

Innovaties modelleren zoet-zout grondwater

Gualbert Oude Essink

Deltares/UU

Meer informatie:

www.zoutzout.deltares.nl

www.freshsalt.deltares.nl

Co-auteurs:

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Sense of urgency zoet-zout modellen














- **30%** of global population lives **within 100km** of the coastline
- **<5m ASL**: 320 million people and 1.5 million km²

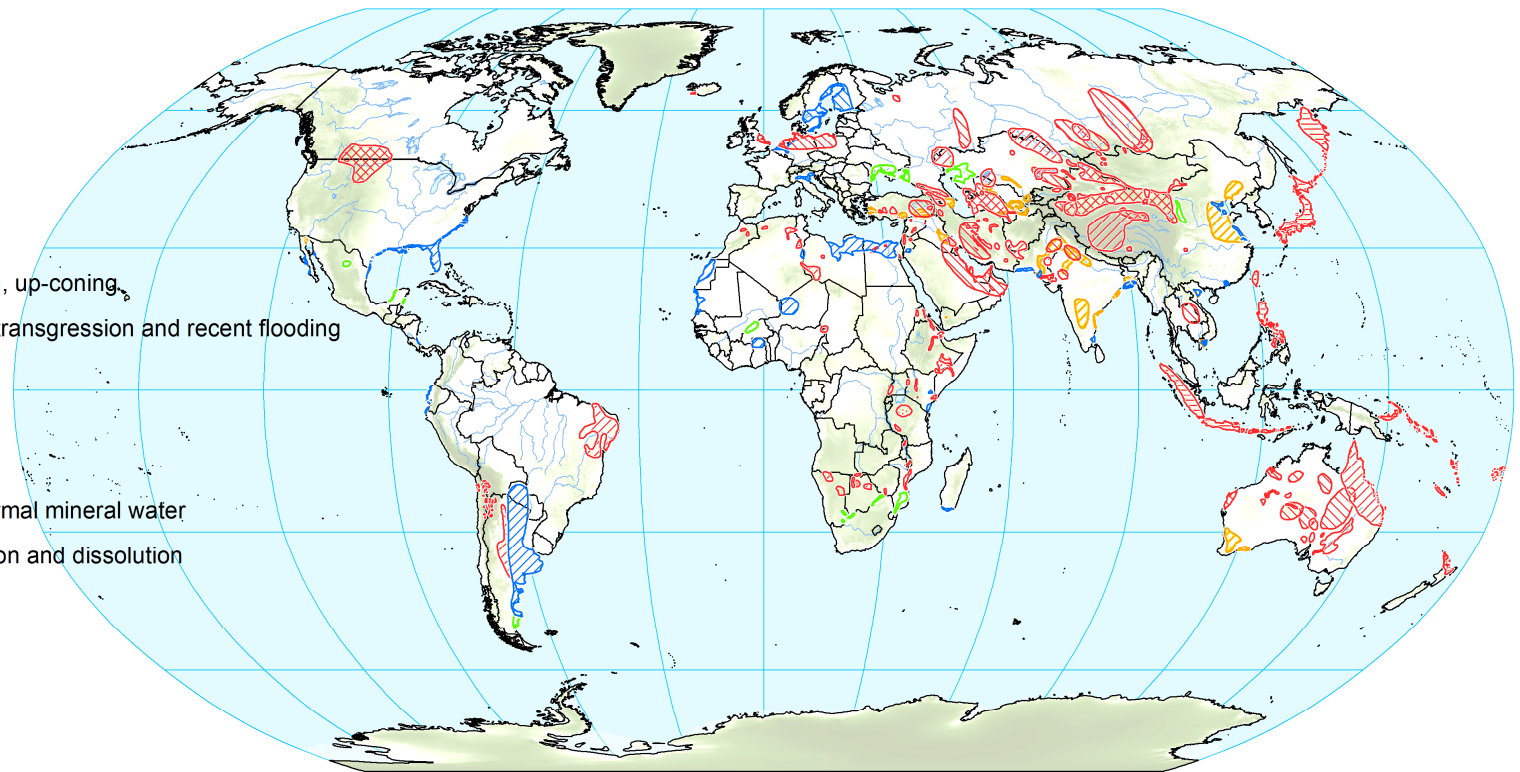
Saline Groundwater of the World

Legend

Groundwater_Salinity

Genetic Category

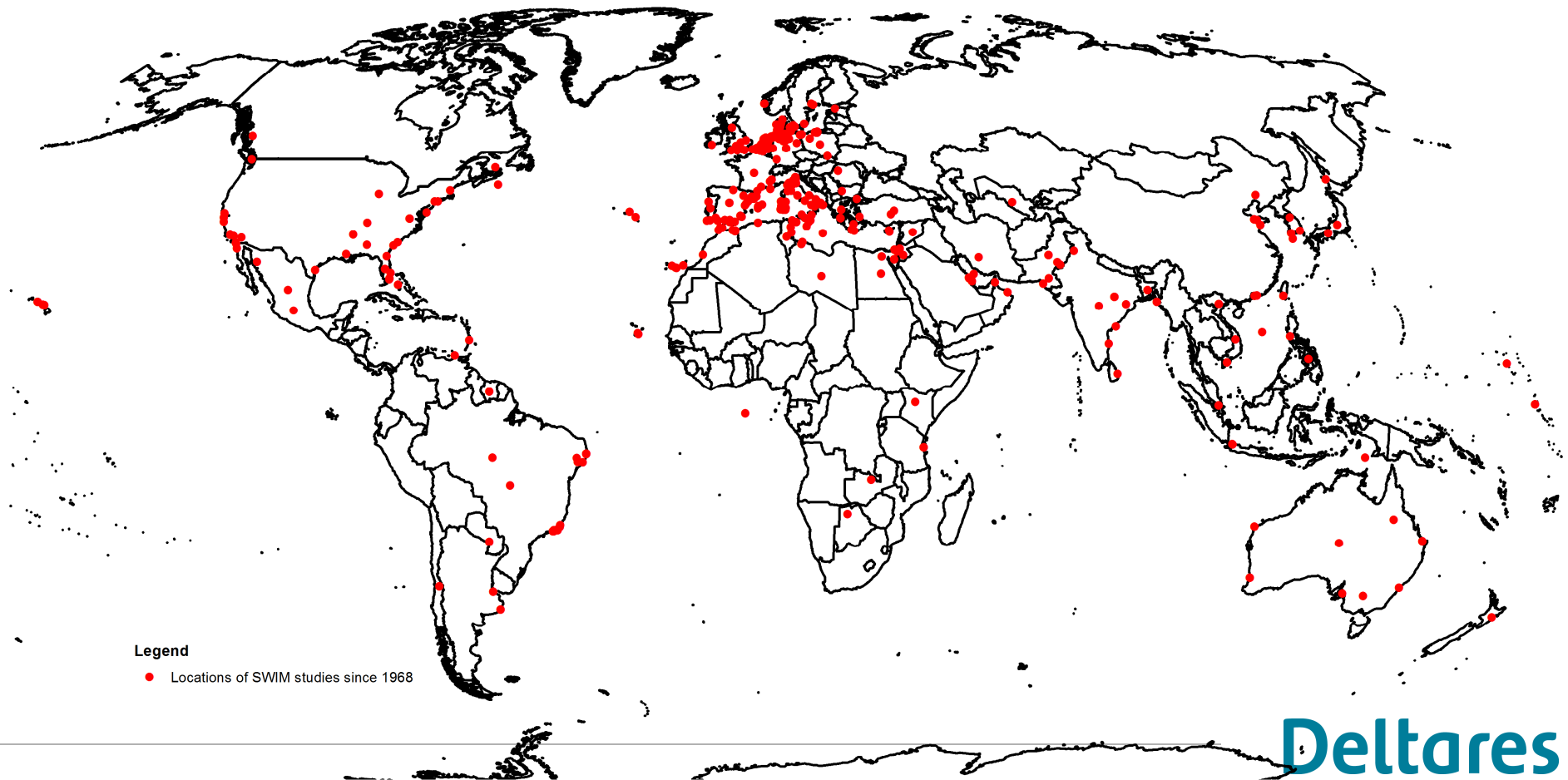
-  A0 Marine origin
-  A1 Connate
-  A2 Marine transgression
-  A4 Lateral seawater intrusion, up-coning
-  A7 Combination of connate, transgression and recent flooding
-  B0 Natural terrestrial origin
-  B1 Evaporation
-  B2 Dissolution
-  B4 Igneous activity hydrothermal mineral water
-  B5 Combination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



Global Overview of Saline Groundwater Occurrence and Genesis (IGRAC 2009)

Sense of urgency zoet-zout modellen

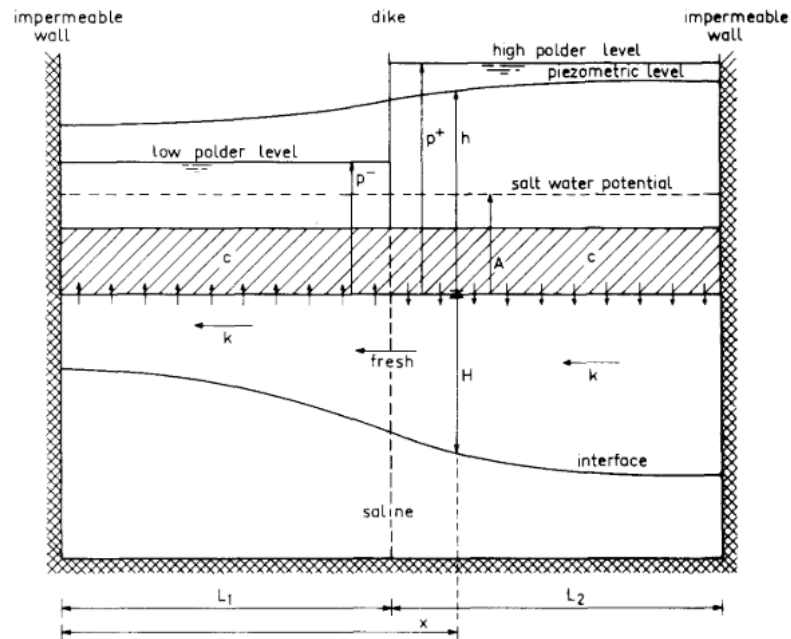
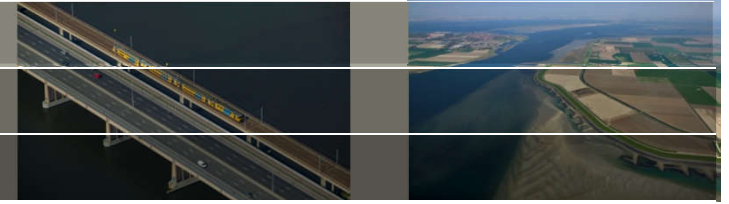
- **30%** of global population lives **within 100km** of the coastline
- **<5m ASL**: 320 million people and 1.5 million km²
- Cases with registered salt water intrusion issues, and counting



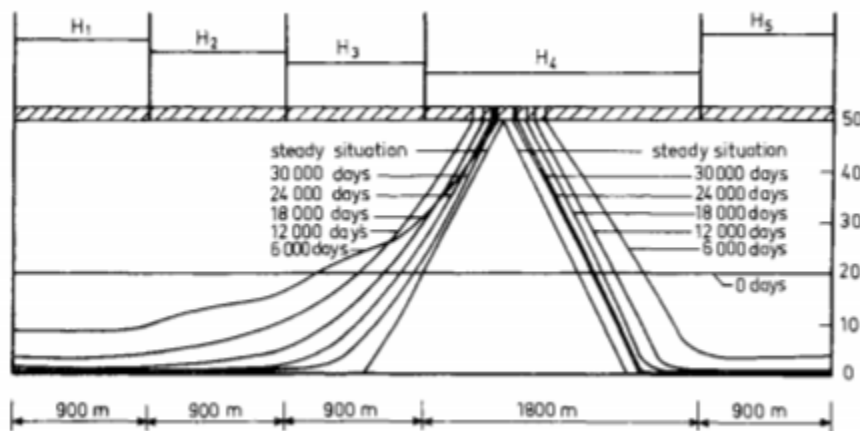
Sense of urgency zoet-zout modellen

- Nieuwe klimaat gerelateerde vraagstukken
 - Effecten extreme zeespiegelstijging
 - Effecten droogte en zoetwater
- Drukke in de ondergrond (WKO, wateropslag)
- De ondergrond als oplossing:
 - Strategische zoetwatervoorraden
 - Aquifer Storage and Recovery in het kustgebied
 - COASTAR: *Brackish groundwater is the new fresh!*

1970s: Scherpe grensvlakken

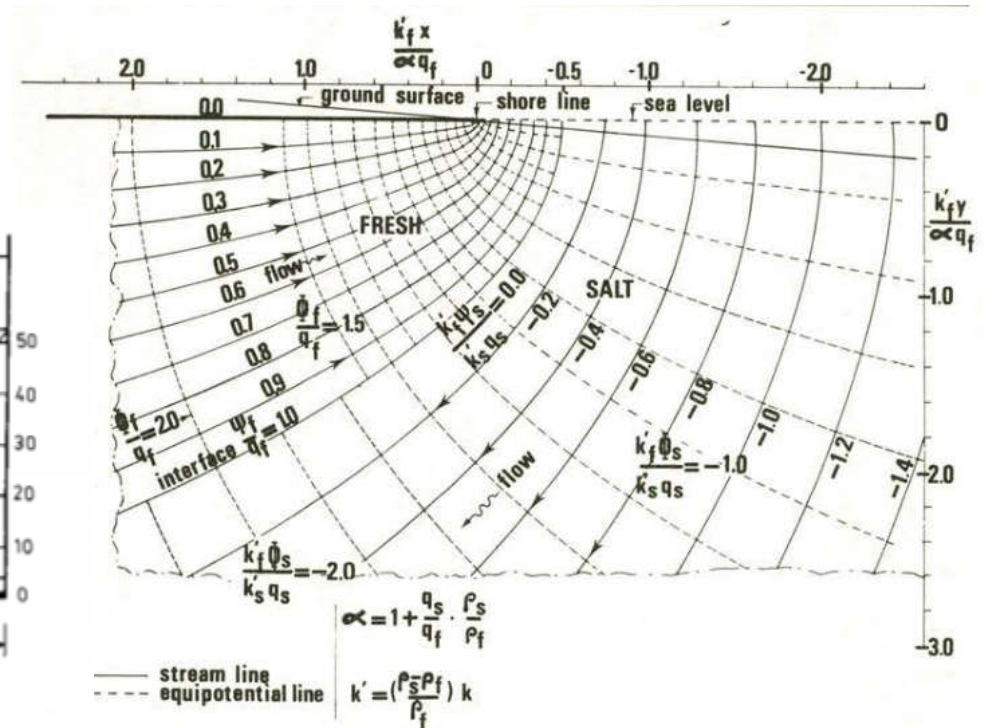


Van Dam, 1976



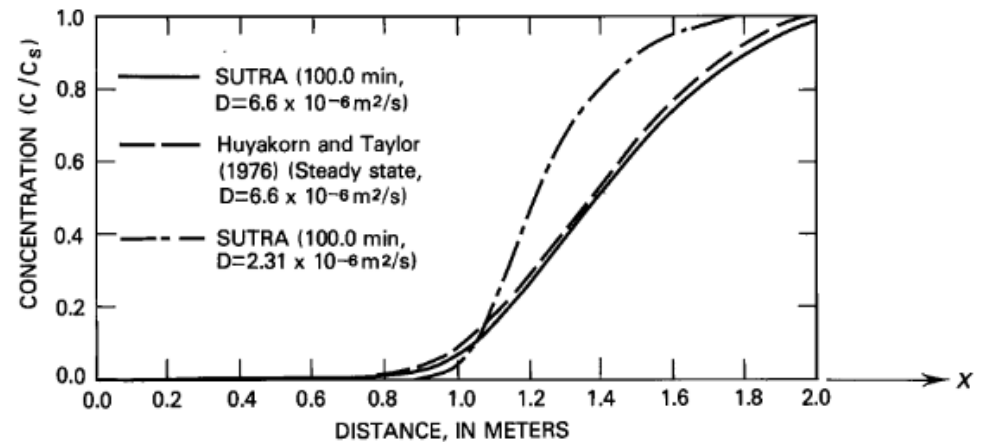
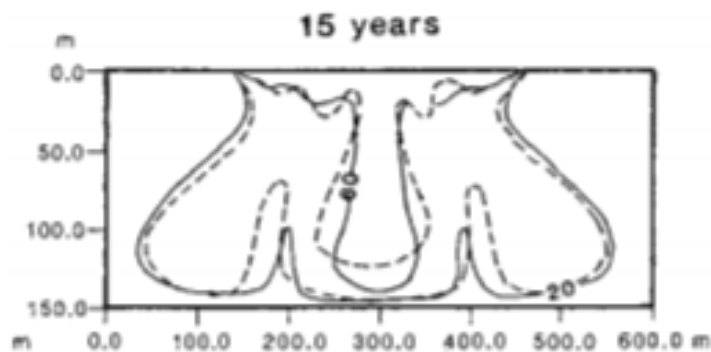
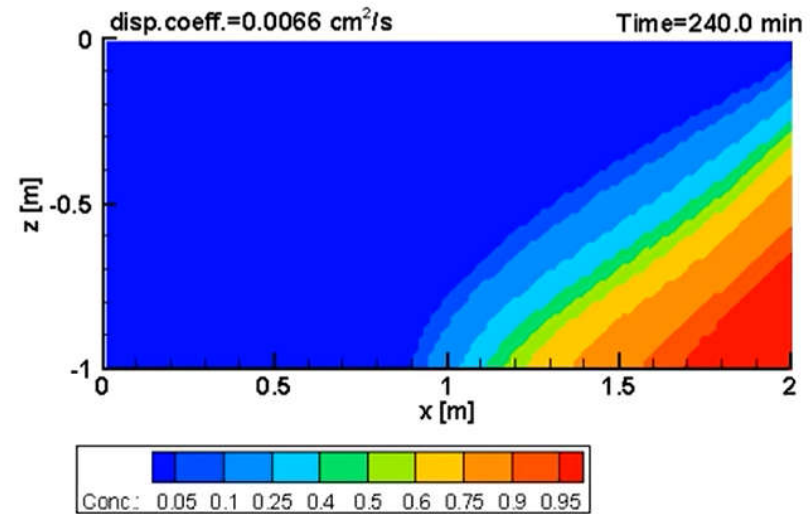
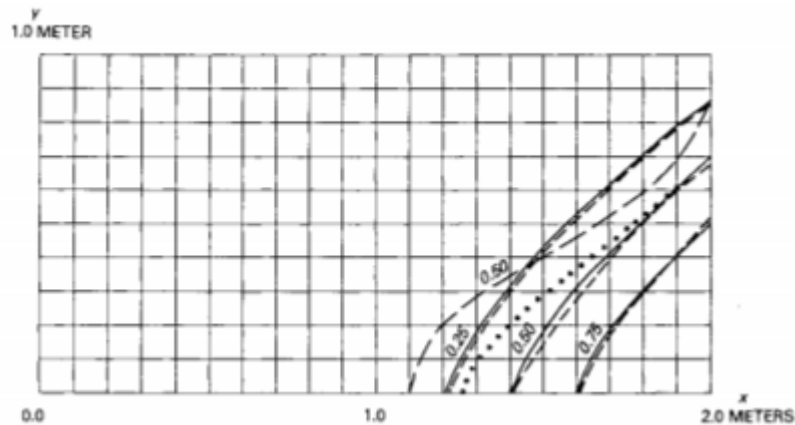
Berger en Ten Hoorn, 1984

