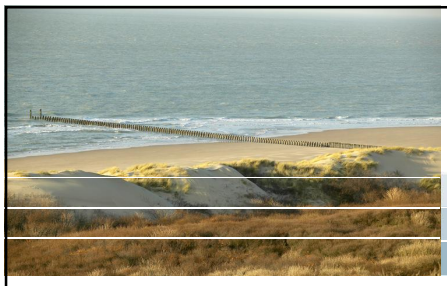

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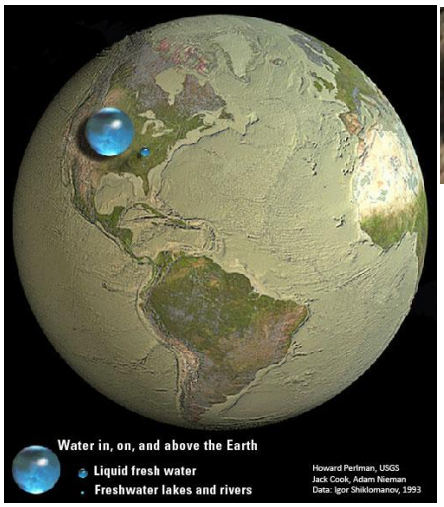
Fresh groundwater in the coastal zone

Vulnerability of groundwater systems to flooding events

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

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

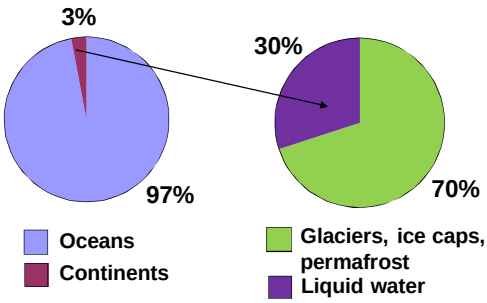
Volumes of water on Earth: a scarce product



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

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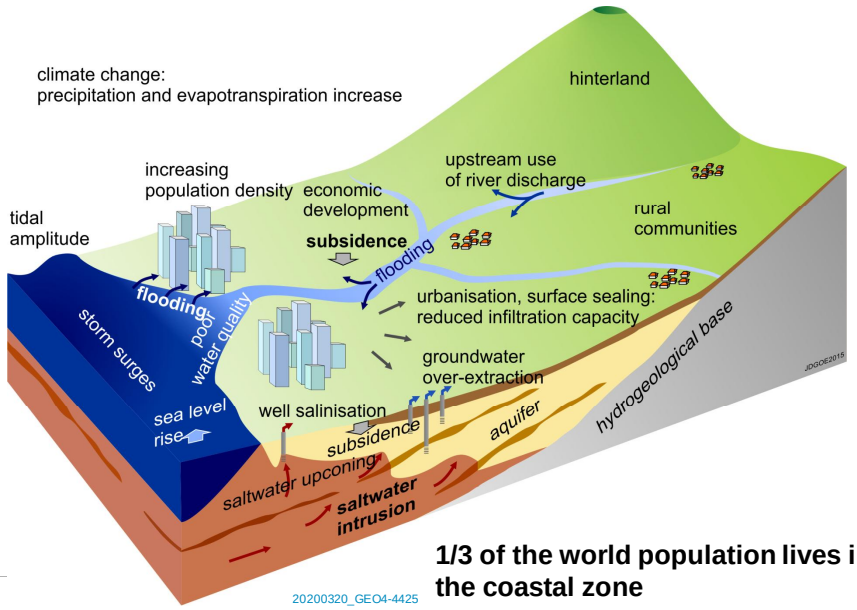
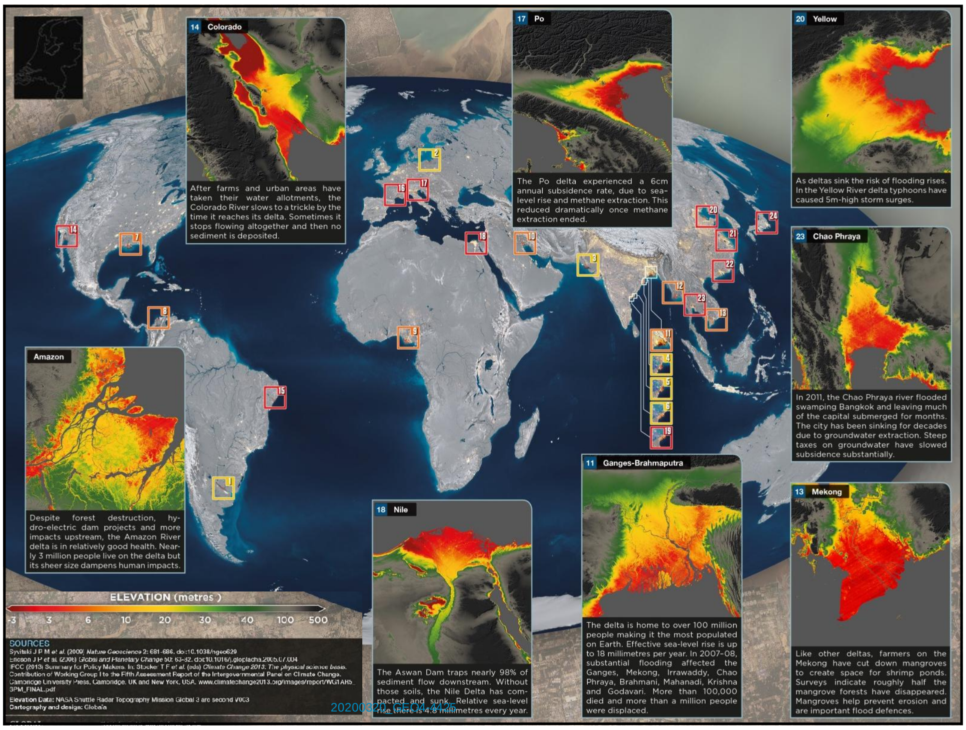
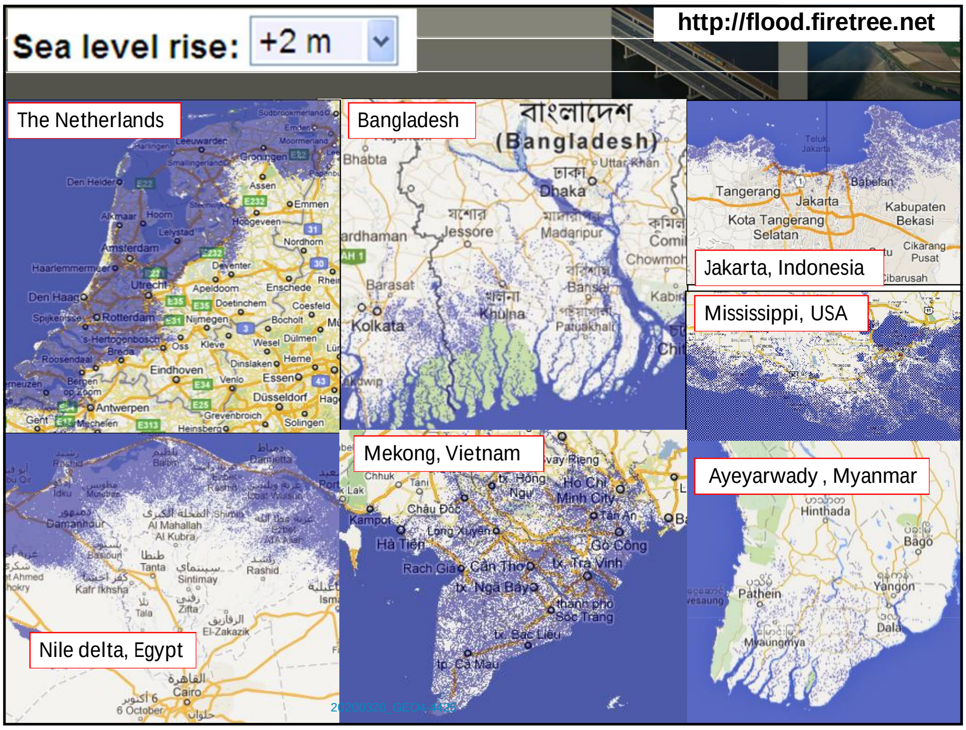
Threaths to deltas worldwide: subsidence, salinisation, depletion, sealing, sea level rise, CC



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

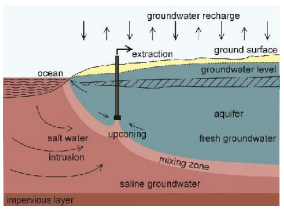


14 Colorado
After farms and urban areas have taken their water allotments, the Colorado River slows to a trickle by the time it reaches its delta. Sometimes it stops flowing altogether and then no sediment is deposited.
17 Po
The Po delta experienced a 6cm annual subsidence rate, due to sea-level rise and methane extraction. This reduced dramatically once methane extraction ended.
20 Yellow
As deltas sink the risk of flooding rises. In the Yellow River delta typhoons have caused 5m-high storm surges.
23 Chao Phraya
In 2011, the Chao Phraya river flooded swamping Bangkok and leaving much of the capital submerged for months. The city has been sinking for decades due to groundwater extraction. Steep taxes on groundwater have slowed subsidence substantially.
Amazon
Despite forest destruction, hydro-electric dam projects and more impacts upstream, the Amazon River delta is in relatively good health. Nearly 3 million people live on the delta but its sheer size dampens human impacts.
18 Nile
The Aswan Dam traps nearly 98% of sediment flow downstream. Without those soils, the Nile Delta has compacted and sunk. Relative sea-level rise there is 4.8 millimetres every year.
11 Ganges-Brahmaputra
The delta is home to over 100 million people making it the most populated on Earth. Effective sea-level rise is up to 18 millimetres per year. In 2007–08, substantial flooding affected the Ganges, Mekong, Irrawaddy, Chao Phraya, Brahmani, Mahanadi, Krishna and Godavari. More than 100,000 died and more than a million people were displaced.
13 Mekong
Like other deltas, farmers on the Mekong have cut down mangroves to create space for shrimp ponds. Surveys indicate roughly half the mangrove forests have disappeared. Mangroves help prevent erosion and are important flood defences.
ELEVATION (metres)
SOURCES

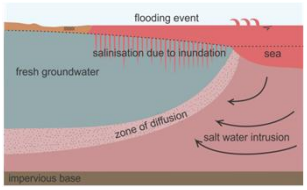


Sea level rise: +2 m
http://flood.firetree.net
The Netherlands
Bangladesh
Jakarta, Indonesia
Mississippi, USA
Nile delta, Egypt
Mekong, Vietnam
Ayeyarwady , Myanmar

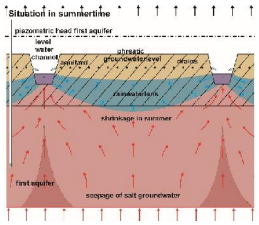
Salinisation processes at local scale



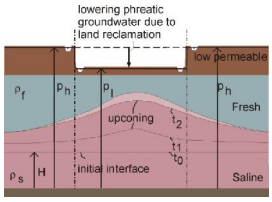
Salt water intrusion groundwater



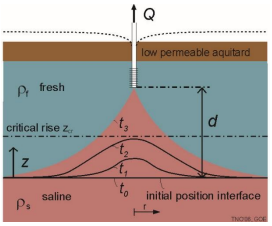
Inundation saline seawater



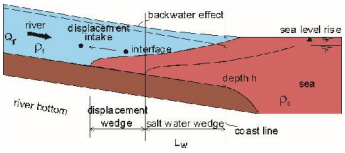
Shallow rainwaterlens



Upconing low-lying area



Upconing extraction

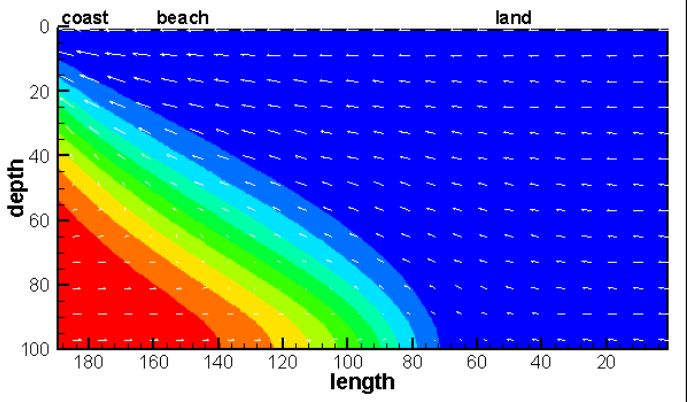


Salt water intrusion surface water

20200320_GEO4-4425

Impact of sea level rise on a coastal groundwater system:

a conceptual model of saltwater intrusion



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GOE, 2009

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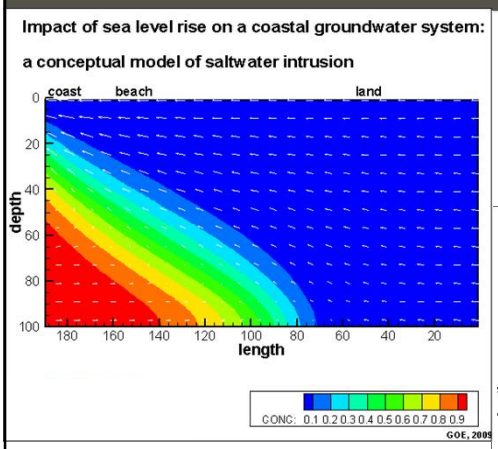
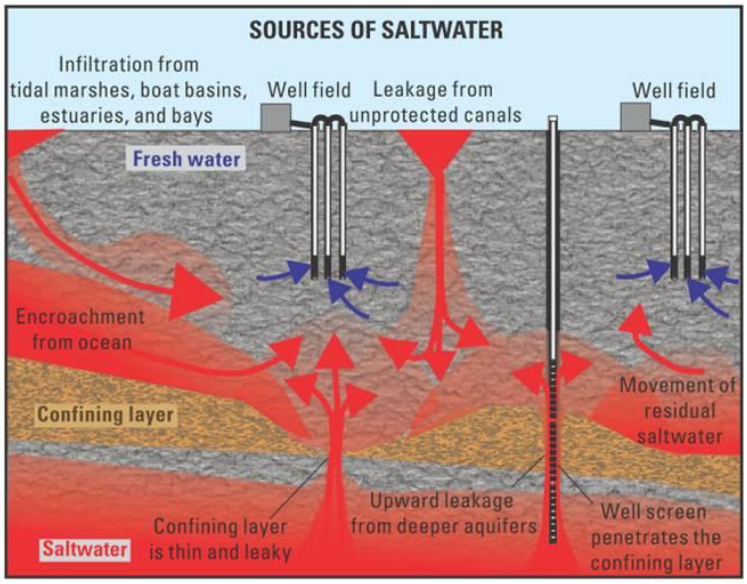
Sea level rise and salt water intrusion



Impact of sea level rise on a coastal groundwater system:
a conceptual model of saltwater intrusion
coast
beach
land
depth
length
CONC: 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
GOE, 2009

Combining salinization processes coastal zone



Prinos, 2014

In 1 liter ocean: about 35 gr salt

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

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

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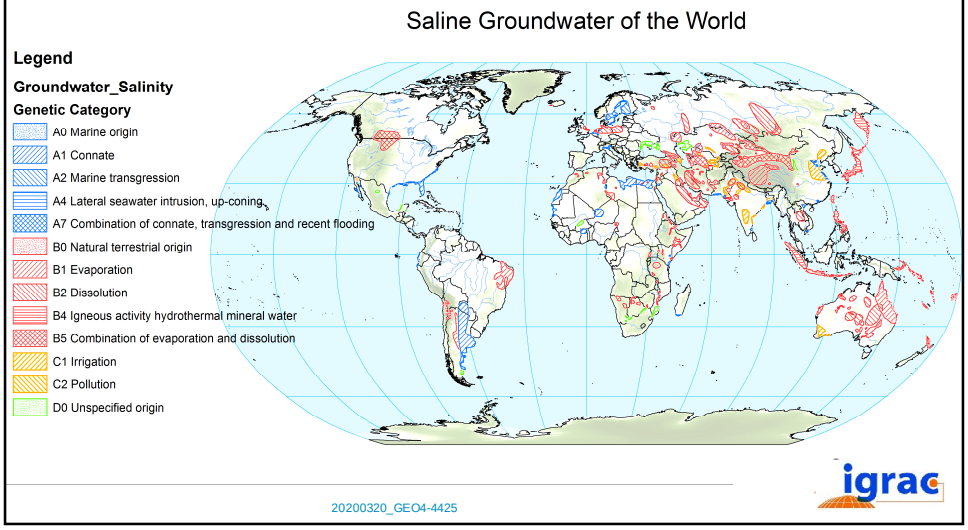
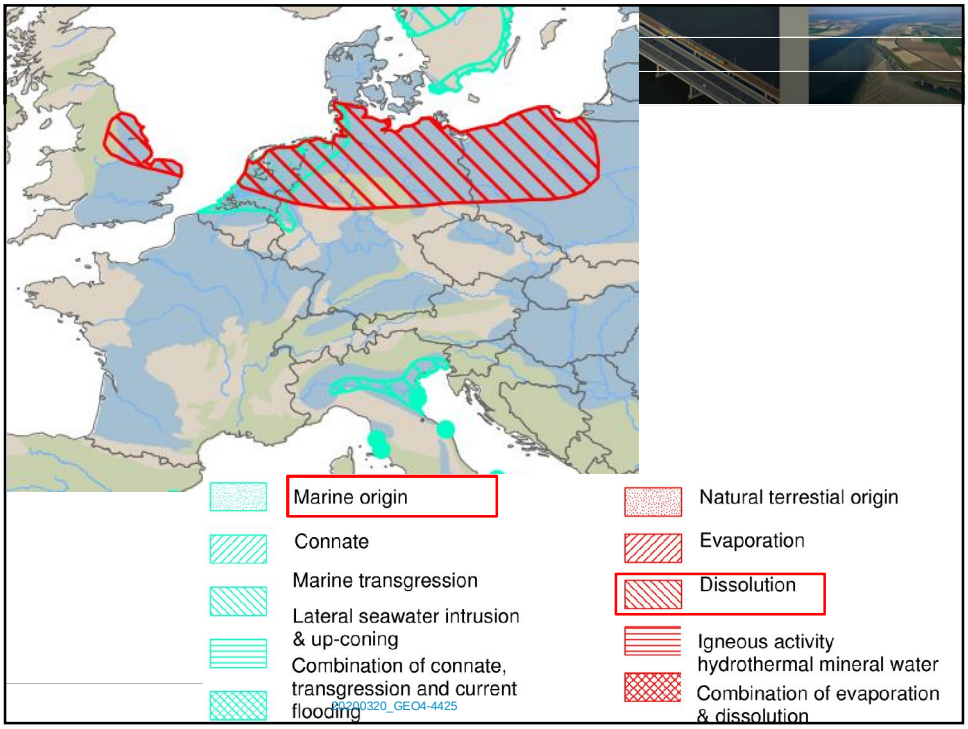
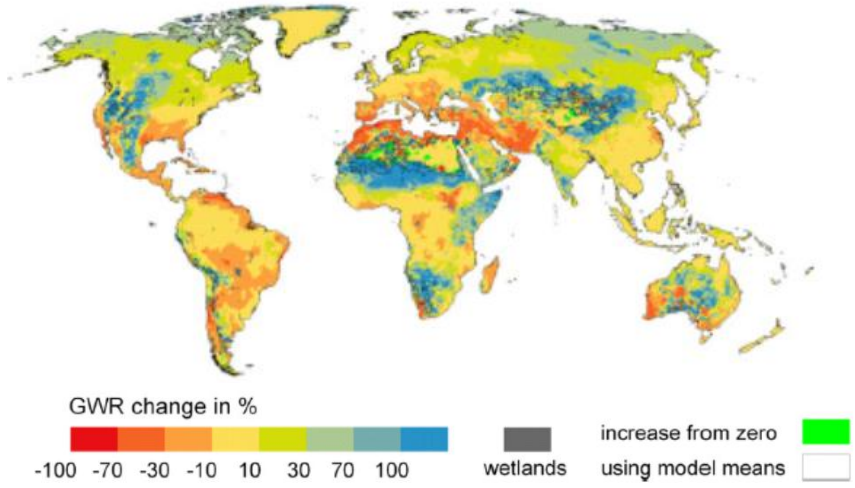
Rice can grow well in water with a salt content less than about 2.0 gr salt in 1 liter water

Stress 1: there is salt everywhere





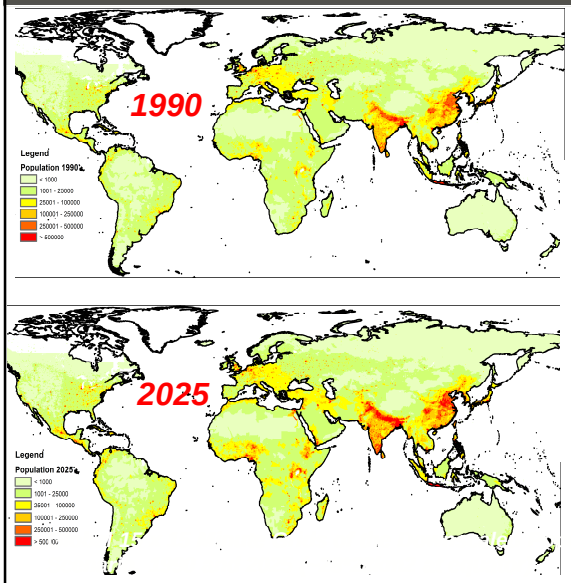
Stress 2: Change in groundwater recharge by end of century



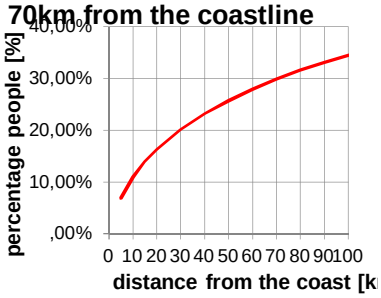
Projected percent changes of groundwater recharge by the end of this century with respect to present (1971–2000)
WaterGAP model with five different GCMs for RCP8.5

