Integrated use of investigation methods to understand the processes of salt water intrusion

Kristine Walraevens
Laboratory for Applied Geology and Hydrogeology
Ghent University

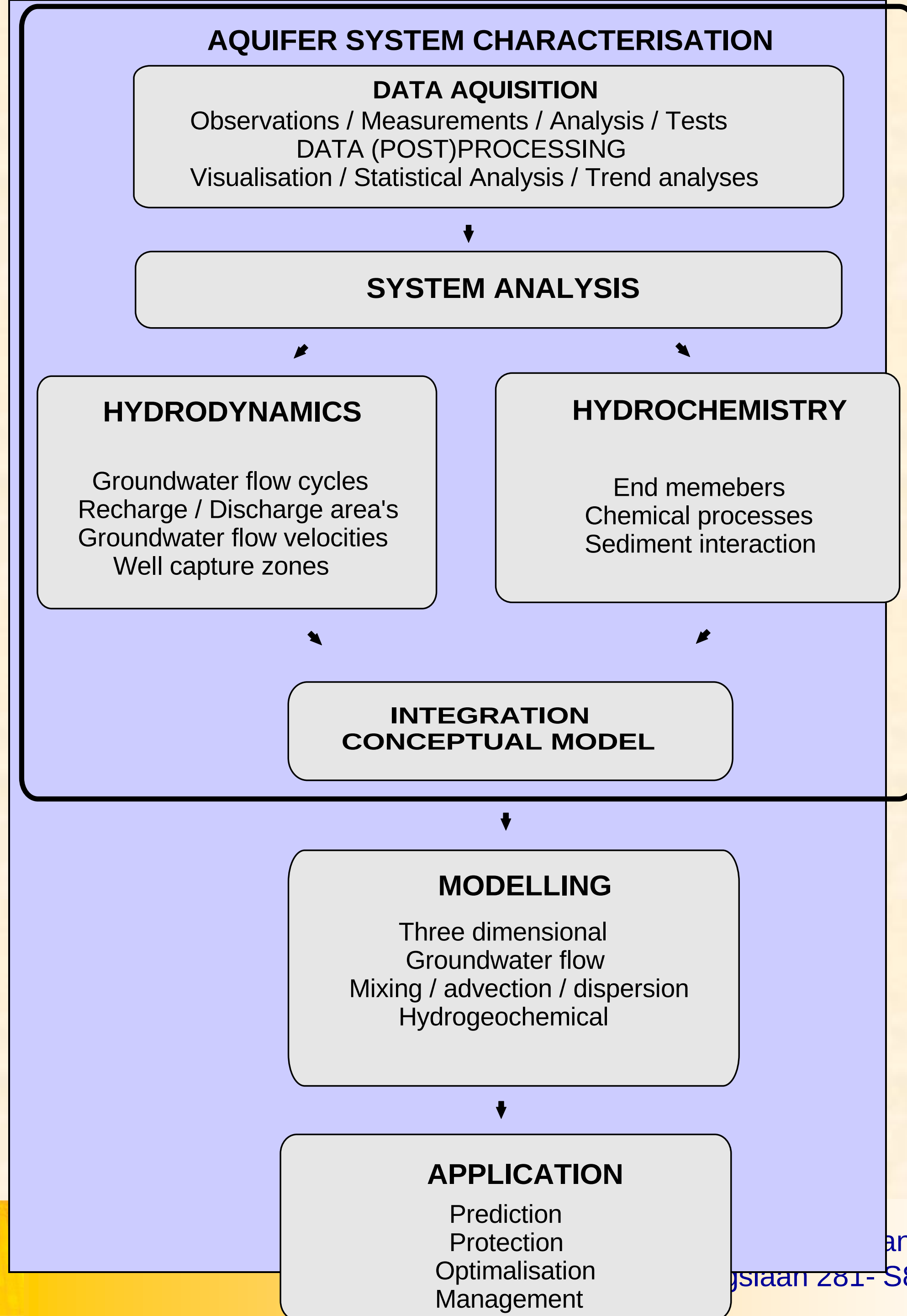
need of using multiple investigation methods in an integrated way

↓

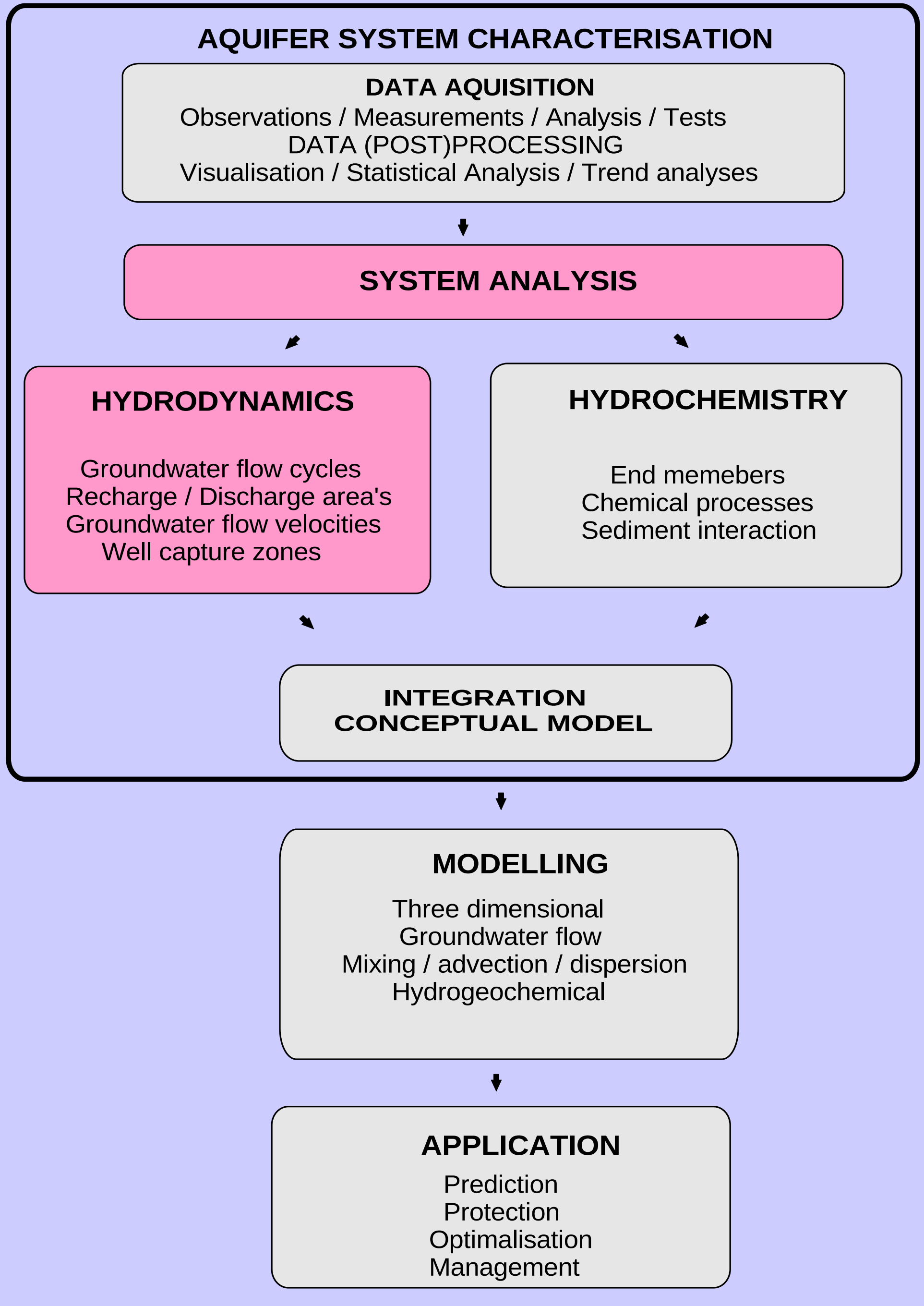
understand the complexity of the processes related to salt water intrusion

