SWIBANGLA

On modeling salt water intrusion

Managing Salt Water Impacts in Bangladesh

Deltares Enabling Delta Life | UNESCO-IHE Institute for Water Education | Jahangirnagar University | IRC Supporting water sanitation and hygiene services for life | brac | Department of Public Health Engineering

Project duration May 2013 up to September 2014

SWIBANGLA

OUR FINAL MODELING GOAL

To build a reliable 3D variable-density groundwater flow model of the coastal zone of Bangladesh which can be used as a decision support tool to secure drink water supply, now and in the future

- **Introduction**
- **Modelling examples**
- **Input data**
- **Some results**
- **Concluding remarks**

Modelling: some statements

A MODEL:

Only a simplification of the reality

Modelling: some statements

A MODEL:

Only a tool, no purpose on itself

Modelling: some statements

A MODEL:

Makes analysis of very complex systems possible

Modelling: some statements

A MODEL:

can be used as a database to store your different types of data

Modelling: some statements

A MODEL:

makes simulation of the future system possible

Modelling: some statements

A MODEL:

Garbage in=Garbage out: -> (field)data essential!

Modelling: some statements

A MODEL:

perfect fit measurement and simulation is suspicious

Modelling: some statements

A MODEL:

Tool of communication between scientist and stakeholder

Errors in modelling

- Wrong model concept

  Important resistance layer not considered

- Incomplete equations

  decay term of solute transport not considered

- Inaccurate parameters and variables

  solute mixing parameters (dispersivities), interaction with surface water

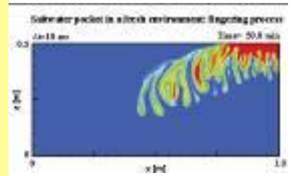
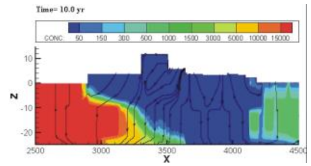
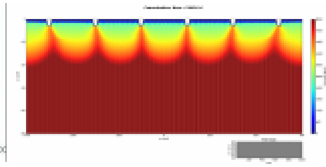
- Errors in computer code

- Numerical inaccuracies

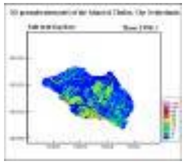
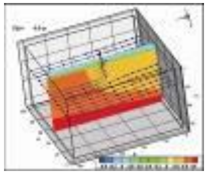
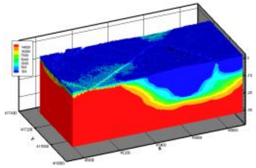
  Δx, Δt, numerical dispersion, oscillation

DIFFERENT MODEL CELL SIZES TO CONSIDER SEVERAL PHENOMENA

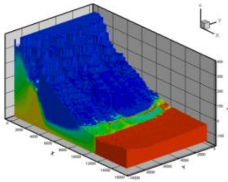
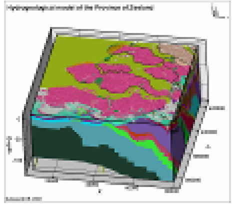
Sub-local: fingering, salty sand boils
Sri Lanka (Tsunami 2004), Zandmotor
cell size=1cm-1m

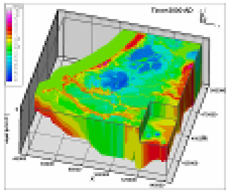
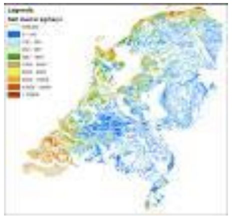
Local: rainwaterlenses, heat-cold
Tholen, Schouwen-Duiveland
cell size=5-25m

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

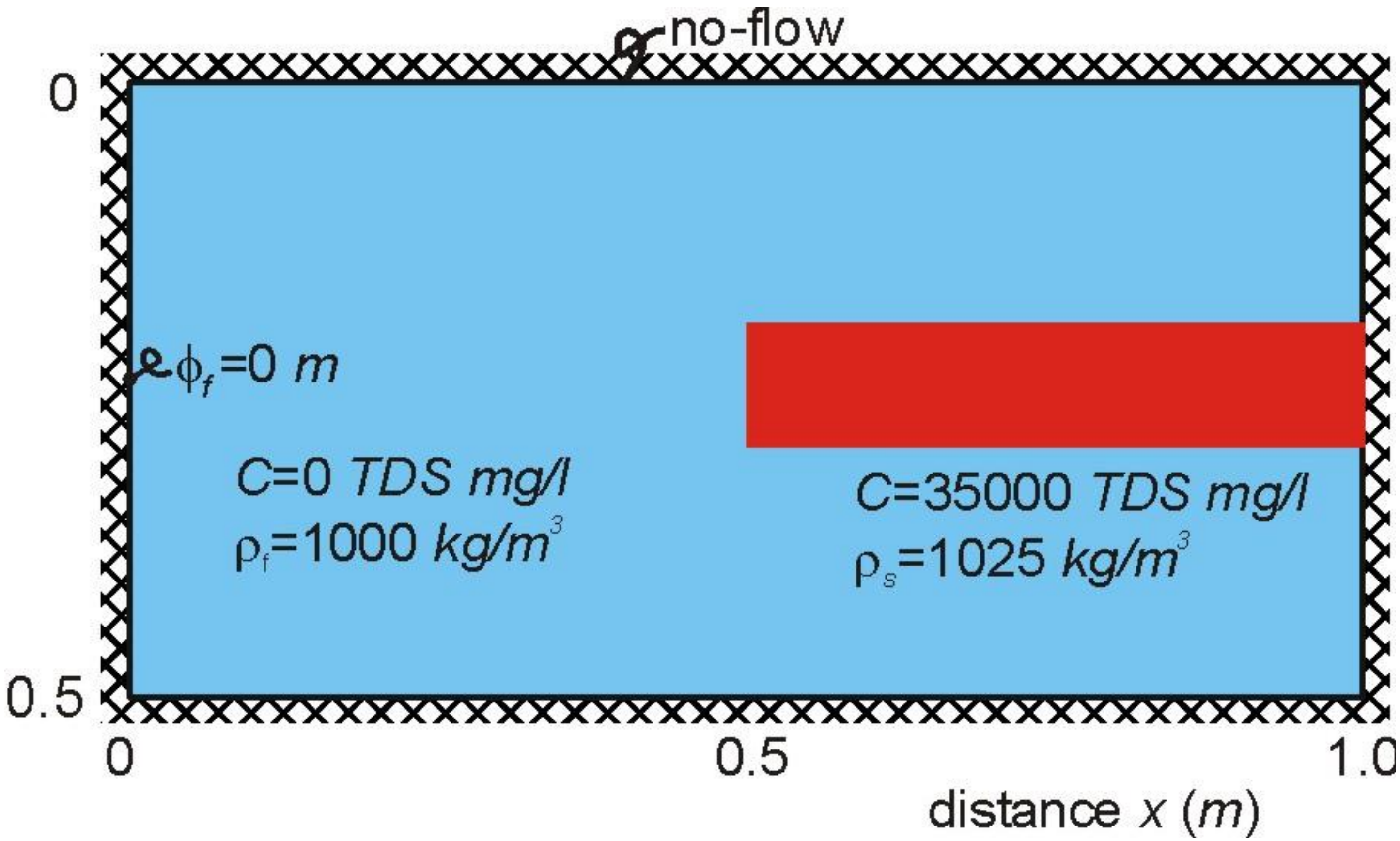



National: salt load
Zuid-Holland, NHI
cell size=250m-1km

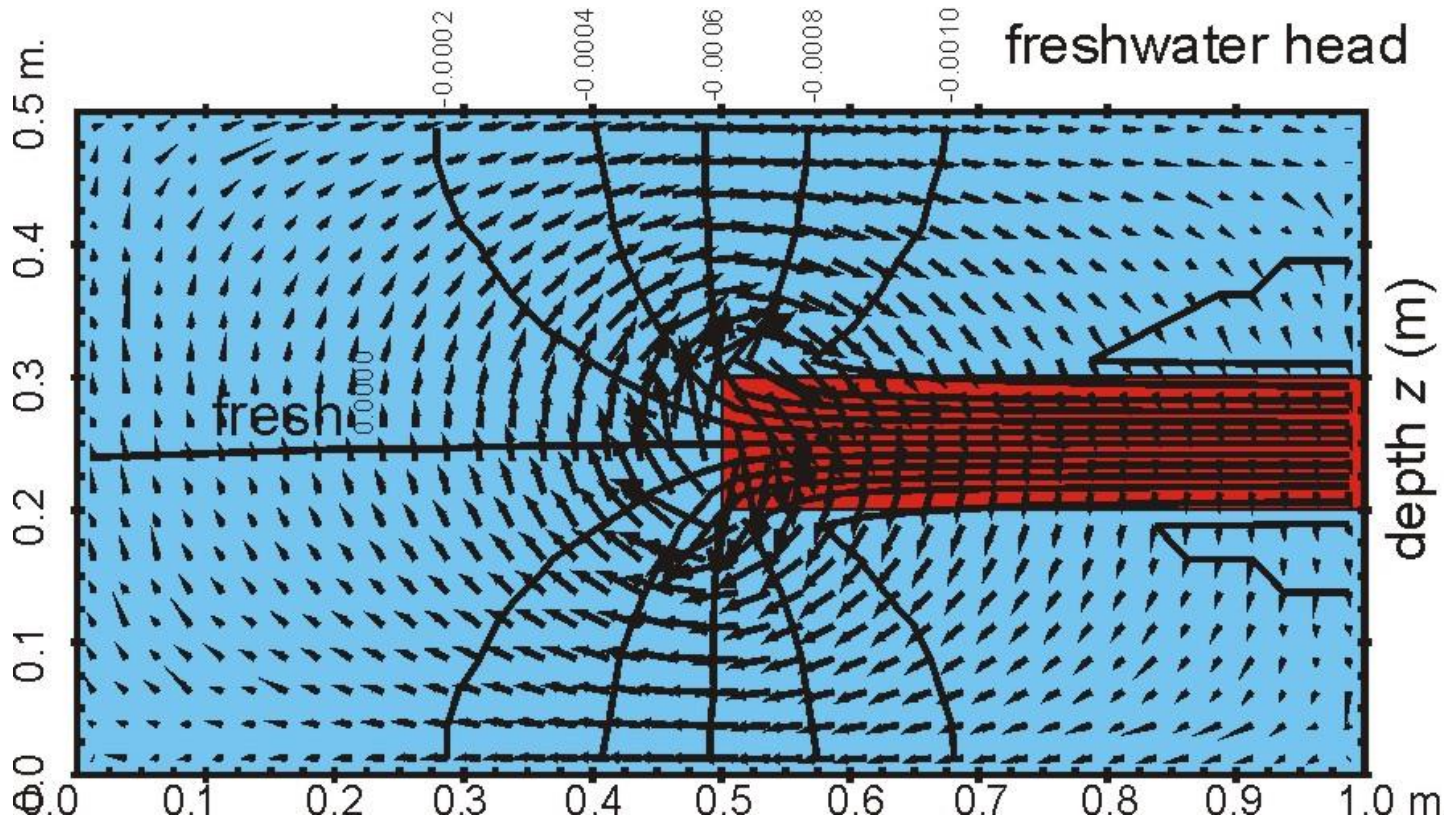



Goal:
To take largest cell size possible to accurately model relevant salinisation processes

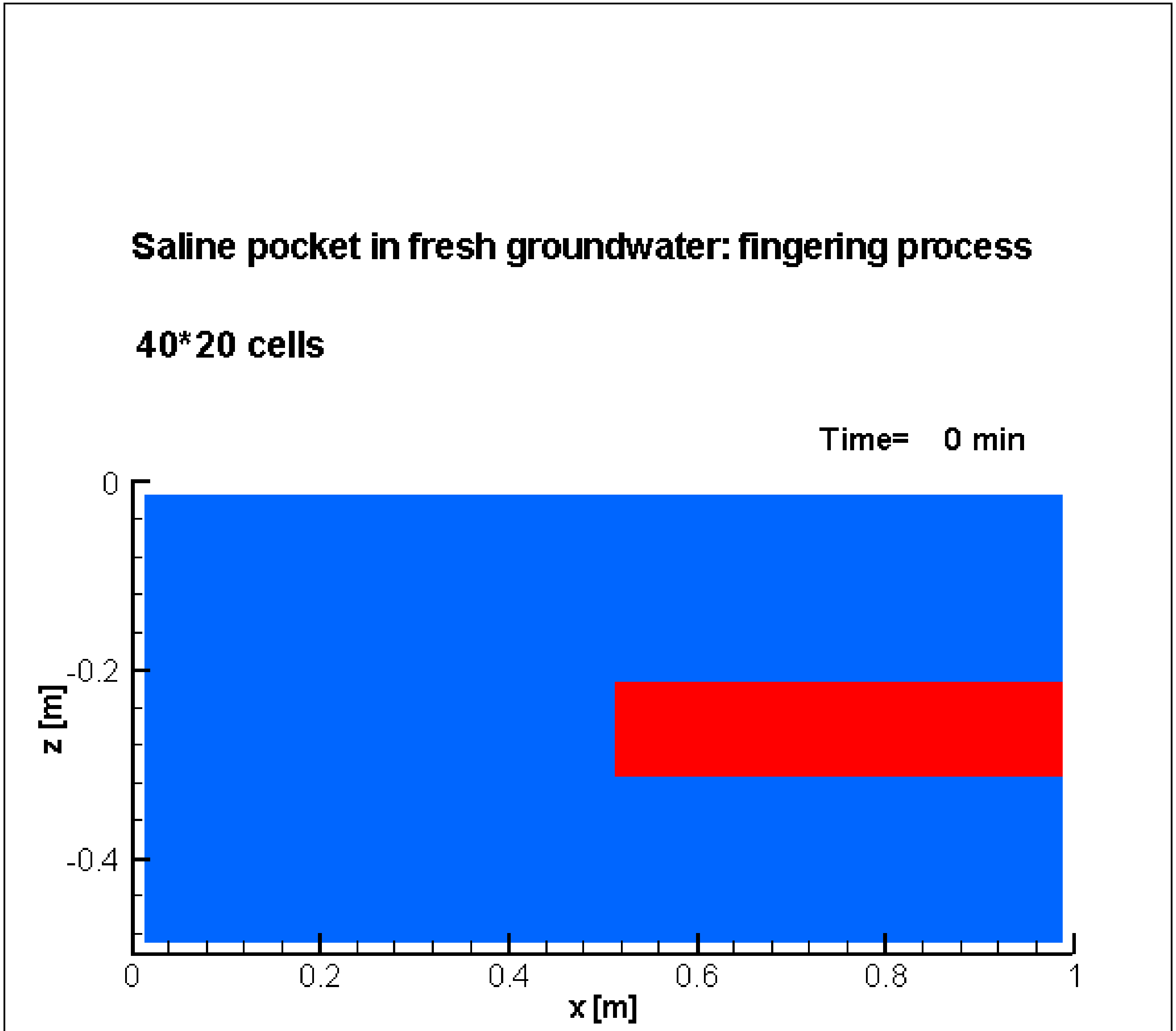
EXAMPLE 1: EFFECT OF SIZE MODEL CELL ON PHYSICAL PROCESS



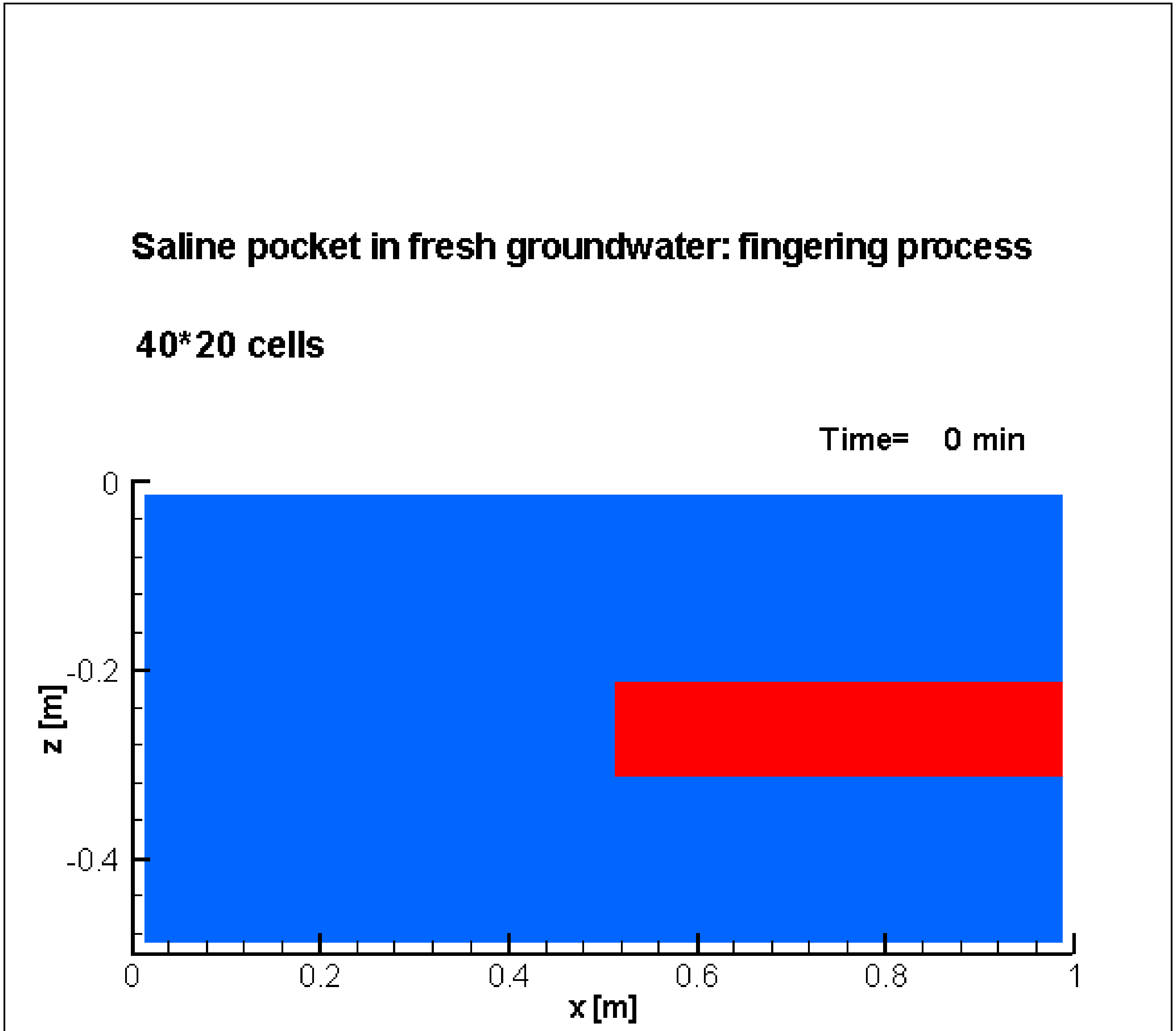
EFFECT OF SIZE MODEL CELL ON PHYSICAL PROCESS



SALT WATER POCKET IN A FRESH ENVIRONMENT



SALT WATER POCKET IN A FRESH ENVIRONMENT



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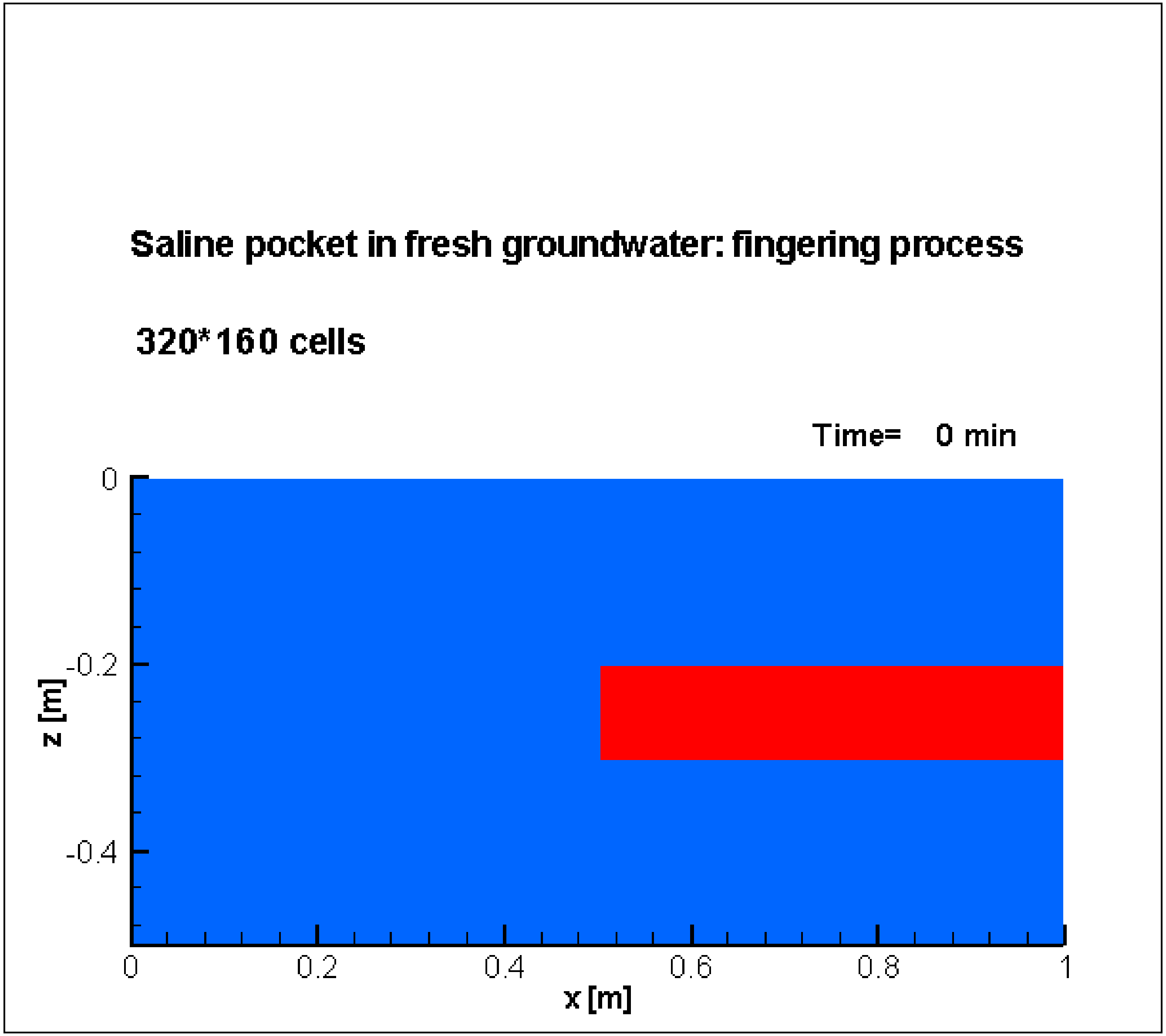
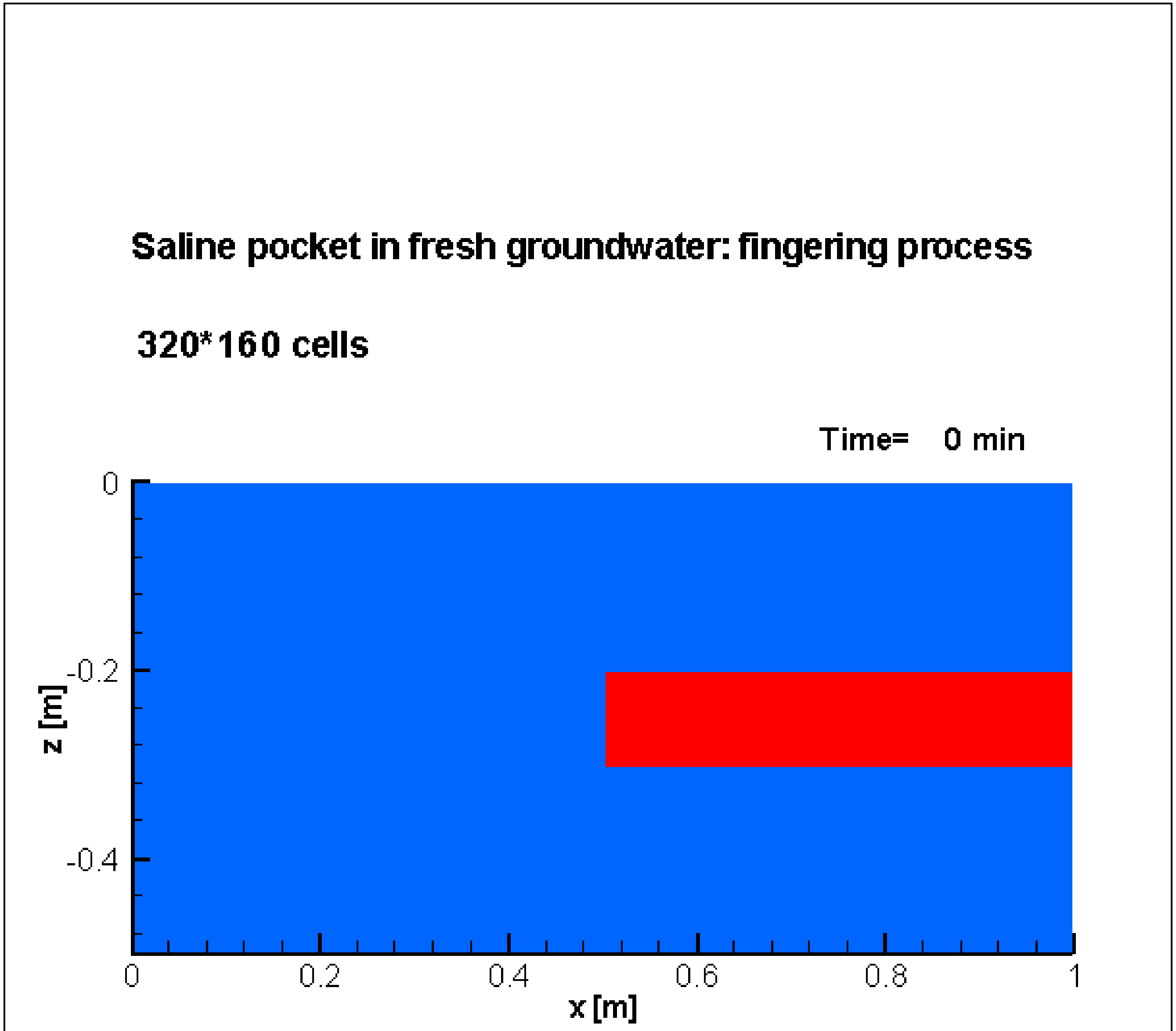
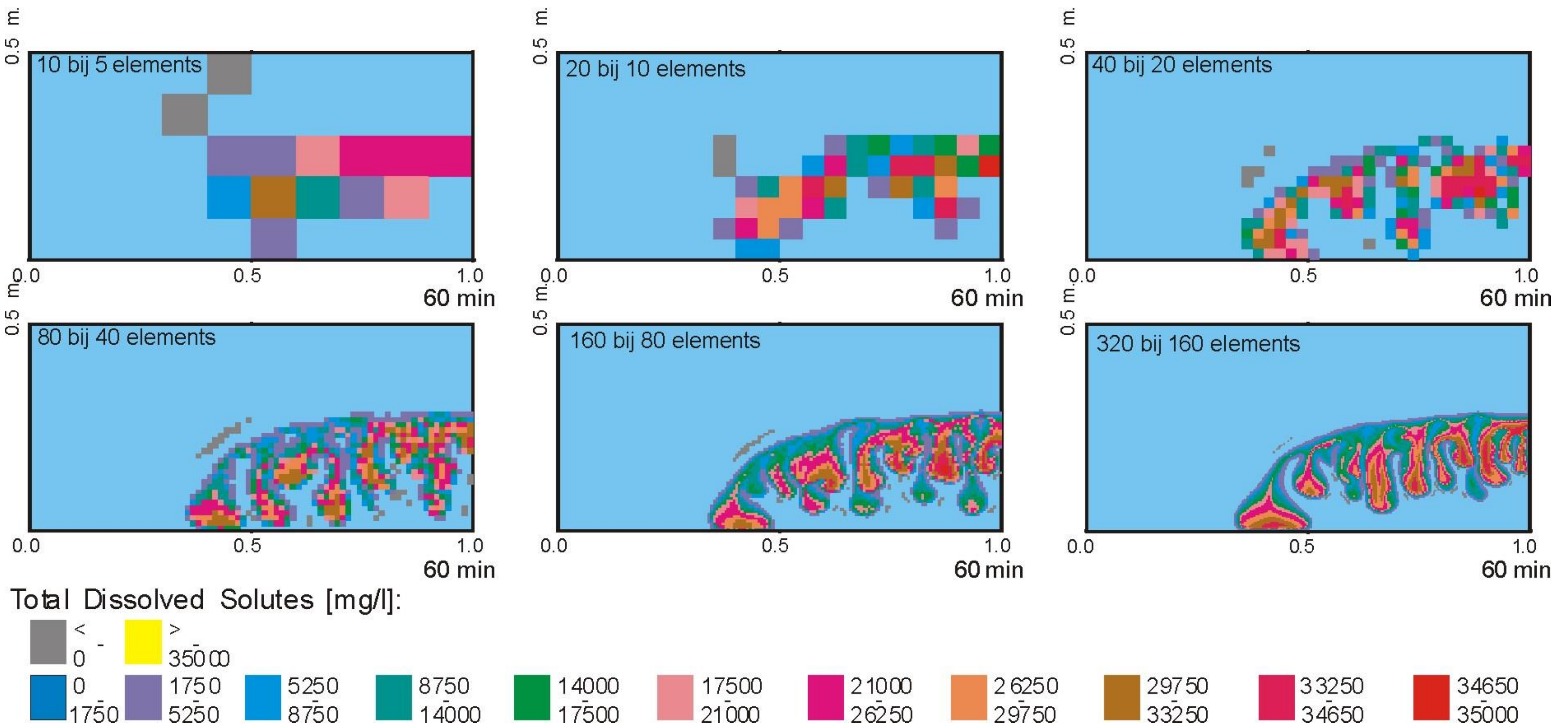


SALT WATER POCKET IN A FRESH ENVIRONMENT

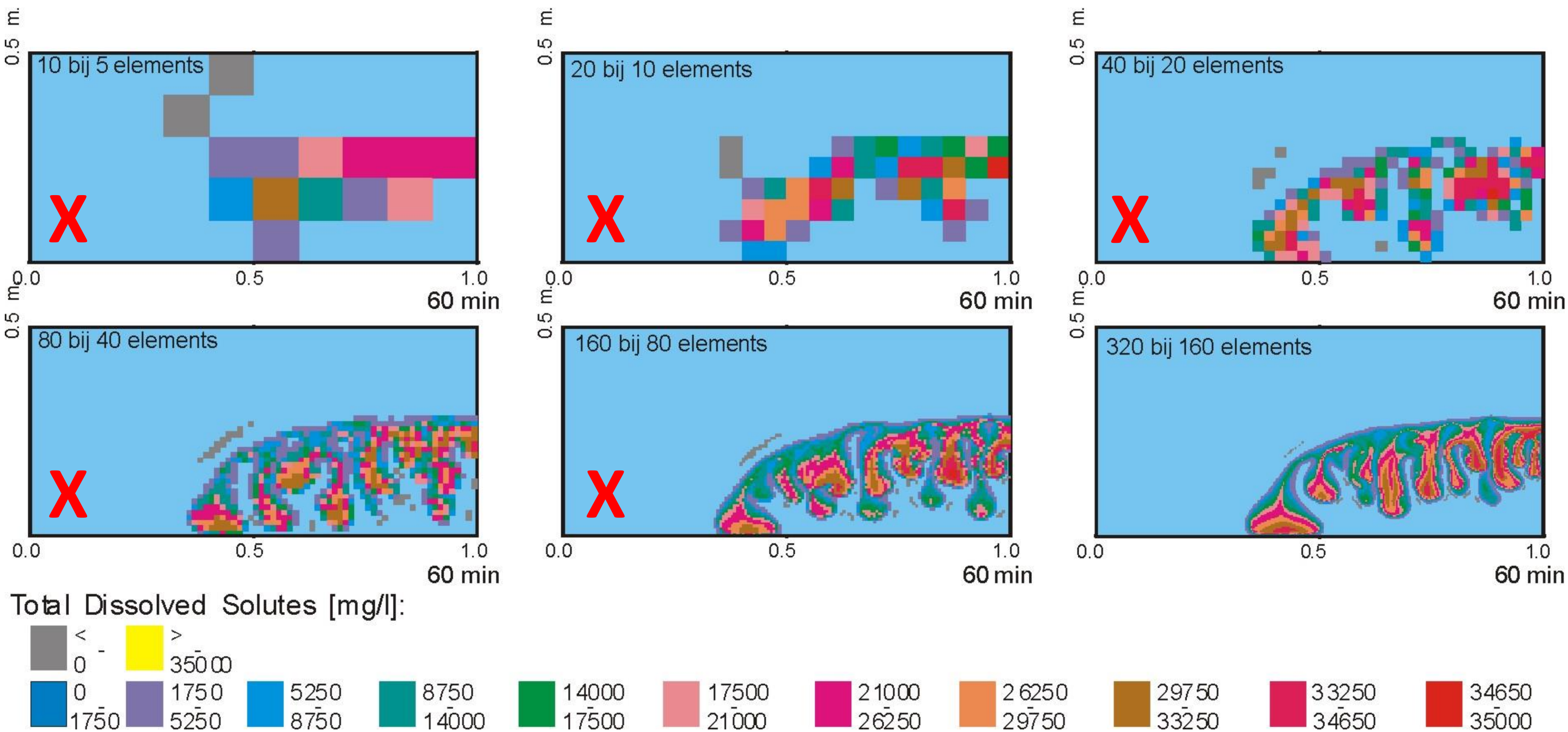


EFFECT OF SIZE MODEL CELL ON PHYSICAL PROCESS



Size of cell has a **large** effect on modelling result!

