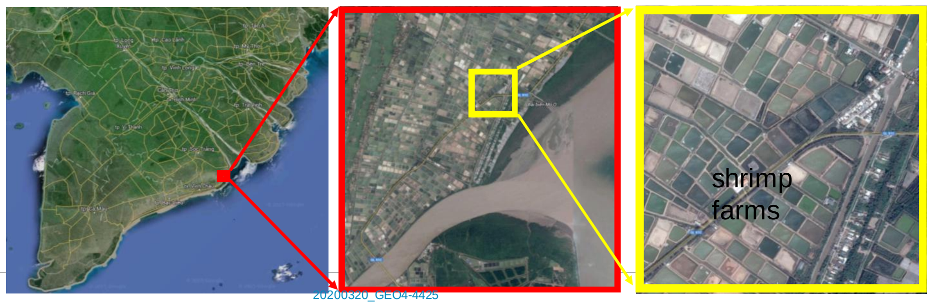
Groundwater overexploitation in Mekong Delta

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



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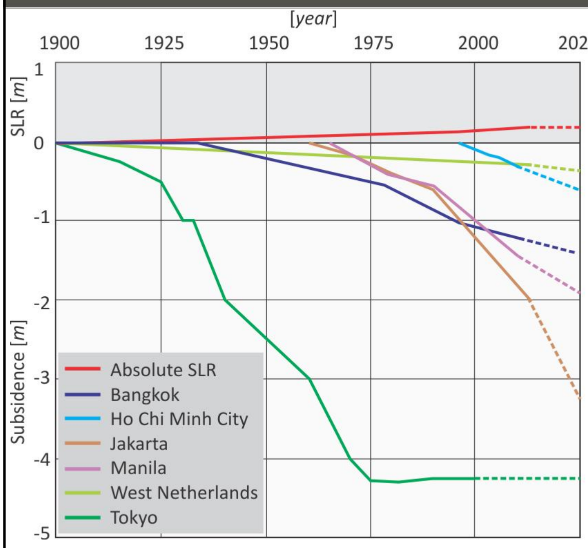
Stress 5: Land subsidence in some major coastal cities



Relative SLR Tokyo is 4.5 m

Subsidence issues are underestimated

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Land subsidence San Joachim Valley, CA, USA

9 m since 1930s

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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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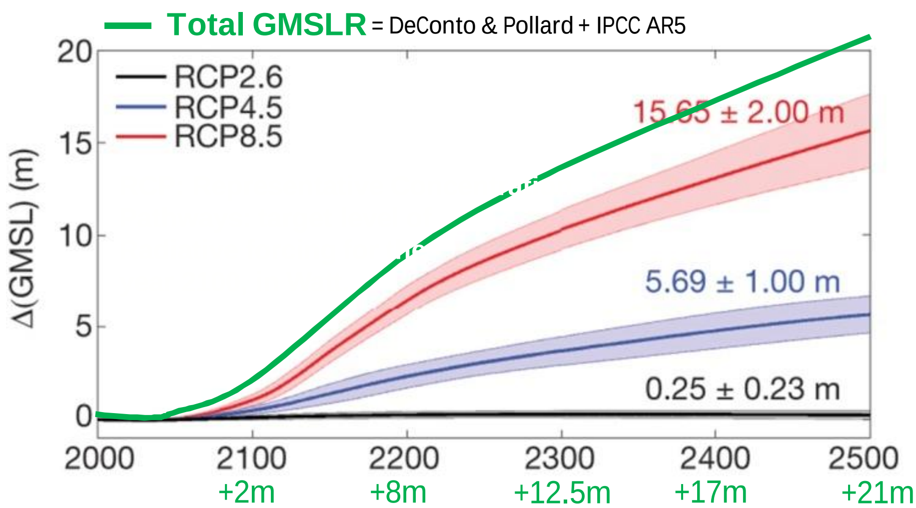
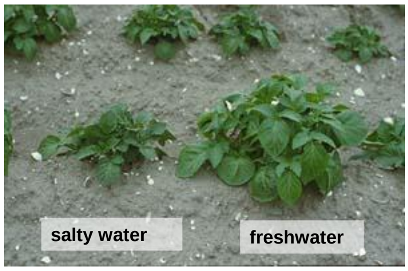
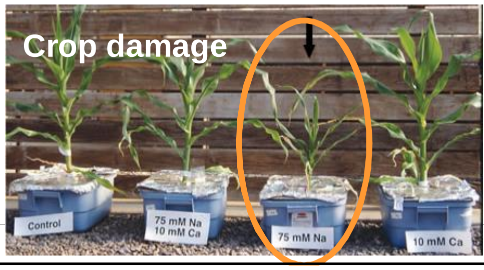
Stress 6: Global Mean Sea Level Rise (GMSL)



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

Salt in water is a problem





Salt in water is a problem

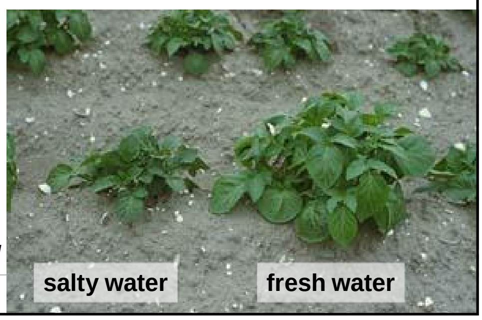
-drinking water:
- taste (100-300 mg Cl-/l)
- long term health effect
- norm: EC& WHO=150 mg Cl-/l (live stock=1500 mg Cl-/l)

-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



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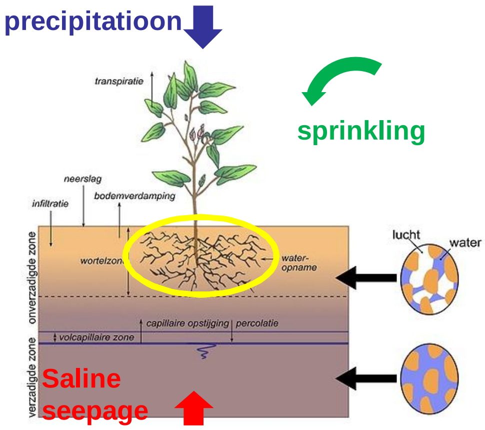
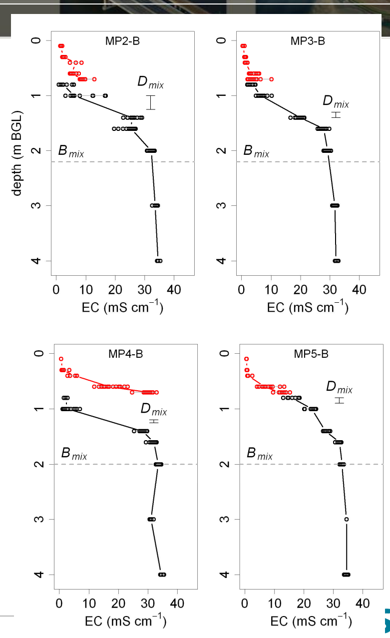
Salt tolerance crops



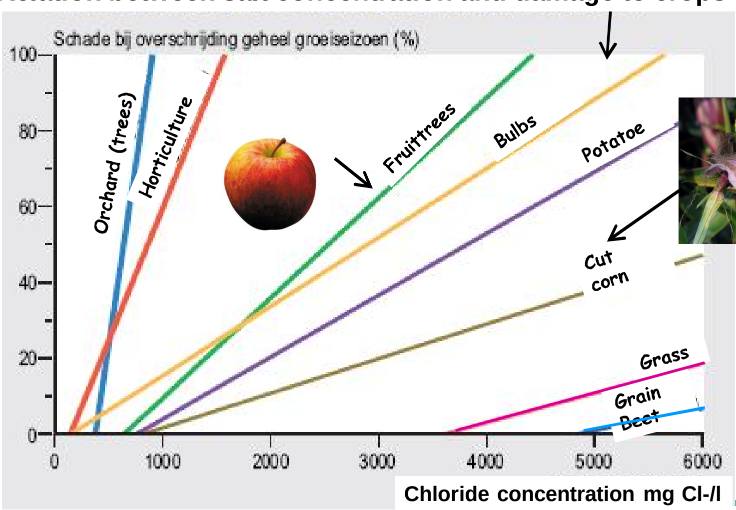


Important parameters:

- **Chloride concentration root zone**
- **Land use**
- **Sensitivity crops**

Salt damage to crops

Relation between salt concentration and damage to crops



Source: MNP, 2005

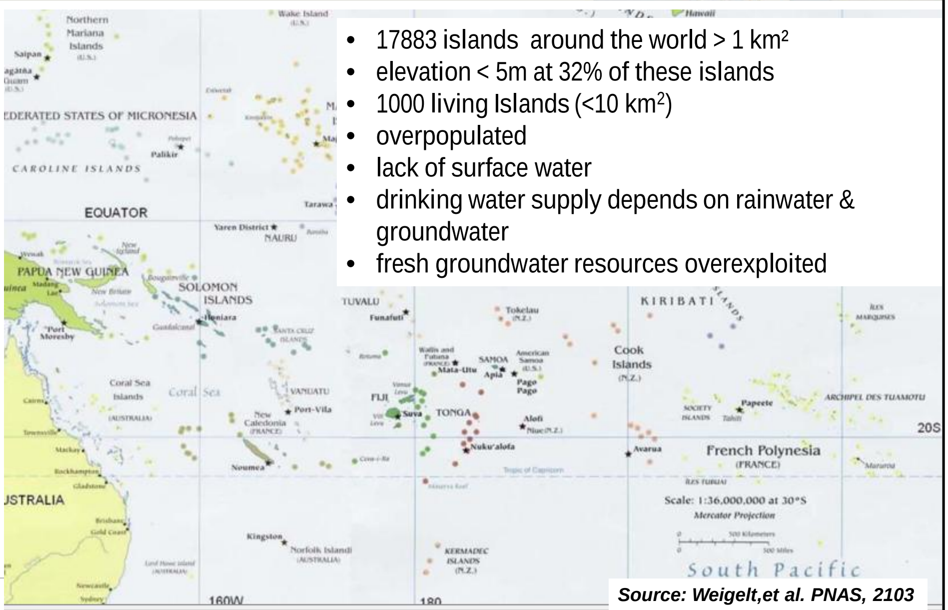
Definition of fresh and saline groundwater

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	

Fresh groundwater resources in SIDS under climate and global stresses

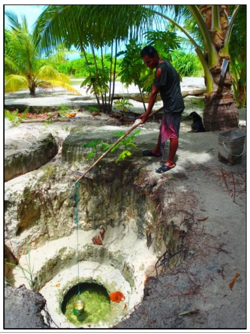
Facts SIDS: small island developing states in Pacific

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



Source: Weigelt,et al. PNAS, 2103

Water resources at SIDS



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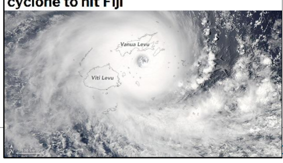
Headlines: SIDS / Water Resources / Climate Change

Before we drown
we may die of thirst

Obama declares disaster as Marshall Islands suffers worst-ever drought

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

Winston the strongest, first Category 5 cyclone to hit Fiji



1907 (Vanuatu) (most likely 1905-1906)
'Emau – we are having a very long drought here and in much need of rain to water the ground...The Emau people have no water either to drink or cook food with, and are boating over from Efate. The coconut trees are ceasing to bear, and some of them are dying....'
The New Hebrides Magazine January 1907 and August 1908.

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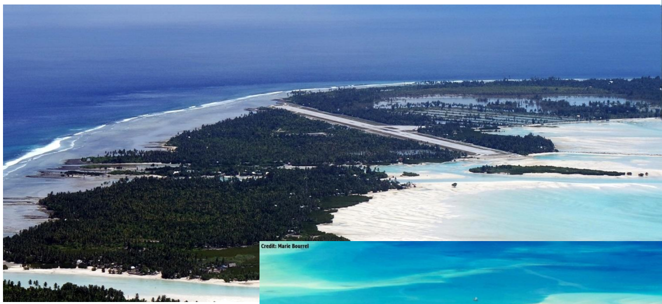
Case Kiribati: fresh water supply



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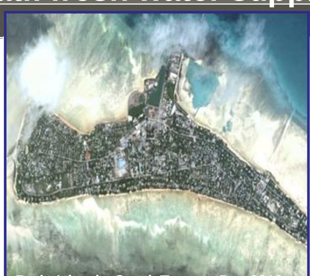
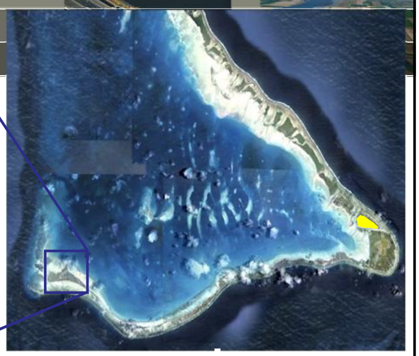
Case Kiribati: fresh water supply



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



Today

38 litres per person per day

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

~50%

Supply system losses

Current estimates of leakages and losses in transmission

~2 x

More people

Potential population increase at current growth rates

>5%

Climate impact

Potential climate change impact on sustainable yield over 20 year period

2035

<9 litres per person per day

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

Source: Hebblethwaite, D. (2015)

The challenge

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

Anote Tong President of Kiribati

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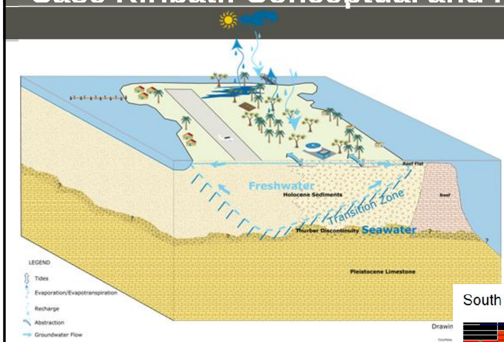
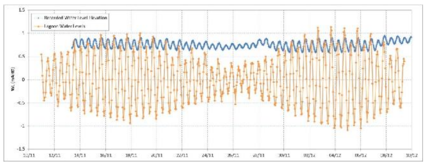
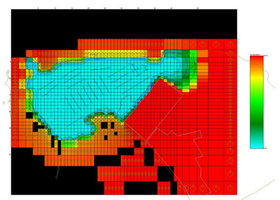
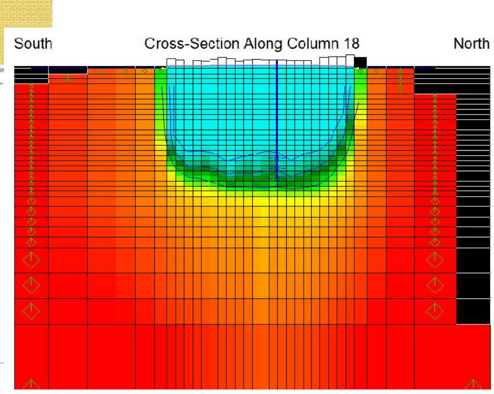
Case Kiribati: Conceptual and numerical modelling tools

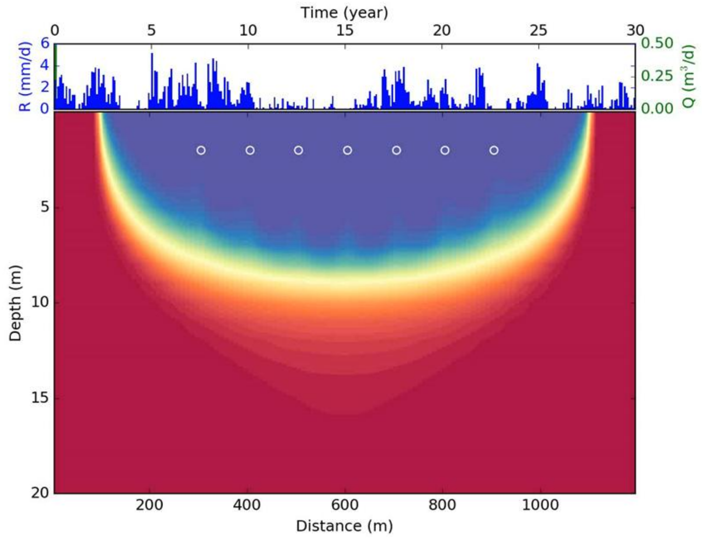




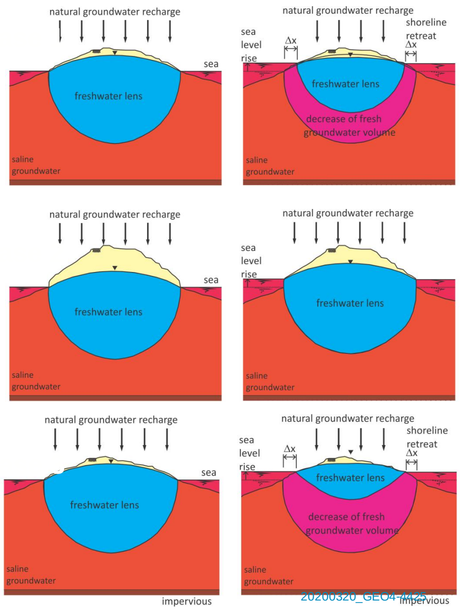




Case Kiribati: Numerical modelling tools



Stresses to fresh groundwater lenses



Case Kiribati: Understanding the groundwater system

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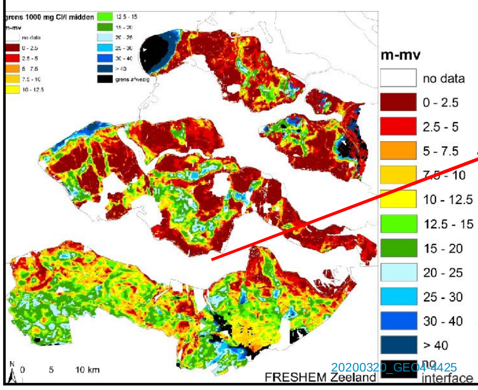
Mapping the salinity distribution

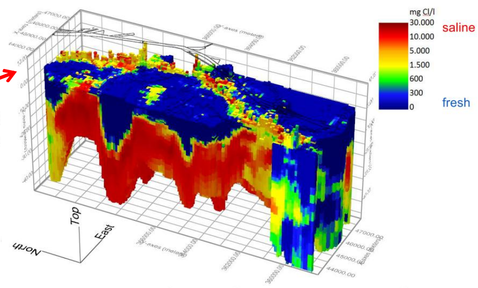
TNO innovation for life

BGR

Deltares Enabling Delta Life



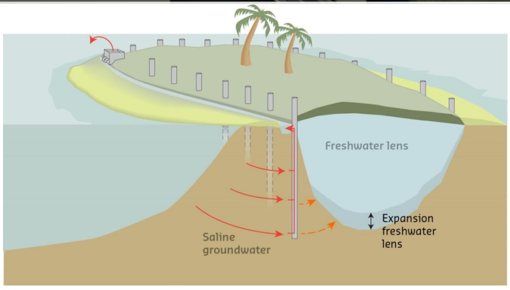
FRESHEM Zeeland

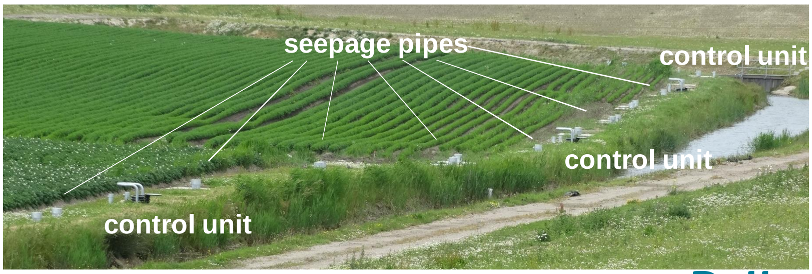


FRESHEM pilot Canal zone, visualization in iMOD

Seepage systems

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





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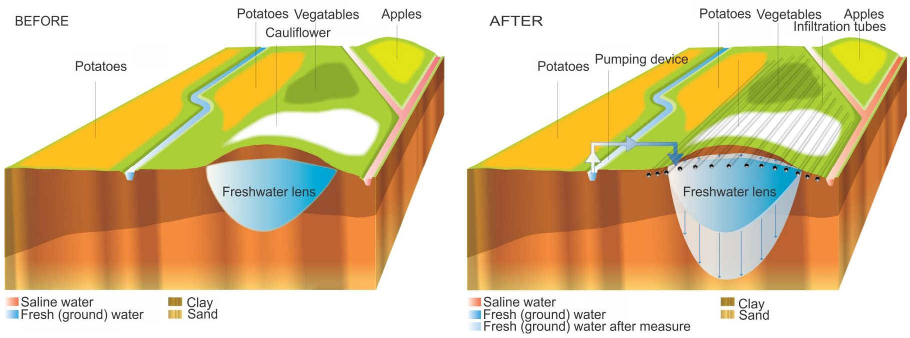
ASR / MAR