Portmann et al, 2013, ERL
From: Wada

Stress 3: Population growth 1990-2025, needing water



people in the first 70km from the coastline



20200320_GEO4-4425

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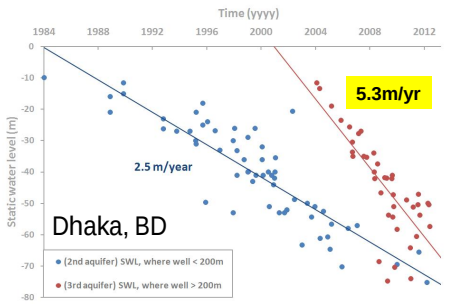
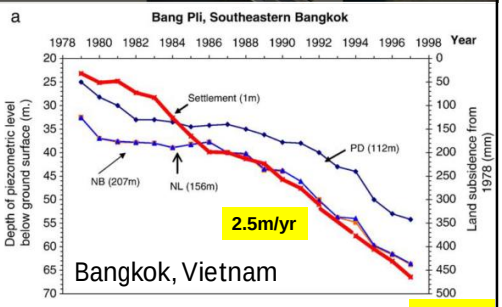
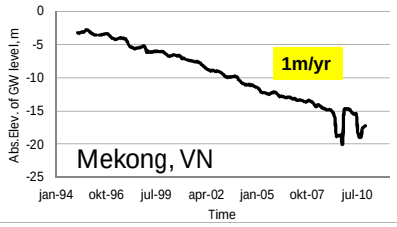
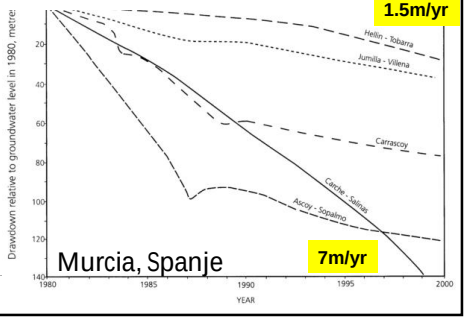
Stress 4: Serious overexploitation coastal aquifers worldwide





Elev. of GW level in aquifer n_2[1]





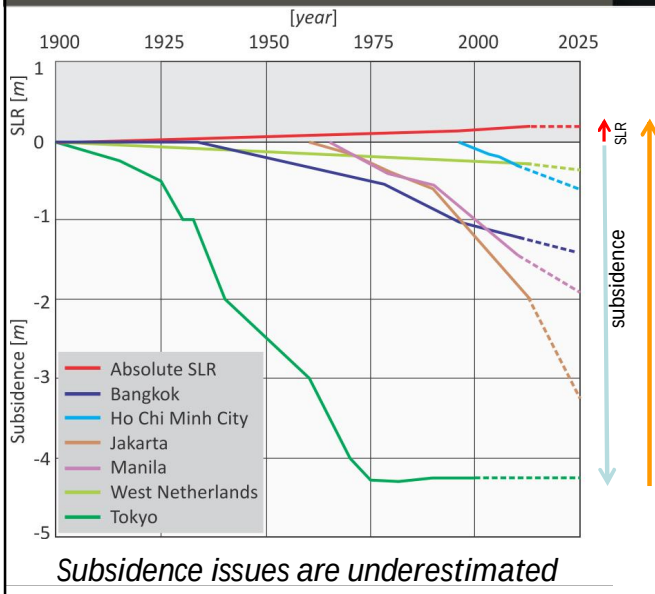
20200320_GEO4-4425

Groundwater overexploitation in Mekong Delta

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

20200320_GEO4-4425

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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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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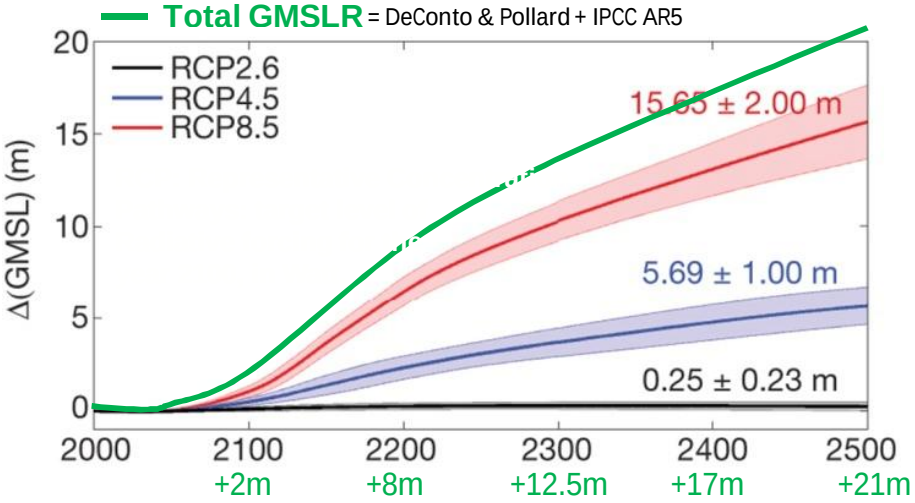
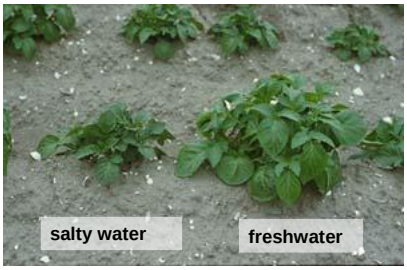
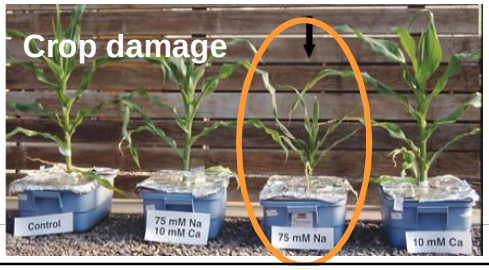
Stress 6: Global Mean Sea Level Rise (GMSL)



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

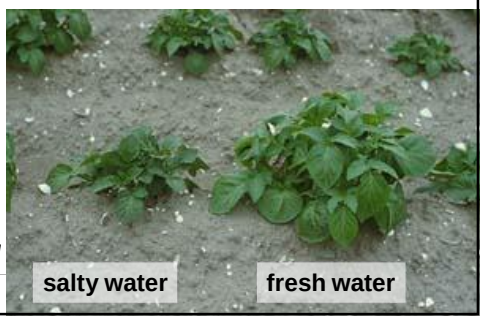
-drinking water:
- taste (100-300 mg Cl-/l)
- long term health effect
- norm: EC& WHO=150 mg Cl-/l (live stock=1500 mg Cl-/l)

-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

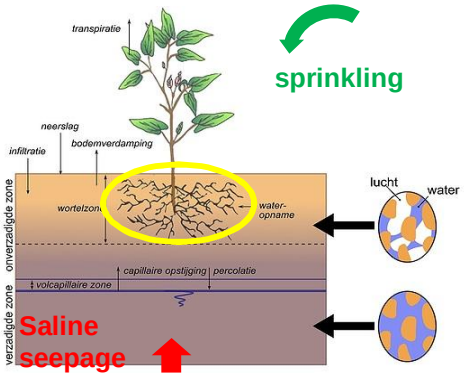
Source: Proefstation voor de Akkerbouw en Groenteteelt, Lelystad

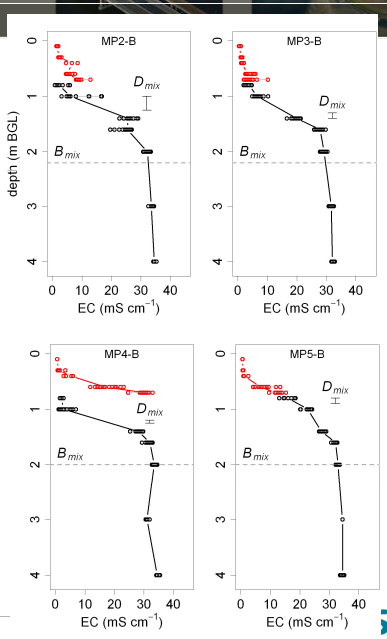


Salt tolerance crops

precipitatioon

sprinkling



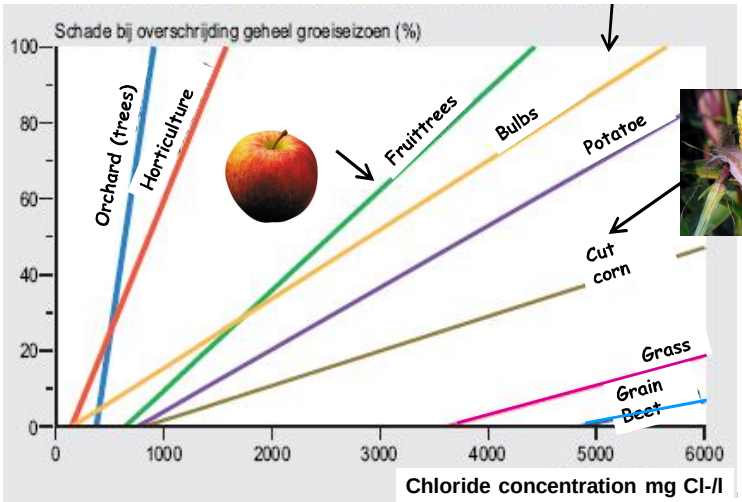


Important parameters:

- **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	

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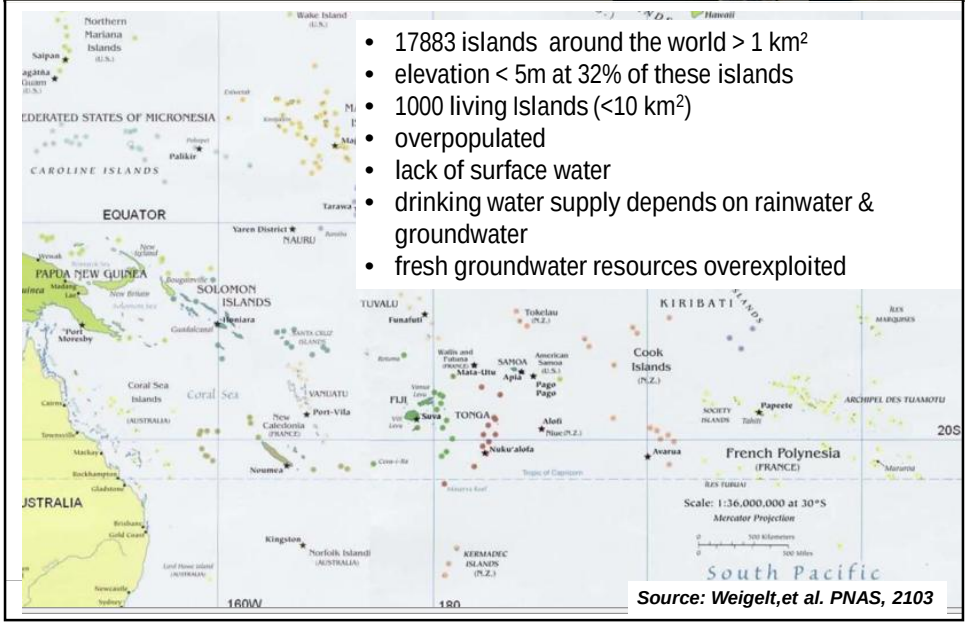
Fresh groundwater resources in SIDS under climate and global stresses

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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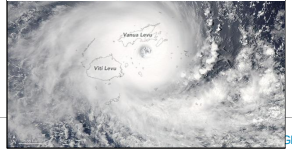
Headlines: SIDS / Water Resources / Climate Change

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

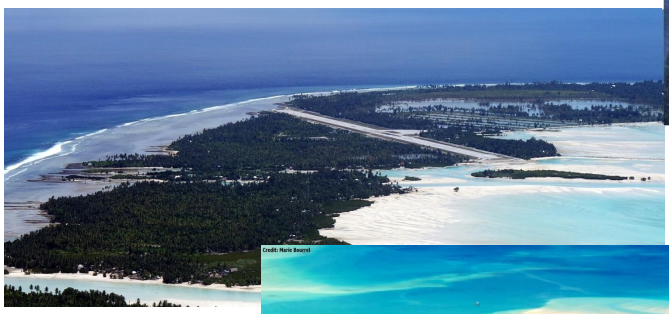
Winston the strongest, first Category 5 cyclone to hit Fiji



1907 (Vanuatu) (most likely 1905-1906)

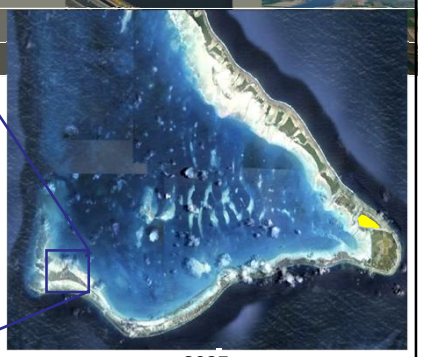
'Emau – we are having a very long drought here and in much need of rain to water the ground...The Emau people have no water either to drink or cook food with, and are boating over from Efate. The coconut trees are ceasing to bear, and some of them are dying....'
The New Hebrides Magazine
January 1907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

Case Kiribati: fresh water supply



Case Kiribati: fresh water supply

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



Today

38 litres per person per day

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

~50%

Supply system losses

Current estimates of leakages and losses in transmission

~2 x

More people

Potential population increase at current growth rates

>5%

Climate impact

Potential climate change impact on sustainable yield over 20 year period

2035

<9 litres per person per day

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

Source: Hebblethwaite, D. (2015)

The challenge

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

Anote Tong President of Kiribati

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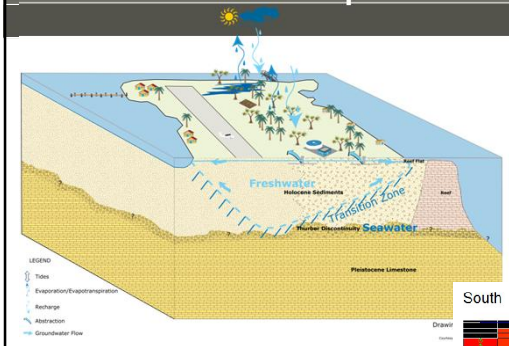
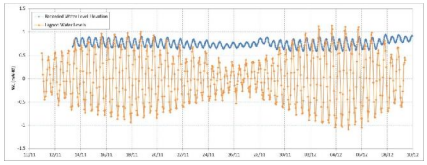
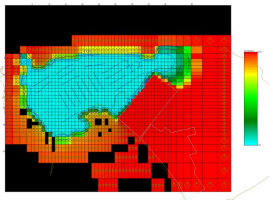
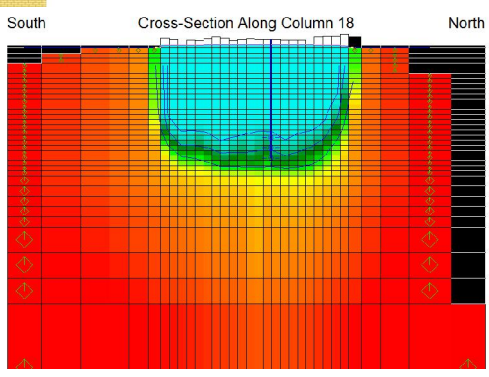
Case Kiribati: Conceptual and numerical modelling tools

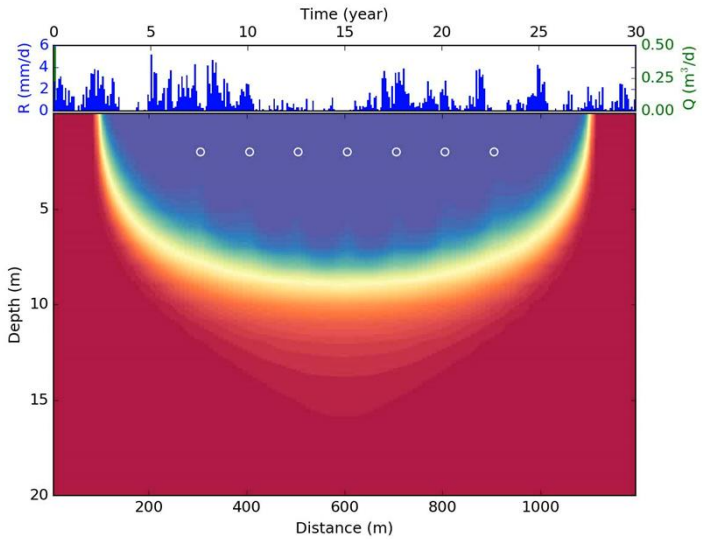




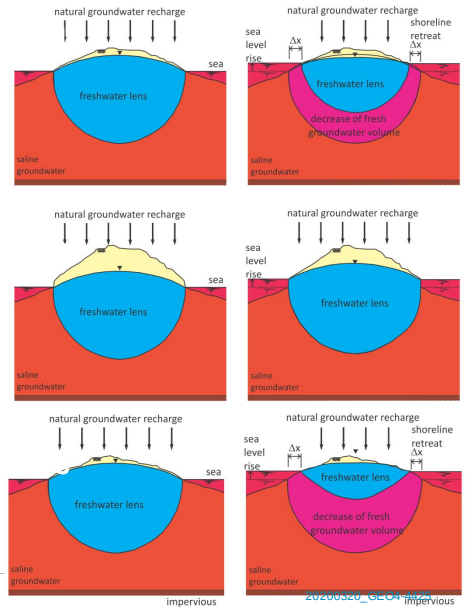




Case Kiribati: Numerical modelling tools



Stresses to fresh groundwater lenses



Case Kiribati: Understanding the groundwater system



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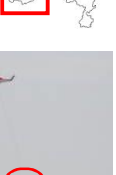
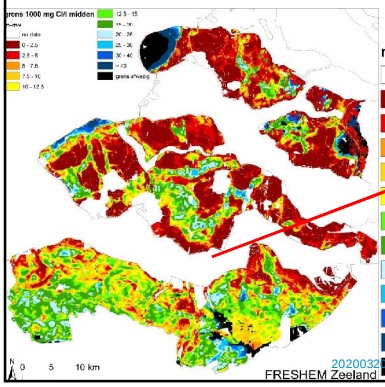
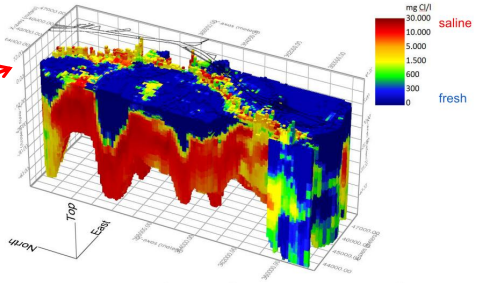
Mapping the salinity distribution

TNO innovation for life BGR Deltares Enabling Delta Life

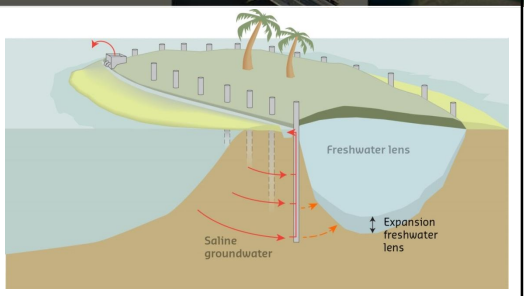
FRESHEM Zeeland

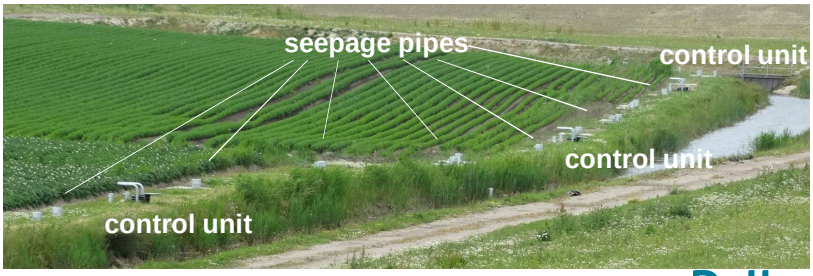


FRESHEM pilot Canal zone, visualization in iMOD

Seepage systems

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





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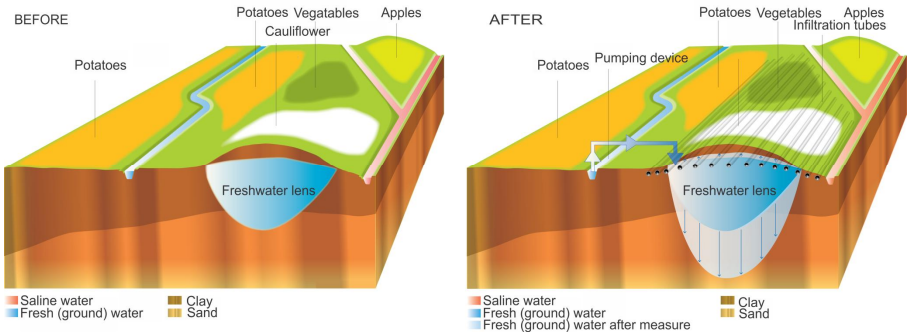
ASR / MAR

Aquifer Storage and Recovery / Managed Aquifer Recharge



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GO-FRESH
imaGeau
FUGRO

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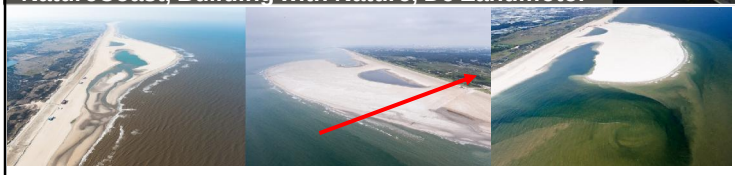
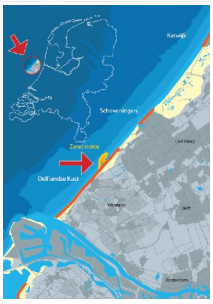
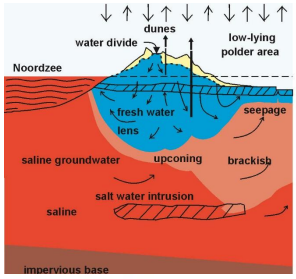
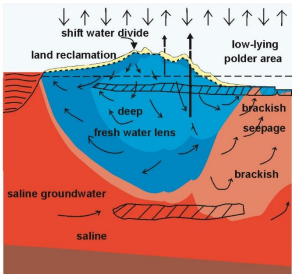
Increase strategic freshwater reservoirs in the coastal zone

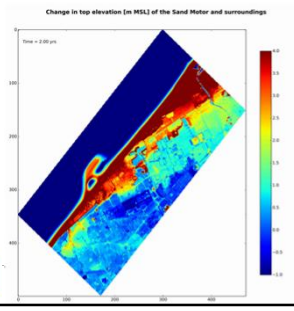
NatureCoast, Building with Nature, De Zandmotor