↓

appropriate monitoring scheme


AQUIFER SYSTEM CHARACTERISATION
DATA AQUISITION
Observations / Measurements / Analysis / Tests
DATA (POST)PROCESSING
Visualisation / Statistical Analysis / Trend analyses
SYSTEM ANALYSIS
HYDRODYNAMICS
Groundwater flow cycles
Recharge / Discharge area's
Groundwater flow velocities
Well capture zones
HYDROCHEMISTRY
End memebers
Chemical processes
Sediment interaction
INTEGRATION
CONCEPTUAL MODEL
MODELLING
Three dimensional
Groundwater flow
Mixing / advection / dispersion
Hydrogeochemical
APPLICATION
Prediction
Protection
Optimalisation
Management

UNDERSTANDING NATURAL GROUNDWATER QUALITY CONTROLS



UNDERSTANDING NATURAL GROUNDWATER QUALITY CONTROLS

AQUIFER SYSTEM CHARACTERISATION

DATA AQUISITION
Observations / Measurements / Analysis / Tests
DATA (POST)PROCESSING
Visualisation / Statistical Analysis / Trend analyses

SYSTEM ANALYSIS

HYDRODYNAMICS

Groundwater flow cycles
Recharge / Discharge area's
Groundwater flow velocities
Well capture zones

HYDROCHEMISTRY

End memebers
Chemical processes
Sediment interaction

INTEGRATION
CONCEPTUAL MODEL

MODELLING

Three dimensional
Groundwater flow
Mixing / advection / dispersion
Hydrogeochemical

APPLICATION

Prediction
Protection
Optimalisation
Management

UNDERSTANDING NATURAL GROUNDWATER QUALITY CONTROLS

AQUIFER SYSTEM CHARACTERISATION

DATA AQUISITION
Observations / Measurements / Analysis / Tests
DATA (POST)PROCESSING
Visualisation / Statistical Analysis / Trend analyses

↓

SYSTEM ANALYSIS

↙ ↘

HYDRODYNAMICS

Groundwater flow cycles
Recharge / Discharge area's
Groundwater flow velocities
Well capture zones

HYDROCHEMISTRY

End memebers
Chemical processes
Sediment interaction

↘ ↙

INTEGRATION CONCEPTUAL MODEL

↓

MODELLING

Three dimensional
Groundwater flow
Mixing / advection / dispersion
Hydrogeochemical

↓

APPLICATION

Prediction
Protection
Optimalisation
Management

COASTAL AQUIFERS

→ **confrontation between marine and continental conditions, resulting from stress:**

SALINIZATION of fresh aquifers

- **natural origin: marine transgression, flooding**
- **anthropogenic: overexploitation**

FRESHENING of saline aquifers

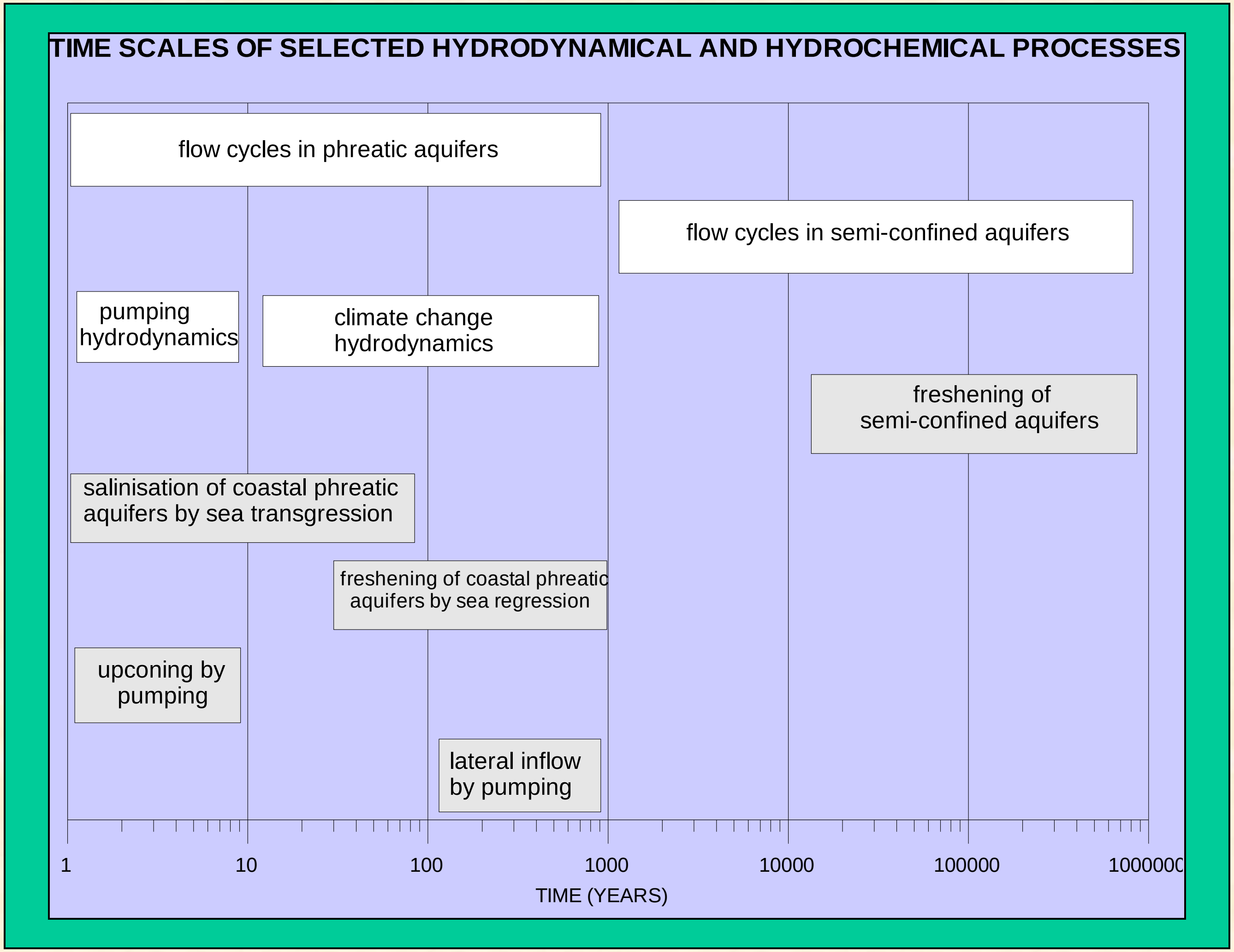
- **natural origin: dune belt development**
- **anthropogenic: artificial recharge**