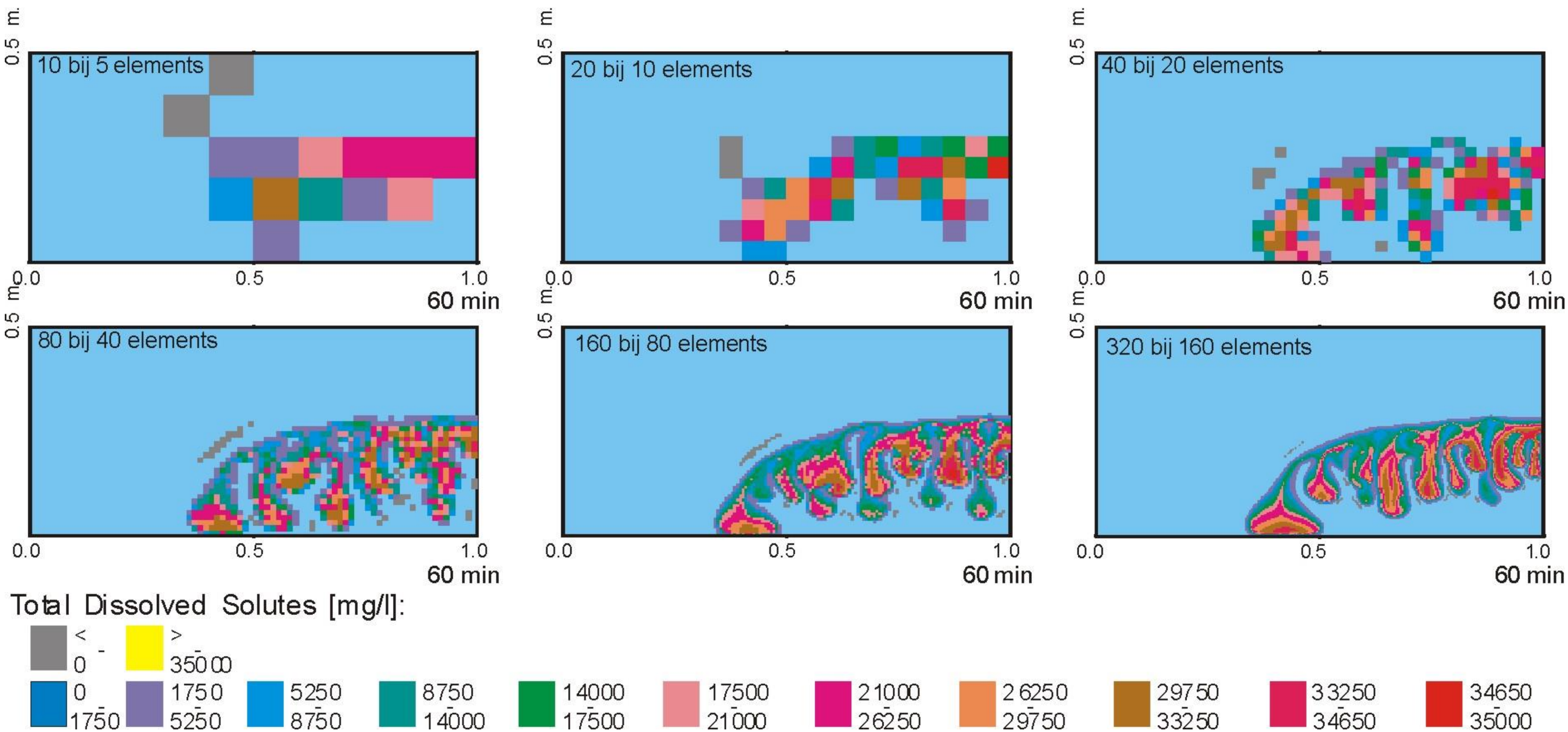
EFFECT OF SIZE MODEL CELL ON PHYSICAL PROCESS



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

Size of cell has a **large** effect on modelling result!

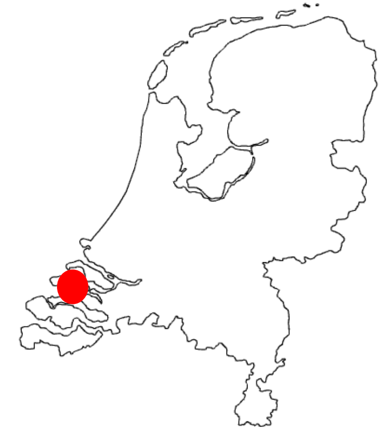
EFFECT OF SIZE MODEL CELL ON PHYSICAL PROCESS

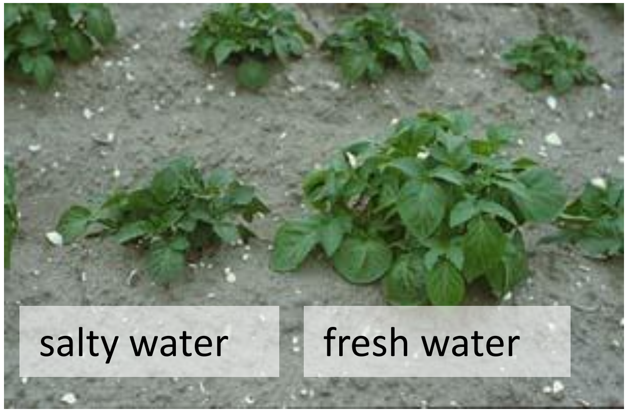


All models are GOOD for predicting moment of touching bottom!

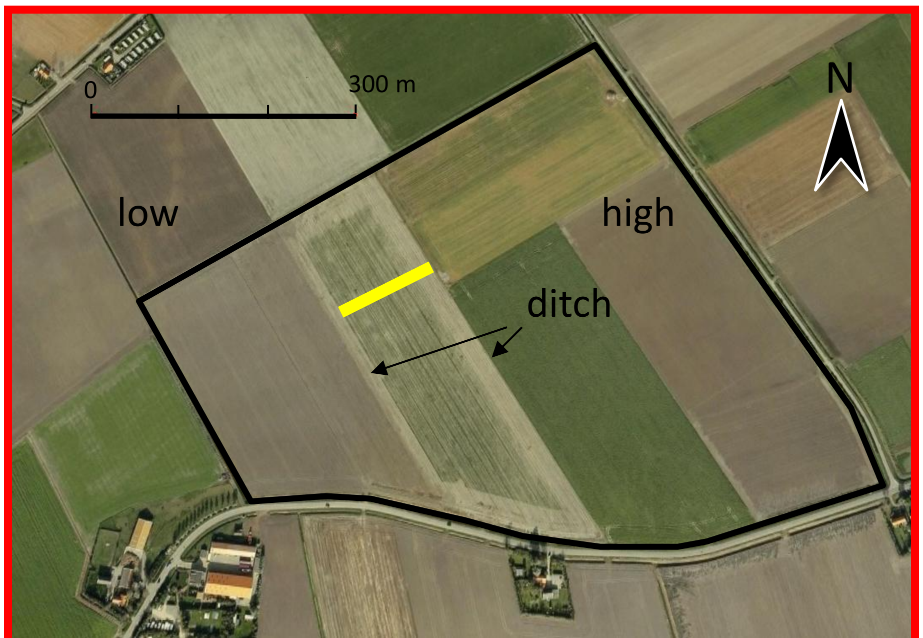
Size of cell has a **large** effect on modelling result!

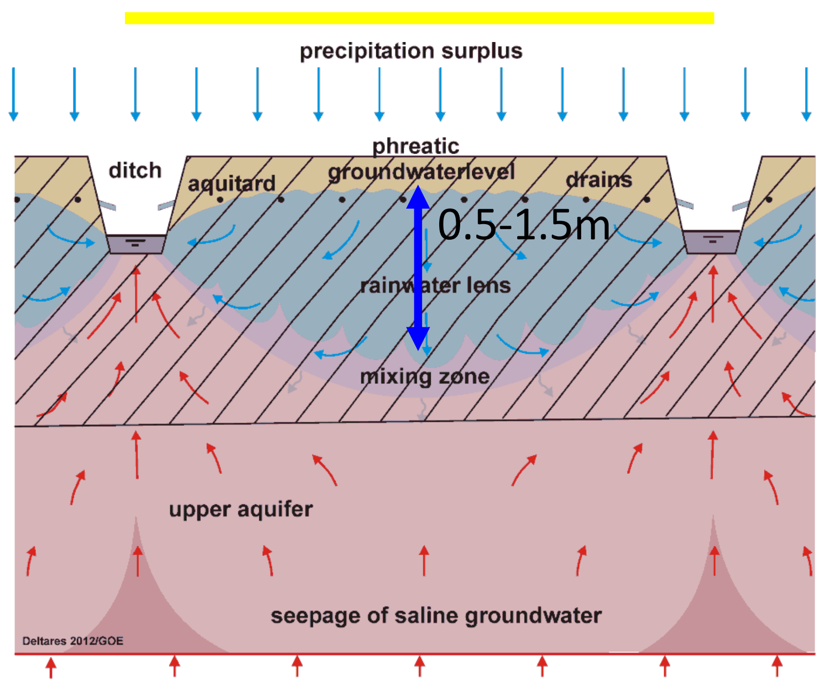
EXAMPLE 2: CASE ON A LOCAL 3D MODEL





Local model:
3D, MOCDENS3D
salt-fresh
5*5m2 cells



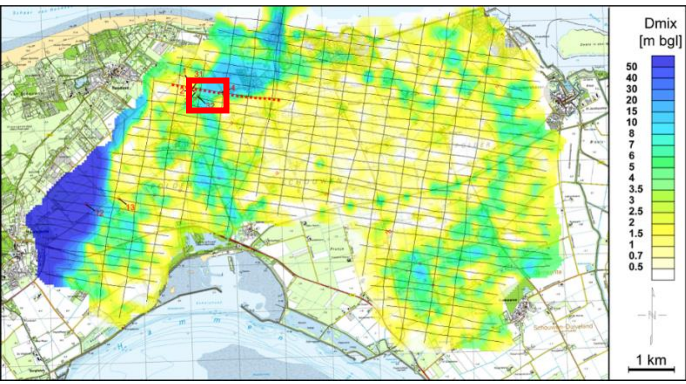


shallow fresh water lens

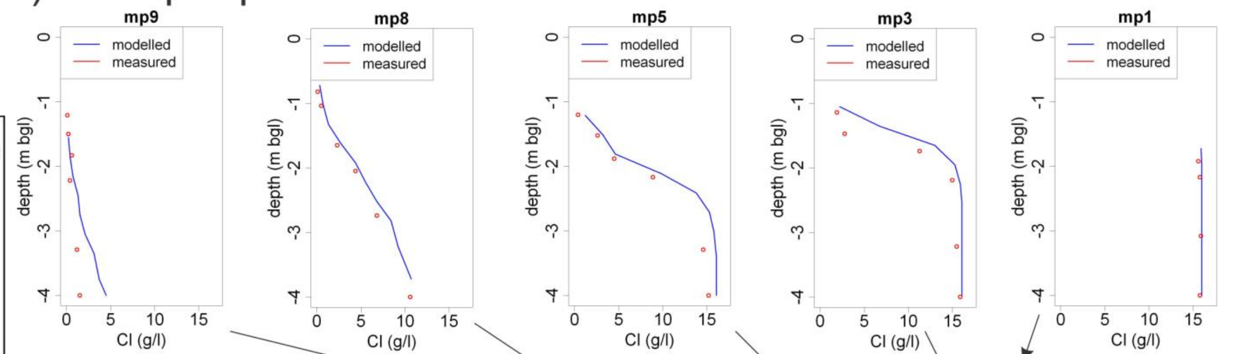
De Louw et al., Hydrol. Earth Syst. Sci. Discuss., 8, 7657-7707, 2011.

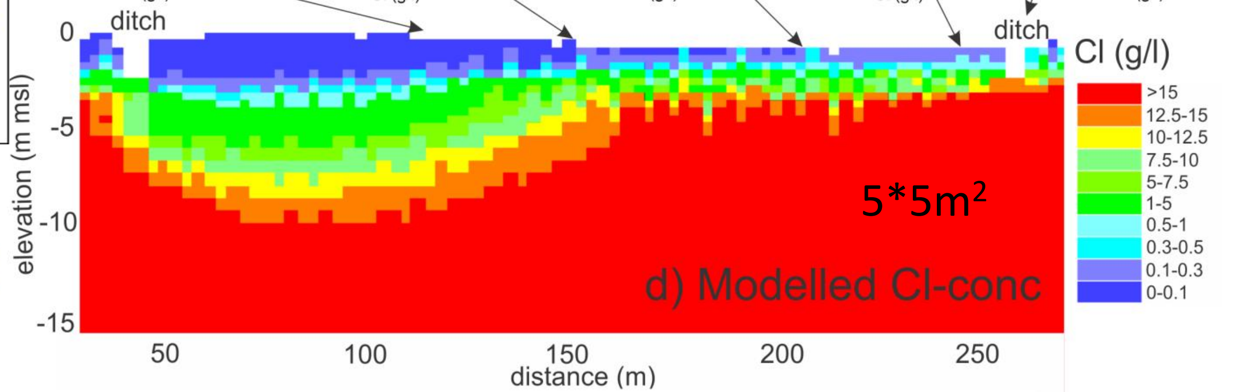
COMPARISON MONITORING DATA WITH MODEL RESULTS

a) Airborne EM



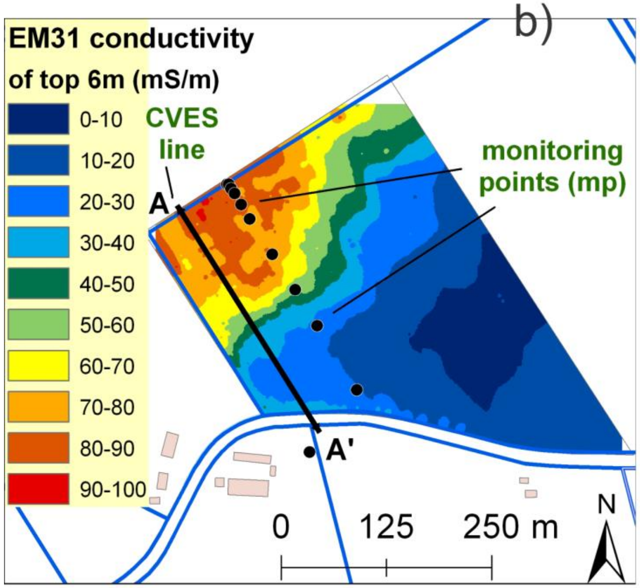
c) Cl-depth profiles

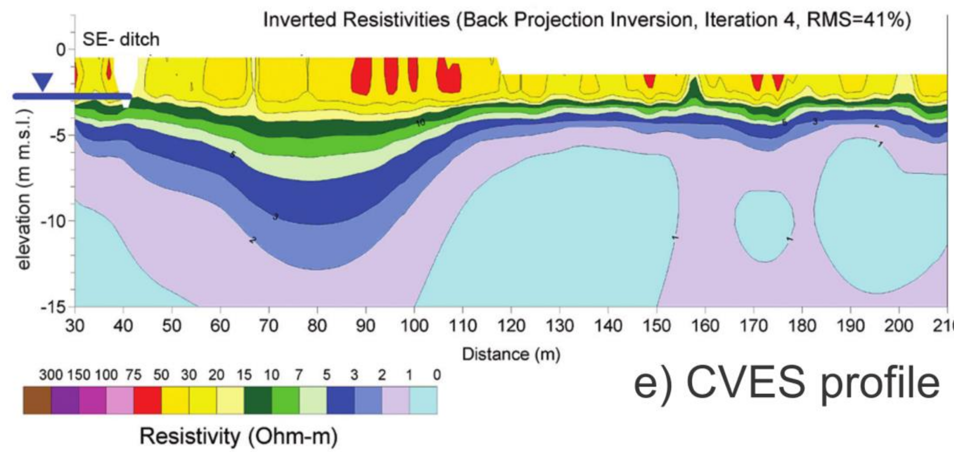




d) Modelled Cl-conc

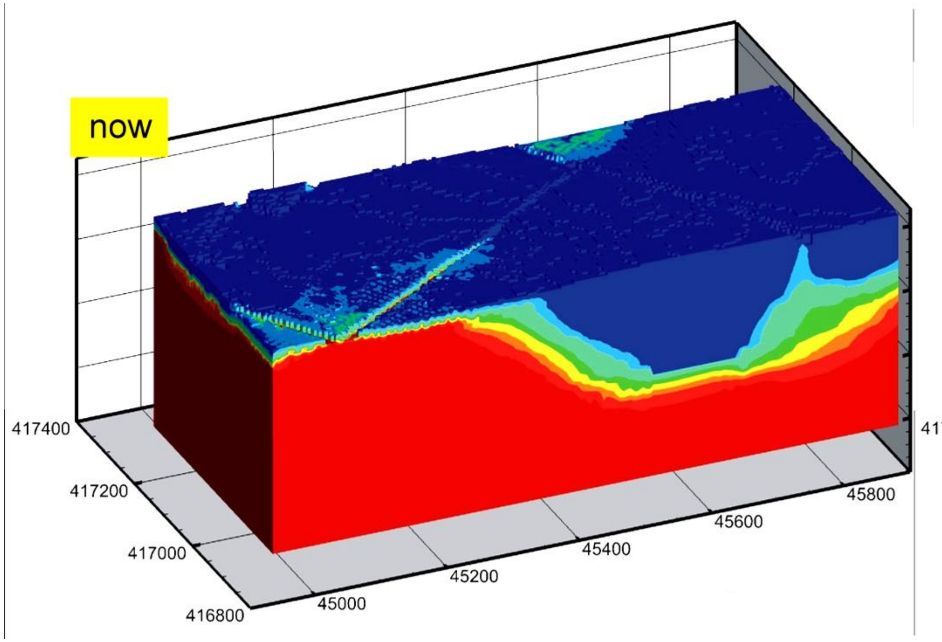
b)



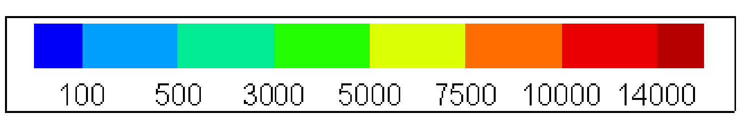


e) CVES profile

MODELLING CL-CONC. WITH DIFFERENT CC SCENARIOS

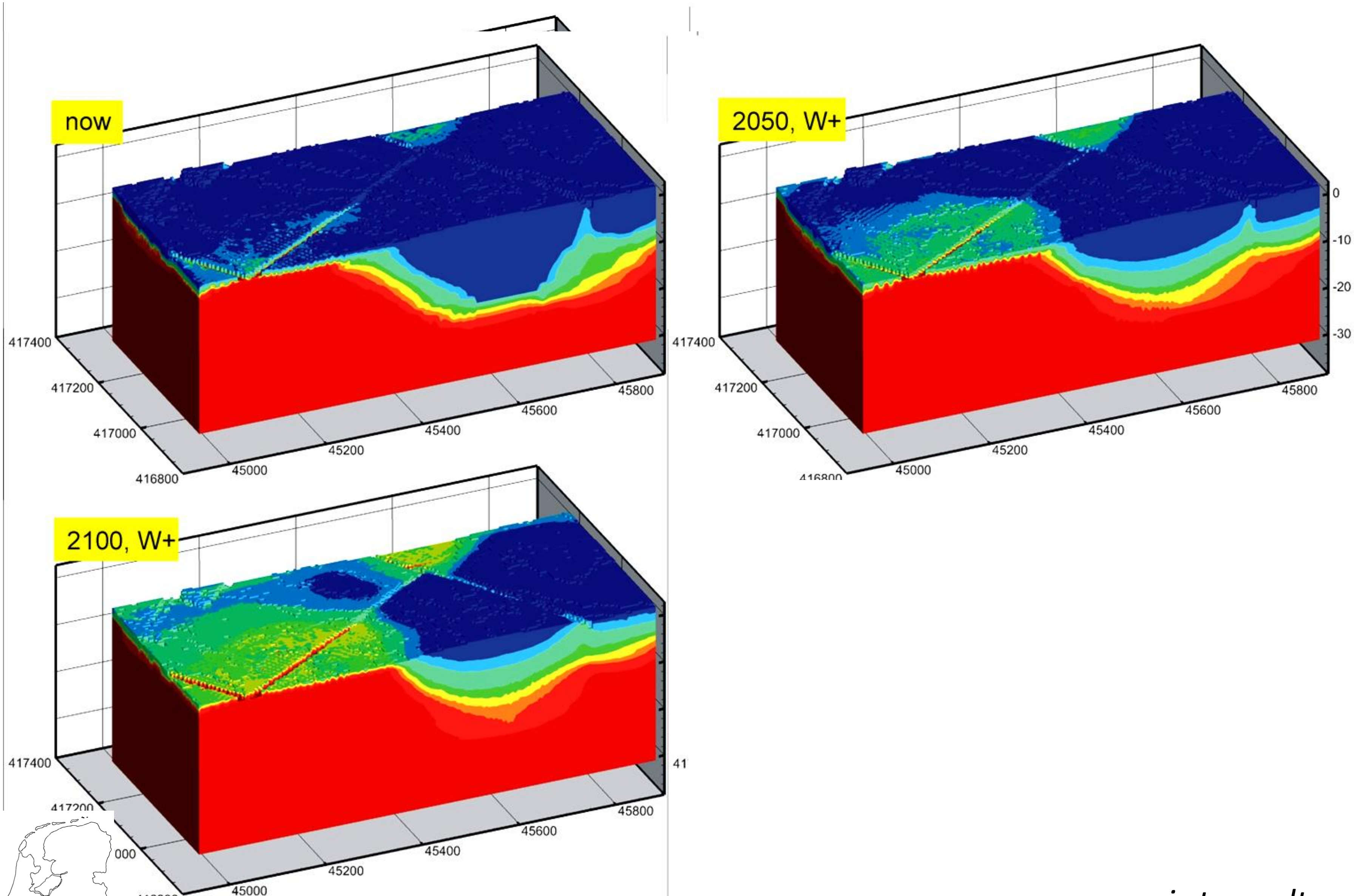


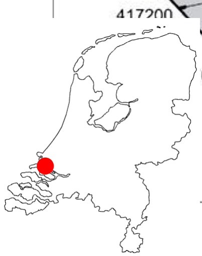
724 SFWMD

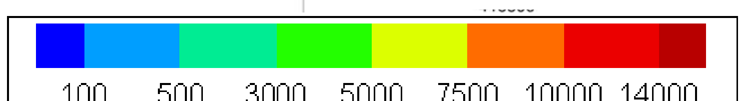


green is too salty
to grow fresh crops

MODELLING CL-CONC. WITH DIFFERENT CC SCENARIOS







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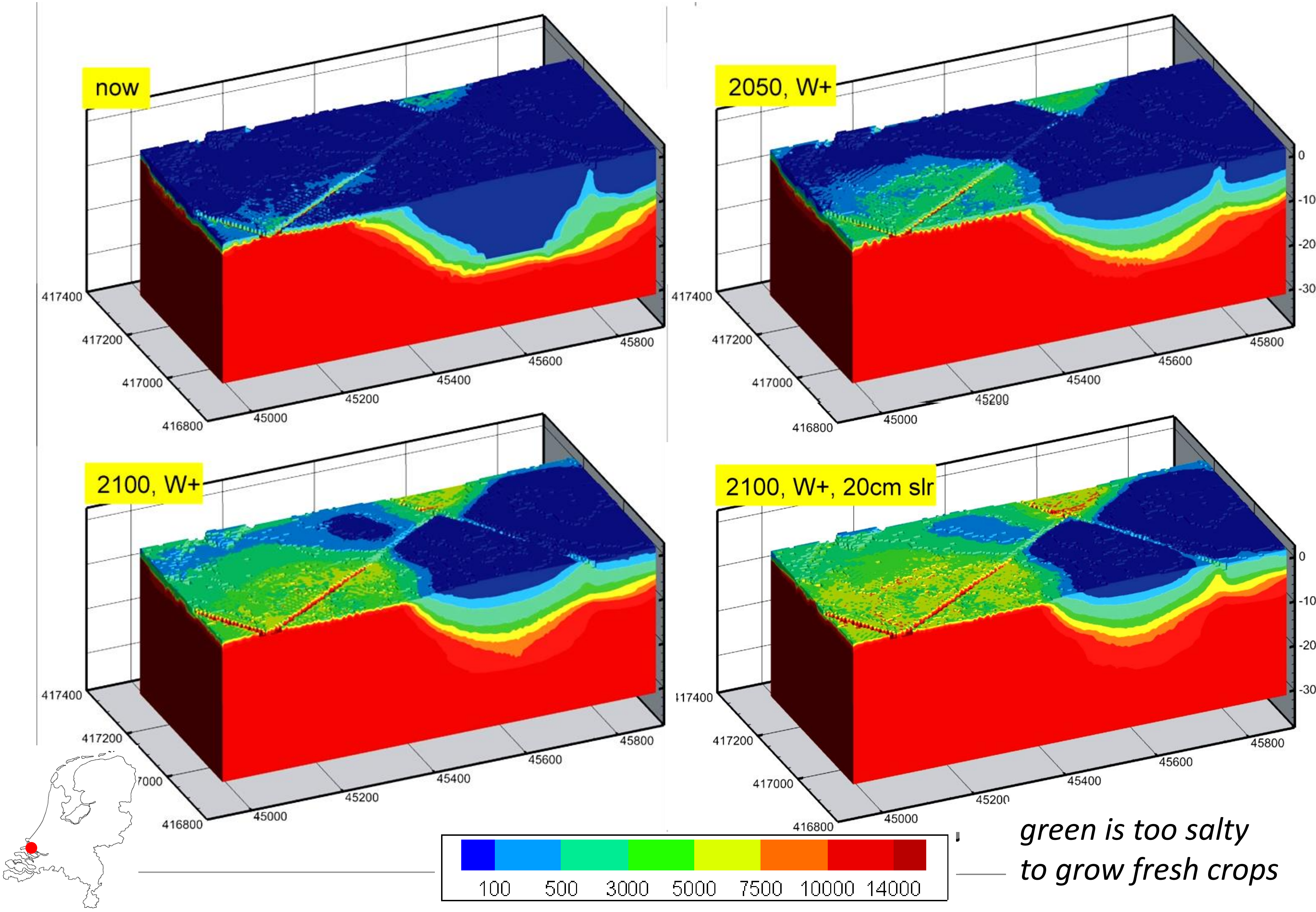

