Geophysics Applied to Coastal Aquifer Studies

Gualbert Oude Essink

Deltares
Enabling Delta Life

Manual: *I know nothing* (Fawlty Towers)

Need more information?:

- Helga Wiederhold
- Yossi Yechieli
- Vincent Post
- Luc Lebbe/Alexander Vandenbohede
- Perry de Louw/Pieter Pauw
- Frans Schaars
- Carlos Duque
- …?

Outline

Just impressions!

- Introduction
- Basic stuff
- Stuff I like
- AEM

As a non-geophysicist

- Geophysics can give nice information about aquifer, but it remains indirect information, so interpretation is needed
- There are many techniques and I do not know what is good for me … so shop and ask around

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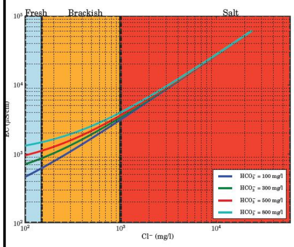
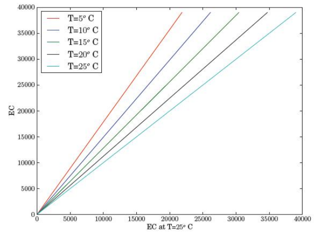
Outline

Basic stuff

EC and Chloride



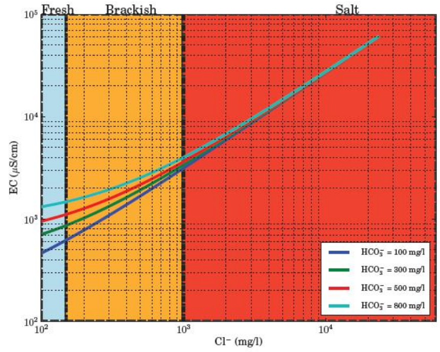
EC-Cl at different HCO_3^- concentrations.



(b) EC and temperature standardized EC.

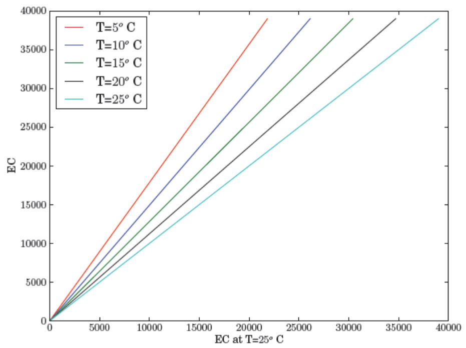
P. Pauw, 2009

EC and Chloride



EC-Cl at different HCO_3^- concentrations.

EC and Chloride



(b) EC and temperature standardized EC.

Airborne measurements

Measuring system	Physical parameter	Geology/terrain information
radar	EM traveltime	Terrain elevation
Infrared photography	Infrared radiation	Surface temperature
Time domain EM Frequency domain EM	Electr. resistivity from induced EM fields	Lithology Water salinity
Magnetic gradiometer	Magnetic field (variations)	Lithology (magnetite) Artefacts Steel/Iron objects
Spectral gamma	Radiation (gamma)	Soil type Surface lithology Recent disturbence

Source: Koos Groen

Surface measurements

Measuring system	Physical parameter	Geology/terrain information
Ground penetrating radar	EM traveltime, diaelectric constant,	Lithology Soil moisture
ERT	Electr. resistivity	Lithology Water salinity
Time domain EM Frequency domain EM	Electr. resistivity	Lithology Water salinity
Magnetometer (total field, gradiometer)	Magnetic field (variations) magnetic susceptibility	Lithology (magnetite) Artefacts Steel/Iron objects (UXO)
Spectral gamma	Radiation (gamma)	Soil type Surface lithology Recent disturbence

Source: Koos Groen

Cone Penetration Tests

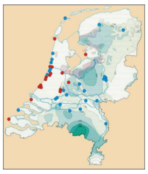
Measuring system	Physical parameter	Geology/terrain information
mechanical CPT	Cone resistance Friction resistance	Lithology Geotechnical parameters
Electrical conductivity	Electrical formation conductivity	Water salinity
Contnuous water pressure	Water pressure	Lithology Piezometric head
Water pressure dissipation in clay layers	Water pressure in time	Permeability clays
BAT sampling in CPT casing		Water chemistry
ROST, MIP		Contamination of hydrocarbons (high concentration)
Camera sonde	Visual view	Lithology, contamination, gas

Source: Koos Groen

Monitoring salt in groundwater

Why monitoring?

- Mapping salt concentrations in the groundwater
- Detection of trends (upconing near pumping stations)
- System and process knowledge
- Input for a groundwater model



Pumping stations with salinisation

Pumping stations closed due to salinisation

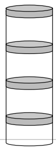
Methods:

1. **Direct**: water sample available
2. **Indirect**: conductance of the subsoil

Source: V. Post, 2007

Monitoring salt in groundwater: Direct methods

Method	Advantage	Disadvantage
1. Observation well	•High accuracy •Detection trends	•Costly •Point measurement
2. Well screens in observation well	•High accuracy •Detection trends •High vertical resolution	•Costly
3. Sediment sample (extraction milliliters of water)	•High accuracy •High vertical resolution	•Very costly and time consuming



Direct methods 1 and 2

Source: V. Post, 2007

Monitoring salt in groundwater: Indirect methods

Indirect methods measure the **conductance** of:

1. **The groundwater**
   - High conductance: saline groundwater
   - Low conductance: fresh groundwater

AND

2. **The soil**
   - High conductance: clay, sand
   - Low conductance: coarse sand, gravel

Hence information about the lithology (sand, clay etc) is needed!