⇒ **both processes may have contributed to groundwater quality in the aquifer**

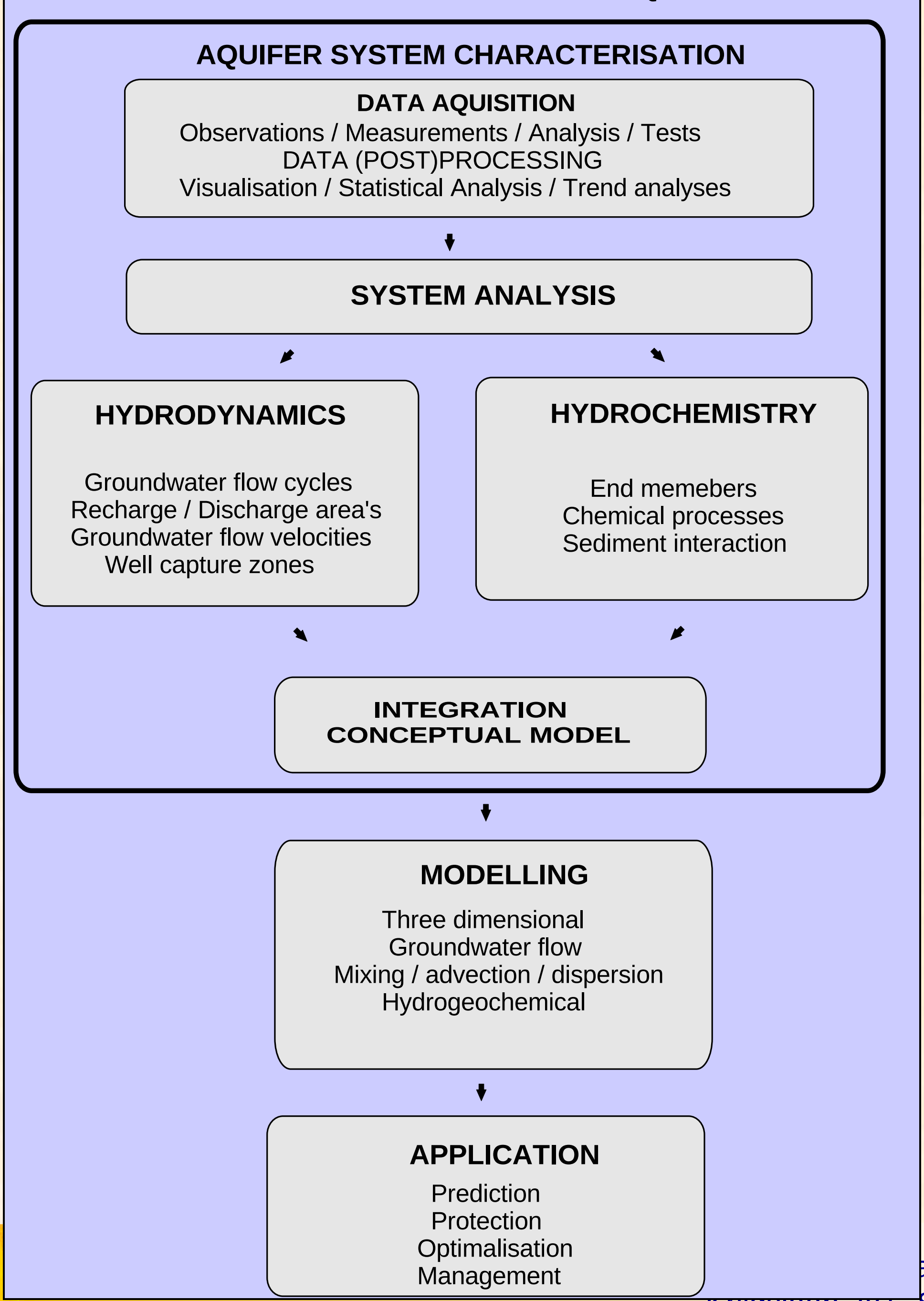
TIME SCALES

Different stress mechanisms have their own time scales

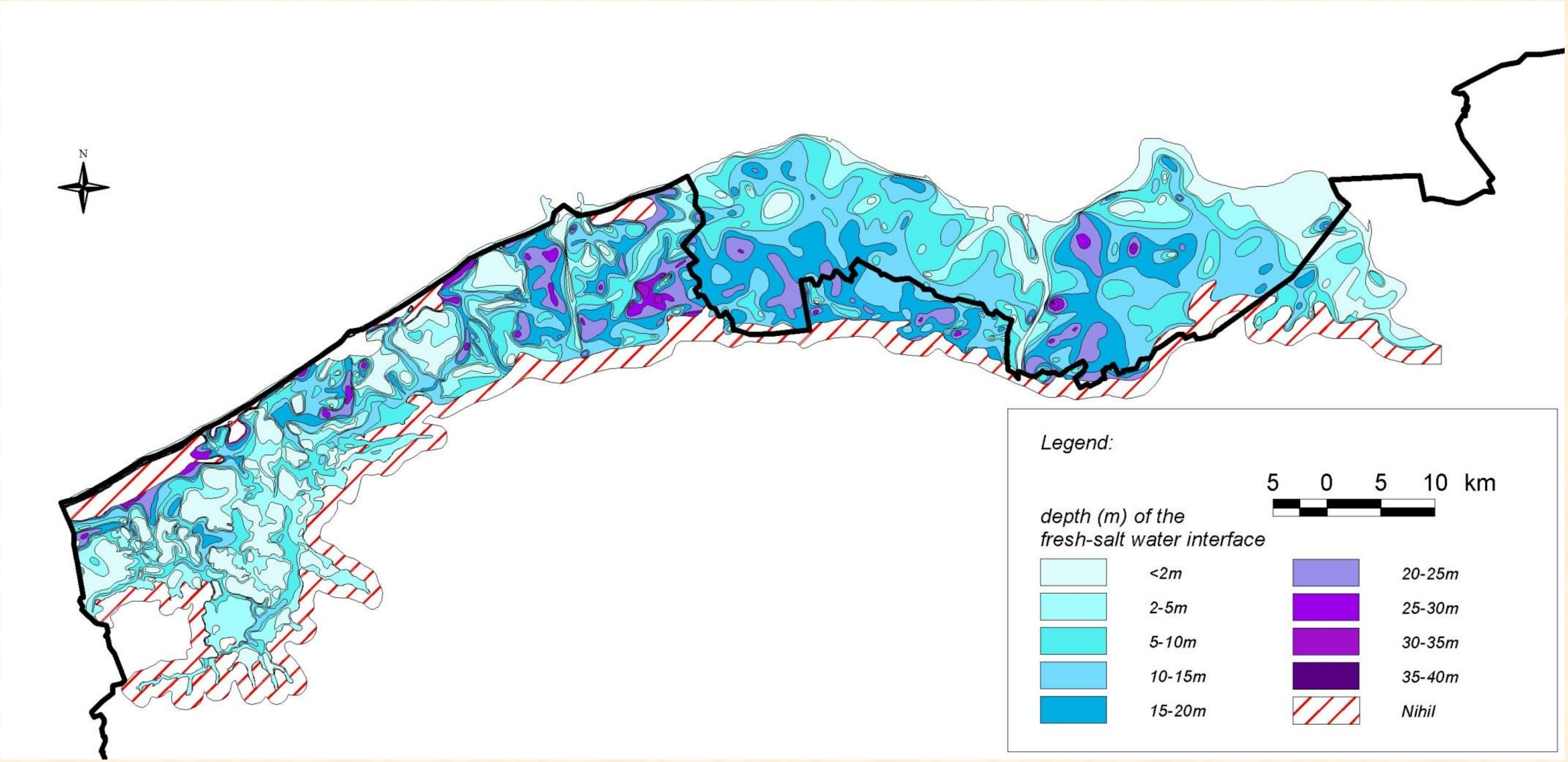
$\Rightarrow$ groundwater quality (incl.fresh/salt water distribution) is often determined by long-term hydrogeological and physiographical history