Aquifer Storage and Recovery / Managed Aquifer Recharge



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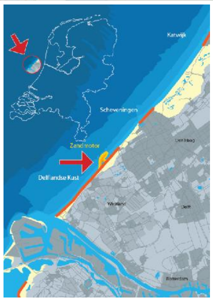
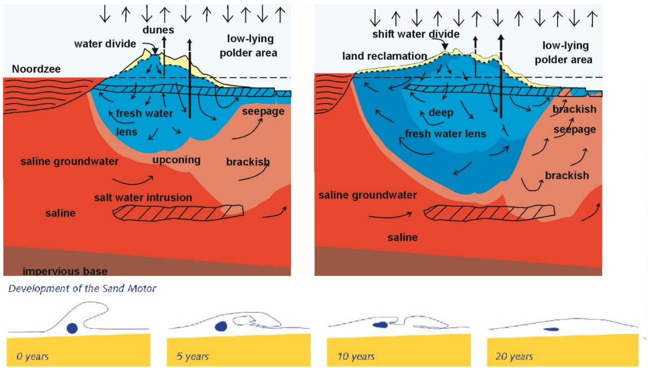
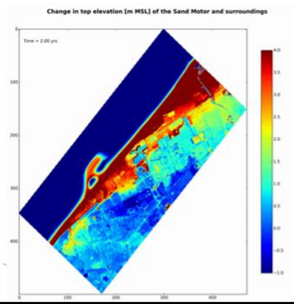
Increase strategic freshwater reservoirs in the coastal zone

NatureCoast, Building with Nature, De Zandmotor







Salt resistant crops on salinized soils

MEIJER FOR SURE

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[1]

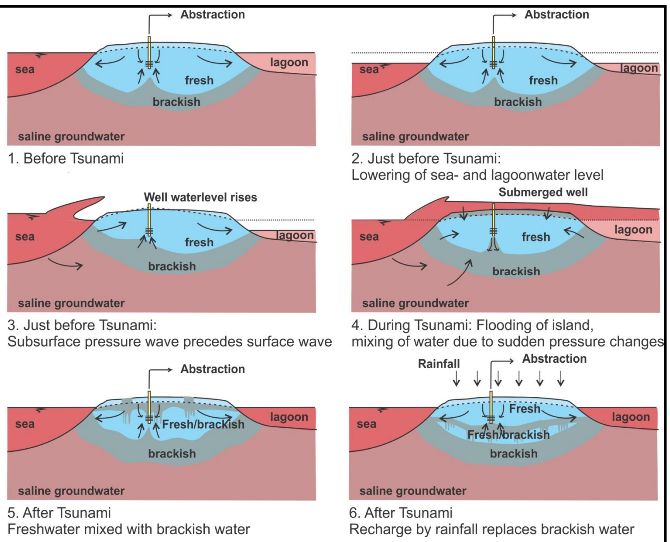
Global Quick Scan of the Vulnerability of Groundwater systems to Tsunamis*

**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*



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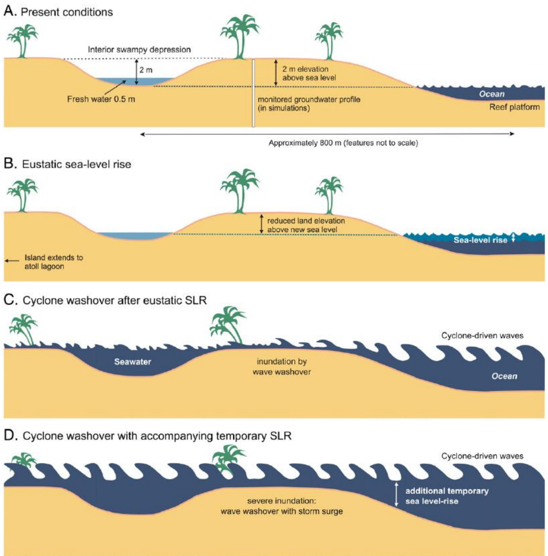
The fate of freshwater lenses on atoll islands



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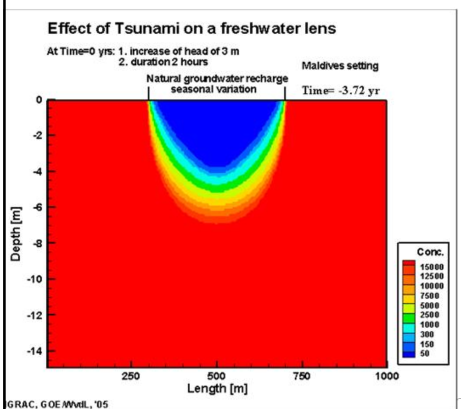
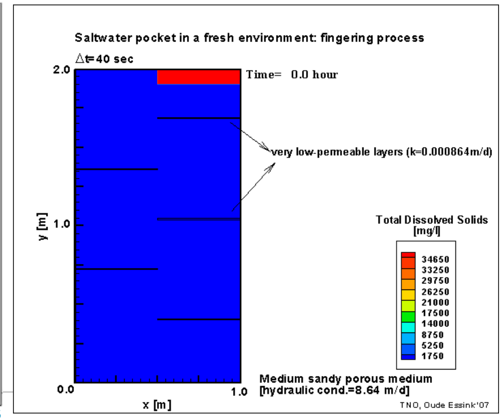
Salinisation processes of fresh groundwater reserves

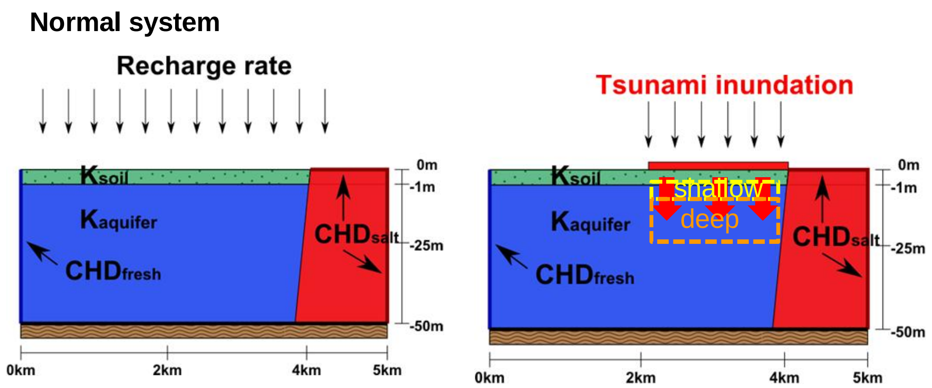
Impression of relevant salinisation processes in coastal aquifers:

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



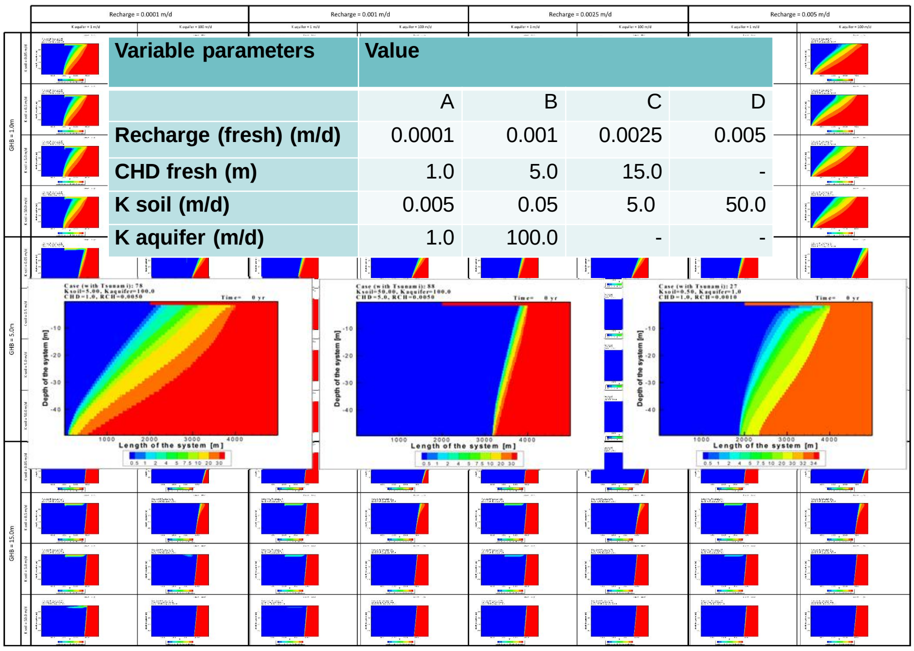


Concept 2D modelling variable-density groundwater flow and coupled salt transport



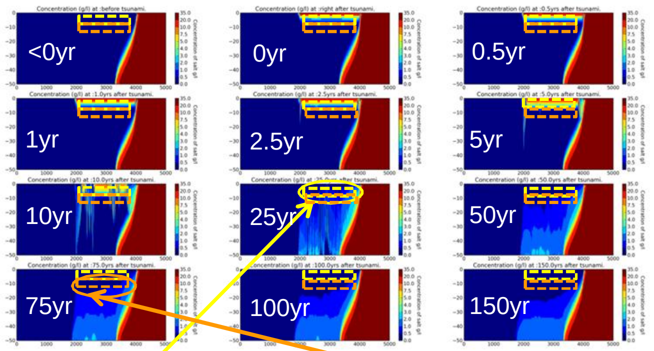
- Focus on coastal *deep* and *shallow* fresh groundwater resources
- How long does it takes before the groundwater system is fresh again, available for groundwater extractions?

Deltares

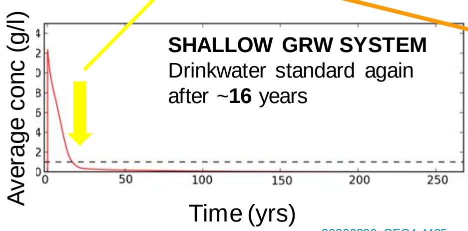


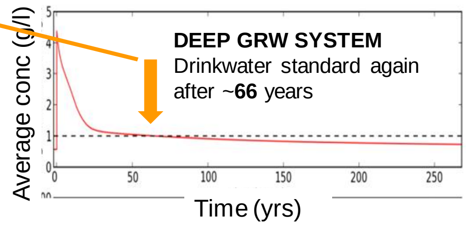
Variable parameters	Value			
	A	B	C	D
Recharge (fresh) (m/d)	0.0001	0.001	0.0025	0.005
CHD fresh (m)	1.0	5.0	15.0	-
K soil (m/d)	0.005	0.05	5.0	50.0
K aquifer (m/d)	1.0	100.0	-	-

Results of one case



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



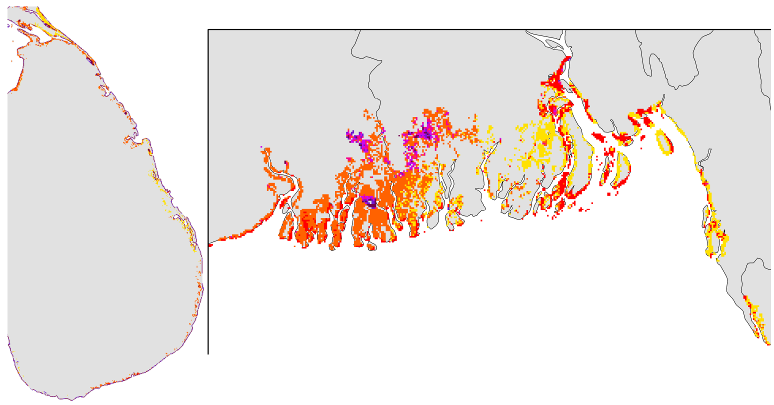


Mapping the results

- 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

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



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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

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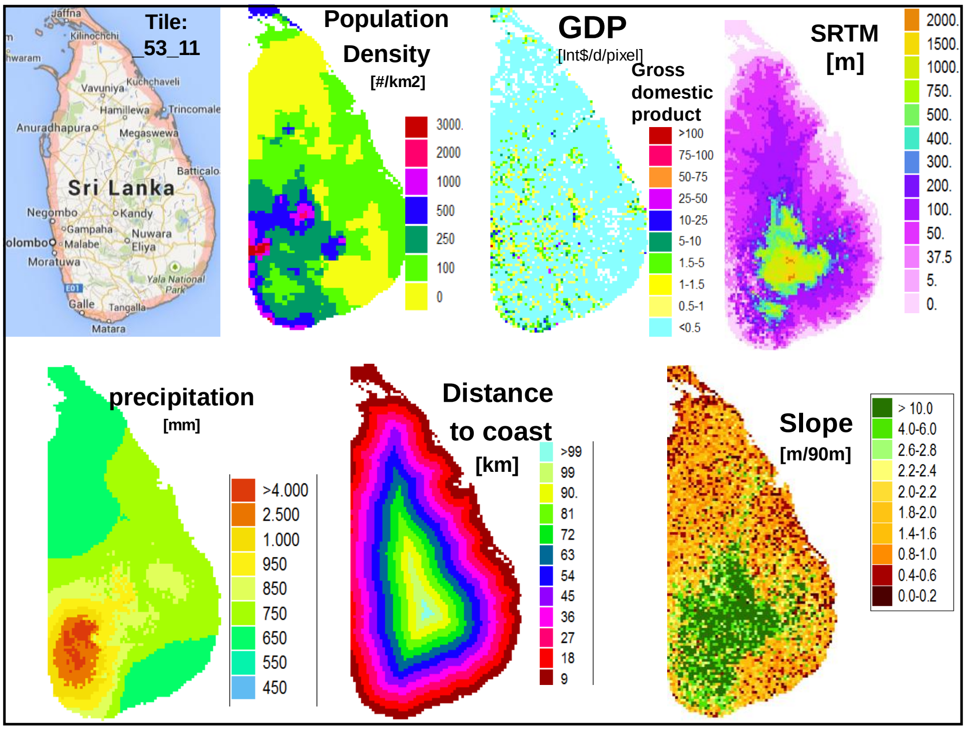

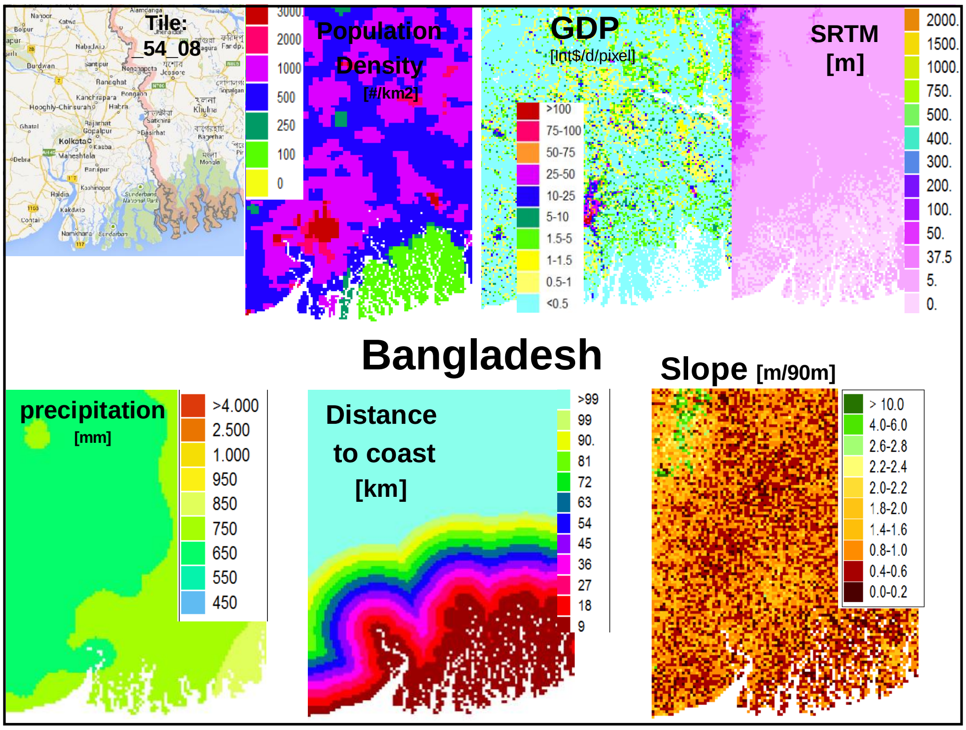

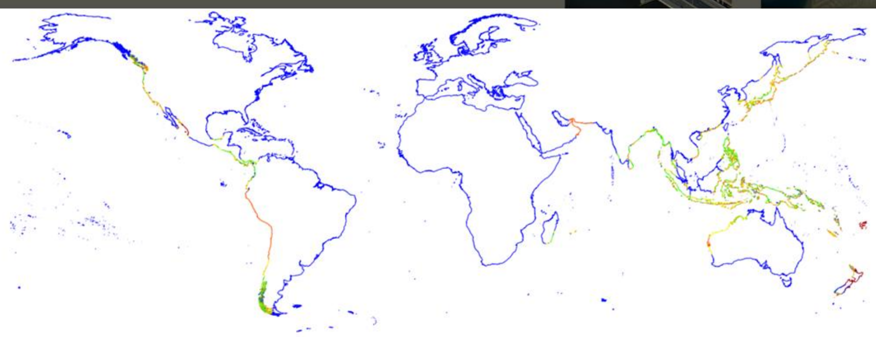

Vulnerability of groundwater aquifers to tsunami effects, evaluated as time (yrs.) necessary for aquifer to reach 95% fresh-water distribution of pre-tsunami state, indicating drinking water availability using groundwater resources in coastal zones after flooding disasters

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Concluding

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

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Hydraulic conductivity (m/day)

Geological classification	K
clay	10^{-8} - 10^{-2}
fine sand	1 - 5
medium sand	5 - 20
coarse sand	20 - 100
gravel	100 - 1000
sand and gravel mixes	5 - 100
clay, sand, gravel mixes (till)	10^{-3} - 10^{-1}
sandstone, carbonate rock	10^{-3} - 10^{0}
shale	10^{-7}
dense solid rock	< 10^{-5}
fractured or weathered rock (core samples)	almost 0 - 3.10^{2}
volcanic rock	almost 0 - 1.10^{3}