Source: V. Post, 2007

Monitoring salt in groundwater: Indirect methods

Method	**Advantages**	**Disadvantages**
1. Electrical conductance measurements	•High resolution (3D) •Depth ~200 m	•Time consuming
2. Electromagnetic measurements	•Fast	•Limited vertical resolution •Sensitive for underground conductors (pipes)
3. Satellites	•Suitable for large areas	•Small vertical resolution •Low accuracy

Source: V. Post, 2007

Electrical conductance measurements

Measuring:

- **Inside a borehole**
- From surface level
- From the air

Source: TNO

Source: V. Post, 2007

Electrical conductance measurements

Measuring:

- Inside a borehole
- **From surface level (depth ~ 200 m)**
- From the air

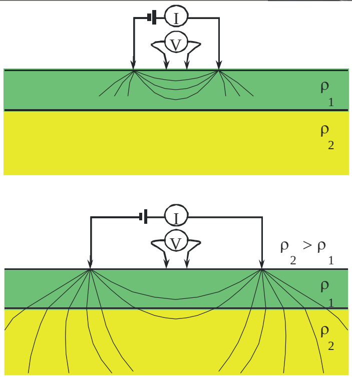
Source: Vitens

Source: V. Post, 2007

Principle geo-elektrical measurement

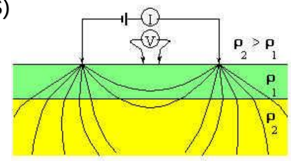
I: currentelektrode, V: potentialelektrodes, Ra: appearant elektrical resistiuvity

Ra = constant * V/I

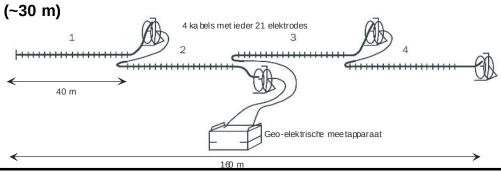


Types geo-elektrical measurements

- Vertical Electrical Sounding (VES)
  - 4 elektrodes at surface
  - 1D elektrical resistivity profile
  - Labor intense
  - Accurate, great depths
  - Deep hydrogeology



- Continue Vertical Elektrical Sounding (CVES)
  - >80 elektrodes at surface
  - 2D elektrical resistivity subsurface
  - Limited depth (~30 m)

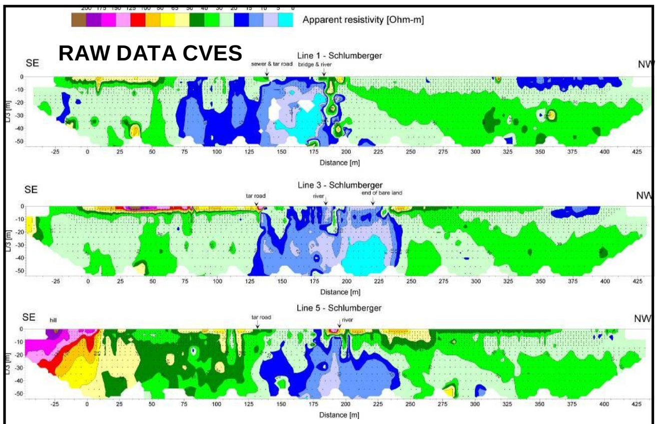


VES measurement end 1950s/begin 1960s

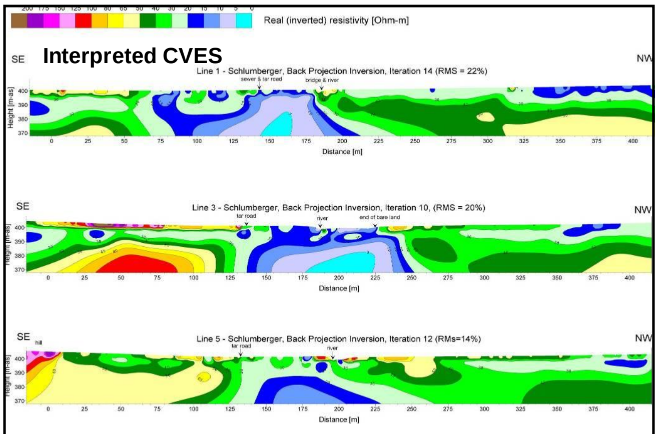
VES measurement end 1950s/begin 1960s

CVES measurements 2010s

RAW DATA CVES



Interpreted CVES



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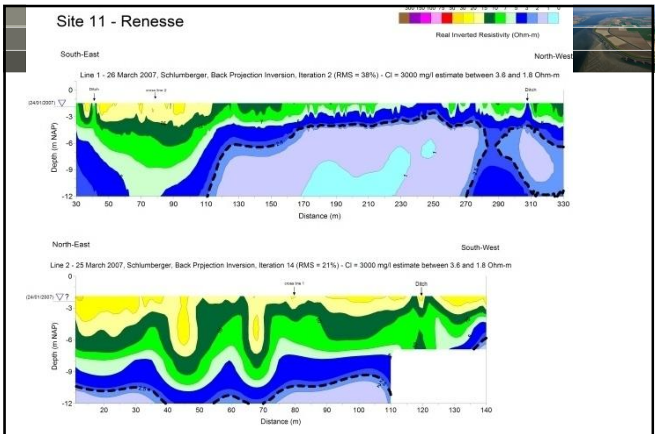
Site 11 - Renesse



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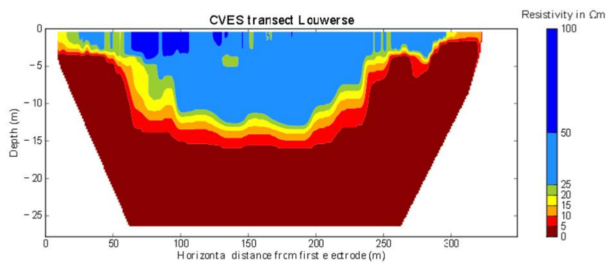
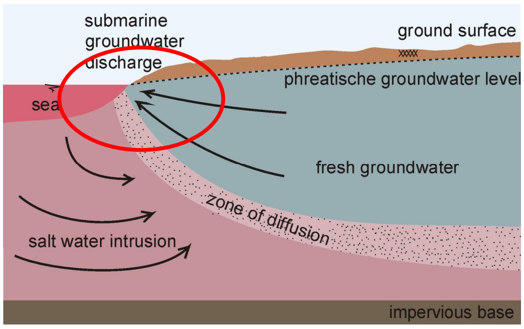
Possible measures for sandy creeks



