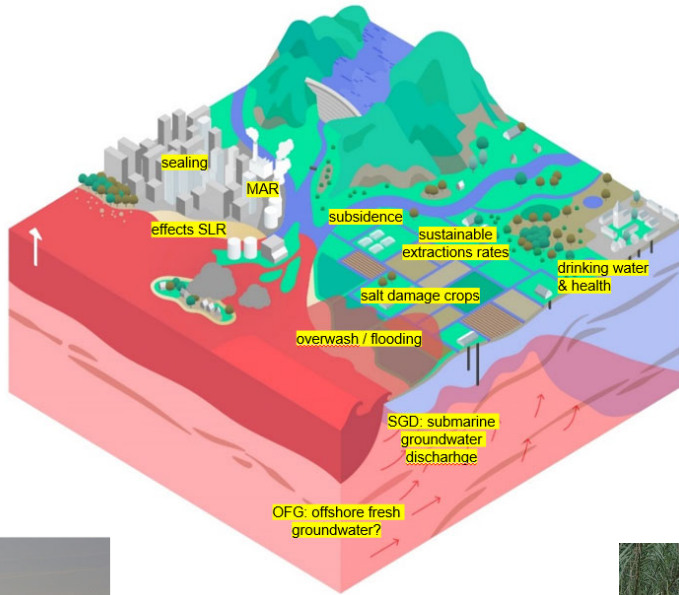


# Navigating groundwater salinity in (coastal) groundwater models: insights, challenges, innovations



Gualbert Oude Essink, Daniel Zamrsky, Jude King, Perry de Louw, Joost Delsman, Marc Bierkens and others

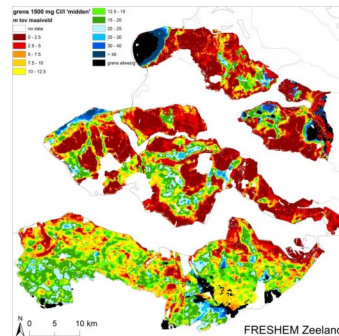
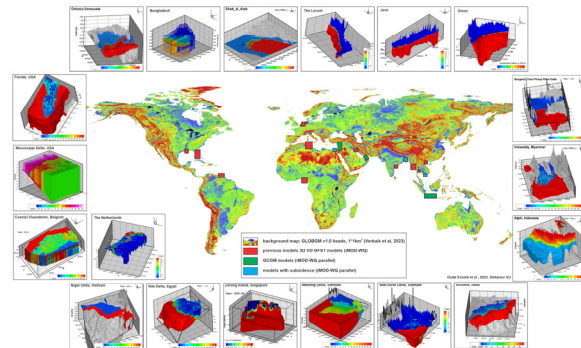
[gualbert.oudeessink@deltares.nl](mailto:gualbert.oudeessink@deltares.nl)

This pptx in pdf on the wiki <http://freshsalt.deltares.nl/>



Utrecht University

Deltares



# Motivation

- Coastal regions seriously rely on groundwater, but **domestic and agricultural water use** leads to **salinization, subsidence, and droughts, endangering water security.**
- **Climate change** worsens these issues by **altering precipitation patterns and raising sea levels**, threatening **food security, public health, and ecosystems.**
- **Groundwater models**, integrated with **salt transport and local hydrogeological data**, could help **assess these human and climate impacts** on coastal groundwater, and could support **water managers** with **more informed decision making.**
- The **confidence in groundwater salinity models** depends on **understanding** groundwater salinity distribution, which is complex due to its **variability and changing historical conditions.**

# Interesting developments in (coastal) groundwater salinity modelling

## Data

- **1:** Airborne groundwater salinity mapping
- **2:** Citizen science, using simple monitoring devices for salinity
- **3:** Data mining hydrogeology, using Large Language Models
- **4:** Integrating techniques from 0D/1D/2D data to 3D model input (groundwater salinity, geology)

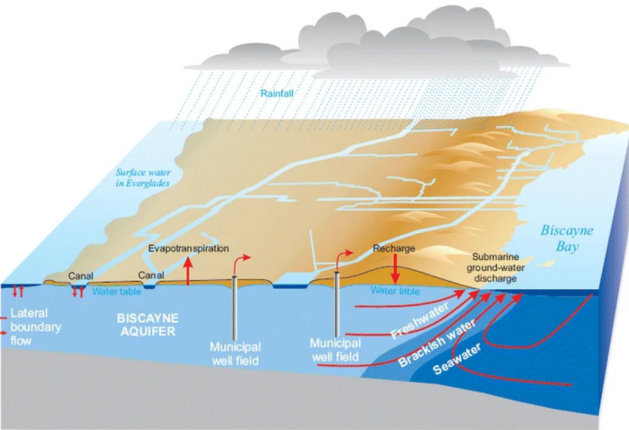
## Model

- **5:** Parallel computing plus smart model parameters
- **6:** Paleo-reconstructions to improve initial groundwater salinity distribution
- **7:** Building and running parallel large-scale groundwater salinity models using multiple cores

## Knowledge sharing

- (Open) python tools, open sources, GitHub, repositories, webportals,

When modeling groundwater salinity, let us move beyond the classical Henry conceptualization to better capture the complexities of fresh-salt groundwater interactions.