Van der Veer, 1977



1980s: 2D vertikaal profiel: bijv. Case Henry, SUTRA

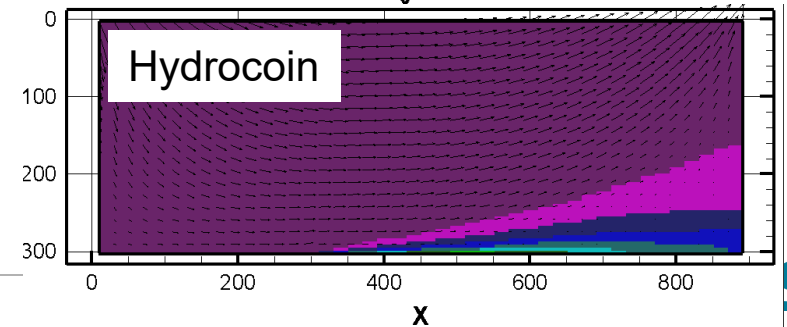
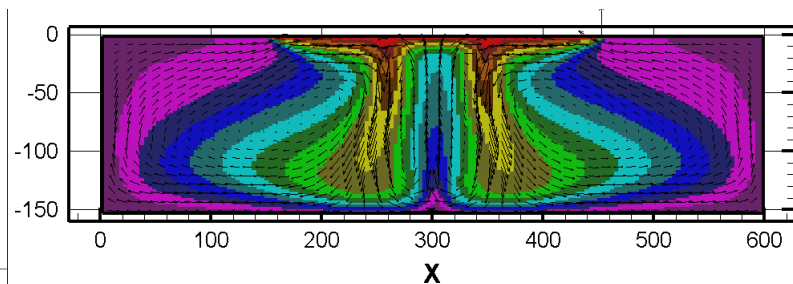
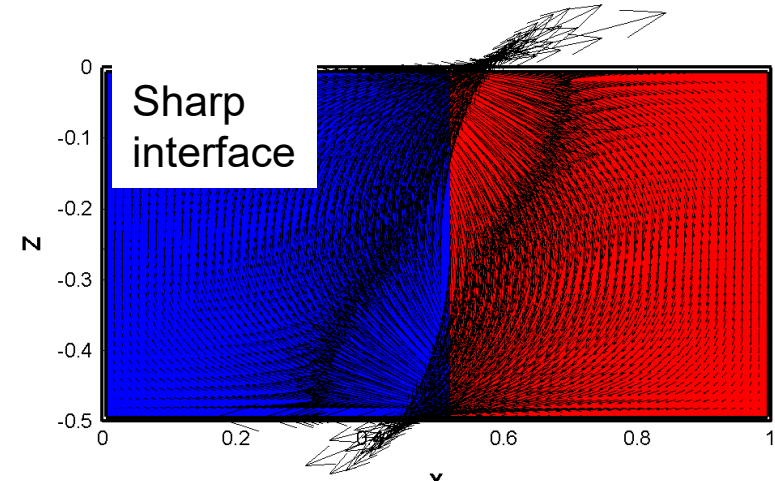
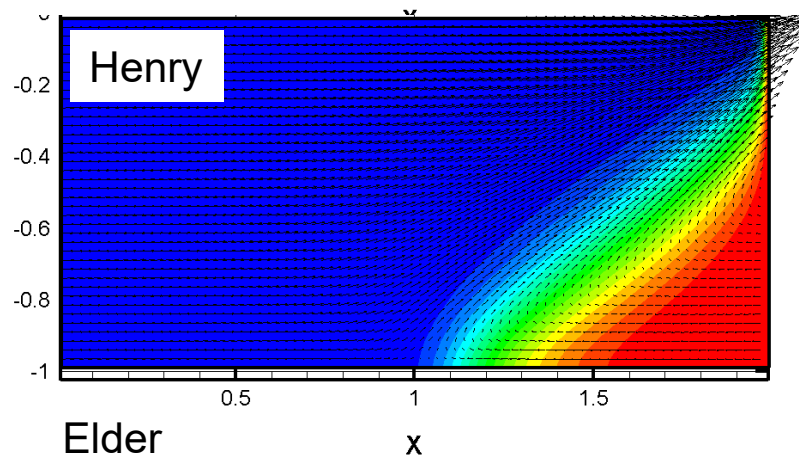
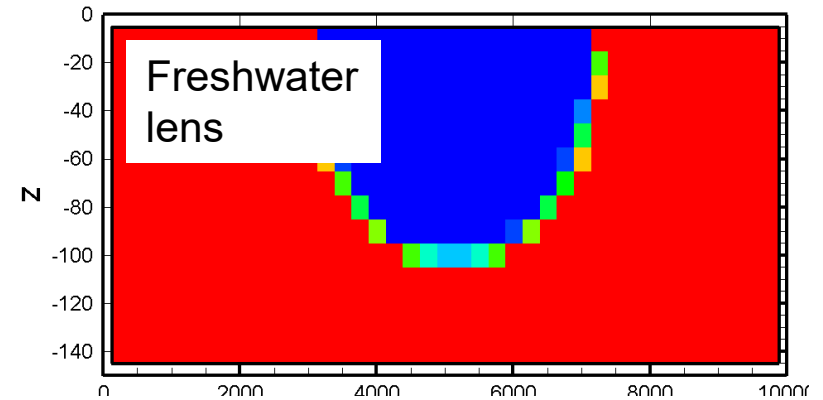
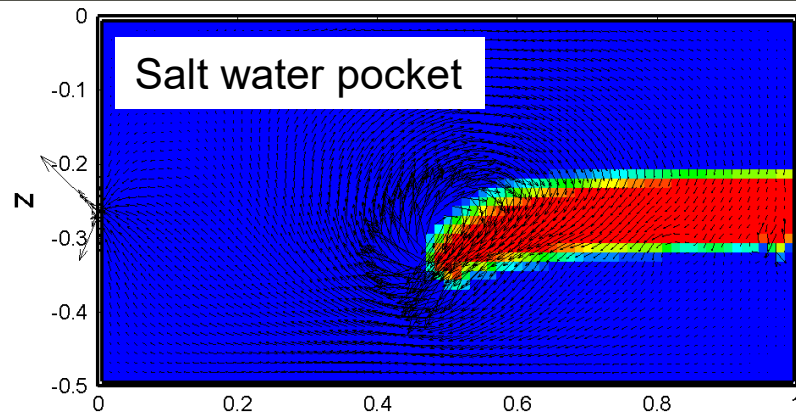
Henry's problem: sea water intrusion in coastal aquifers



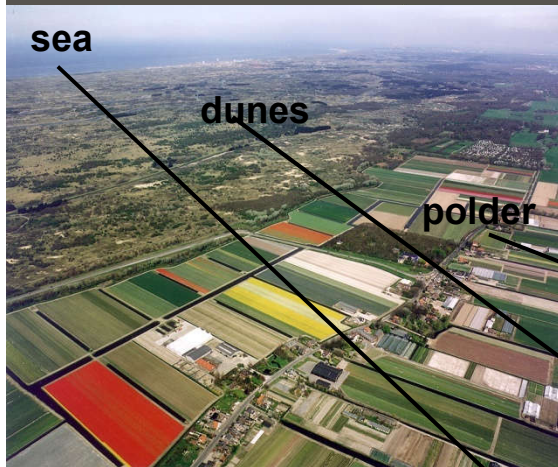
Voss, 1984

Figure 6.10. Match of isochlors along bottom of aquifer for num (1976) and SUTRA.

1980-1990s: heel veel Benchmarks testing



Mijn eerste computer model (1990)

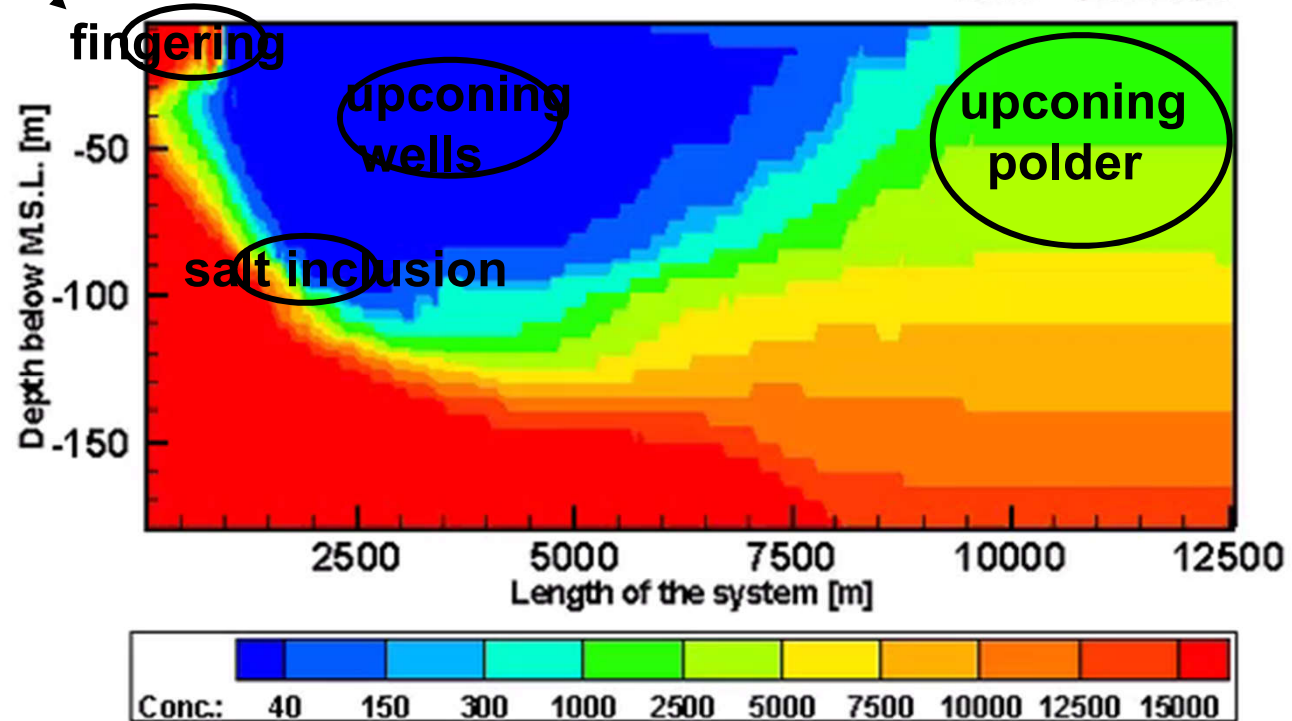


Salinisation of the groundwater flow system

caused due to groundwater extractions and lowering of the ground surface of the Haarlemmermeer polder

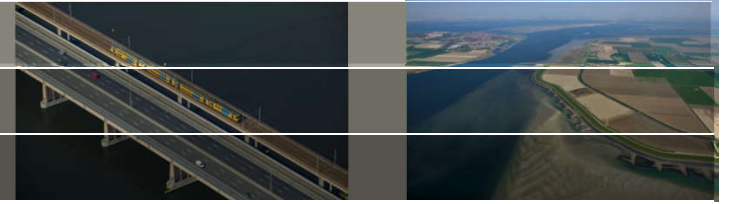
Profile Amsterdam Waterworks-Haarlemmermeerpolder

Time= 1854 AD



Saltwater intrusion in the Dutch coastal zone

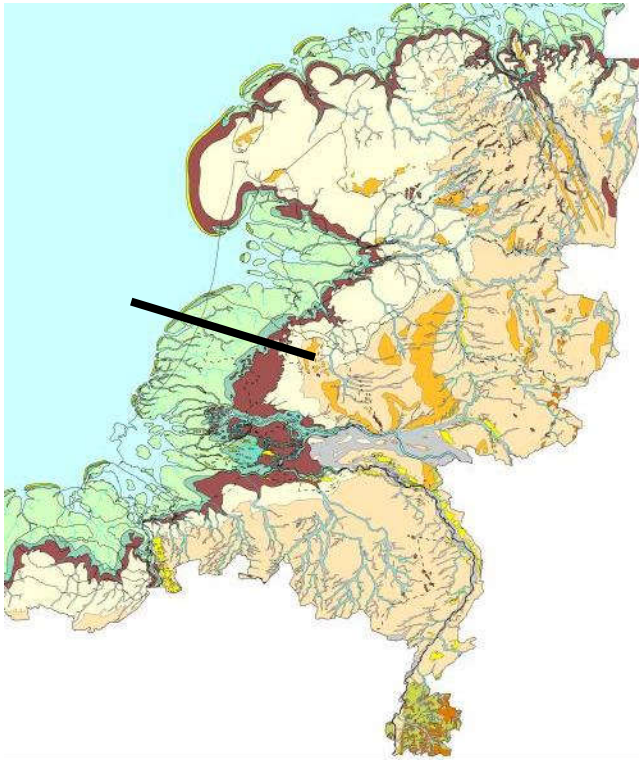
Nieuwe zaken anno 2019:



1. paleohydrogeografische reconstructies
2. datacollectie (AEM zoet-zout)
3. clipping toolboxes (imod-python)
4. MODFLOW6
5. Parallel SEAWAT
6. globale hydrogeologische databases
7. gekoppelde processen in modellen

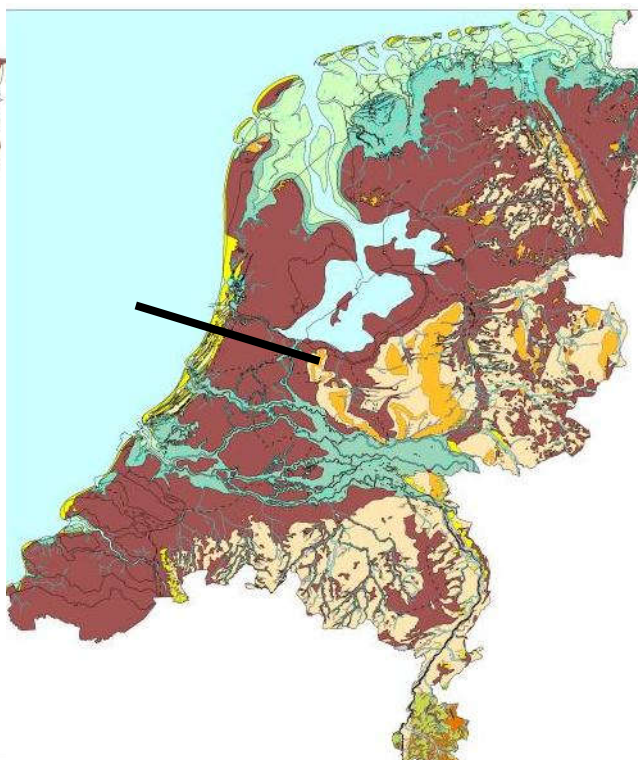
Paleohydrogeografische reconstructies

5500 BC



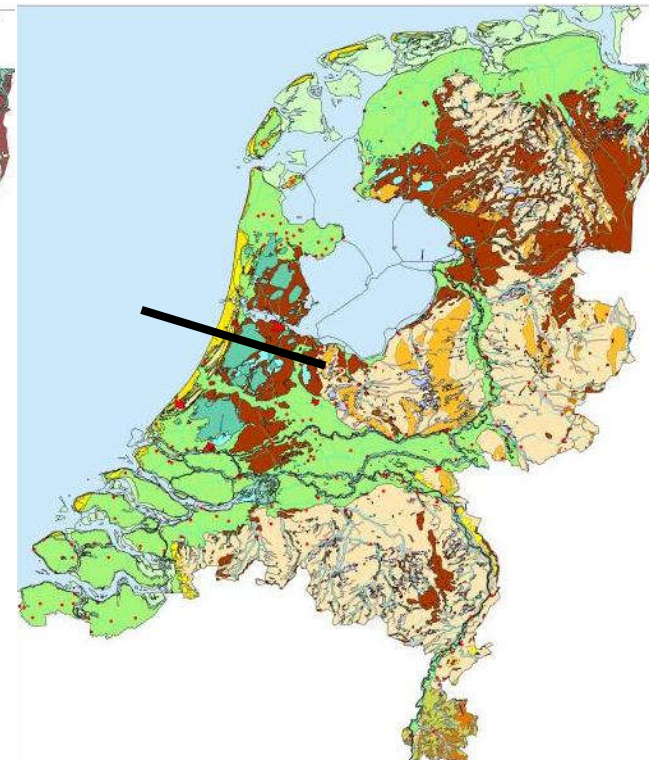
Maximal transgression

100 AD



Peat development

1850 AD



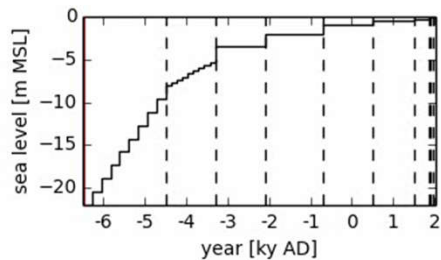
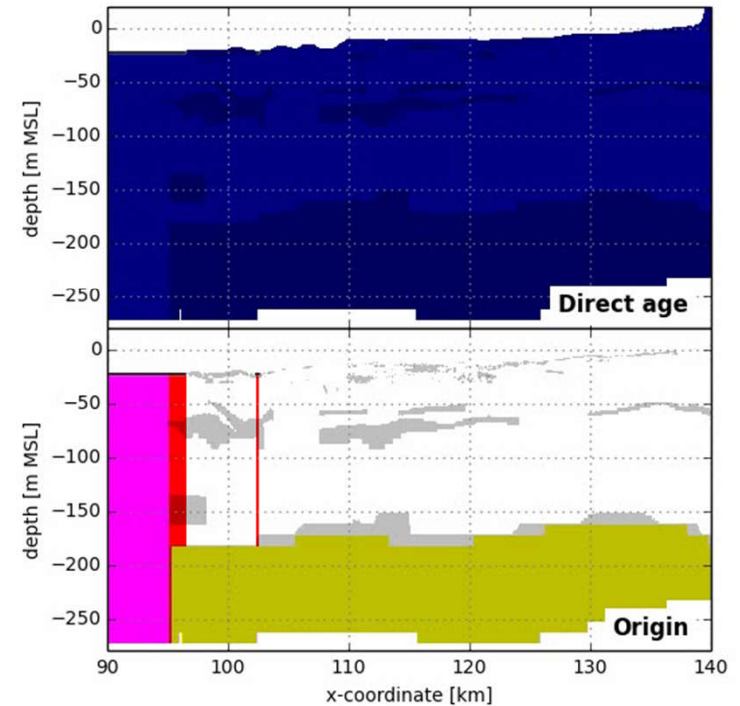
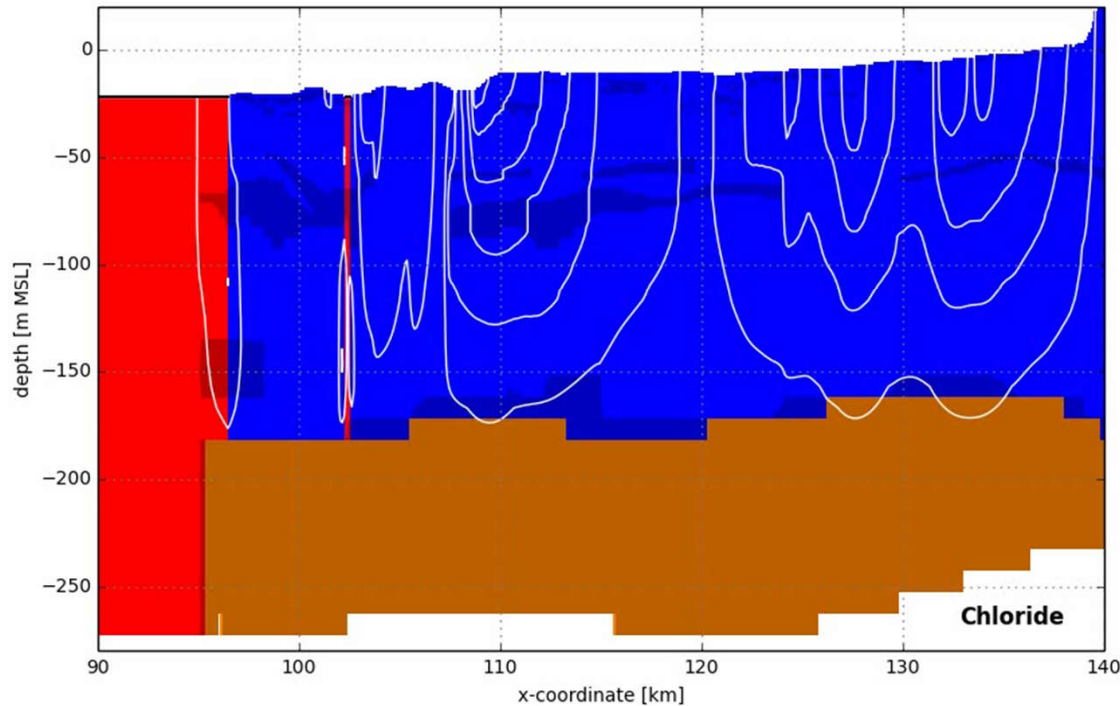
Reclaimed land, polder

Om zoet-zout verdeling en grondwater fluxen te schatten

Development saline groundwater in the Holocene

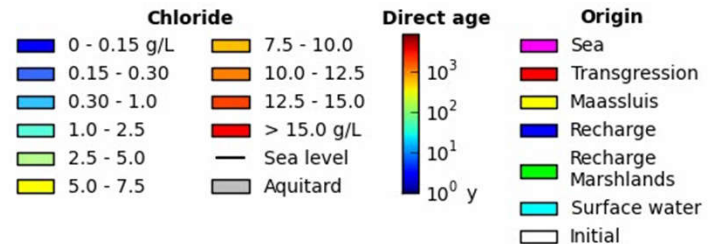
Supplementary information to Delsman et al., 2014. Palaeo-modelling of coastal salt water intrusion during the Holocene: an application to the Netherlands.