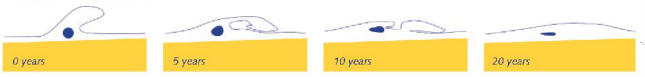




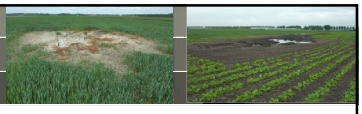








Salt resistant crops on salinized soils



Meijer FOR SURE

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2020035-GEO4-4425

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Enabling Delta Life

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

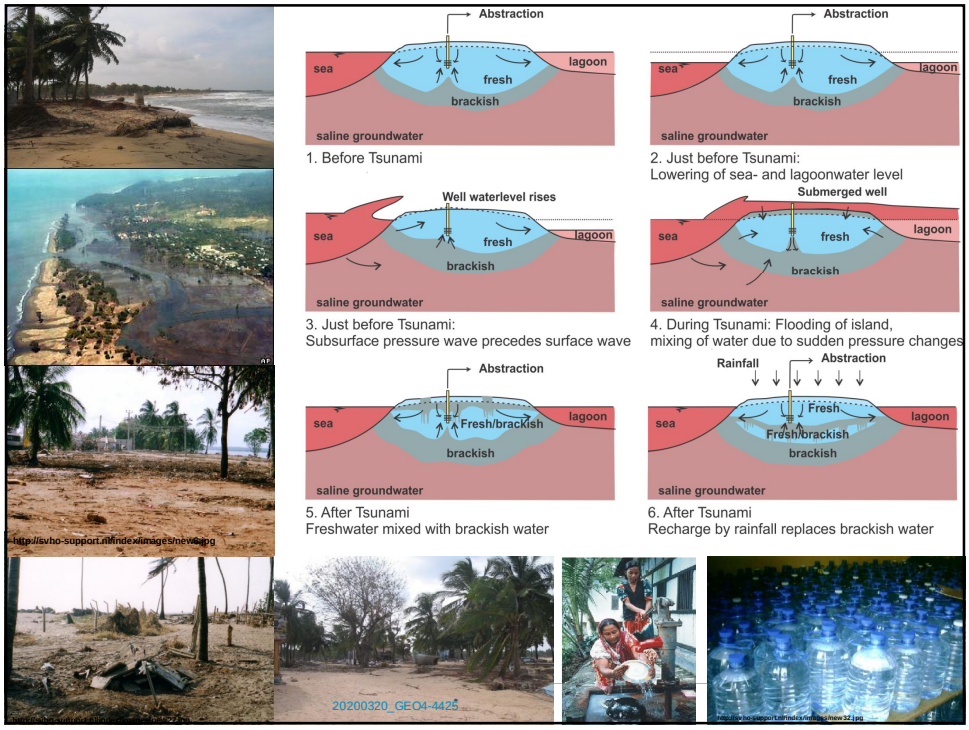
**or other flooding events*

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

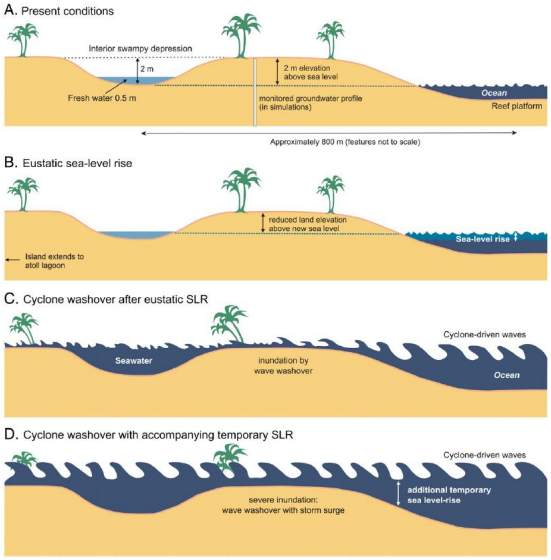
[2] WAGENINGEN UR

[3] Universiteit Utrecht

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



The fate of freshwater lenses on atoll islands



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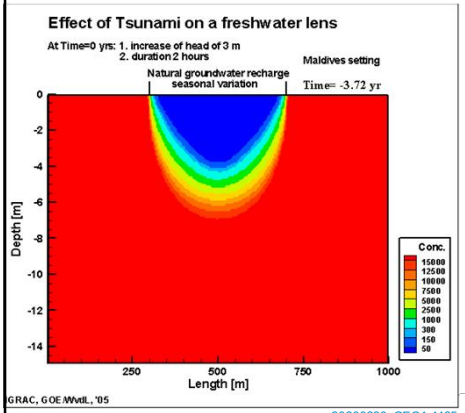
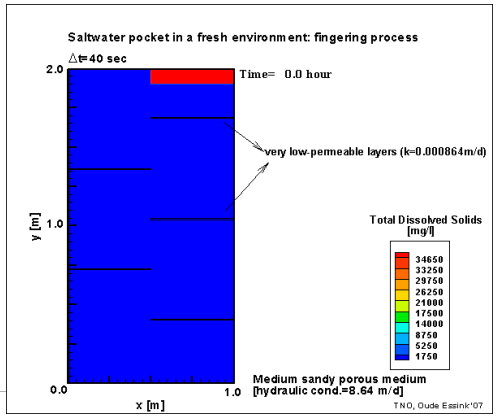
Salinisation processes of fresh groundwater reserves

Impression of relevant salinisation processes in coastal aquifers:

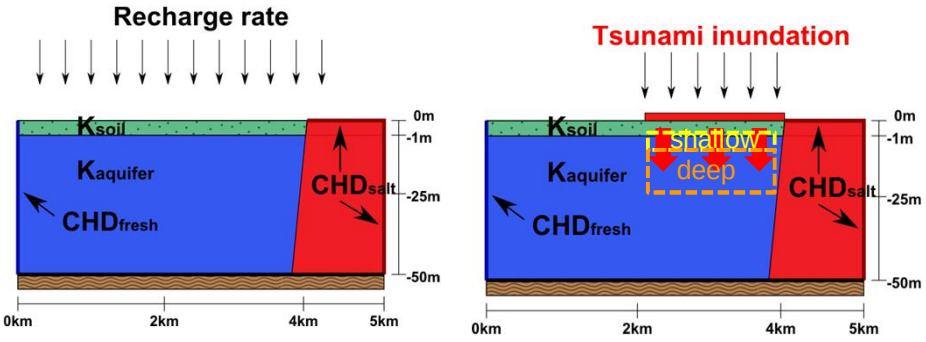
- Contamination freshwater lens after sea water flooding
- Saline fingering processes in the subsoil





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

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?

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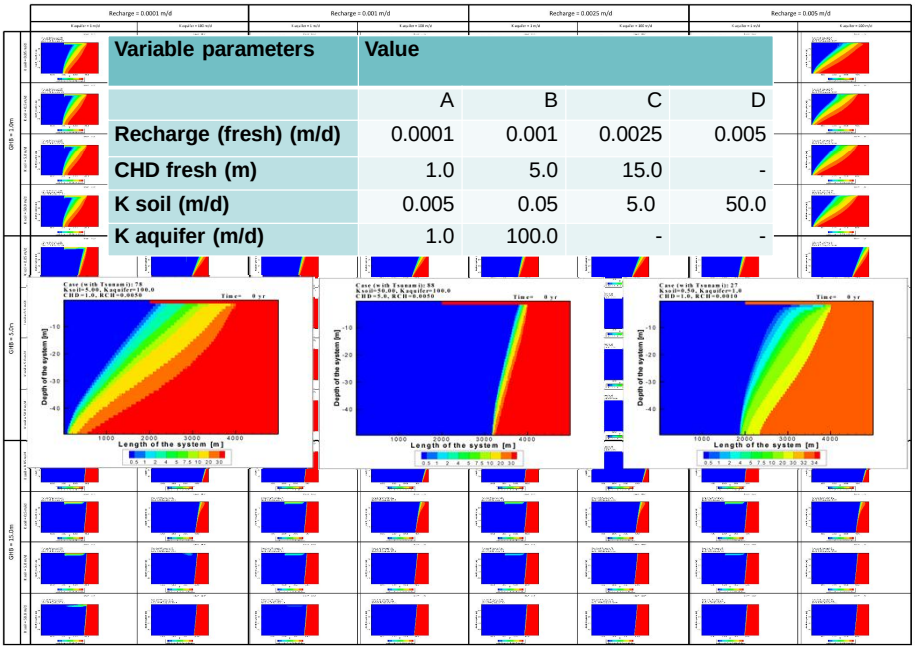
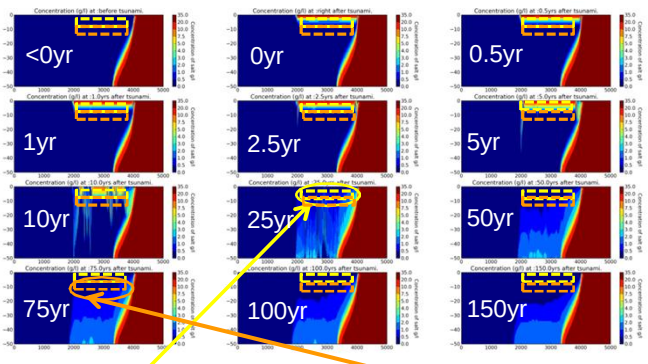
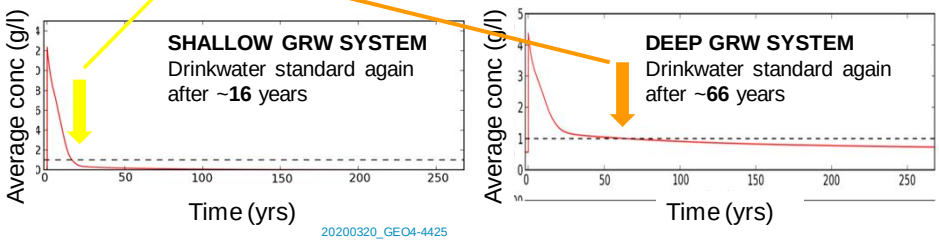


Variable parameters	Value			
	A	B	C	D
Recharge (fresh) (m/d)	0.0001	0.001	0.0025	0.005
CHD fresh (m)	1.0	5.0	15.0	-
K soil (m/d)	0.005	0.05	5.0	50.0
K aquifer (m/d)	1.0	100.0	-	-

Results of one case



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



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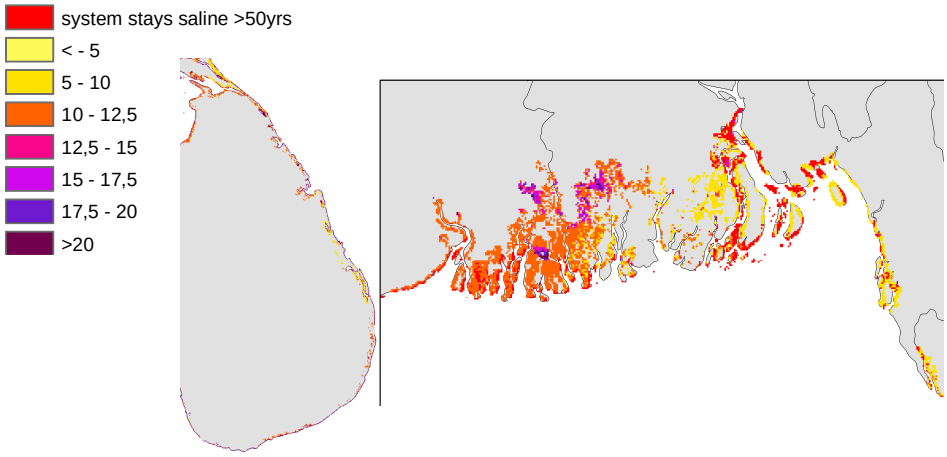
Mapping the results

- 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



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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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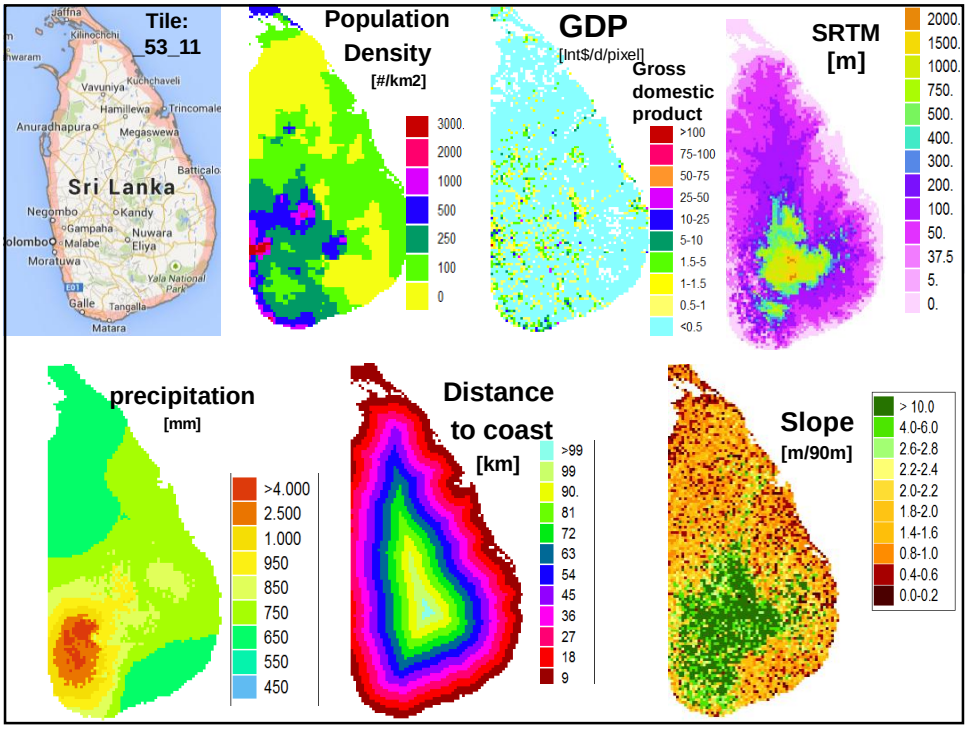

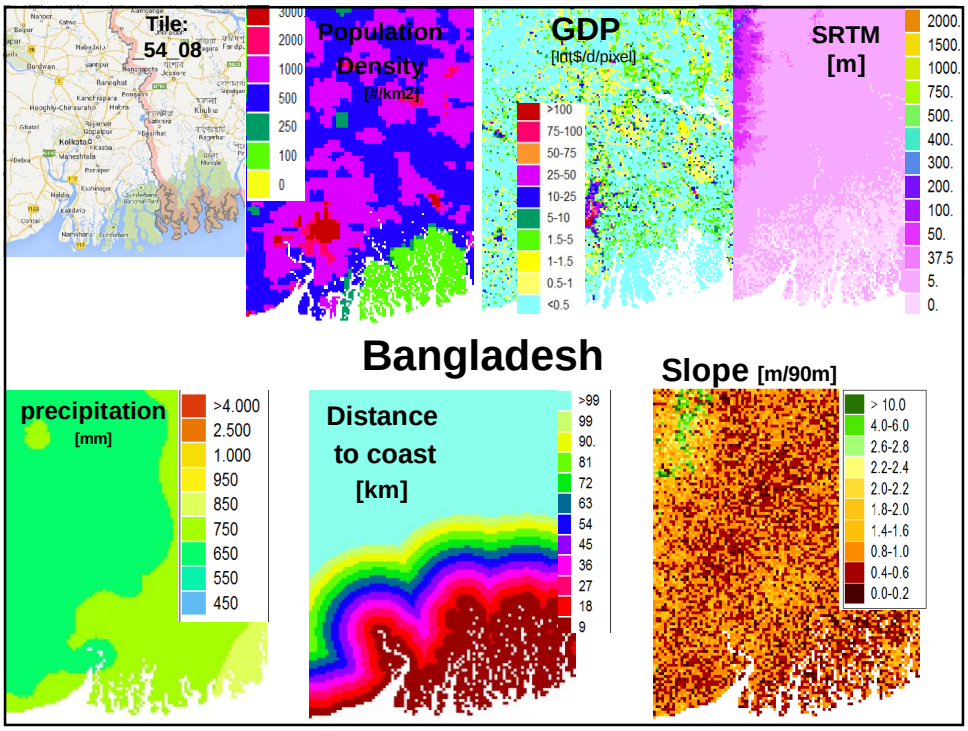

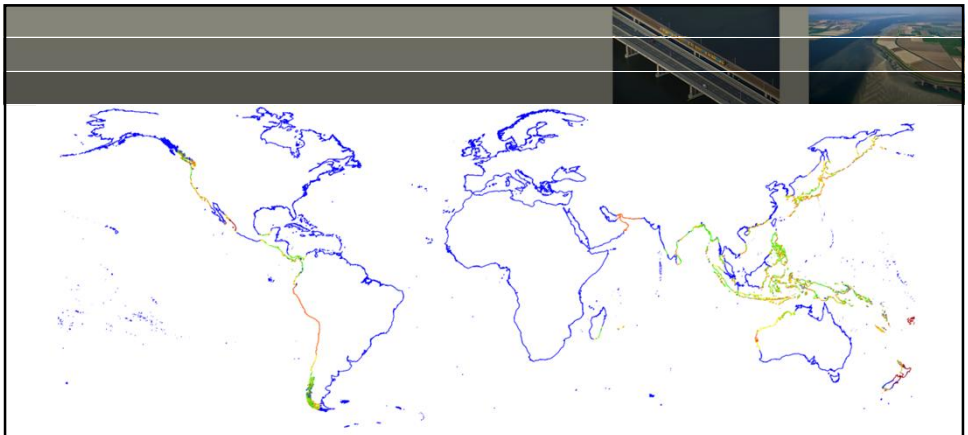

Vulnerability of groundwater aquifers to tsunami effects, evaluated as time (yrs.) necessary for aquifer to reach 95% fresh-water distribution of pre-tsunami state, indicating drinking water availability using groundwater resources in coastal zones after flooding disasters

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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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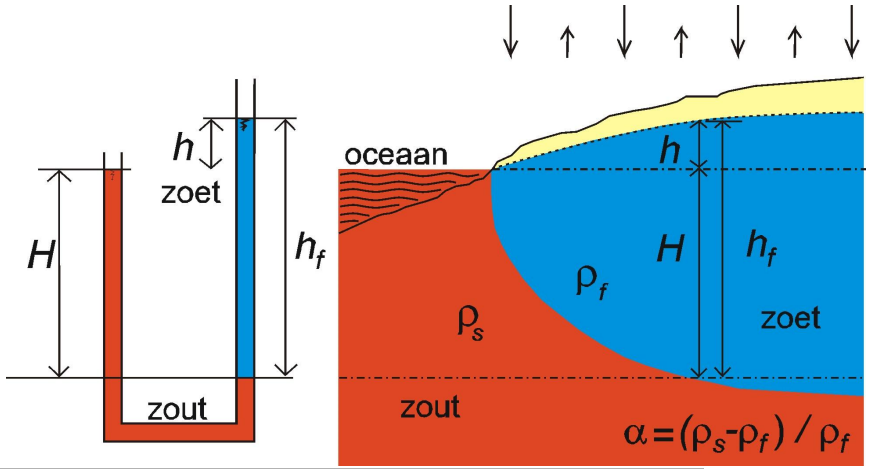
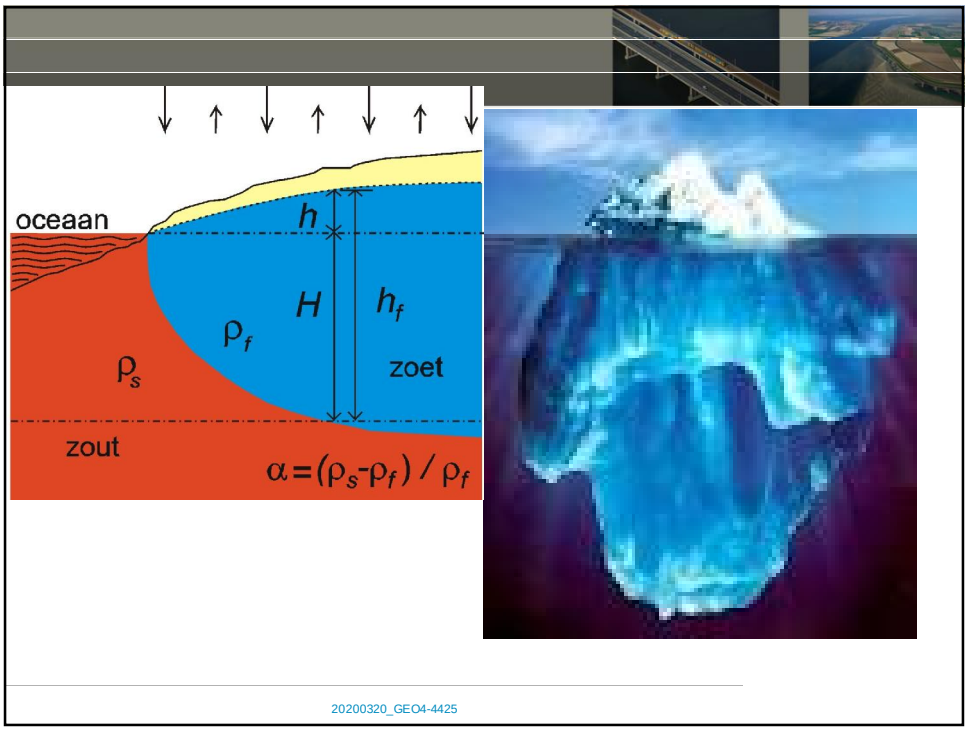
Badon Ghijben-Herzberg principle