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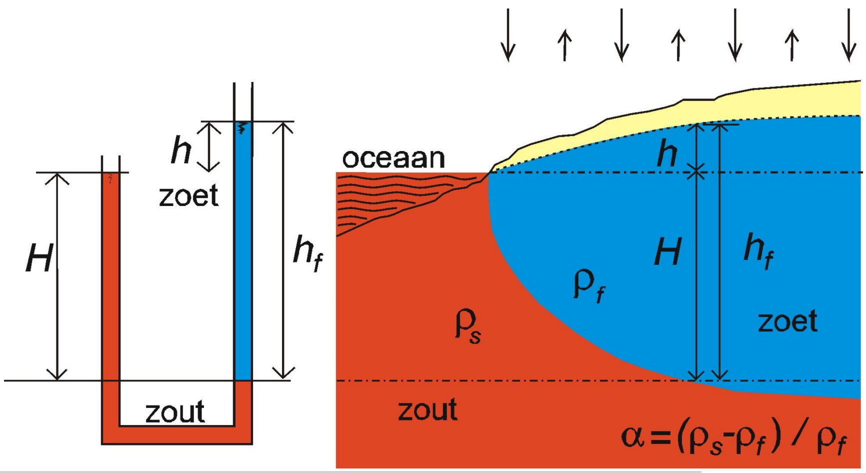
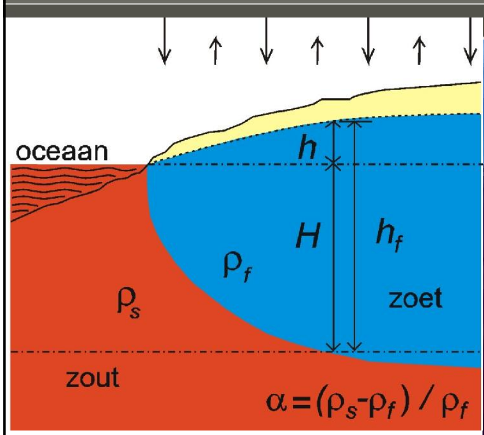
Badon Ghijben-Herzberg principle

The principle suggests an interface between fresh and saline groundwater

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



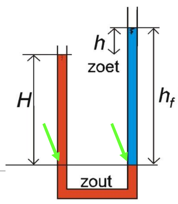


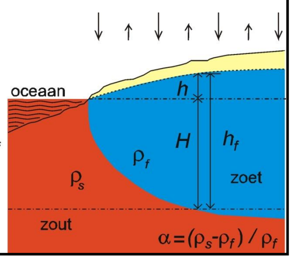
pressure saline groundwater=pressure fresh groundwater

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

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

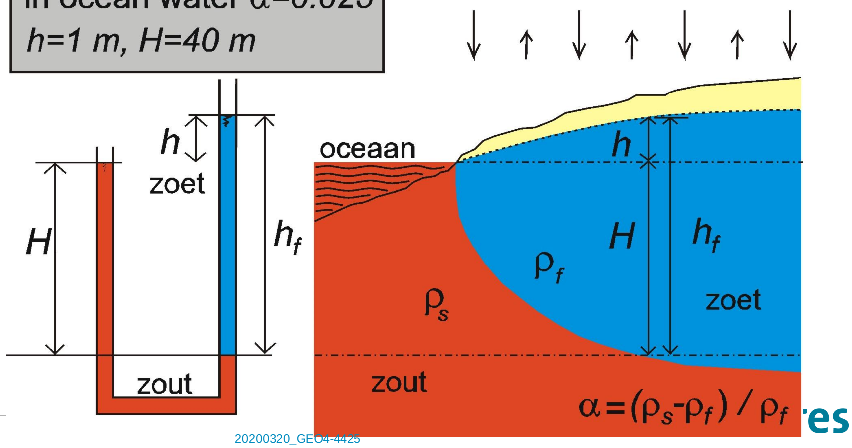
$$h = \alpha H$$





$$h = \alpha H$$

h=αH
in ocean water α=*0.025*
h=1 m, H=40 m



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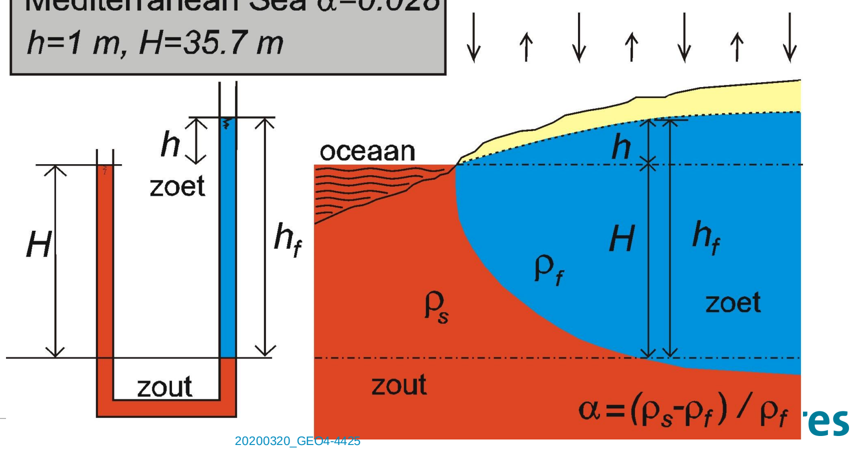
$$h = \alpha H$$

h=αH
Mediterranean Sea α=*0.028*
h=1 m, H=35.7 m



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Badon Ghyben-Herzberg principle

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

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

Badon Ghyben-Herzberg principle

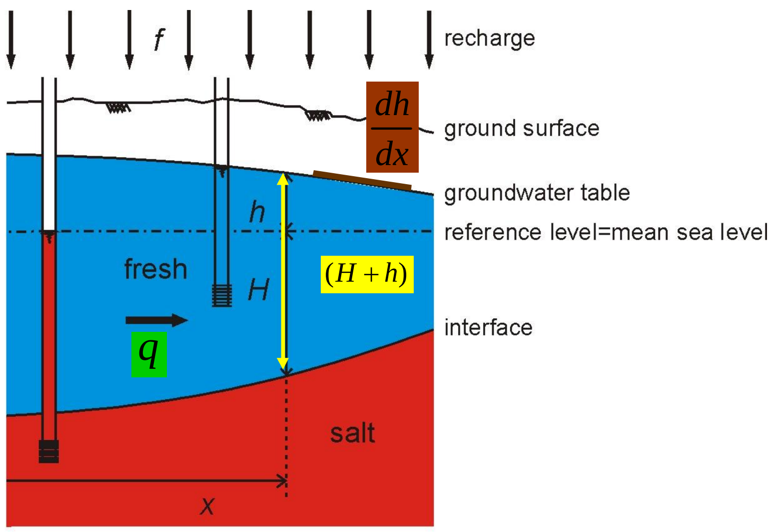
What is the case then $h \neq \alpha H$?

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

Analytical solutions

Deltares

Unconfined aquifer (1D situation)



Unconfined aquifer (1D situation)

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

(II) Continuity $dq = f dx$

(III) BGH $h = \alpha H$

Unconfined aquifer (1D situation)

$dq = f dx$ integration gives $q = fx + C1$

$$-k(H+h)\frac{dh}{dx} = fx + C1$$

$$h = \alpha H \quad \rightarrow \quad -k(H+\alpha H)\alpha \frac{dH}{dx} = fx + C1$$

$$HdH = -\frac{fx + C1}{k\alpha(1+\alpha)}dx$$

Unconfined aquifer (1D situation)

$$HdH = -\frac{fx + C1}{k\alpha(1+\alpha)}dx$$

integration
gives

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

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

Unconfined aquifer (1D situation)

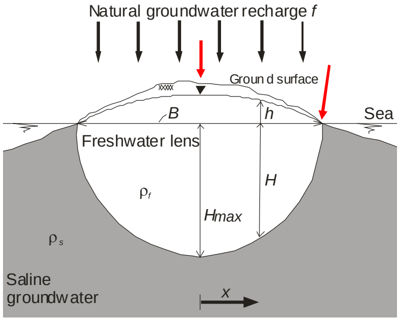
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}}$$

$$h = \alpha H$$

$$q = fx + C1$$

Example 1: Elongated island

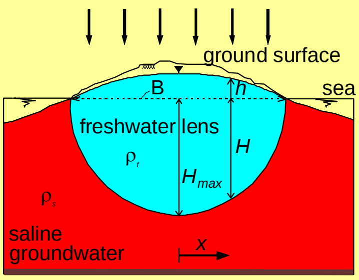
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}} \qquad q = fx + C1$$



Boundary conditions

$$x = 0 : q = 0 \rightarrow C1 = 0$$
$$x = 0.5B : H = 0 \rightarrow C2 = fB^2/8$$

Example of analytical solutions (I)



Depth of fresh-saline interface H

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

$$h = \alpha H$$

Maximal thickness lens

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

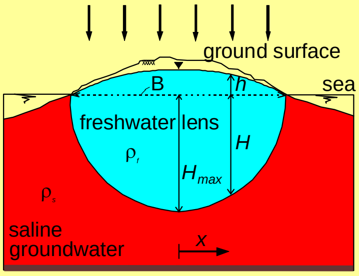
Volume lens

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

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

Lecture notes p. 32

Example of analytical solutions (II)



Depth of fresh-saline interface H

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

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

$$n_e = 0.35$$

Maximal thickness lens

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

Volume lens (wrong in lectures notes)

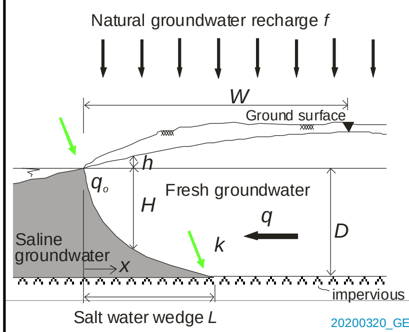
$$V = 35203\text{m}^3/\text{m}'$$

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

Lecture notes p. 32

Example 2: salt water wedge

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



Boundary conditions

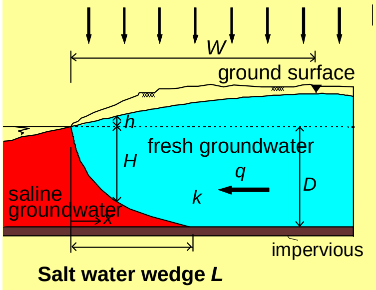
$$x = 0 : q = q_0 \rightarrow q_0 = -fW \rightarrow C1 = q_0$$

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

Length of salt water wedge

$$x = L : H = D$$

Example of analytical solutions (II)



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

$$q_0 = -fW$$

$$h = \alpha H$$

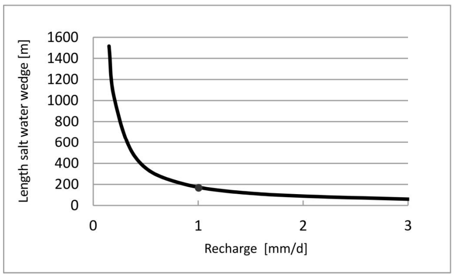
Example:

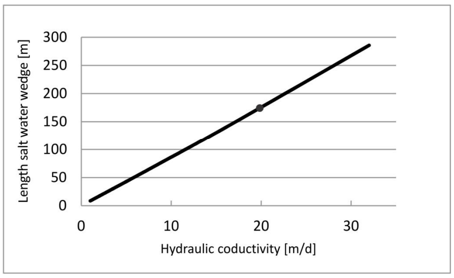
$$W = 3000\text{m}, f = 0.001\text{m/day}, \alpha = 0.020, k = 20\text{m/day}, D = 50\text{m}$$

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

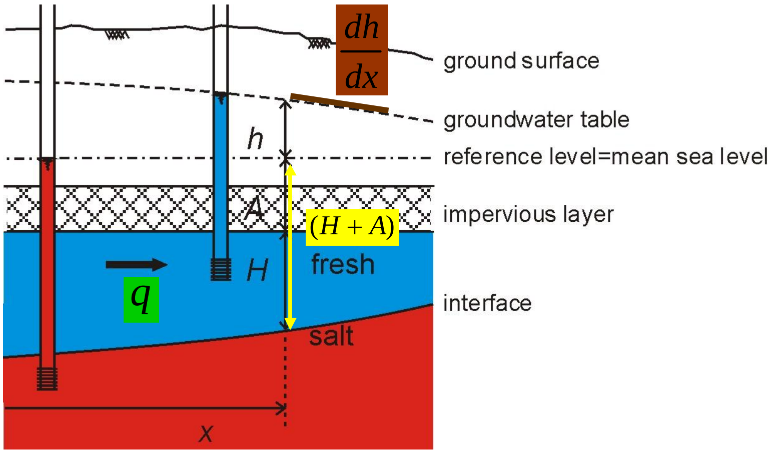
Lecture notes p. 33

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





Confined aquifer (1D situation)



Confined aquifer (1D situation)

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

(II) Continuity $$q = q_o$$

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

Confined aquifer (1D situation)

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

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

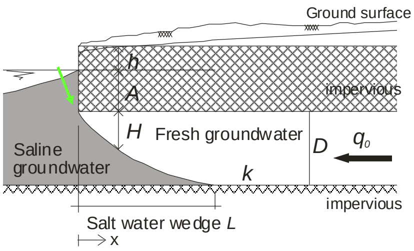
integration gives

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

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

Example 3: salt water wedge confined aquifer

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



Boundary condition

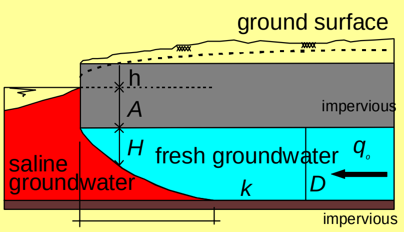
$$x = 0 : H = 0 \rightarrow C = 0$$

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

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

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

Example of analytical solutions (III)



Salt water wedge L

Length of salt water wedge

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

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

Example:

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

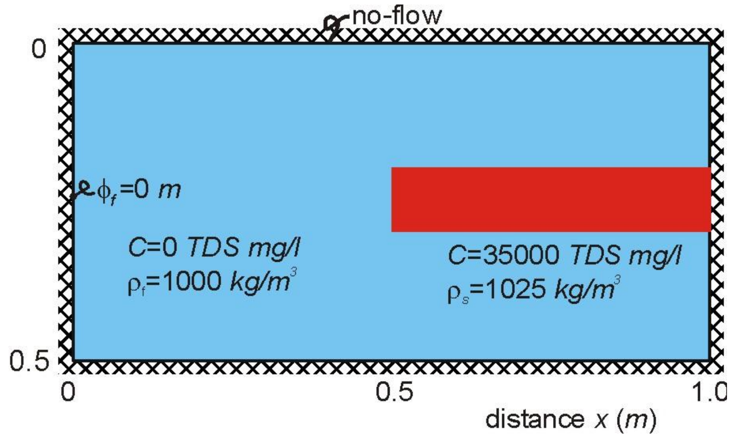
$$L = 250\text{m}$$

Lecture notes p. 35-36

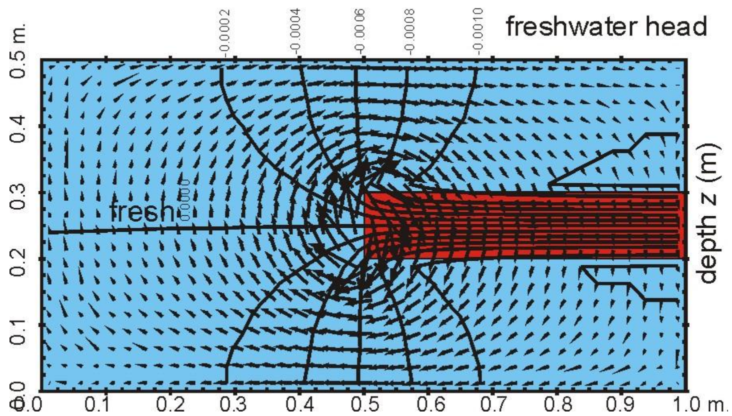
Thank you for your attention!

More information:
freshsalt.deltares.nl

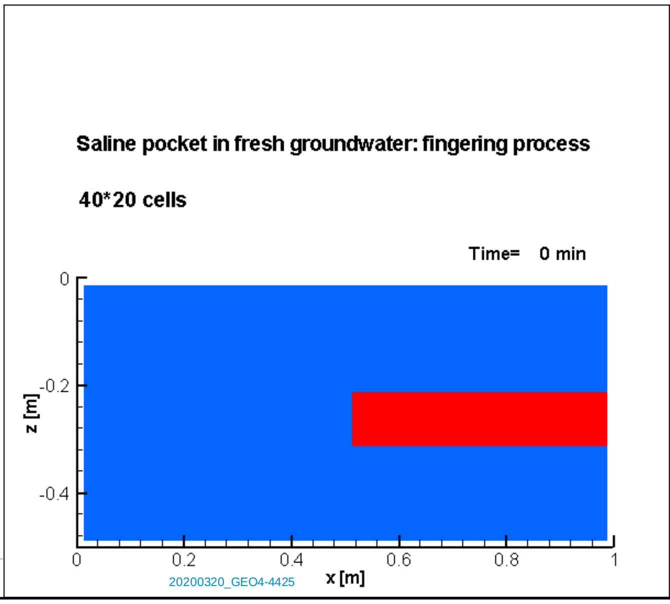
Effect of size model cell on physical process



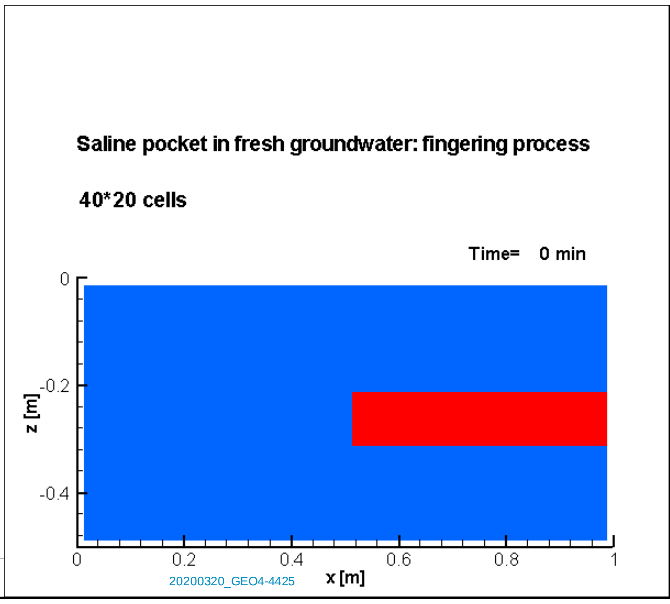
Effect of size model cell on physical process



SALT WATER POCKET IN A FRESH ENVIRONMENT



SALT WATER POCKET IN A FRESH ENVIRONMENT

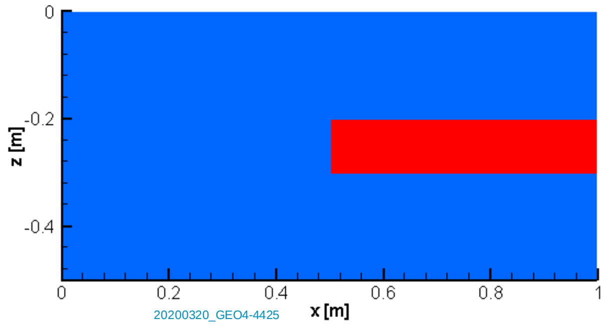


SALT WATER POCKET IN A FRESH ENVIRONMENT

Saline pocket in fresh groundwater: fingering process

320*160 cells

Time= 0 min



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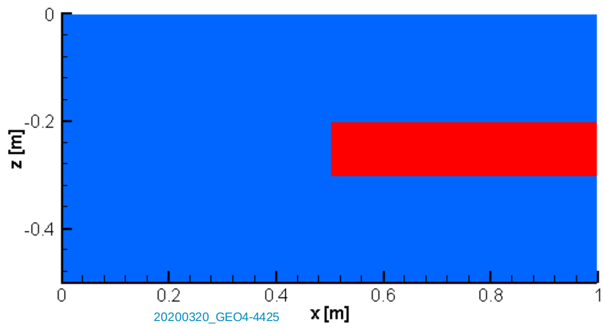
SALT WATER POCKET IN A FRESH ENVIRONMENT