Langevin., 2003

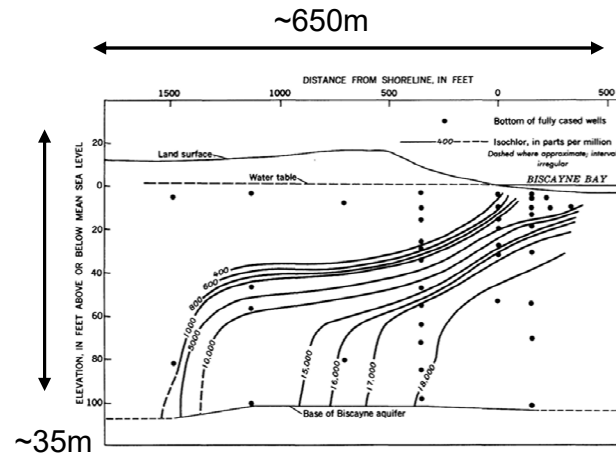
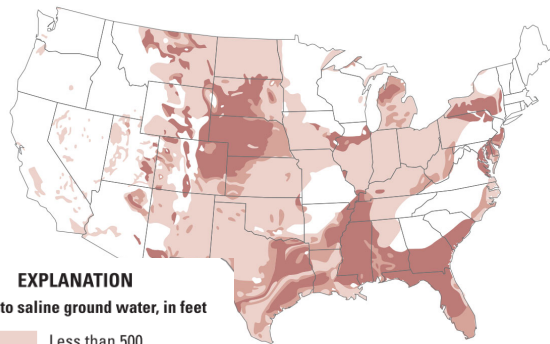
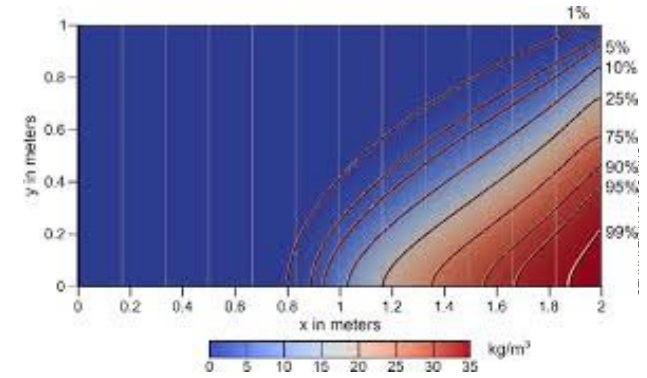


FIGURE 4.—Section through the Cutler area, near Miami, Fla., showing the zone of diffusion, September 6, 1968.

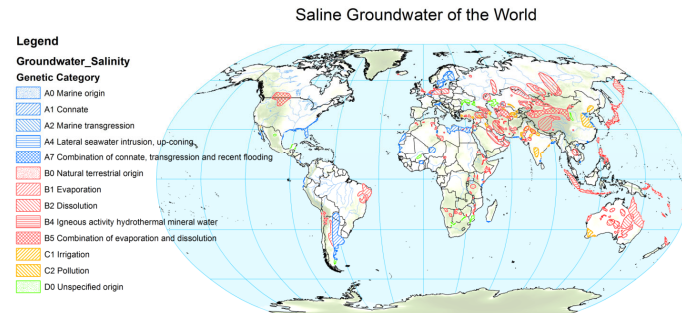
Kohout et al., 1964



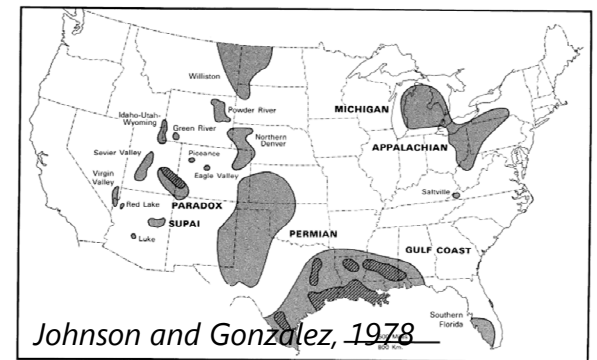
**EXPLANATION**  
Depth to saline ground water, in feet

- Less than 500
- 500 to 1,000
- Greater than 1,000
- Inadequate information

Reilly et al., 2008



Van Weert et al., 2009



Johnson and Gonzalez, 1978

- Area underlain by rock salt
- Area of salt domes or salt anticline

# Component 1: Airborne groundwater salinity mapping

Deltares



## Method:

Combination helicopter measurements with knowledge about subsurface and processes in fresh-saline groundwater, and geostatistical mapping via (multiple) indicator kriging.

## Results:

- Mapping of 3D groundwater salinity and clay layers

*Delsman et al., 2018*

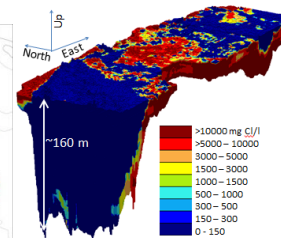
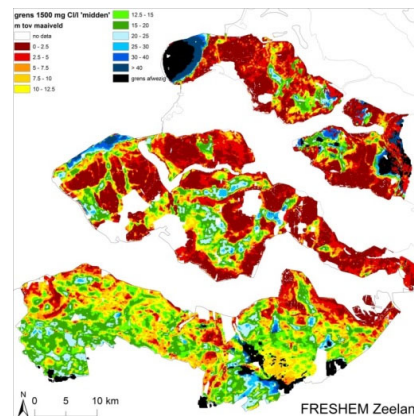
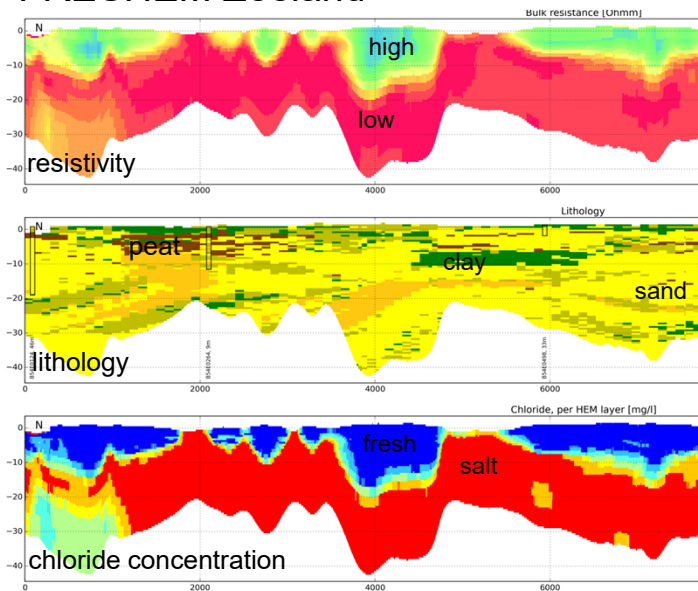
TNO innovation for life