The principle suggests an interface between fresh and saline groundwater

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



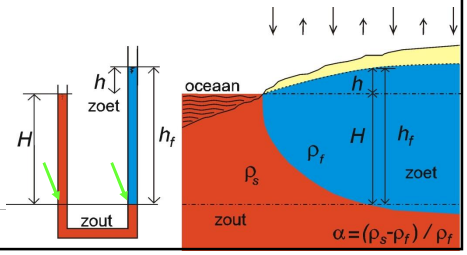


pressure saline groundwater=pressure fresh groundwater

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

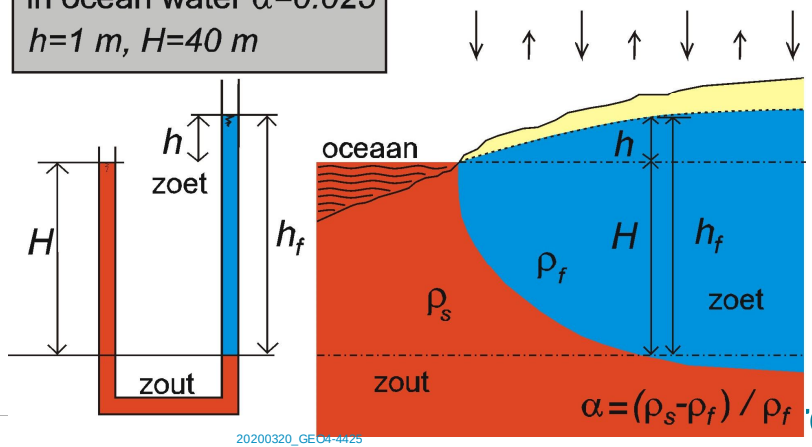
$$h = \frac{\rho_s - \rho_f}{\rho_f} H$$

$$h = \alpha H$$



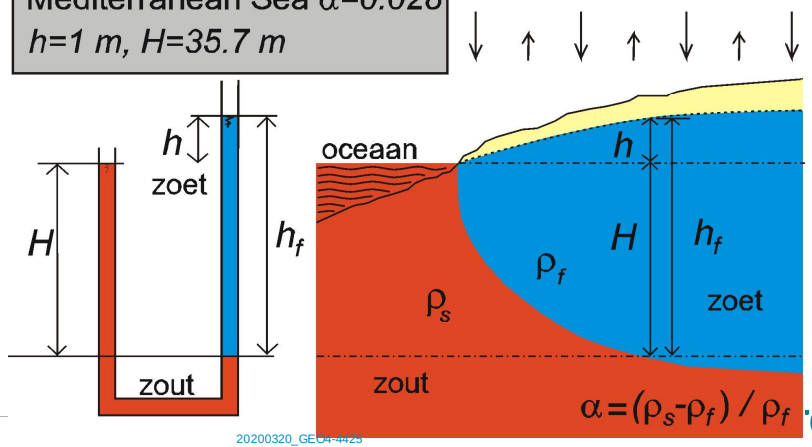
$$h = \alpha H$$

$h=\alpha H$
in ocean water $\alpha=0.025$
$h=1$ m, $H=40$ m



$$h = \alpha H$$

$h=\alpha H$
Mediterranean Sea $\alpha=0.028$
$h=1$ m, $H=35.7$ m



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

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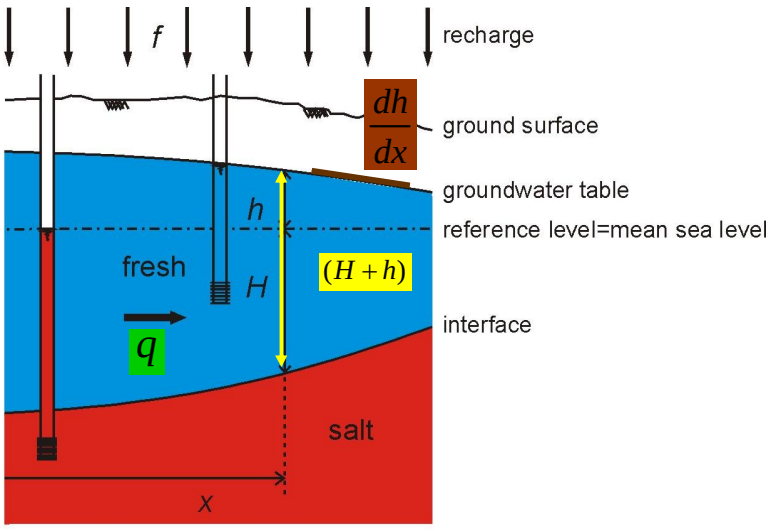
Unconfined aquifer (1D situation)



Unconfined aquifer (1D situation)

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

(II) Continuity $dq = fdx$

(III) BGH $h = \alpha H$

Unconfined aquifer (1D situation)

$dq = fdx$ integration gives $q = fx + C1$

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

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

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

Unconfined aquifer (1D situation)

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

integration gives

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

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

Unconfined aquifer (1D situation)

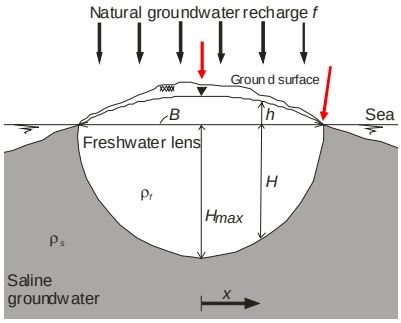
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}}$$

$$h = \alpha H$$

$$q = fx + C1$$

Example 1: Elongated island

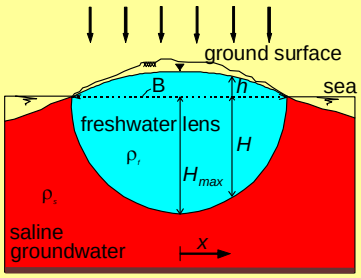
$$H = \sqrt{\frac{-fx^2 - 2C1x + 2C2}{k\alpha(1+\alpha)}} \qquad q = fx + C1$$



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

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

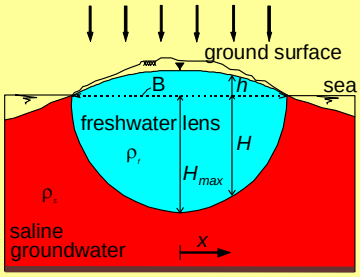
Volume lens

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

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

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)

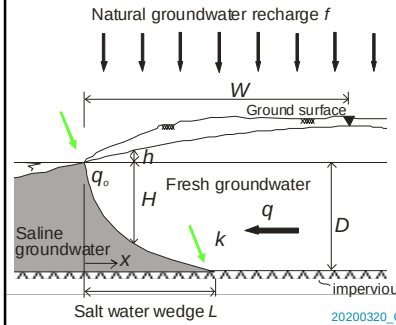
$V = 35203\text{m}^3/\text{m}'$

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

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

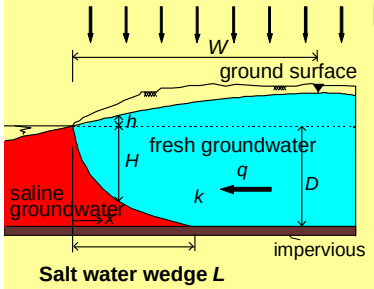
$x = 0 : q = q_0 \rightarrow q_0 = -fW \rightarrow C1 = q_0$

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

Length of salt water wedge

$x = L : H = D$

Example of analytical solutions (II)



Salt water wedge *L*

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

$$q_0 = -fW$$

$$h = \alpha H$$

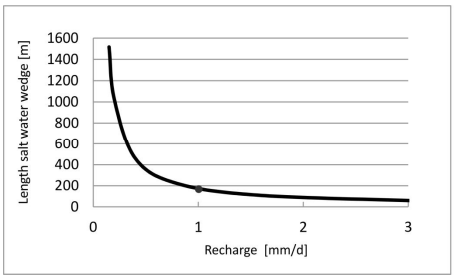
Example:

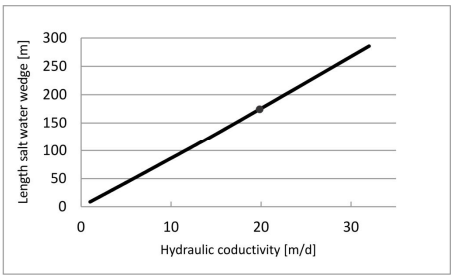
$$W = 3000\text{m},\ f = 0.001\text{m/day}, \alpha = 0.020, k = 20\text{m/day}, D = 50\text{m}$$

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

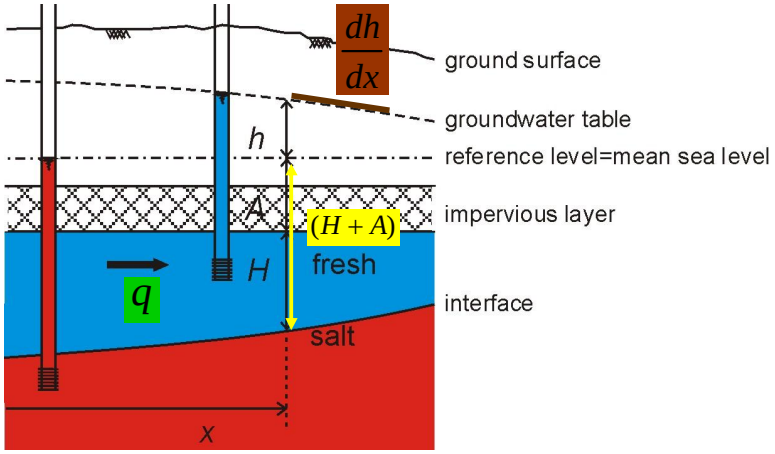
Lecture notes p. 33

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)

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

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

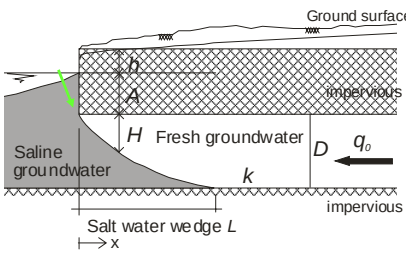
integration gives

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

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

Example 3: salt water wedge confined aquifer

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



Boundary condition

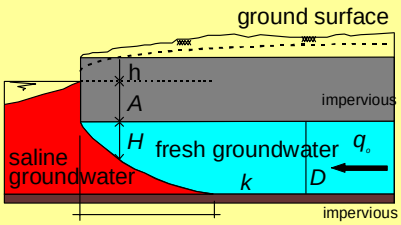
$$x = 0 : H = 0 \rightarrow C = 0$$

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

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:

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

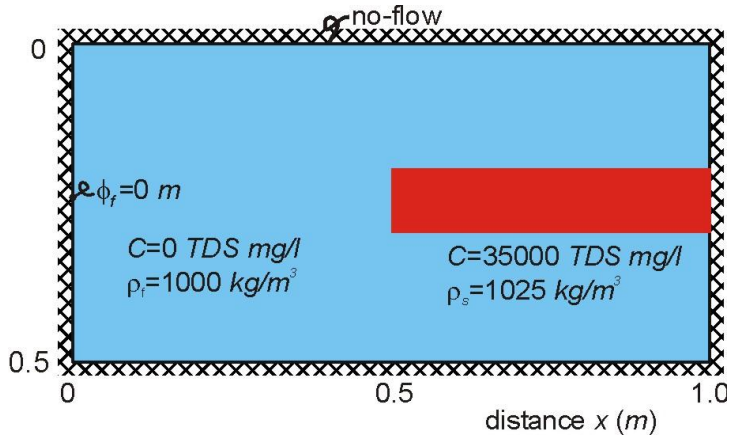
$$L = 250\text{m}$$

Lecture notes p. 35-36

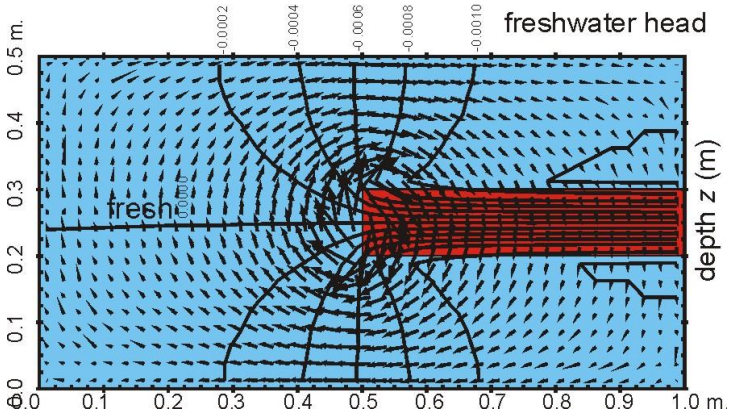
Thank you for your attention!

More information:
freshsalt.deltares.nl

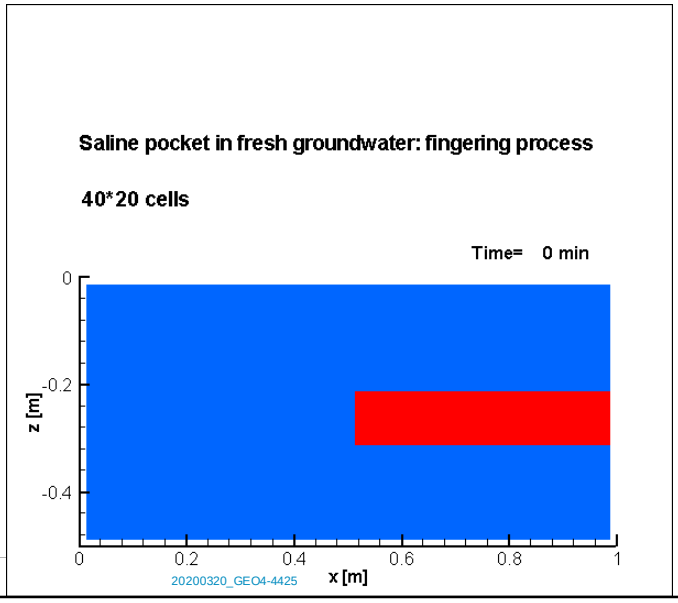
Effect of size model cell on physical process



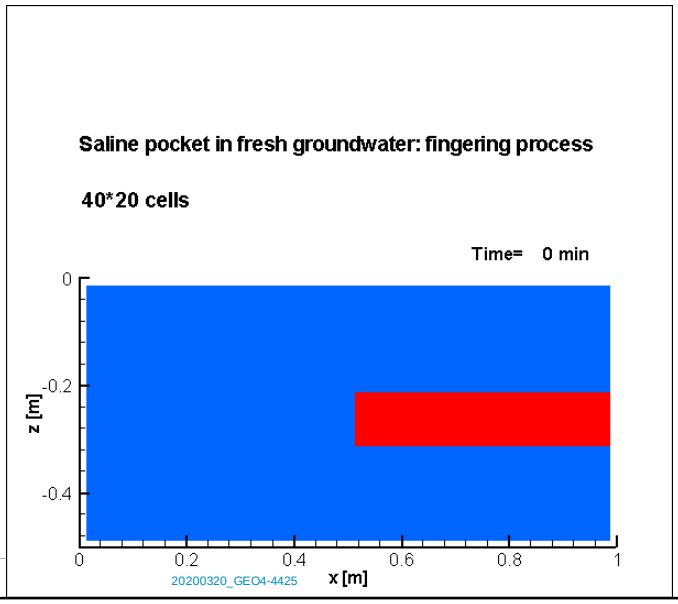
Effect of size model cell on physical process



SALT WATER POCKET IN A FRESH ENVIRONMENT



SALT WATER POCKET IN A FRESH ENVIRONMENT



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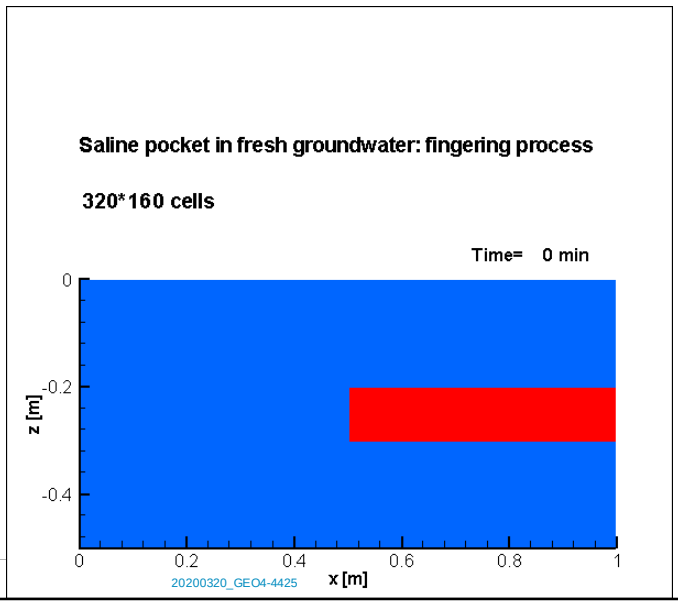
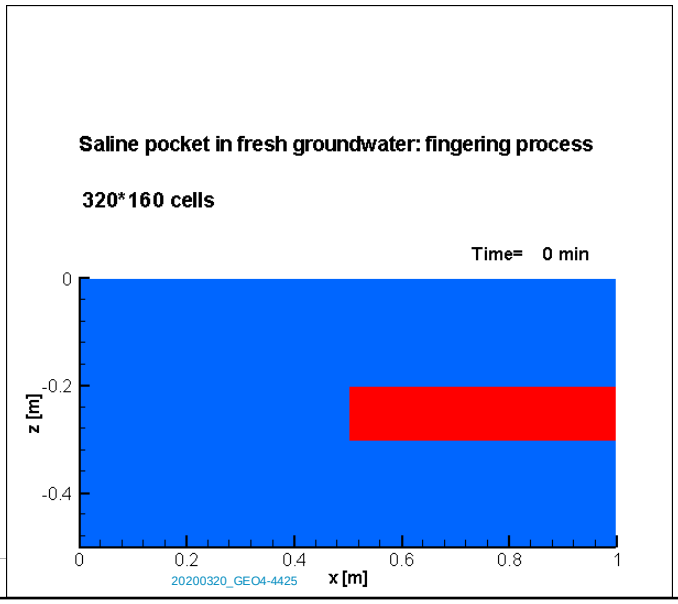
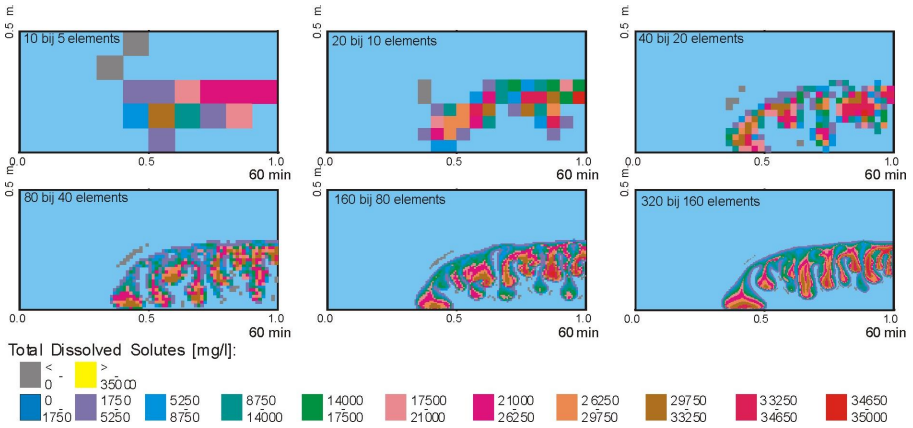


SALT WATER POCKET IN A FRESH ENVIRONMENT

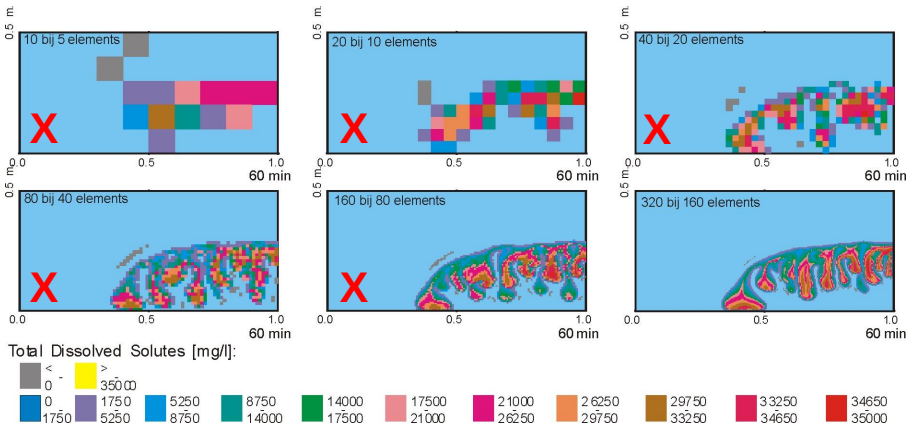


Effect of model cell size on physical process



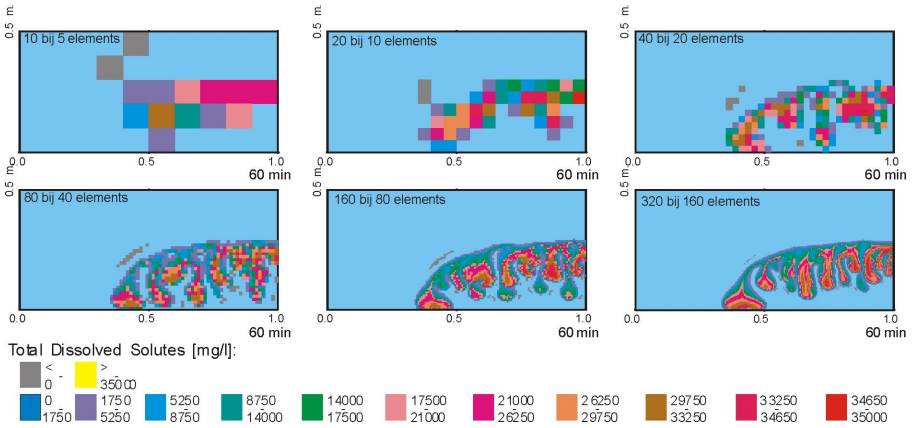
Model size cell has a **large** effect on modelling result!