Saline pocket in fresh groundwater: fingering process

320*160 cells

Time= 0 min



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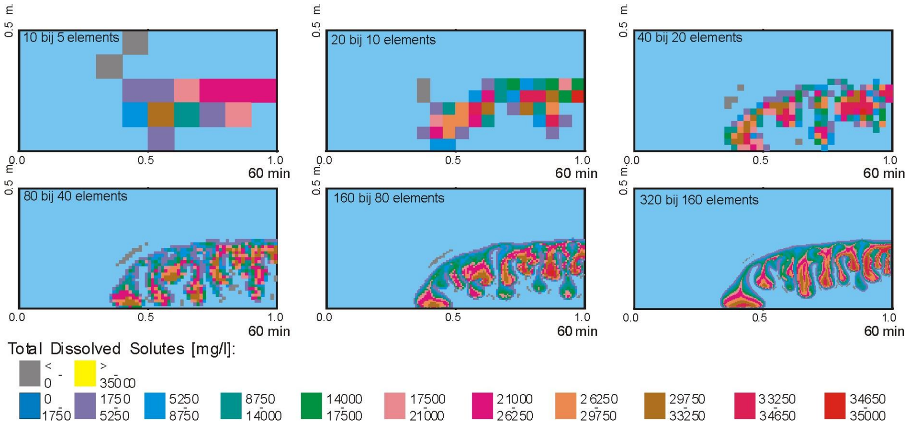
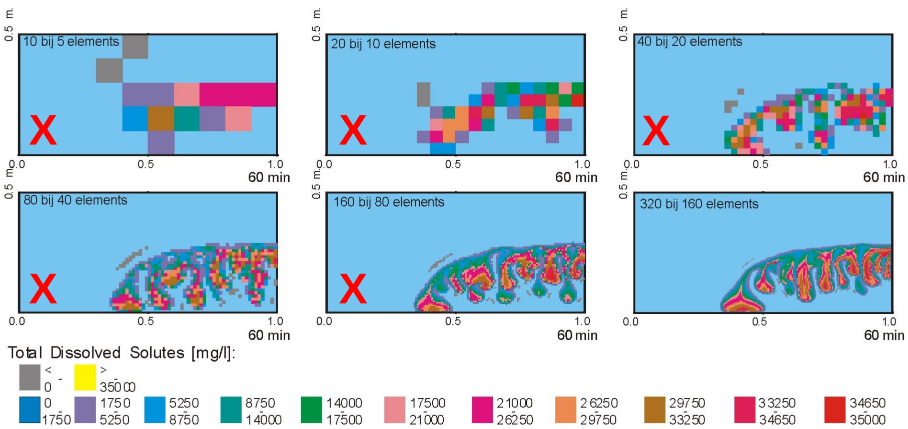
Effect of model cell size on physical process



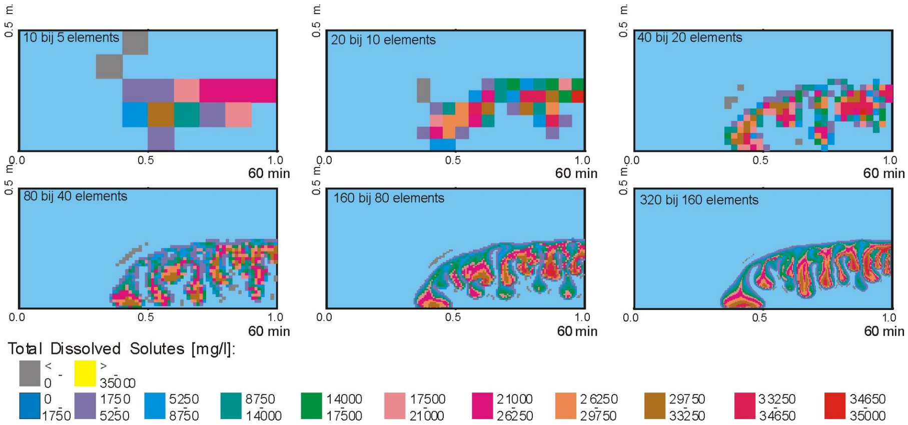
Model size cell has a **large** effect on modelling result!

Effect of size model cell on physical process



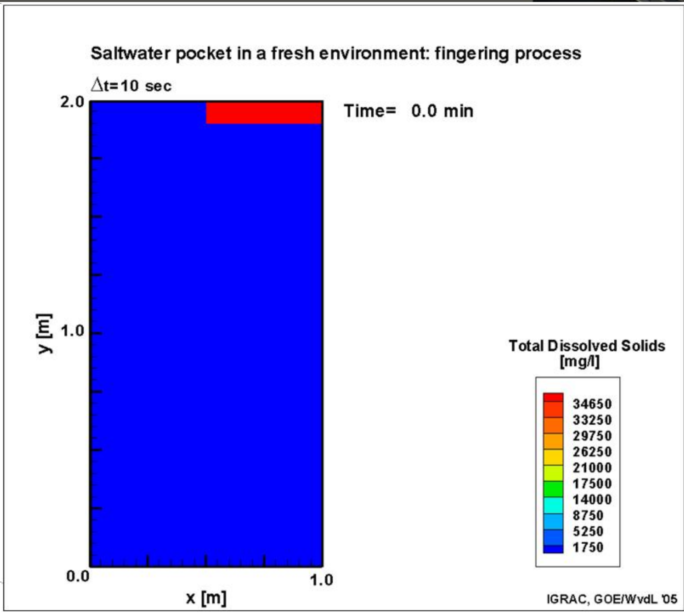
X= LOUSY models for predicting exact number of salt water fingers

Effect of size model cell on physical process



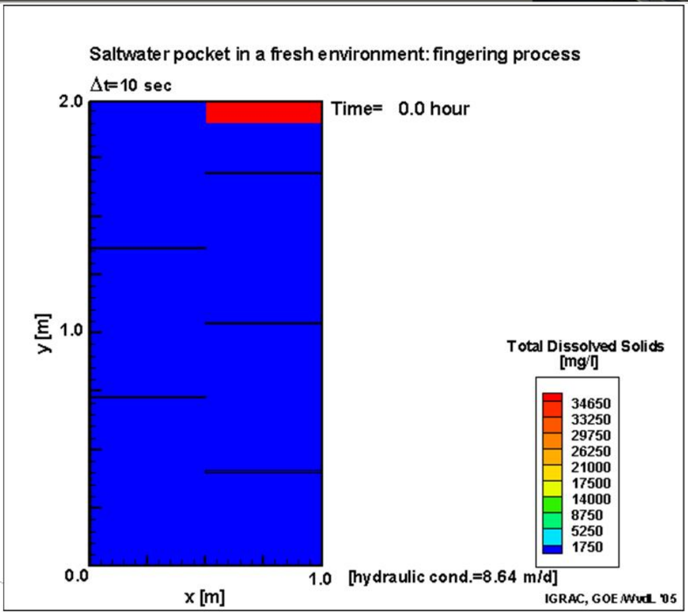
All models are GOOD for predicting moment of touching bottom (60min)!

Fingering processes in the subsoil



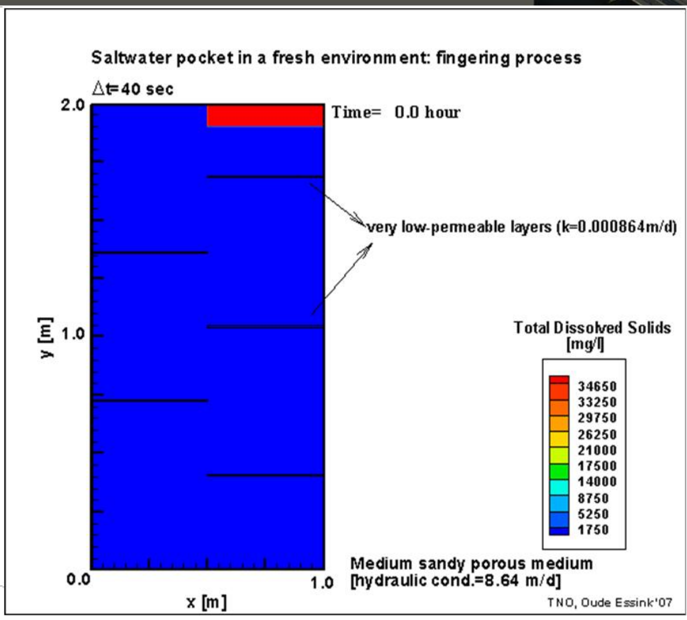
Deltares

Fingering processes in the subsoil



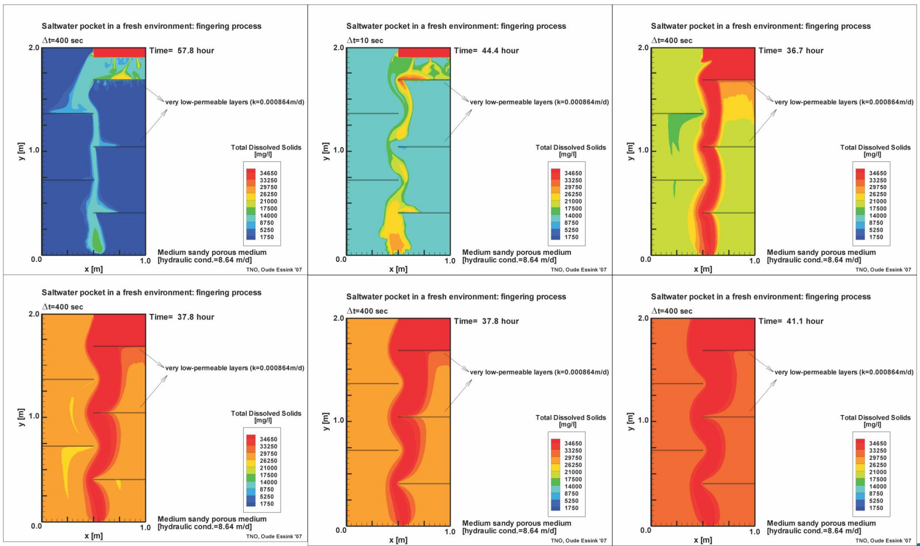
Deltares

Fingering processes in the subsoil



Deltares

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



Deltares

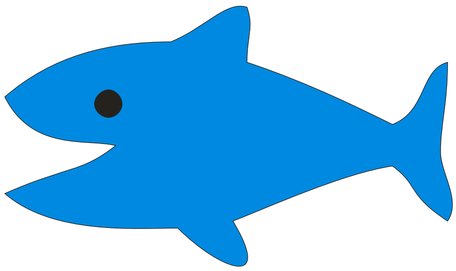
Base idea

Many local solutions for fresh groundwater supply can have regional impact

Deltares

Starring

solution fresh groundwater supply

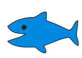


20200320_GEO4-4425

Deltares

Starring

Local solution fresh groundwater supply



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Starring

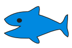
climate and global change

Deltares

Starring

climate and global change

Local solution fresh groundwater supply

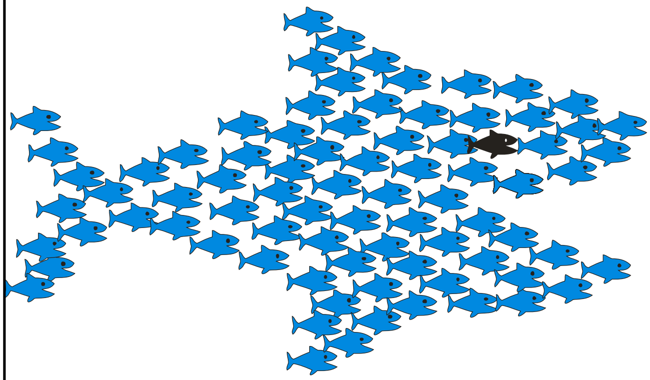


climate and global change

What should be the response?

Many local solutions fresh groundwater supply

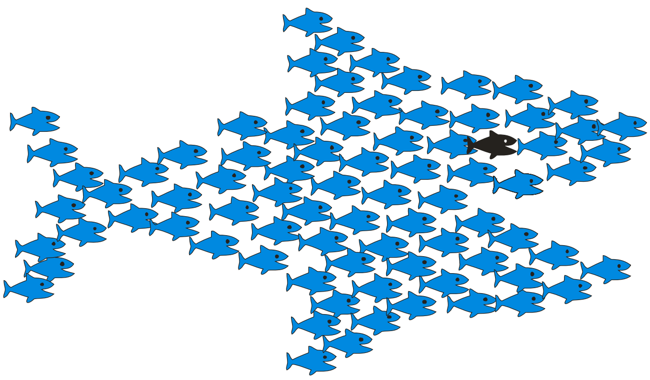
climate and global change



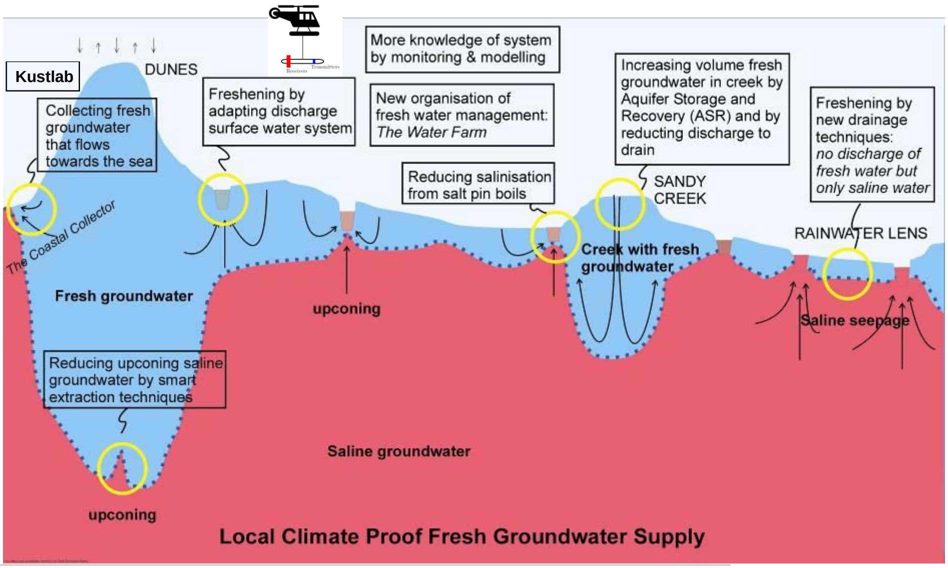
Many local solutions for fresh groundwater supply can have regional impact

Key activities

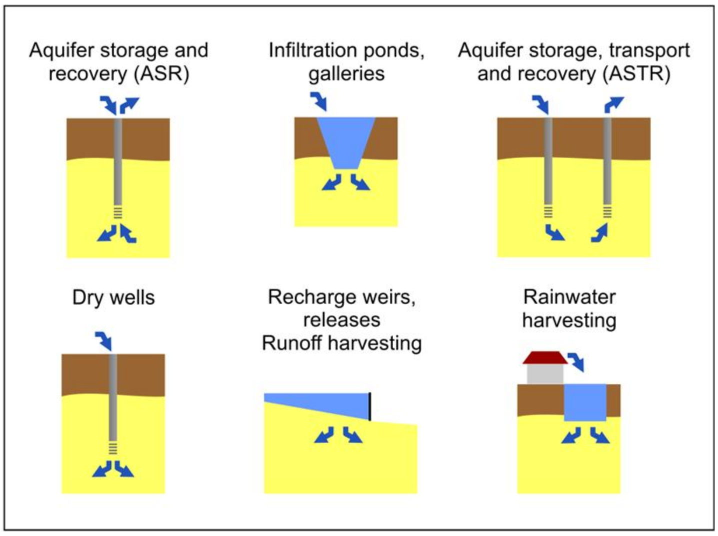
- upscaling local cases to regional strategy
- assess economical feasibility
- increase impact: communicate our showcases
- working together



Local climate proof fresh water supply



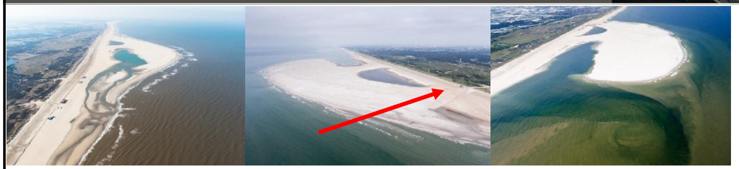
Aquifer Storage and Recovery / Managed Aquifer Recharge

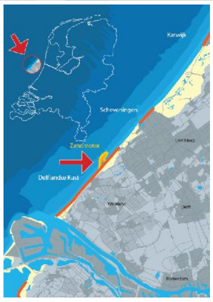


Deltares

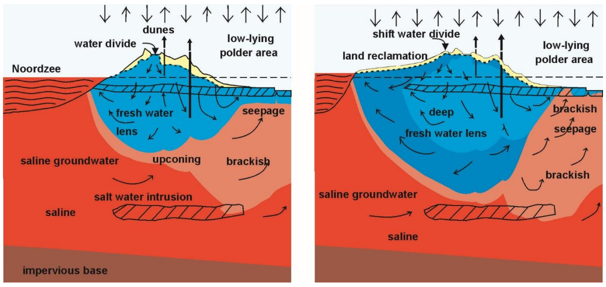
20200320_GEO4-4425

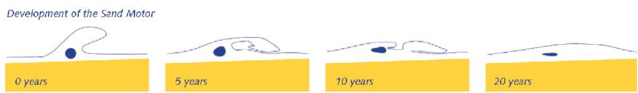
Increase strategic freshwater reservoirs in the coastal zone

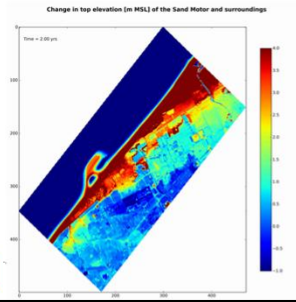




NatureCoast, Building with Nature, De Zandmotor

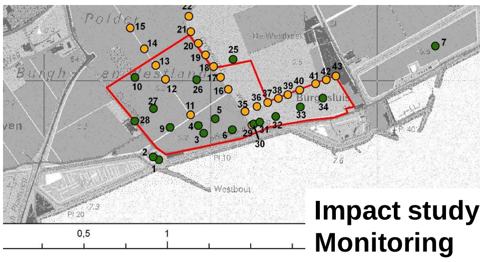




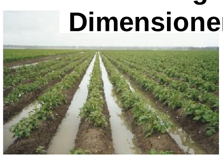


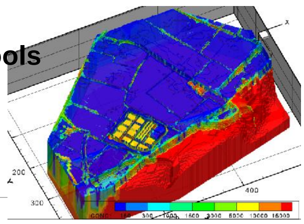
The Coastal Laboratory: aquaculture on fertile land

Three elements in one masterplan:
- **Coastal protection**
- **Sustainable food supply (aquaculture)**
- **Landscape and nature development**