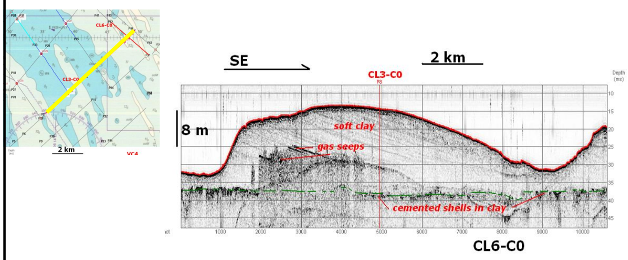
Stuff I like

groundwater in the coastal zone



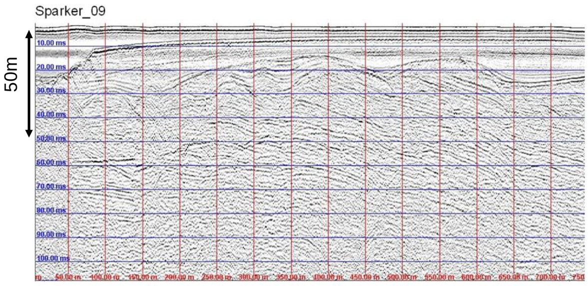
2D seismics: Example of chirper data (for SGD)

A chirp is a signal in which the frequency increases ('up-chirp') or decreases ('down-chirp') with time



2D seismics: Example sparker data

A sparker is a marine seismic impulsive source used for high-resolution seismic surveys.



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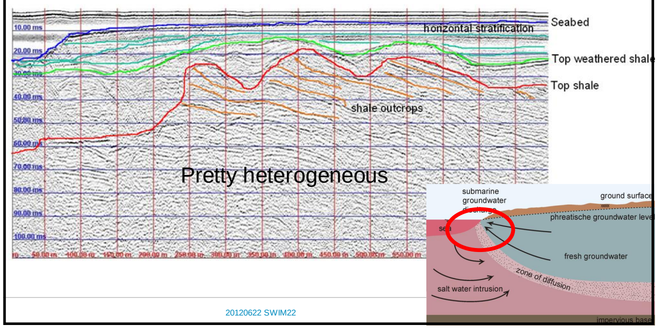
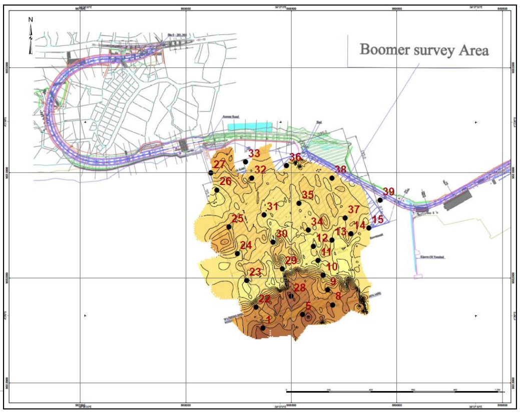
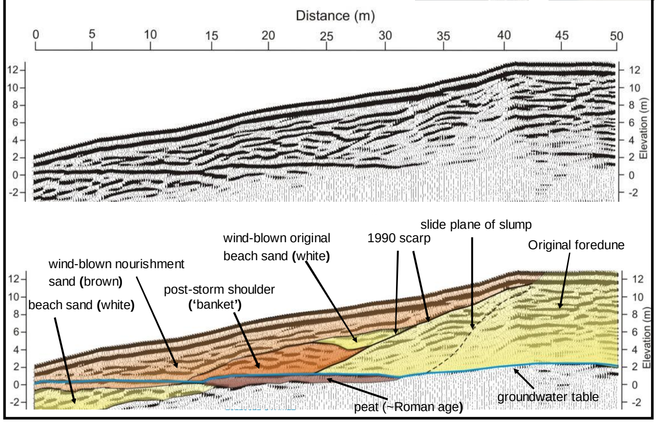


Interpreted sparker data showing thickness of deposits

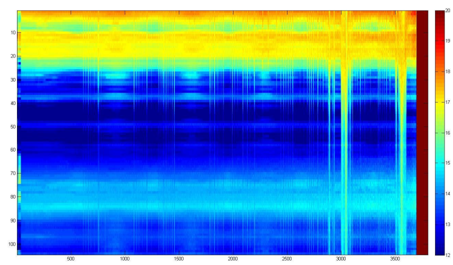


GPR image frontal dune (100 MHz)

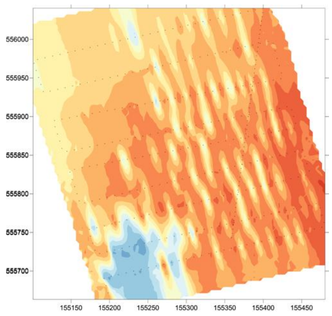


Monitoring sand transport using fiber optic cables

Raw data

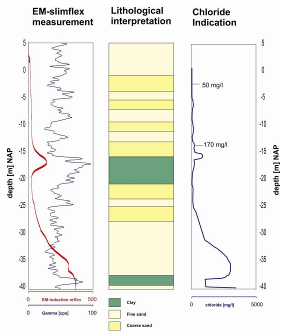


Bathymetry



EM Slimflex well logging tool

Slim and flexible
High resolution data
More data points
Easy to handle



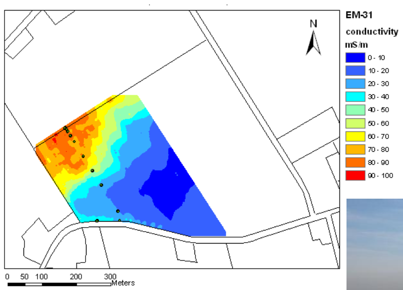
- EM34

generally used for lateral variations in subsurface conductivity

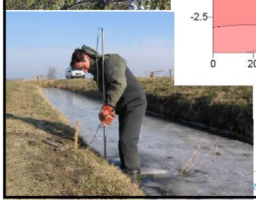
- EM39

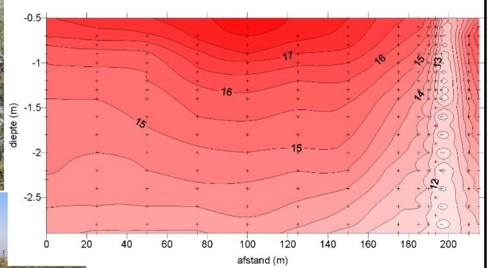
~EM31/34, but in borehole

EM31: lateral variability of the subsurface bulk conductivity



Temperature measurements





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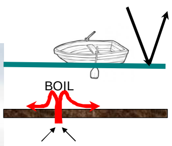
LARS technology (TNO Industry): Thermal Infra-red

Altitude: 0-150 m
Temp-detection using Thermal Infra Red sensors (only surface !)