Model time: 6500 BC

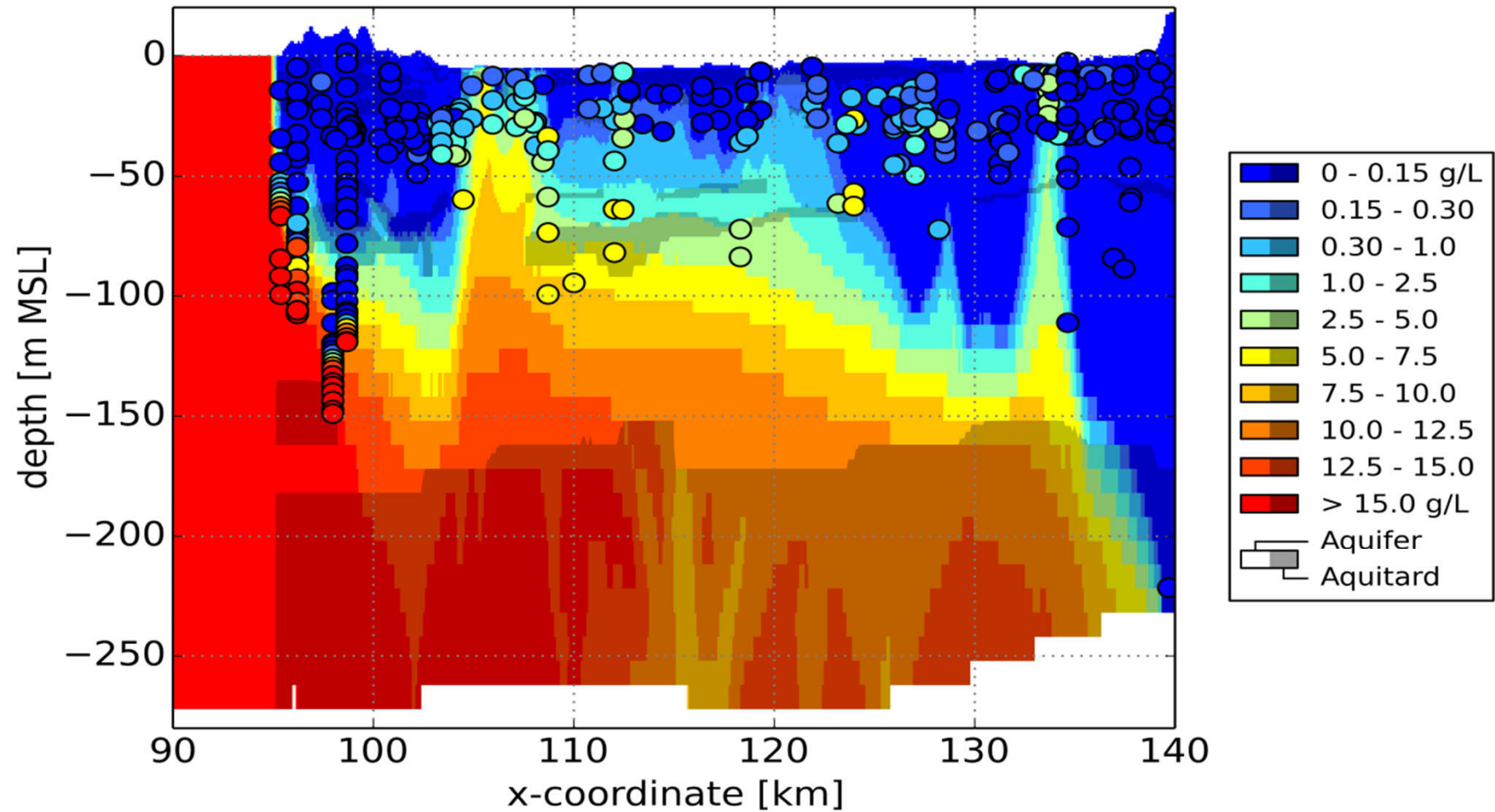
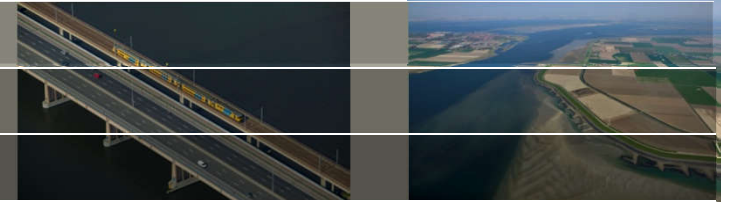


Timeslice 1: 6500 BC - 4500 BC

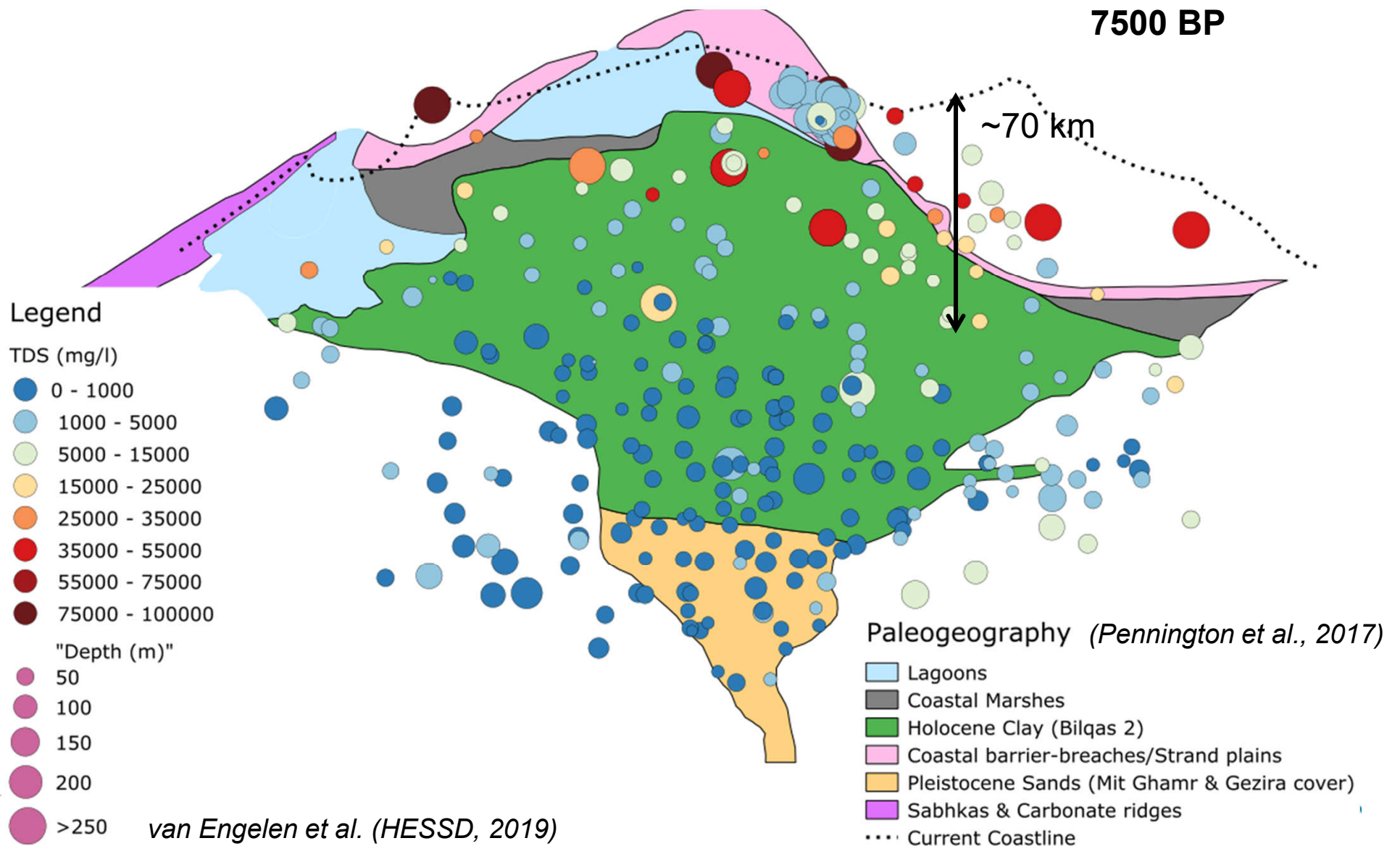
- Sea level rise, linearly from 22 to 8 m BSL
- Maximum transgression extent reached
- Tidal area develops over Pleistocene surface, "basal" peat deposits left mostly intact
- Surface drainage



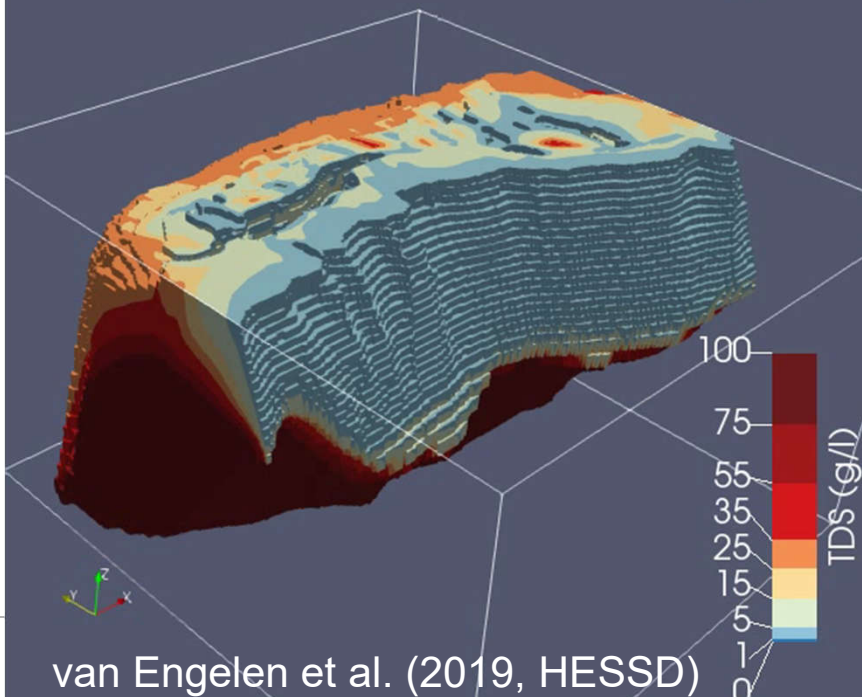
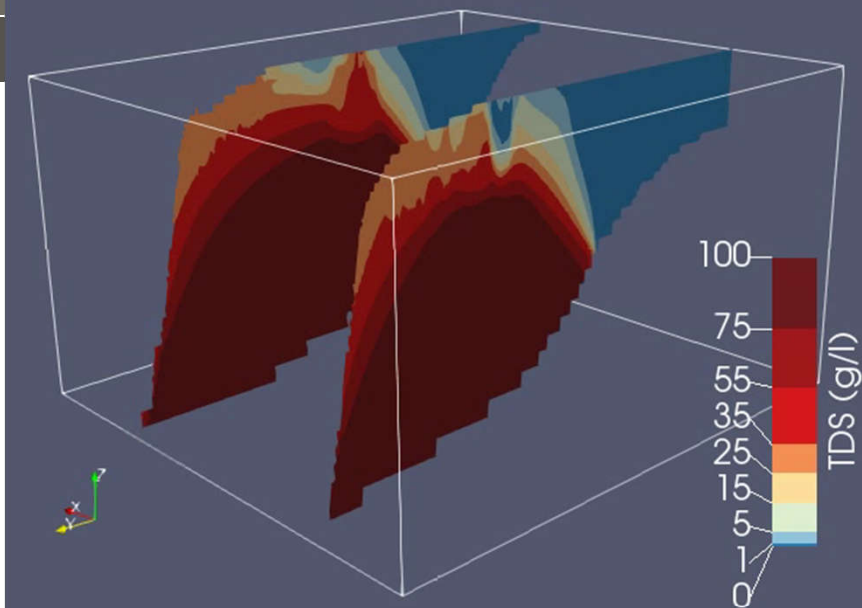
Model versus measurements



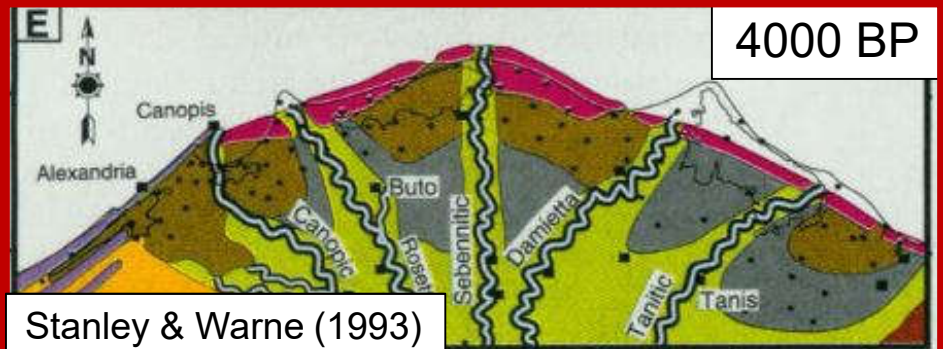
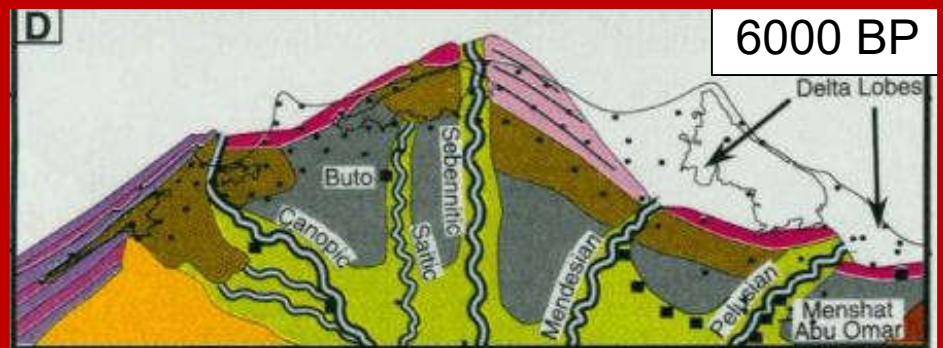
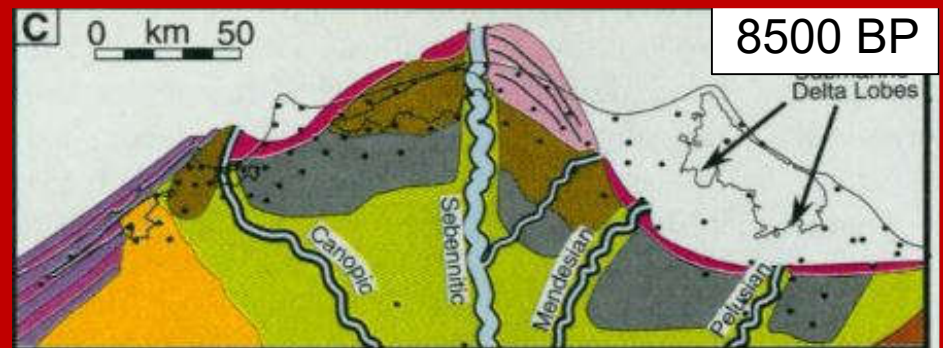
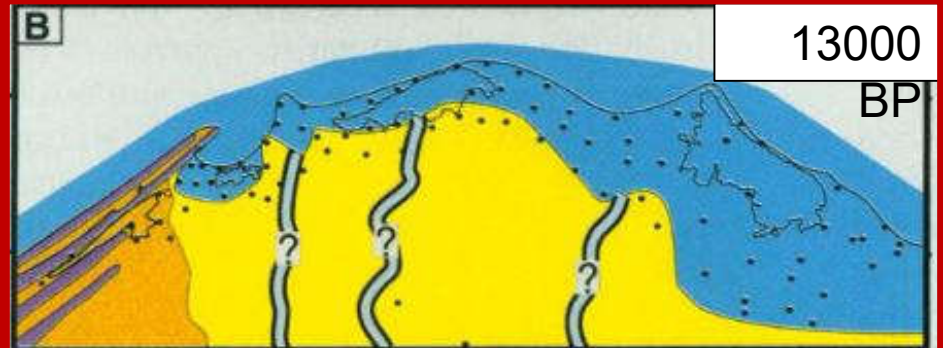
Paleohydrogeology Nile Delta: a data-poor delta



Time: 13000 year BP

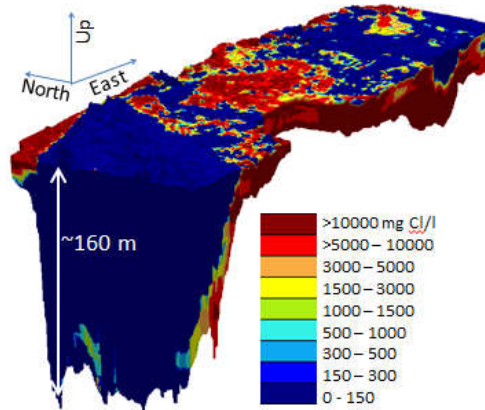


van Engelen et al. (2019, HESSD)

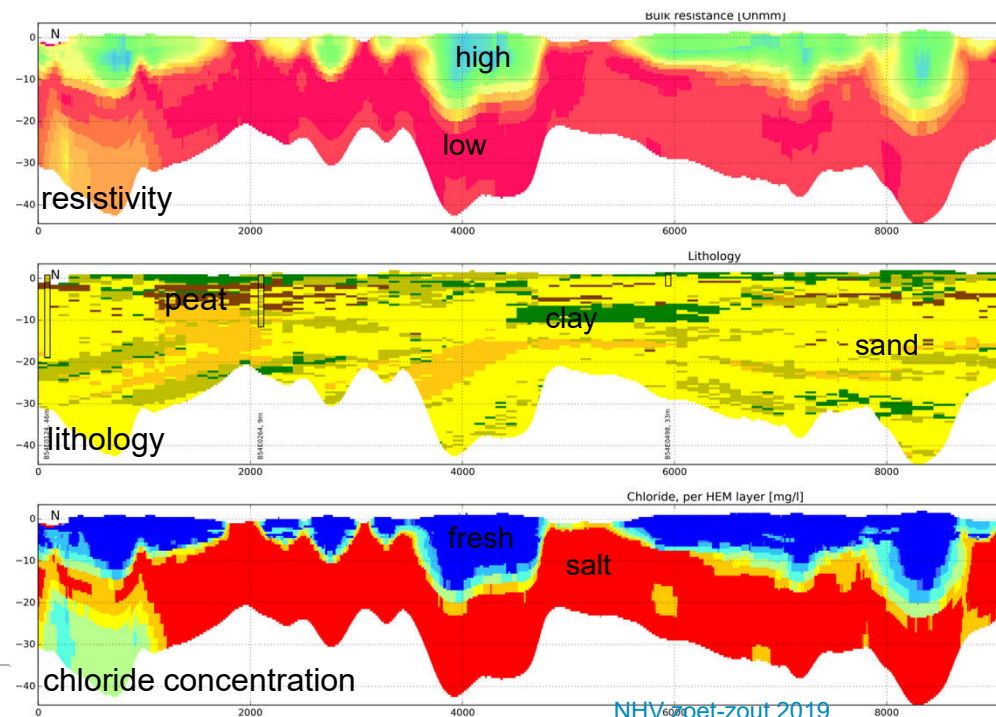


Stanley & Warne (1993)

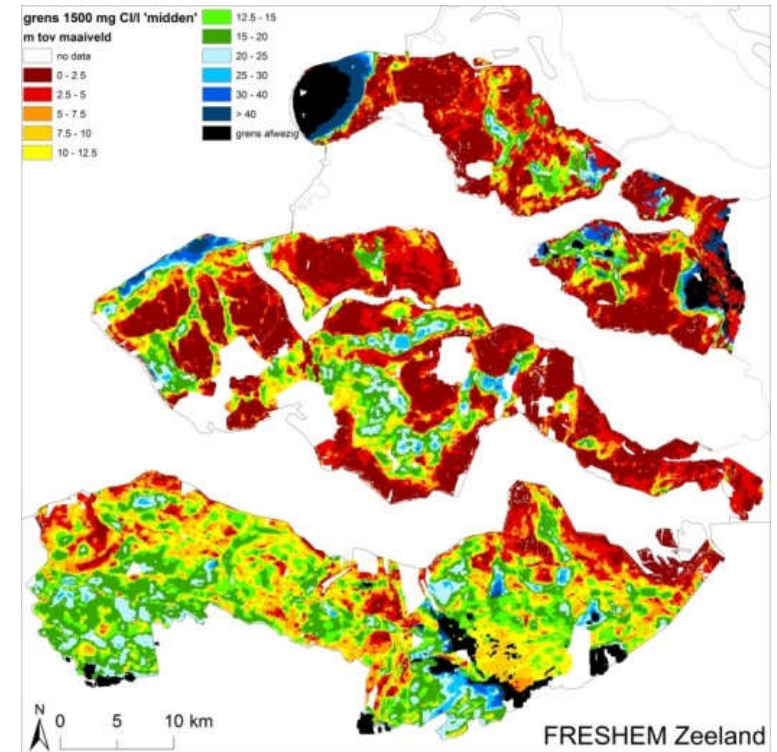
Data collectie: Airborne zoet-zout grondwater kartering



FRESHEM Zeeland



NHV zoet-zout 2019



TNO innovation for life

BGR

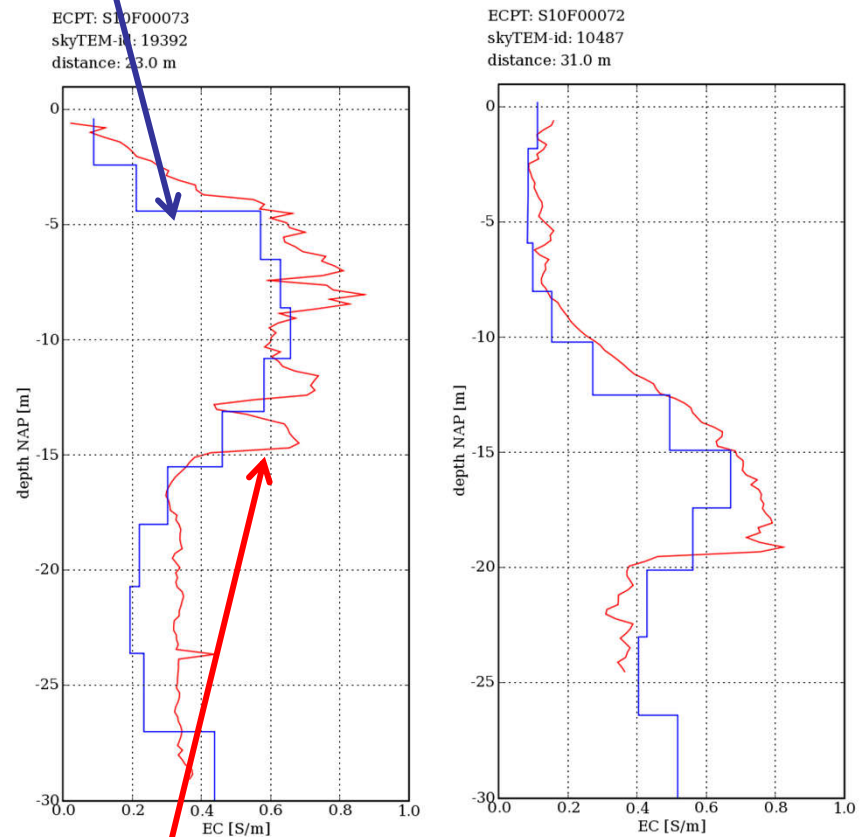
Deltares

Data collectie: Airborne zoet-zout grondwater kartering



How much samples in 1 week on 900km²?