Effect of size model cell on physical process



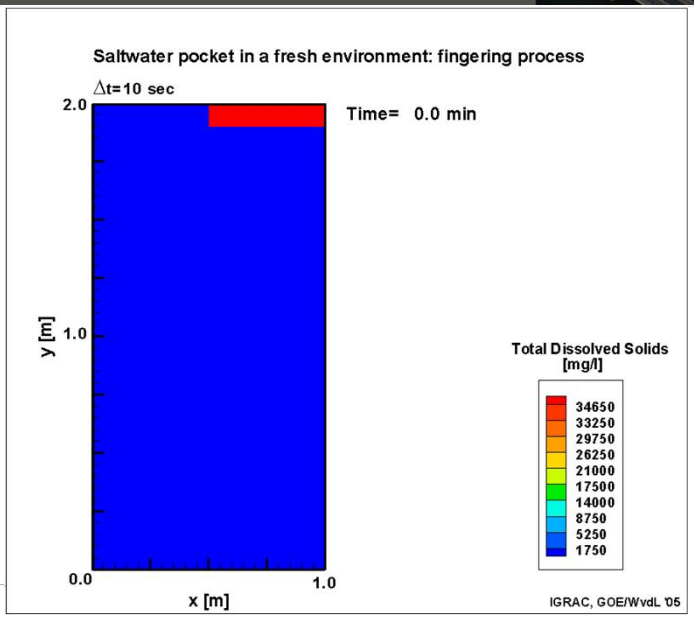
X= LOUSY models for predicting exact number of salt water fingers

Effect of size model cell on physical process



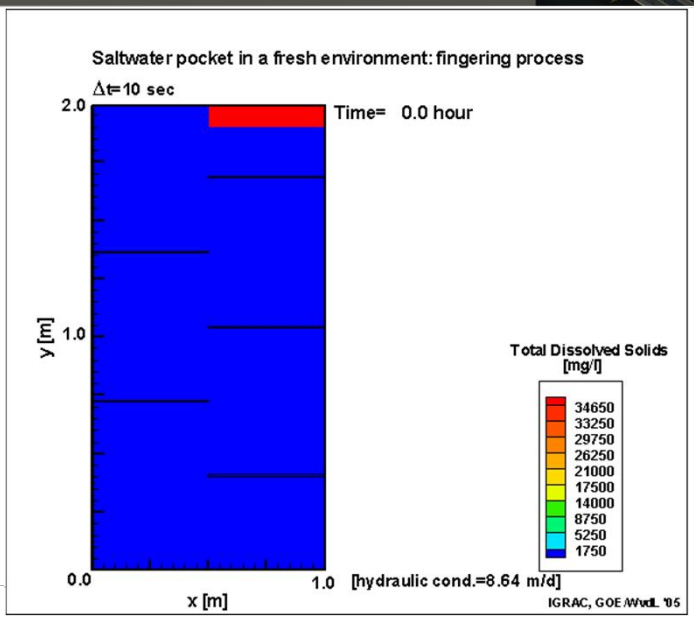
All models are GOOD for predicting moment of touching bottom (60min)!

Fingering processes in the subsoil



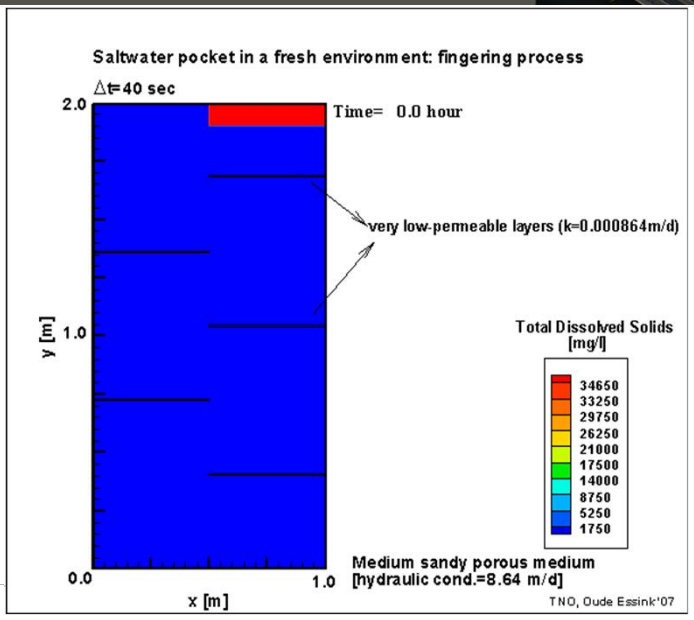
Deltares

Fingering processes in the subsoil



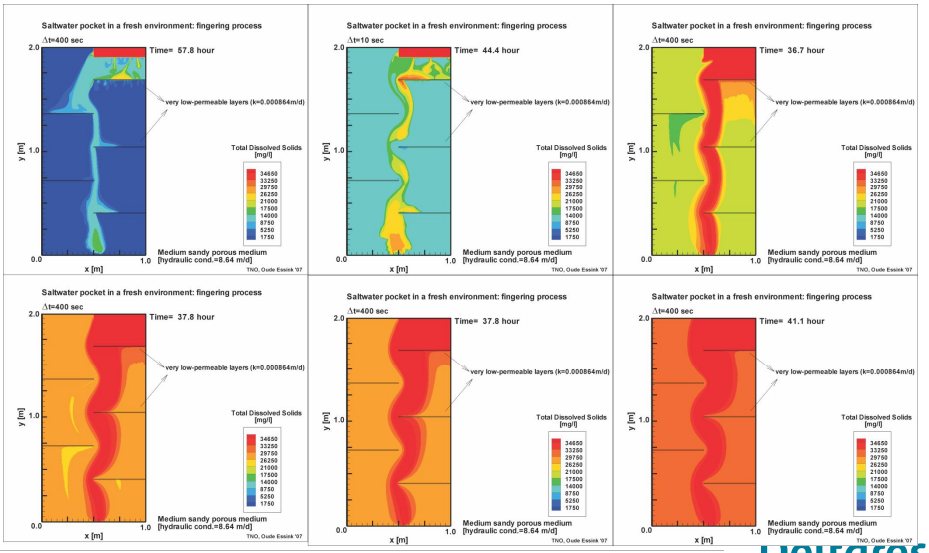
Deltares

Fingering processes in the subsoil



Deltares

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



Deltares

Base idea

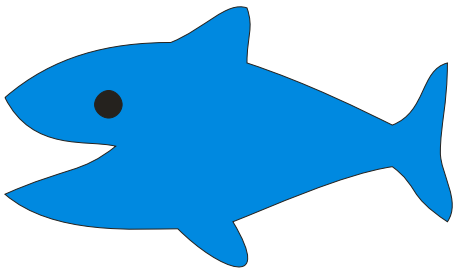
Many local solutions for fresh groundwater supply can have regional impact

20200320_GEO4-4425

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

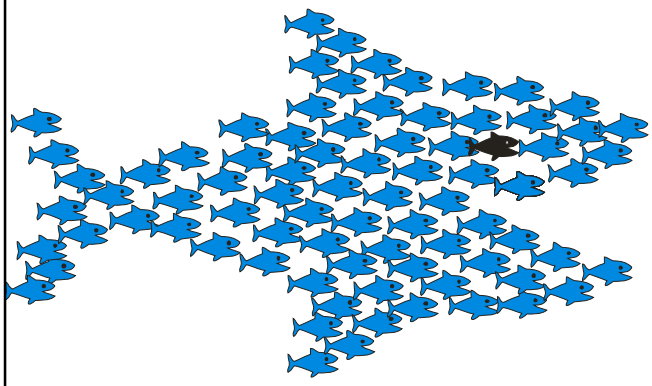
Local solution fresh groundwater supply

climate and global change

What should be the response?

Many local solutions fresh groundwater supply

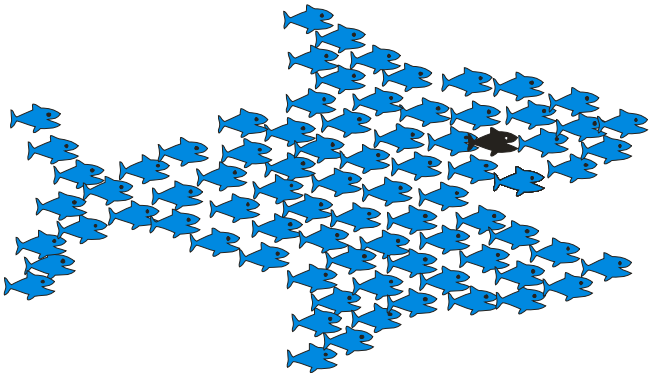
climate and global change



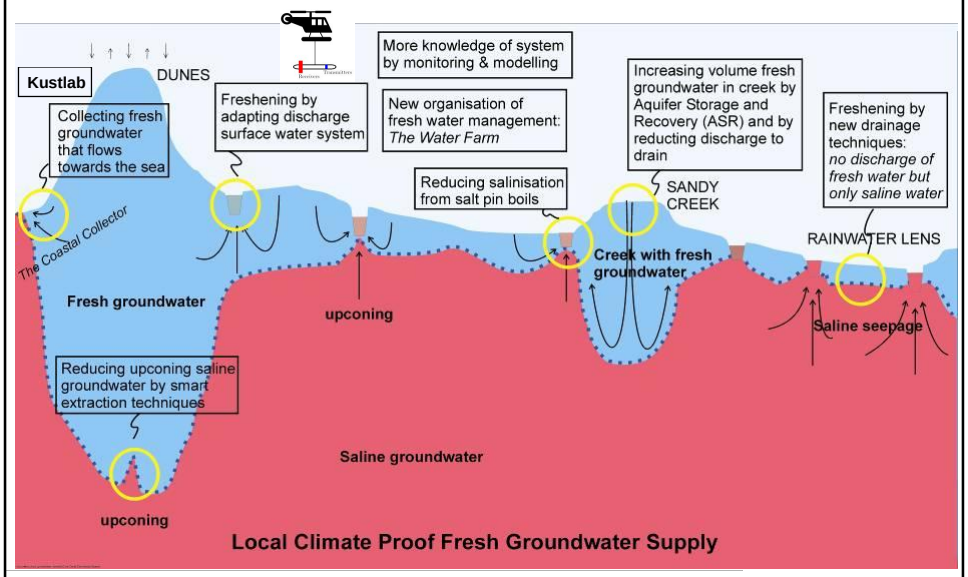
Many local solutions for fresh groundwater supply can have regional impact

Key activities

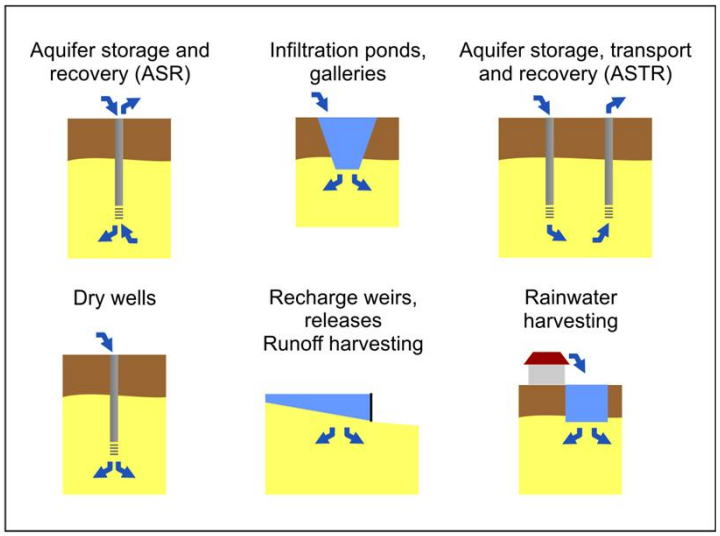
-upscaling local cases to regional strategy
-assess economical feasibility
-increase impact: communicate our showcases
-working together



Local climate proof fresh water supply

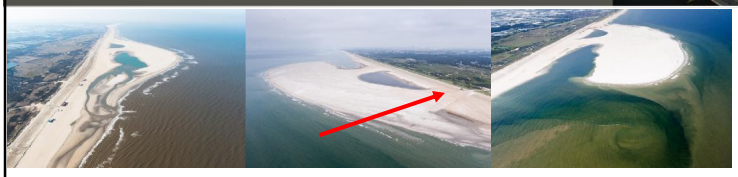


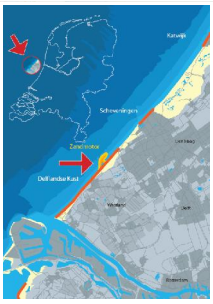
Aquifer Storage and Recovery / Managed Aquifer Recharge



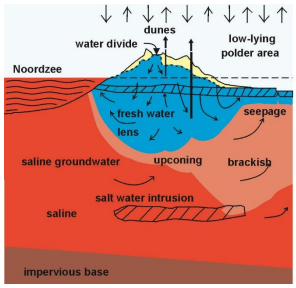
Deltares

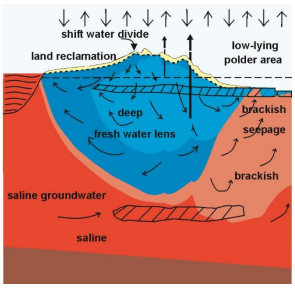
Increase strategic freshwater reservoirs in the coastral zone

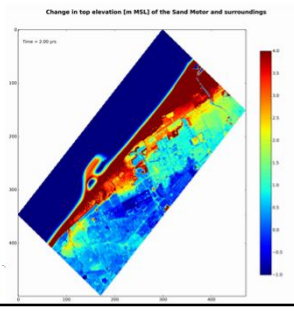


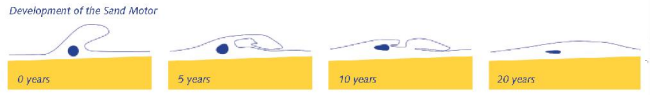


NatureCoast, Building with Nature, De Zandmotor





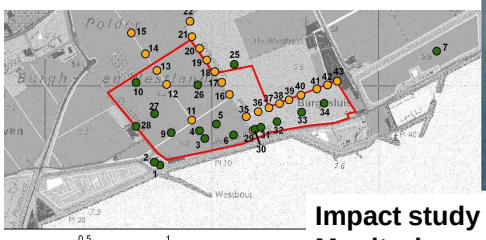




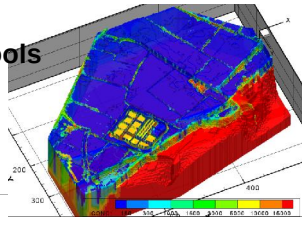
The Coastal Laboratory: aquaculture on fertile land

Three elements in one masterplan:

- **Coastal protection**
- **Sustainable food supply (aquaculture)**
- **Landscape and nature development**



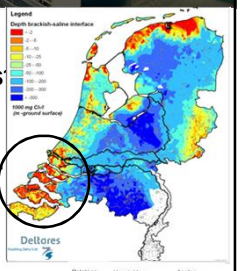
Impact study
Monitoring
Dimensionering saline pools

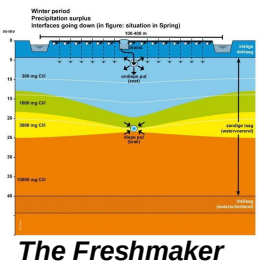


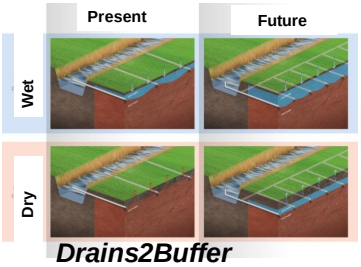
GO-FRESH: Local measures to increase fresh water supply

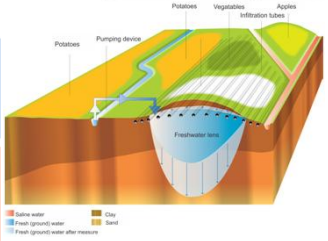
Goal:
Increasing fresh groundwater reservoirs in saline coas

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









The Freshmaker
Injection fresh water and extraction saline

Drains2Buffer
Smart deep drainage protects thin freshwater lens

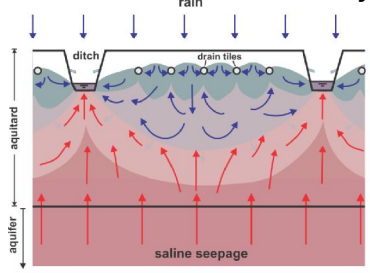
Creek Ridge Infiltration Te
Elevation ground water level
by infiltration surface

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

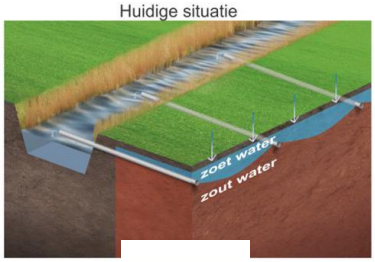
Deltares

Drains2Buffer

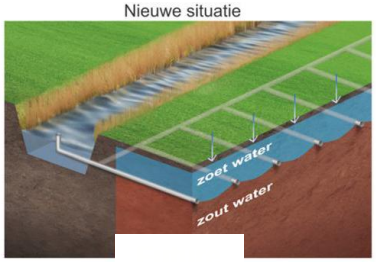
Increase rainwater lens volume to reduce root zone salinity



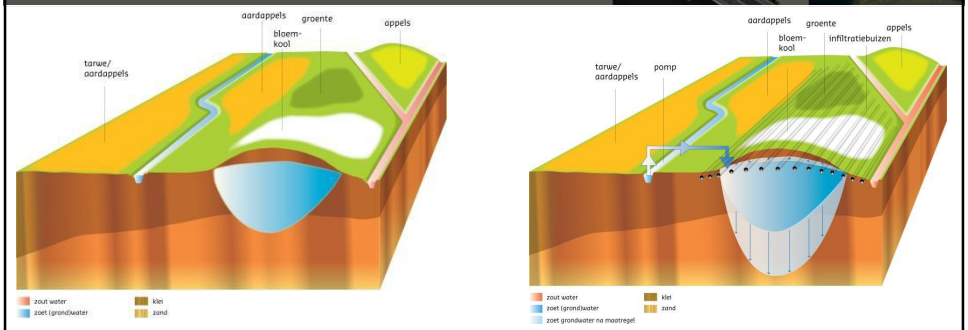
Huidige situatie

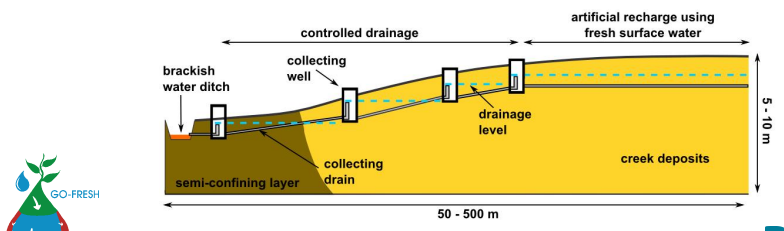


Nieuwe situatie



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

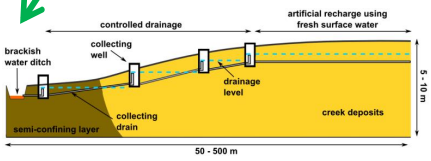


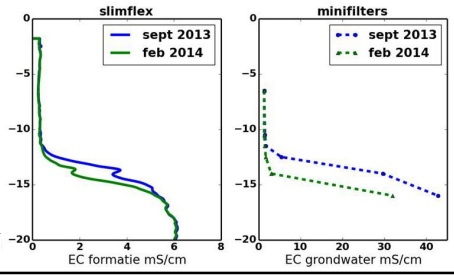


GO-FRESH

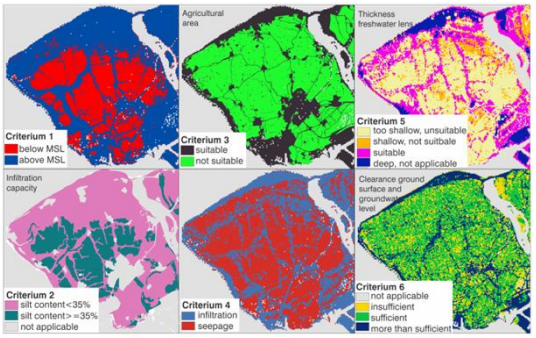
Deltares

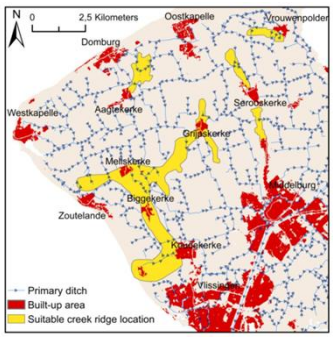
Pilot Creek ridge infiltration





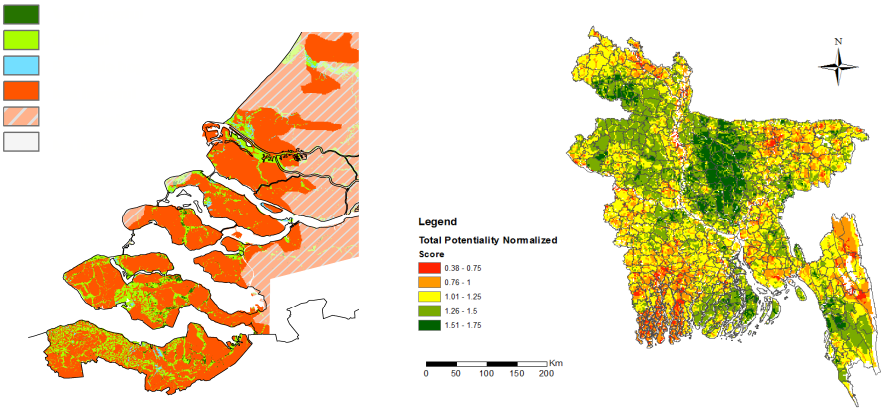
Up-scaling: potential and vulnerability maps at different scales