green is too salty to grow fresh crops

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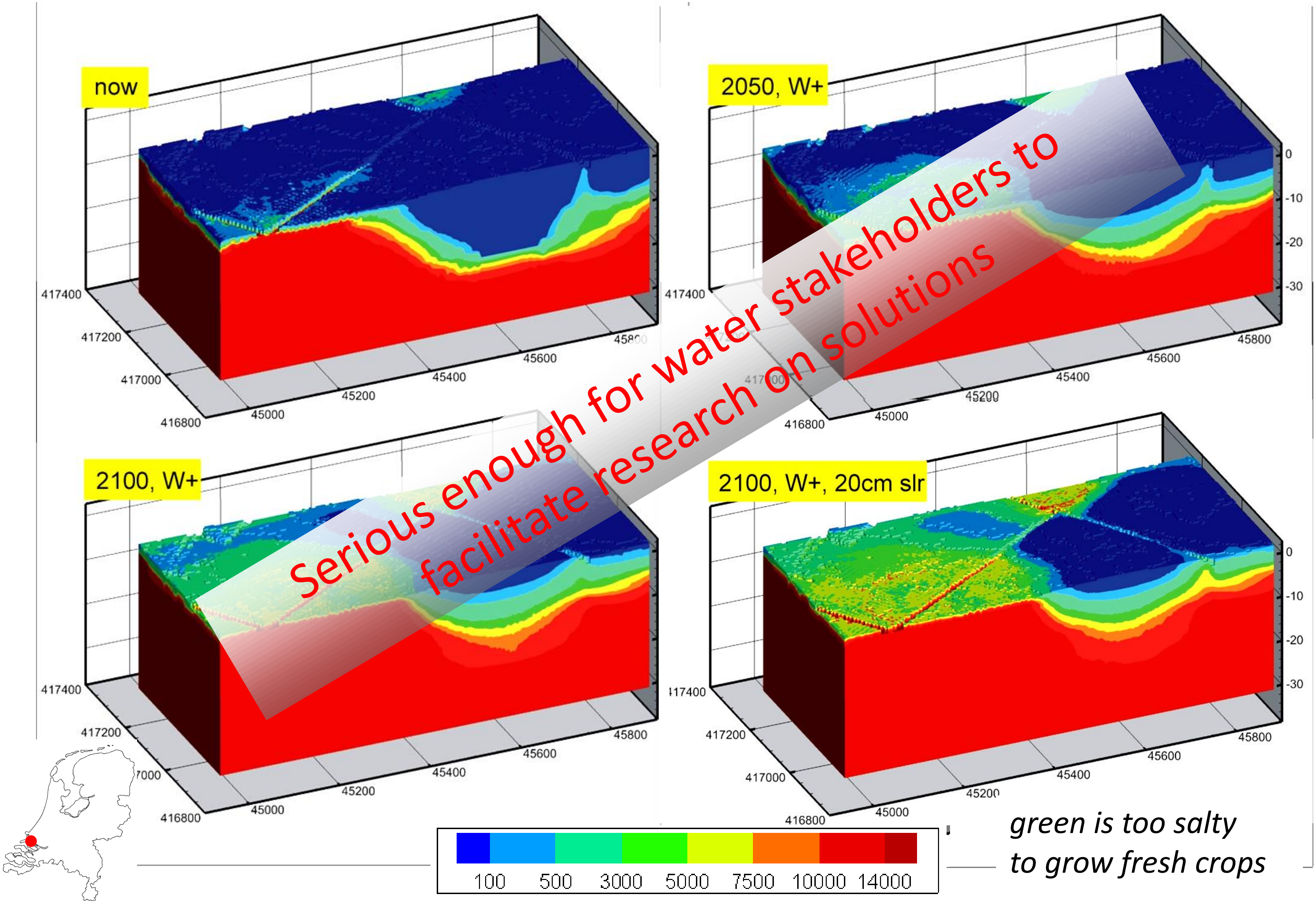
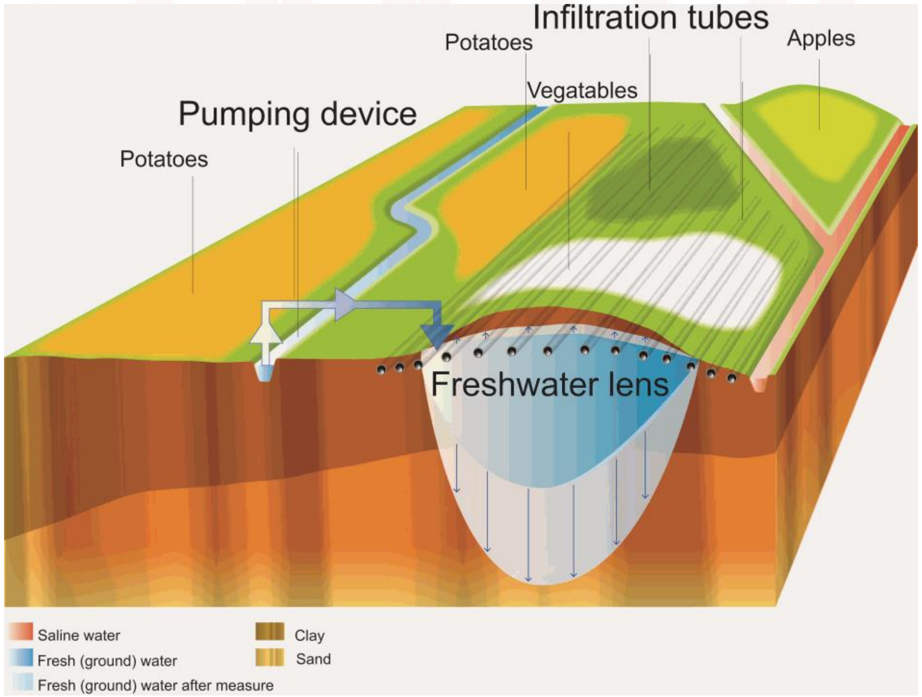
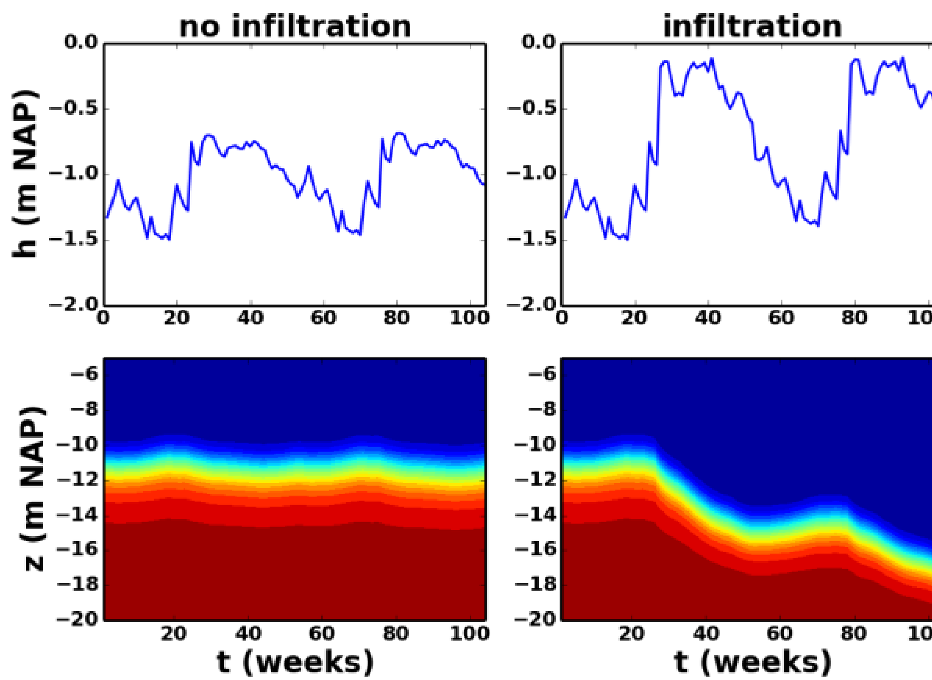


green is too salty
to grow fresh crops

CREEKRIDGE INFILTRATION SYSTEM: AQUIFER STORAGE SYSTEM



Modelling result



Monitoring result

GO-FRESH

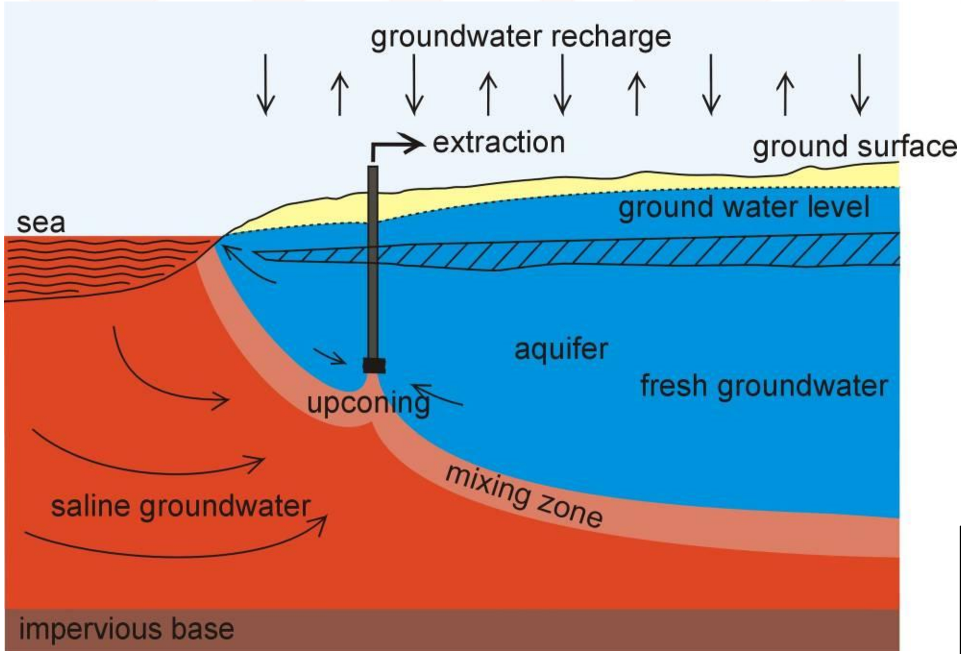
Geohydrological Opportunities for FRESH Water Supply

STAKEHOLDER PARTICIPATION AND KNOWLEDGE TRANSFER

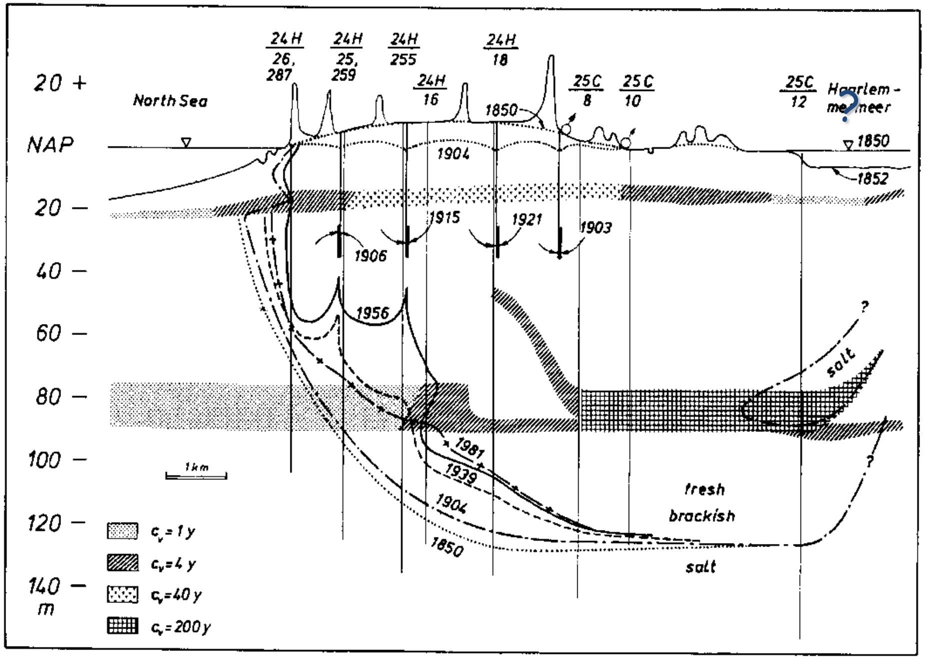
GO-FRESH

Geohydrological Opportunities for FRESH Water Supply

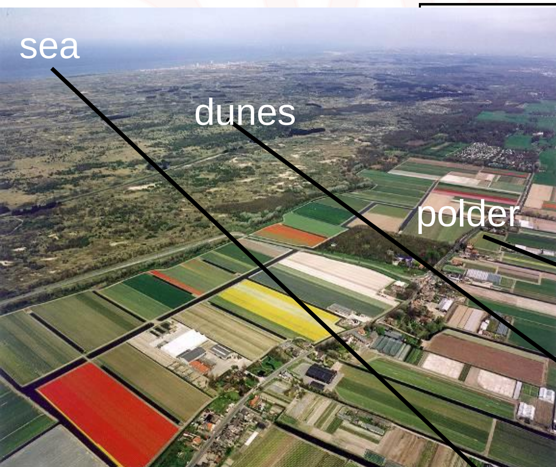
EXAMPLE 3: UPCONING OF BRACKISH-SALINE GROUNDWATER

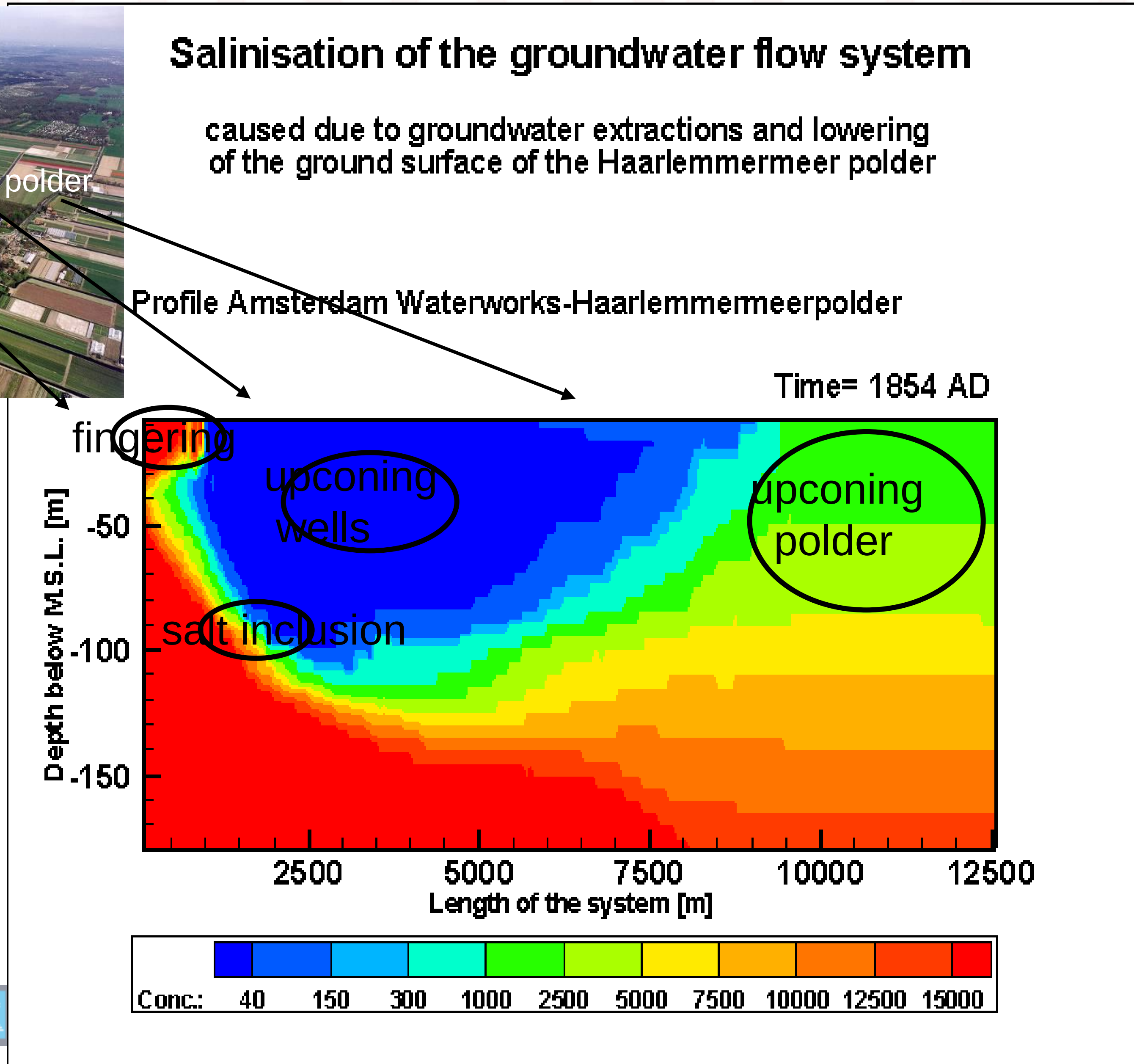


Stuyfzand, 1993



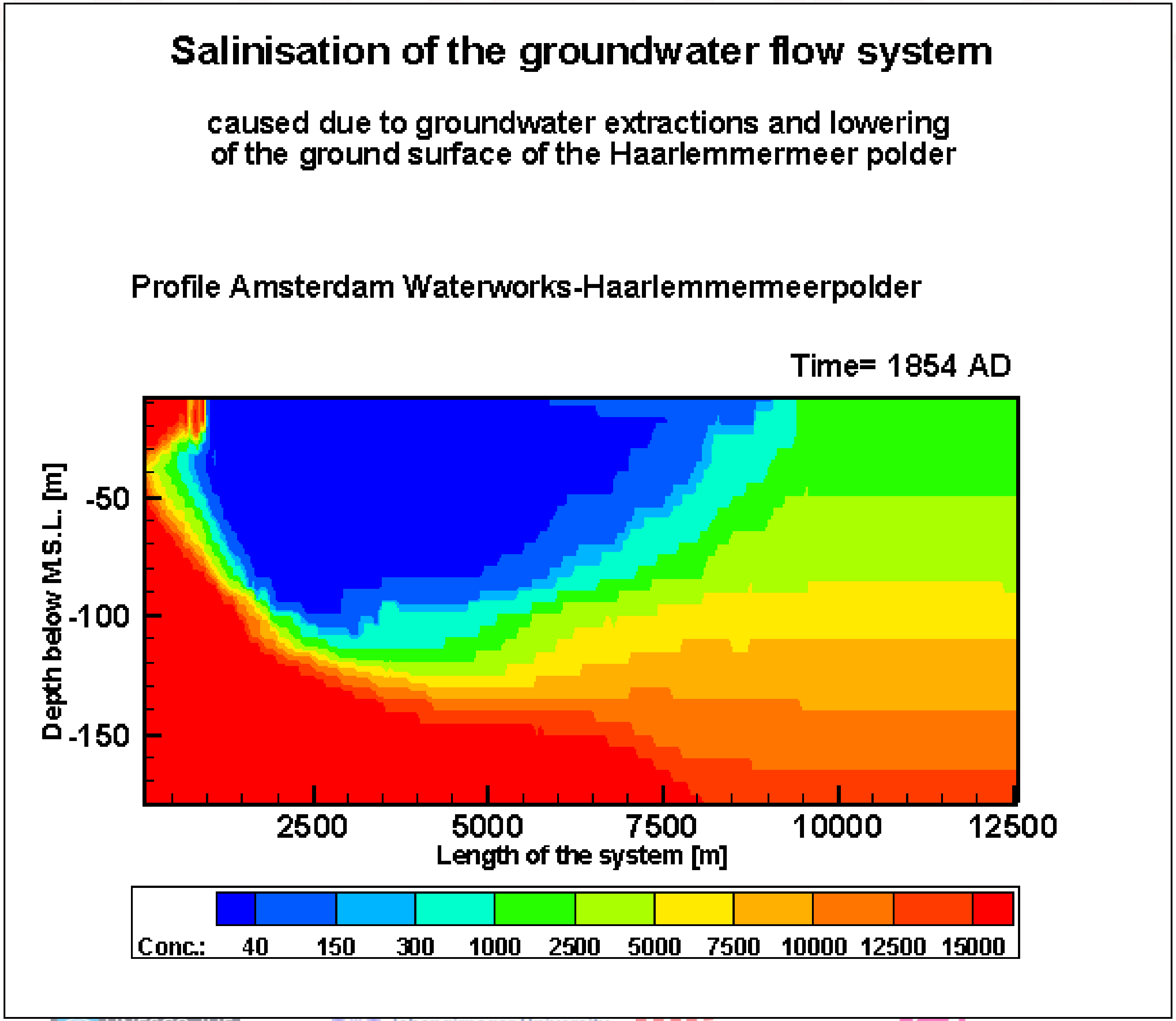
SALTWATER INTRUSION IN THE DUTCH COASTAL ZONE





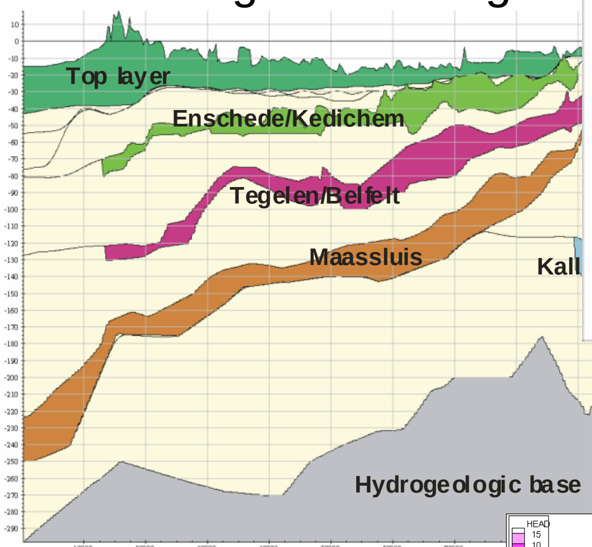
Deltares
Enabling Delta Life

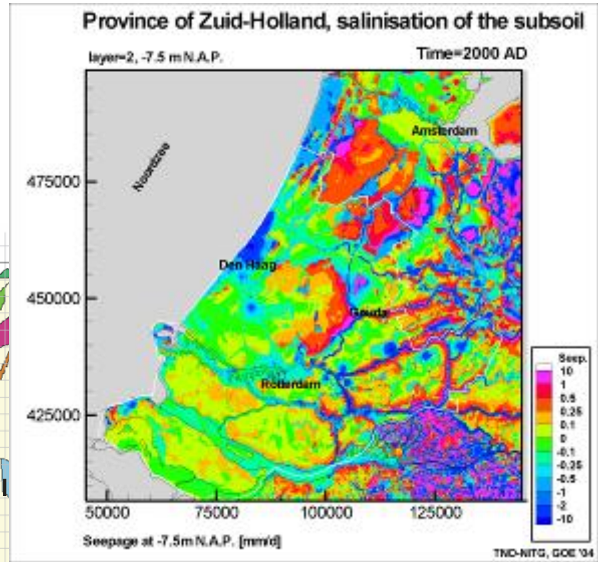
SALTWATER INTRUSION IN THE DUTCH COASTAL ZONE

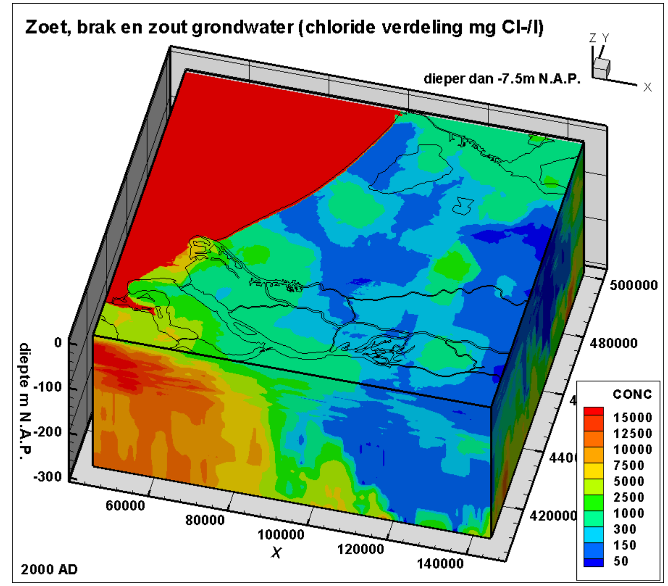


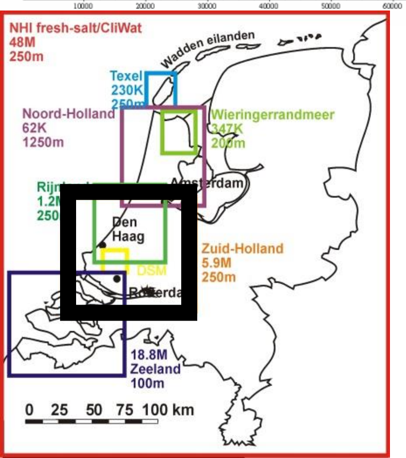
EXAMPLE 4
3D FRESH-SALT MODEL PROVINCE ZUID-HOLLAND

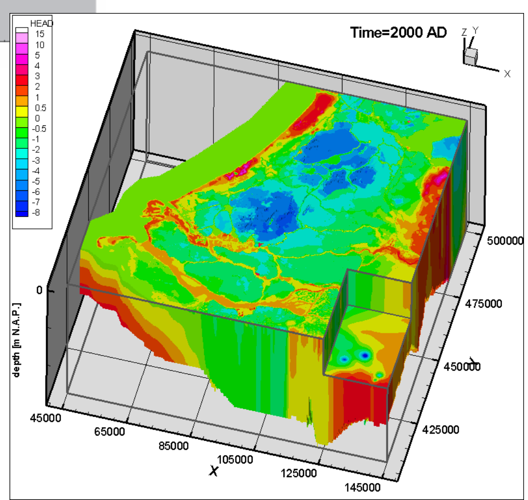
- Land subsidence
- Sea level rise
- Change in recharge

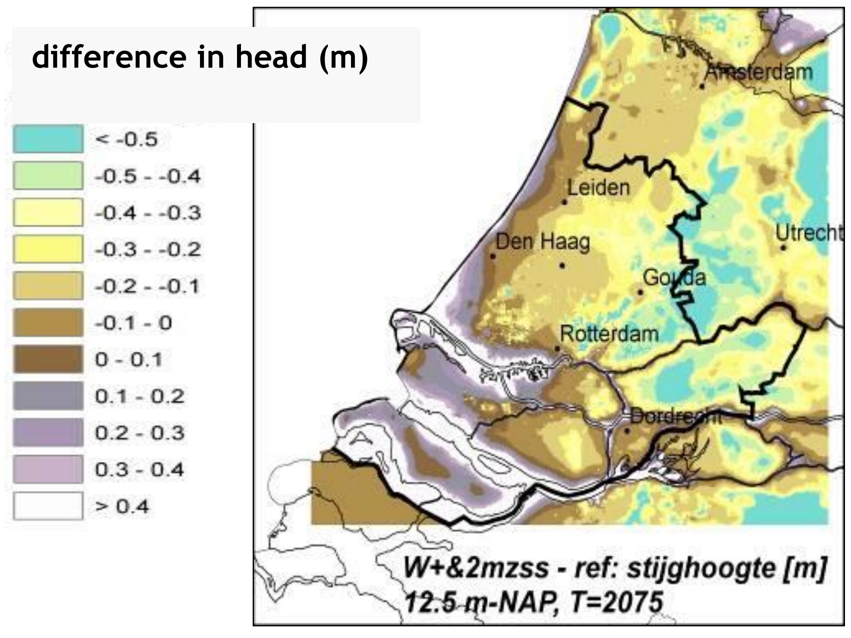






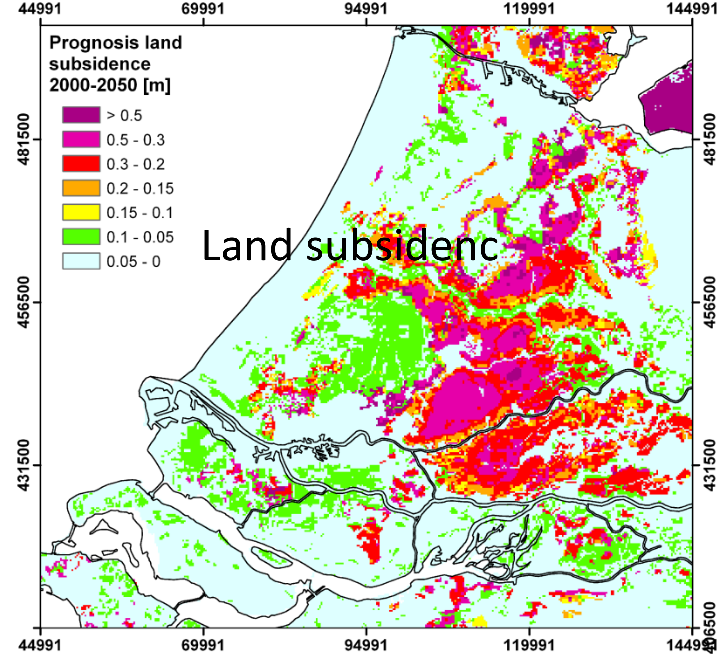






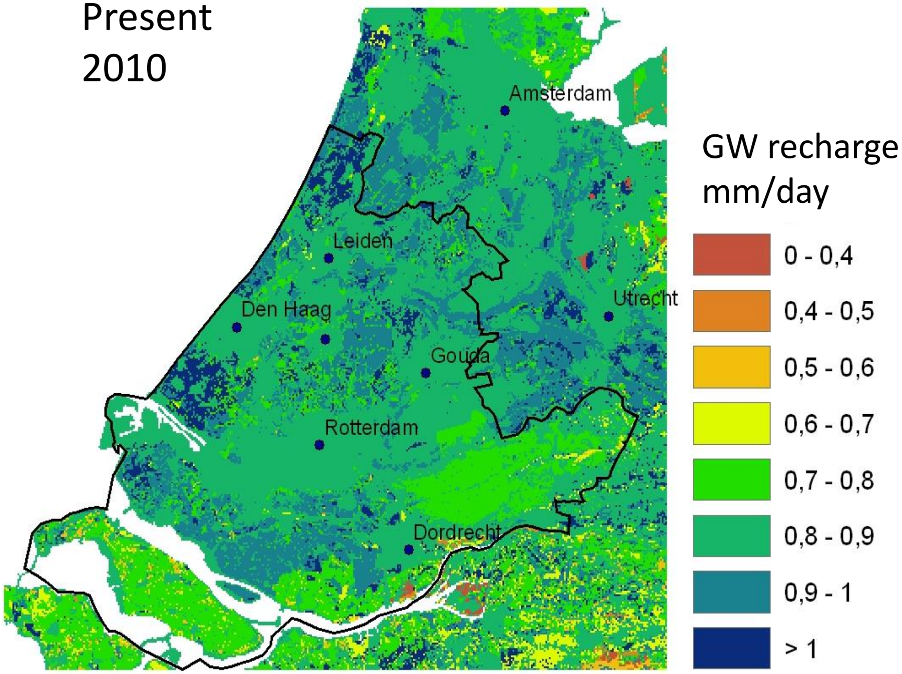
MODELSTUDY ZUID-HOLLAND

- 100km * 92.5km * 300m depth
- ~4 million active cells
- Land subsidence
- Sea level rise
- Change in natural groundwater recharge