TIME SCALES OF SELECTED HYDRODYNAMICAL AND HYDROCHEMICAL PROCESSES
flow cycles in phreatic aquifers
flow cycles in semi-confined aquifers
pumping hydrodynamics
climate change hydrodynamics
freshening of semi-confined aquifers
salinisation of coastal phreatic aquifers by sea transgression
freshening of coastal phreatic aquifers by sea regression
upconing by pumping
lateral inflow by pumping
1
10
100
1000
10000
100000
1000000
TIME (YEARS)

UNDERSTANDING NATURAL GROUNDWATER QUALITY CONTROLS

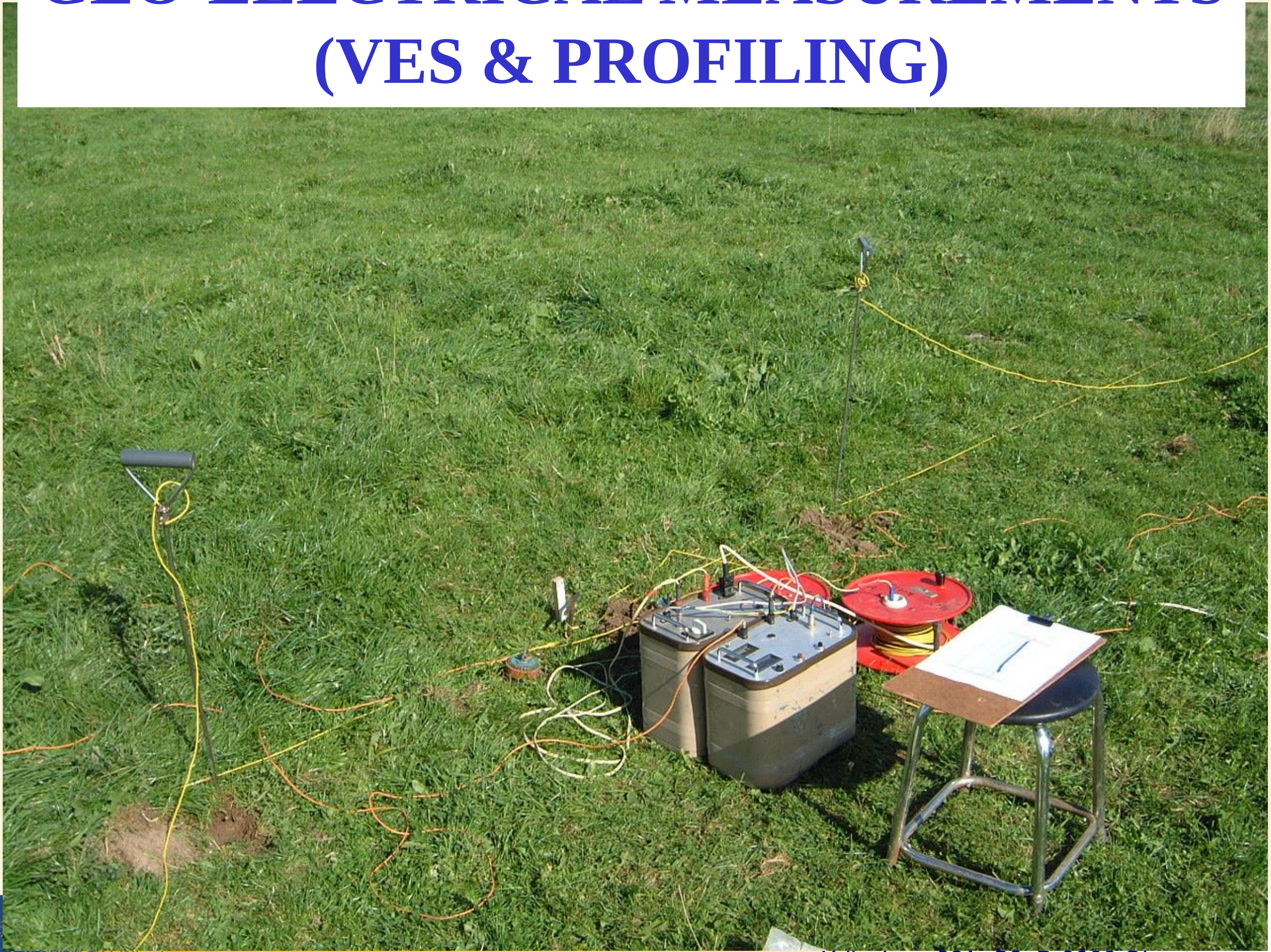


DEPTH OF FRESH/SALT WATER INTERFACE

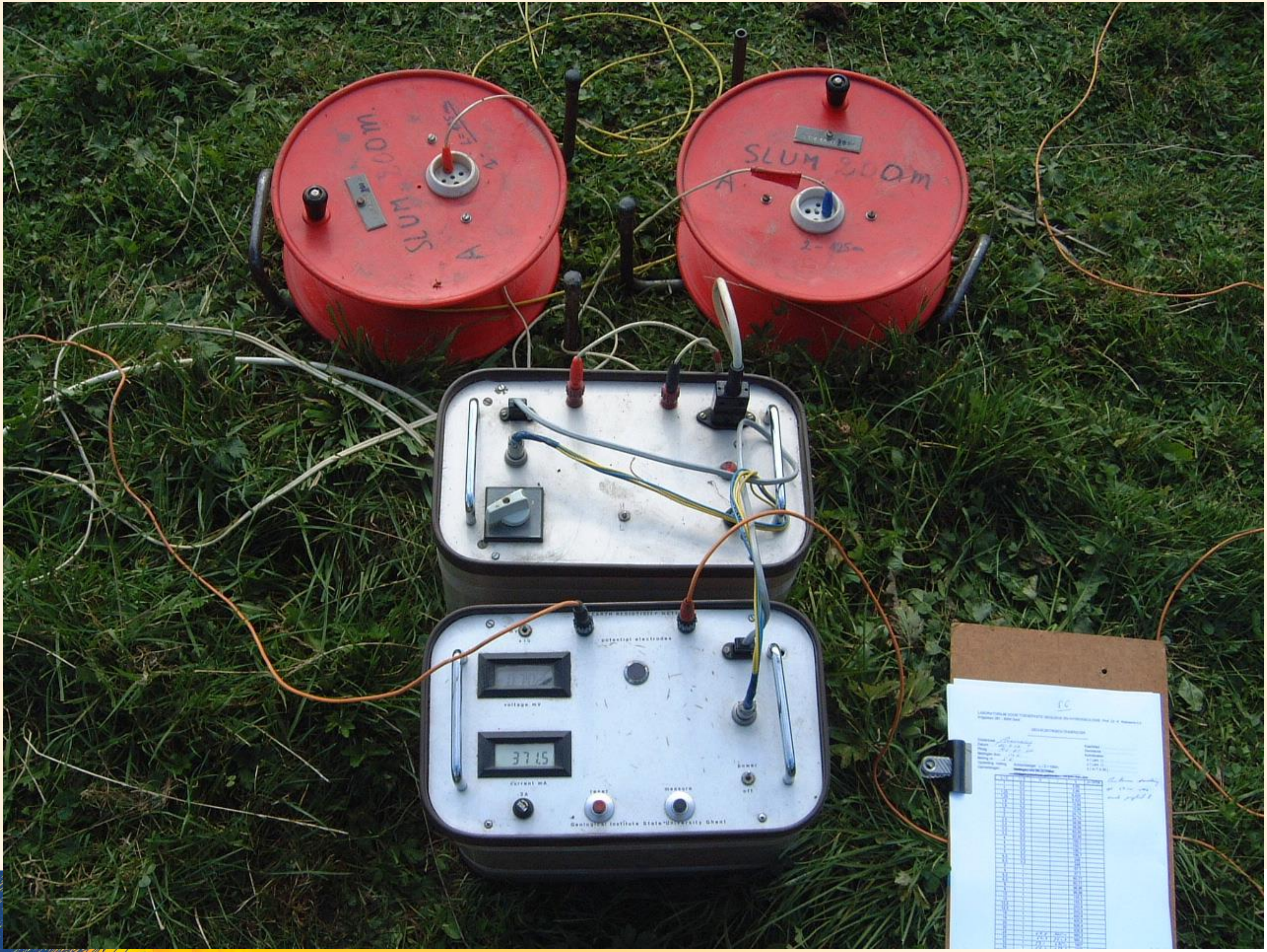


For Belgian coast alone: based on > 1700 VES

GEO-ELECTRICAL MEASUREMENTS (VES & PROFILING)