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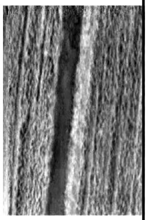
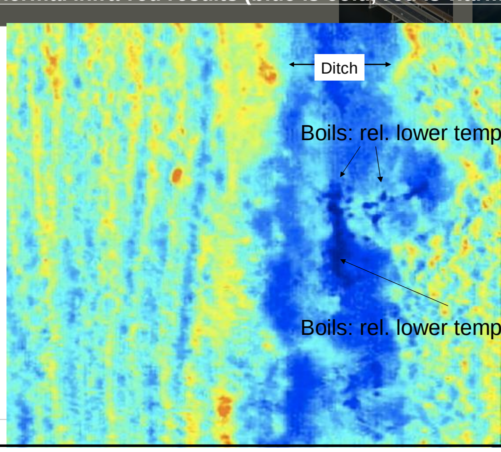


Thermal infra-red results (blue is cold, red is warm)



AEM

HEM and SKY-TEM

HEM is helicopter-borne frequency-domain

how much of the signal lies within each given frequency band

SkyTEM is helicopter-borne time domain
a signal changes over time

Larger penetration, but slower

Tools and AEM advantages

Key issues to achieve fresh water management:

- **Characterize** groundwater systems, **identify** fresh water resources (quantity and quality) and make **predictions** of changes in these resources
- Have cost-efficient tools such as geophysical methods and numerical models

Advantages AEM:

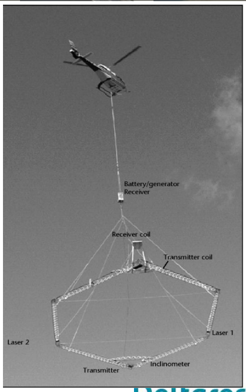
- Collection data very fast (within 1 yr a distribution, not just after 10's of yrs)-> interesting for data-poor countries
- 3D result (standard methods are 0D, 1D or 2D)
- Change in fresh-saline distribution can be detected by repetition measurement

AEM to detect fresh and saline groundwater

Electrical conductance measurements

Measuring:

- Inside a borehole
- From surface level
- **From the air**



Source: V. Post, 2007

20120622 SWIM22

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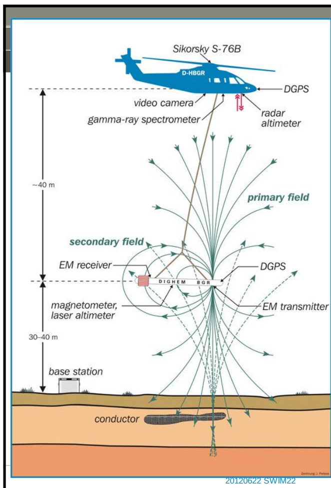

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Monitoring salt in groundwater: Indirect methods

Electrical conductance measurements

ρ_s=F* ρ_w

ρ_s = resistance subsoil & groundwater
ρ_w = resistance groundwater
F = formation factor

Lithology	**F**
Gravel with sand	7
Coarse sand	5
Sand with silt	2 - 3
Clay	*1-3**
peat	*1**

F varies with the resistance of the groundwater

If the lithology is known AND the measurement is in an aquifer
→ ρ_w can be calculated

20120622 SWIM22

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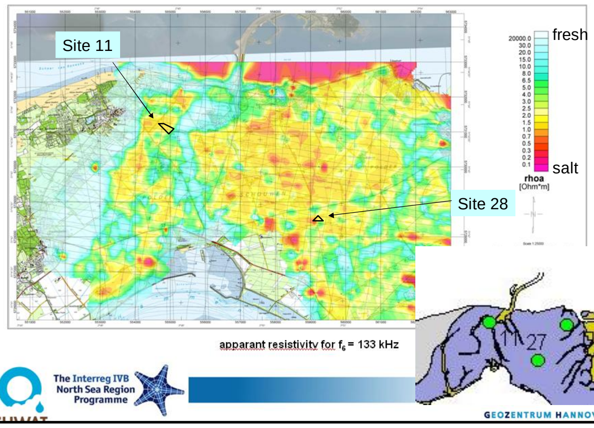
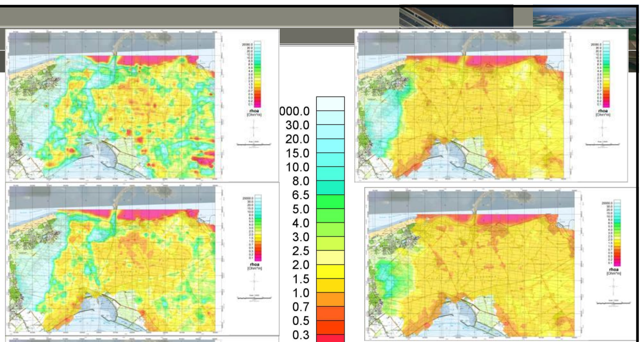
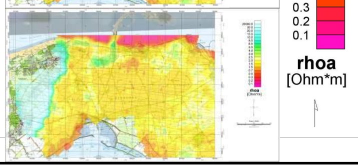
HEM results