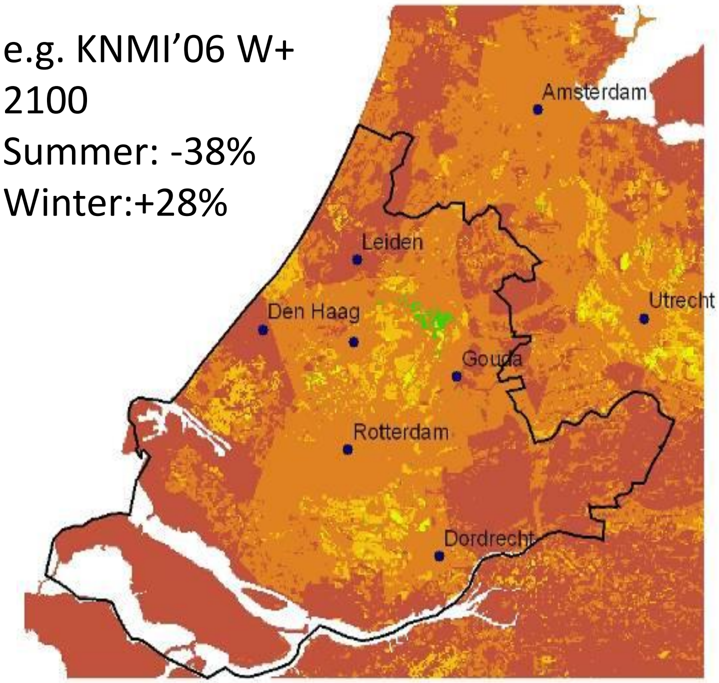


4 recharge scenarios

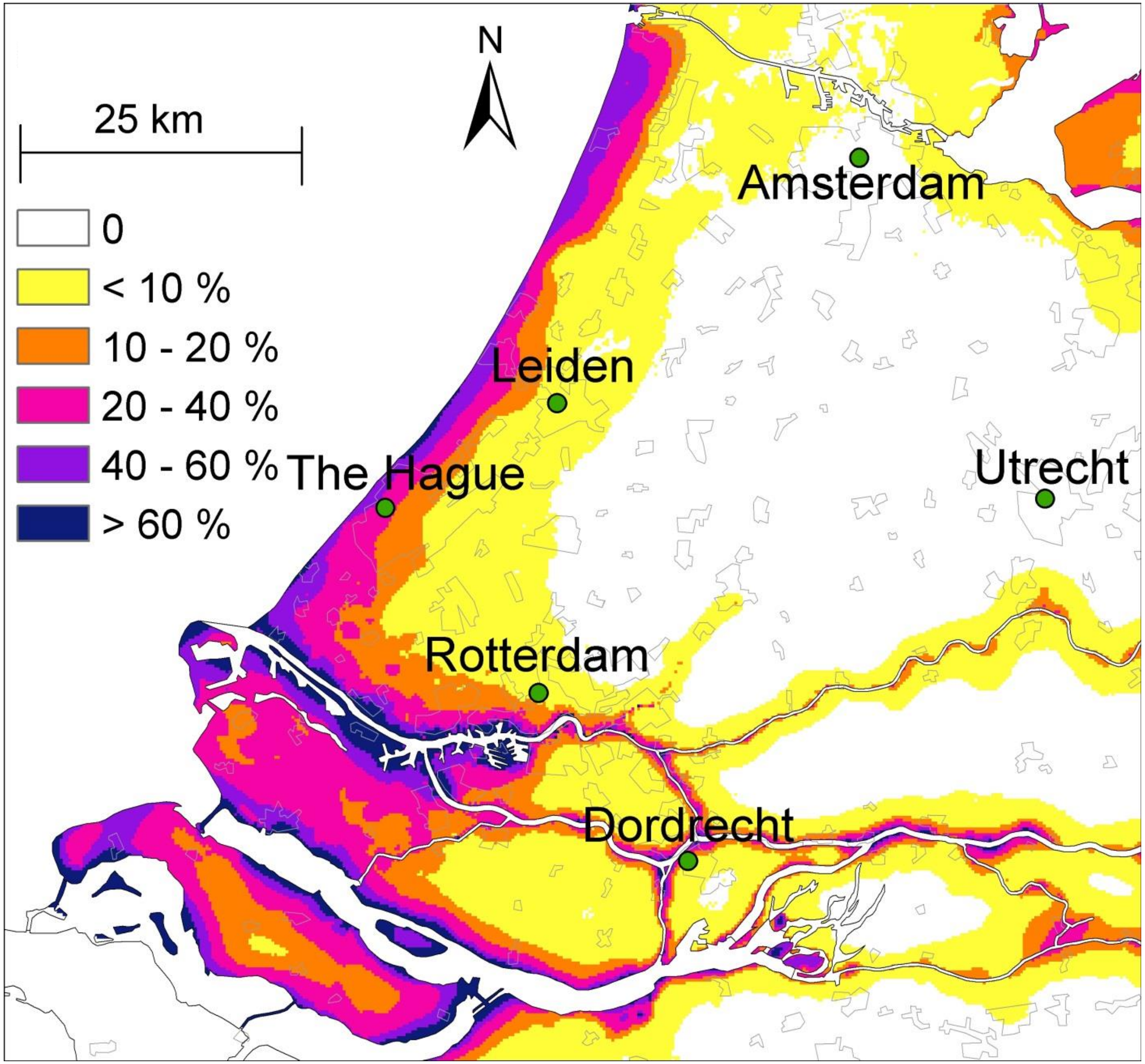
Present
2010



e.g. KNMI'06 W+
2100
Summer: -38%
Winter:+28%

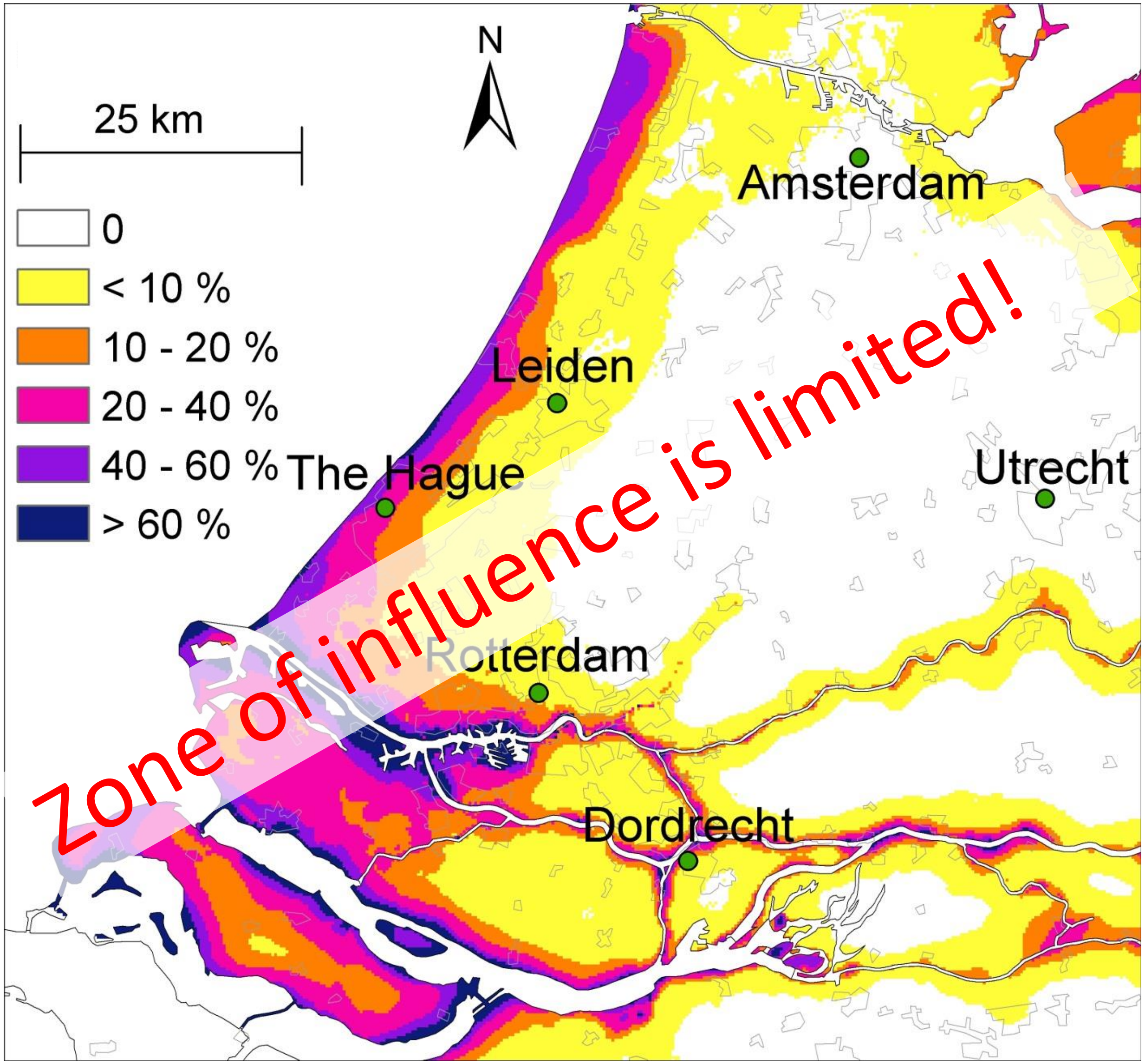


ZONE OF INFLUENCE OF SEA LEVEL RISE



backwater effect surface water

ZONE OF INFLUENCE OF SEA LEVEL RISE



backwater effect surface water

ZONE OF INFLUENCE OF SEA LEVEL RISE

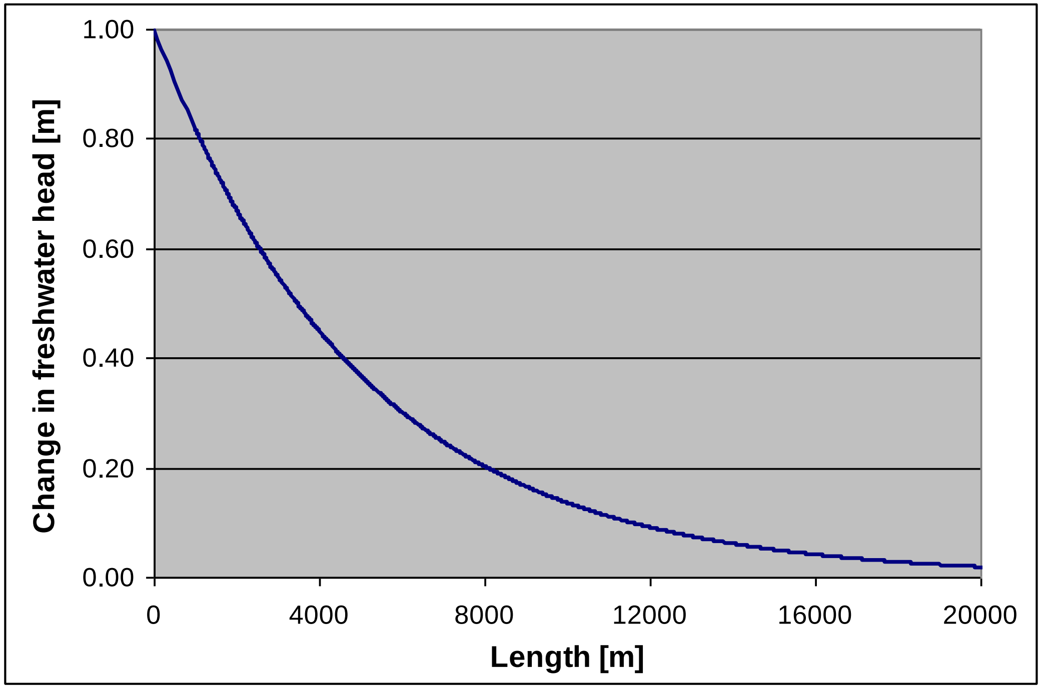
Case 1 with subsoil parameters

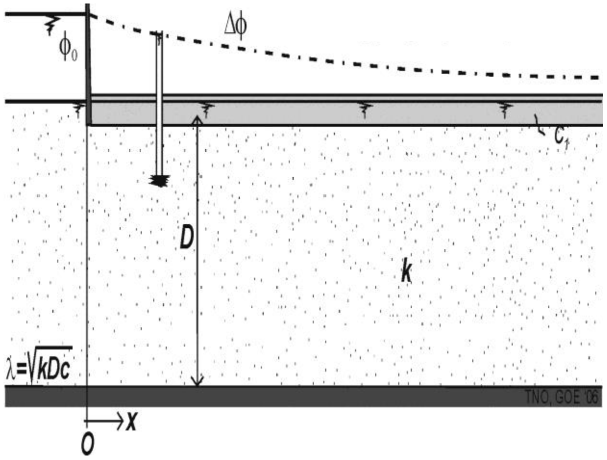
kD = 5000 m2/day
c = 5000 day
λ = 5000 m

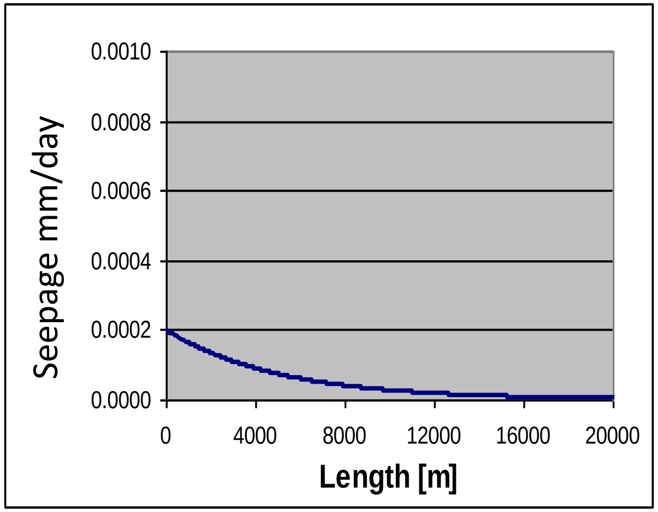
$$\Delta\phi(x) = \phi_0 e^{-x/\lambda}$$

$$\Delta q(x) = \Delta\phi(x) / c$$

λ= sqrt(kDc)



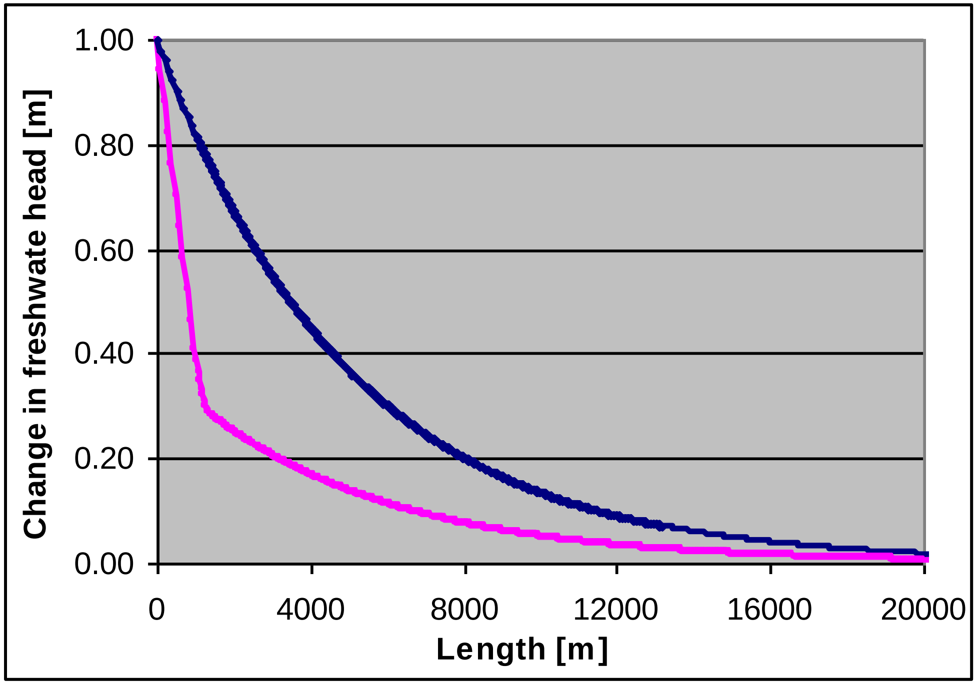


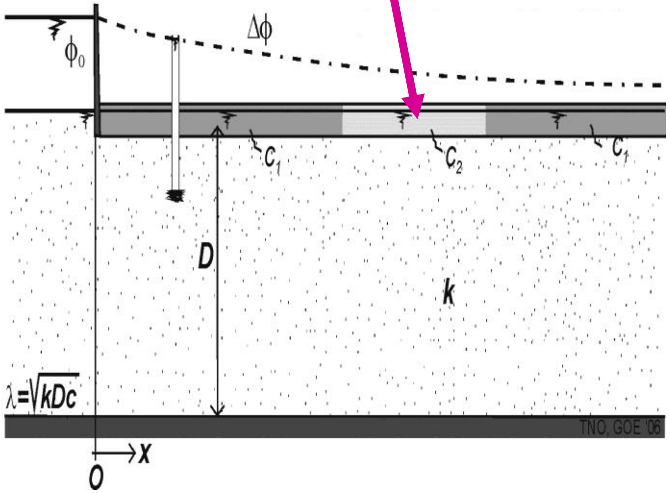


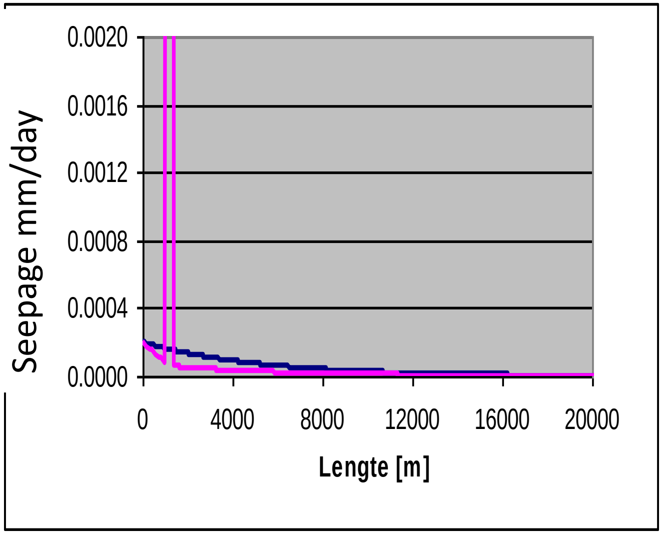
ZONE OF INFLUENCE OF SEA LEVEL RISE:
Case 2 with subsoil parameters

GOOD PERMEABLE AQUITARD

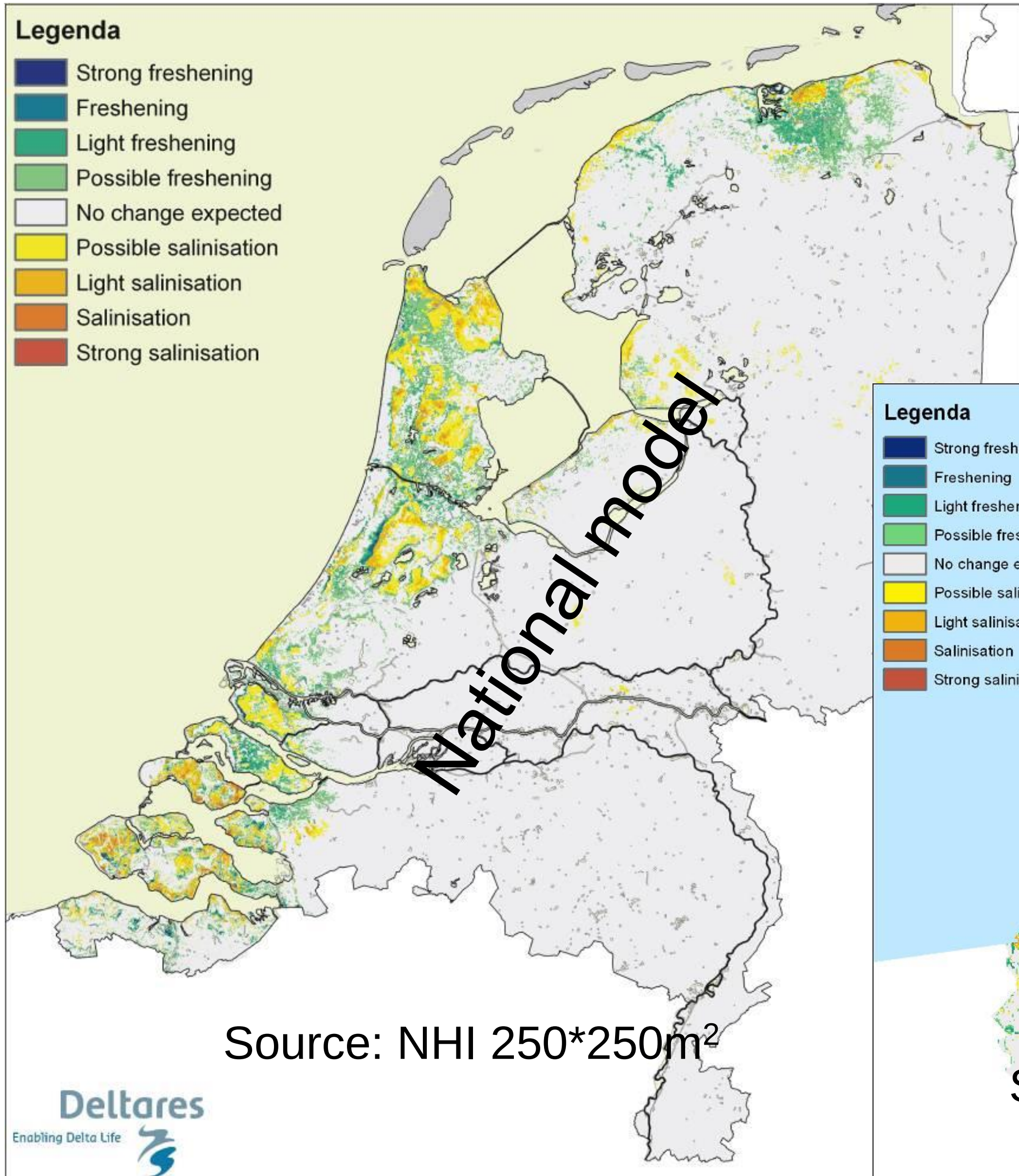
kD = 5000 m2/dag
c1 = 5000 dag   c2 = 50 dag



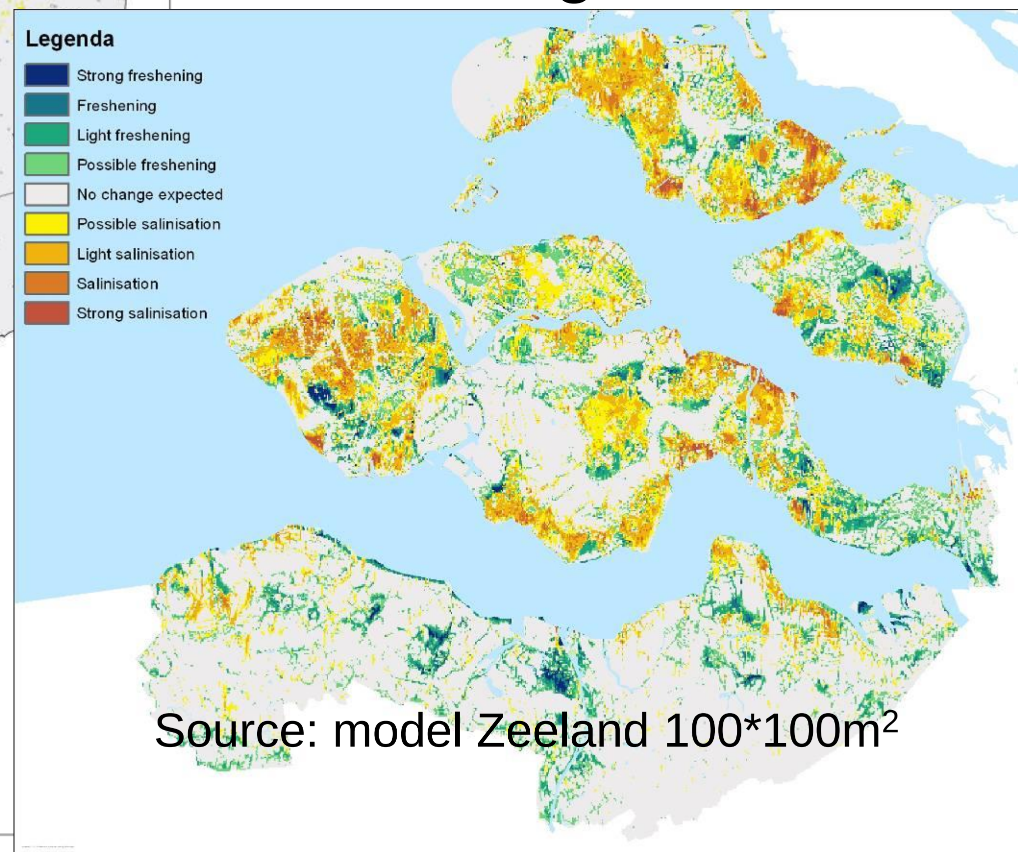




EXAMPLE 5
SALINISATION AND FRESHENING UNDER GLOBAL STRESSES



Regional model



EXAMPLE 6

Thé Dutch Integrated Modelling Example

The Netherlands Hydrological Instrument

THE NETHERLANDS HYDROLOGICAL INSTRUMENT

Main goals for water management of our national government:

- To protect The Netherlands from flooding
- To make Fresh Water Supply Climate Change Proof

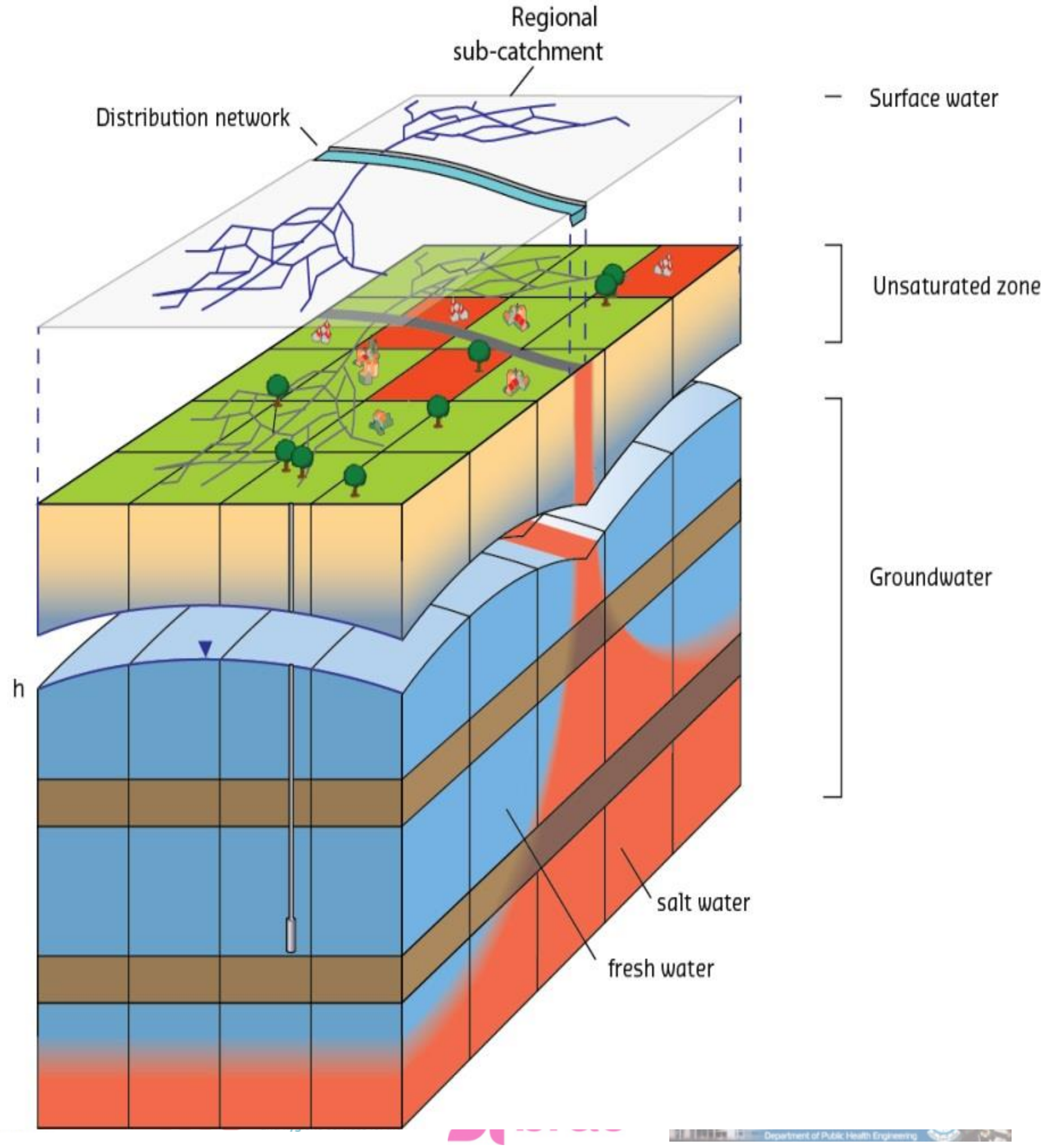
They needed a model that can assess the effects of:

- Droughts (water demands) = main goal of NHI
- Sea level rise and precipitation pattern
- Land subsidence
- Adaptive and mitigative strategies
- Changing water management (lake saline again, lake higher water level)
- Coming years: nutrient emissions and pesticide leaching, etc.