GEO-ELECTRICAL MEASUREMENTS

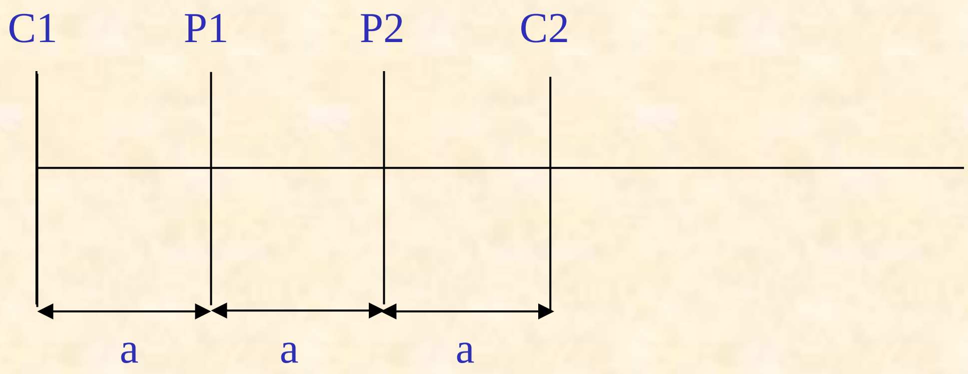


GEO-ELECTRICAL MEASUREMENTS

$$\rho = \frac{\Delta V}{I} k$$

GEO-ELECTRICAL MEASUREMENTS

Conventional Wenner



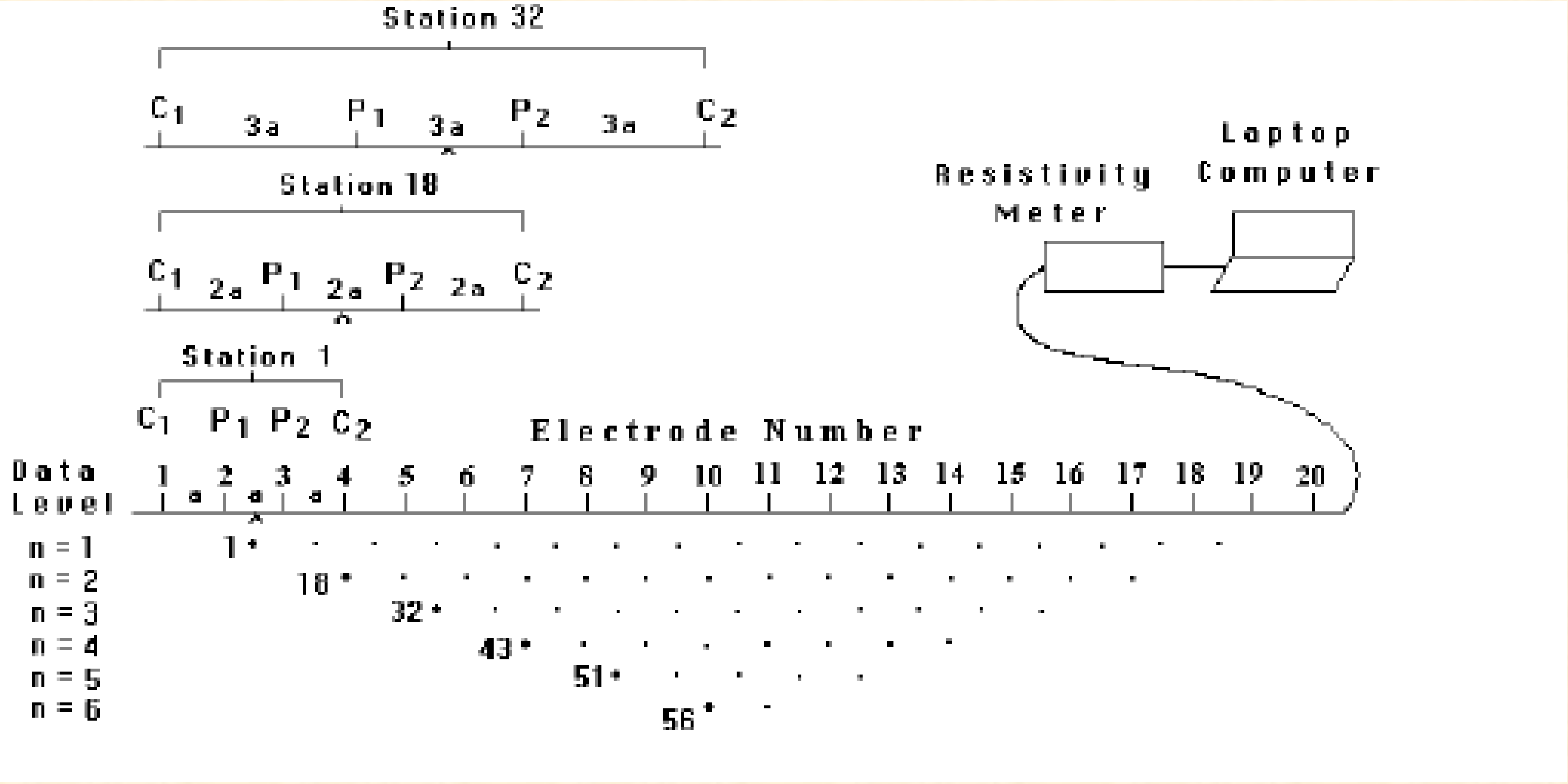
$k = 2\Pi a$

GEO-ELECTRICAL MEASUREMENTS

GEO-ELECTRICAL MEASUREMENTS

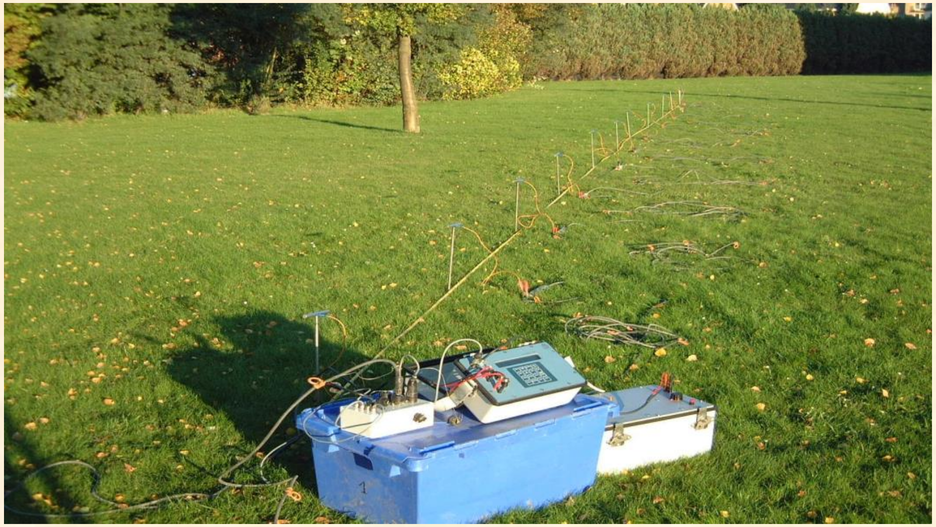
GEO-ELECTRICAL MEASUREMENTS

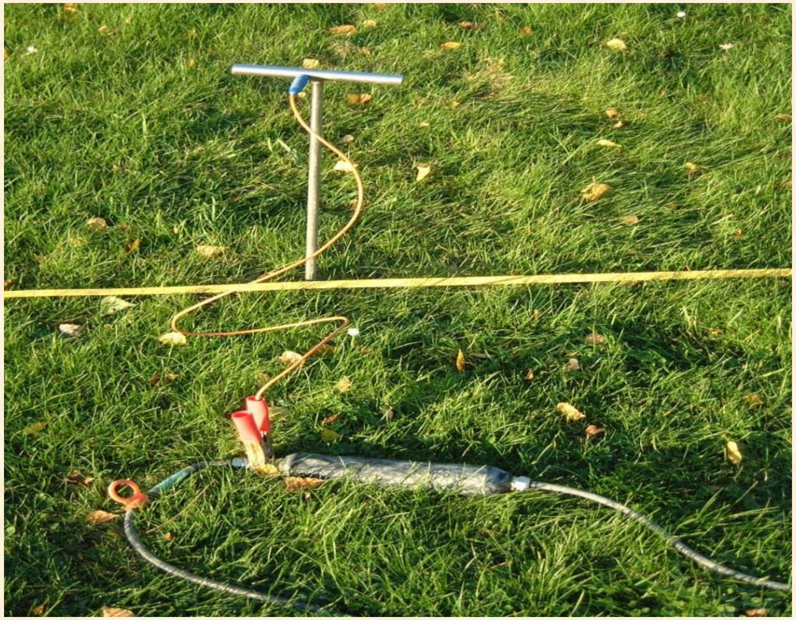
ELECTRICAL TOMOGRAPHY (CVES)


Station 32
C1 3a P1 3a P2 3a C2
Station 18
C1 2a P1 2a P2 2a C2
Station 1
C1 P1 P2 C2
Electrode Number
Resistivity Meter
Laptop Computer
Data Level
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
a a a
n = 1
n = 2
n = 3
n = 4
n = 5
n = 6
1
18
32
43
51
56

Equipment:

- measuring device with microprocessor
- generator or battery
- multiplexer
- addressable electrodes