Deltares

Up-scaling: potential and vulnerability maps at different scales

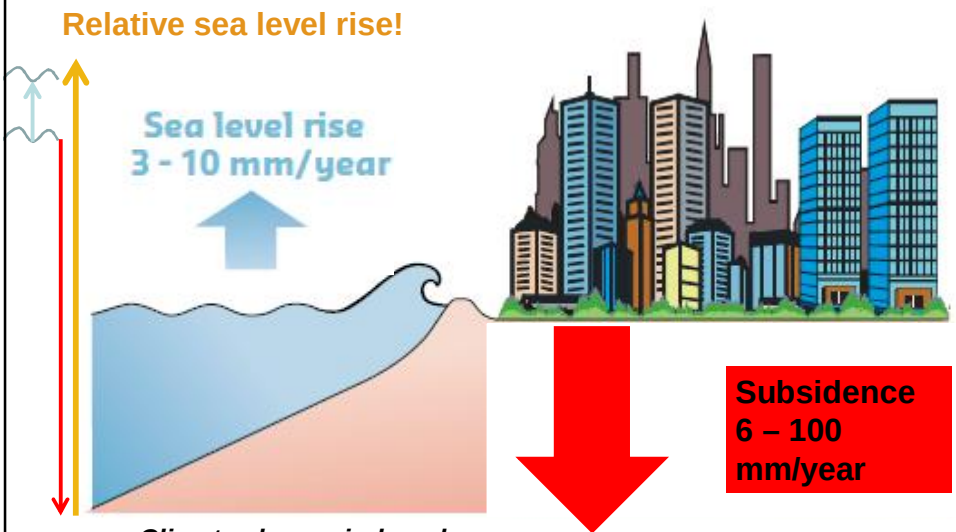


Creek Ridge Infiltration

Deltares

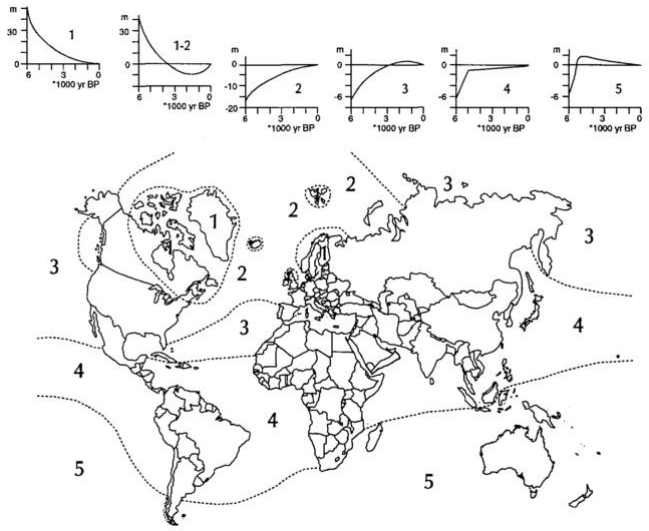
Sinking delta cities

Absolute Sea Level Rise *versus* Subsidence



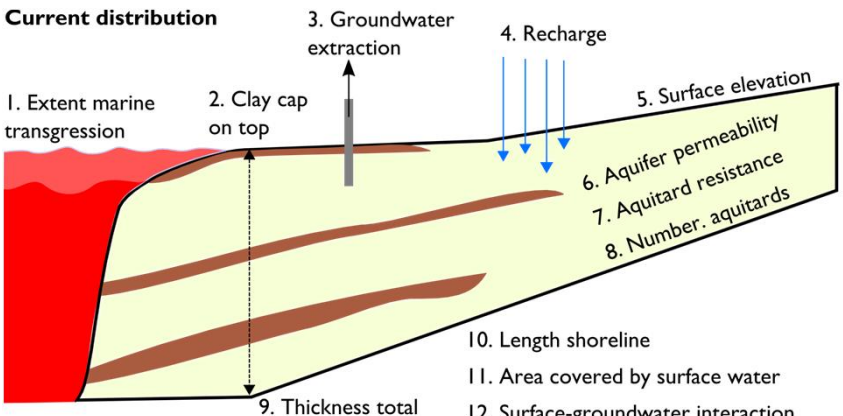
Climate change induced

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

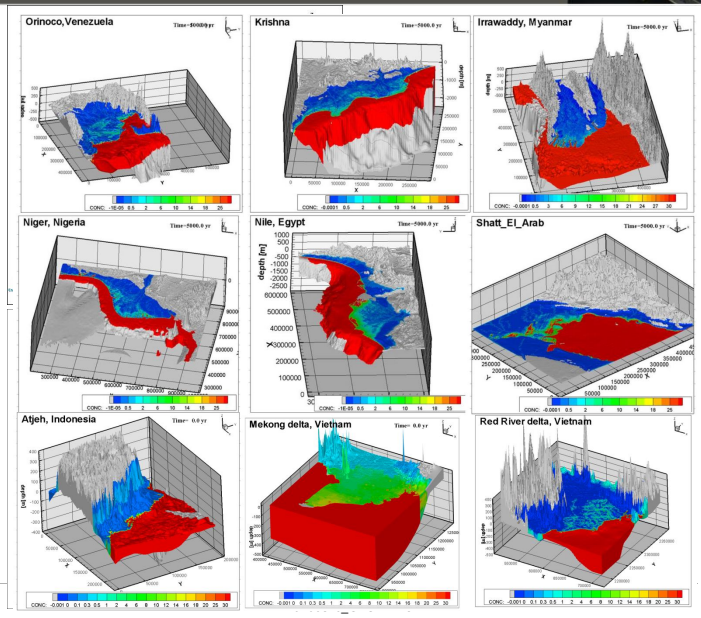
Factors determining fresh groundwater resources delta's



See presentation D. Zamrsky at SWIM

See poster J. Van Engelen at SWI

Numerical 3D models groundwater coastal zone



Deltares

Comparing the four deltas

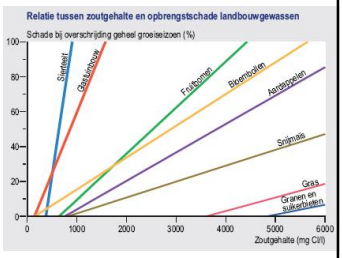
	Mekong Vietnam	Nile Egypt	Ganges-Brahma-putra, Kulna area, Bangladesh	Rhine-Meuse Netherlands
Responsible institutes data collection	DWRPIS Division for Water Resources Planning and Investigation for the South of Viet Nam	RIGW Research Institute for Groundwater	DPHE Department of Public Health Engineering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

Source: Roest et al., 2003 en Haskoning

20200320_GEO4-4425

Deltares

Sea level rise: +2 m

Nederland

Myanmar, Ayeyarwady

http://flood.firetree.net

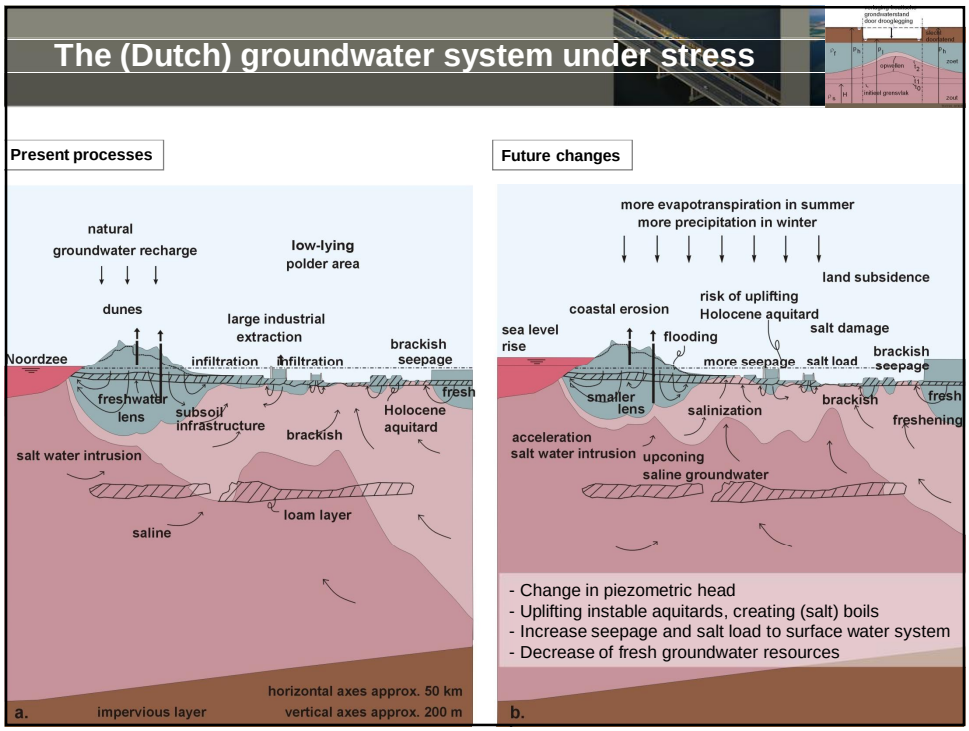
Nile delta, Egypt

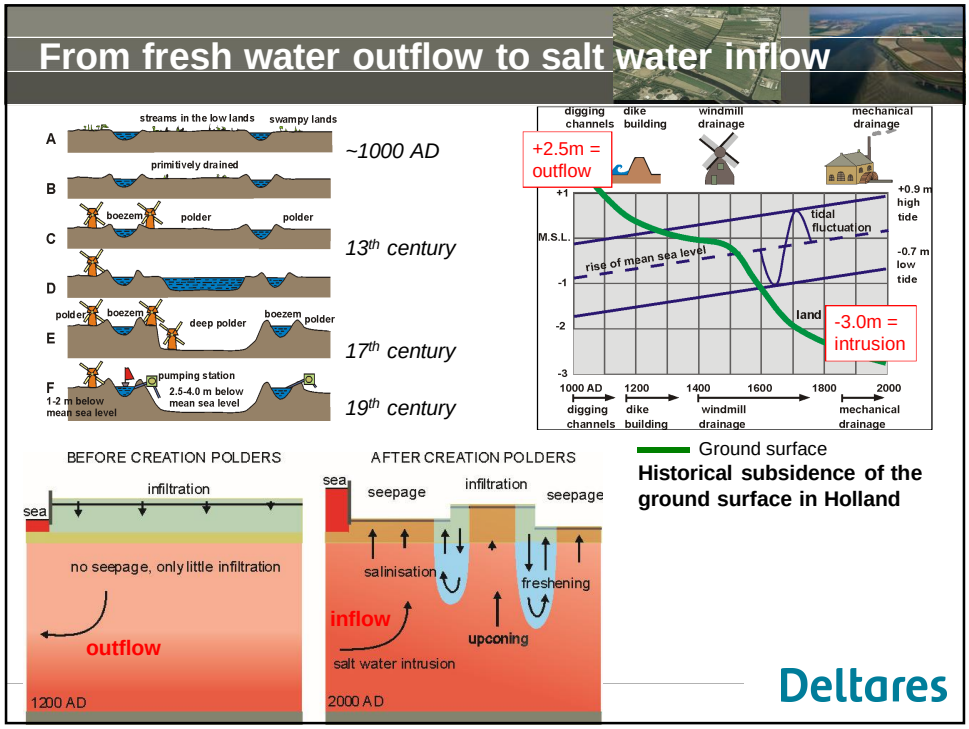
To get an idea about the effect on deltaic areas worldwide, just check the Dutch siutaion

Mississippi, USA

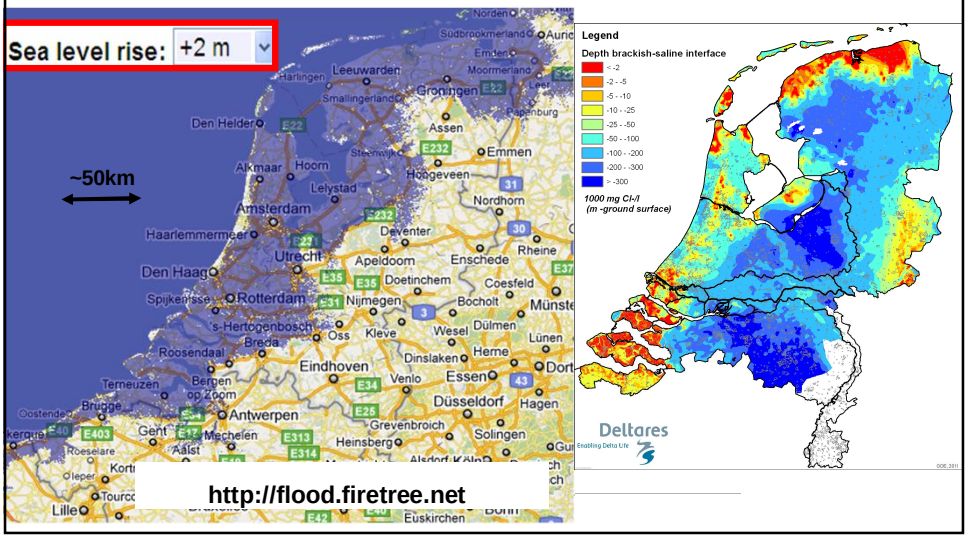
Bangladesh

Mekong delta

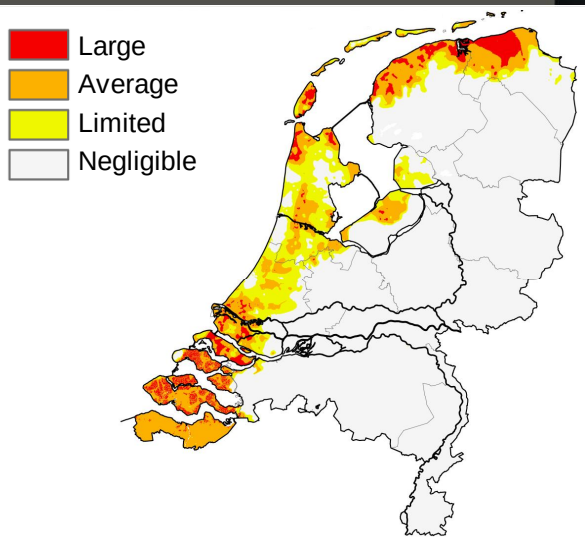

The (Dutch) groundwater system under stress
Present processes
Future changes
natural
groundwater recharge
low-lying
polder area
dunes
large industrial
extraction
Noordzee
infiltration
infiltration
brackish
seepage
fresh
freshwater
lens
subsoil
infrastructure
brackish
Holocene
aquitard
salt water intrusion
loam layer
saline
horizontal axes approx. 50 km
a.
impervious layer
vertical axes approx. 200 m
more evapotranspiration in summer
more precipitation in winter
land subsidence
risk of uplifting
Holocene aquitard
coastal erosion
sea level
rise
flooding
salt damage
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
digging
channels
dike
building
windmill
drainage
mechanical
drainage
BEFORE CREATION POLDERS
infiltration
sea
no seepage, only little infiltration
outflow
1200 AD
AFTER CREATION POLDERS
sea
seepage
infiltration
seepage
salinisation
freshening
inflow
upconing
salt water intrusion
2000 AD
Ground surface
Historical subsidence of the
ground surface in Holland
Deltares

The Netherlands: low-lying lands and saline groundwater



Zones of risk of salinisation



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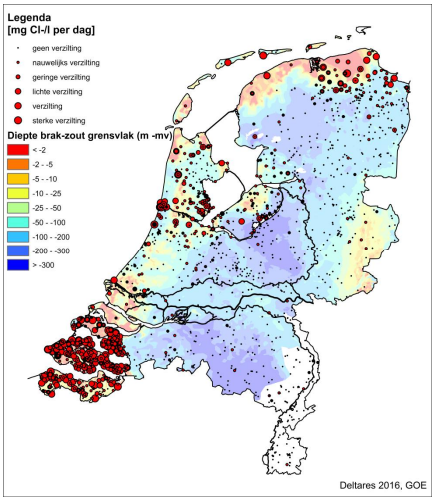
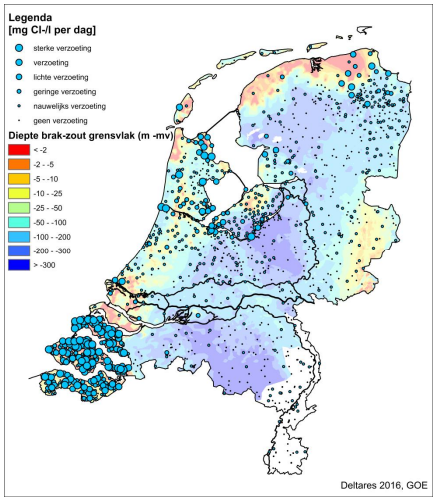
Salinisation-freshening groundwater: measurements





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20200320_GEO4-4425

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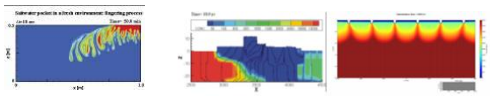
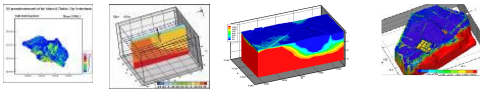
Different model cell sizes to consider several phenomena

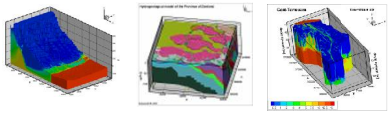
Sub-local: fingering, salty sand boils
Sri Lanka (Tsunami 2004), Zandmotor
cell size=1cm-1m



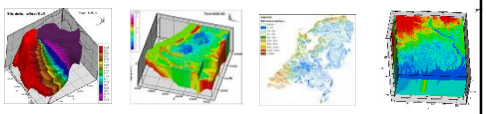
Local: rainwaterlenses, heat-cold
Tholen, Schouwen-Duiveland
cell size=5-25m



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

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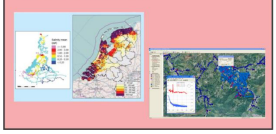
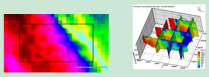
Modelling tools: iMOD Open Source

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

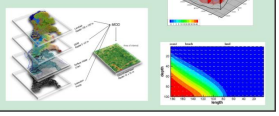


⟷

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

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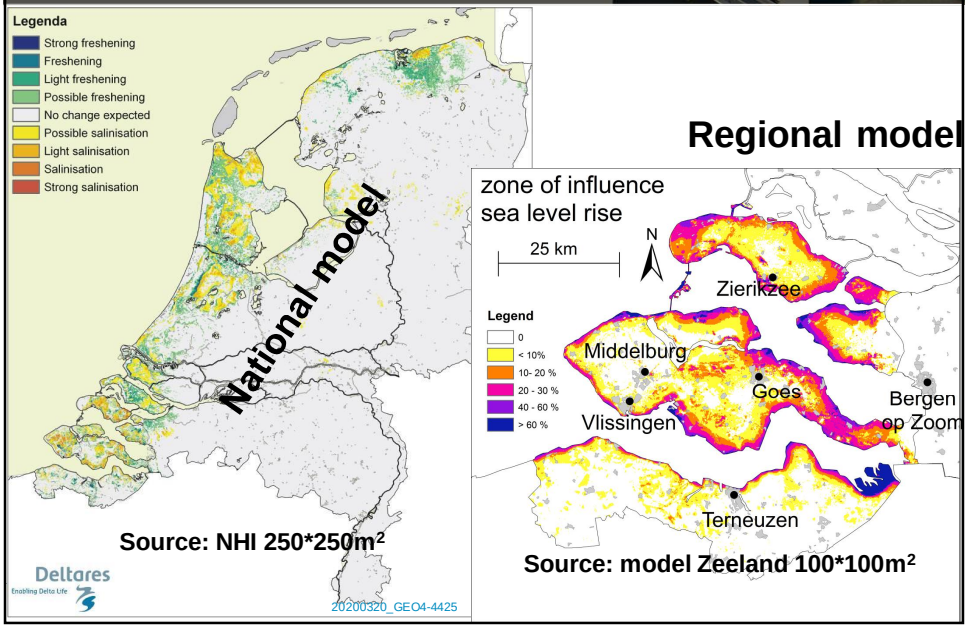
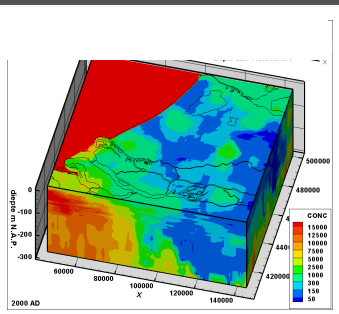
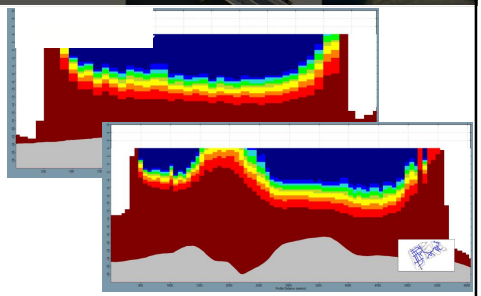
Salinisation & freshening under Climate & Global stress



3D Regional coastal groundwater model studies

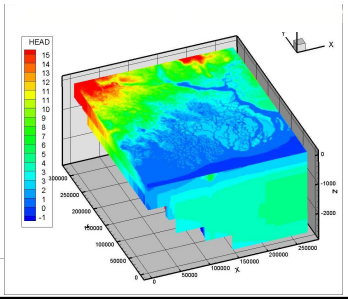




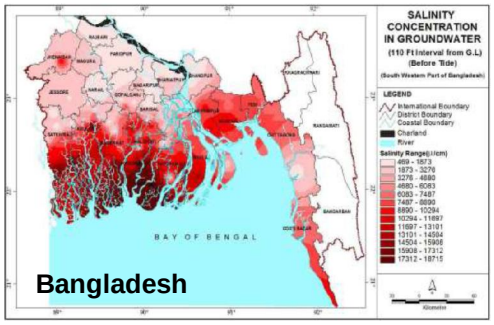
Modelling:
- variable-density groundwater flow, coupled solute transport

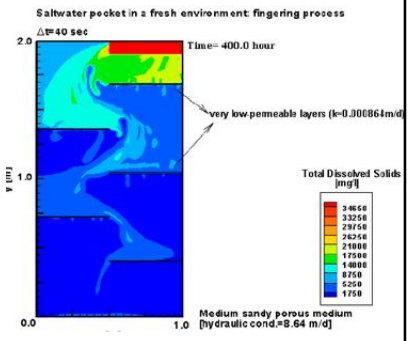
Simulating effects of:
- autonomous processes (change extraction rates)
- sea level rise, changing recharge pattern
- land subsidence

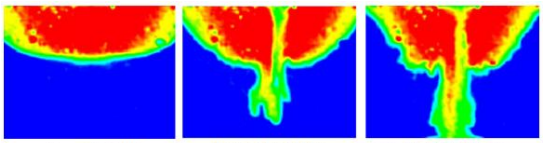
Quantifying:
- hydraulic head
- saline seepage / infiltration
- fresh groundwater resources



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)

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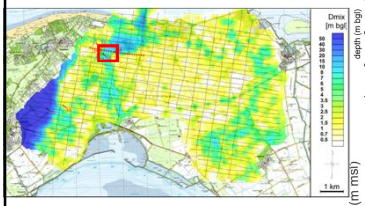
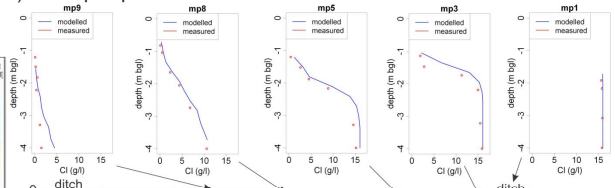
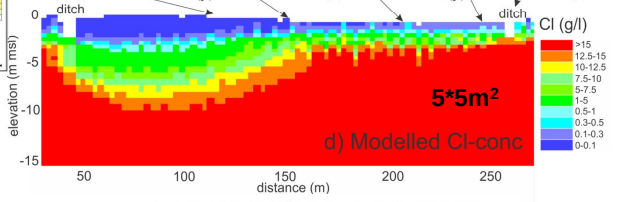
Comparison monitoring data with model results