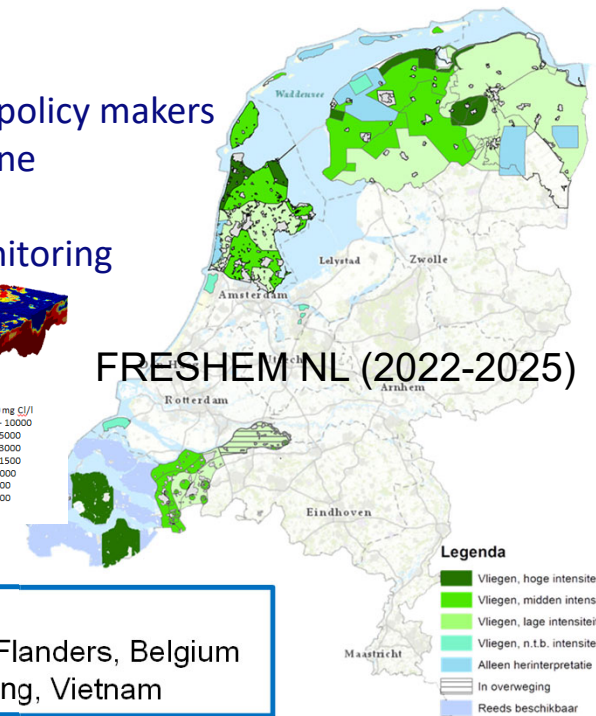
## Applications:

- strategic fresh groundwater users & policy makers
- support ASR (COASTAR) in coastal zone
- identify brackish water potential
- improve groundwater models & monitoring

## FRESHEM Zeeland



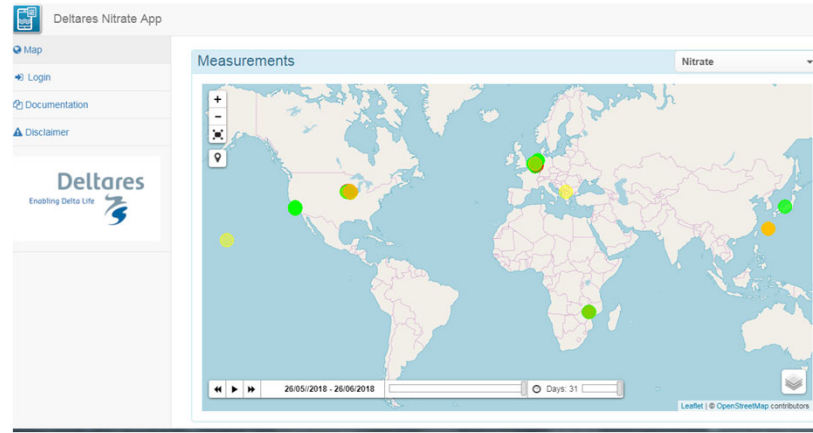
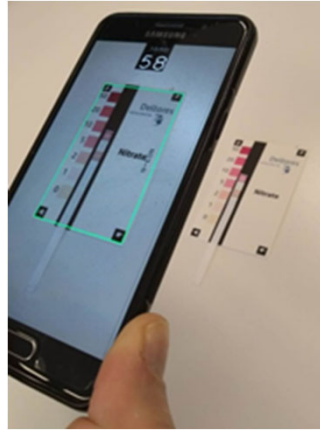
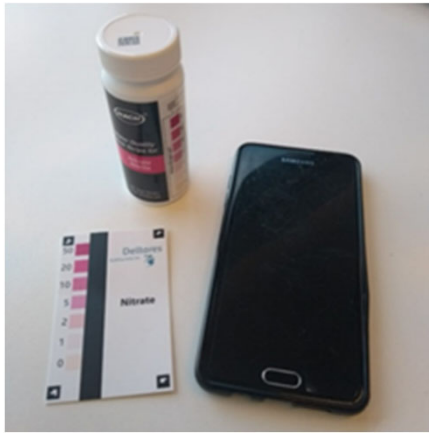
## FRESHEM NL (2022-2025)



## International:

- Project in Flanders, Belgium
- Pilot Mekong, Vietnam

# Component 2: Citizen science, using simple monitoring devices for salinity, especially in data-poor areas



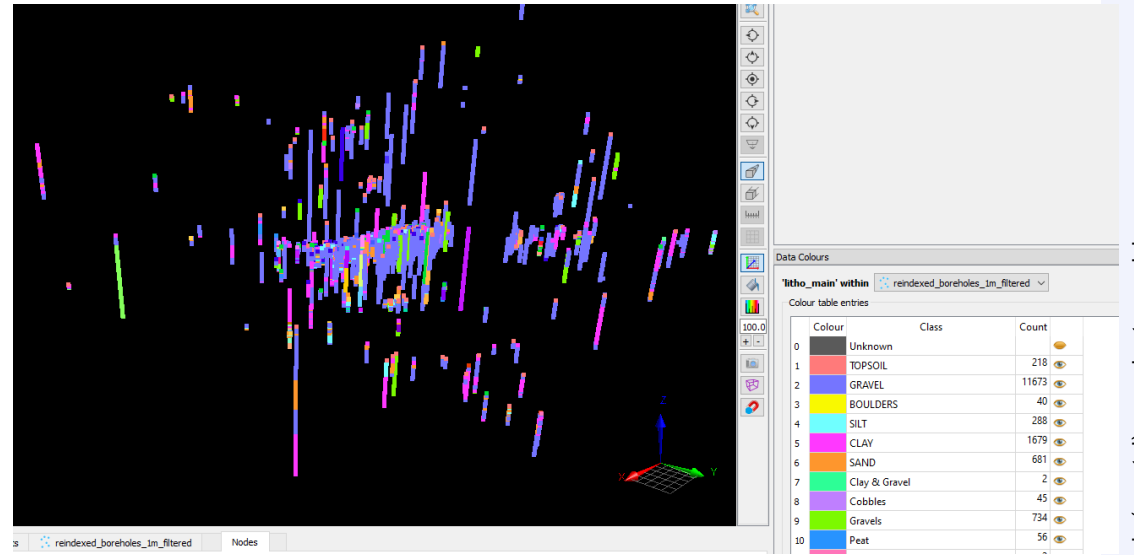
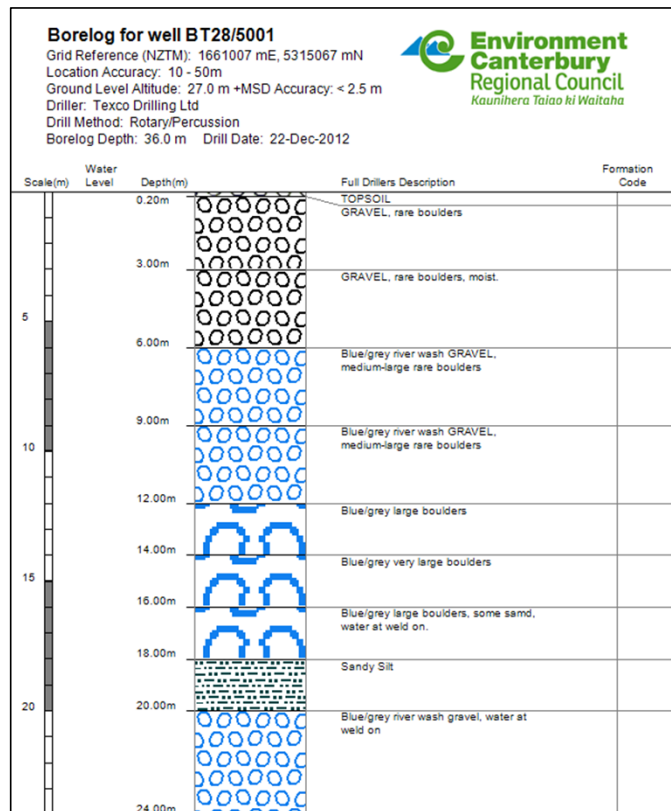
e.g., Aquality App