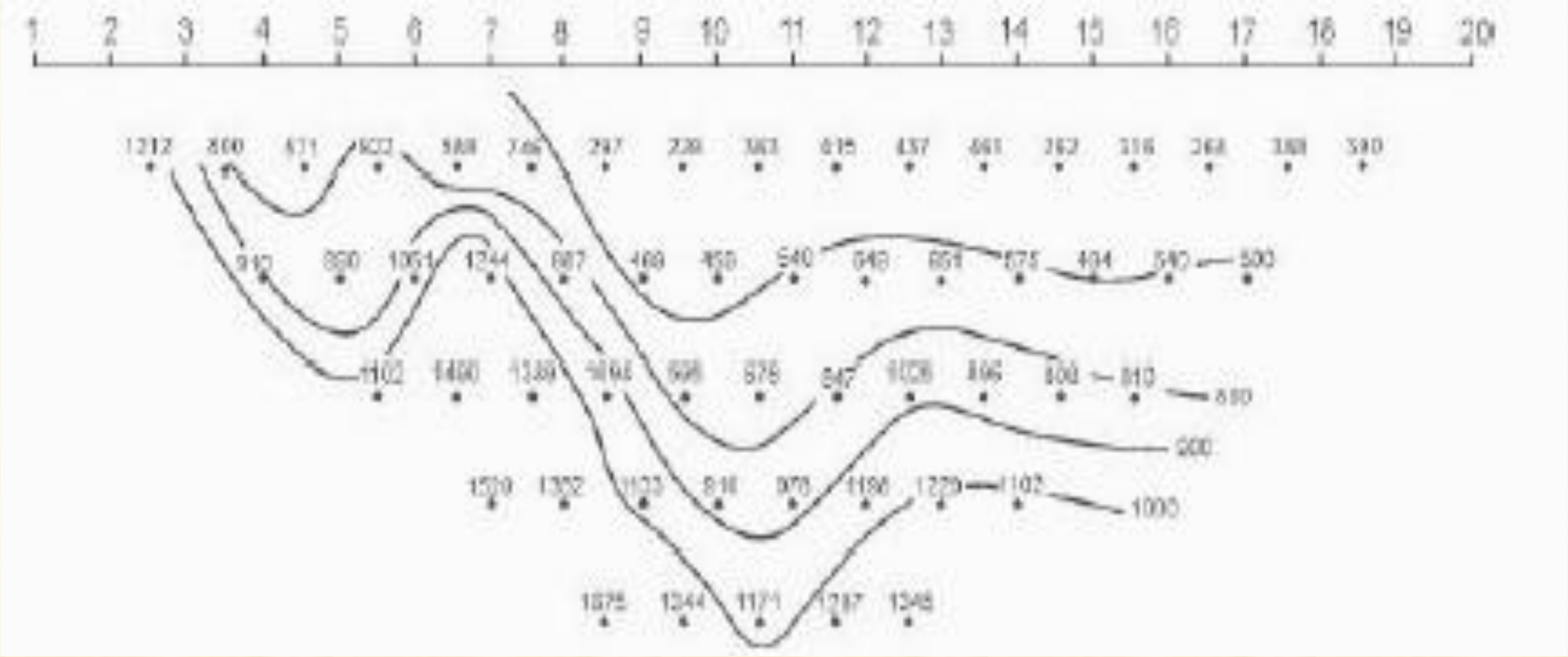


Pseudo-section:

representation of measured **<u>apparent</u>** resistivity

→ approximate and modified resistivity distribution

→ also dependent on measuring configuration



Laboratory for applied Geology and Hydrogeology
Krijgslaan 281- S8, B-9000 Ghent


DRILLING

DRILLING

LN & SN LOGGING

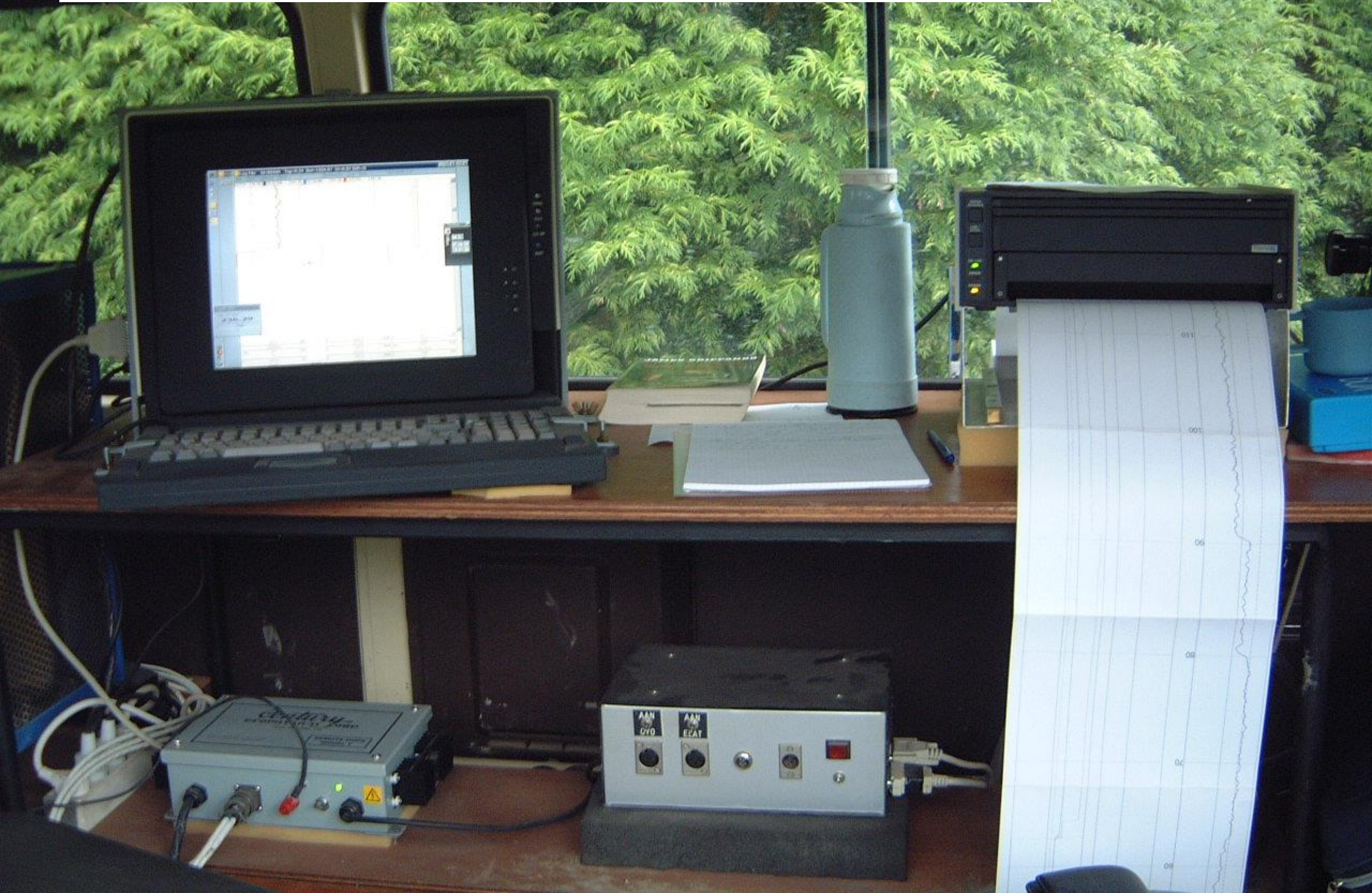
PIEZOMETER INSTALLATION