The Interreg IVB North Sea Region Programme

GEOZENTRUM HANNOVER





HEM results with depth

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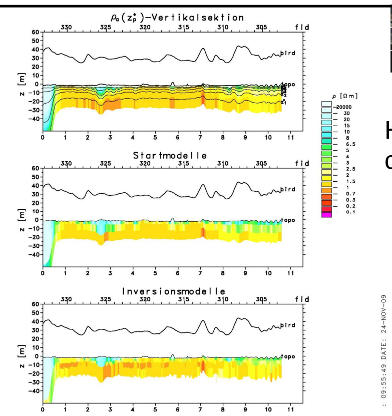


HEM results in cross section

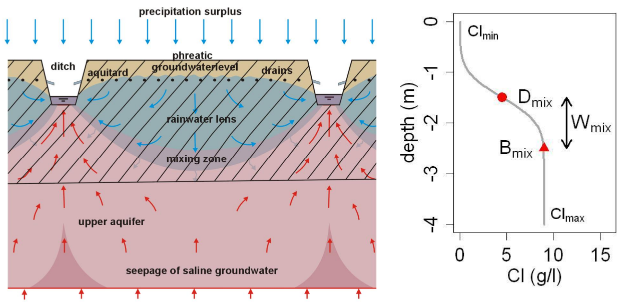
The Interreg IVB North Sea Region Programme

CLIWAT

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

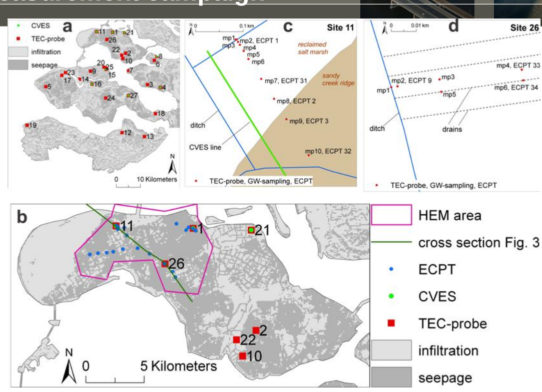
GEOZENTRUM HANNOVER

Rainwater lenses in saline seepage areas Zeeland

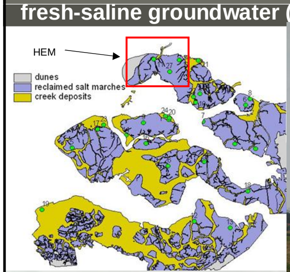


De Louw et al, 2011

Measurement campaign



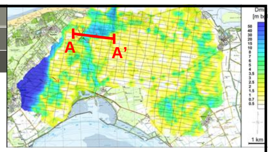
Helicopter-EM measurements to identify the interface fresh-saline groundwater (BGR)

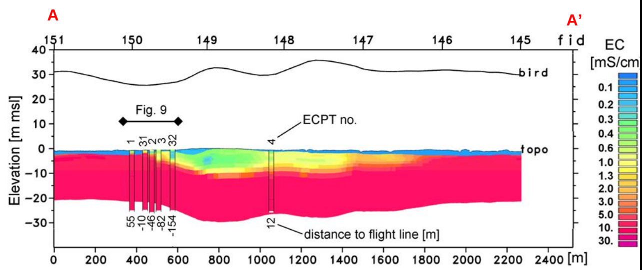


Interreg project

CLIWAT CLIMATE & WATER

Thickness rainwater lenses (Dmix) with HEM





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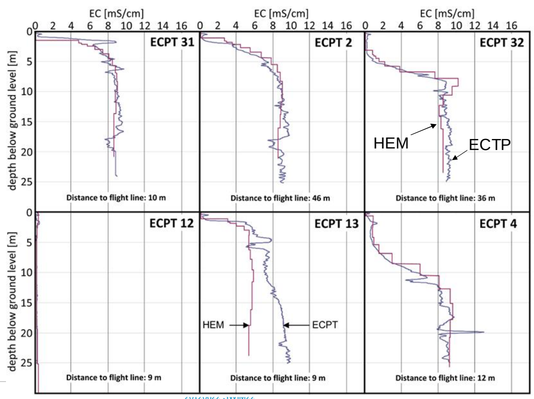
Comparing HEM - ECPT



AEM to detect fresh and saline groundwater

AEM application: creation of a 3D chloride concentration field for numerical modeling

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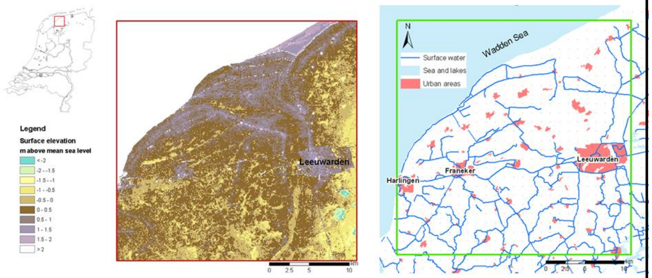
Case Fryslân



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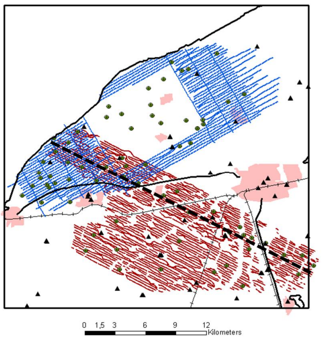
AEM in Fryslân



German Federal Institute for Geosciences and Natural Resources (BGR)

University of Aarhus, Denmark

TNO

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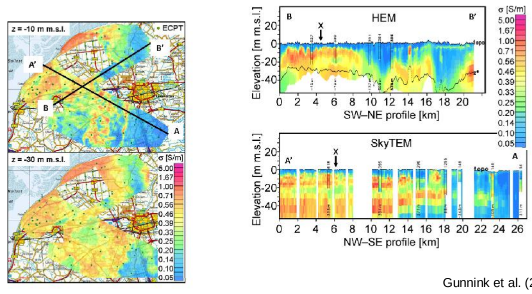
Mapping the EC with AEM

2D bulk EC field ⟶ 3-D model of bulk EC for every cell of 100x100x0.5m



Gunnink et al. (2012)