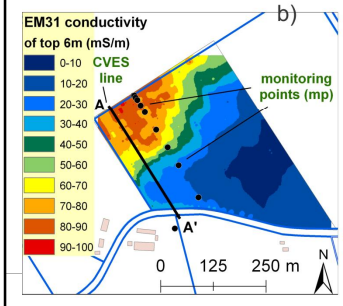
a) Airborne EM

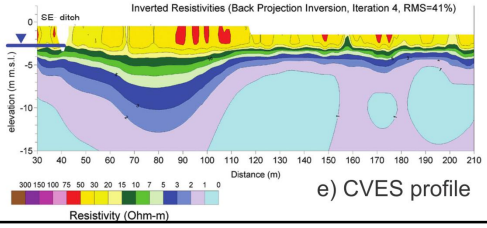


c) Cl-depth profiles

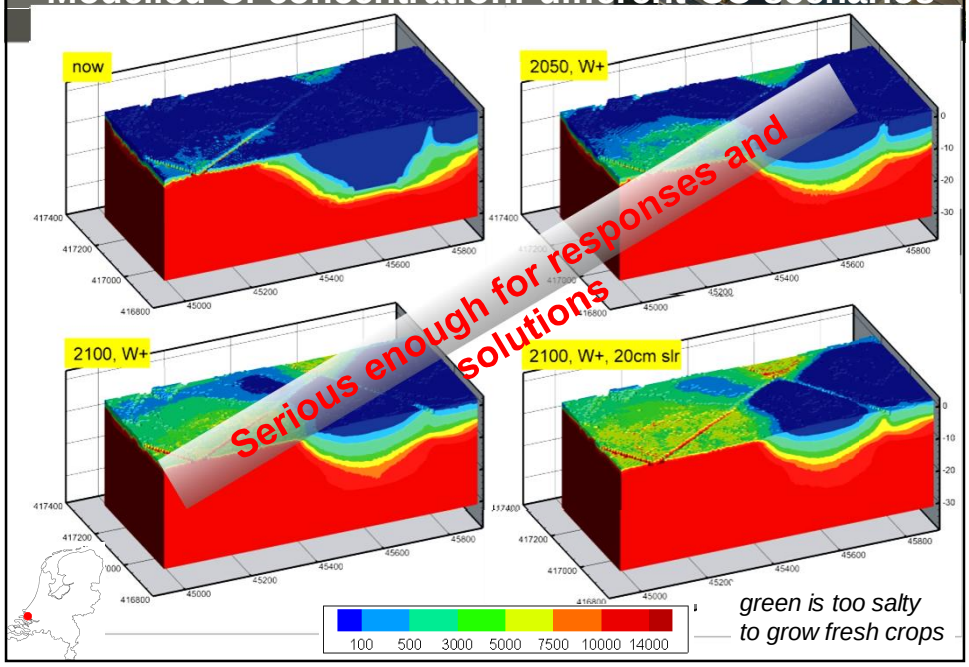




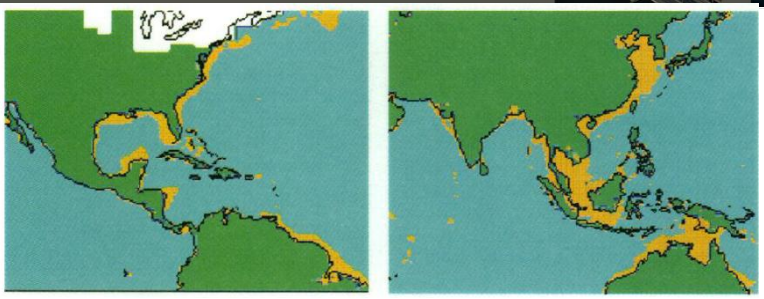




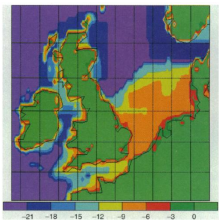
Modelled Cl-concentration: different CC scenarios

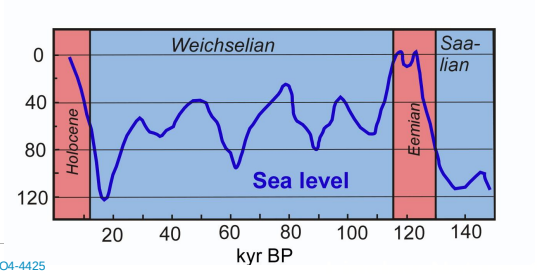


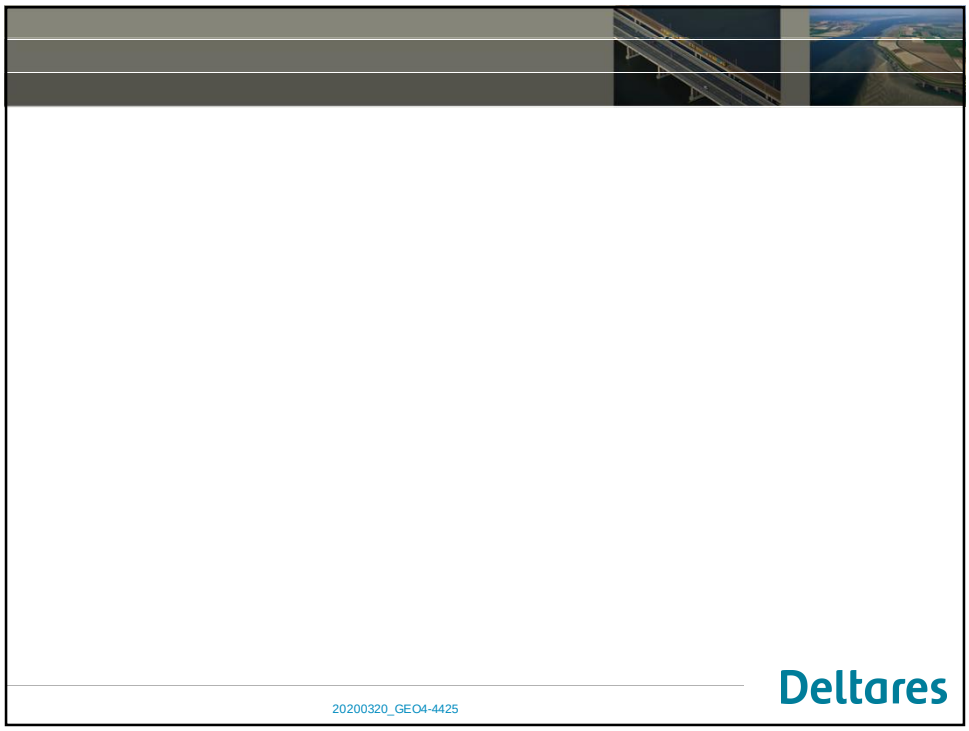
Coastal zone cases around the world
Occurrence related to dynamic sea-levels and coastlines



Peltier, *Science*, 1994







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Methodology Vulnerability Tsunami Index

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

Elevation	ID_{elev}
Slope	ID_{slope}
Distance to coast	ID_{dist}

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

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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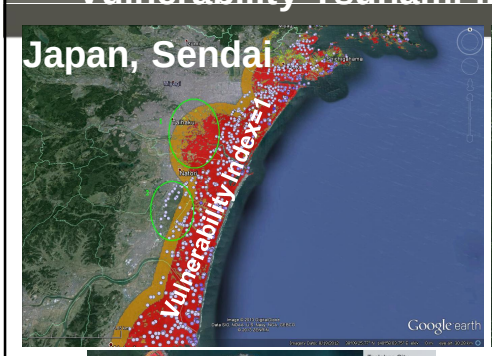
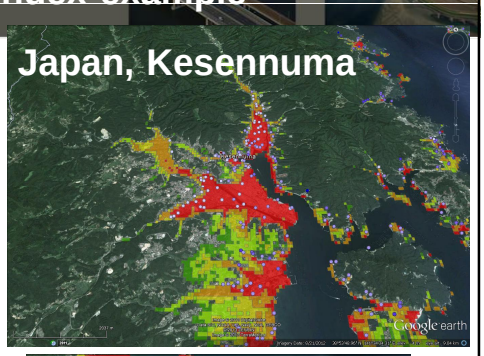
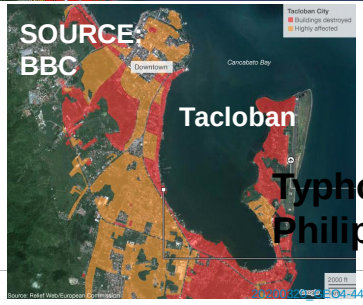
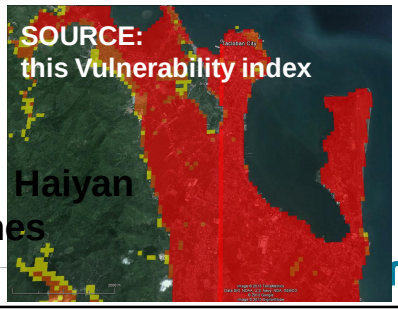
Vulnerability Tsunami index example







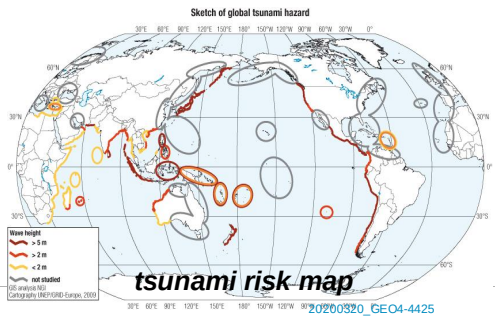


res

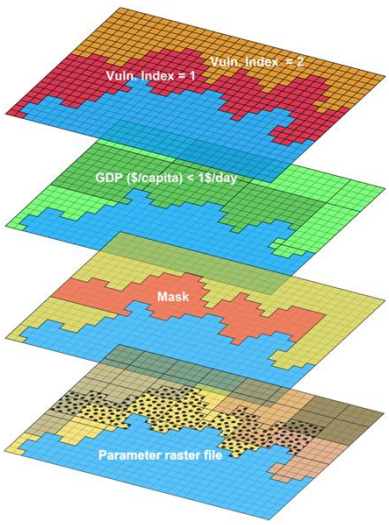
Socio-economic factor and parameter values statistics

- **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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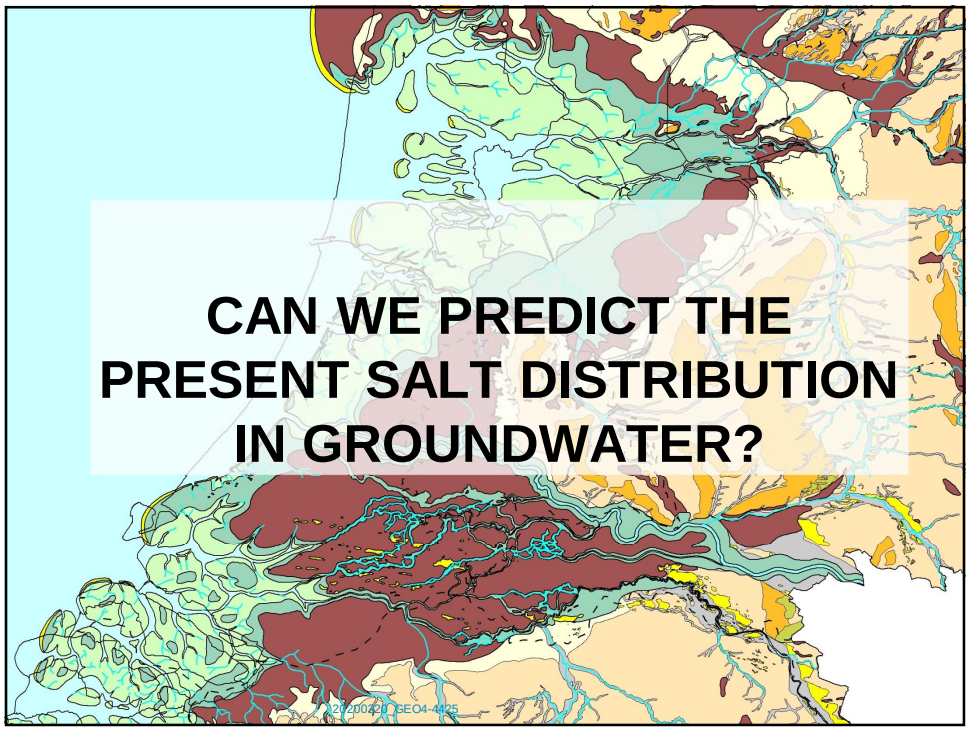
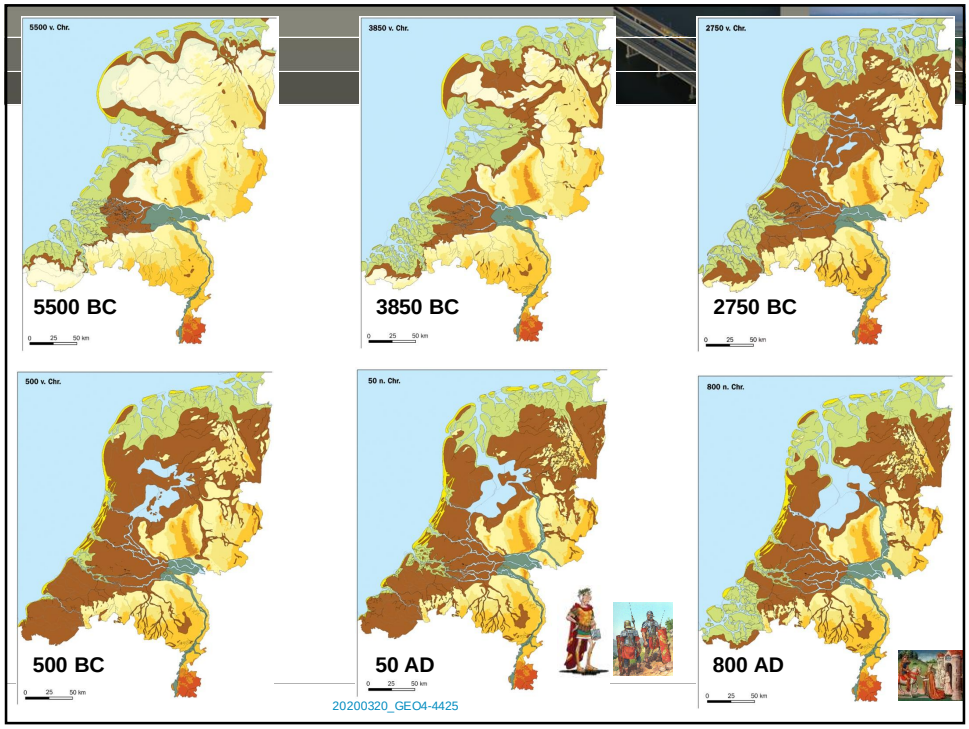
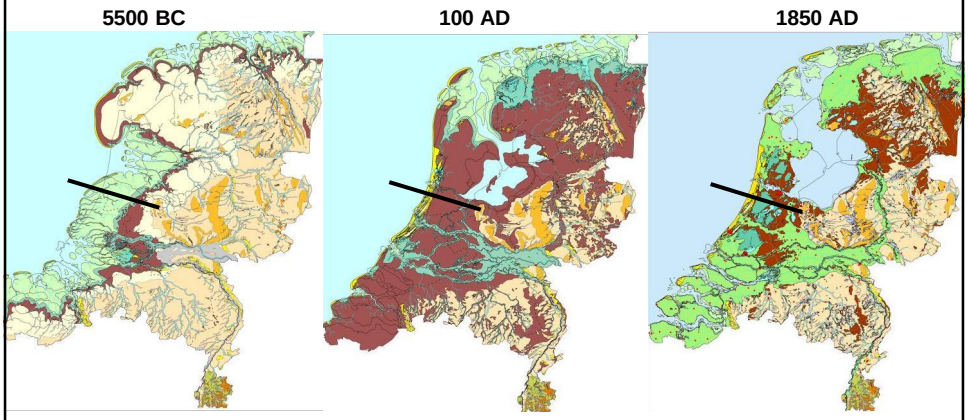
Palaeo-hydrogeographical modelling

Delsman et al., HESS, 20


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



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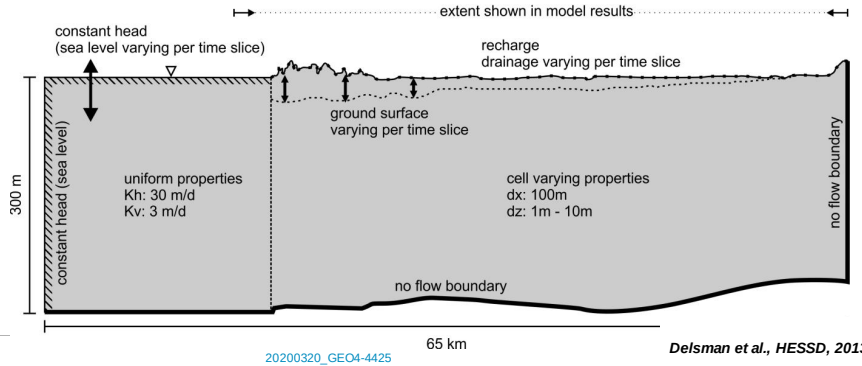
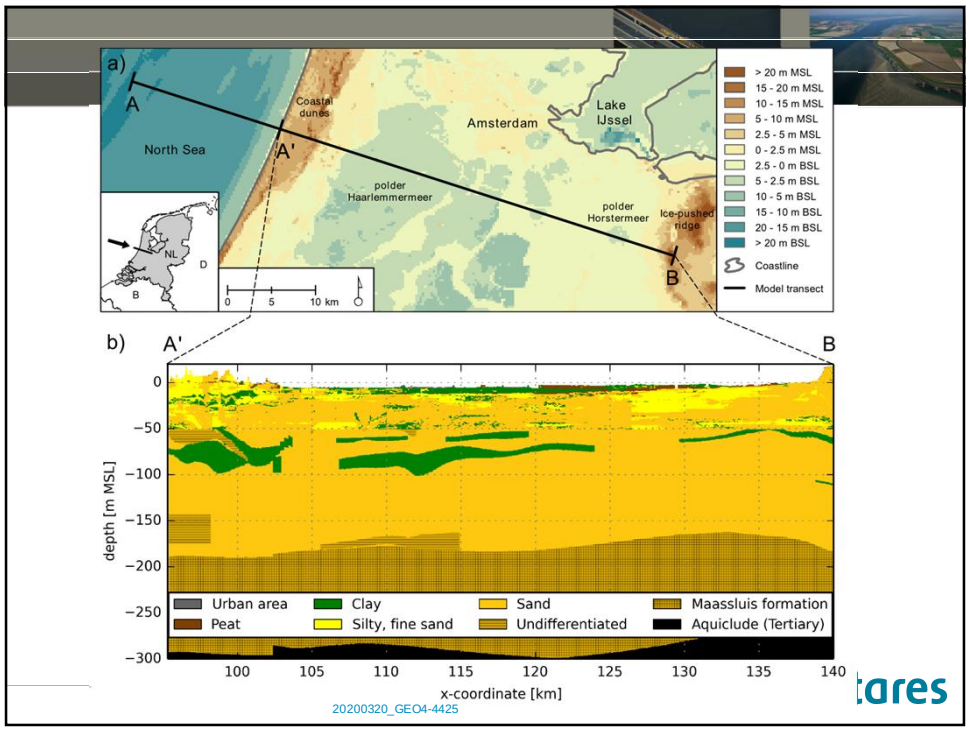
Atlas NL in het Holoceen (Vos et al, 2011)

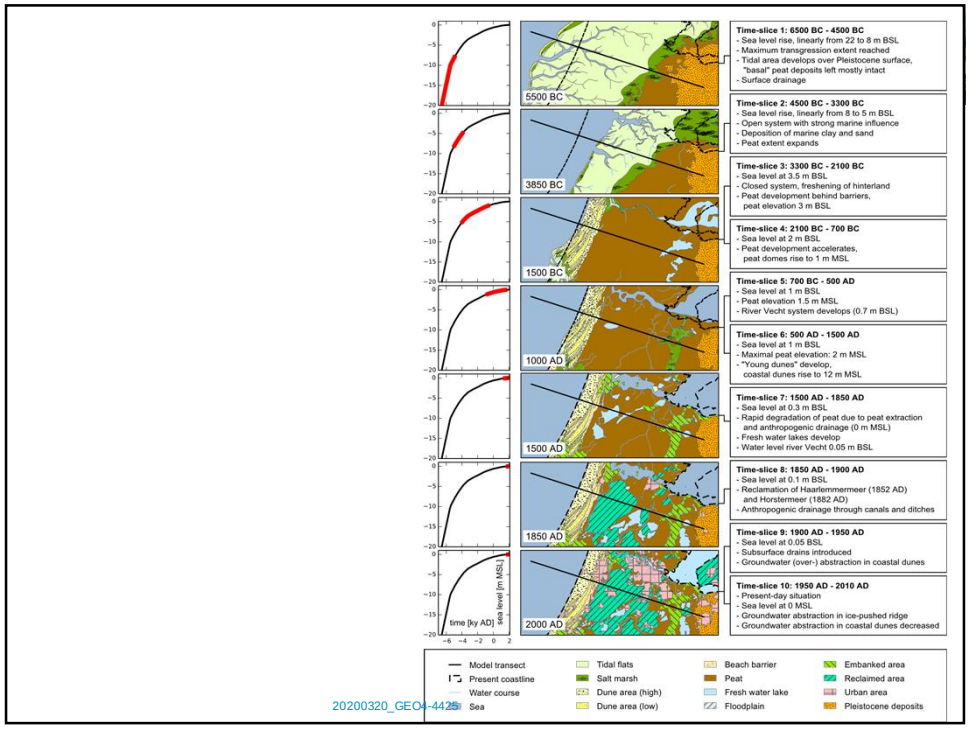
Occurrence of salt under the polder Haarlemmermeer