So we made NHI! First model dates from 2006.

THE NETHERLANDS HYDROLOGICAL INSTRUMENT

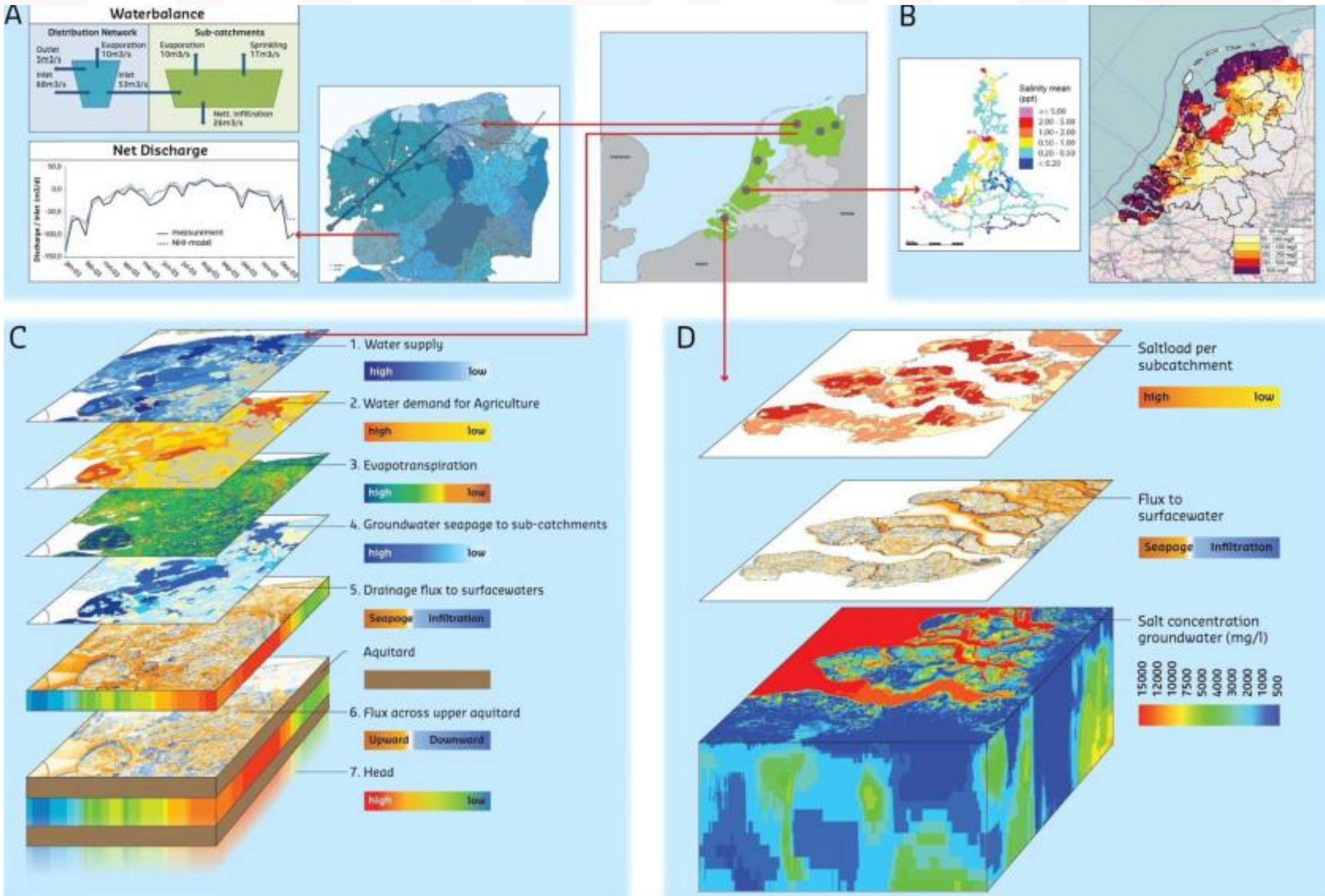
- $\Delta x = 250$m
- 1200 columns
- 1300 rows
- 7 layers
- ~2.5M stresses



COMPONENTS

water balance of sub-catchments and main surface waters

salt in surface water system



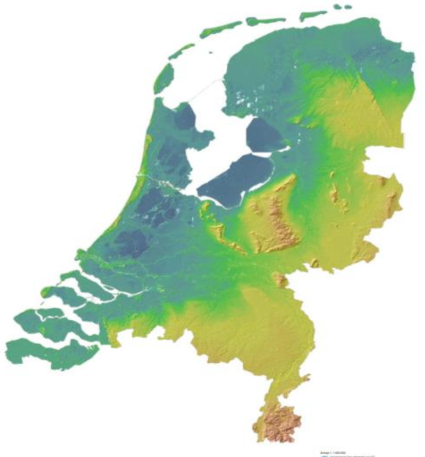
fluxes and heads in unsaturated and saturated groundwater

salt concentration in saturated groundwater and salt flux to surface water.

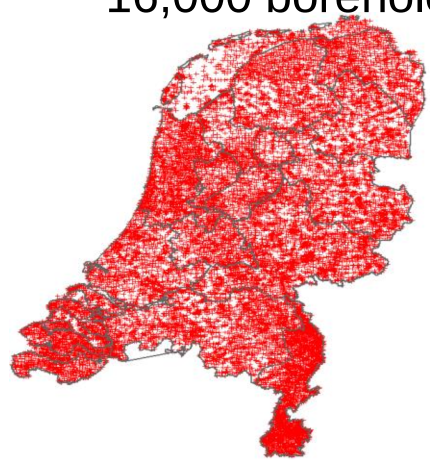
COMPONENTS

Domain	Computation Unit	Unit size	Time step	Scale of process	Purpose	Present name
Surface Water	Node-node	1-25km	1-10day	Nationwide	Optimization of water distribution	DM
Surface Water	Line	0.5km	1day	Nationwide	Flow and Transport	LSM
Surface Water	Polygon	05.-5km2	1-10day	Subcatchment	Distribution to users of groundwater & surface water	Mozart
Soil Vegetation Atmosphere	Grid cell	250m	1day	Plot, colomn	Transfer of Water in root zone, soil water deficit	MetaSWAP
Groundwater	Grid cell	250m	1day	Regional	Flow and Transport	MODFLOW-SEAWAT

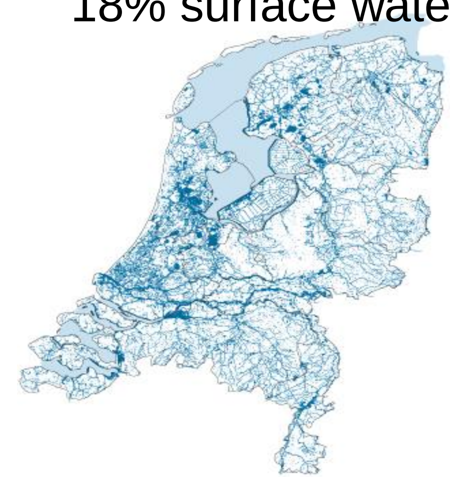
DEM 0.5m x 0.5m



~16,000 boreholes



18% surface water



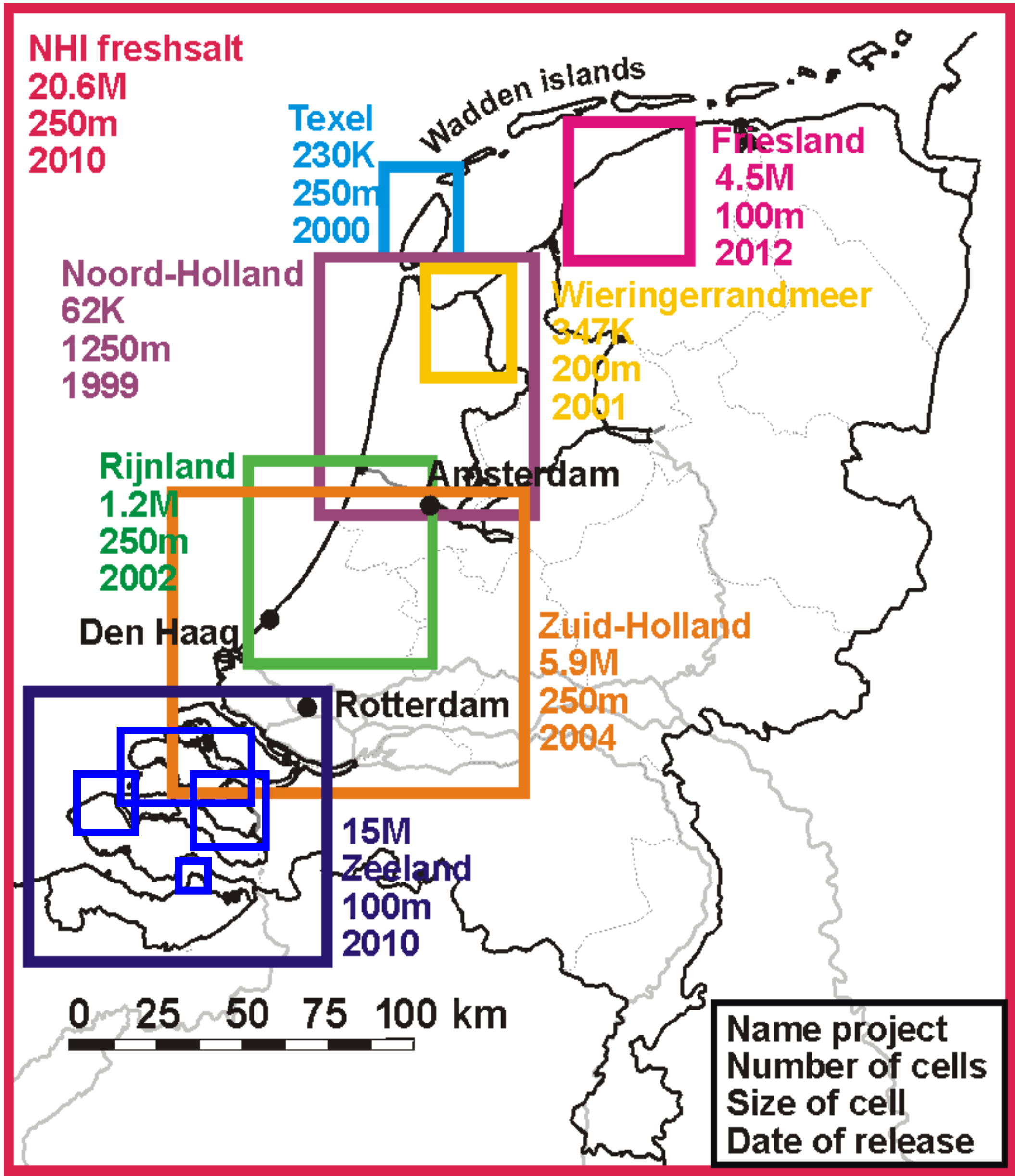
De Lange et al., 2014. An operational, multi-scale, multi-model system for consensus-based, integrated water management and policy analysis: The Netherlands Hydrological Instrument. Environmental Modelling & Software 59, 98–108.

NUMERICAL MODELLING OF SALT WATER INTRUSION

Characteristics:
- variable-density groundwater
- fresh, brackish and saline
- 3D, non-steady
- coupled solute transport
- heat transport

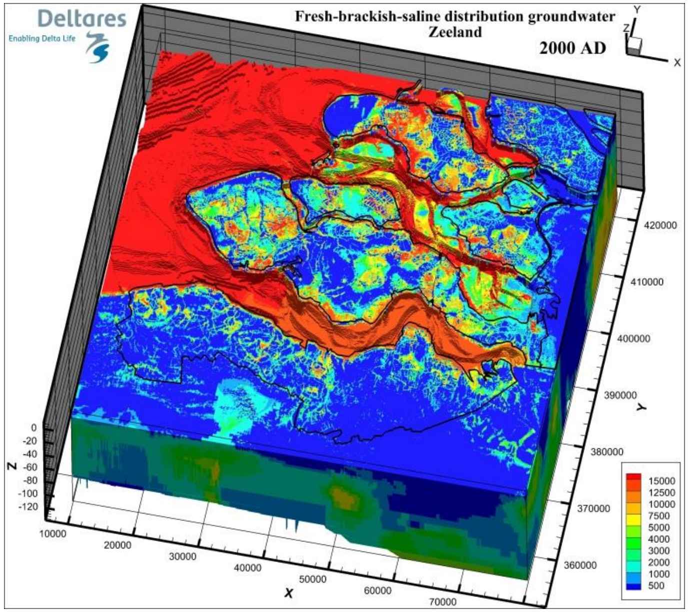
Assess combined effects:
- past land subsidence polders
- sea level rise
- changing recharge pattern
- land subsidence
- changing extraction rates
- adaption measures

Software (MODFLOW family)**:**
SEAWAT, MOCDENS3D
MT3D, iMOD, link NHI, etc.

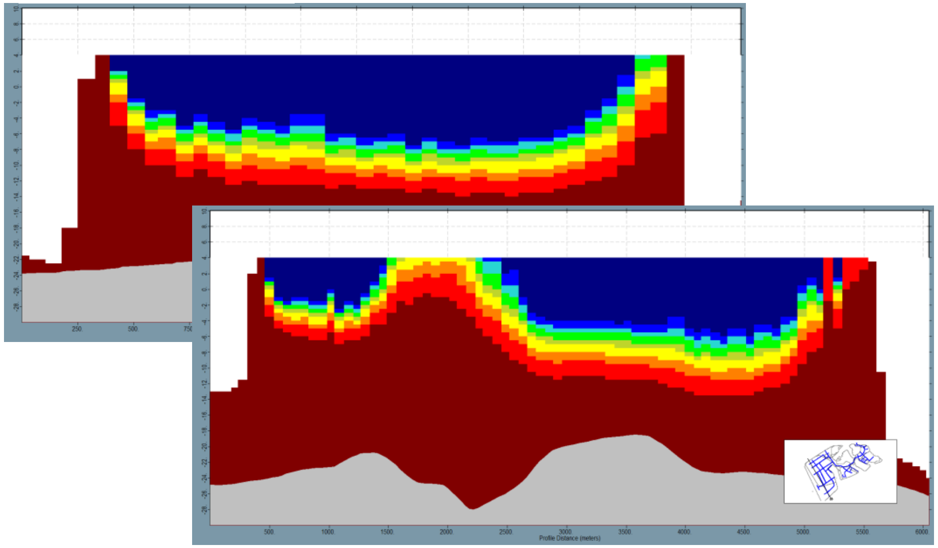


3D REGIONAL COASTAL GROUNDWATER MODEL STUDIES

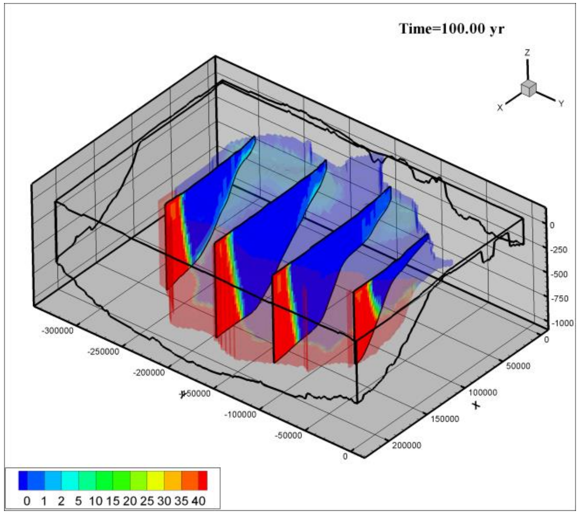
Netherlands, Zeeland



Singapore



Nile Delta, Egypt

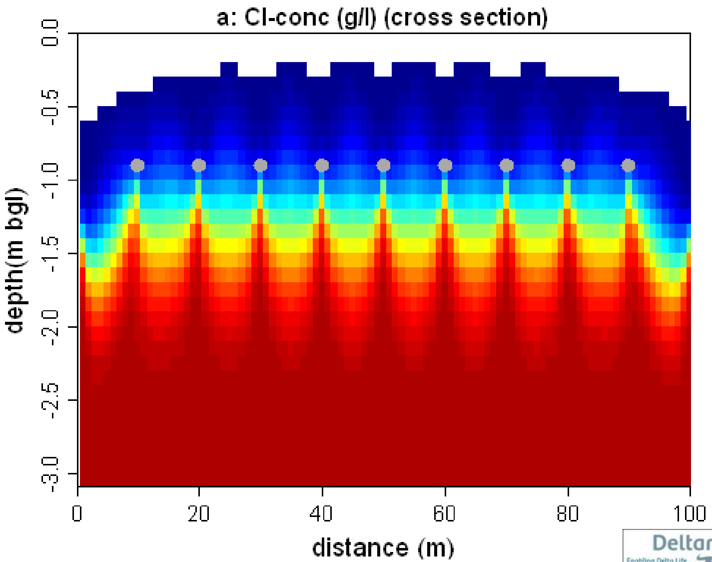


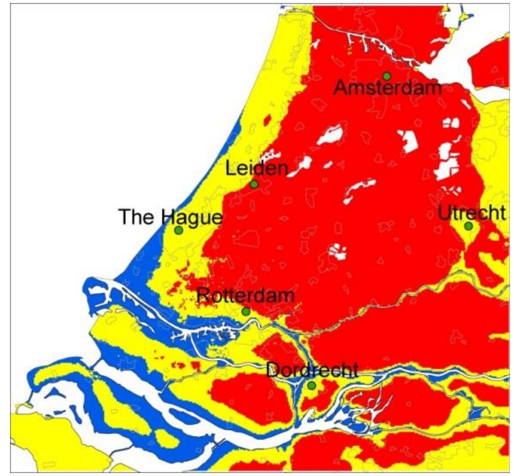
Modelling:
- variable-density groundwater flow, coupled solute transport

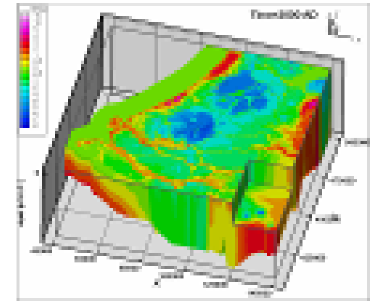
Simulating effects of:
- autonomous processes (change extraction rates)
- sea level rise, changing recharge pattern
- land subsidence

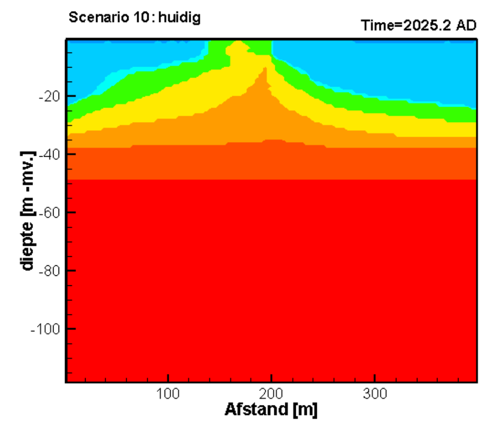
Quantifying:
- hydraulic head
- saline seepage / infiltration
- fresh groundwater resources

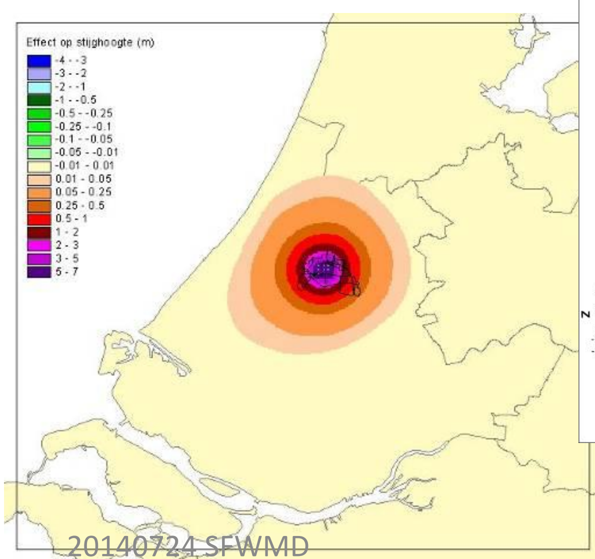
NUMERICAL MODELLING FRESH-SALT GROUNDWATER IN NL

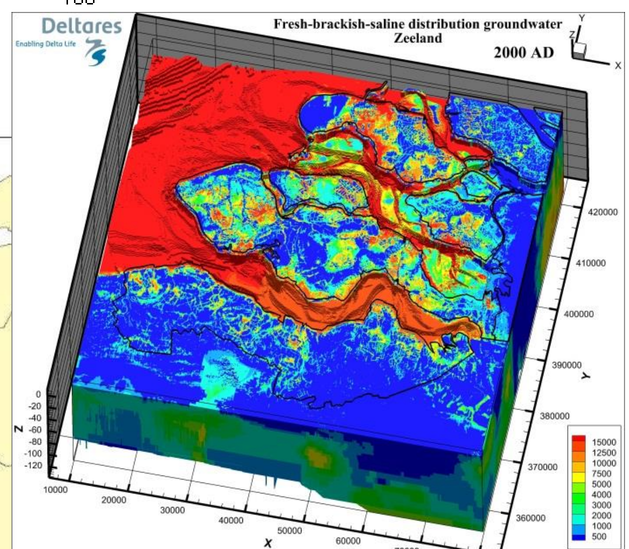


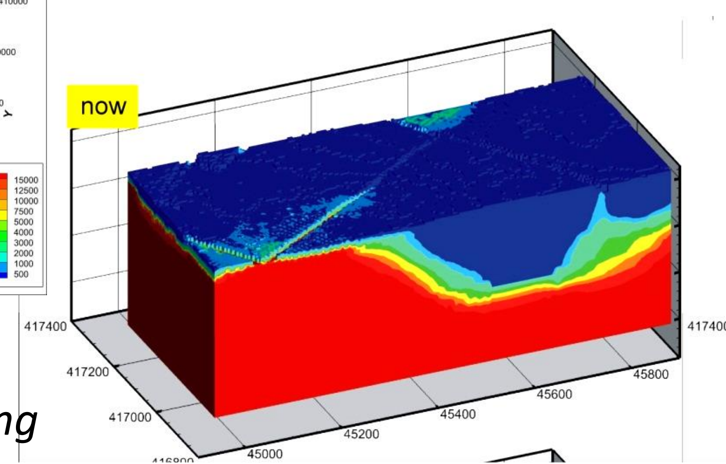












modelling without salt is wrong

TWO APPROACHES OF MODELLING DELTAIC AREAS

2D Conceptual modelling

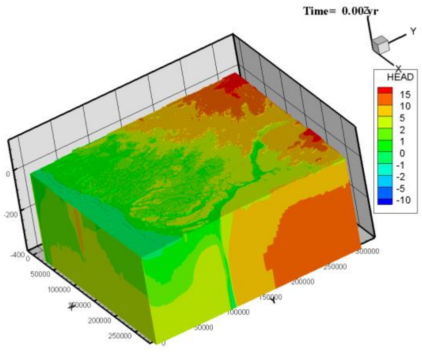
- Improves conceptual understanding of the groundwater system
- Scientific papers

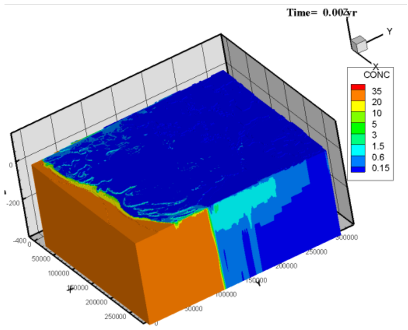
3D Variable-density groundwater flow modelling

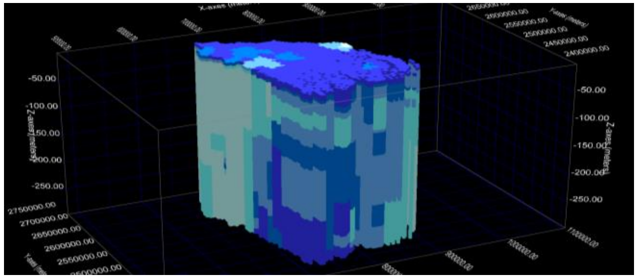
- Often actual situation in the field
- Real problems under pressure
- Focus on case studies with impact analysis

QUESTIONS TO BE ANSWERED

- Where are the present fresh-saline interfaces?
- How will these interfaces evolve in the following decades?
- What is the effect of the extractions in the vertical distribution of the salinity?
- Guiding the positioning of monitoring and data collection
- Guiding the positioning of (new) extraction wells



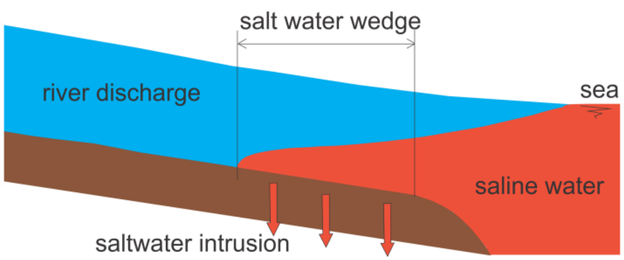




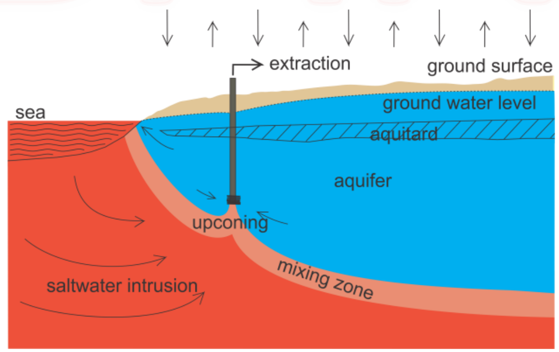
WHY A 3D VARIABLE-DENSITY GROUNDWATER MODEL

- To better **understand** and **visualize** the groundwater dynamics and relevant salinity processes:
  - lateral surface salt water intrusion
  - lateral salt groundwater intrusion
  - vertical up-coning under extractions and low-lying areas
  - infiltration of salt water due to inundations caused by storm surges.
- To **provide** Bangladeshi water managers and universities with an **instrument** for their **mandates** on secure water supply, now and in the future
- To **assess** the impact of **global and climate change** (including the effect of **sea level rise**)
- To give future local models **correct boundary conditions**

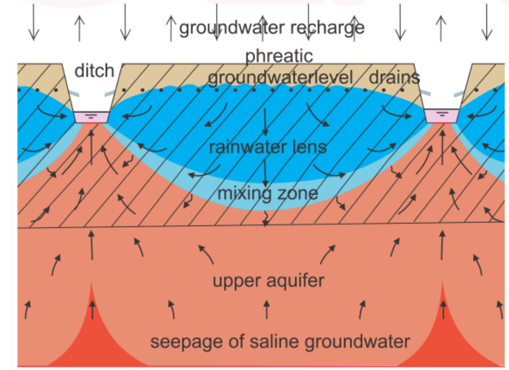
SALINIZATION PROCESSES



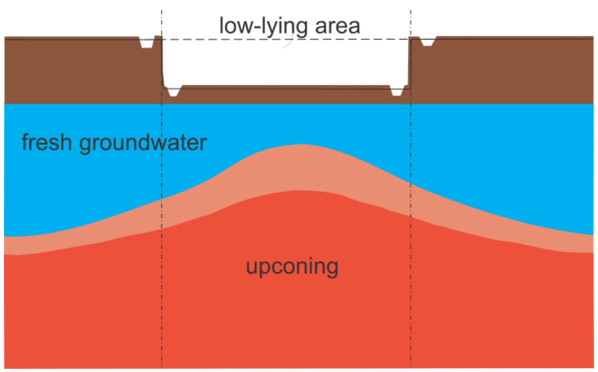
Salt water intrusion
surface water (and groundwater)



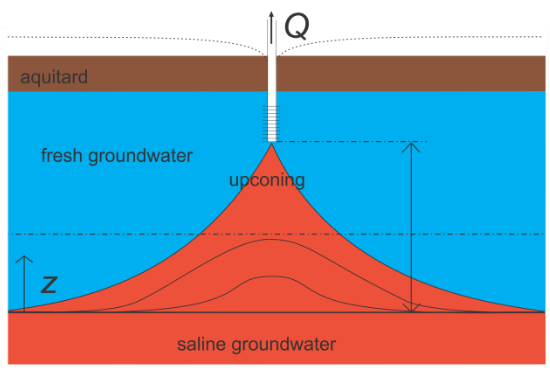
Salt water intrusion
groundwater



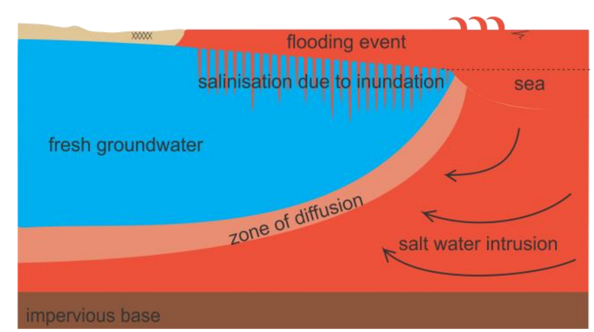
Shallow freshwater lenses
and saline seepage



Upconing low-lying area



Upconing under
groundwater extraction



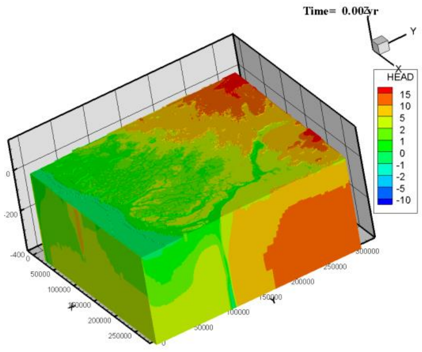
Shallow vertical salt water
intrusion after flooding
event (storm surge)