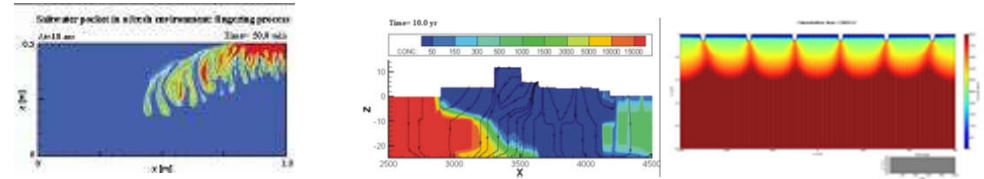
AEM: ~80000 data points



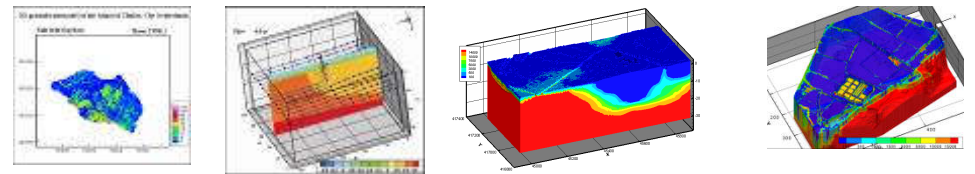
In-situ: ~100 data points

Verschillende modelcelgroottes voor verschillende processen

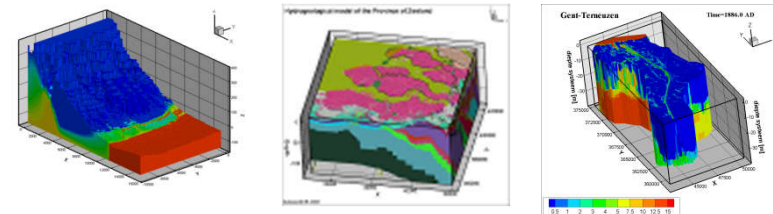
Sub-local: fingering, salty sand boils
Sri Lanka (Tsunami 2004), Zandmotor
cell size=1cm-1m



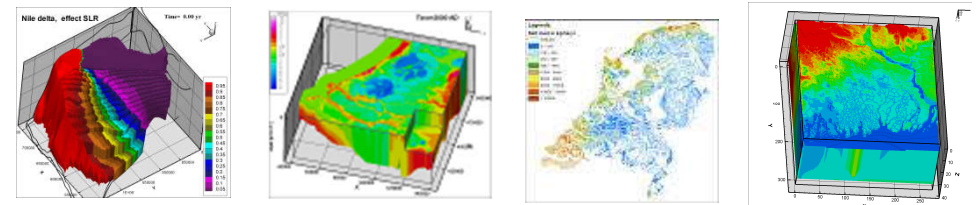
Local: rainwaterlenses, heat-cold
Tholen, Schouwen-Duiveland
cell size=5-25m



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



National: fresh groundwater resources
Nile Delta, BD, Zuid-Holland
cell size=250m-1km

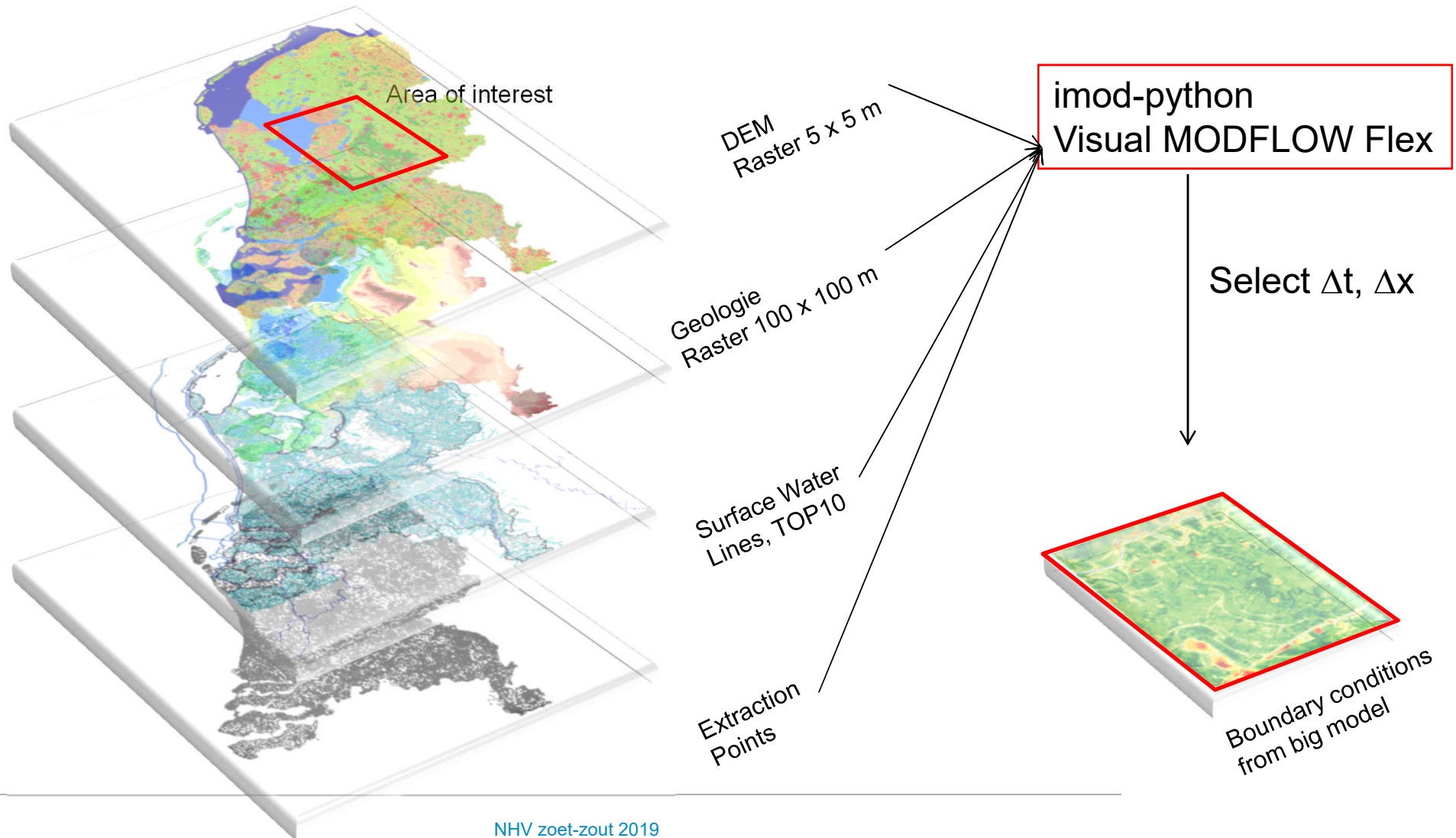


Goal:

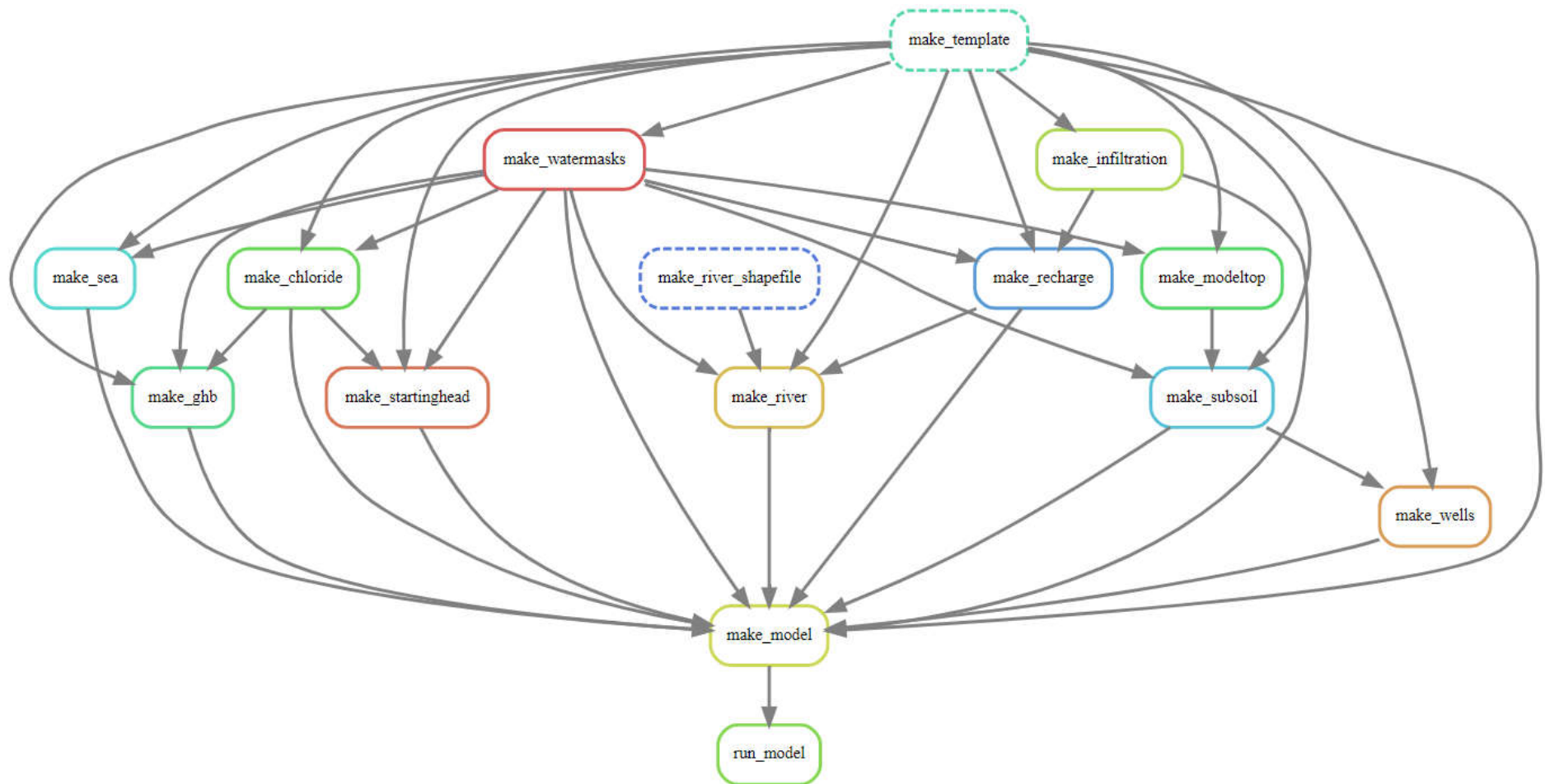
To take largest cell size possible to accurately model
relevant salinisation processes

So... use clipping toolboxes to create local models

Data on highest resolution possible



























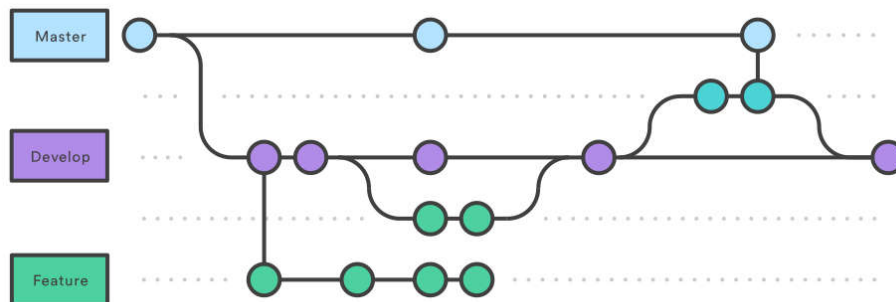
Van hydrogeologische invoerdata naar model



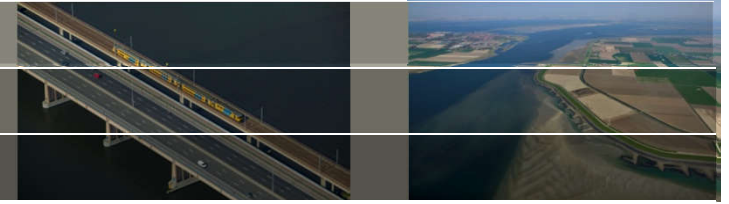
Versiebeheer: reproduceerbaar en transparant

Archivering van aanpassingen
en veranderingen

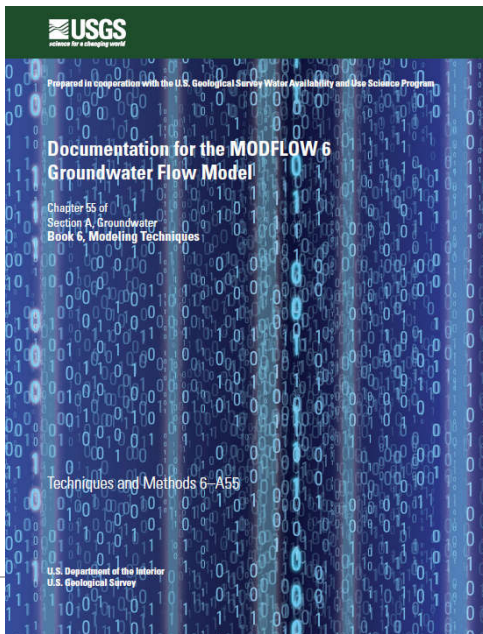
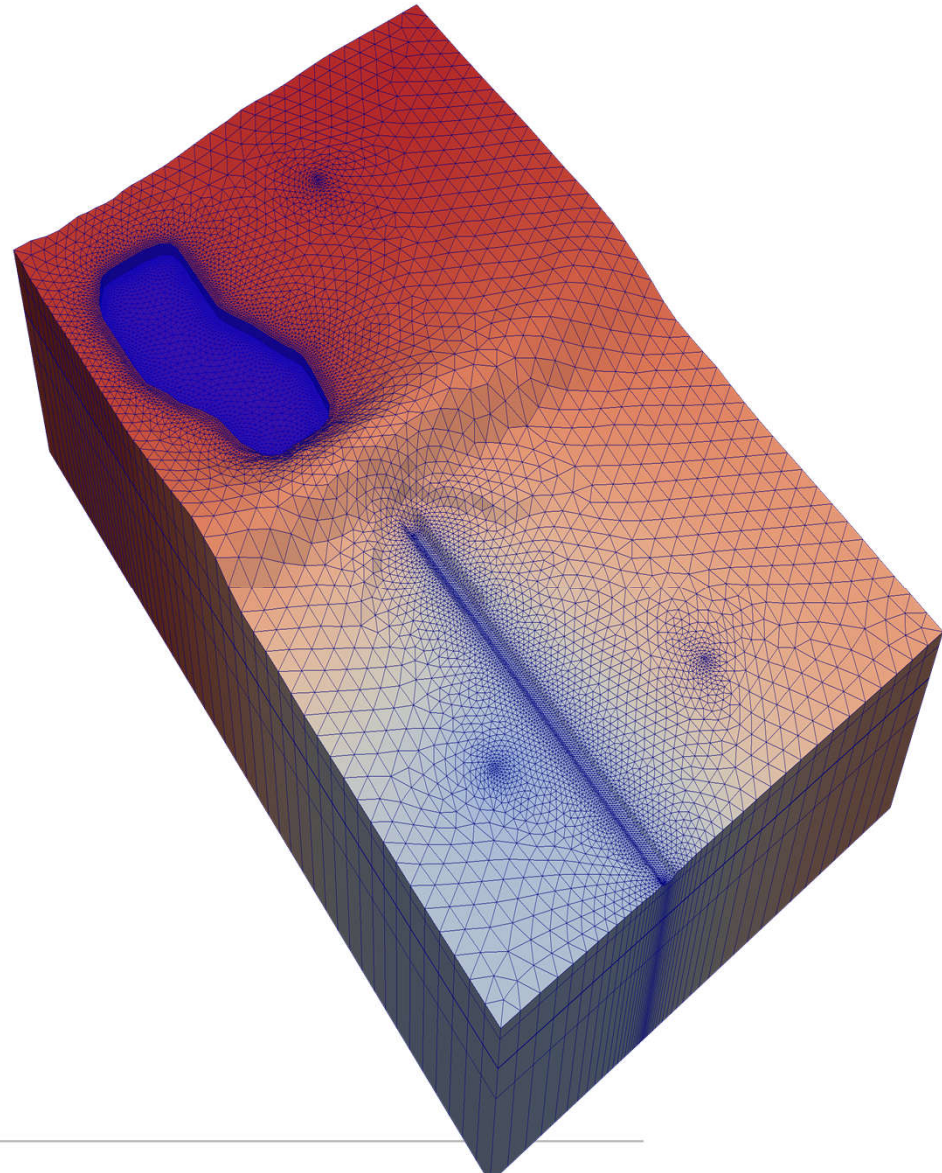
19 Jul, 2019 4 commits		
	Add infiltration ponds as input, use conductance method Huite Bootsma authored 2 months ago	dfa34bff  
	Add summer and winter stages for river Huite Bootsma authored 2 months ago	99454d32  
	Use the right array for conductance, add density Huite Bootsma authored 2 months ago	0f263e25  
	Add templates to water_mask input Huite Bootsma authored 2 months ago	7754d4b4  
18 Jul, 2019 7 commits		
	Add modeltop to subsoil input Huite Bootsma authored 2 months ago	590e3c5c  
	Update ghb creation to include fixed head on edges Huite Bootsma authored 2 months ago	34a127c8  
	Drop unnecessary coords from template_2d Huite Bootsma authored 2 months ago	4c784844  
	Regrid chloride chunking along z, much more efficient Huite Bootsma authored 2 months ago	b6d09225  