# Component 3: Data mining hydrogeology, using Large Language Models

## Structured data from images

Tested on ~500 borehole images from New Zealand, provided by Utrecht University



Index	top_m	bot_m	litho_main	litho_description	x_coordinate	y_coordinate	ground_level	grid_reference	id
0	0	3	TOPSOIL	TOPSOIL GRAVEL, rare boulders	1661007	5315067	27	NZTM	BT28_5001.png
1	3	6	GRAVEL	GRAVEL, rare boulders, moist.	1661007	5315067	27	NZTM	BT28_5001.png
2	6	9	GRAVEL	Blue/grey river wash GRAVEL, medium-large rare boulders	1661007	5315067	27	NZTM	BT28_5001.png
3	9	12	GRAVEL	Blue/grey river wash GRAVEL, medium-large rare boulders	1661007	5315067	27	NZTM	BT28_5001.png
4	12	15	BOULDERS	Blue/grey large boulders	1661007	5315067	27	NZTM	BT28_5001.png
5	15	18	BOULDERS	Blue/grey large boulders, some sand, water at weld on.	1661007	5315067	27	NZTM	BT28_5001.png
6	18	20	SILT	Sandy Silt	1661007	5315067	27	NZTM	BT28_5001.png
7	20	24	GRAVEL	Blue/grey river wash gravel, water at weld on	1661007	5315067	27	NZTM	BT28_5001.png
8	24	27	BOULDERS	Blue/grey large boulders and sand, water	1661007	5315067	27	NZTM	BT28_5001.png
9	27	30	BOULDERS	Blue/grey large boulders, rare white stone meal, large river wash gravel, water 1 l/s	1661007	5315067	27	NZTM	BT28_5001.png
10	30	36	GRAVEL	Blue/grey medium to large river wash gravel, water 1-2 l/s.	1661007	5315067	27	NZTM	BT28_5001.png

# Component 3: Data mining hydrogeology, using Large Language Models

## Structured data from images

Handles handwritten data, also in other languages

*work in progress*

FORMATION LOG SHEET

Date drilled: 26-5/95  
 Date logged: 26/5/95  
 Geologist: GAE  
 Latitude: 70° 25.674'S

Hole number: T 100 C = WISSONG  
 Project: CPTN  
 Location: 3.5 km. off 20, 202° S / 10 770° E  
 Longitude: 70° 41.512' E

From	To	Rock Type	Description
0	2 m	Soil / overburden	
2	11 m	Grey-silt with some sand	coarse - fine (silty) sands; poor sorting subangular - rounded fragments loosely consolidated (possibly some caliche cement)
11	22	yellow brown sand	to whitish - greyish brown fine - coarse sized; subangular - rounded loosely consolidated; clasts in contact Iron-oxid?
22	29	Silicified (Lahar)	in white sandy matrix; consolidated biscuit fragments up to pebblesize (p. tip to 10-15 cm); some lamination
29	102	Oxidised weathered schist	x fine scoriacity; general grey fragments white bands: calcite (HCL; porous) x red brown bands (limonite) / Iron oxid clasts band smaller to occur elsewhere
102	125	Basalt	fresh basalt, small to medium olivine phenocrysts, black glassy groundmass
125	126	Frank chlorite schist	epidote, calcite (HCL), quartz, schistosity, silty, (possibly up to 30 (Gt))



top_m	bot_m	litho_main	litho_description
0	2	Soil/Organic	Coarse-fine (silty) sands, poor sorting
2	11	Grey silt with some sand	Subangular to rounded fragments, poorly consolidated (possibly some volcanic glass)
11	22	Yellow/brown Sand	Coarse to fine grain brown, ferroan coated,...
22	29	Silicified (Lahar)	White sandy matrix (poorly sorted, bimodal)...
29	102	Oxidised weathered basalt	Some scoriacity, general clay fragments, wh...
102	125	Basalt	Fresh basalt, small to medium olivine phenocrysts, black glassy groundmass
125	126	Frank chlorite schist	Epidote, calcite (HCL), quartz, schistosity, silty, (possibly up to 30 (Gt))