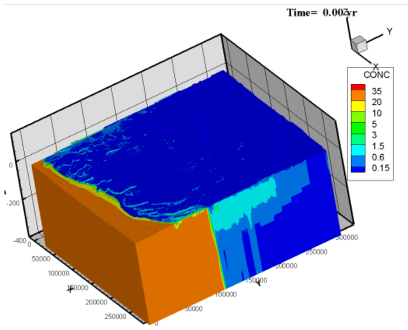
COMPUTER CODE

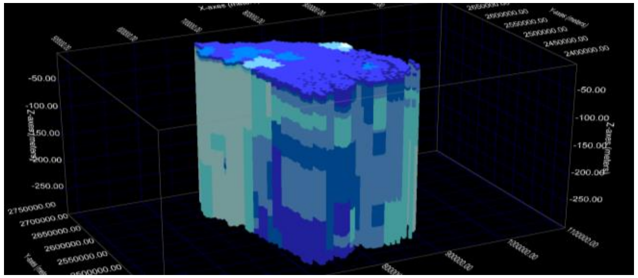
- 3D numerical variable-density groundwater flow and coupled salt transport model of the central coastal zone of Bangladesh

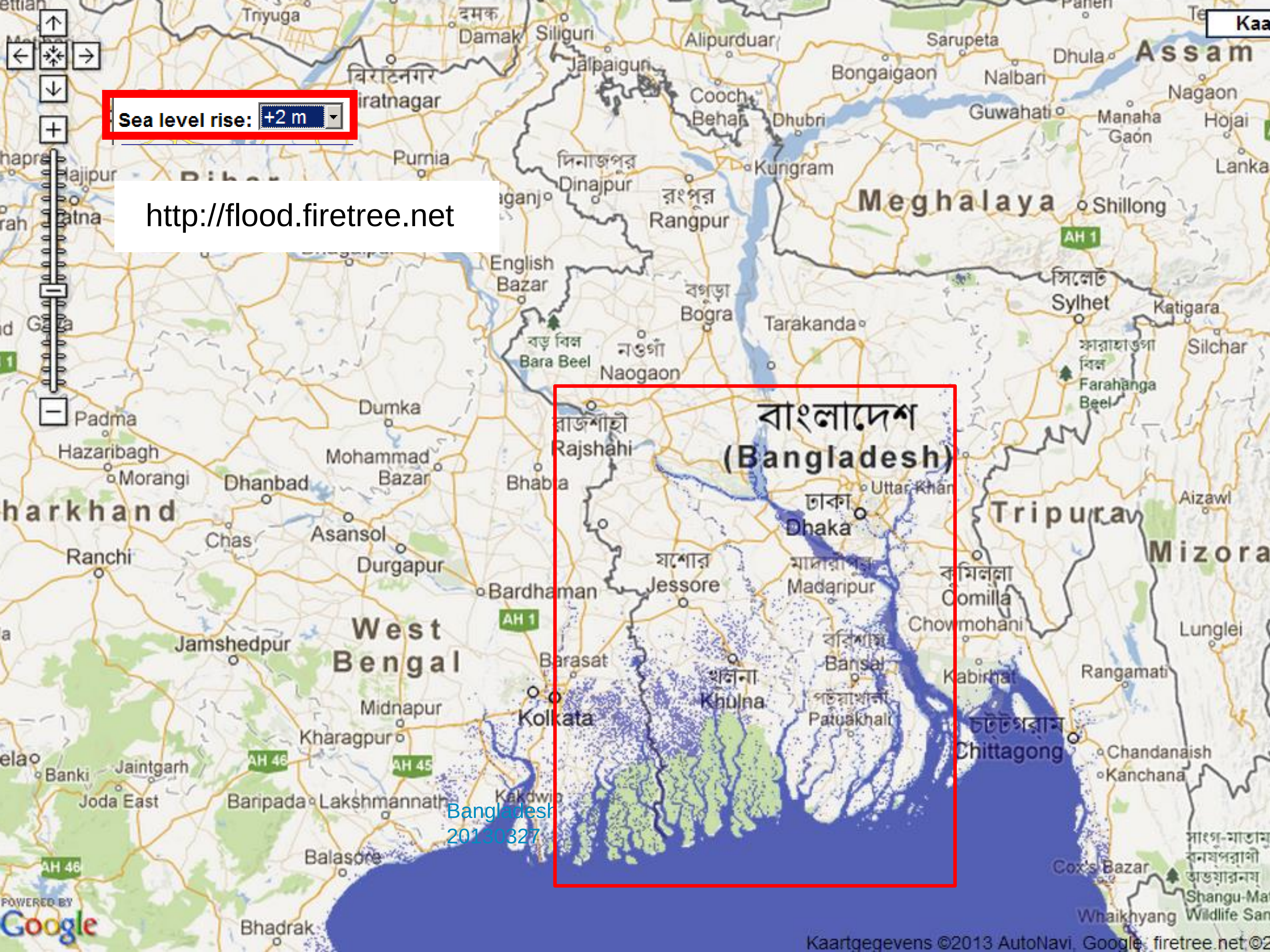
- Built in SEAWAT (="MODFLOW-MT3DMS-density")

- Extended with iMOD functionality









Sea level rise: +2 m
http://flood.firetree.net
বাংলাদেশ
(Bangladesh)
Bangladesh
20130327
Triyuga
Damak
Siliguri
Jalpaiguri
Alipurduar
Sarupeta
Dhula
Assam
Bongaigaon
Nalbari
Nagaon
Cooch Behar
Dhubri
Guwahati
Manaha Gaon
Hojai
iratnagar
Purnia
Dinajpur
Kurigram
Lanka
Rangpur
Meghalaya
Shillong
AH 1
English Bazar
Sylhet
Katigara
Bogra
Tarakanda
Silchar
Bara Beel
Naogaon
Farahanga Beel
Padma
Dumka
Rajshahi
Hazaribagh
Mohammad Bazar
Morangi
Dhanbad
Bhabla
Uttar Khan
Dhaka
Aizawl
harkhand
Tripura
Chas
Asansol
Mizora
Ranchi
Durgapur
Jessore
Madaripur
Comilla
Bardhaman
Chowmohani
West Bengal
Lunglei
Jamshedpur
Barasat
Barisal
Kabirhat
Rangamati
Khulna
Patuakhali
Kolkata
Midnapur
Chittagong
Kharagpur
Chandanaish
Banki
Jaintgarh
AH 46
AH 45
Kanchana
Joda East
Baripada
Lakshmannath
Kakdwip
Balasore
Cox's Bazar
Bhadrak
Whaikhyang
POWERED BY Google
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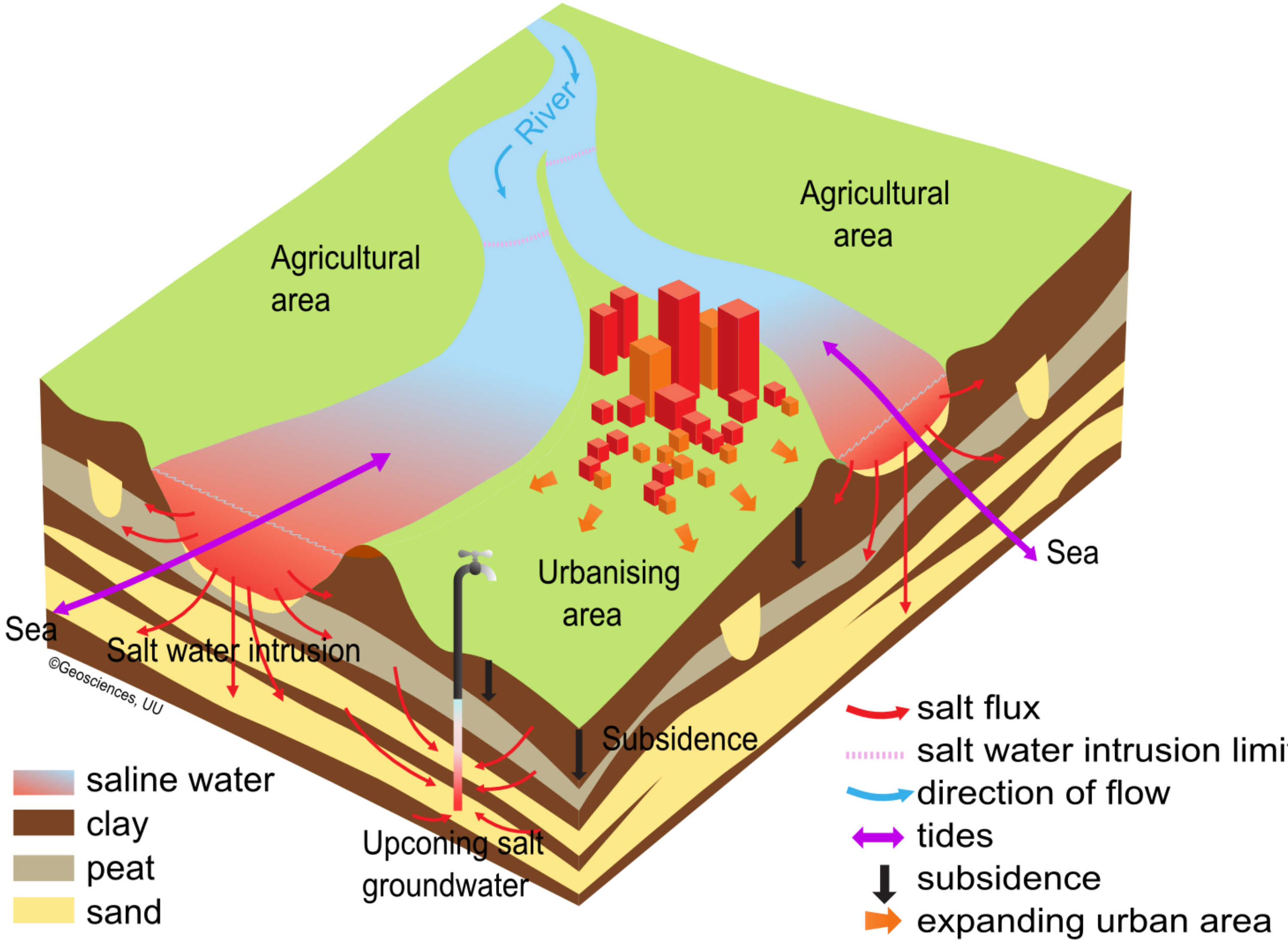
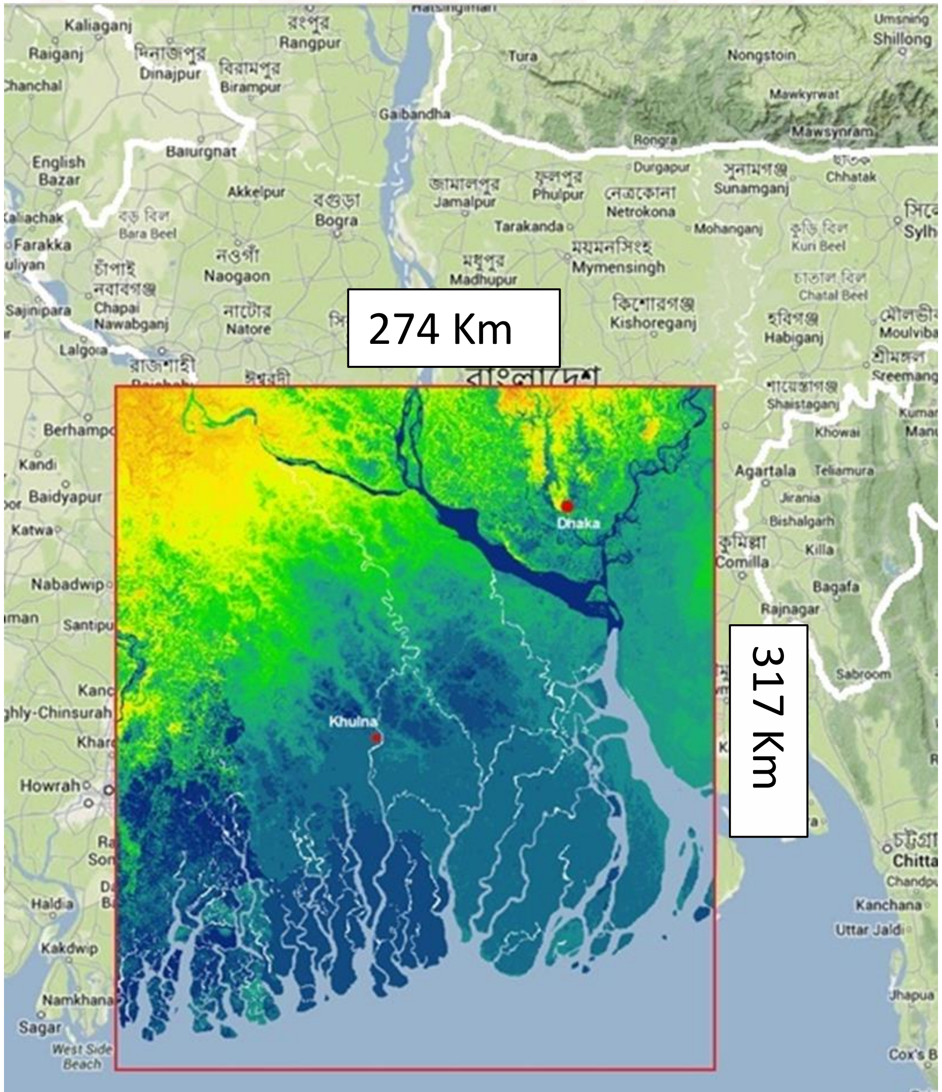
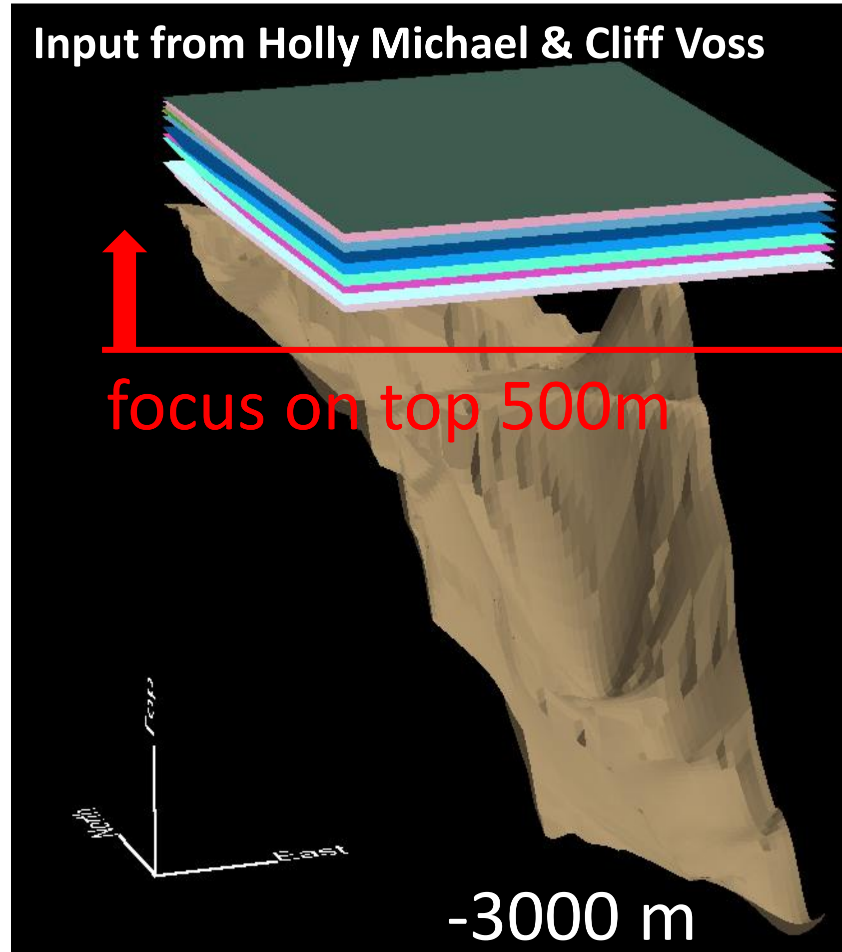
SALINIZATION PROCESSES IN THE COASTAL ZONE



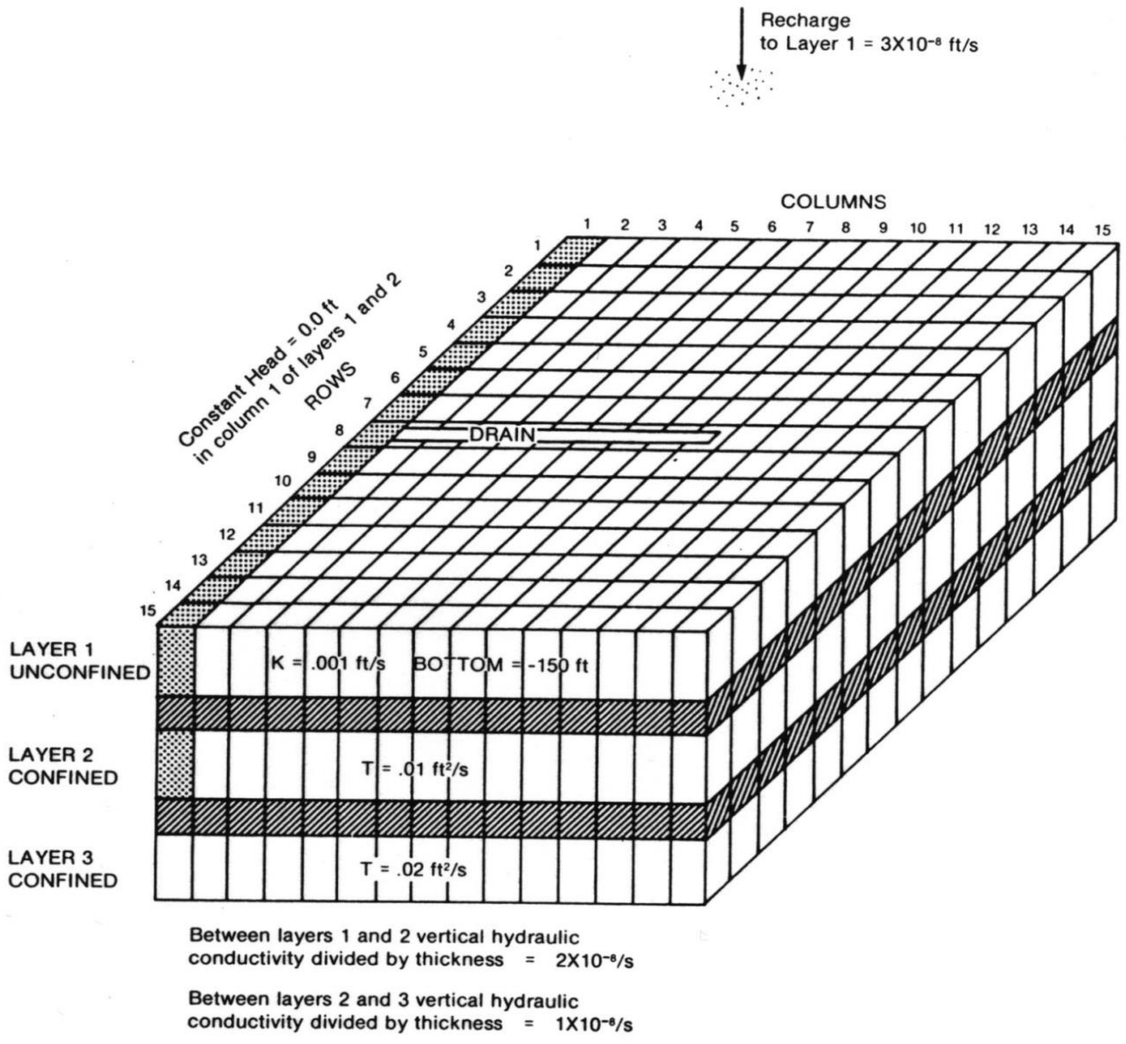
MODEL GEOMETRY: MODEL EXTENT



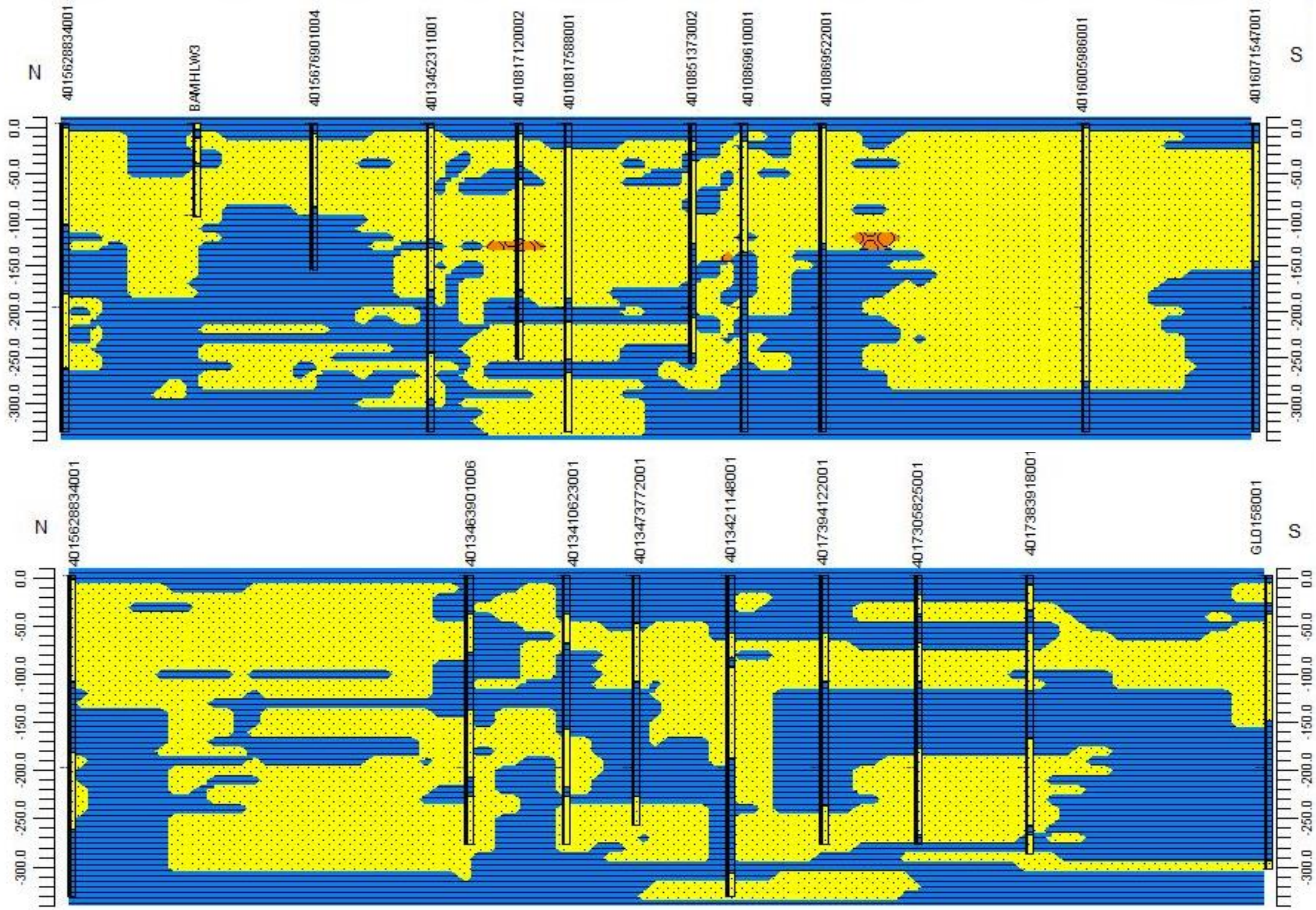
Bottom boundary: Boka Bil formation hydrological base (no flow)

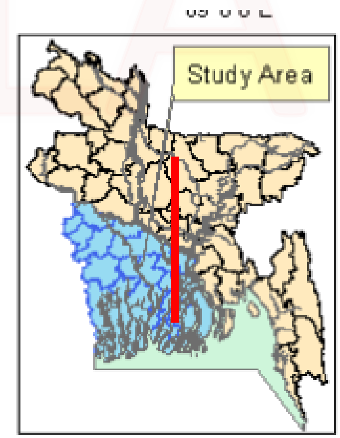


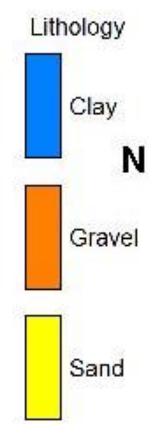
THE MODFLOW GRID



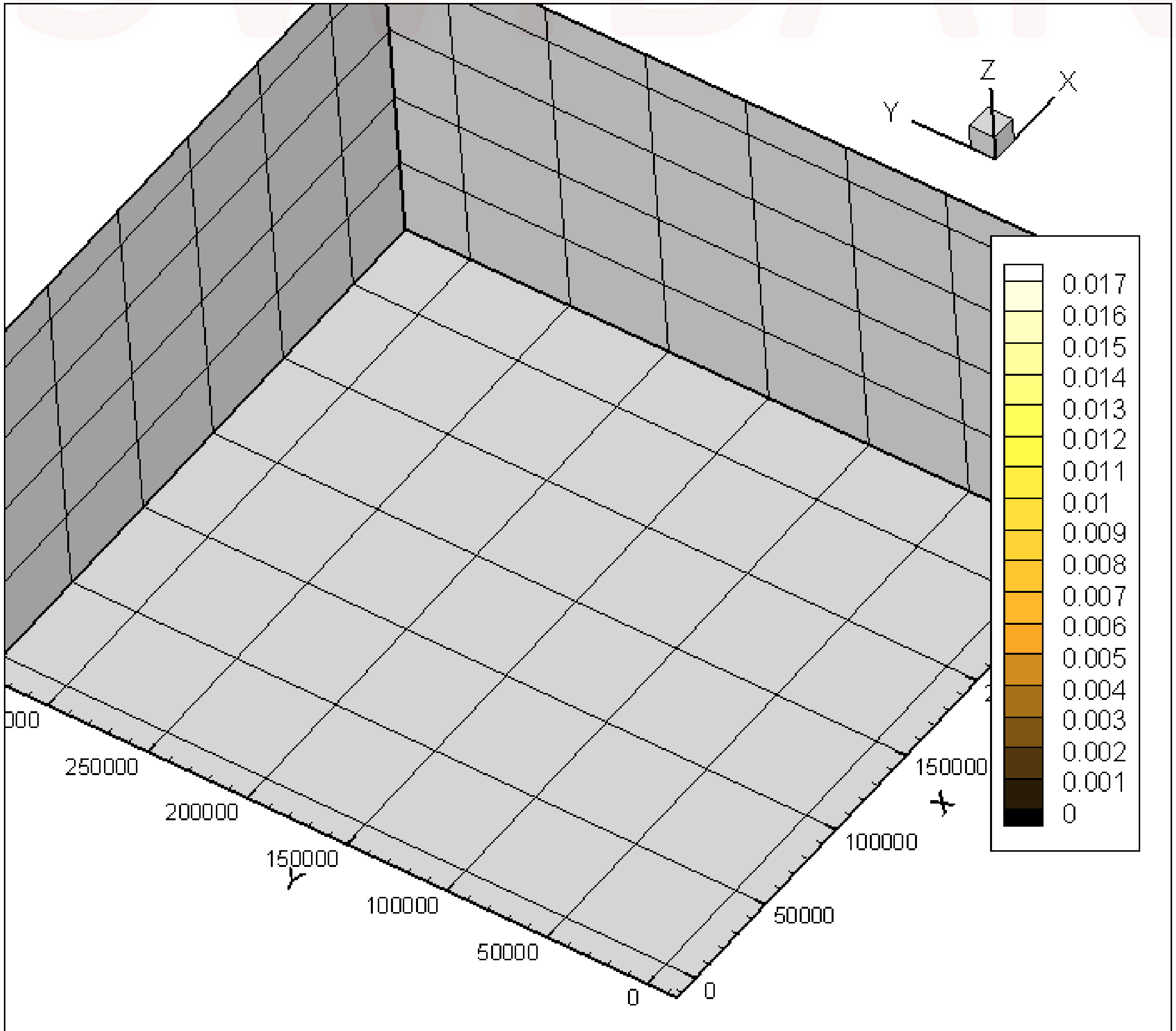
N-S CROSS-SECTIONS OF BAGERHAT, IT IS A PATHY COMPLEX GEOLOGIC SYSTEM

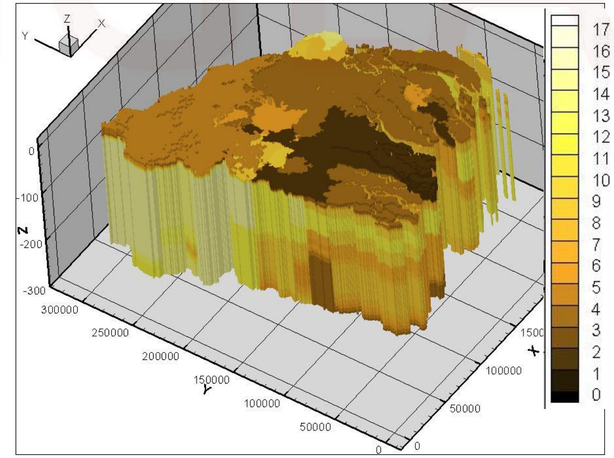




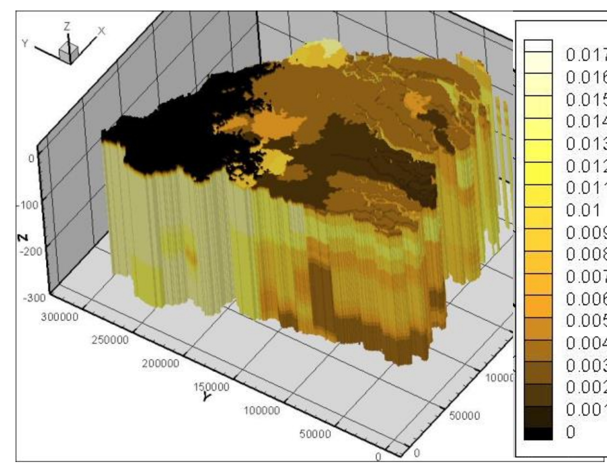


GEOLOGY





K_h=hor. cond. [m/d]