MODFLOW 6: zoet-zout



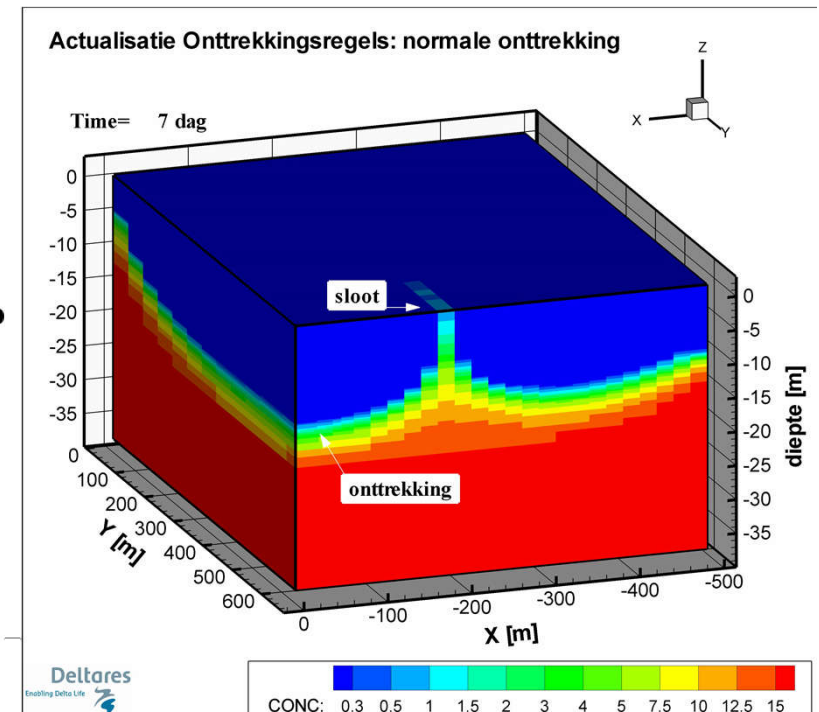
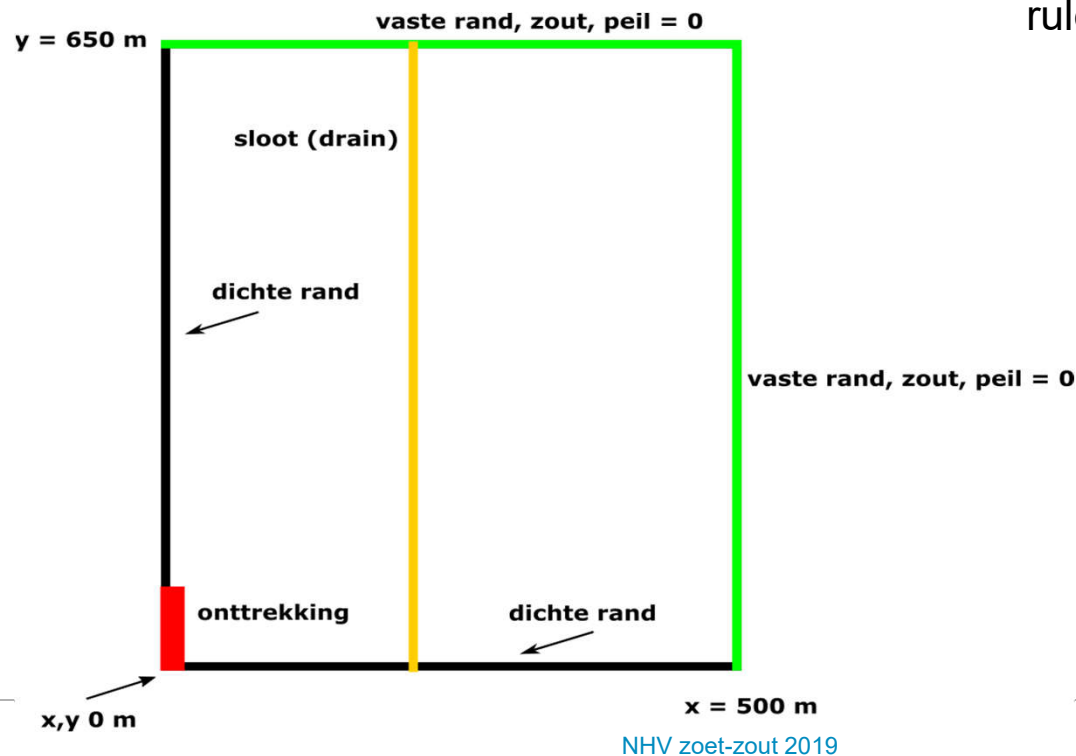
- Detail / rekenkracht daar waar nodig (onttrekkingen, opp.water)
- Onregelmatig grid
- XT3D package voor volledig 3D anisotropie



Performed activities

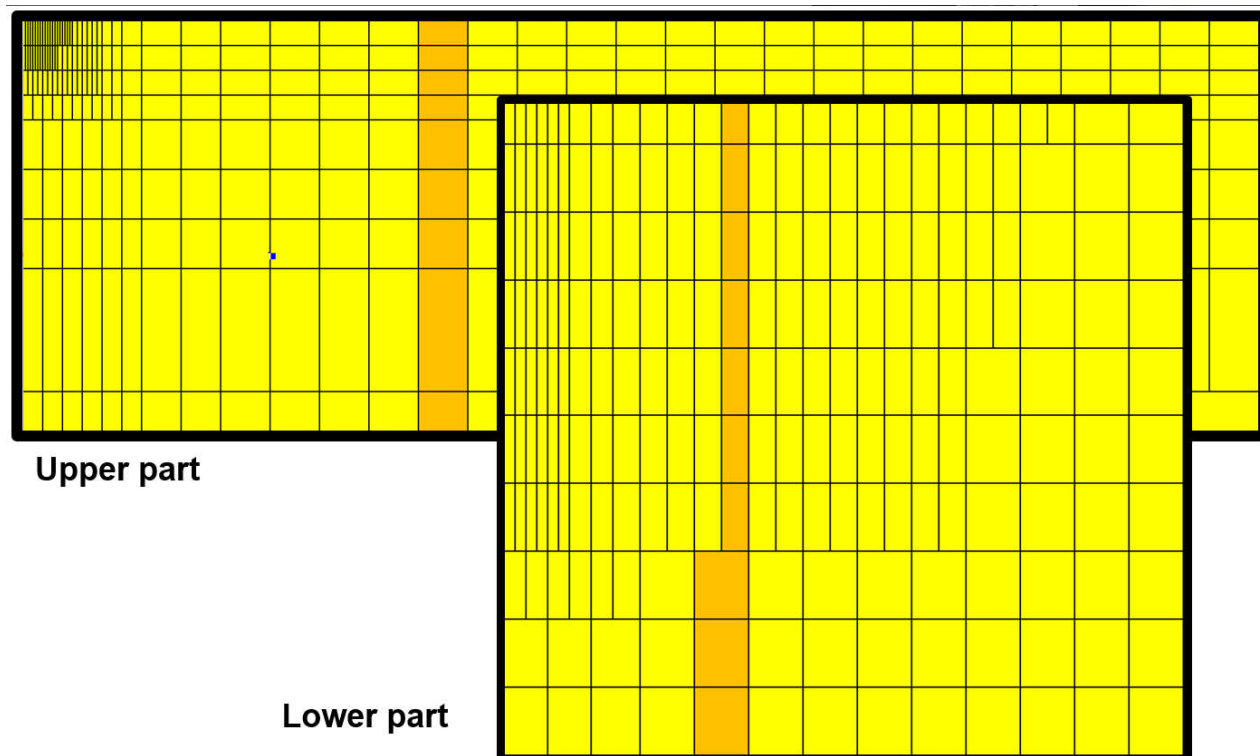
- Got code from Github and compiled it (september 2018)
- Read the manuals
- Built a test model in MF6 with structured and unstructured grid, to compare with SEAWAT v4.

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

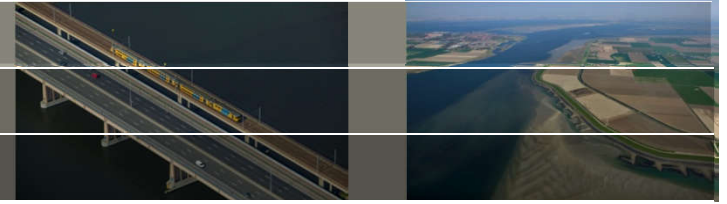


Testing different grids and run times

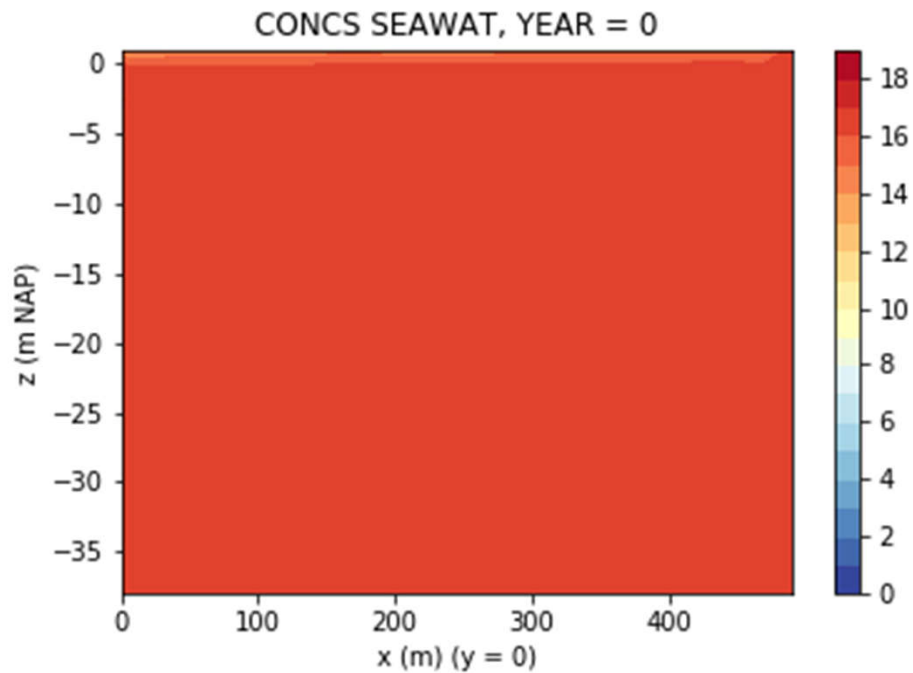
- Original grid: 77112 cells (already optimized using non-equidistant grid)
- Unstructured grid: 40068 cells
- Therefore reduced simulation times are expected.



Density effects

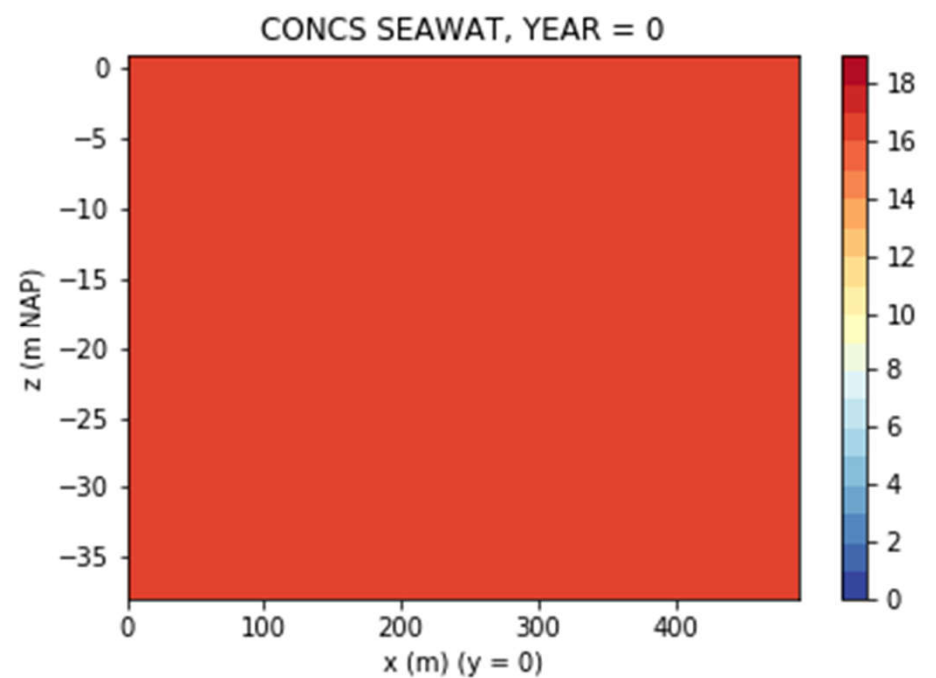


No density effects



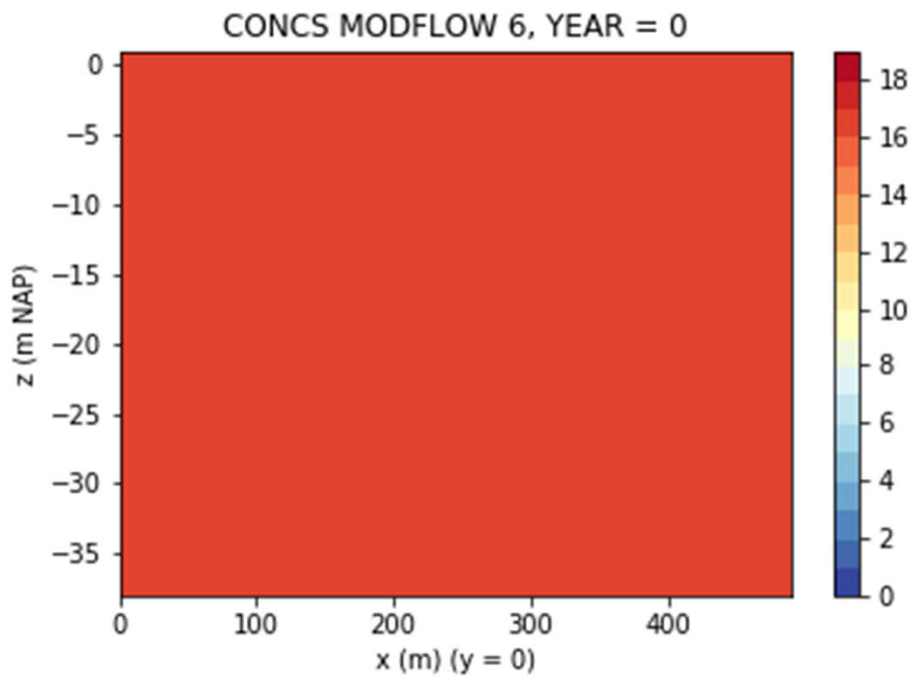
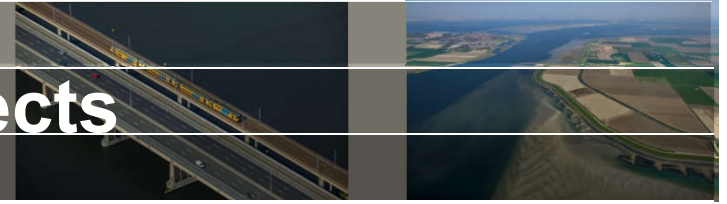
MF6

Density effects

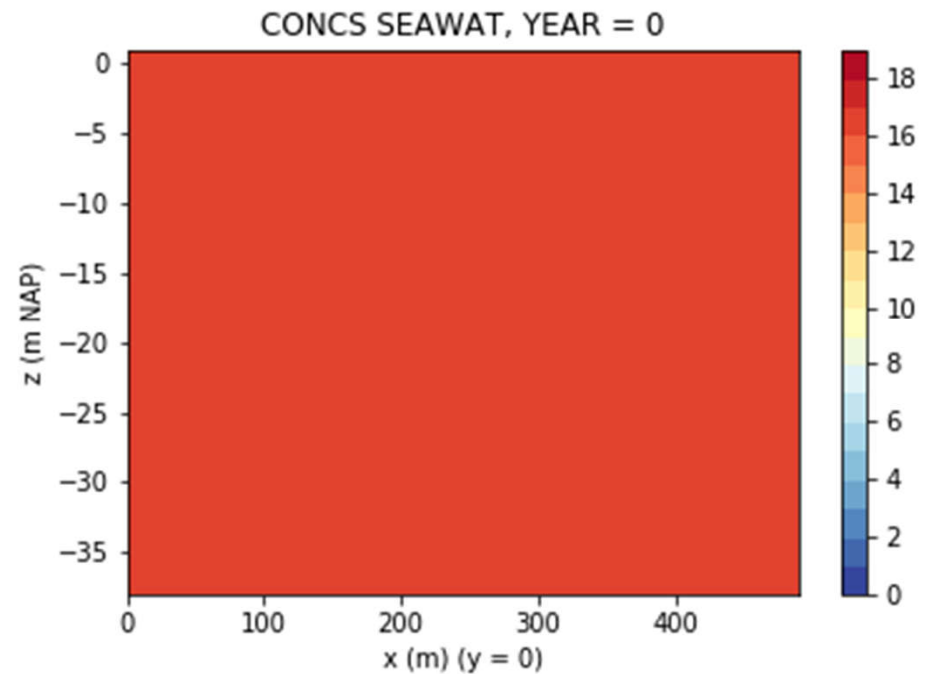


SEAWAT v4

Regular grid, **with** density effects



MF6



SEAWAT v4

Parallele computing zoet-zout grondwater

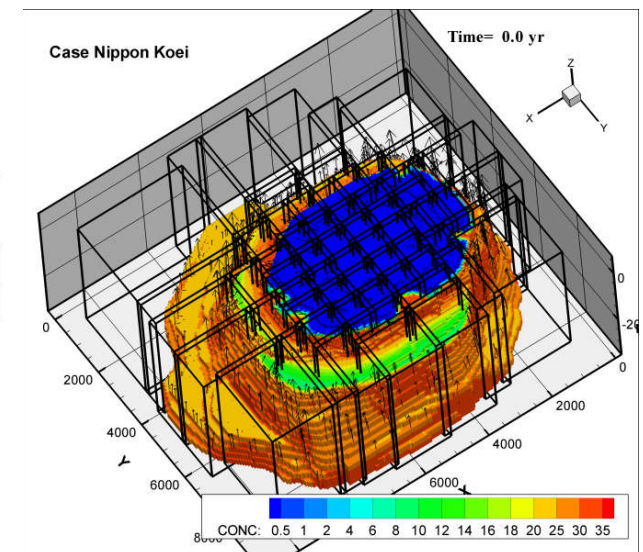
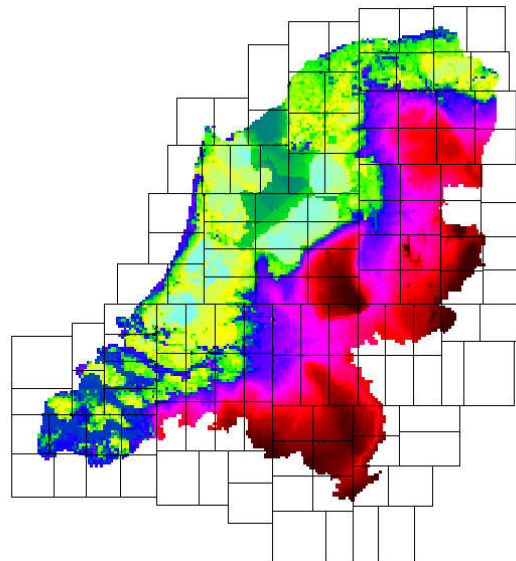
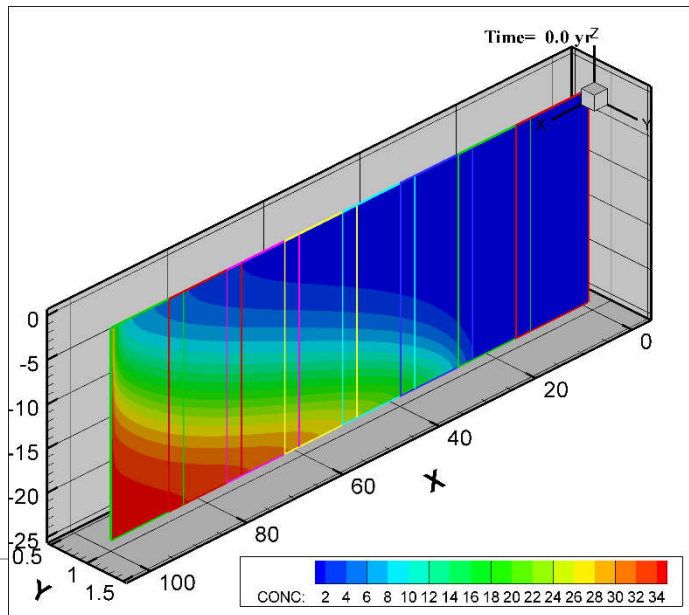
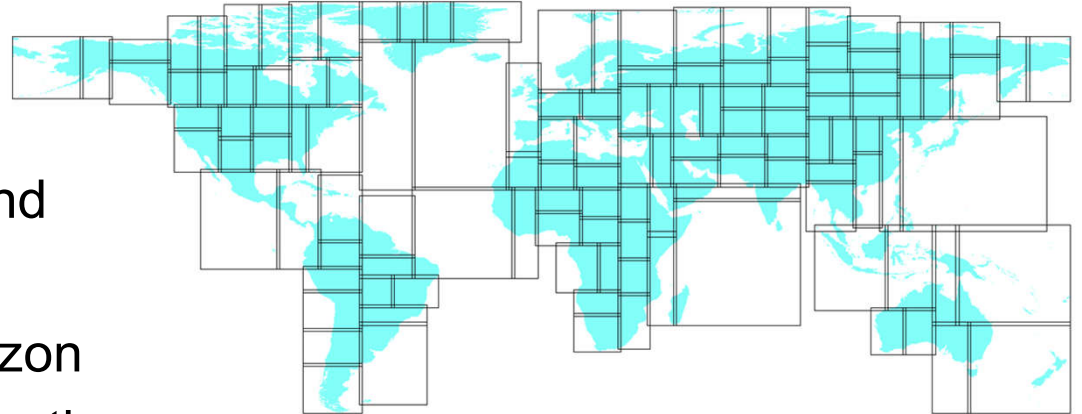
Version iMOD-WQ/SEAWAT 5.0