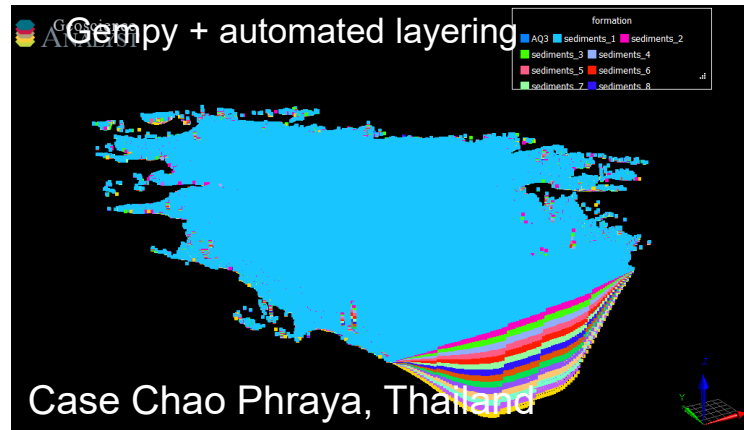
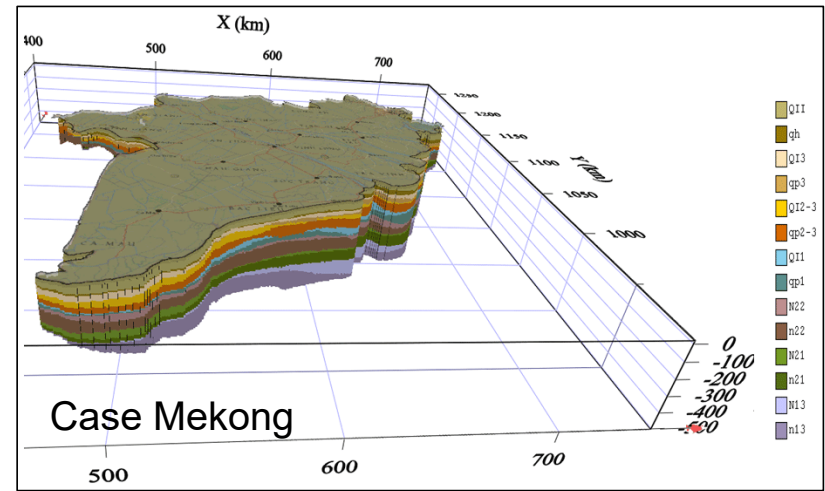
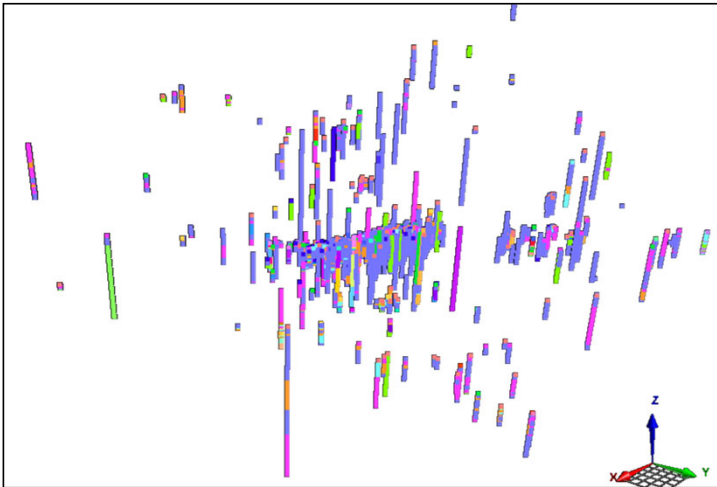
# Component 4: Integrating techniques from 0D/1D/2 data to 3D model input

## Data to construct large-scale hydrogeological models

Now, models can (mainly) parameterised in two ways with data-mining:

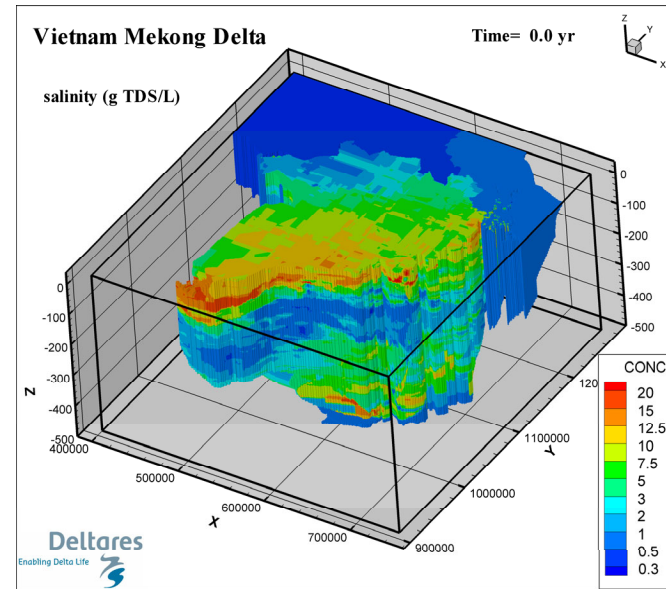
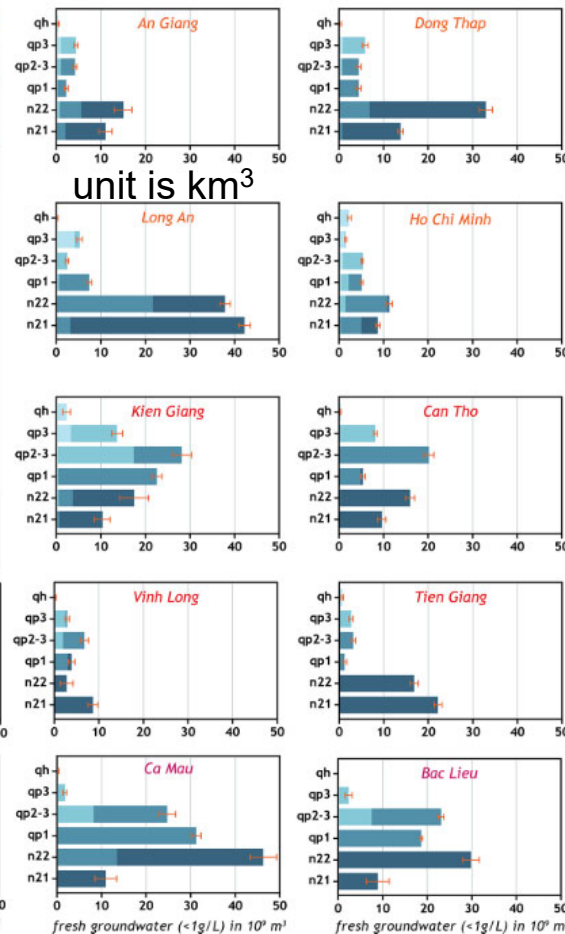
1. Hydrogeological properties
2. Initial salinity distributions

Demonstration of 3D interpolation for hydrogeological properties



# Component 4: Integrating techniques from 0D/1D/2 data to 3D model input

Example Mekong delta: based on measurements, we estimated the volume of fresh groundwater (km<sup>3</sup>) per province per aquifer



(total: some 830 to 900 km<sup>3</sup> fresh groundwater)

ref:

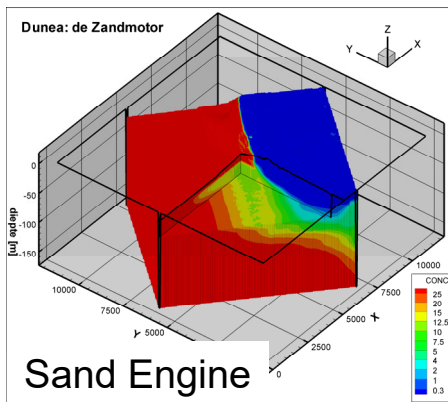
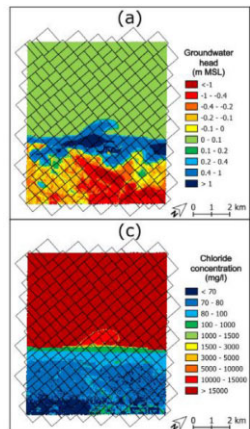
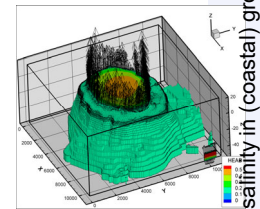
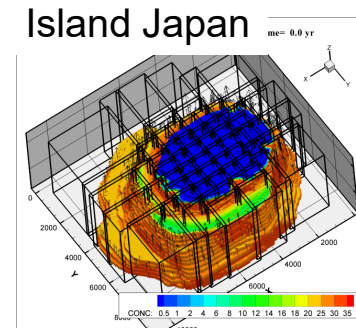
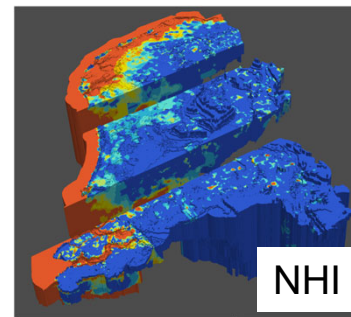
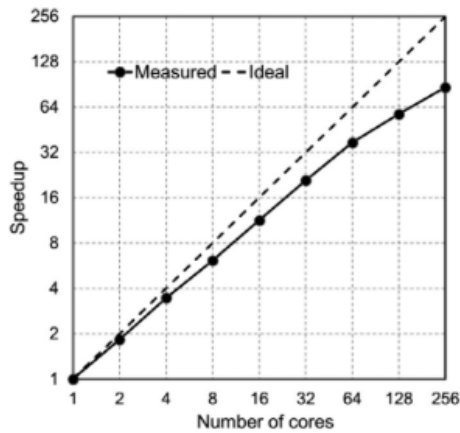
Gunnink, J.L., Pham, V.H., Oude Essink, G.H.P., Bierkens, M.F.P. 2021 The 3D groundwater salinity distribution and fresh groundwater volumes in the Mekong Delta, Vietnam, inferred from geostatistical analyses. *Earth Syst. Sci. Data* 13, 3297–3319. <https://doi.org/10.5194/essd-13-3297-2021>

# Component 5: parallel computing plus smart model parameters

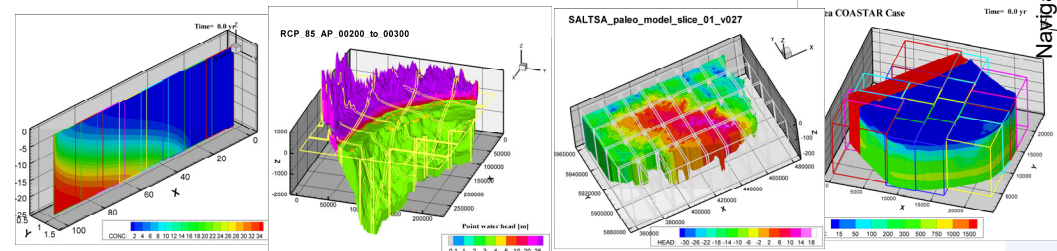
- Split into (tens of) partitions, leading to a significant reduction in computation time
- Speed-ups of at least 10 up to 100 times, depending on cores, solver iterations and data exchange efficiencies

Three examples of speed-ups:

1. Sand Engine: from 1hr 47min 55sec -> 2min 40sec: factor **40\***
2. NHI fresh-salt: from ~30 days to ~2days: **15\***
3. Island Japan: from 5d0h36m to 5m59s: **1209\***



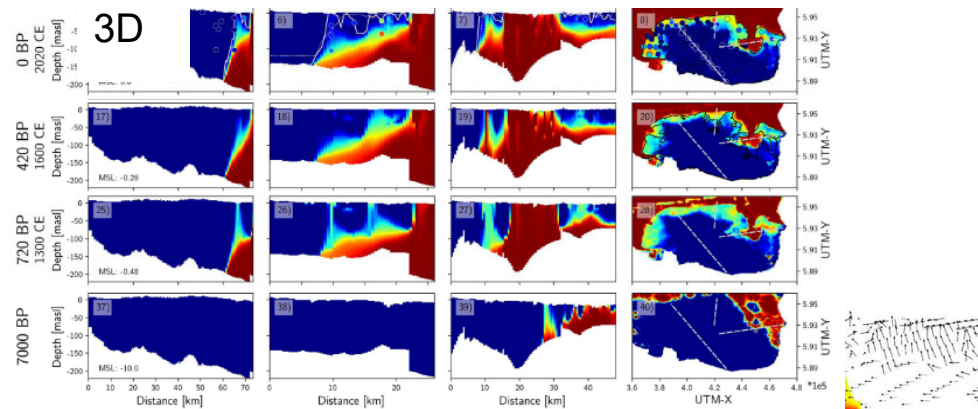
Verkaik, J. et al., 2021. Adv. Water Resources



# Component 6: Paleo-reconstructions to improve initial groundwater salinity

Parallel computer power is utilised to simulate 3D reconstructions of past hydrological conditions (in data-poor areas), improving understanding of present groundwater salinity.