Impact study
Monitoring
Dimensionering saline pools

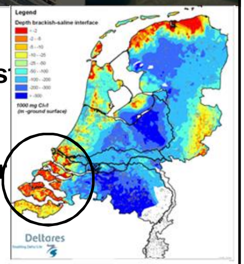


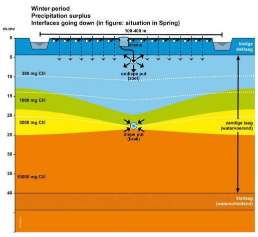


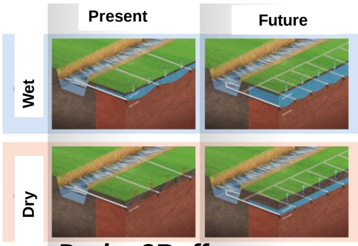
GO-FRESH: Local measures to increase fresh water supply

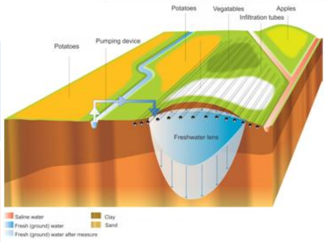
Goal:
Increasing fresh groundwater reservoirs in saline coas

Method:
3 Field tests: infiltration of freshwater in times of water









The Freshmaker
Injection fresh water and extraction saline

Drains2Buffer
Smart deep drainage protects thin freshwater lens

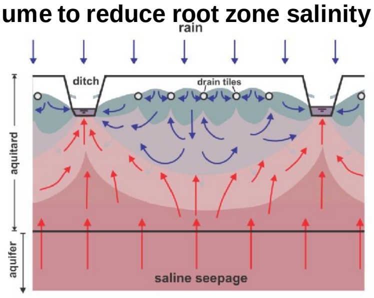
Creek Ridge Infiltration T
Elevation ground water level by infiltration surface

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

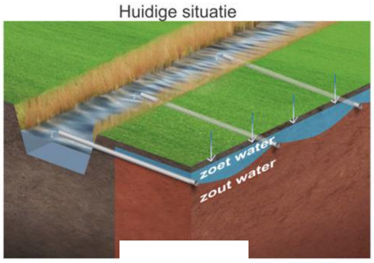
Deltares

Drains2Buffer

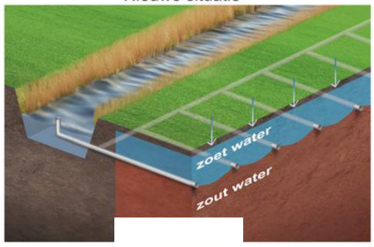
Increase rainwater lens volume to reduce root zone salinity



Huidige situatie

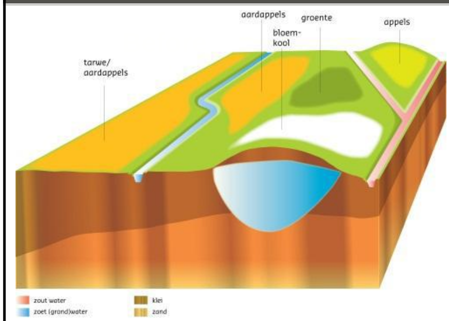


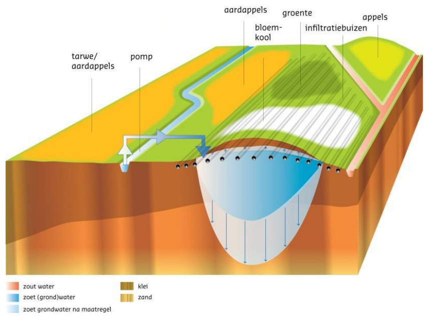
Nieuwe situatie

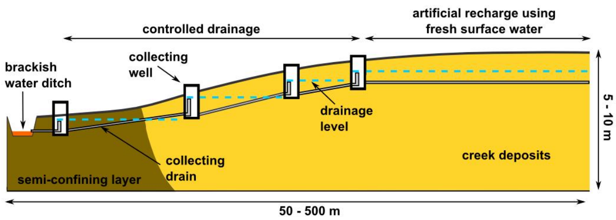


GO-FRESH

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



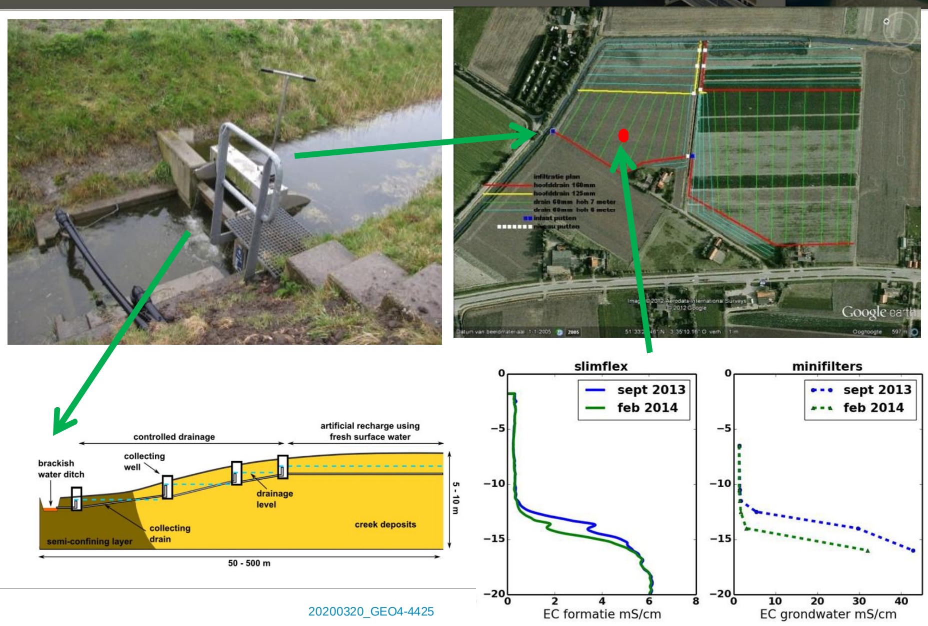




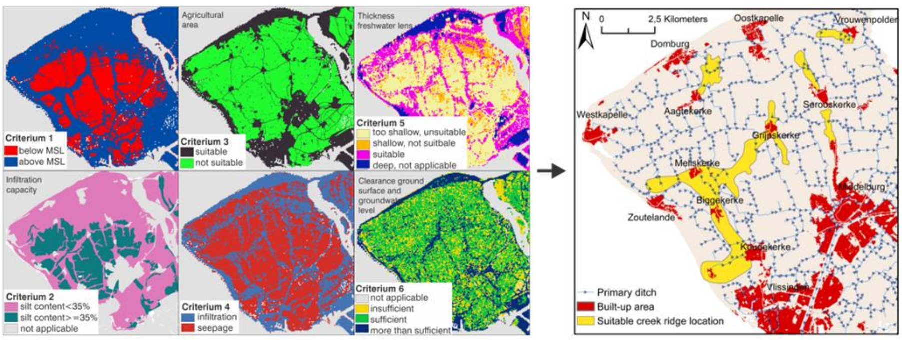
GO-FRESH

Deltares

Pilot Creek ridge infiltration

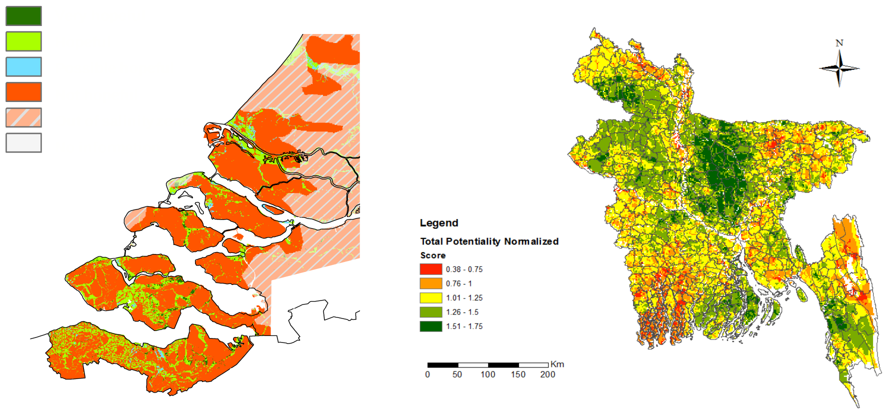


Up-scaling: potential and vulnerability maps at different scales



Deltares

Up-scaling: potential and vulnerability maps at different scales



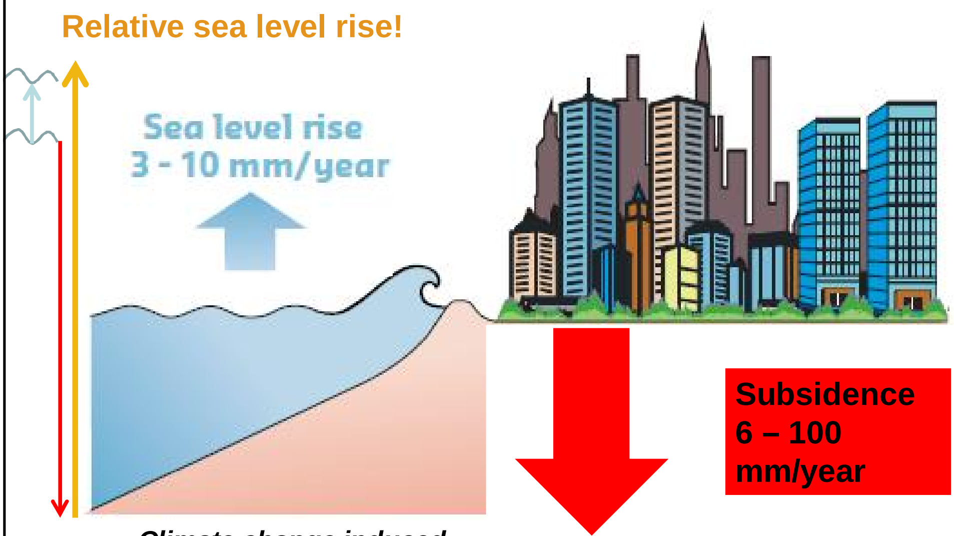
Creek Ridge Infiltration

Deltares

20200320_GEO4-4425

Sinking delta cities

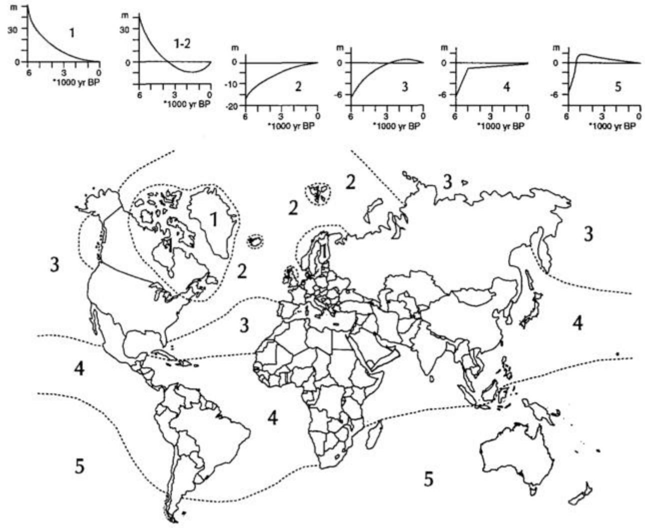
Absolute Sea Level Rise *versus* Subsidence



Climate change induced

20200320_GEO4-4425

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

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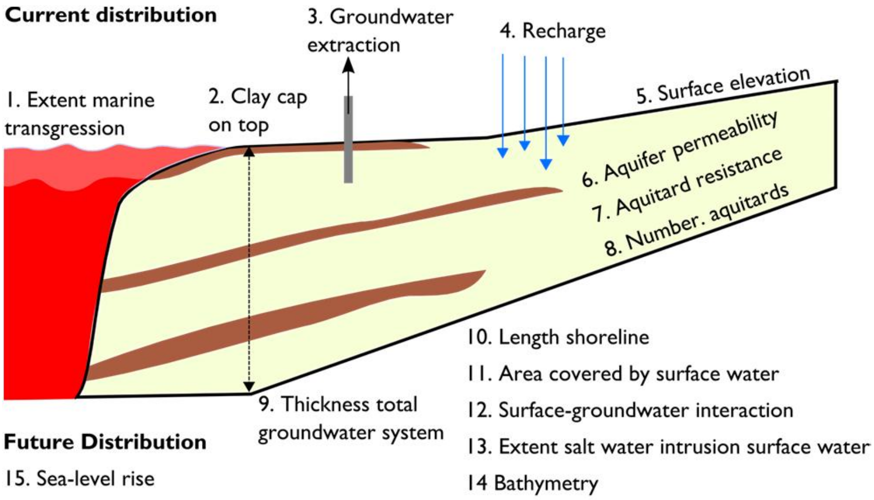
Factors determining fresh groundwater resources delta's

Current distribution



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

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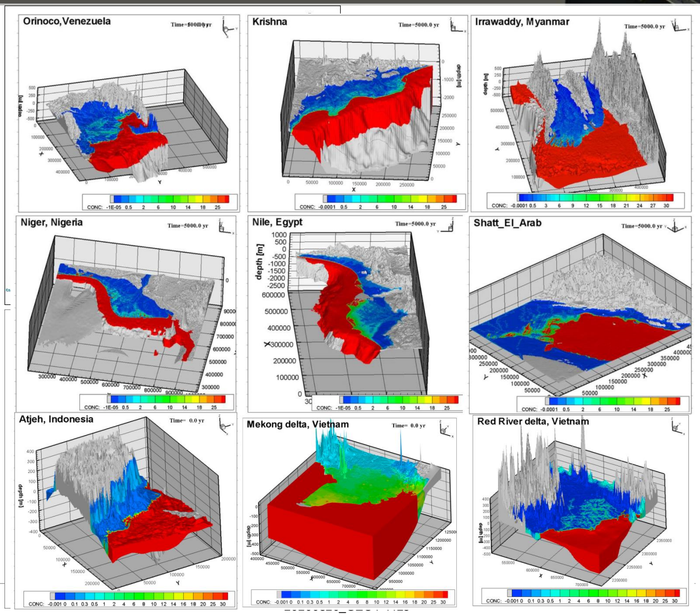
Numerical 3D models groundwater coastal zone



Deltares

Comparing the four deltas

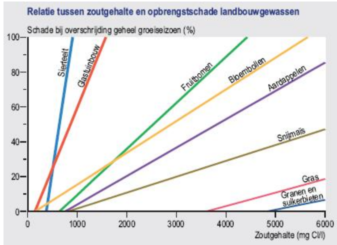
	Mekong Vietnam	Nile Egypt	Ganges-Brahma-putra, Kulna area, Bangladesh	Rhine-Meuse Netherlands
Responsible institutes data collection	DWRPIS Division for Water Resources Planning and Investigation for the South of Viet Nam	RIGW Research Institute for Groundwater	DPHE Department of Public Health Engineering 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 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