Beta version released deze maand

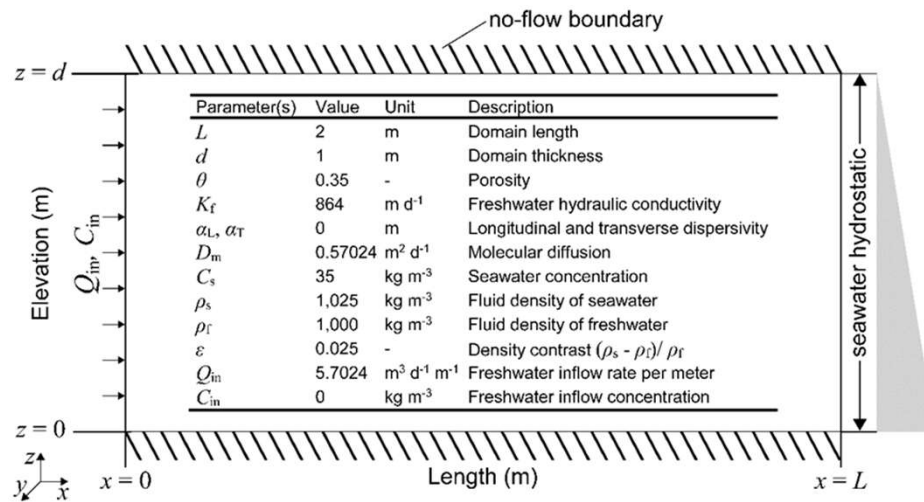
iMOD runfile formats

Draaien op bijv. rekencorens Amazon

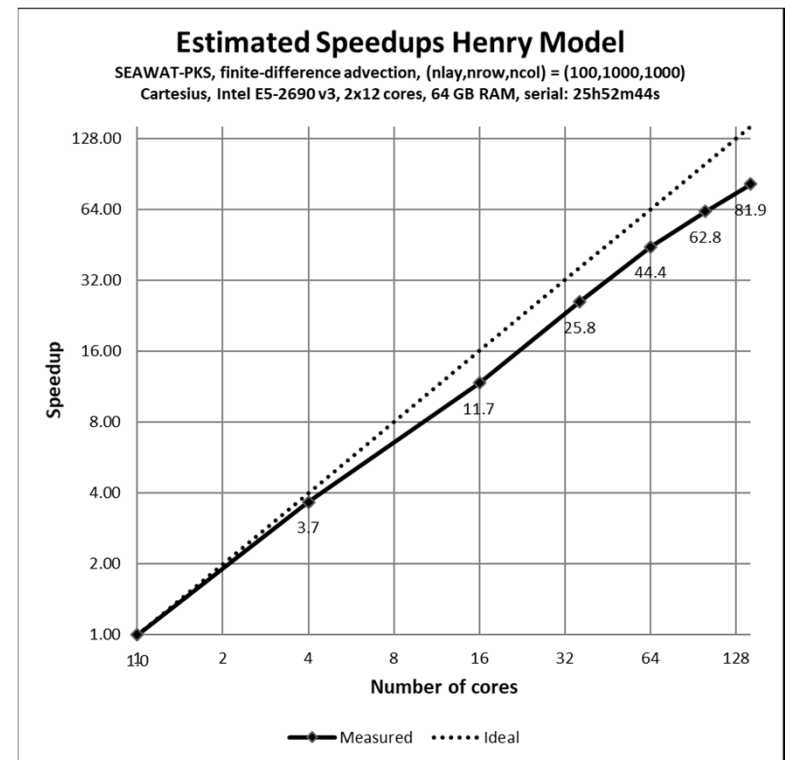
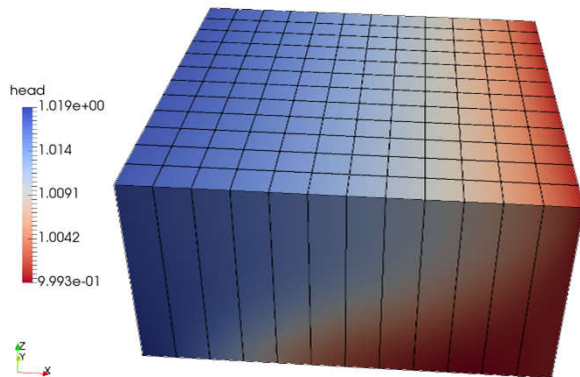
Beperking: dataopslag en visualisatie



Case #1/3: Henry 3D, FD, 100M cells



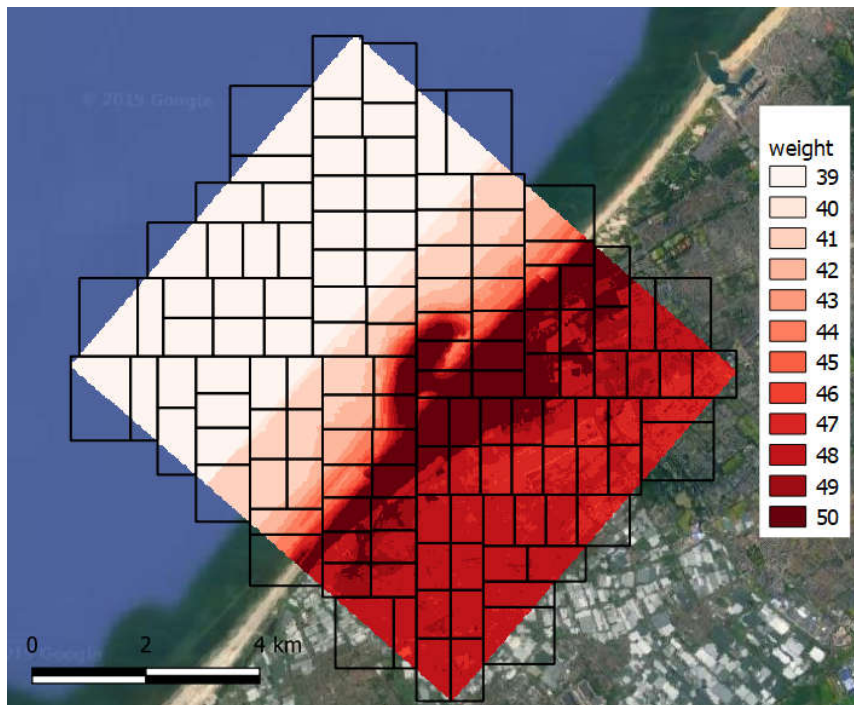
1000 x 1000 x 100
 $\Delta x = \Delta y = 0.002\text{m}; \Delta z = 0.01\text{m}$



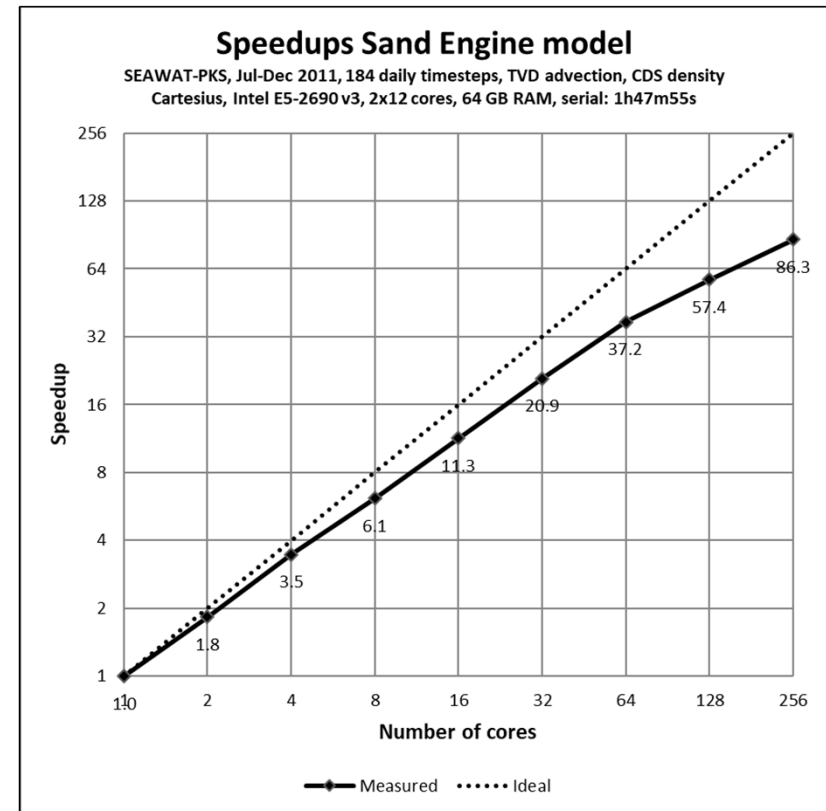
16:57:46 (1 core) → 00:12:26 (144 cores)

Case #2/3: Sand Engine, TVD, 10M cells, Jul-Dec 2011

468 x 468 x 50; 25m cell sizes



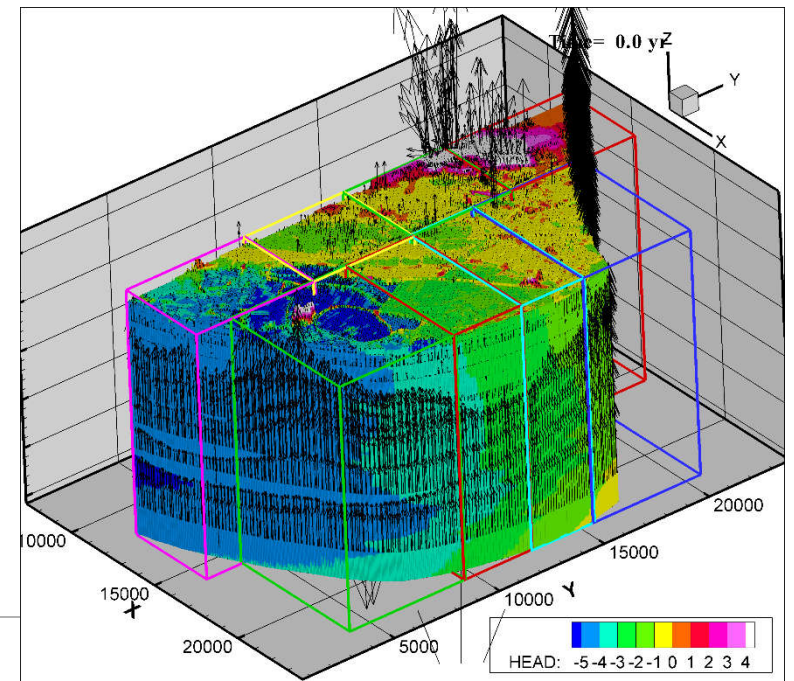
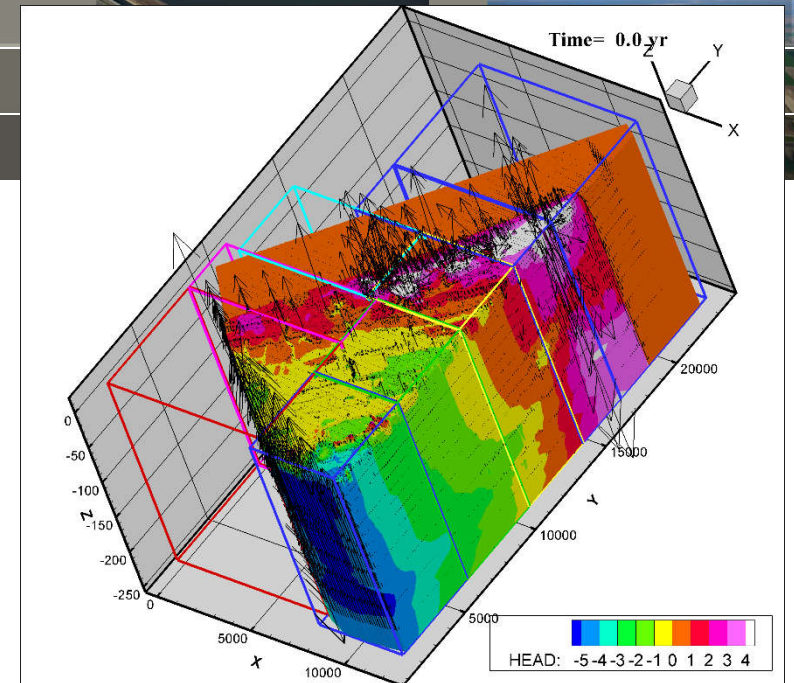
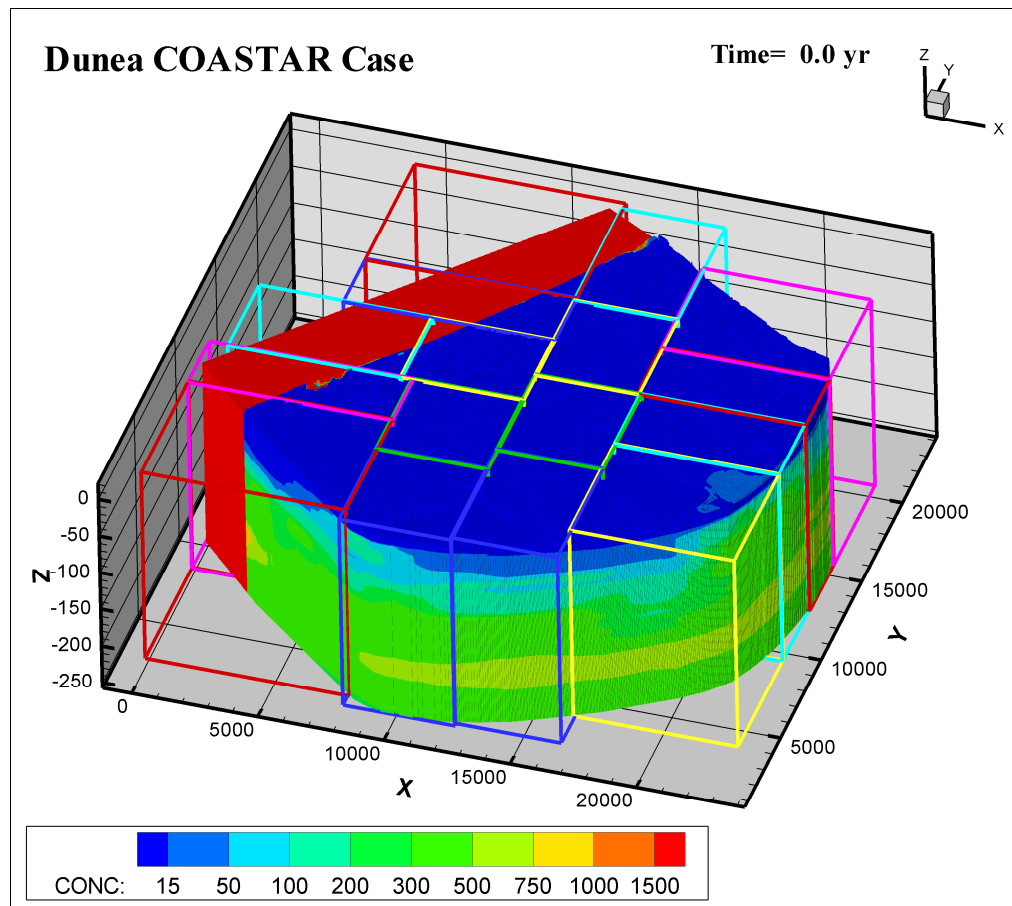
partitioning weights
for example of 128 cores



01:47:55 (1 core) → 00:01:15 (256 cores)

Case #3/3 Dunea case

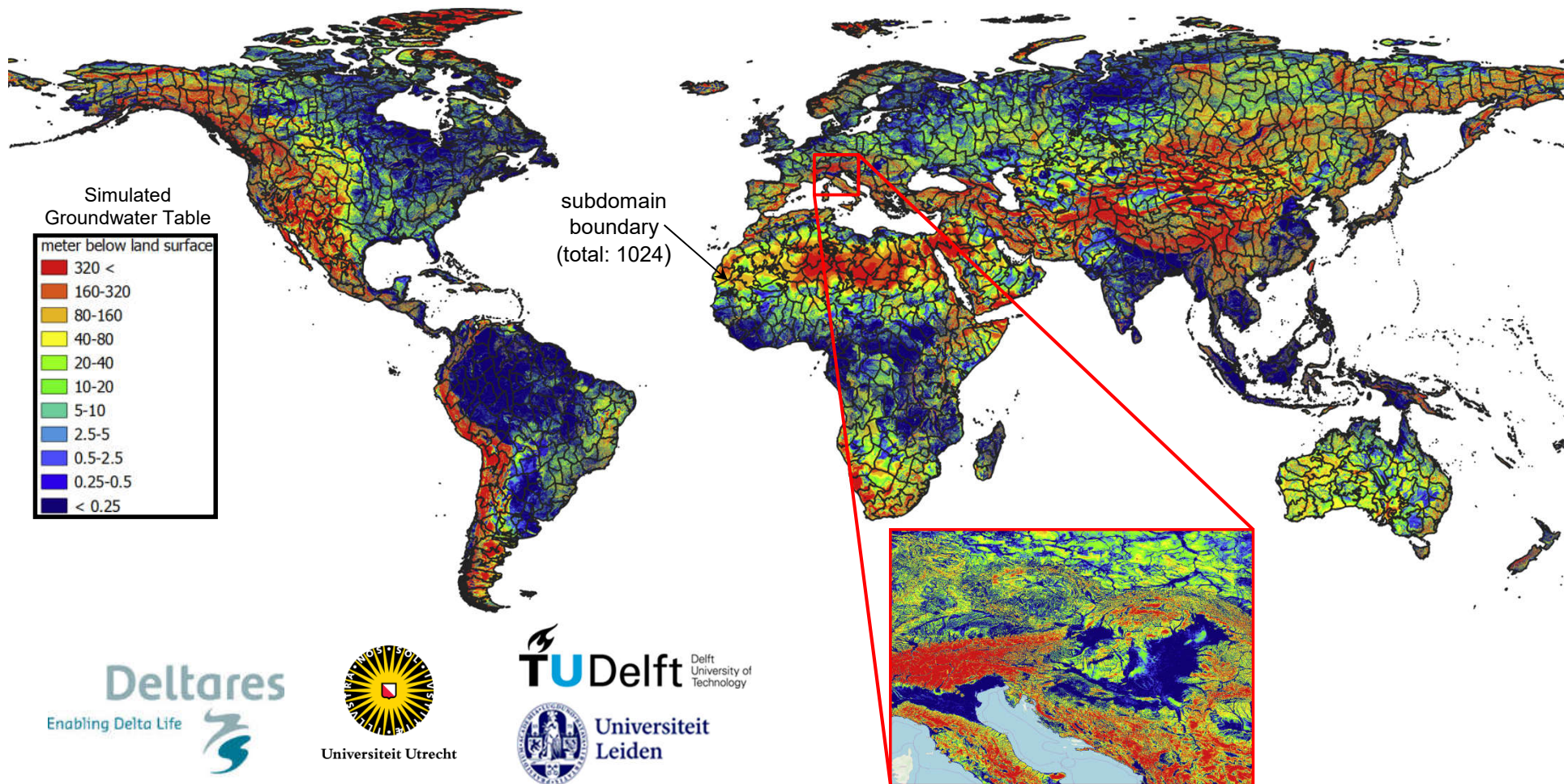
COASTAR Dunea Case
3D Model draait op o.a. 16 Amazone rekencores



Simulation Results PCR-GLOBWB GGM 1 km

First Results Steady-State PCR-GLOBWB-MODFLOW 1km
(428M cells, 2 layers, max. 612 cores in parallel)