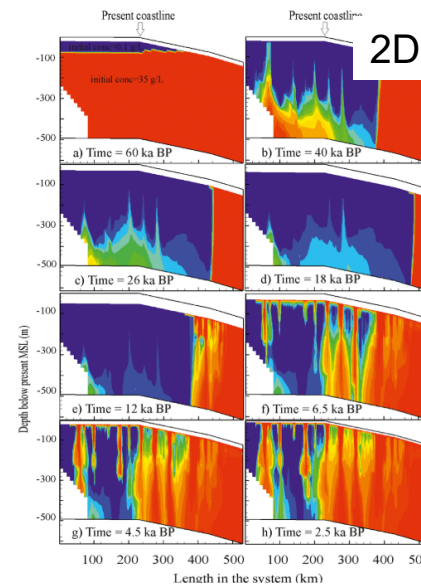
## Northwest Germany



Seibert et al., 2023 WRR

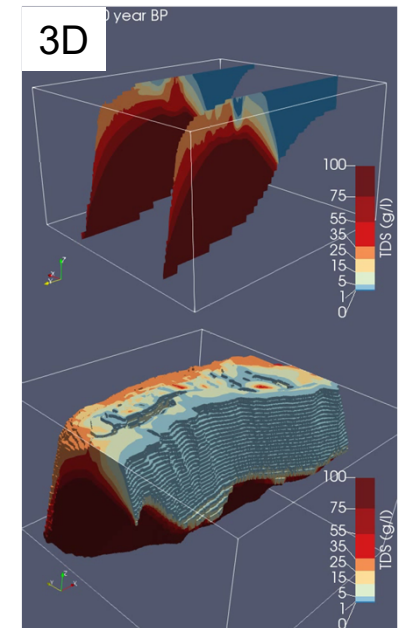
## Origin of sources and ~age dating

### Mekong delta



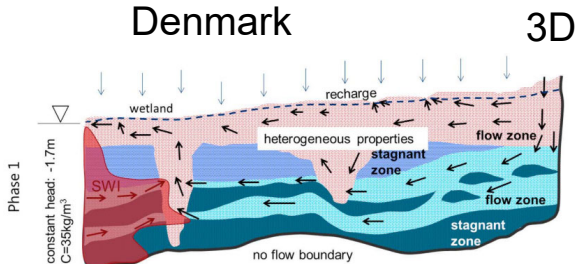
Hung et al., 2019 JoH, RS

### Nile delta

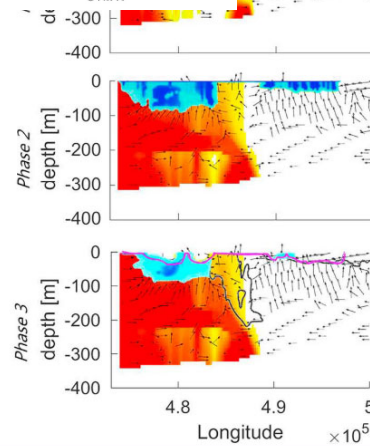


Van Engelen et al., 2019. HESS

### Denmark

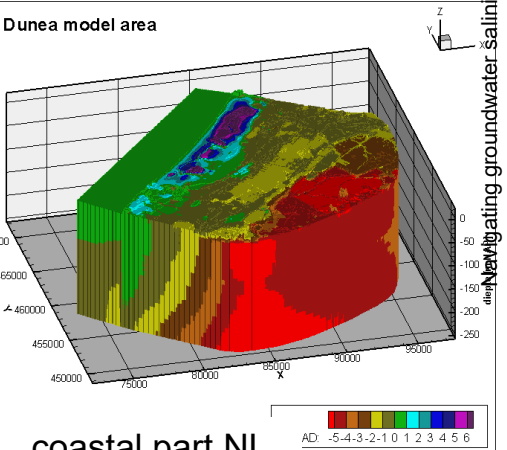
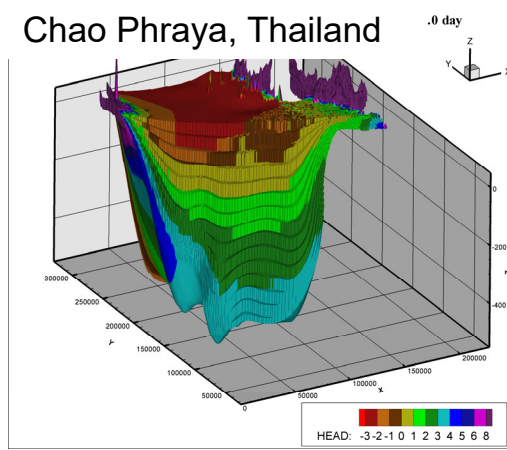
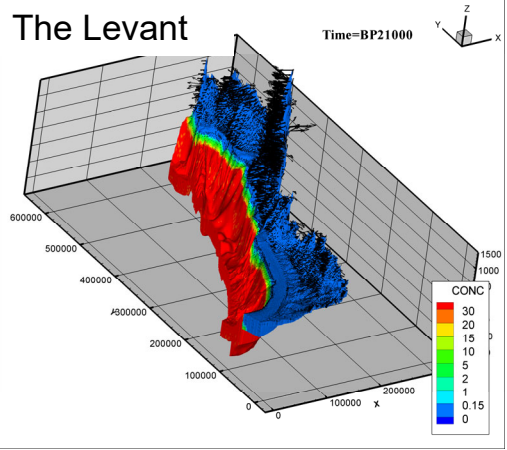
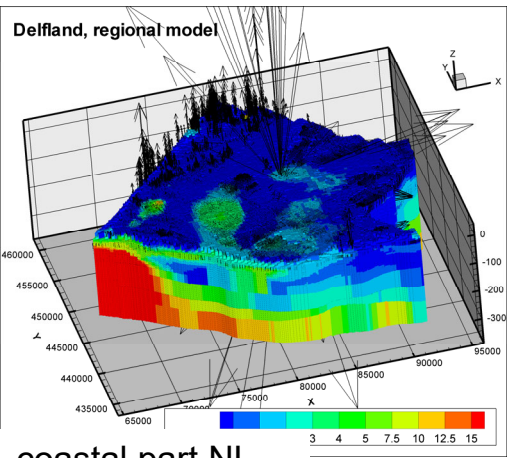
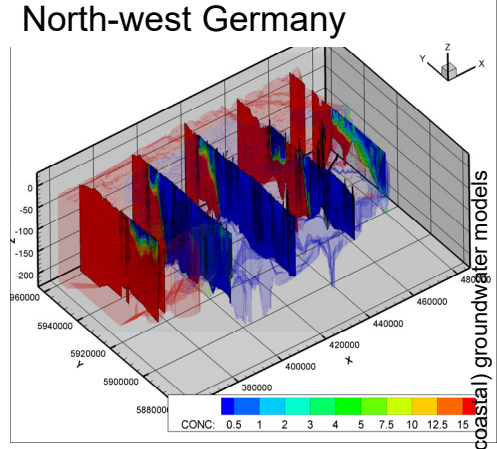
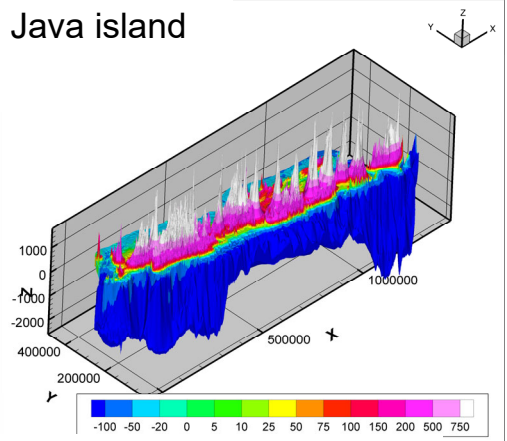
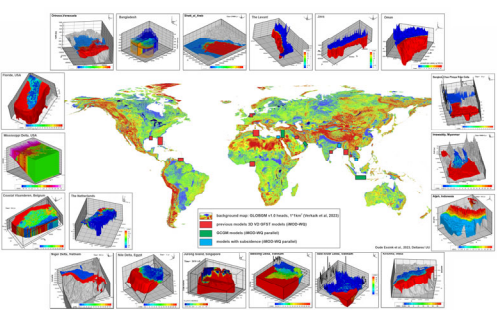