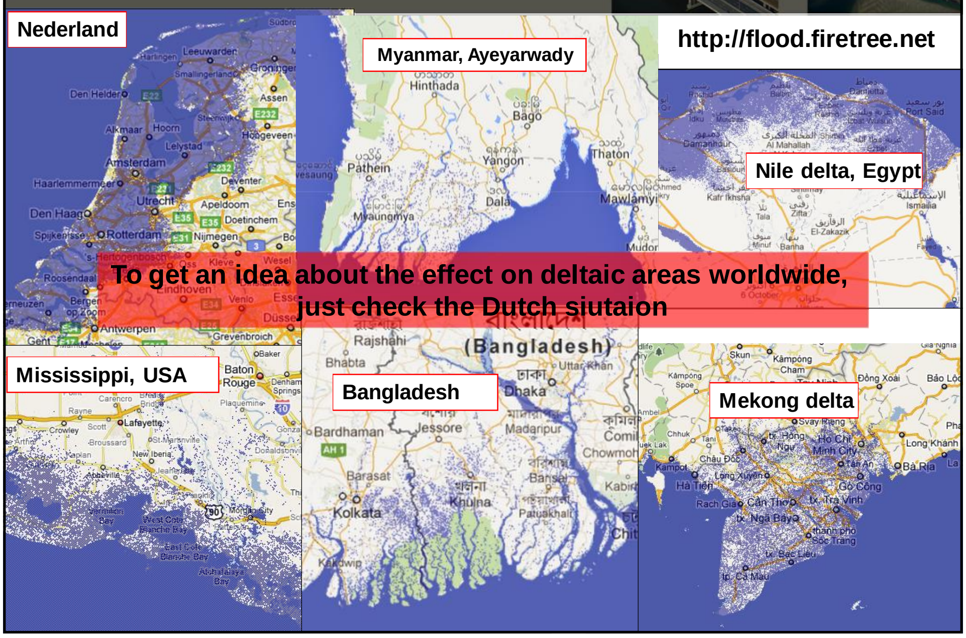


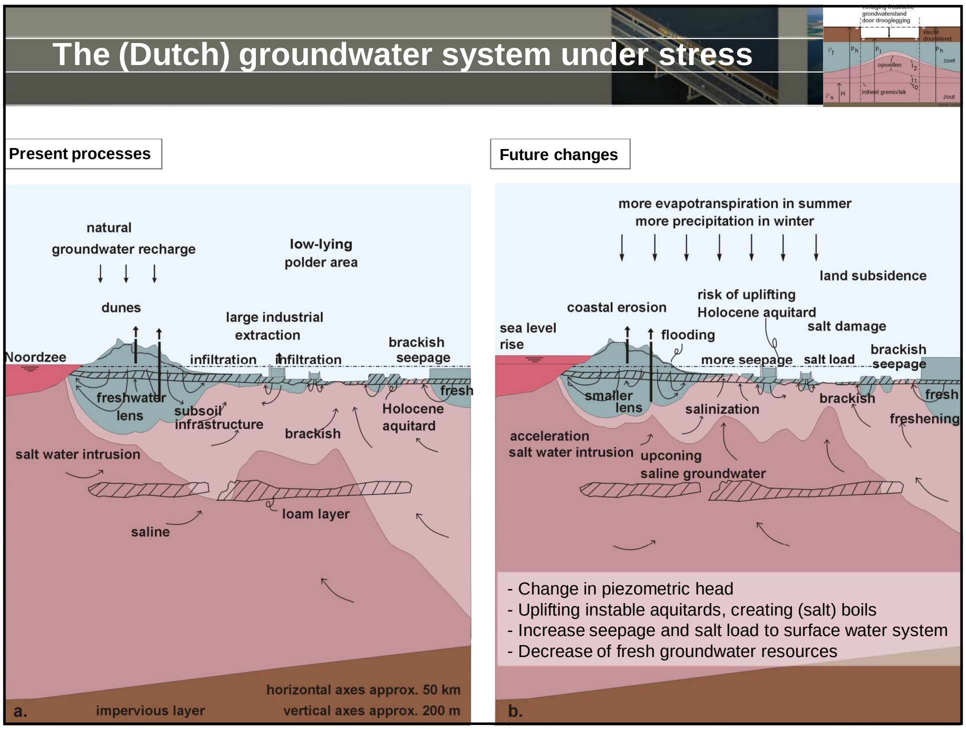
Source: MNP, 2005

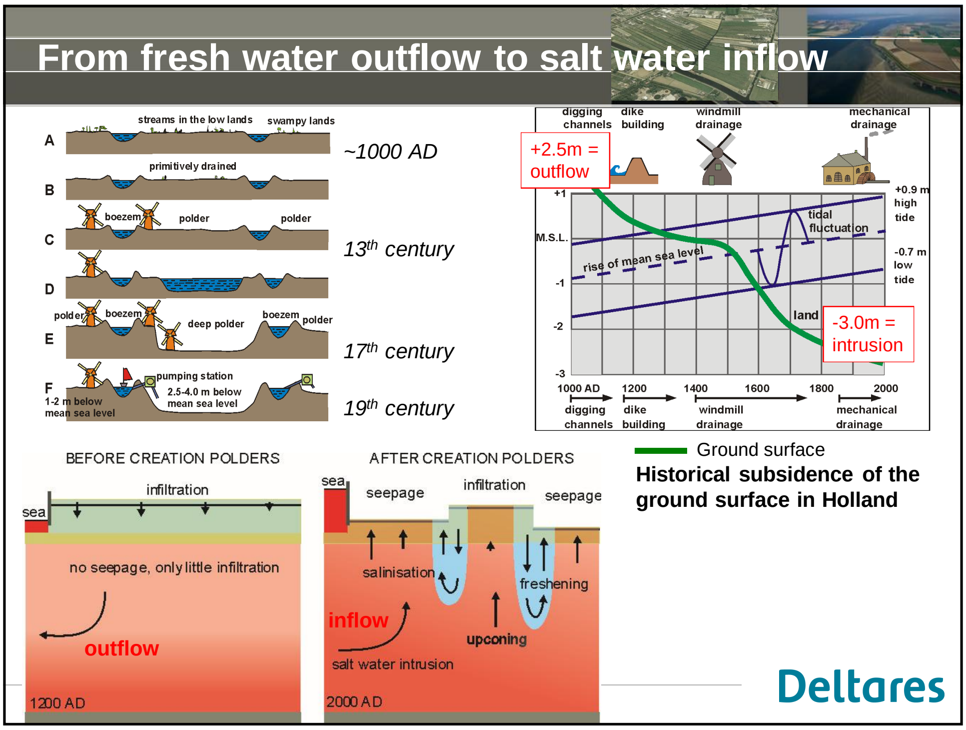
Deltares

Source: Roest et al., 2003 en Haskoning 20200320_GEO4-4425

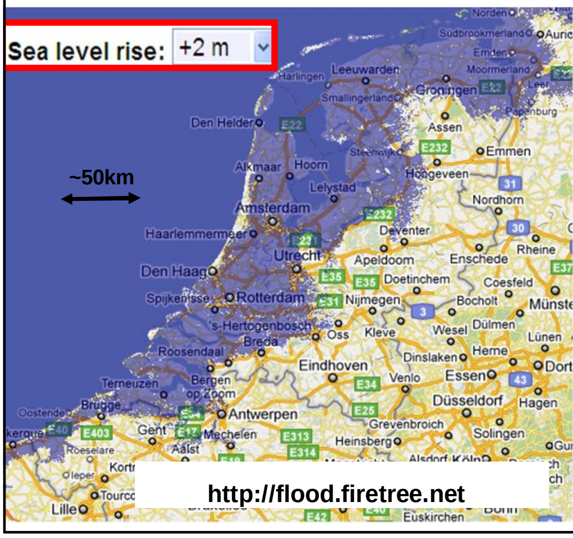
Sea level rise: +2 m

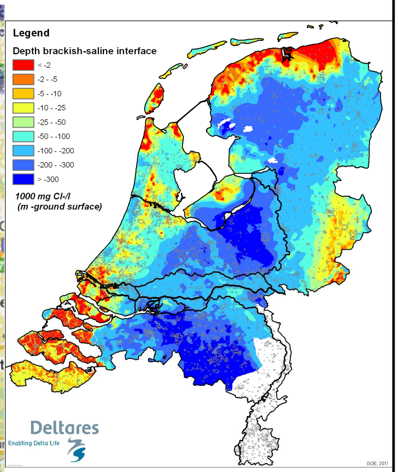



The (Dutch) groundwater system under stress
Present processes
Future changes
natural
groundwater recharge
low-lying
polder area
dunes
large industrial
extraction
brackish
seepage
Noordzee
infiltration
infiltration
fresh
freshwater
lens
subsoil
infrastructure
Holocene
aquitard
brackish
salt water intrusion
loam layer
saline
horizontal axes approx. 50 km
vertical axes approx. 200 m
a.
impervious layer
more evapotranspiration in summer
more precipitation in winter
land subsidence
coastal erosion
risk of uplifting
Holocene aquitard
salt damage
sea level
rise
flooding
more seepage
salt load
brackish
seepage
smaller
lens
salinization
brackish
fresh
freshening
acceleration
salt water intrusion
upconing
saline groundwater
- Change in piezometric head
- Uplifting instable aquitards, creating (salt) boils
- Increase seepage and salt load to surface water system
- Decrease of fresh groundwater resources
b.

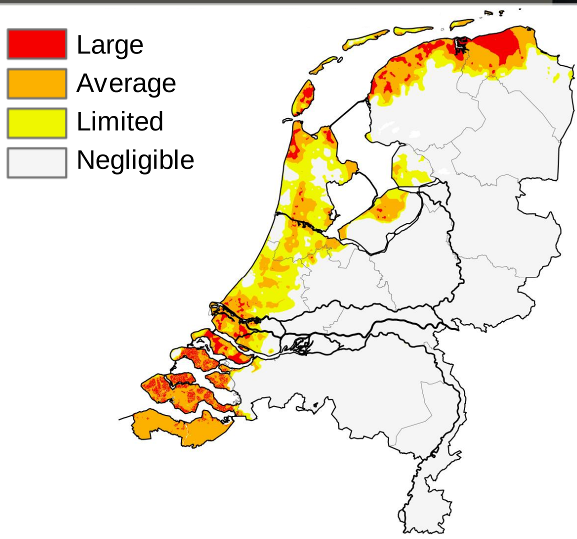

From fresh water outflow to salt water inflow
streams in the low lands
swampy lands
A
~1000 AD
primitively drained
B
boezem
polder
polder
C
13th century
D
polder
boezem
deep polder
boezem
polder
E
17th century
pumping station
2.5-4.0 m below
mean sea level
F
1-2 m below
mean sea level
19th century
digging
channels
dike
building
windmill
drainage
mechanical
drainage
+2.5m =
outflow
+1
M.S.L.
-1
-2
-3
+0.9 m
high
tide
-0.7 m
low
tide
tidal
fluctuation
rise of mean sea level
land
-3.0m =
intrusion
1000 AD
1200
1400
1600
1800
2000
Ground surface
Historical subsidence of the
ground surface in Holland
BEFORE CREATION POLDERS
AFTER CREATION POLDERS
infiltration
sea
no seepage, only little infiltration
outflow
1200 AD
sea
seepage
infiltration
seepage
salinisation
freshening
inflow
upconing
salt water intrusion
2000 AD
Deltares

The Netherlands: low-lying lands and saline groundwater





Zones of risk of salinisation



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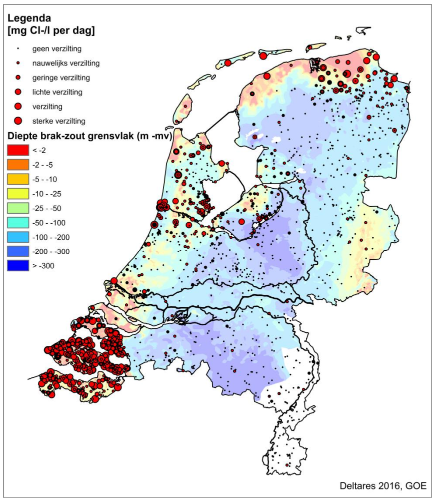
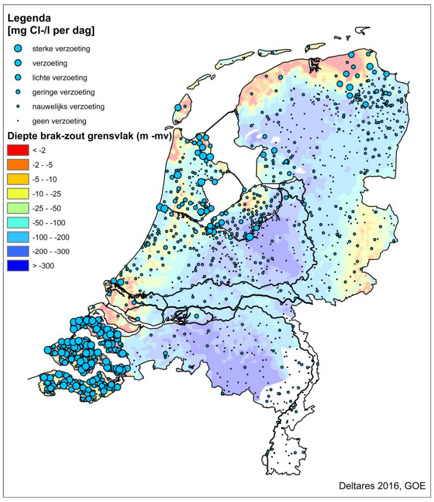
Salinisation-freshening groundwater: measurements





Deltares

Deltares

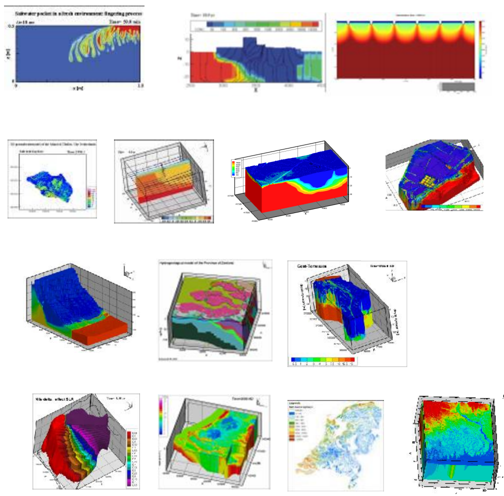
Different model cell sizes to consider several phenomena

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

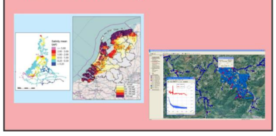


Goal:
To take largest cell size possible to accurately model relevant salinisation processes

Deltares

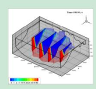
Modelling tools: iMOD Open Source

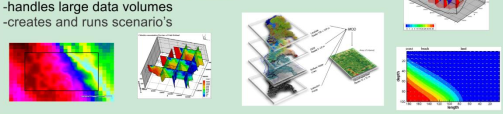
Flexible Mesh/SOBEK
major features:
- salt water intrusion & surface water quality
- 1D network or 2D horizontal grid
- powerful hydrodynamic simulation engine
- complex flows & water related processes
- dispersion coëfficiënt calibrated with field data & model results from DELFT3D
- also flood forecasting



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

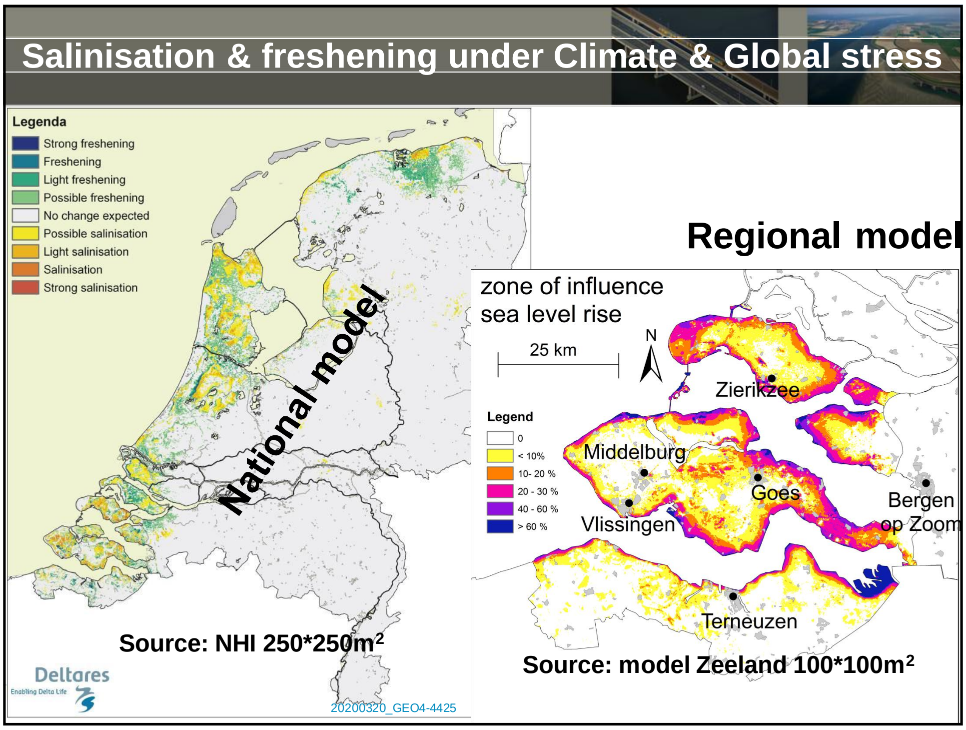
SUB-CR (subsidence)
major features:
- core is **MODFLOW**
- includes slow subsidence (creep)
- saturated and unsaturated zone

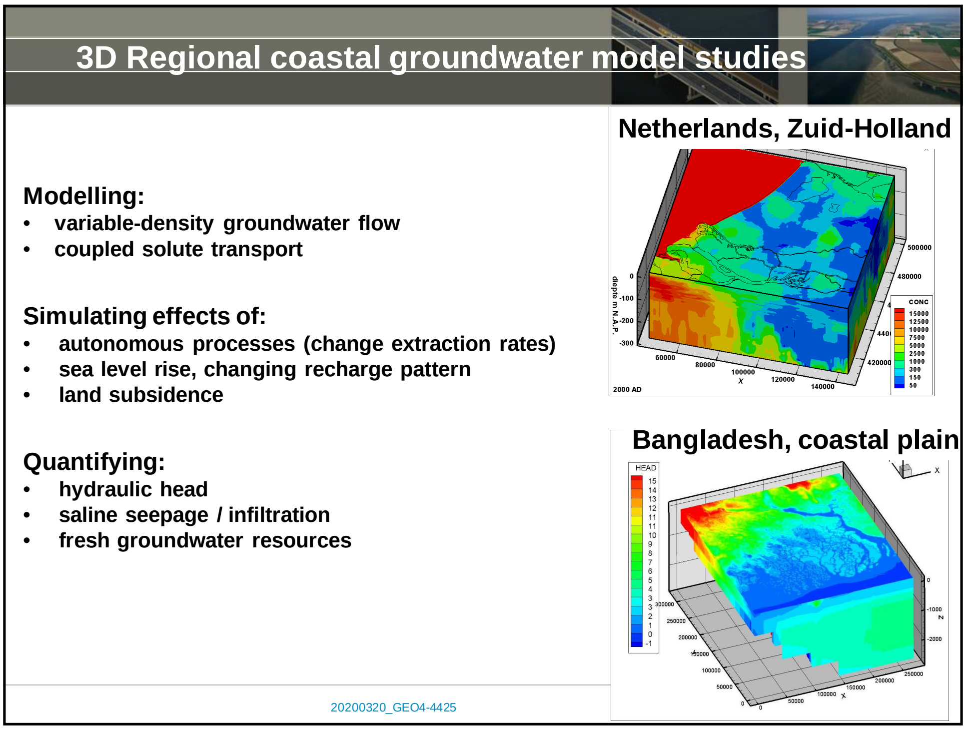




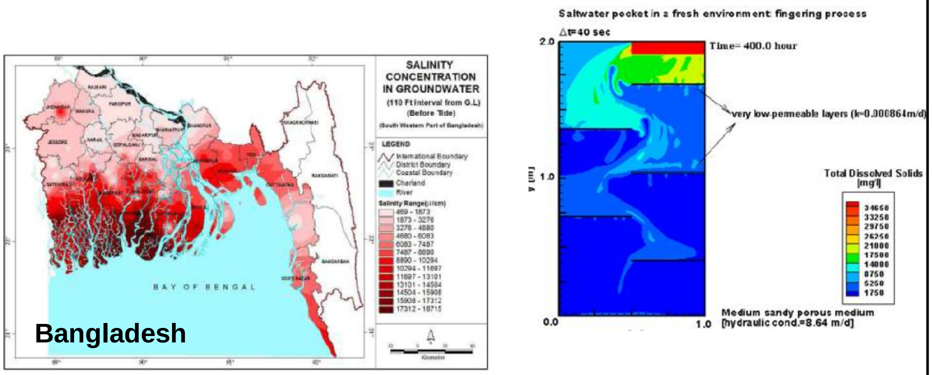
http://oss.deltares.nl/web/imod

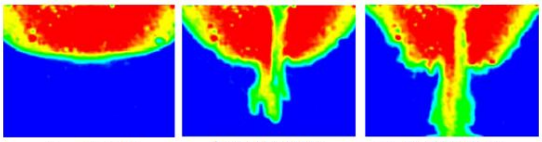
Deltares


Salinisation & freshening under Climate & Global stress
Legenda
Strong freshening
Freshening
Light freshening
Possible freshening
No change expected
Possible salinisation
Light salinisation
Salinisation
Strong salinisation
National model
Source: NHI 250*250m2
Deltares
Enabling Delta Life
Regional model
zone of influence
sea level rise
25 km
N
Legend
0
< 10%
10- 20 %
20 - 30 %
40 - 60 %
> 60 %
Zierikzee
Middelburg
Goes
Vlissingen
Bergen op Zoom
Terneuzen
Source: model Zeeland 100*100m2
20200320_GEO4-4425


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
Netherlands, Zuid-Holland
Bangladesh, coastal plain
20200320_GEO4-4425

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)