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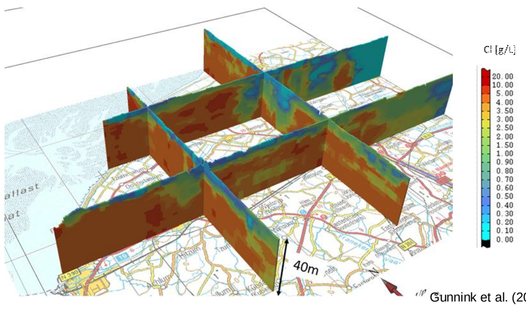
From a 3D EC field to a 3D chloride field

Bulk EC + Groundwater EC + Formation Factor ⟶ Cl concentration per cell



Gunnink et al. (2012)

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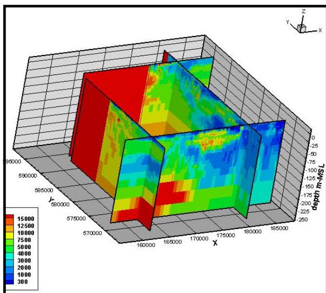
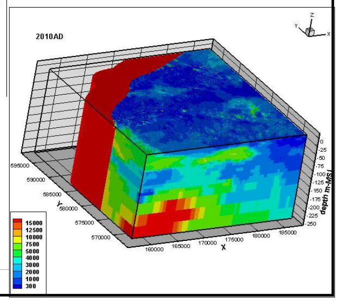
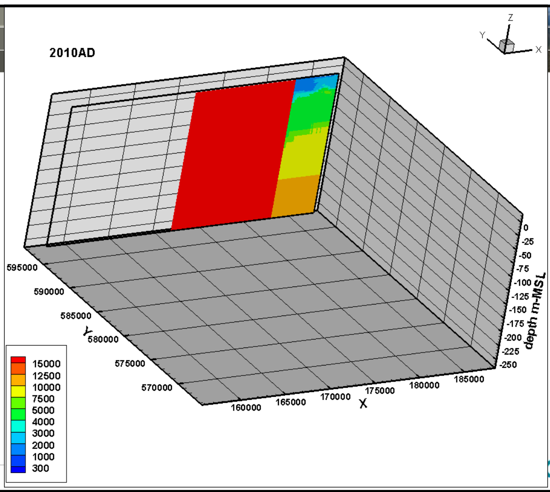
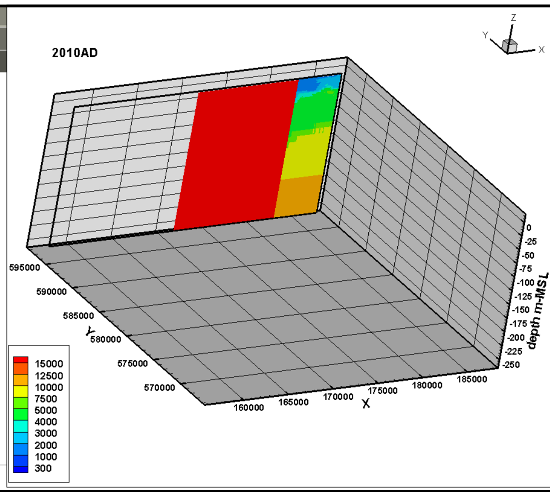




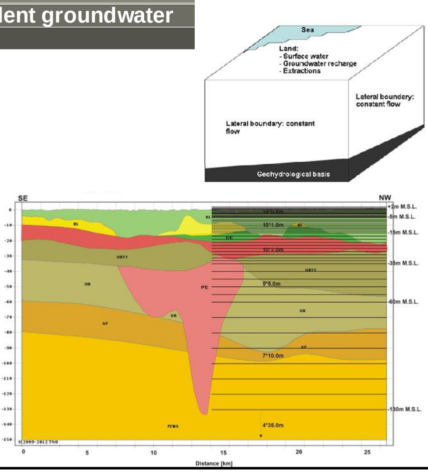




Density dependent groundwater model

300 columns
300 rows
100x100m cells
50 model layers

Calibrated
Validated



Conclusions and recommendations

Conclusions:

- AEM is an efficient method to map groundwater salinity
- The 3D fields can be used in numerical models and give reliable information
- Models with a good initial 3D field give quality results and can be used for prediction of the effects of the climate change or strategy measures

Recommendations for follow up:

- Further investigation on the conversion of EC to chloride concentration
- Further investigation on the uncertainties in EC field generation

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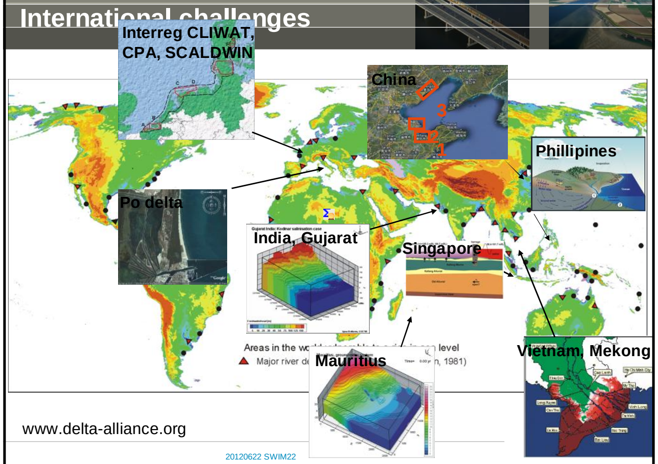
International challenges



www.delta-alliance.org

Singapore: Aerial View of Marina Barrage

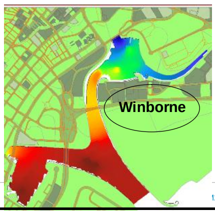
Salinity contribution from groundwater resources?