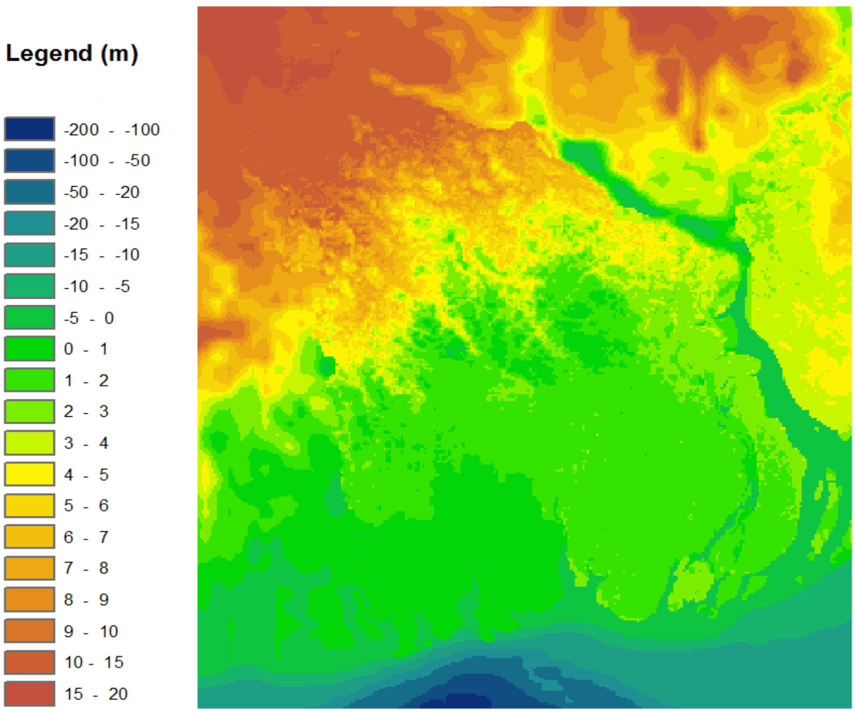


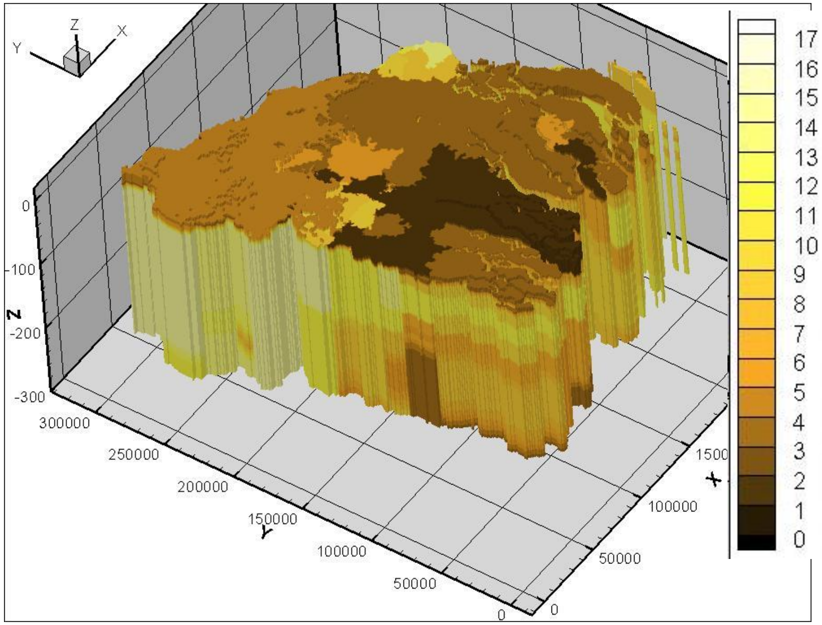
K_v=vert. cond. [m/d]

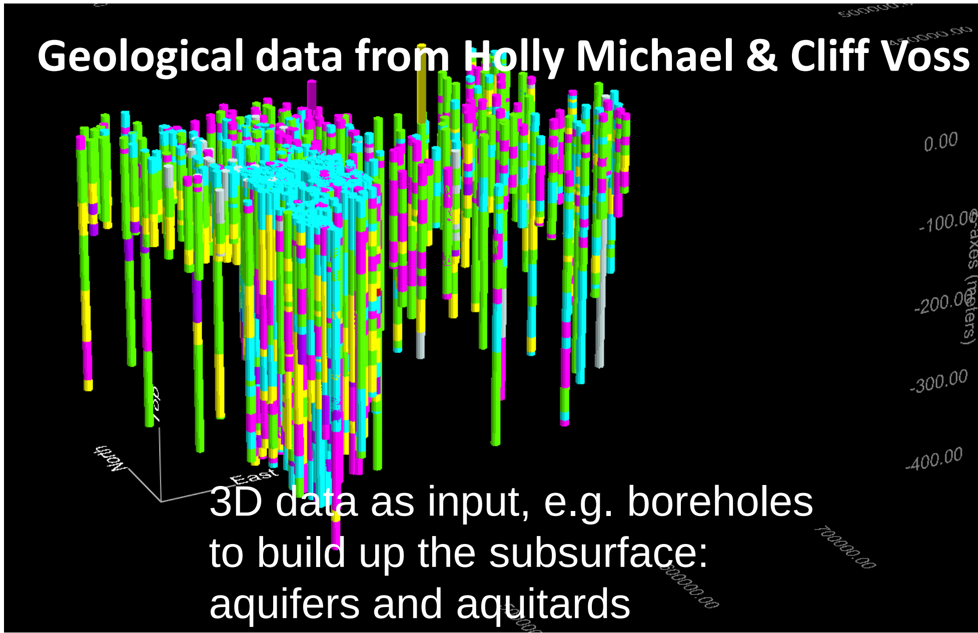
Source: Dr. Bashar

SURFACE LEVEL (DEM)

SUBSURFACE MODEL



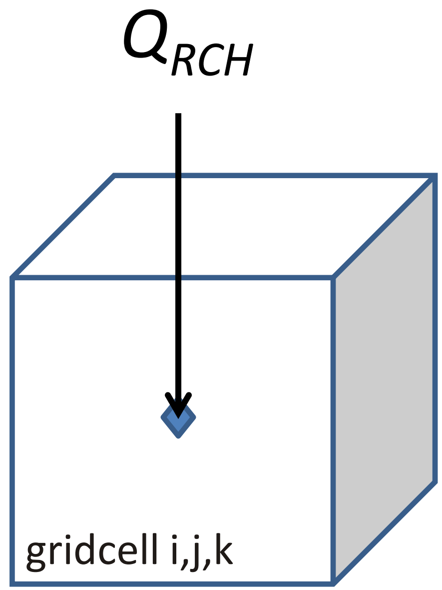




Sources:
CEGIS, BGS, DPHE, 2001

MODELLING RECHARGE

Recharge: the RCH package



$$Q_{RCH} = Q_{i,j,k}$$

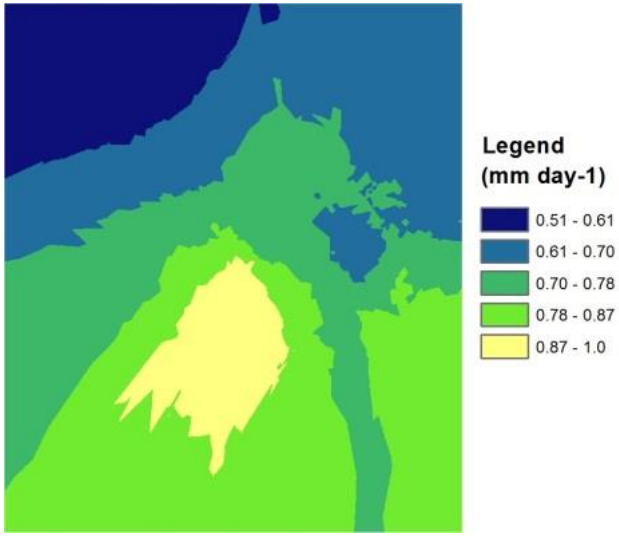
So 1 map needed:
Map of recharge rates

NET GROUNDWATER RECHARGE

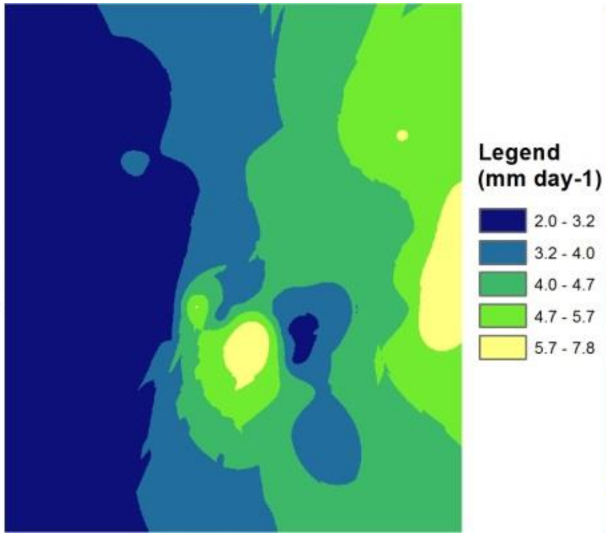
- Interpolation measured data (source CEGIS):
- 4 monitoring stations for evapotranspiration
- 96 monitoring stations for precipitation
- ±1990 – 2011

Data averaged per stress period:

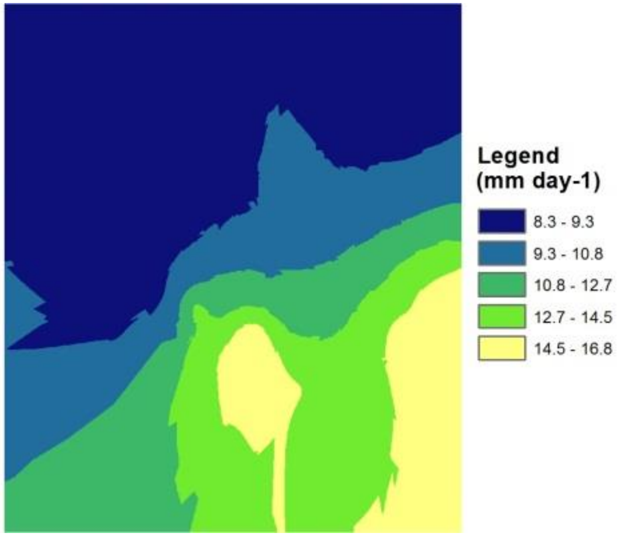
1. Cold and dry
Nov - Feb



2. Hot and humid
Mar - May

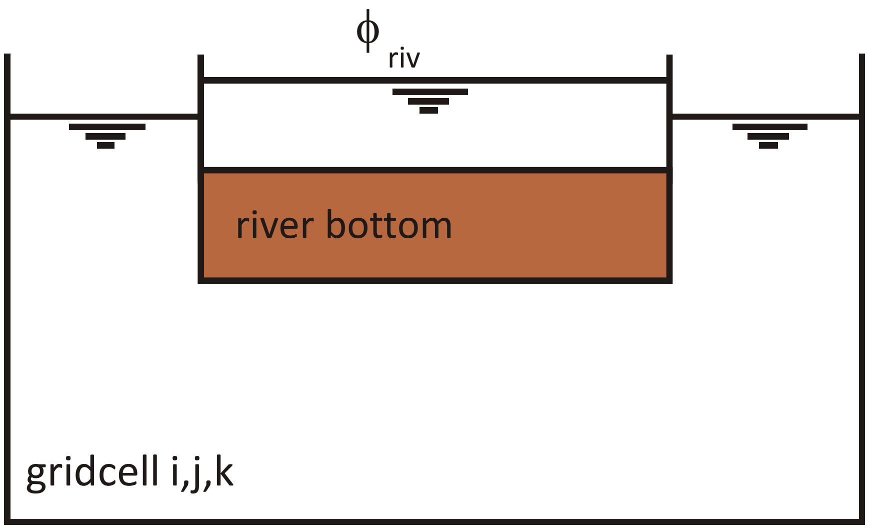


3. Monsoon season
June - October

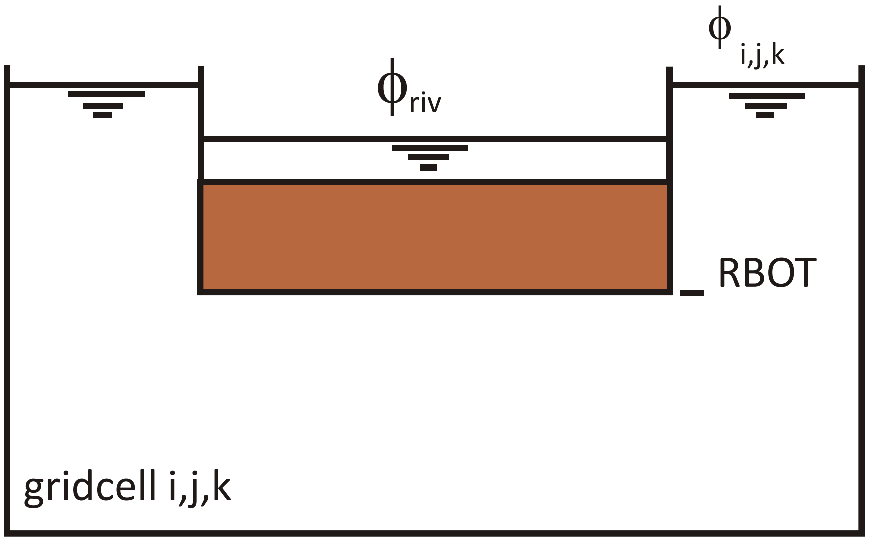


MODELLING SURFACE WATER: RIVER PACKAGE

river loses water



river gains water



$$Q_{riv} = C_{riv}(\phi_{riv} - \phi_{i,j,k})$$

Special case: if $\phi_{i,j,k}$ < RBOT, then

$$Q_{riv} = C_{riv}(\phi_{riv} - RBOT)$$

So 3 maps needed:

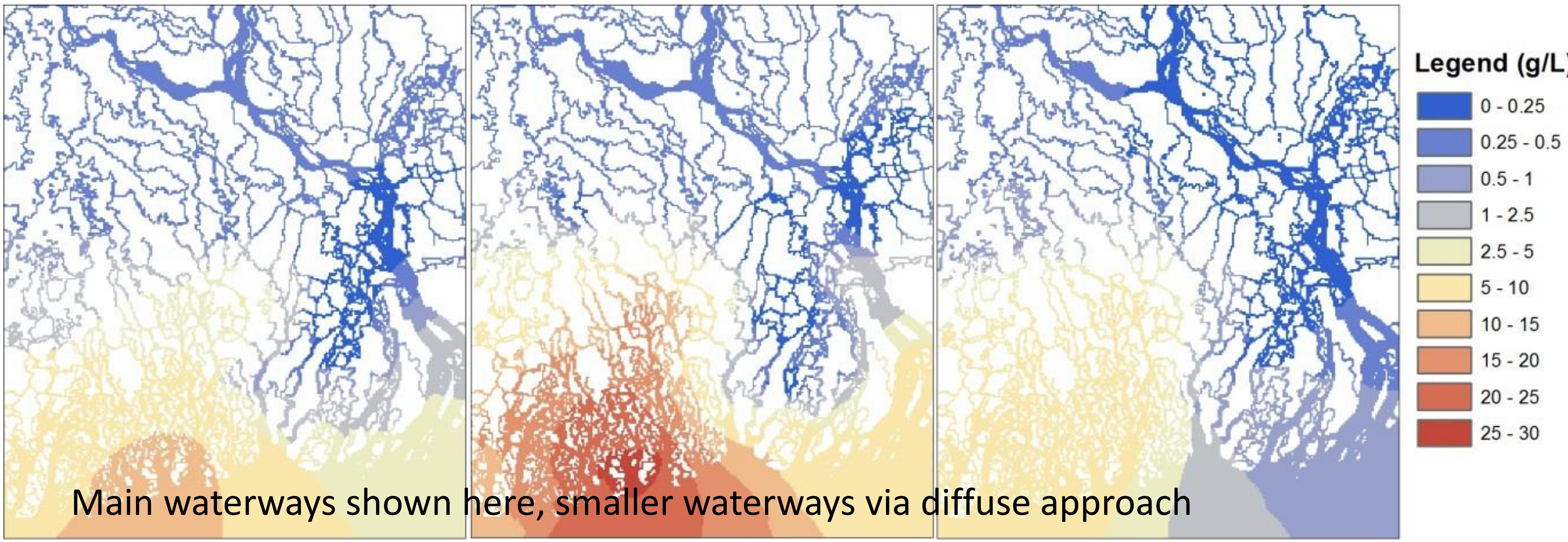
1. Map of river stages
2. Map of river conductances
3. Map of river bottoms

SURFACE WATER: SALINITY LEVELS IN RIVER PACKAGE

1. Cold and dry
Nov - Feb

2. Hot and humid
Mar - May

3. Monsoon season
Jun - Oct

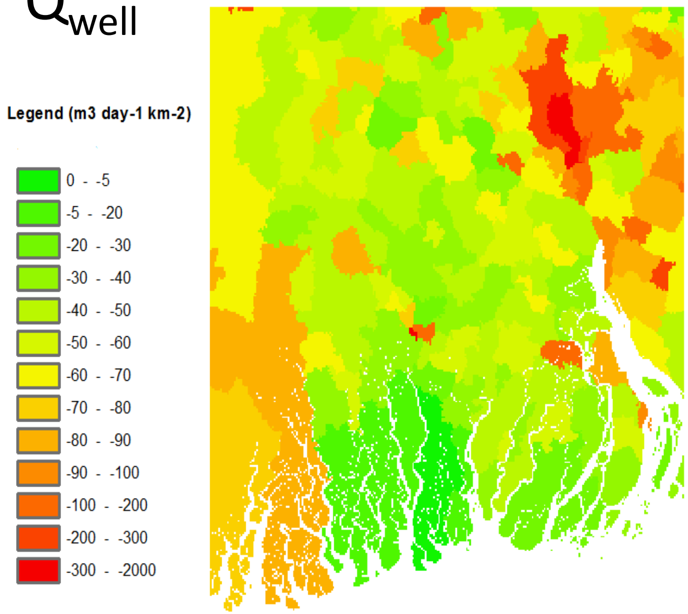


Main waterways shown here, smaller waterways via diffuse approach

Source:
Daily water level data from BWBD (126 locations on river levels)
CEGIS, completed by data from DIVA-GIS (84 monitoring stations on salinity values)

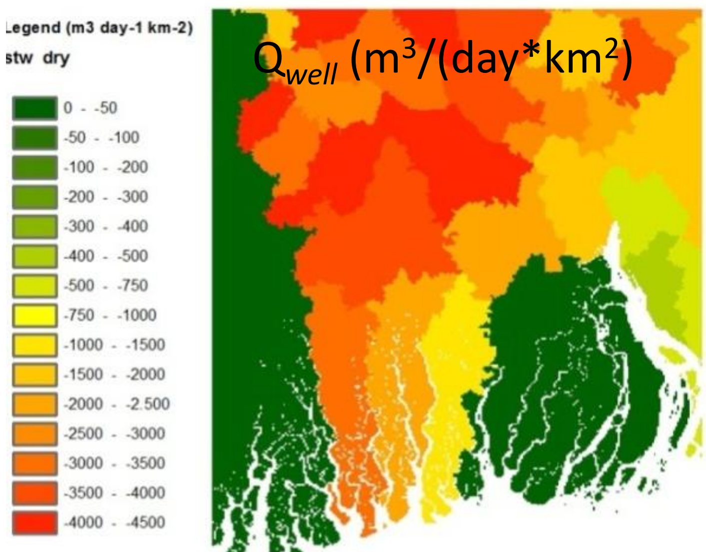
GROUNDWATER EXTRACTIONS

Q_{well}



Domestic&Industrial

- based on population size (cf Michael and Voss, 2009)
- total (domestic + industrial) demand 50 L/day per capita (WARPO, 2000)
- assumed constant throughout the year



shallow, dry

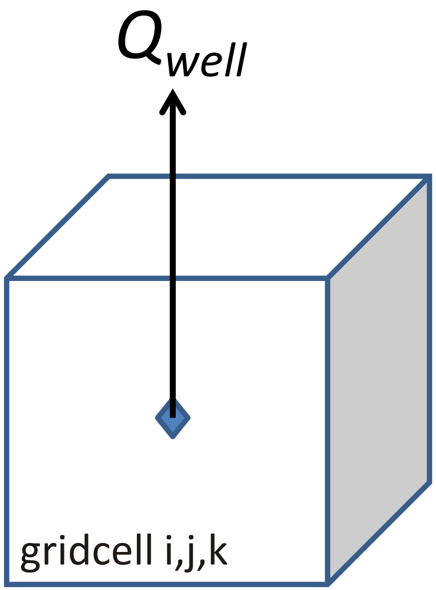
Irrigation for agricultural purposes

- known is area per irrigation type, on district level
- distinction between wet season and dry season
- irrigation Shallow Tube Well : 10-60m depth
- irrigation Deep Tube Well: 60-100m depth

Source: depth based on the well data of DPHE

MODELLING RECHARGE

Extractions: the Well package



$$Q_{wel} = Q_{i,j,k}$$

So one map needed:
Map of well locations with extraction rates

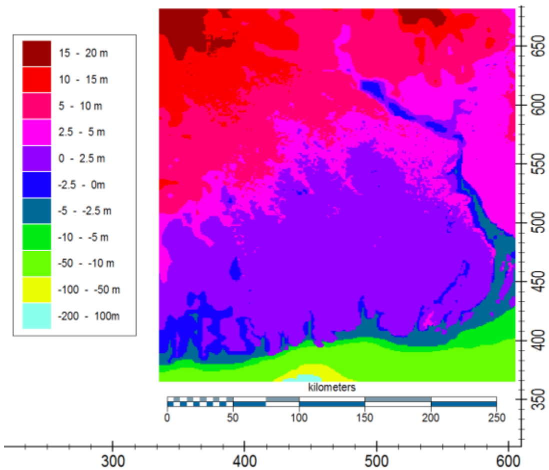
Domestic and Industrial

$$Q_{well}\ (m^3/(day*km^2)) = \frac{\text{Population size * growth rate* Water demand}}{\text{Upazila surface area}}$$

Agricultural

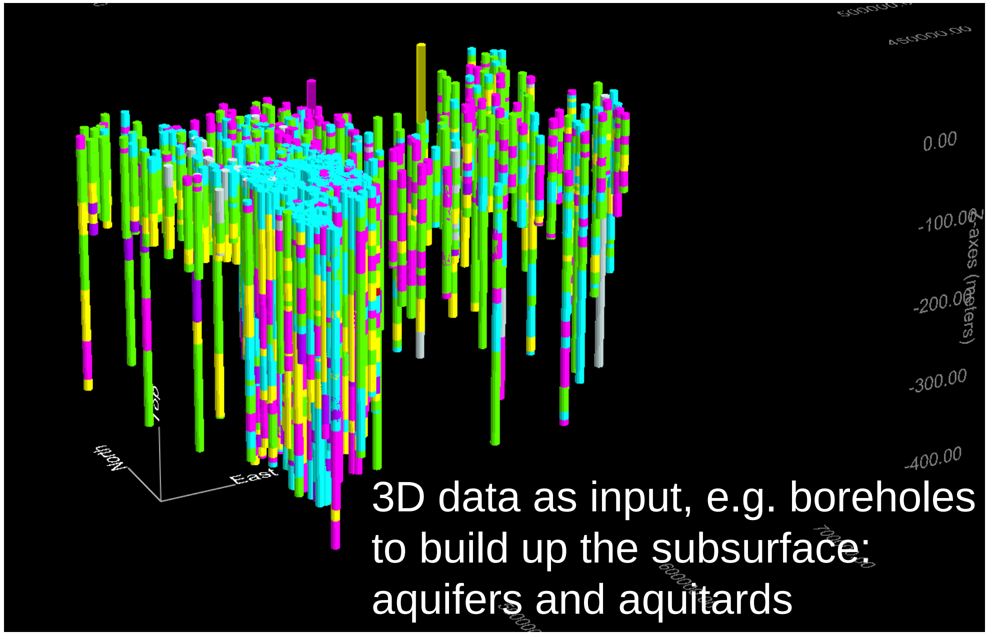
$$Q_{well}\ (m^3/(day*km^2)) = \frac{\text{Irrigated area * withdrawal rate}}{\text{district surface area}}$$

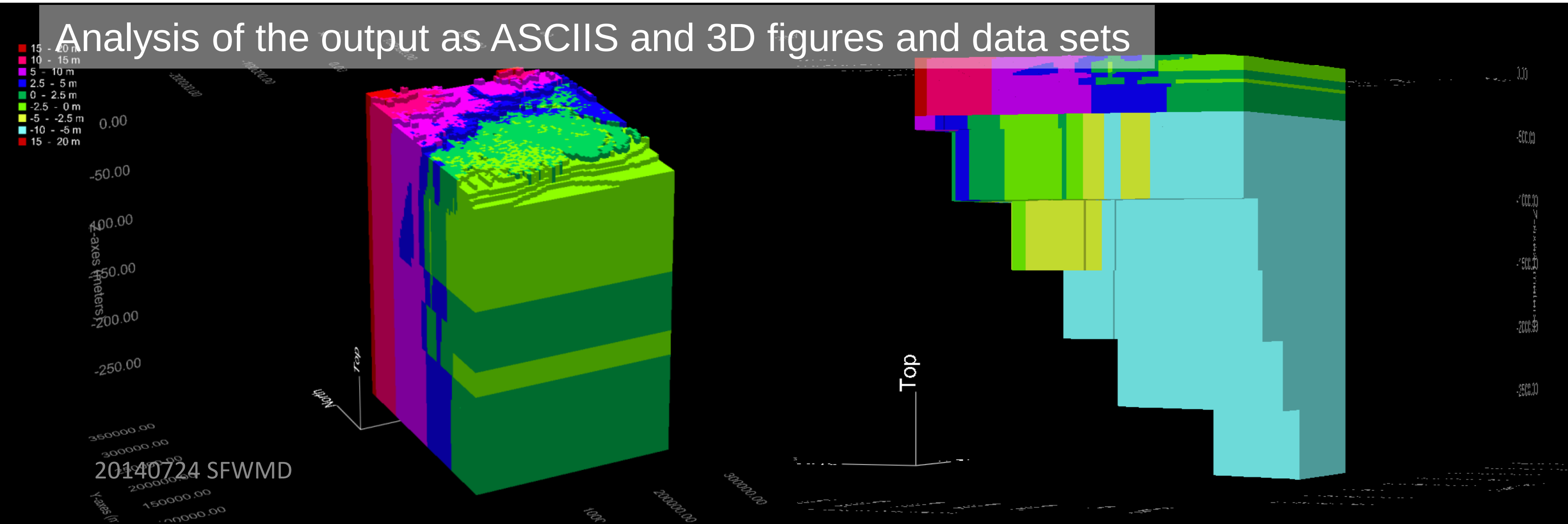
iMOD-SEAWAT TO BUILD A 3D VARIABLE-DENSITY GRW. MODEL