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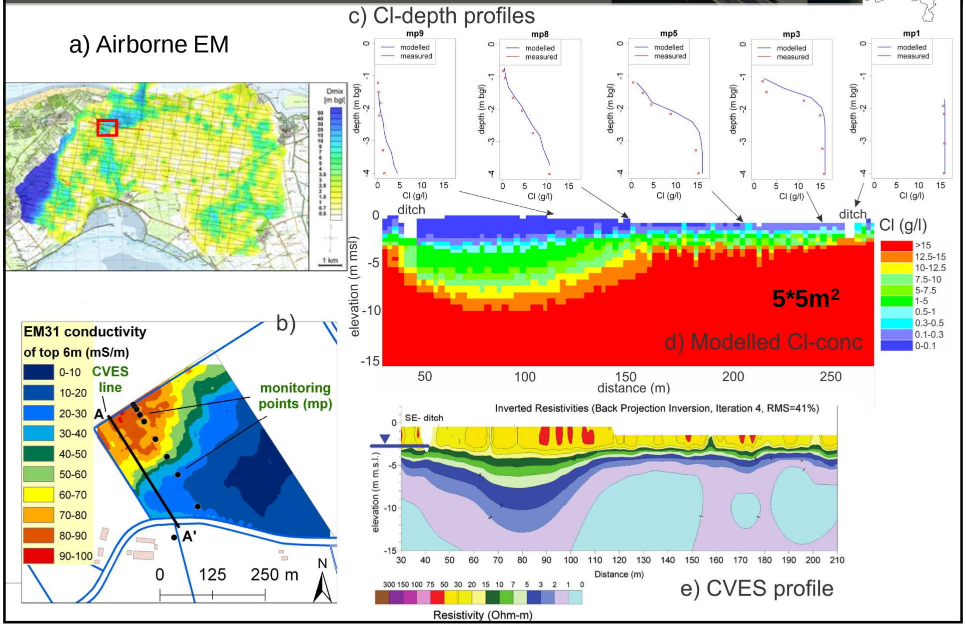
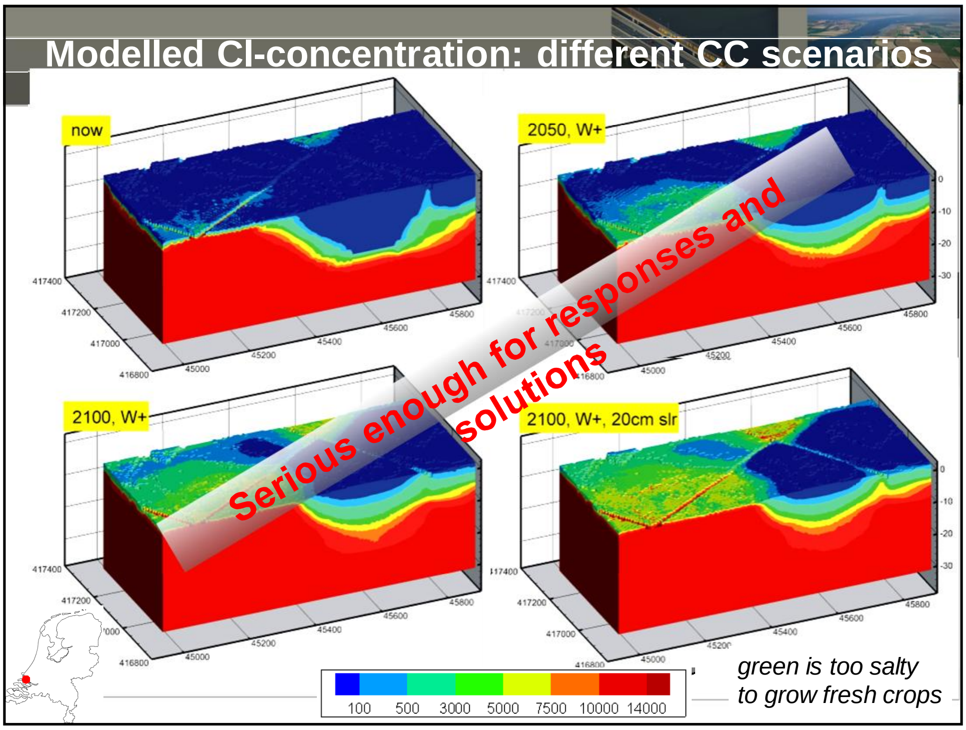
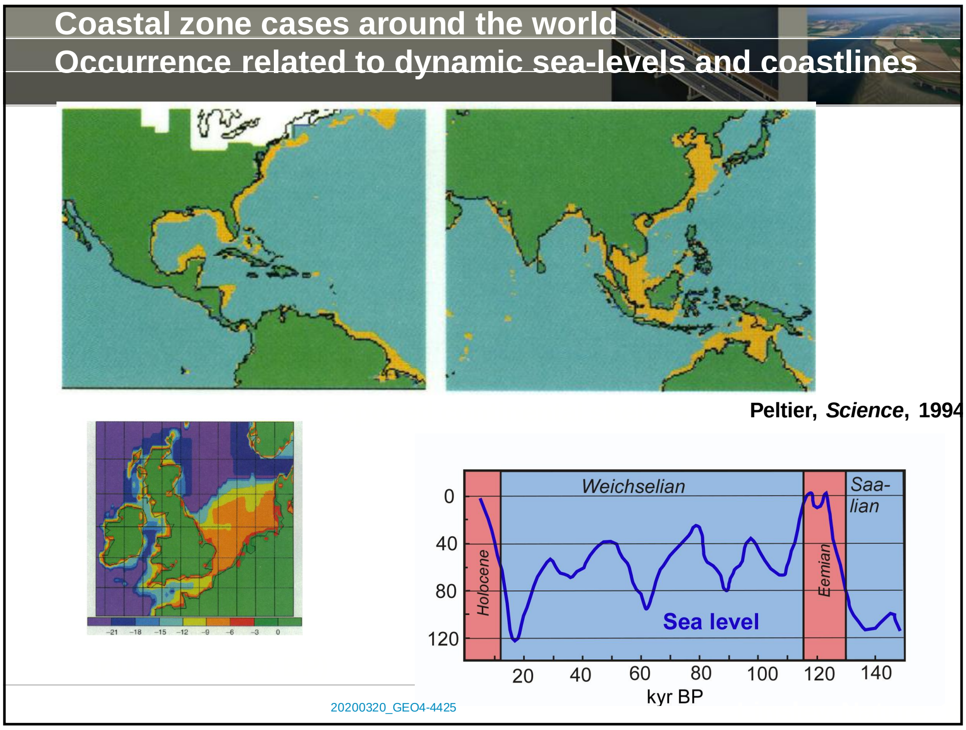
Comparison monitoring data with model results




Modelled Cl-concentration: different CC scenarios
now
2050, W+
2100, W+
2100, W+, 20cm slr
Serious enough for responses and solutions
100 500 3000 5000 7500 10000 14000
green is too salty
to grow fresh crops


Coastal zone cases around the world
Occurrence related to dynamic sea-levels and coastlines
Peltier, Science, 1994
Weichselian
Saa-
lian
Holocene
Eemian
Sea level
0
40
80
120
20 40 60 80 100 120 140
kyr BP
20200320_GEO4-4425

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}

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

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

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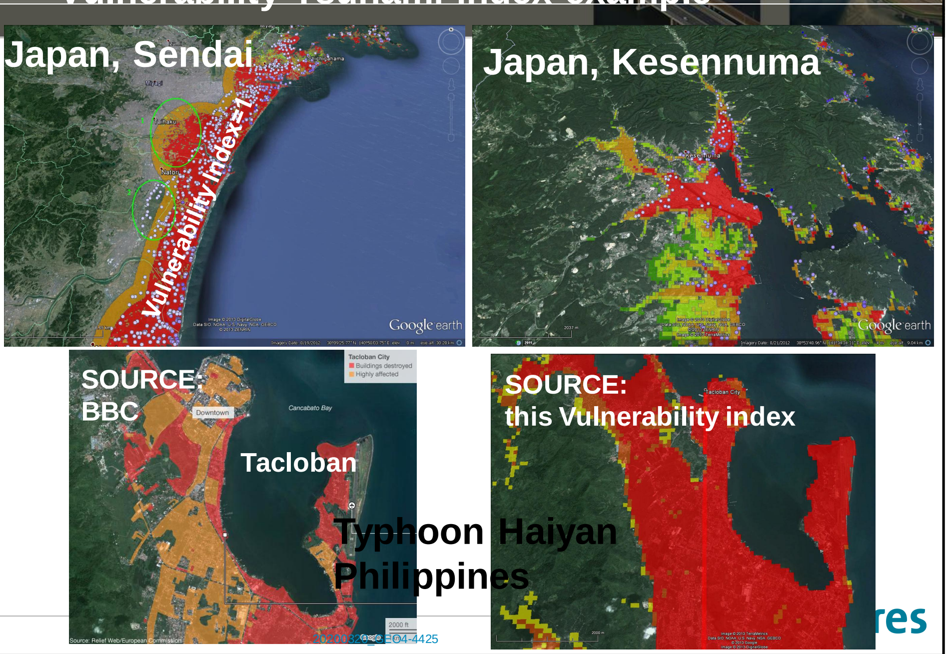
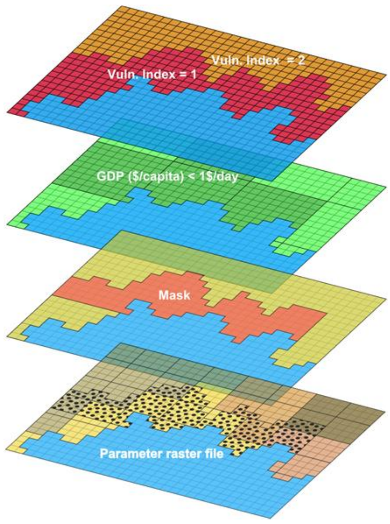
Vulnerability Tsunami index example

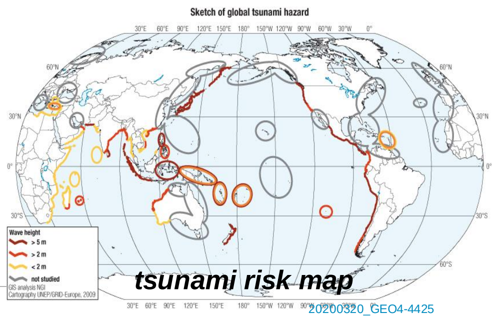


Socio-economic factor and parameter values statistics

- **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)





tsunami risk map

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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

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Palaeo-hydrogeographical modelling

Delsman et al., HESS, 20

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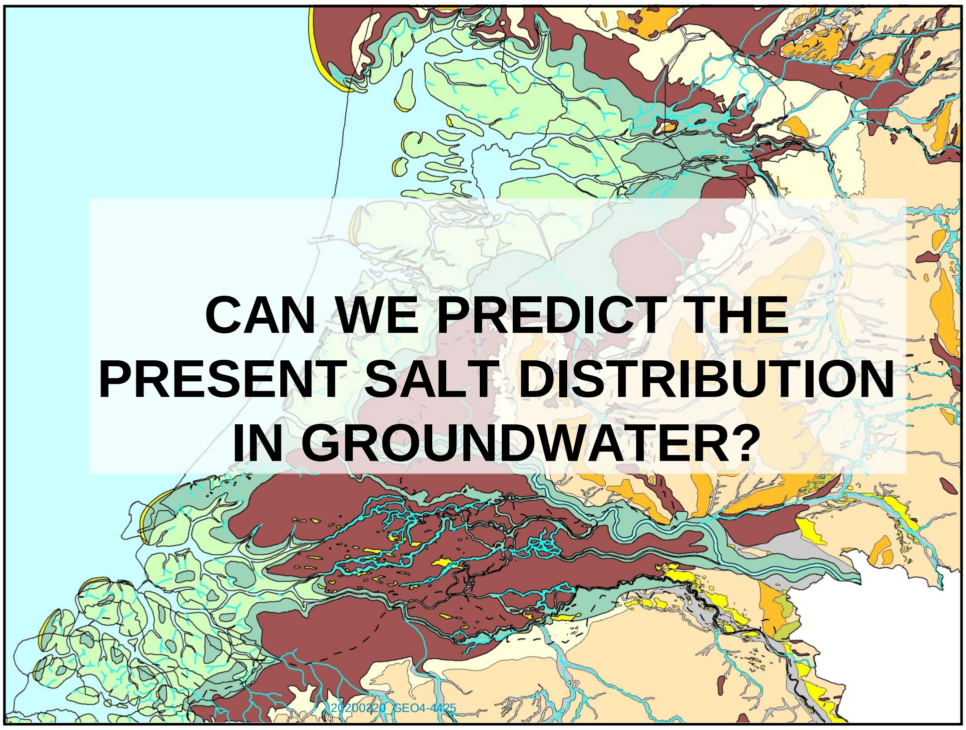
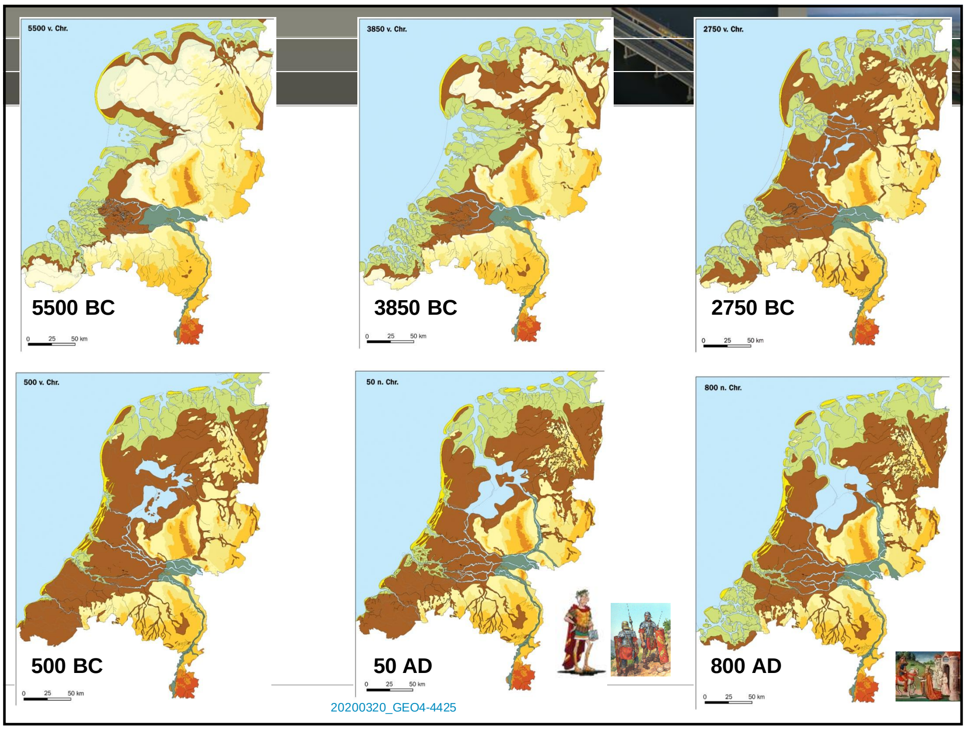
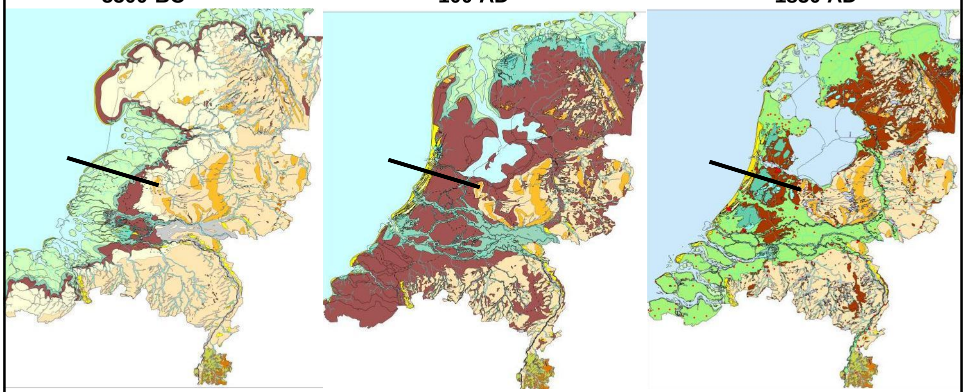

CAN WE PREDICT THE PRESENT SALT DISTRIBUTION IN GROUNDWATER?
20200320_GEO4-4425


5500 v. Chr.
5500 BC
3850 v. Chr.
3850 BC
2750 v. Chr.
2750 BC
500 v. Chr.
500 BC
50 n. Chr.
50 AD
800 n. Chr.
800 AD
20200320_GEO4-4425

Palaeogeographical development

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



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

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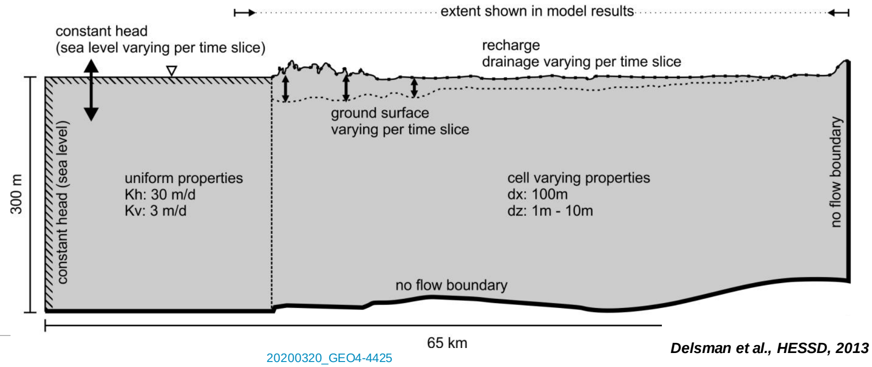
Atlas NL in het Holoceen (Vos et al, 2011)

20200320_GEO4-4425

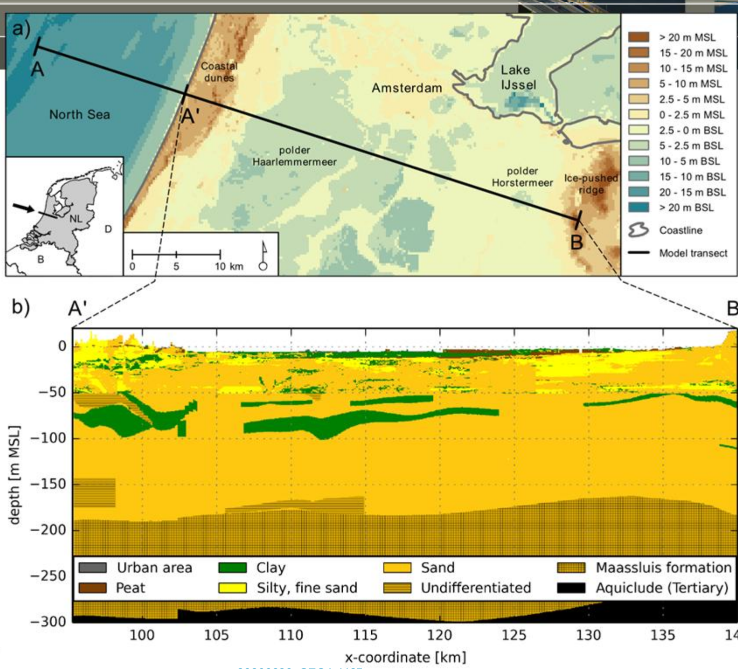
Occurrence of salt under the polder Haarlemmermeer

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

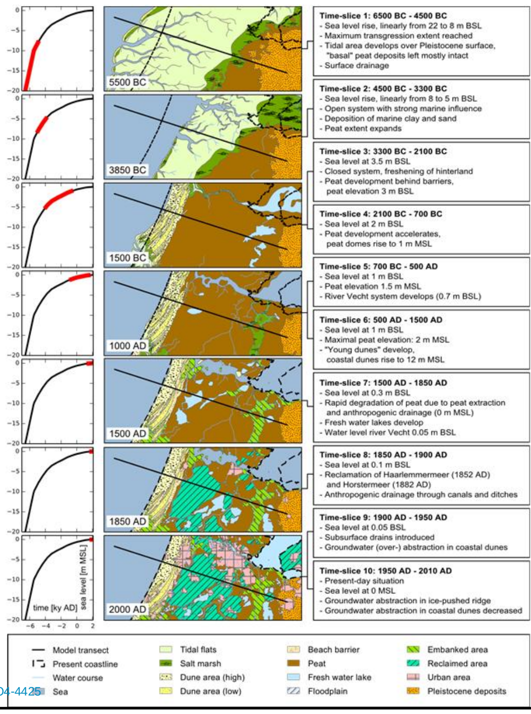


Delsman et al., HESSD, 2013

20200320_GEO4-4425



20200320_GEO4-4425



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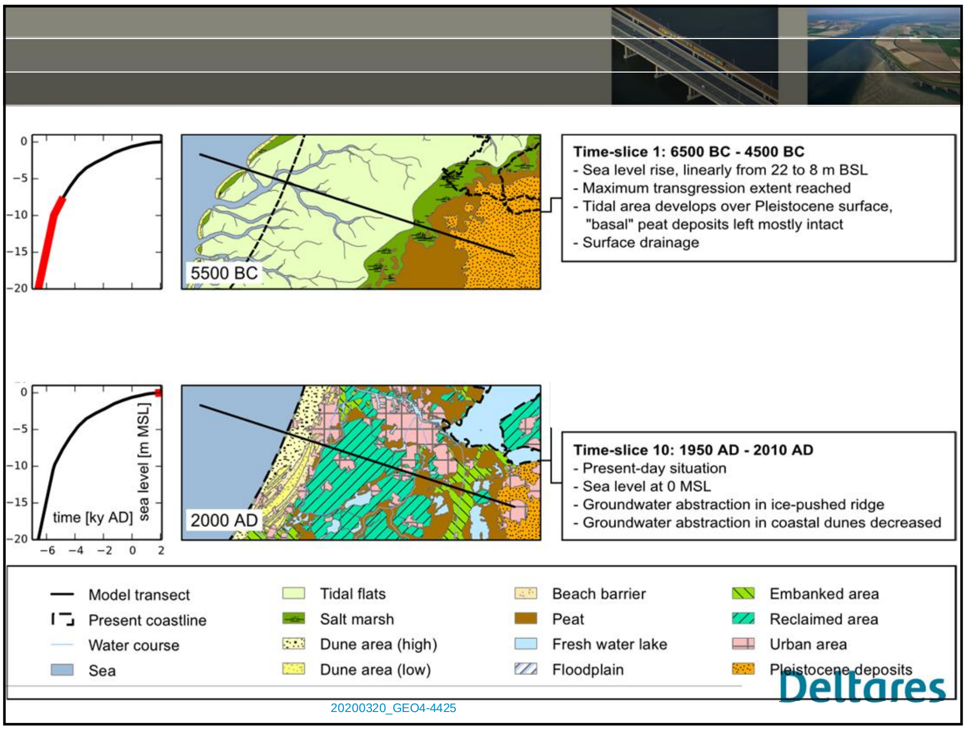