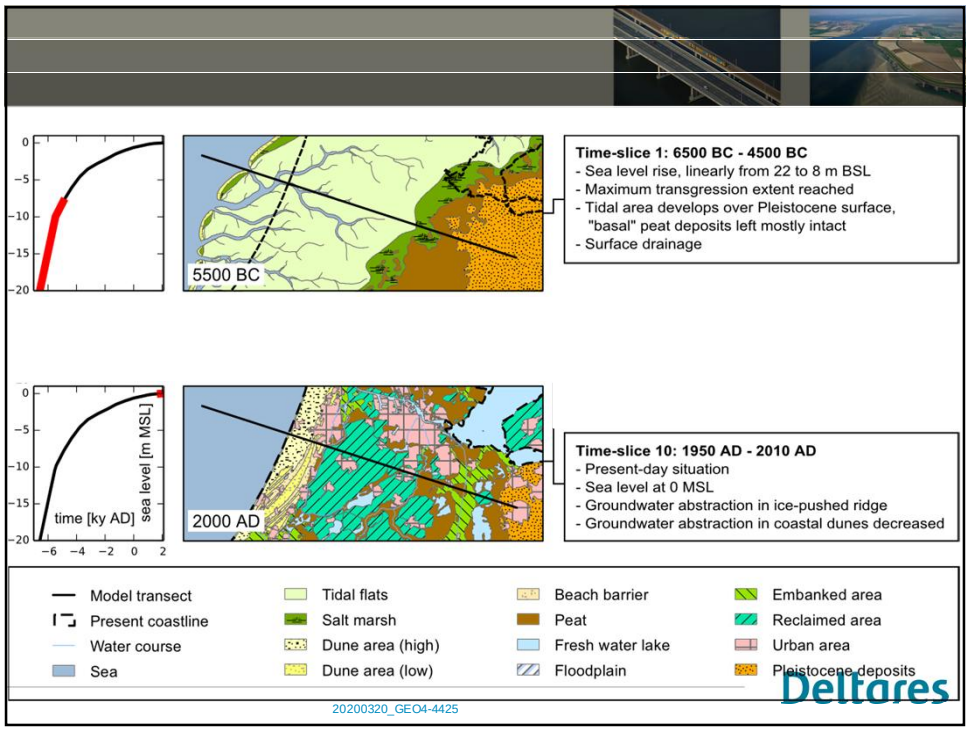
- Model profile Zandvoort - Hoofddorp – Hilversum
- Palaeogeographical development (Vos et al, 2011)
- 6500 BC - 2010 AD
- marine transgression
- Peat development, peat degradation, drainage, reclamation



Delsman et al., 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)
20200320_GEO4-4425


5500 BC
3850 BC
1500 BC
1000 AD
1500 AD
1850 AD
2000 AD
time [ky AD]
Sea level [m MSL]
Time-slice 1: 6500 BC - 4500 BC
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage
Time-slice 2: 4500 BC - 3300 BC
- Sea level rise, linearly from 8 to 5 m BSL
- Open system with strong marine influence
- Deposition of marine clay and sand
- Peat extent expands
Time-slice 3: 3300 BC - 2100 BC
- Sea level at 3.5 m BSL
- Closed system, freshening of hinterland
- Peat development behind barriers, peat elevation 3 m BSL
Time-slice 4: 2100 BC - 700 BC
- Sea level at 2 m BSL
- Peat development accelerates, peat domes rise to 1 m MSL
Time-slice 5: 700 BC - 500 AD
- Sea level at 1 m BSL
- Peat elevation 1.5 m MSL
- River Vecht system develops (0.7 m BSL)
Time-slice 6: 500 AD - 1500 AD
- Sea level at 1 m BSL
- Maximal peat elevation: 2 m MSL
- "Young dunes" develop, coastal dunes rise to 12 m MSL
Time-slice 7: 1500 AD - 1850 AD
- Sea level at 0.3 m BSL
- Rapid degradation of peat due to peat extraction and anthropogenic drainage (0 m MSL)
- Fresh water lakes develop
- Water level river Vecht 0.05 m BSL
Time-slice 8: 1850 AD - 1900 AD
- Sea level at 0.1 m BSL
- Reclamation of Haarlemmermeer (1852 AD) and Horstermeer (1882 AD)
- Anthropogenic drainage through canals and ditches
Time-slice 9: 1900 AD - 1950 AD
- Sea level at 0.05 BSL
- Subsurface drains introduced
- Groundwater (over-) abstraction in coastal dunes
Time-slice 10: 1950 AD - 2010 AD
- Present-day situation
- Sea level at 0 MSL
- Groundwater abstraction in ice-pushed ridge
- Groundwater abstraction in coastal dunes decreased
Model transect
Present coastline
Water course
Sea
Tidal flats
Salt marsh
Dune area (high)
Dune area (low)
Beach barrier
Peat
Fresh water lake
Floodplain
Embanked area
Reclaimed area
Urban area
Pleistocene deposits
20200320_GEO4-4425


sea level [m MSL]
time [ky AD]
5500 BC
2000 AD
Time-slice 1: 6500 BC - 4500 BC
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage
Time-slice 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
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Tidal flats
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Dune area (high)
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Fresh water lake
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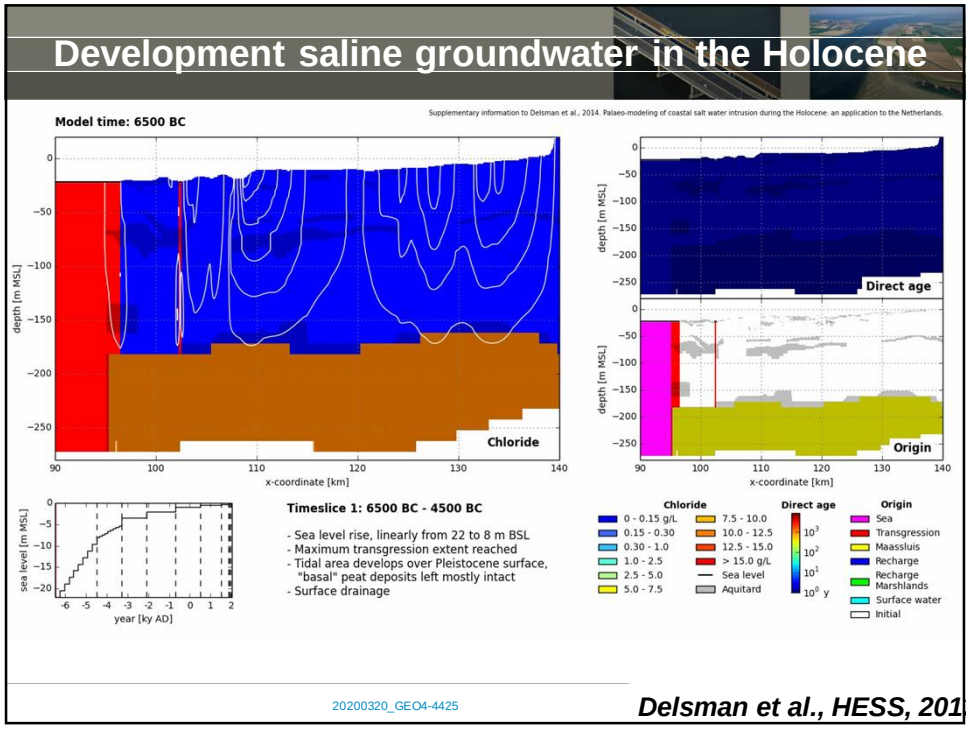
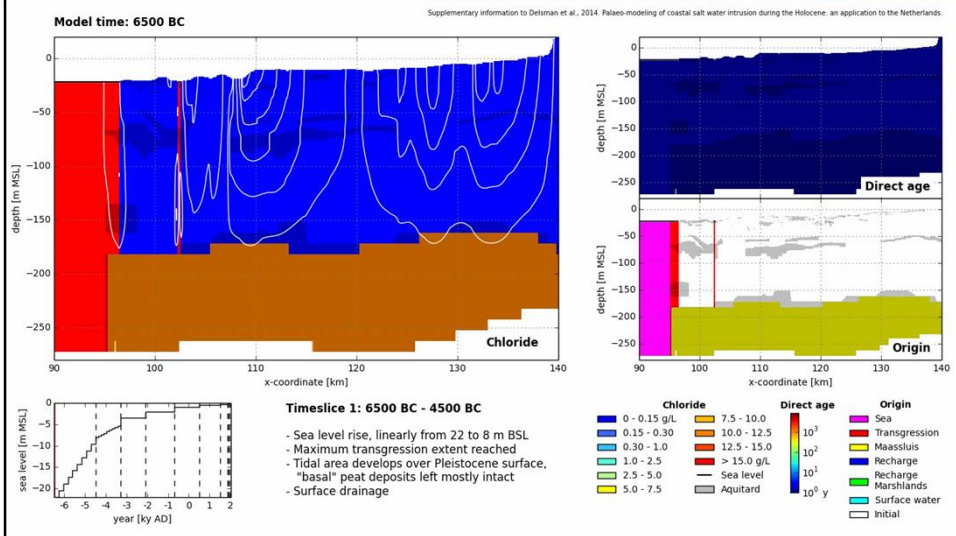
Urban area
Pleistocene deposits
Deltares
20200320_GEO4-4425

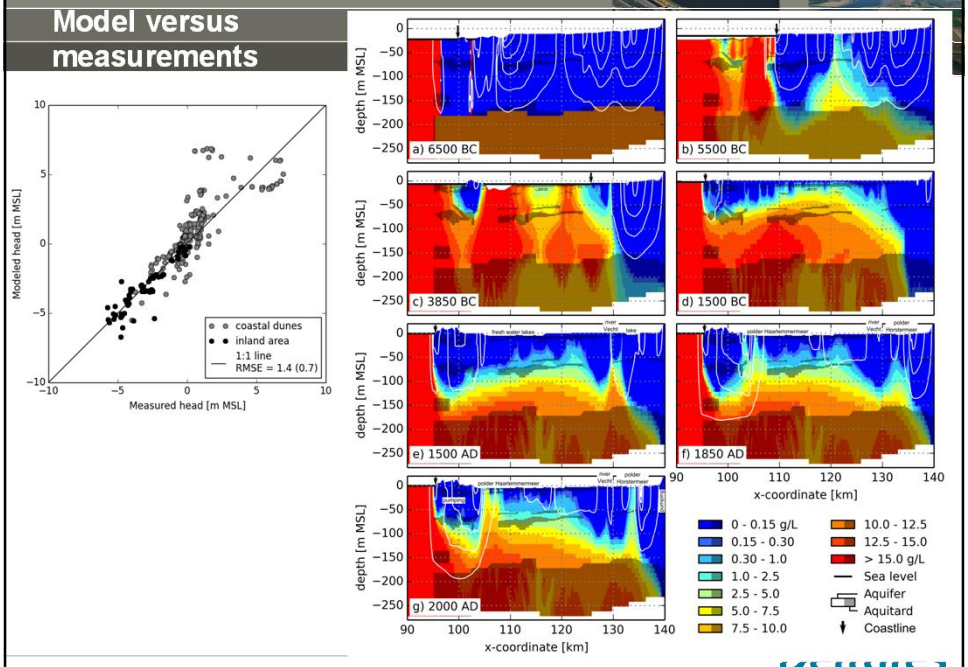

Development saline groundwater in the Holocene
Model time: 6500 BC
Supplementary information to Delsman et al., 2014. Palaeo-modeling of coastal salt water intrusion during the Holocene: an application to the Netherlands.
depth [m MSL]
x-coordinate [km]
Chloride
Direct age
Origin
sea level [m MSL]
year [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
Chloride
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
Direct age
y
Origin
Sea
Transgression
Maassluis
Recharge
Recharge Marshlands
Surface water
Initial
20200320_GEO4-4425
Delsman et al., HESS, 201

Development saline groundwater in the Holocene

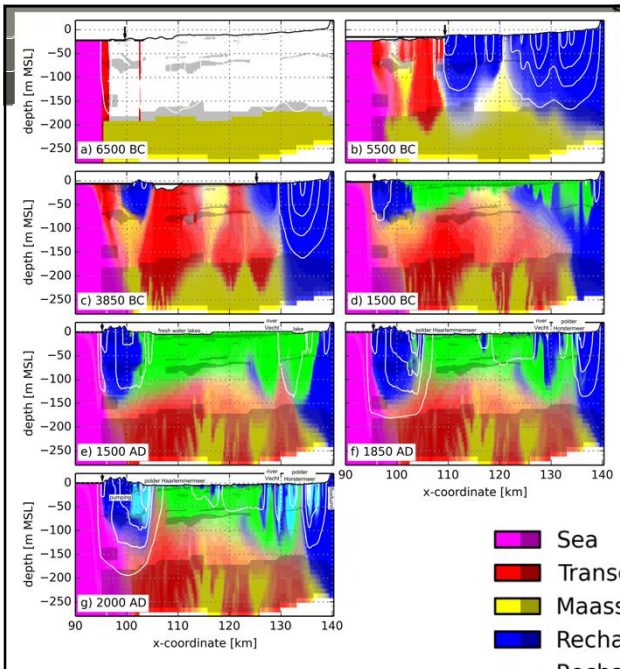


Delsman et al., HESS, 201

Model versus measurements



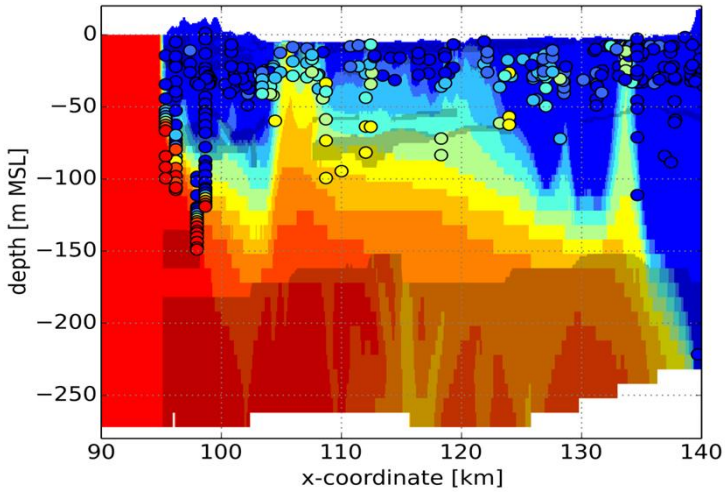
Origin source



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

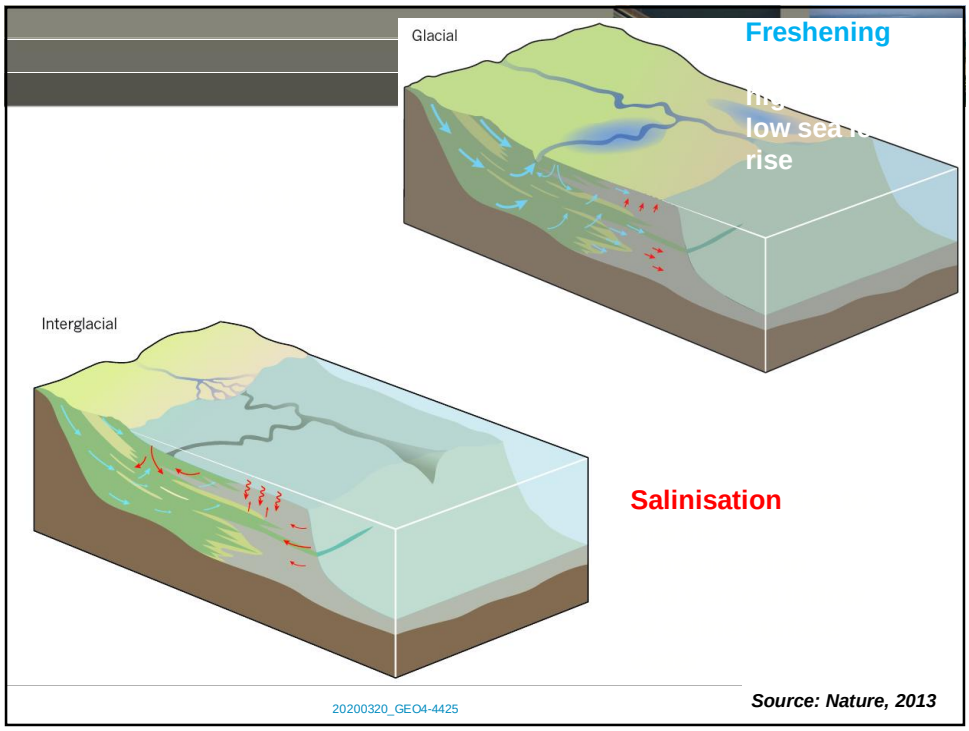
20200320_GEO4-4425

Model versus measurements



Deltares

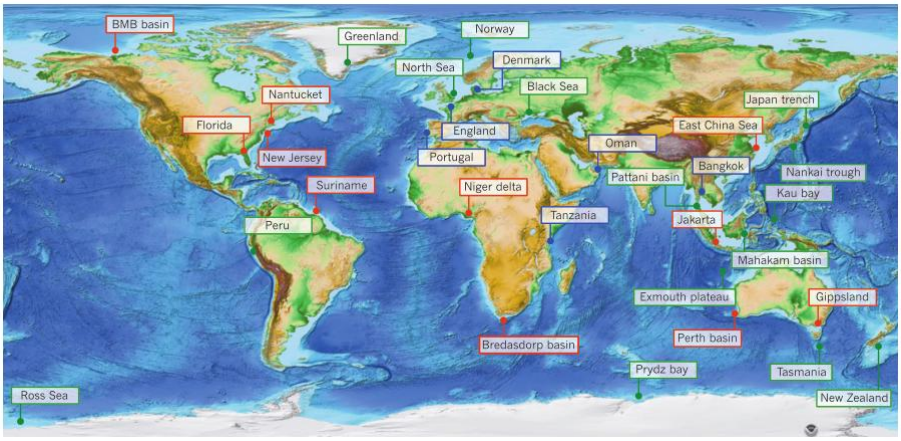
20200320_GEO4-4425



20200320_GEO4-425

Source: Nature, 2013

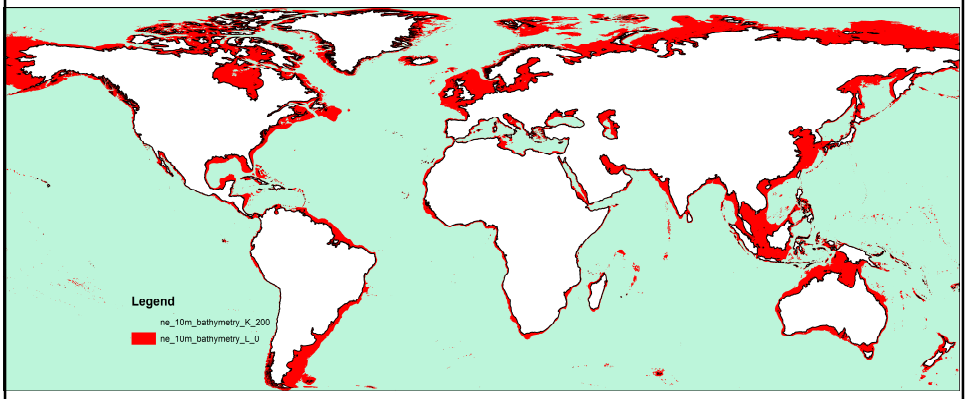
World map of topography and bathymetry showing known occurrences of fresh and brackish offshore



20200320_GEO4-425

Deltares

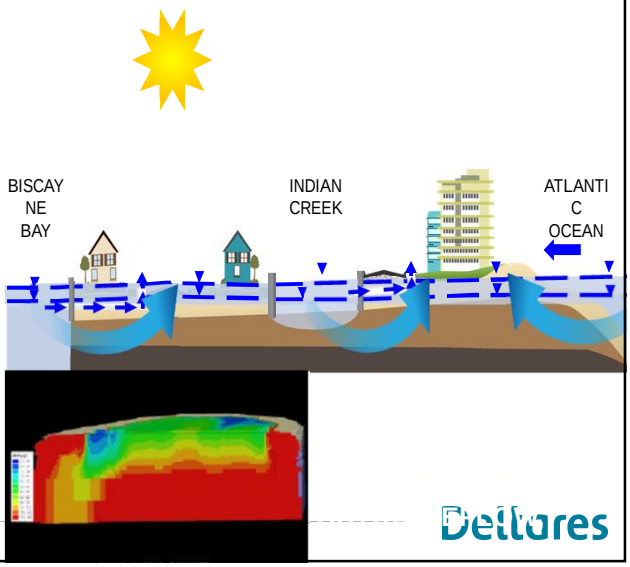
Possible locations of offshore (submarine) groundwater



Deltares

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

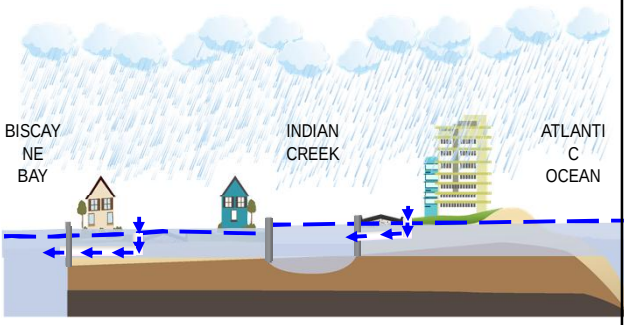
» **Tidal flooding:**
- **Through storm drains**
- **Through groundwater**
- **Exacerbated with SLR**

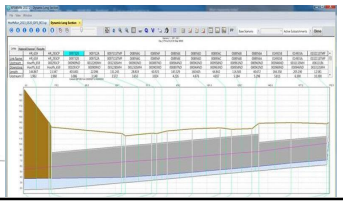


Deltares

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

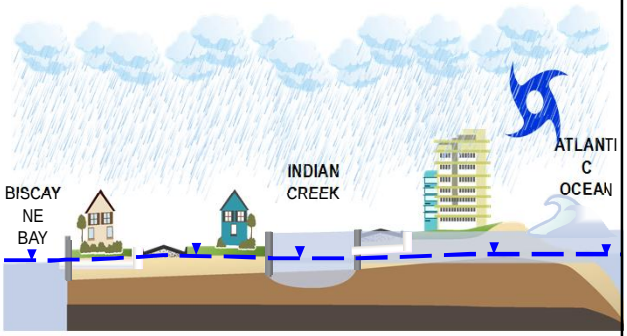


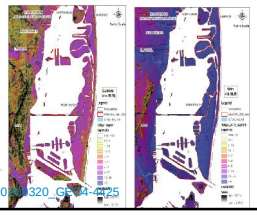


Model Tools: XP-SWMM, MIKE Urban, MIKE Flood, InfoWorks-ICM

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