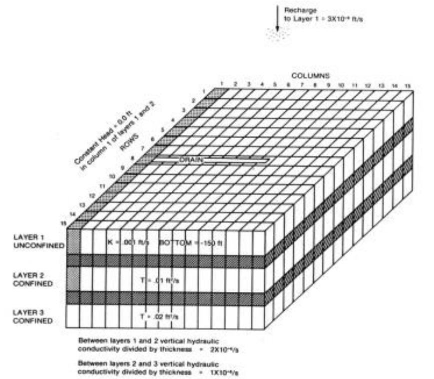
ASCII'S as input

E.g. surface elevation



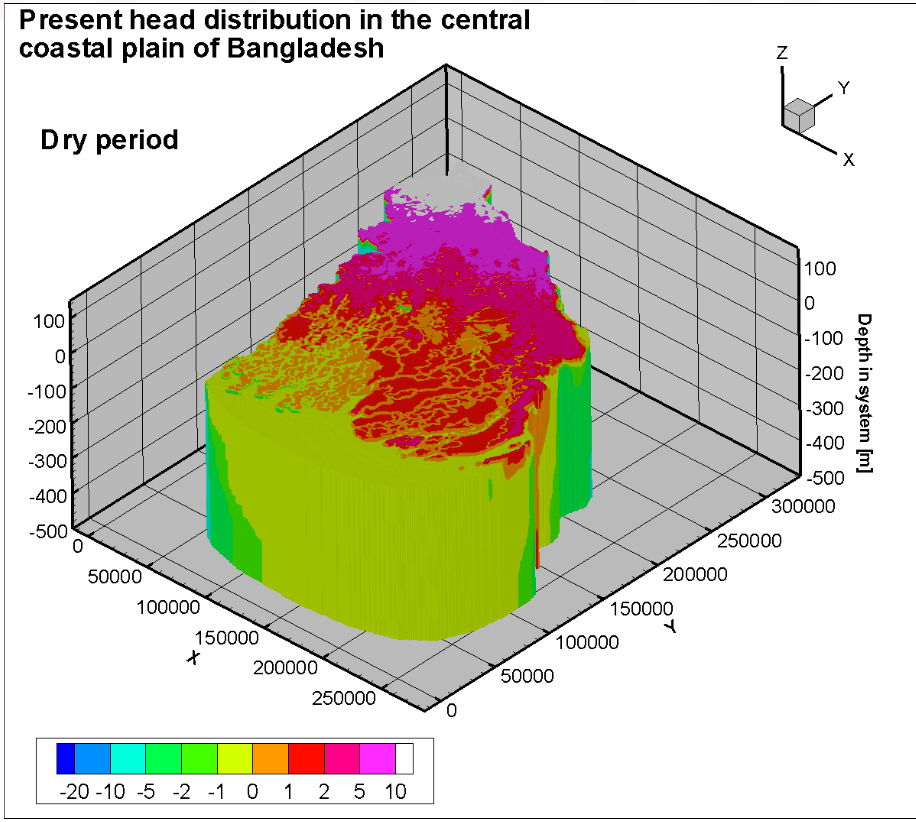


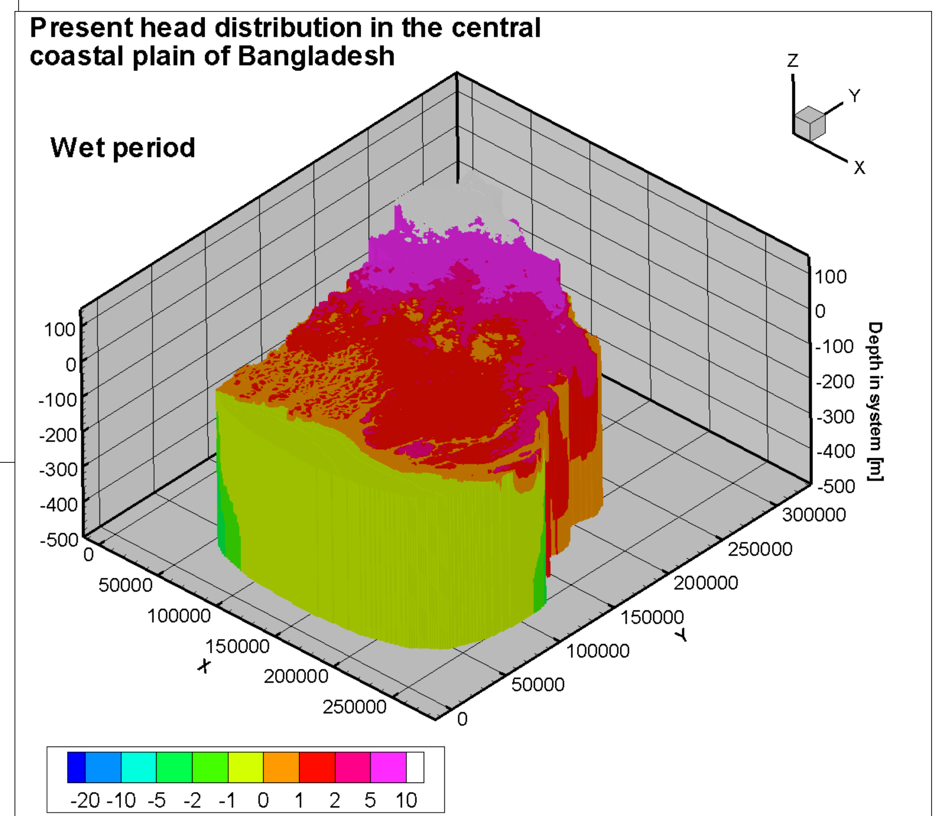
MASS BALANS GROUNDWATER



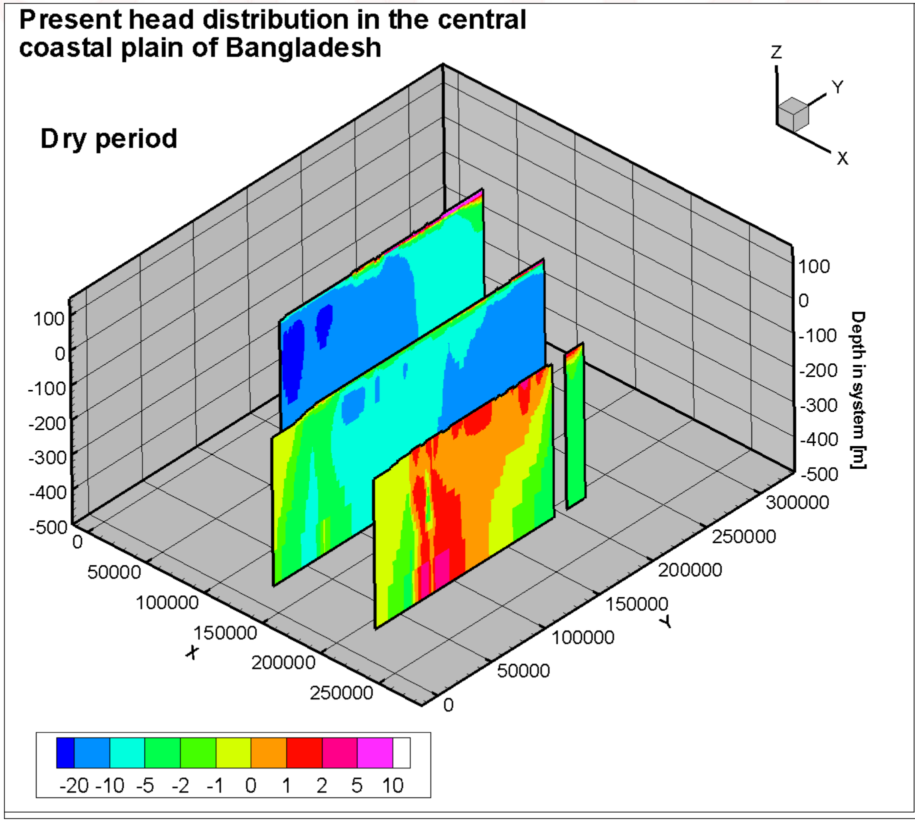
IN	DRY SEASON	WET SEASON
via boundaries	2%	0%
via wells	0%	0%
via river	98%	0%
via recharge	0%	100%
OUT		
via boundaries	0%	1%
via wells	54%	4%
via river	0%	95%
via evapotranspiration	46%	0%

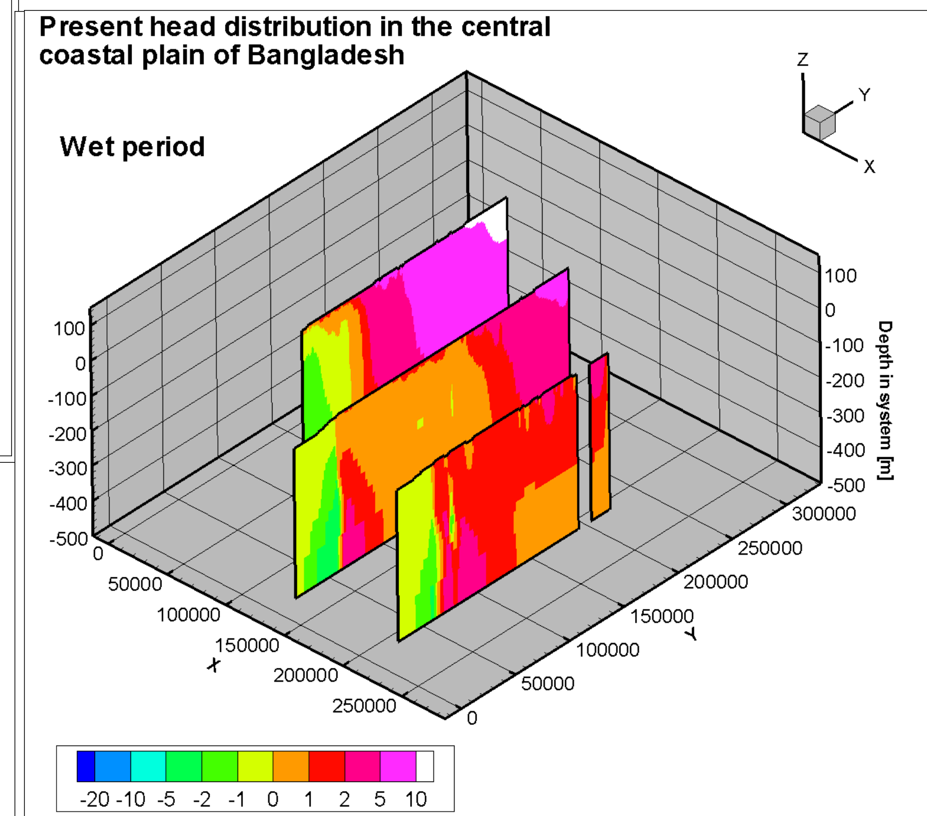
MODEL RESULTS: HEADS



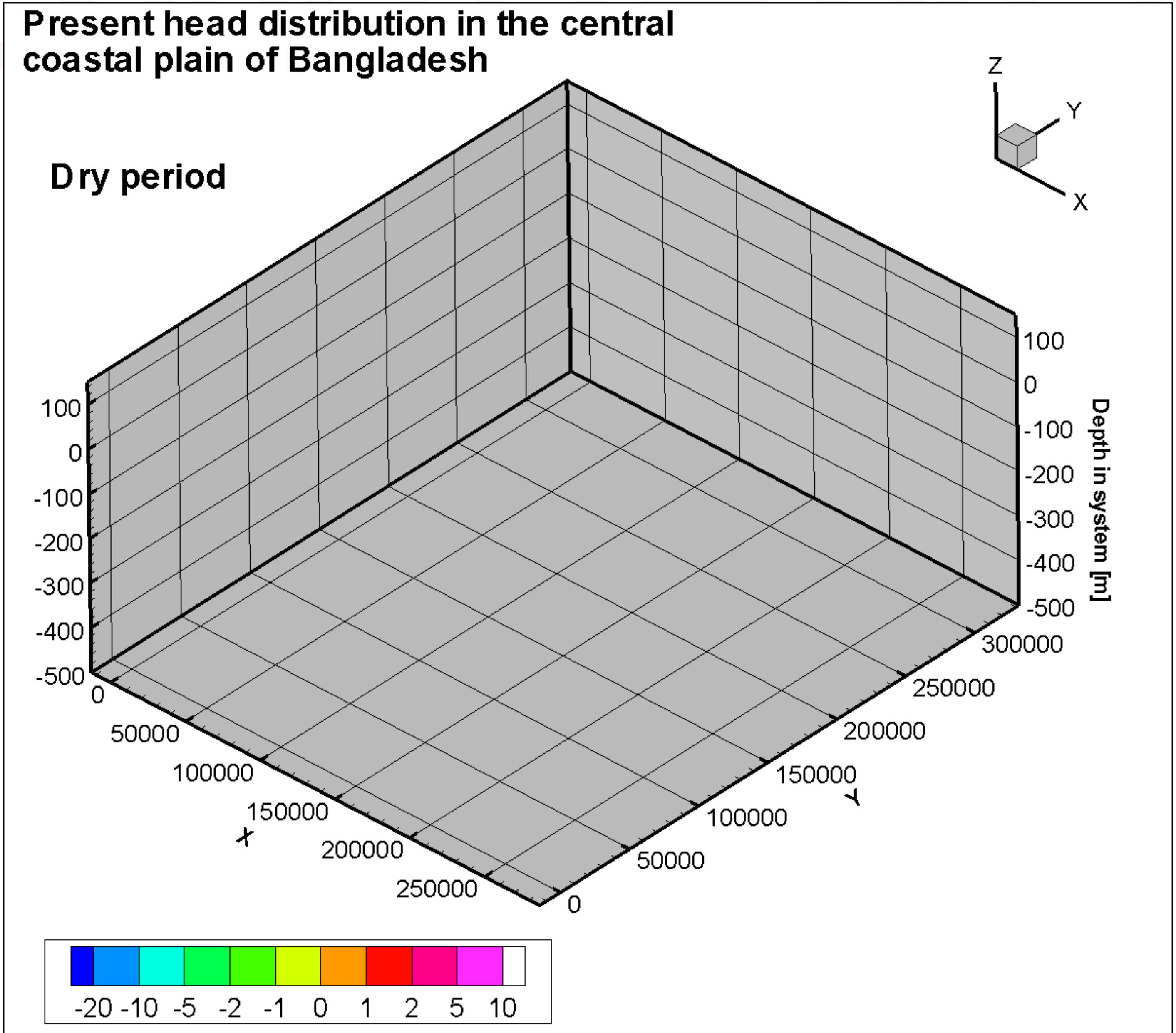


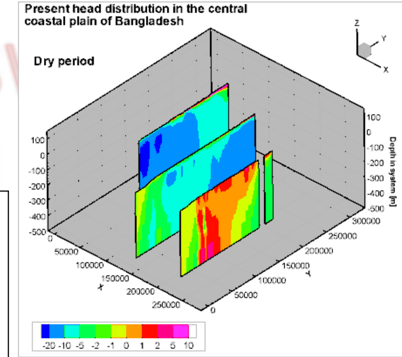
MODEL RESULTS: HEADS



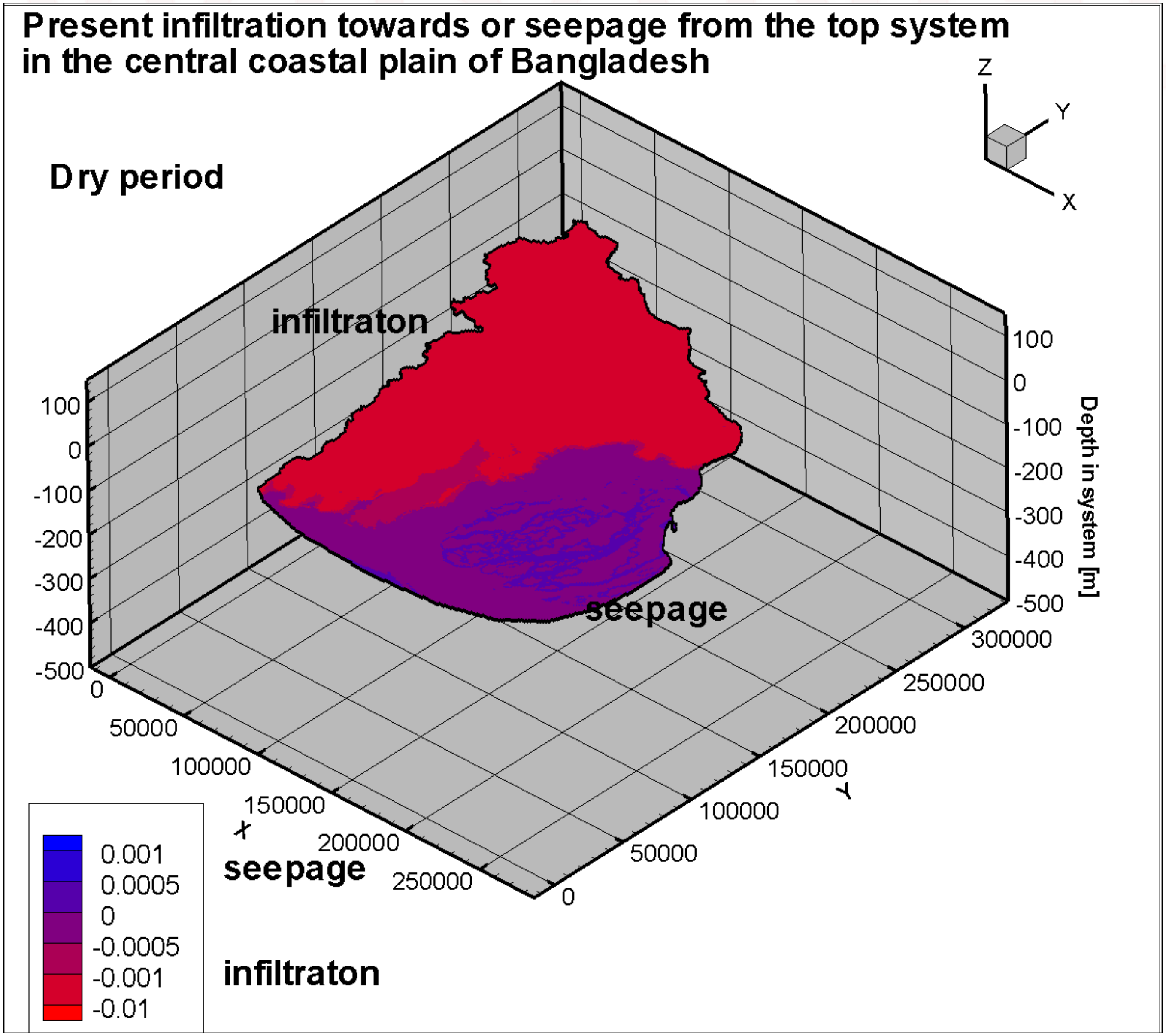


MODEL RESULTS: HEADS

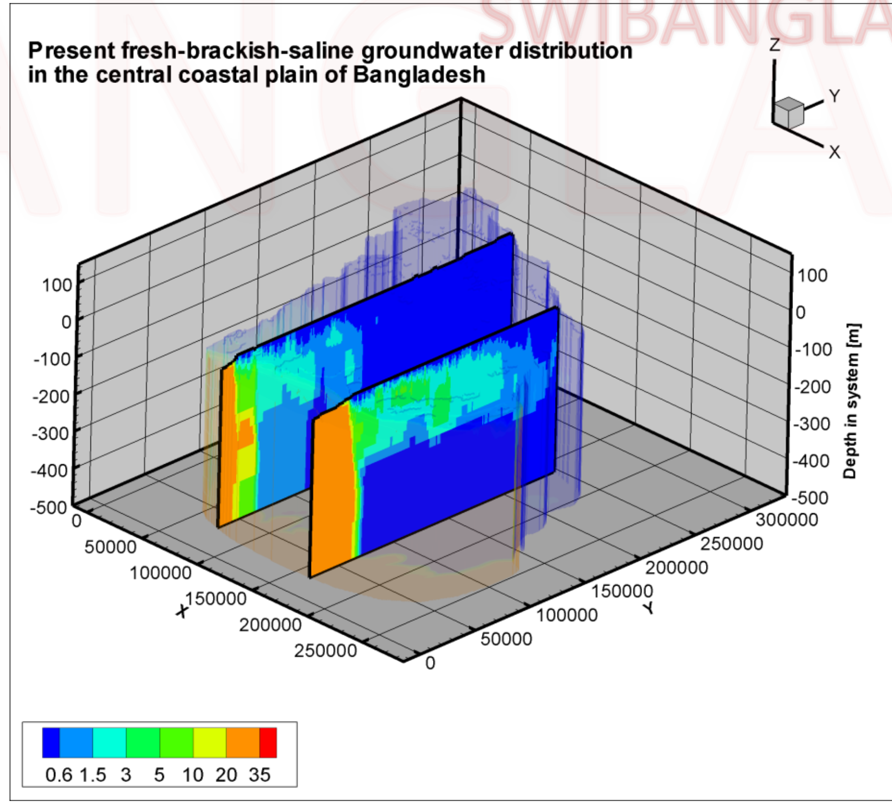


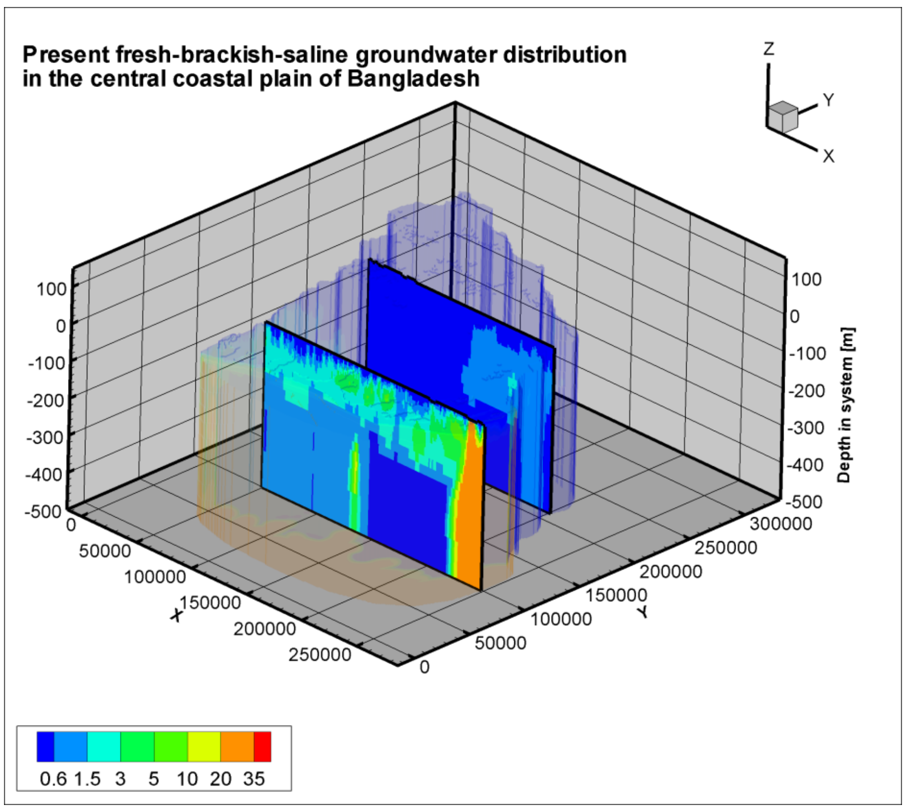


MODEL RESULTS: SEEPAGE/INFILTRATION

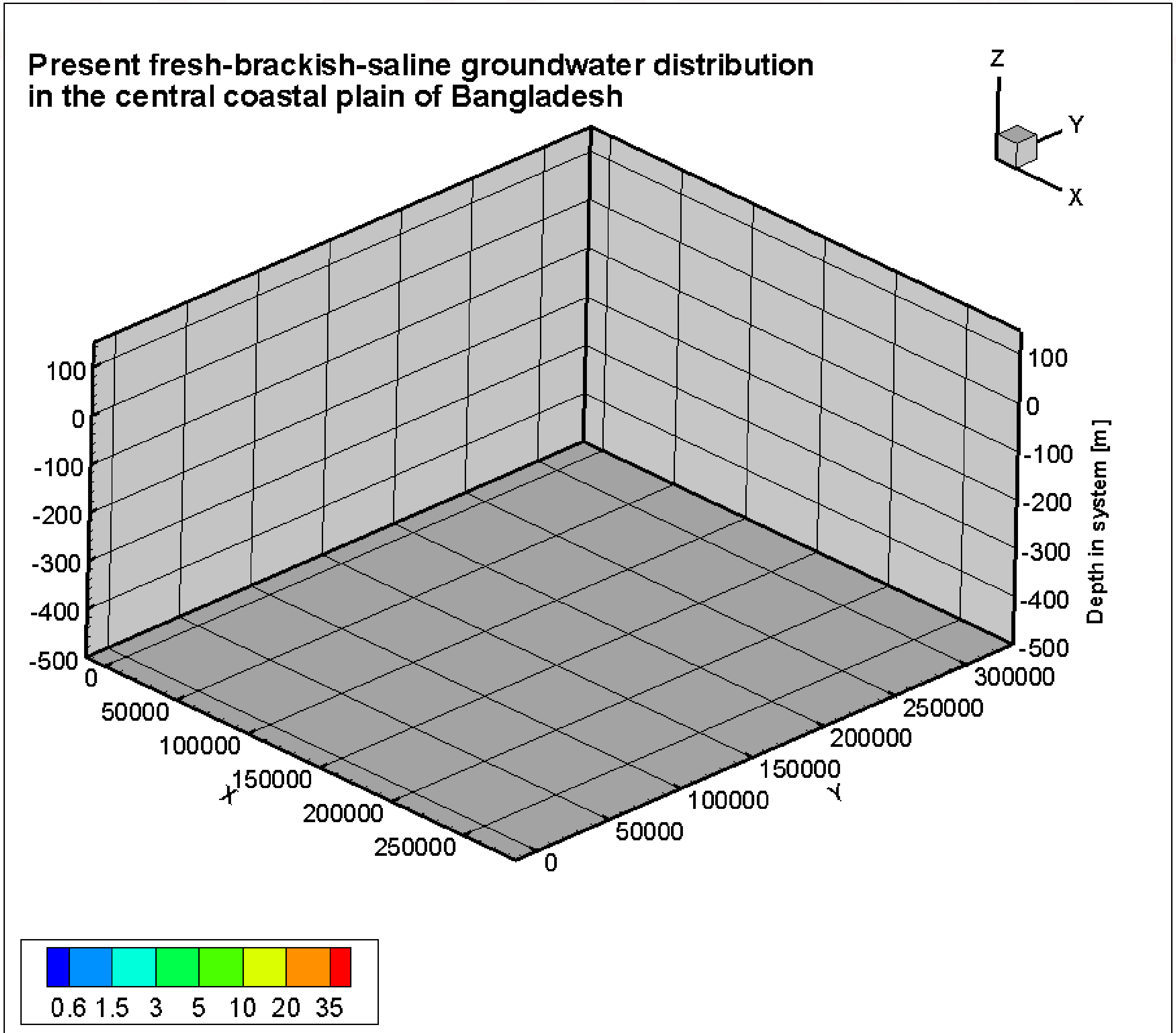


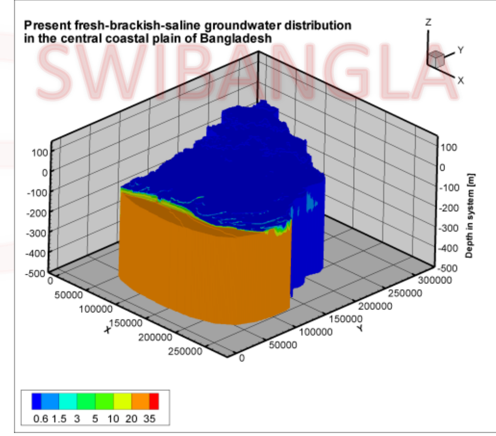
MODEL RESULTS: 3D-SALINITY



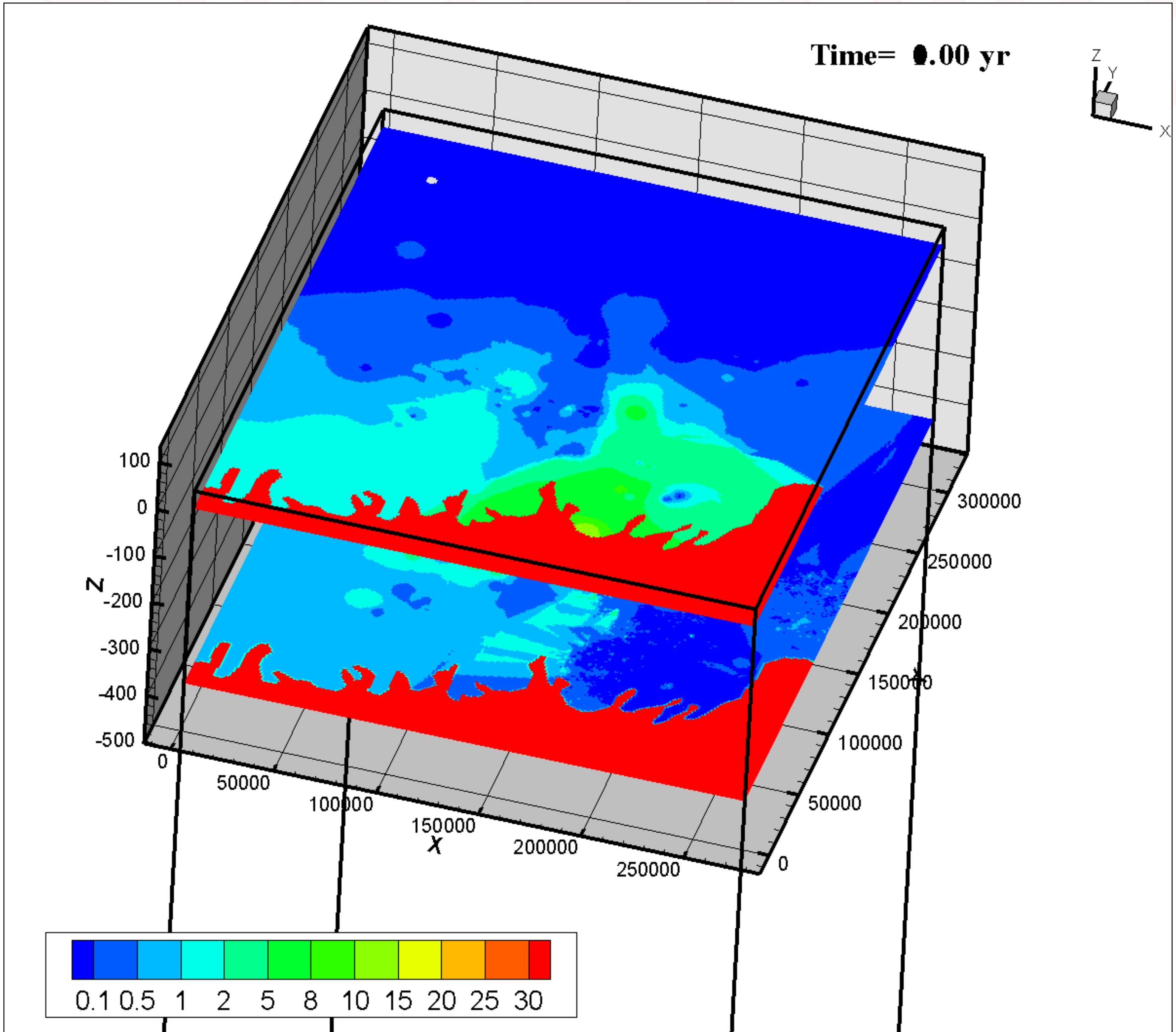


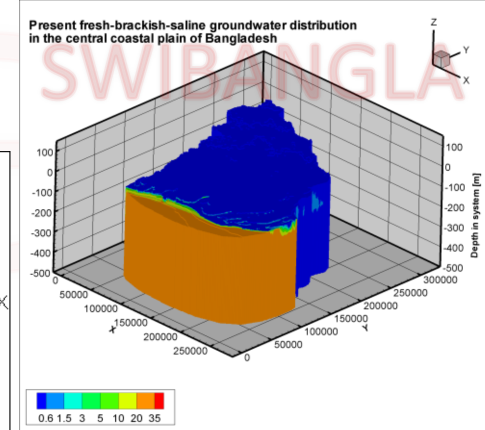
MODEL RESULTS: 3D-SALINITY





MODEL RESULTS: 3D-SALINITY





CONCLUDING REMARKS

1. The 3D model of variable-density groundwater flow and coupled salt transport model is operational in its present base form
2. The used iMOD-SEAWAT modelling tool is OPEN SOURCE
3. The initial fresh-brackish-salt distribution has been improved by the additional data
4. The complex hetereogeneous system can be modelled with the code without numerical problem
5. Different concepts have been tested

Recommendations for improvements:

- Calibration on heads and salinity distribution
- Simulation of non-steady state seasonal groundwater flow

After implementation of these suggestions, the model is suitable to simulate global change scenarios on extraction rates, land subsidence and climate change (sea level rise).

Thank you
for your attention!