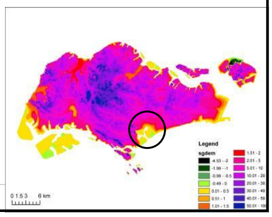
This is the lowest area in the saline environment (see DEM)

Higher concentrations in Kallang Canal, relative far from Barrage itself

Low-lying area (Winborne) is 'managed as a polder' and discharges water with high salinities to Kallang Canal

Ground Penetration Radar executed last week, shows evidence of salt water intrusion via groundwater (details later)





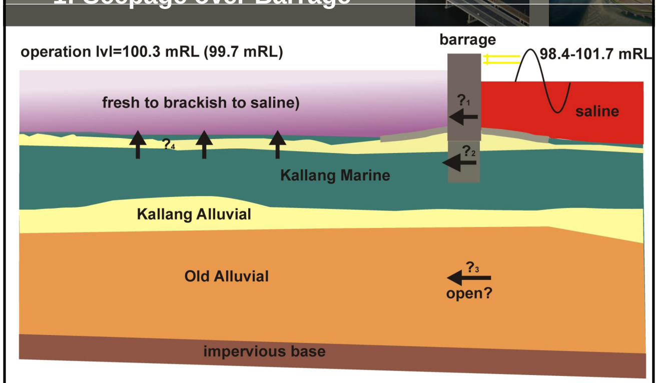
Possible contribution from groundwater

Seepage over The Barrage itself * saline water

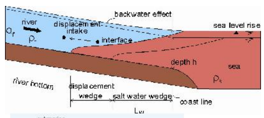
Seepage over waterfront along the whole Reservoir * fresh-brackish water

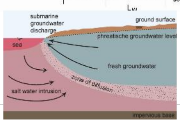
Seepage from the subsurface * brackish water

1: Seepage over Barrage



Vietnam: Changes for fresh agriculture and saline aquaculture





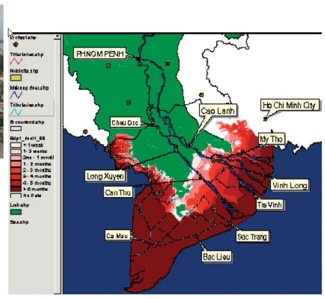


Figure: *Mekong Delta: Simulation of saline intrusion during the dry season drought conditions of 1998. The map shows the duration of salinity levels greater than 1 gram per litre. The area affected exceeds half of the total 55,000 km2 that defines the main delta* (Source: MRC 2003, State of the Basin Report)

Salinity intrusion affected at least 7million ha in dry season 1998 (MRC, 2003; Halcrow, 2004).

Three areas of interest

China: Three study areas

1. Weifang
   - Fresh groundwater 'contaminates' brines
   - Large coastal development

1

2. Yellow River
   - Salinisation of the delta

2

3. Qinhuangdao
   - Salinisation of the coastal zone

3

Three study areas

1. Weifang

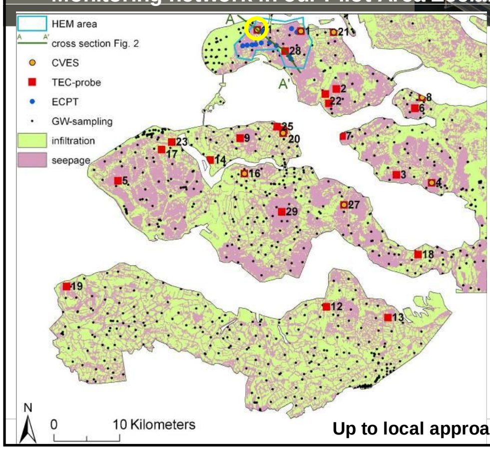
- Impact coastal development on fresh-saline groundwater resources
- Huge land reclamation project
- Monitoring campaign (mainly observation wells)
- Main source: brine groundwater
- Fresh groundwater 'contaminates' brines
- Water system analysis, flow situation
- Analysis monitoring campaign

- Dutch equivalents:
  > effect on groundwater of Zandmotor project and land reclamation at Solleveld
  > brine disposal Zuid-Holland
  > Knowledge for Climate: Climate Proof Fresh Water Supply

Example of combining techniques

Deltares

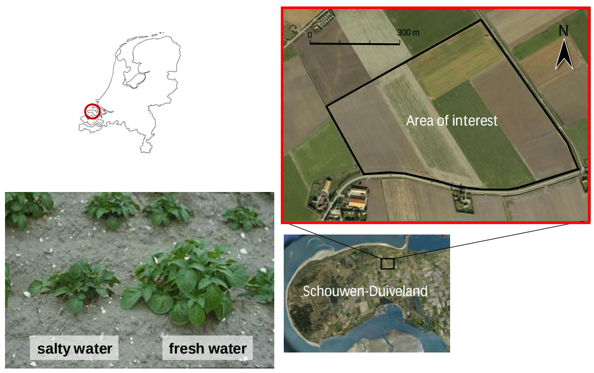
Monitoring network in our Pilot Area Zeeland