PhD Jarno Verkaik

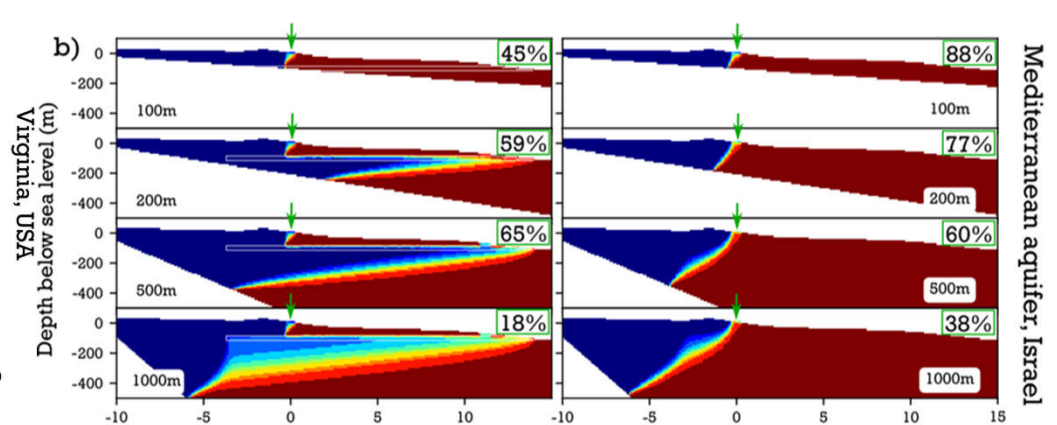
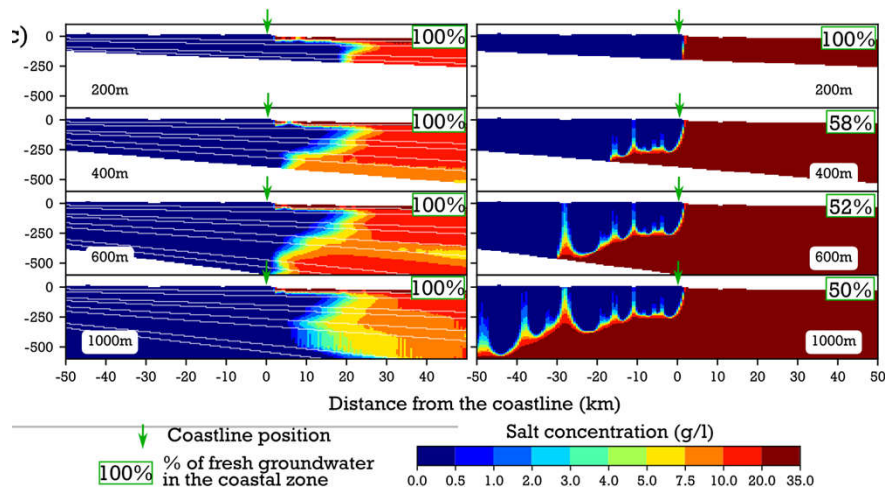
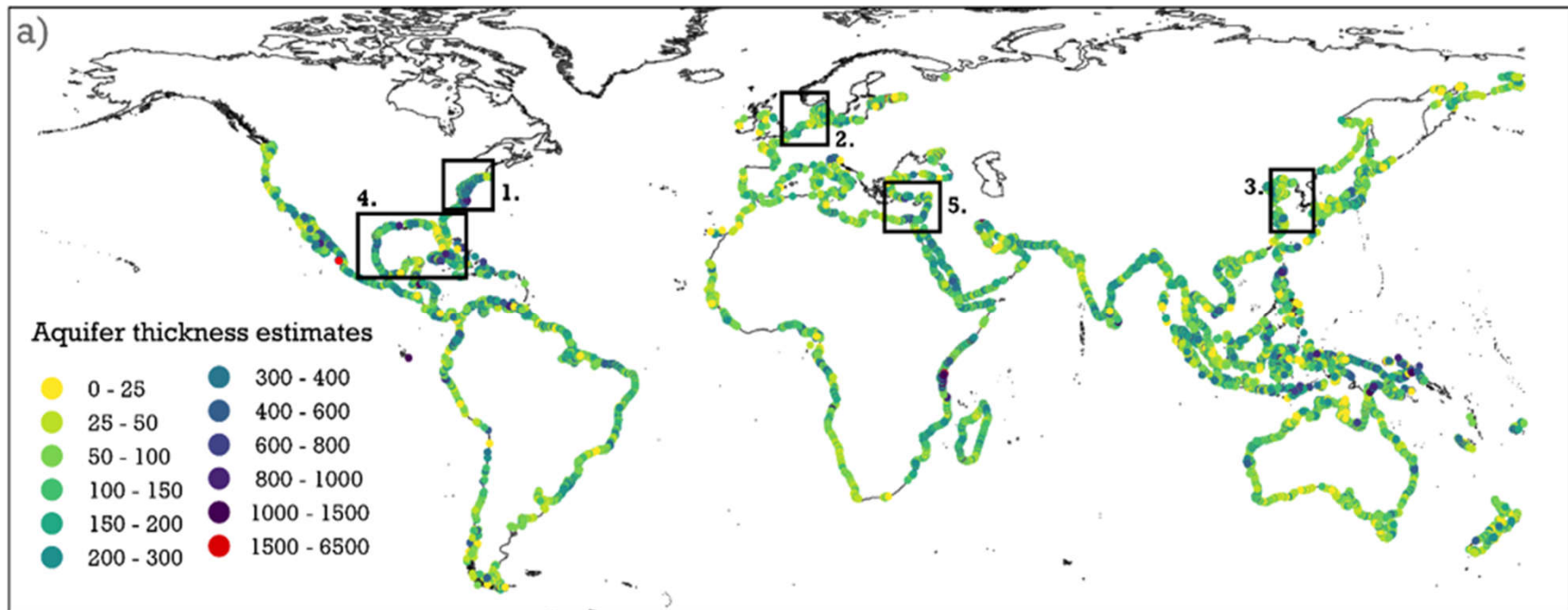


Global hydrogeological databases + clipping toolbox

PhD Daniel Zamrsky

Dataset name	Description	Resolution	Reference
GEBCO 2014^{1,2}	Global topography and bathymetry	30"	(Weatherall et al., 2015)
ATE²	Unconsolidated groundwater system thickness estimation (unconsolidated sediments only)	Vector	(Zamrsky et al., 2018)
P², ET²	Long term average annual precipitation and evapotranspiration	30"	(NTSG, 2019)
GLHYMPS²	Bottom aquifer hydraulic conductivity	30"	(Gleeson et al., 2014)
GLHYMPS 2.0 (GUM)²	Upper aquifer hydraulic conductivity	30"	(Huscroft et al., 2018)
Soilgrids²	Soil layer thickness	30"	(Hengl et al., 2014)
Soil hydraulic properties²	Global soil hydraulic conductivity	30"	(Montzka et al., 2017)
COSCAT^{1,2}	Segmentation of the shelf and basins	Vector	(Meybeck et al., 2006)
MARCAT¹	Segmentation of the shelf and basins, typology	Vector	(Laruelle et al., 2013)
WTD²	Water table depth (relative to sea level)	30"	(Fan et al., 2017)
Ocean floor age¹	Age of oceanic bottom	2'	(Muller et al., 2008)
Delta dispersion¹	Dispersion system classification	Vector	(Walsh and Nittrouer, 2009)
Delta location	Location of 40 largest deltas worldwide	Vector	(Tessler et al., 2015)
LGM¹	Last glacial maximum global extent	Vector	(Ehlers et al., 2011)
Tectonic plate boundaries¹	Indicates passive/active margins	Vector	(Coffin et al., n.d.)
GLIM¹	Global lithology classification	Vector	(Hartmann and Moosdorf, 2012)
Seafloor sediment type	Seafloor lithology classification	6'	(Dutkiewicz et al., 2015)

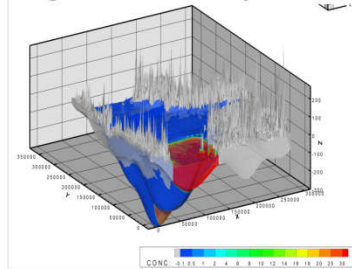
Modelling fresh-saline groundwater coastal zone



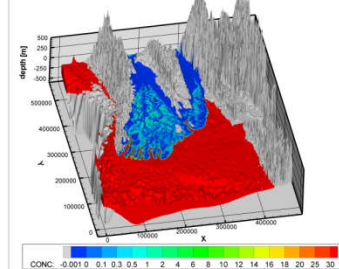
Mediterranean aquifer, Israel

Examples iMOD-WQ/SEAWAT 3D fresh-salt models

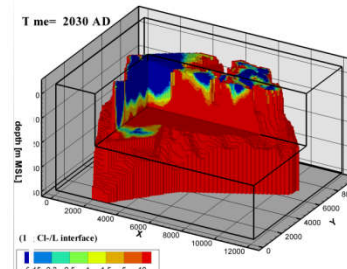
Bangkok, Chao Phraya delta



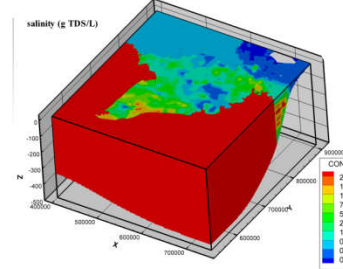
Irrawaddy, Myanmar



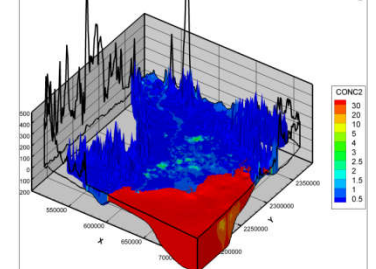
Jurong island, Singapore



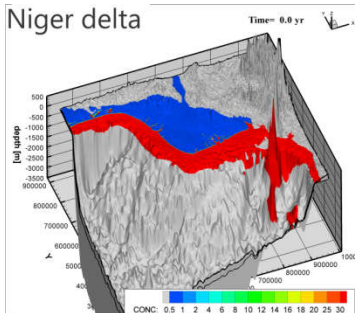
Mekong Delta, Vietnam



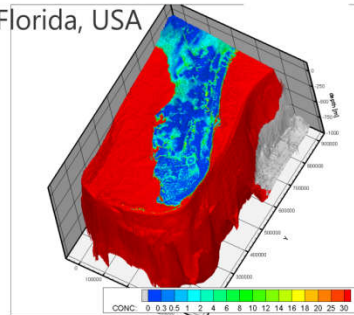
Red River, Vietnam Time= 0.0 yr



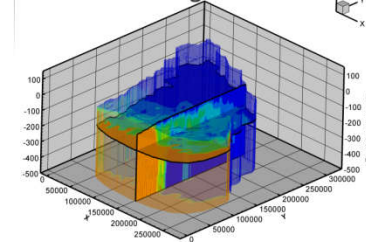
Niger delta



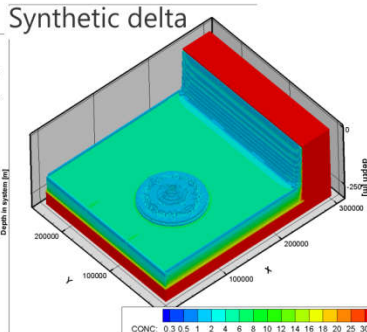
Florida, USA



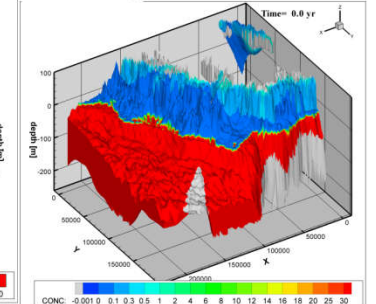
Kulna area, Bangladesh



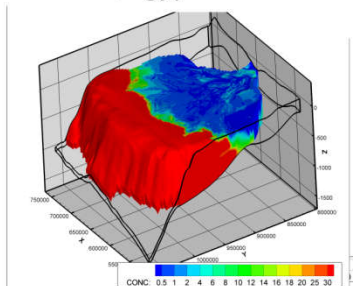
Synthetic delta



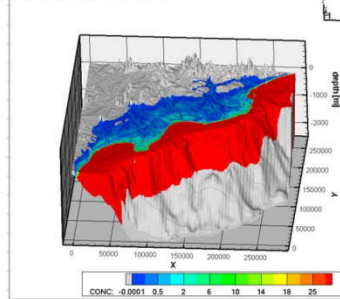
Red River, Vietnam Time= 0.0 yr



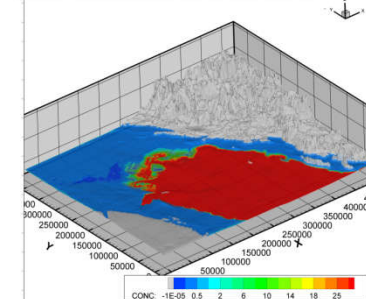
Nile delta, Egypt



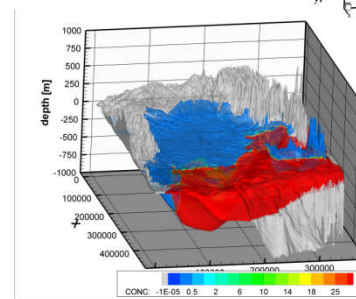
Krishna, India



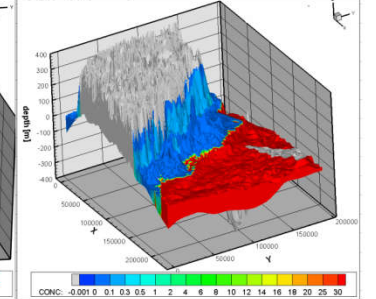
Shatt Al Arab, Iraq/Kuwait



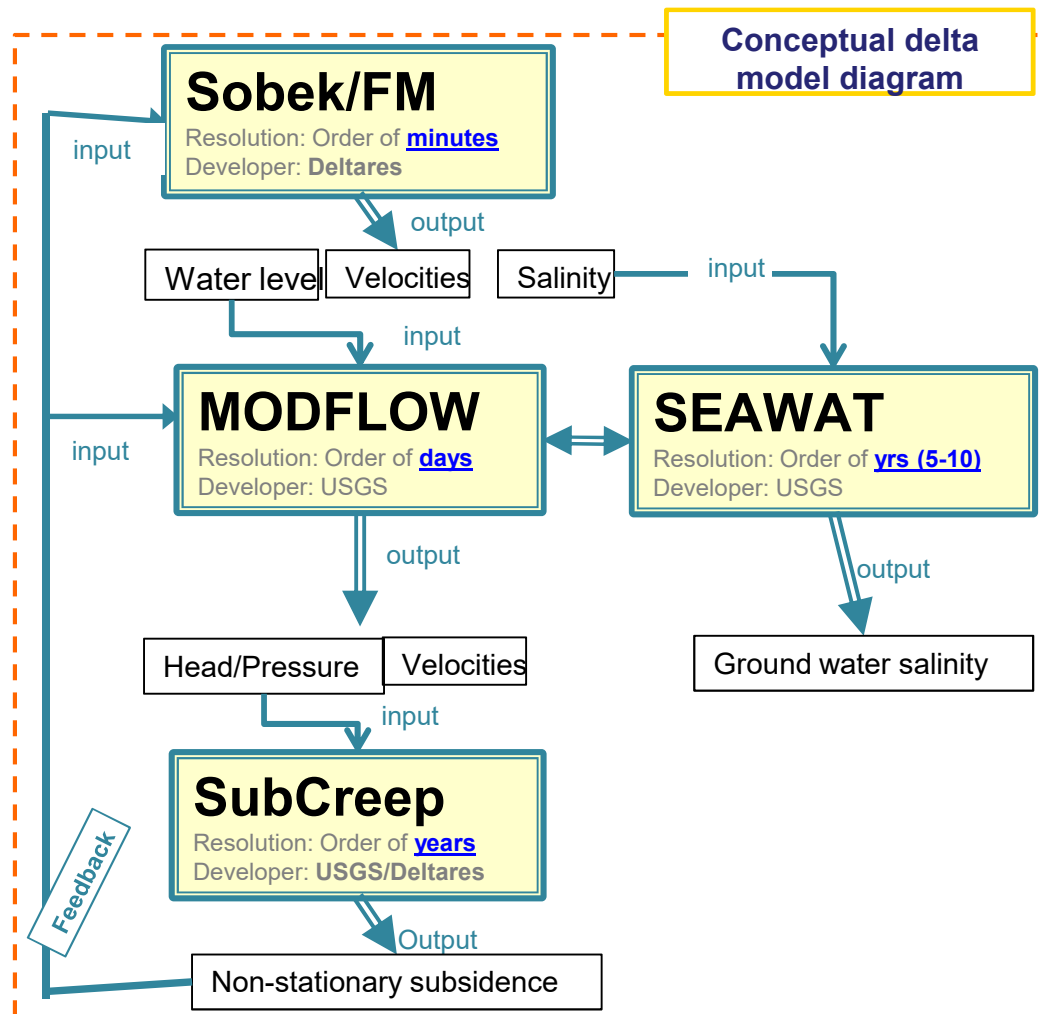
Orinoco, Venezuela



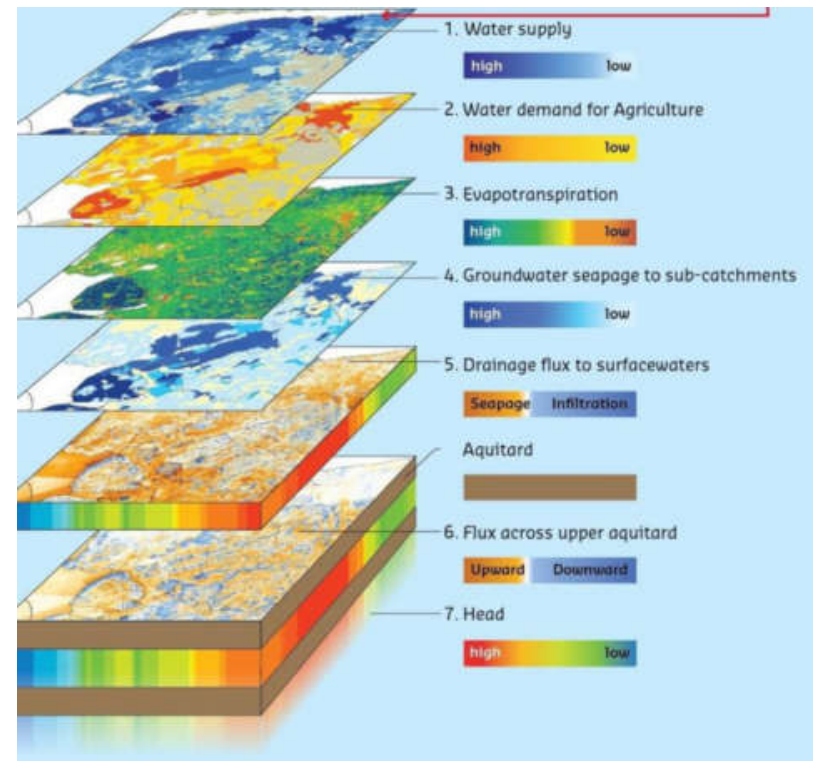
Atjeh, Indonesia



Coupling processes: SWI GW+SW+subsidence



Mekong Delta, VN, 2018



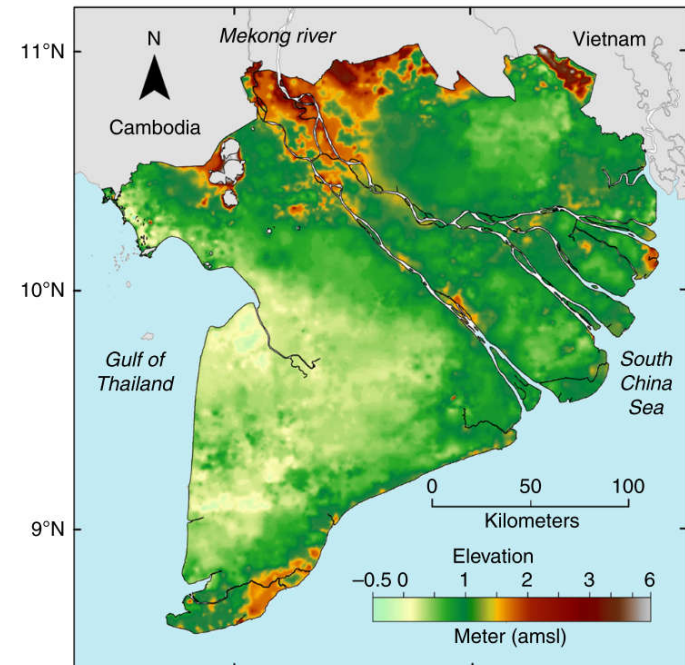
Water model/NHI, NL, 2014

DK model, Denmark, 1996+

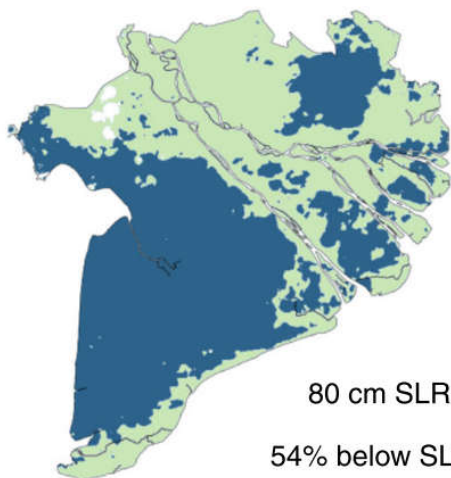
Subsidence and salinity modelling are linked to extractions

No scientific evidence Mekong Delta will go under: PM

By Hoang Thuy, Viet Tuan November 9, 2019 | 01:17 pm GMT+7



New elevation model of the Vietnamese Mekong delta.