5500 BC
Time-slice 1: 6500 BC - 4500 BC
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage
2000 AD
sea level [m MSL]
time [ky AD]
Time-slice 10: 1950 AD - 2010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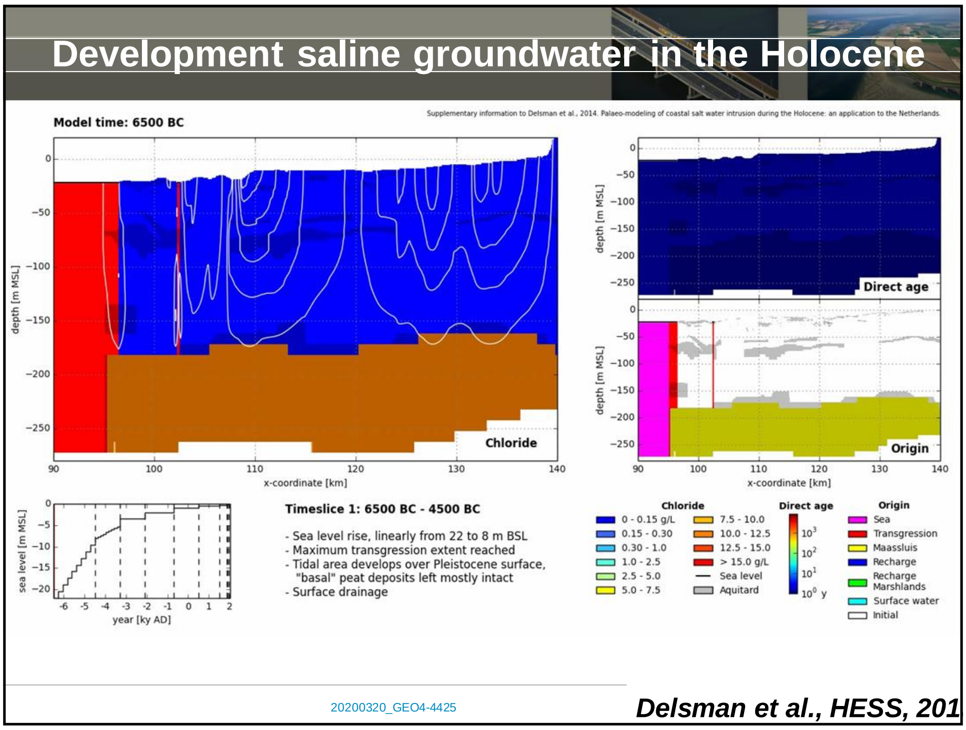
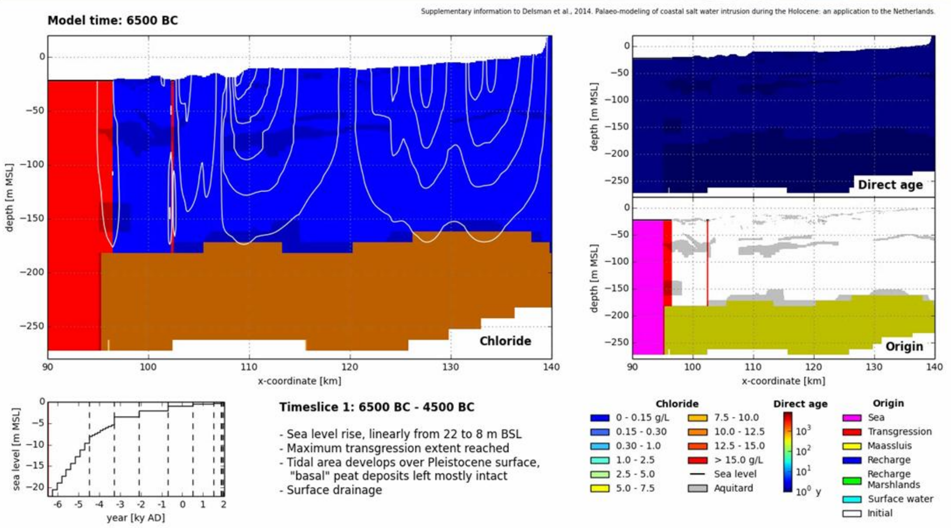


Development saline groundwater in the Holocene
Model time: 6500 BC
Supplementary information to Delsman et al., 2014. Palaeo-modeling of coastal salt water intrusion during the Holocene: an application to the Netherlands.
depth [m MSL]
x-coordinate [km]
Chloride
Direct age
Origin
sea level [m MSL]
year [ky AD]
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
0 - 0.15 g/L
0.15 - 0.30
0.30 - 1.0
1.0 - 2.5
2.5 - 5.0
5.0 - 7.5
7.5 - 10.0
10.0 - 12.5
12.5 - 15.0
> 15.0 g/L
Sea level
Aquitard
Sea
Transgression
Maassluis
Recharge
Recharge Marshlands
Surface water
Initial
20200320_GEO4-4425
Delsman et al., HESS, 201

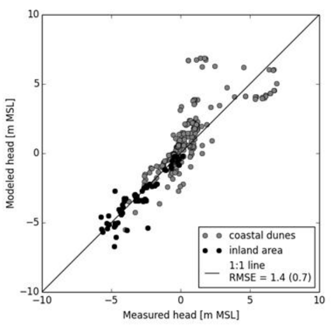
Development saline groundwater in the Holocene

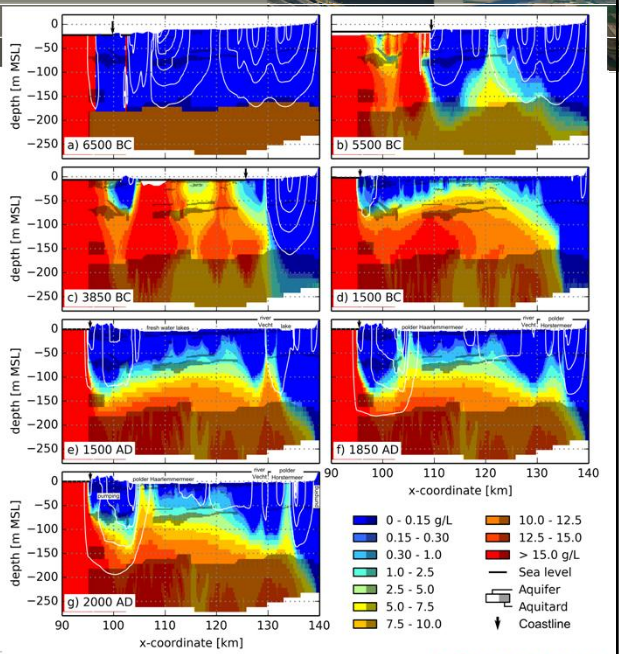


20200320_GEO4-4425

Delsman et al., HESS, 201

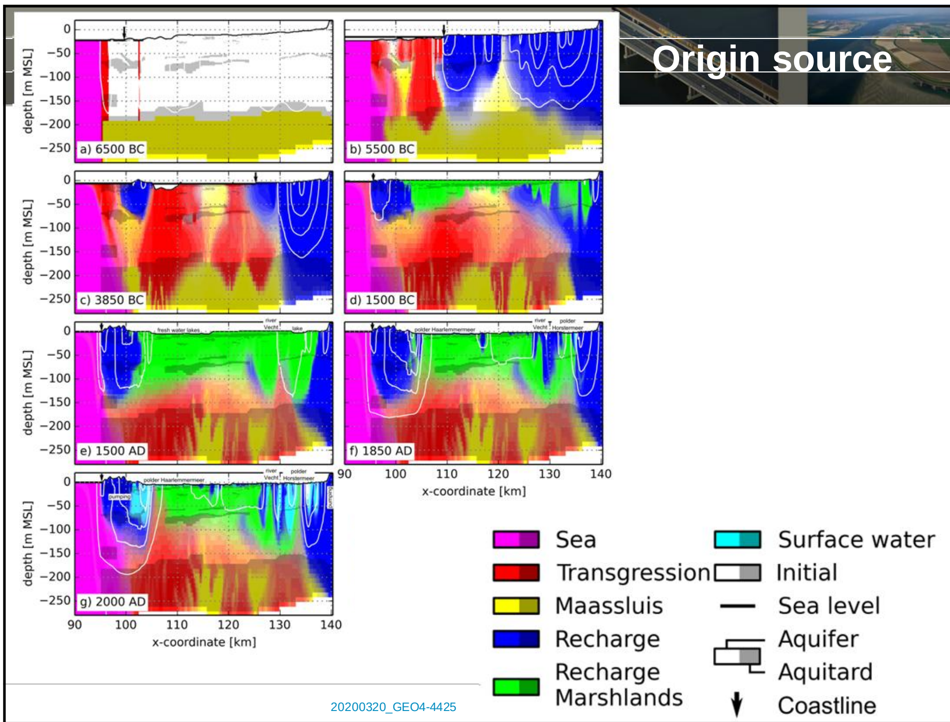
Model versus measurements



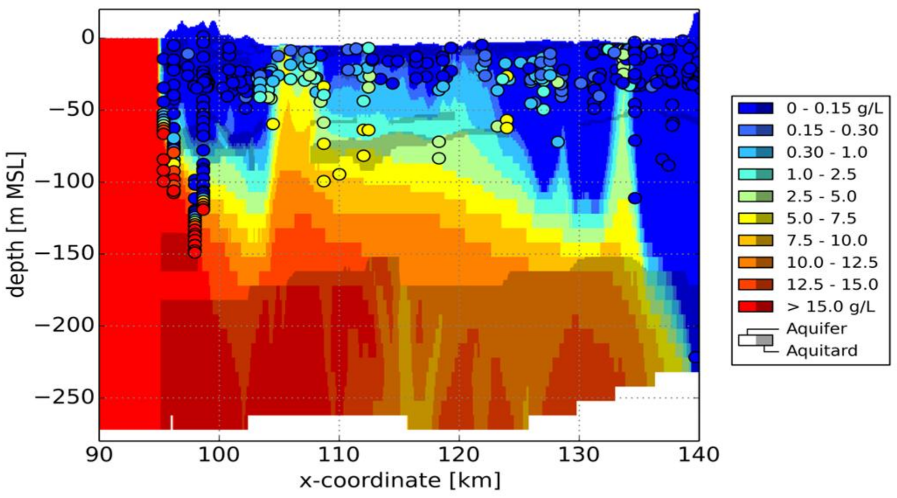


20200320_GEO4-4425

Origin source



Model versus measurements



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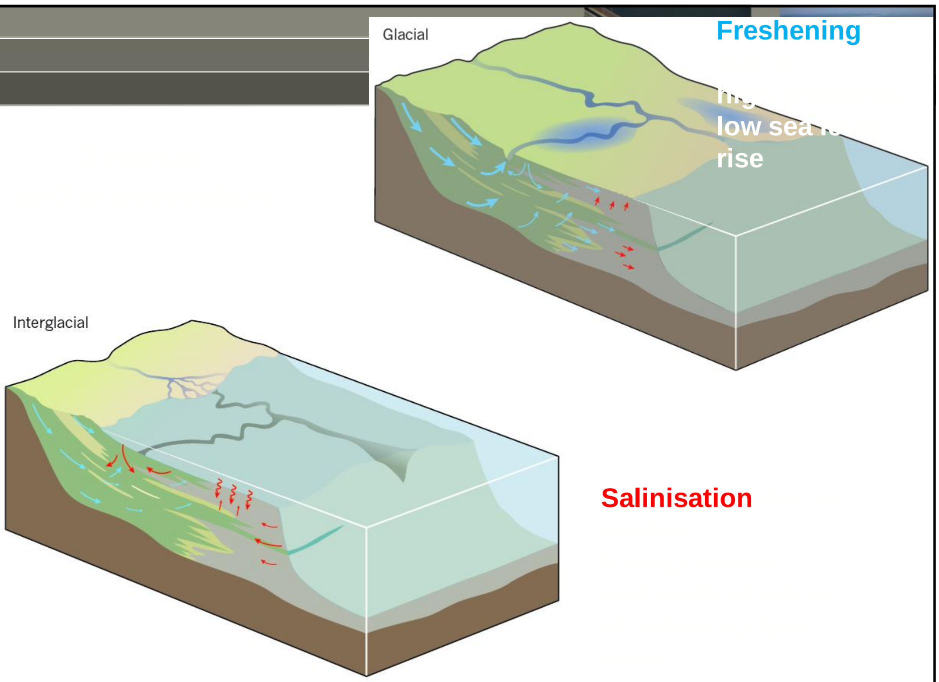

Freshening

Salinisation

Source: Nature, 2013

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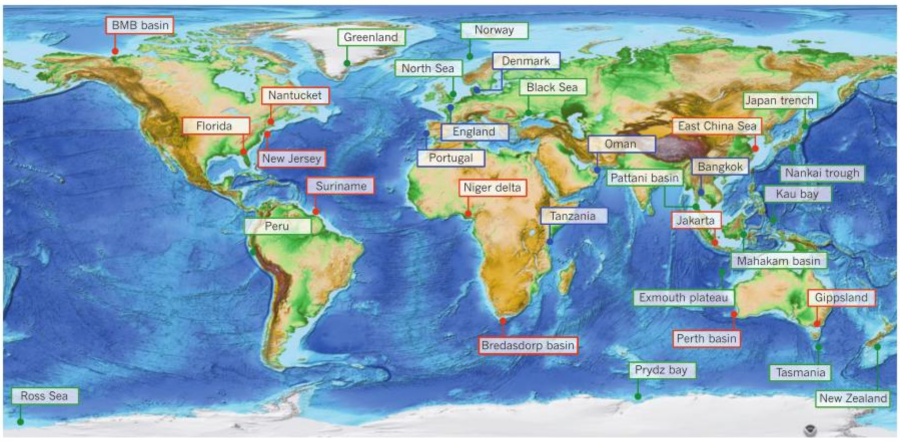
World map of topography and bathymetry showing known occurrences of fresh and brackish offshore



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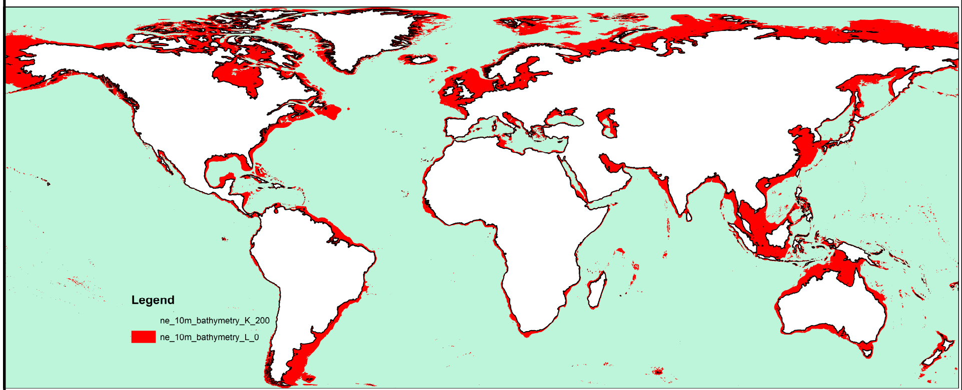
Possible locations of offshore (submarine) groundwater



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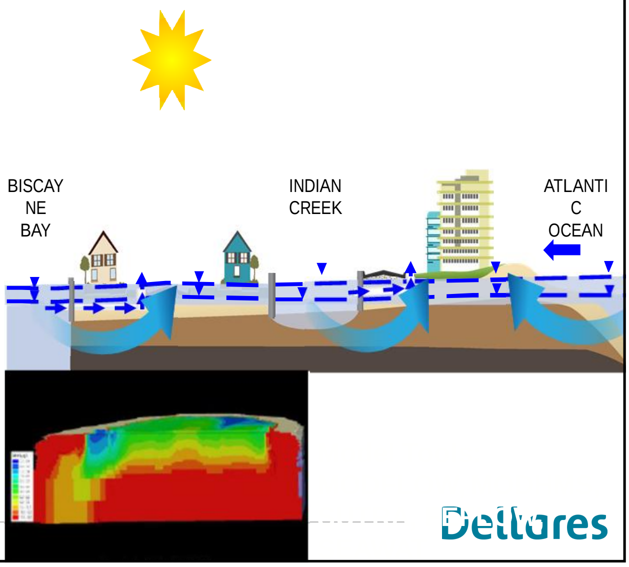
Miami Beach's unique combination of flood conditions makes an integrated model essential

» **Tidal flooding:**
- **Through storm drains**
- **Through groundwater**
- **Exacerbated with SLR**

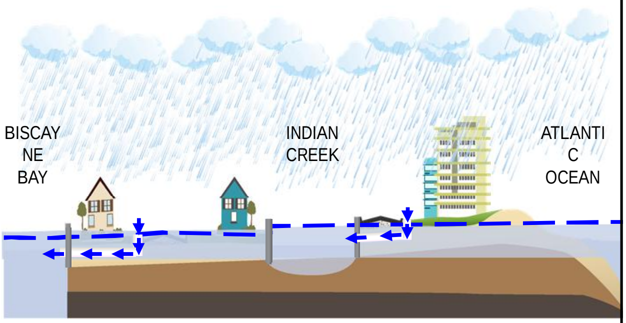


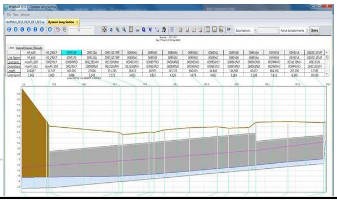
Deltares

Miami Beach’s unique combination of flood conditions makes an integrated model essential

» **Tidal flooding:**
  - **Through storm drains**
  - **Through groundwater**
  - **Exacerbated with SLR**

» **Rainfall flooding**





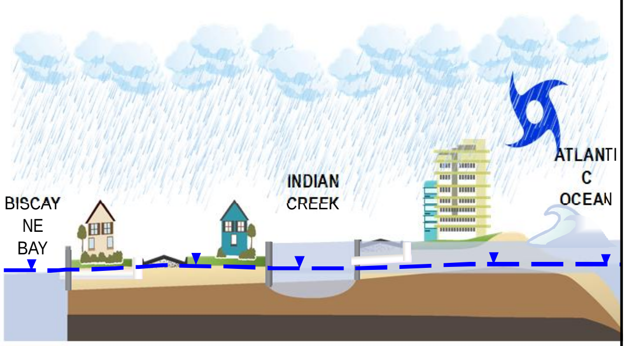
Model Tools: XP-SWMM, MIKE Urban, MIKE Flood, InfoWorks-ICM

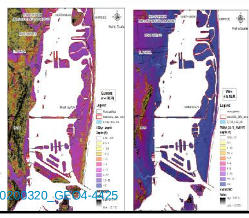
Miami Beach’s unique combination of flood conditions makes an integrated model essential

» **Tidal flooding:**
  - **Through storm drains**
  - **Through groundwater**
  - **Exacerbated with SLR**

» **Rainfall flooding**

» **Storm surge**





Model Tools: MIKE21, ADCIRC, DELFT3D, SFINCS