Up to local approach

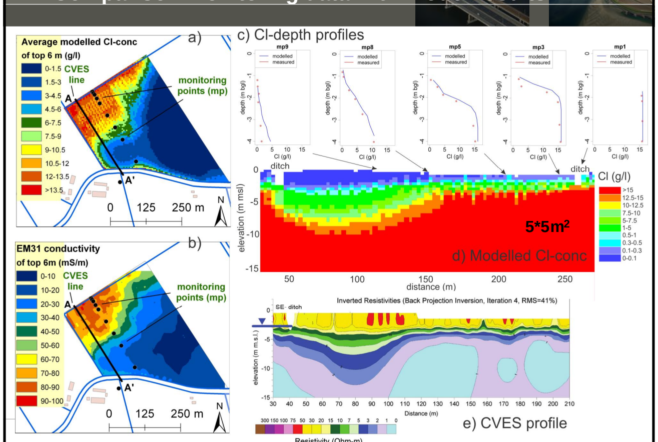
Deltares

Fresh water supply under stress

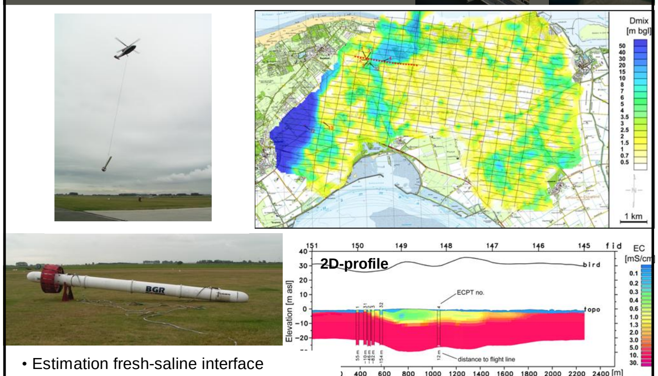


Deltares

Comparison monitoring data with model results

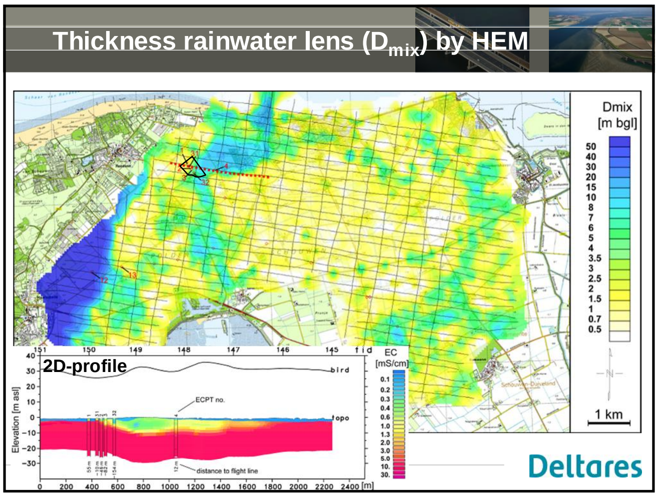


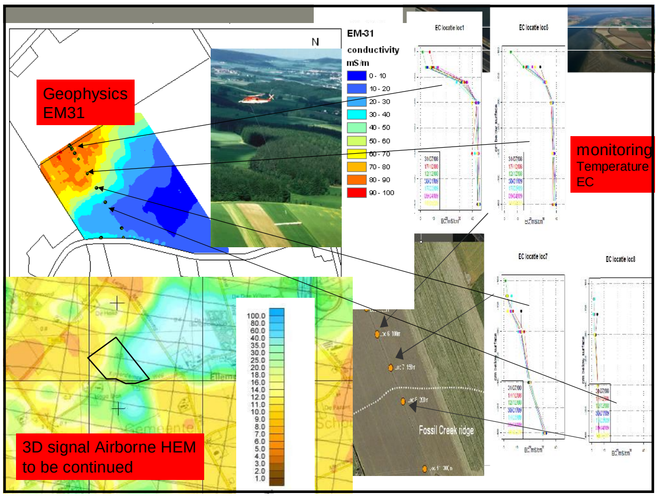
Airborne Electro Magnetic surveys

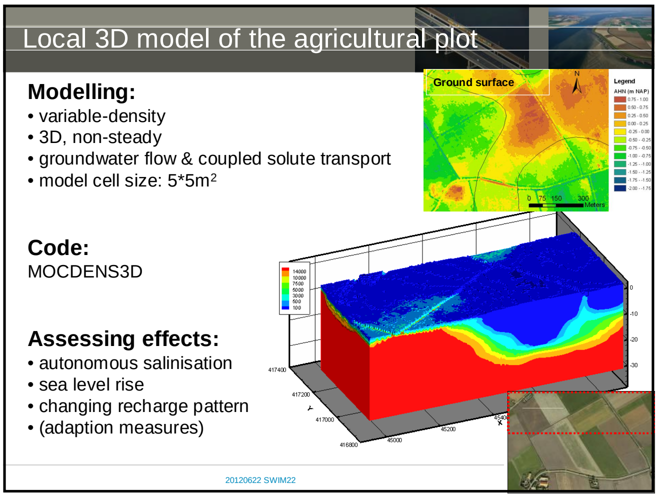


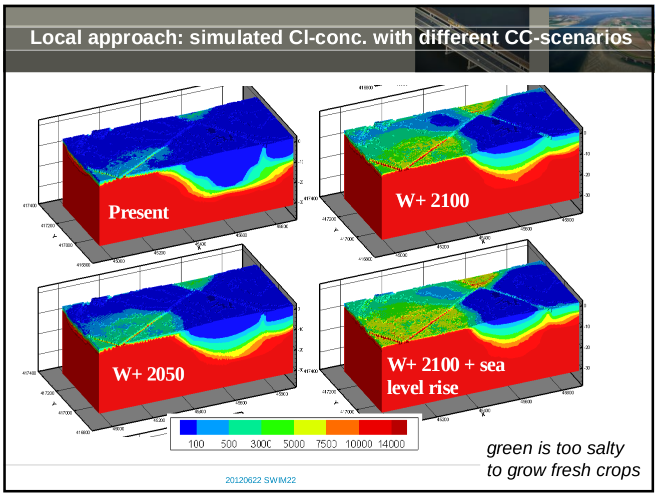
- Estimation fresh-saline interface
- Combining with numerical models
- Improve water management coastal zone

Deltares


Thickness rainwater lens (D_{mix}) by HEM
Dmix
[m bgl]
50
40
30
20
15
10
8
7
6
5
4
3.5
3
2.5
2
1.5
1
0.7
0.5
1 km
2D-profile
Elevation [m asl]
EC
[mS/cm]
0.1
0.2
0.3
0.4
0.6
1.0
1.3
2.0
3.0
5.0
10.
30.
bird
topo
ECPT no.
distance to flight line
Deltares


Geophysics
EM31
EM-31
conductivity
mS/m
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
monitoring
Temperature
EC
3D signal Airborne HEM
to be continued
Fossil Creek ridge


Local 3D model of the agricultural plot
Modelling:
• variable-density
• 3D, non-steady
• groundwater flow & coupled solute transport
• model cell size: 5*5m2
Code:
MOCDENS3D
Assessing effects:
• autonomous salinisation
• sea level rise
• changing recharge pattern
• (adaption measures)
Ground surface
Legend
20120622 SWIM22


Local approach: simulated Cl-conc. with different CC-scenarios
Present
W+ 2100
W+ 2050
W+ 2100 + sea
level rise
100
500
3000
5000
7500
10000
14000
green is too salty
to grow fresh crops
20120622 SWIM22