80 cm SLR

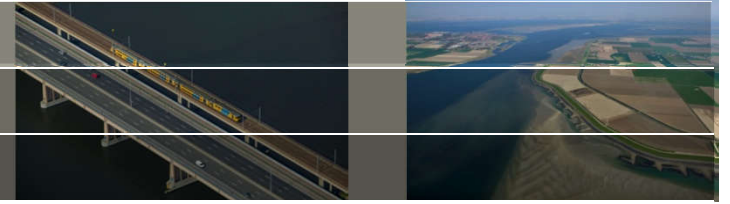
54% below SL

Prime Minister Nguyen Xuan Phuc said "there is no scientific basis" to the recent prediction that the Mekong Delta will be submerged in 30-50 years.

NHV zoet-zout 2019

Deltares

De toekomst

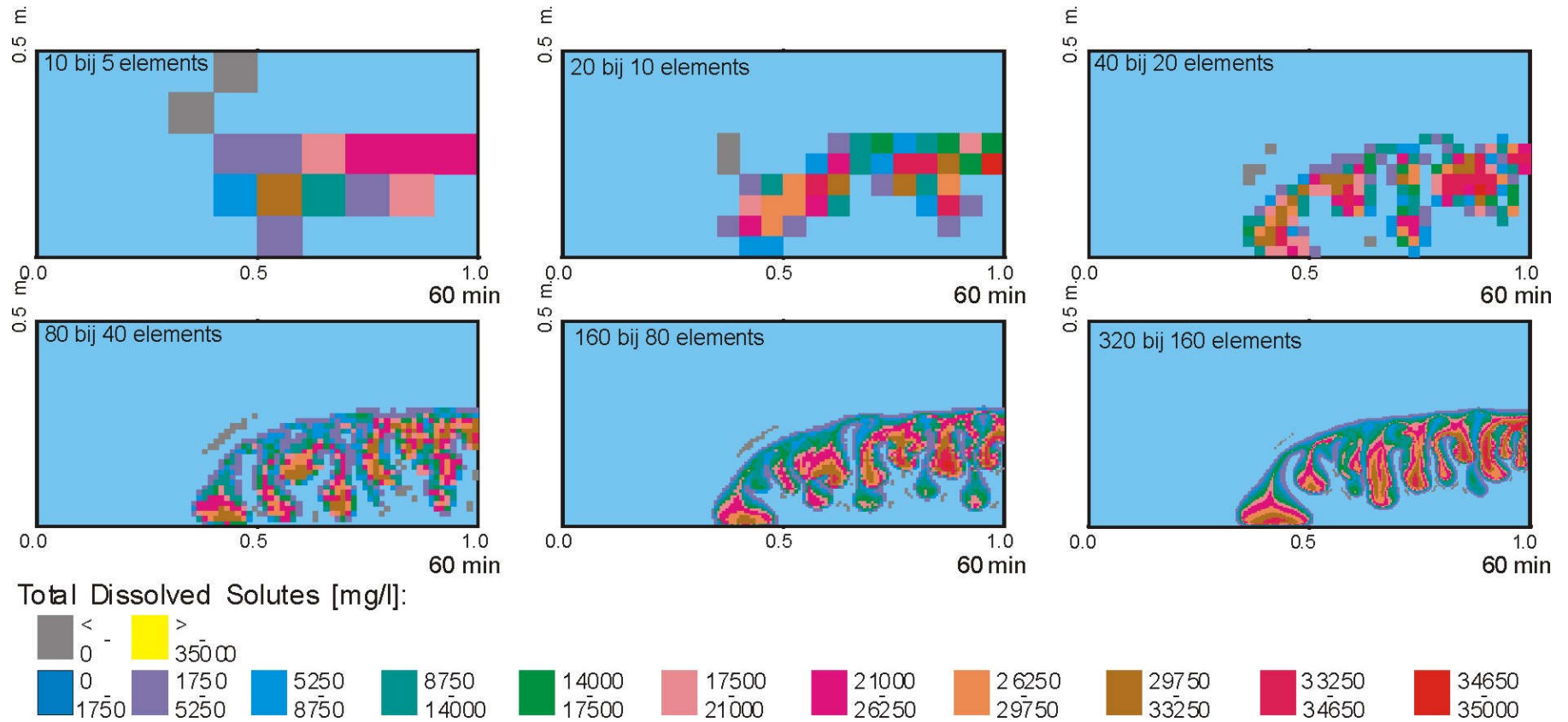


- Het wordt drukker in de ondergrond: meer vragen komen op ons af
- Operationeel zoet grondwaterbeheer voor droogte situaties
- Behoefte aan betere voorspellingsmodellen voor ondersteuning beleid
- Limitaties:
 - Numerieke data opslag en bewerking/visualisatie
 - Tekort aan hydrogeologische data in data-arme gebieden
- MODFLOW 6 is (nog) niet The Holy Grail

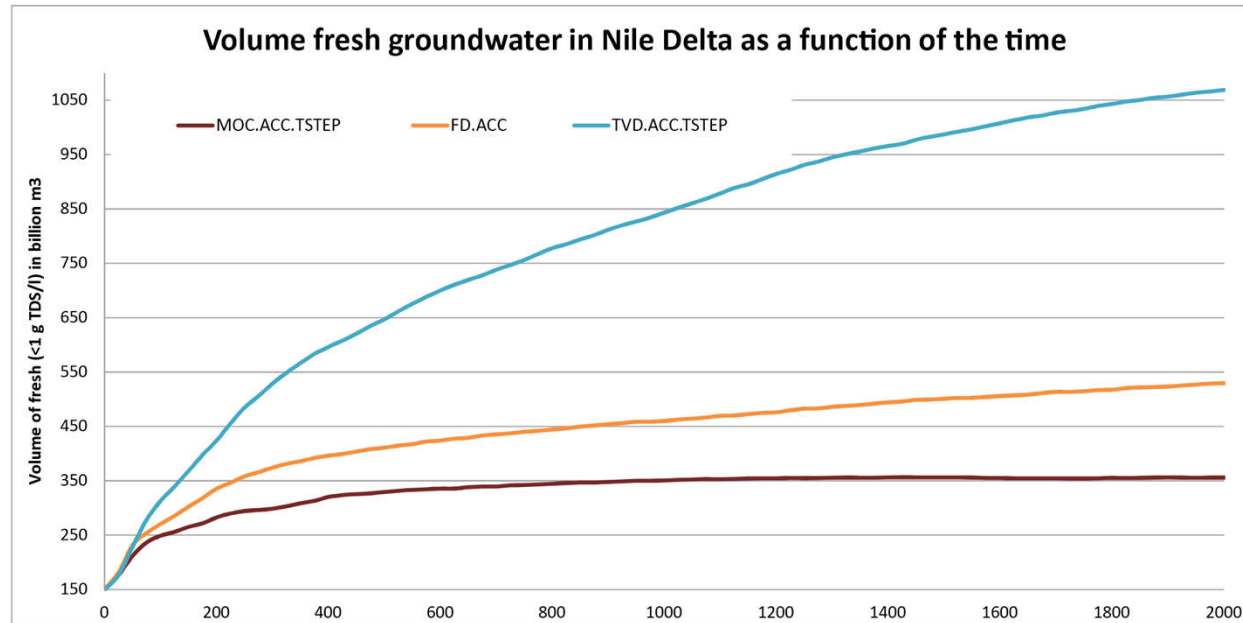
Mogelijke gamechangers:

- Quantum computers
- Water-Energy Nexus: stel: ontzilten brak grondwater wordt zeer goedkoop?

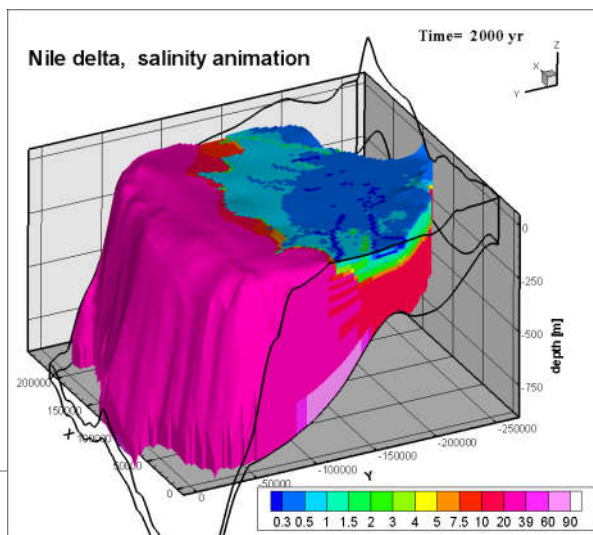
Tip 1 of the day: avoid modelling saline fingers



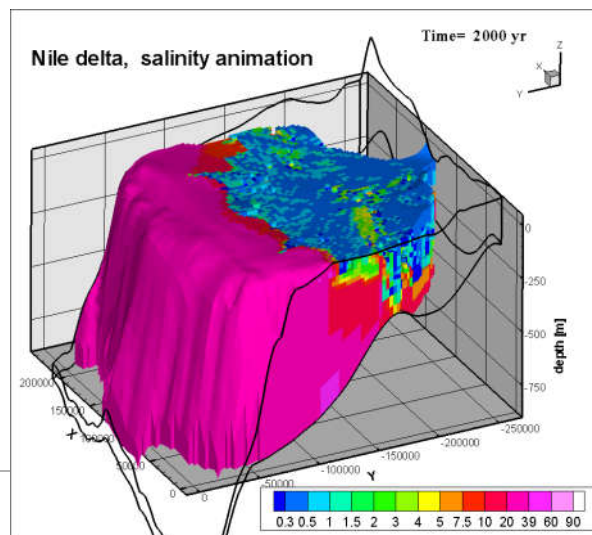
Tip 2 of the day: test your SEAWAT SOLVERS!



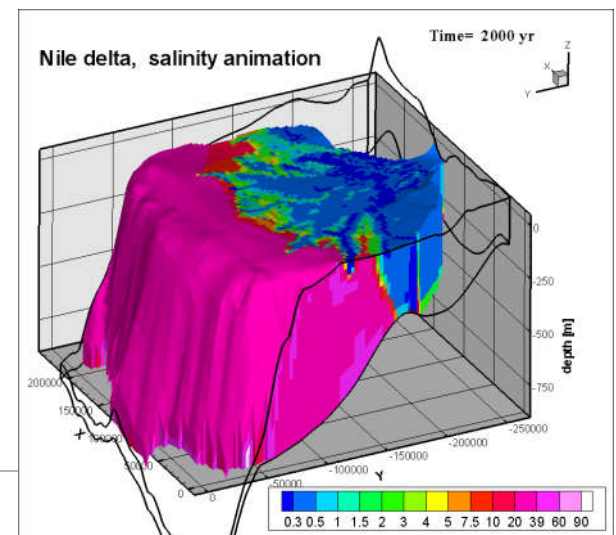
MOC.ACC.TSTEP



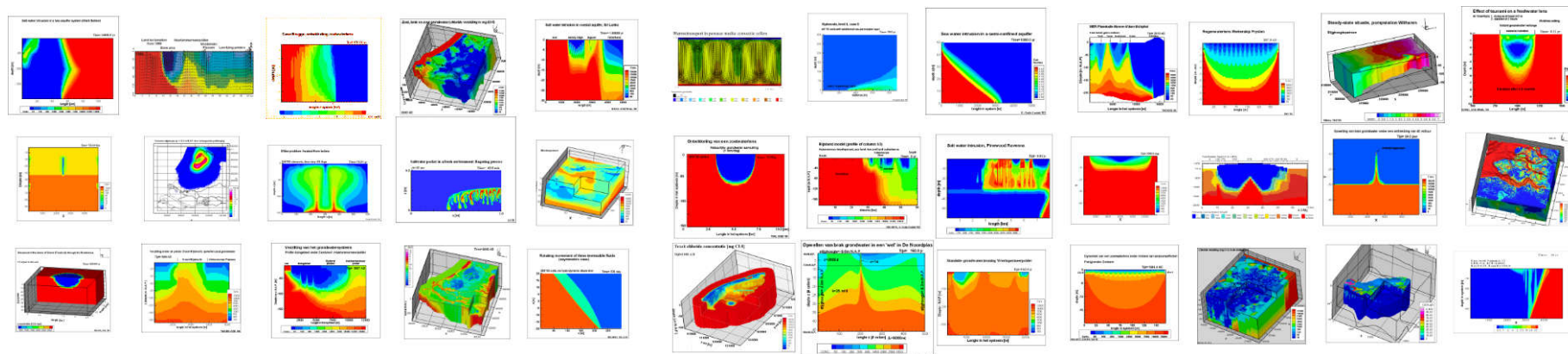
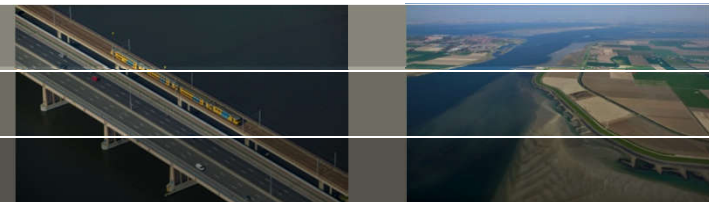
FD.ACC



TVD.ACC.TSTEP



Vragen?



Gualbert Oude Essink

Deltares/UU

Meer informatie:

www.zoutzout.deltares.nl

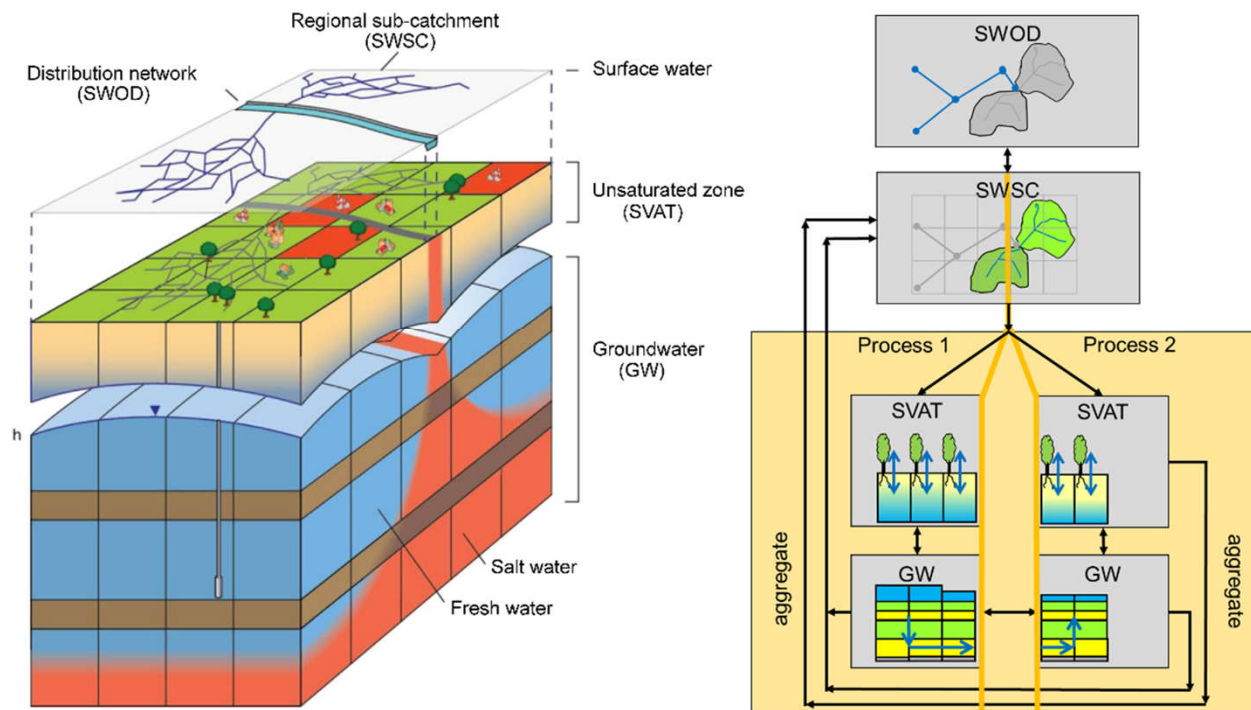
www.freshsalt.deltares.nl

Co-auteurs:

Perry de Louw, Joost Delsman, Gijs Janssen, Jarno Verkaik, Pieter Pauw, Esther van Baaren, Huite Bootsma, Daniel Zamrsky, Joeri van Engelen, Tobias Mulder

Deltares

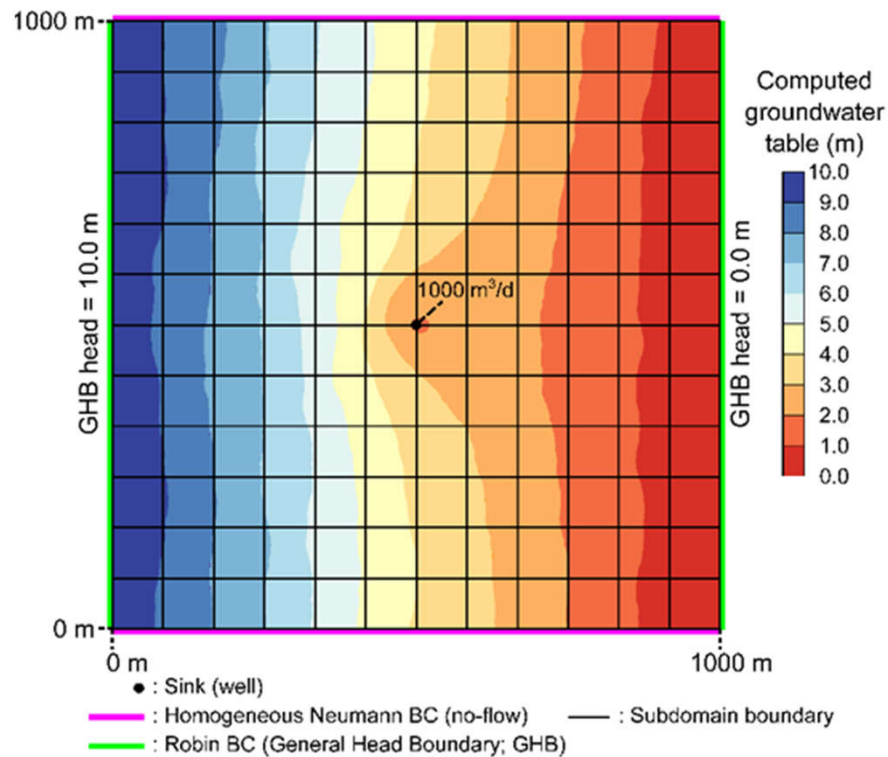
Netherlands Hydrological Instrument (NHI)



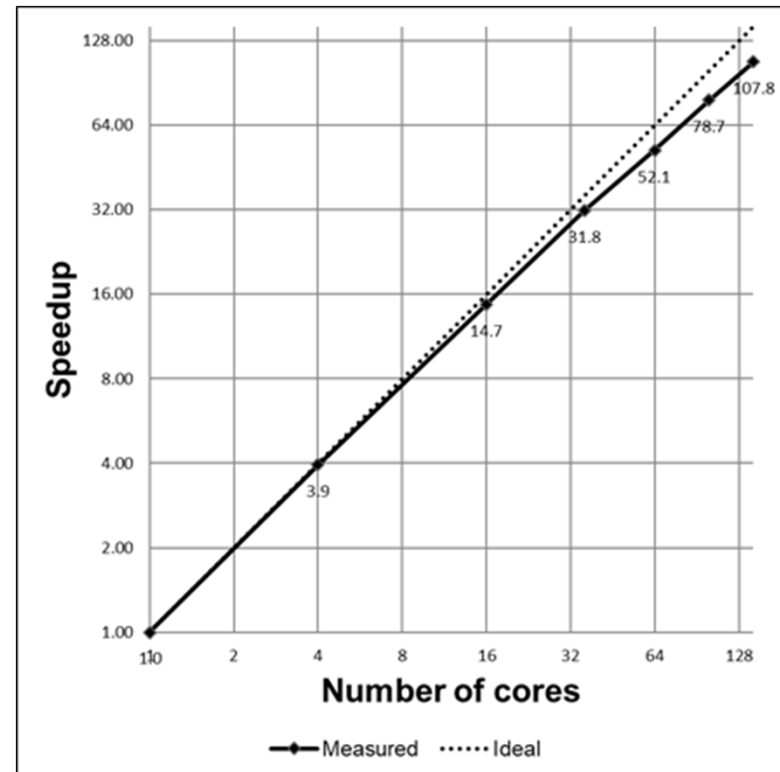
Model	Scale of process	Simulation Code	Equation Solved	Spatial dimension	Computation Units	Temporal dimension
GW	Regional	MODFLOW	3D quasi GW flow equation	250m x 250m	± 10,000,000 grid cells	1 day
SVAT	Plot, column	MetaSWAP	1D Richards emulator	250m x 250m	± 500,000 grid cells	1 day
SWSC	Nationwide	Mozart	0D water balance	0.5 – 5 km ²	± 8,500 polygons	10 days
SWOD	Nationwide	DM	0D water balance	1-25 km	± 250 nodes	10 days

Case #1/5: synthetic, steady-state, 128M cells

8000 x 8000 x 2



@Cartesius, MODFLOW only



4:47:59 (1 core) → 0:02:40 (144 cores)