Meyer, et al., 2019



# Component 7: Building and running large-scale groundwater salinity models, based on global and local (LLM) data using multiple cores

- Components:**
- iMOD-WQ (SEAWAT parallel)
  - later shift to MODFLOW6
  - incl. subsidence
  - multiple model layers
  - open-source (python) tools
  - global datasets
  - high-performance computing
  - LLMs for local data



Newly migrating groundwater salinity in (coastal) groundwater models

# Conclusions

1. By integrating diverse data sources (airborne groundwater salinity mapping, citizen science, and LLM data mining) with advanced modeling techniques (parallel computing and paleo-reconstructions), we now can improve the accuracy of large-scale groundwater salinity models.
2. These models are crucial for understanding complex salinity groundwater systems over time under climate and human stressors, useful for water managers.
3. The use of open-source tools ensures that this knowledge is shared and accessible, fostering innovation, enabling practical applications, and contributing to more effective management of fresh groundwater resources.



Beeld: ©Deltaprogramma

## Grondwaterverziltting en watervraag bij een stijgende zeespiegel

**Deltares**

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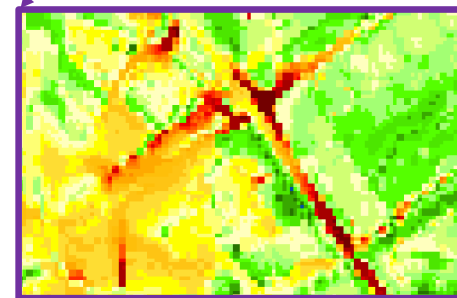
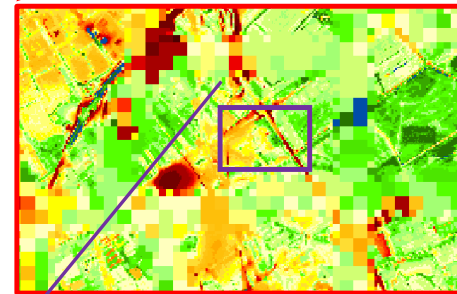
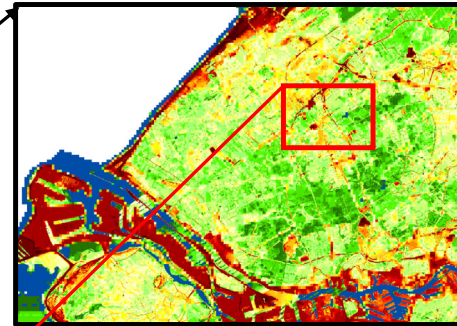
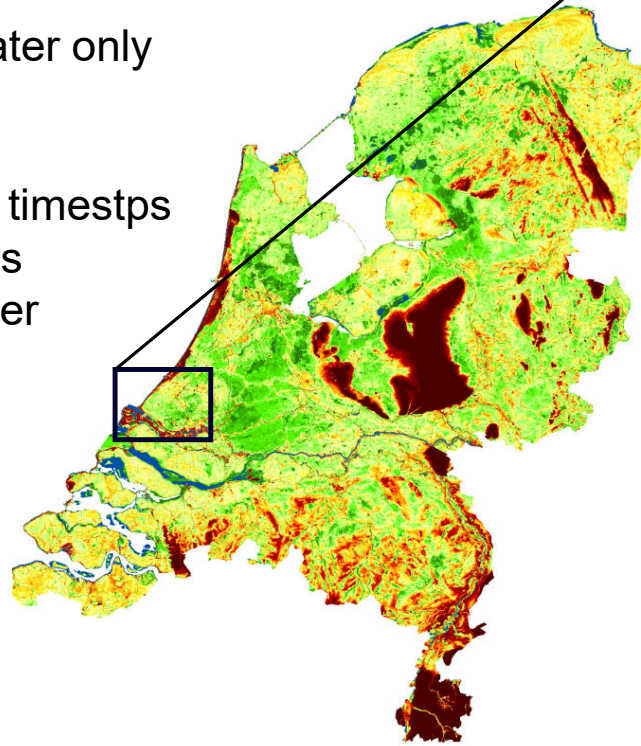
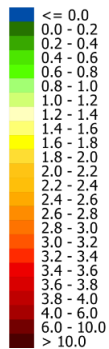


# Hyperresolution quantitative groundwater modelling (national: up to $12.5 \times 12.5 \text{m}^2$ )

## Components:

- MODFLOW6
- quantitative groundwater only
- 1 billion active cells
- 125 model layers
- Simu time 8 yrs, daily timesteps
- testing up to 256 cores
- Snellius supercomputer

Stationaire GWS  
(m-mv)



Verkaik, J., Oude Essink, G. H. P., Bierkens, M. F. P., & Lin, H. X. (202x). Enabling joint national and regional groundwater modeling using unstructured grids and high-performance computing: the case of the Netherlands, submitted to of Environmental Modelling & Software