BACKFILLING OF ANNULAR SPACE

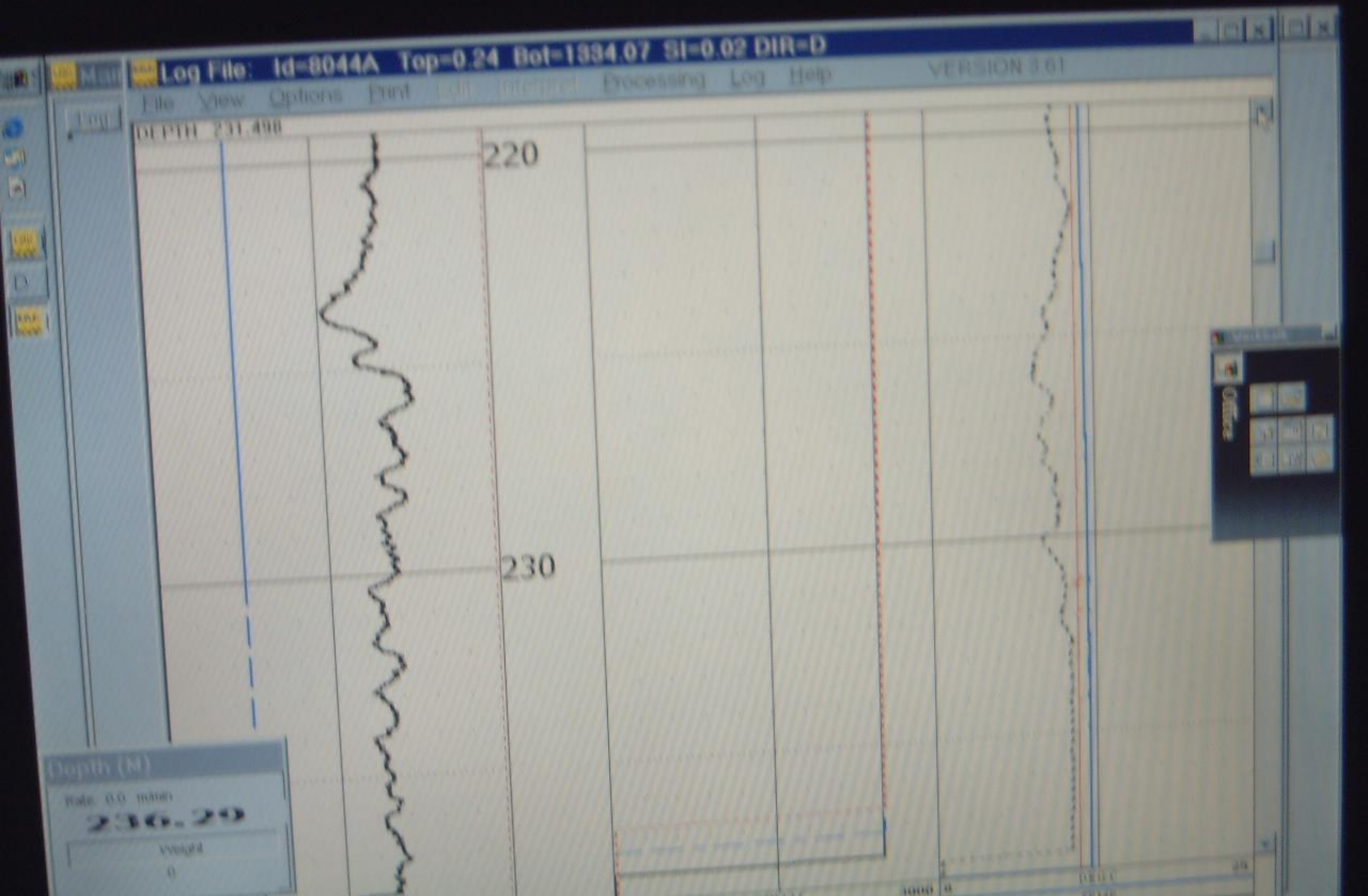
MECHANICAL DRILLING

GEOPHYSICAL WELL LOGGING

GEOPHYSICAL WELL LOGGING



GEOPHYSICAL WELL LOG



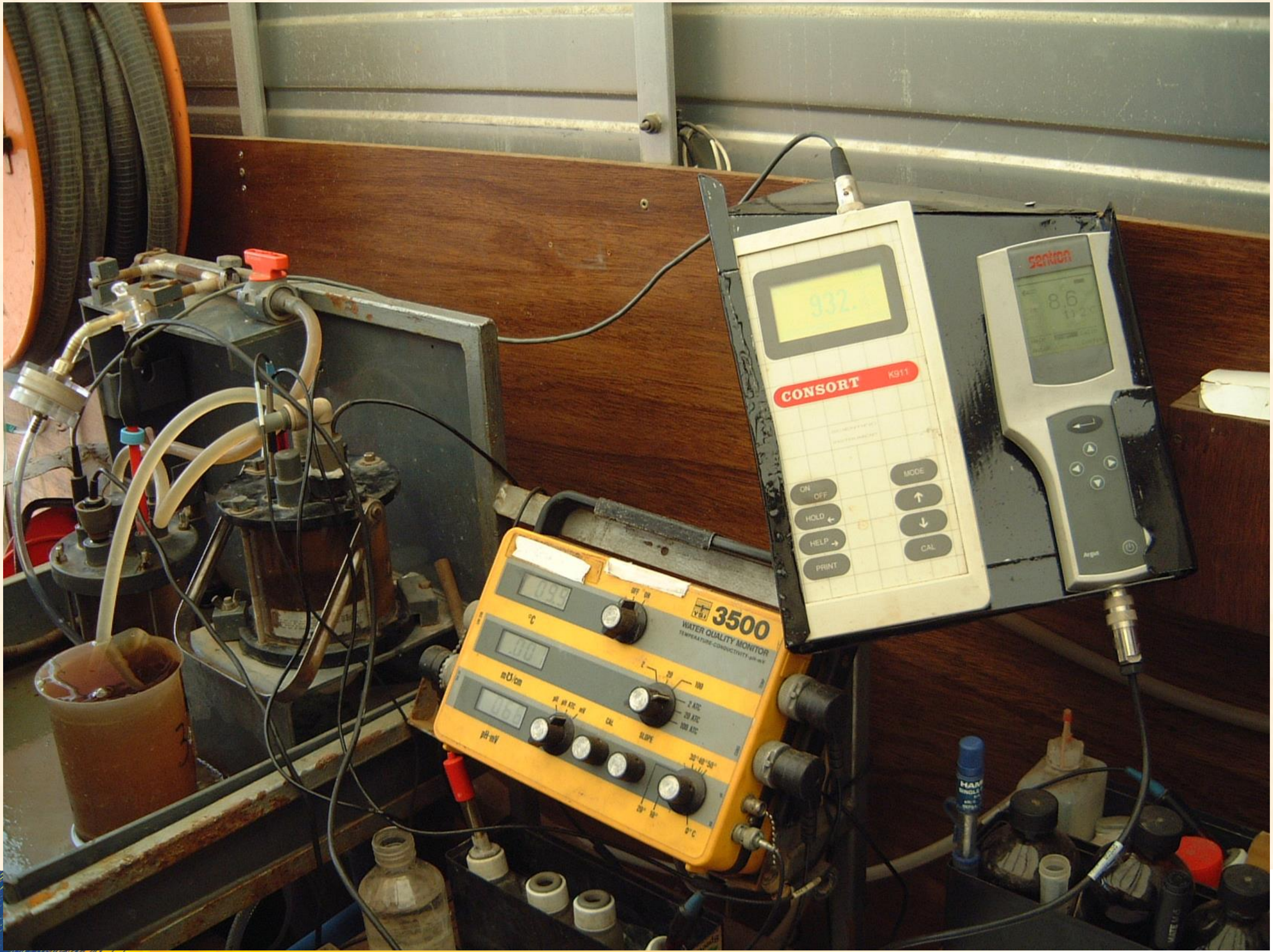
PIEZOMETER INSTALLATION

PIEZOMETRIC MEASUREMENT

PIEZOMETRIC MEASUREMENT

GROUNDWATER SAMPLING

GROUNDWATER SAMPLING

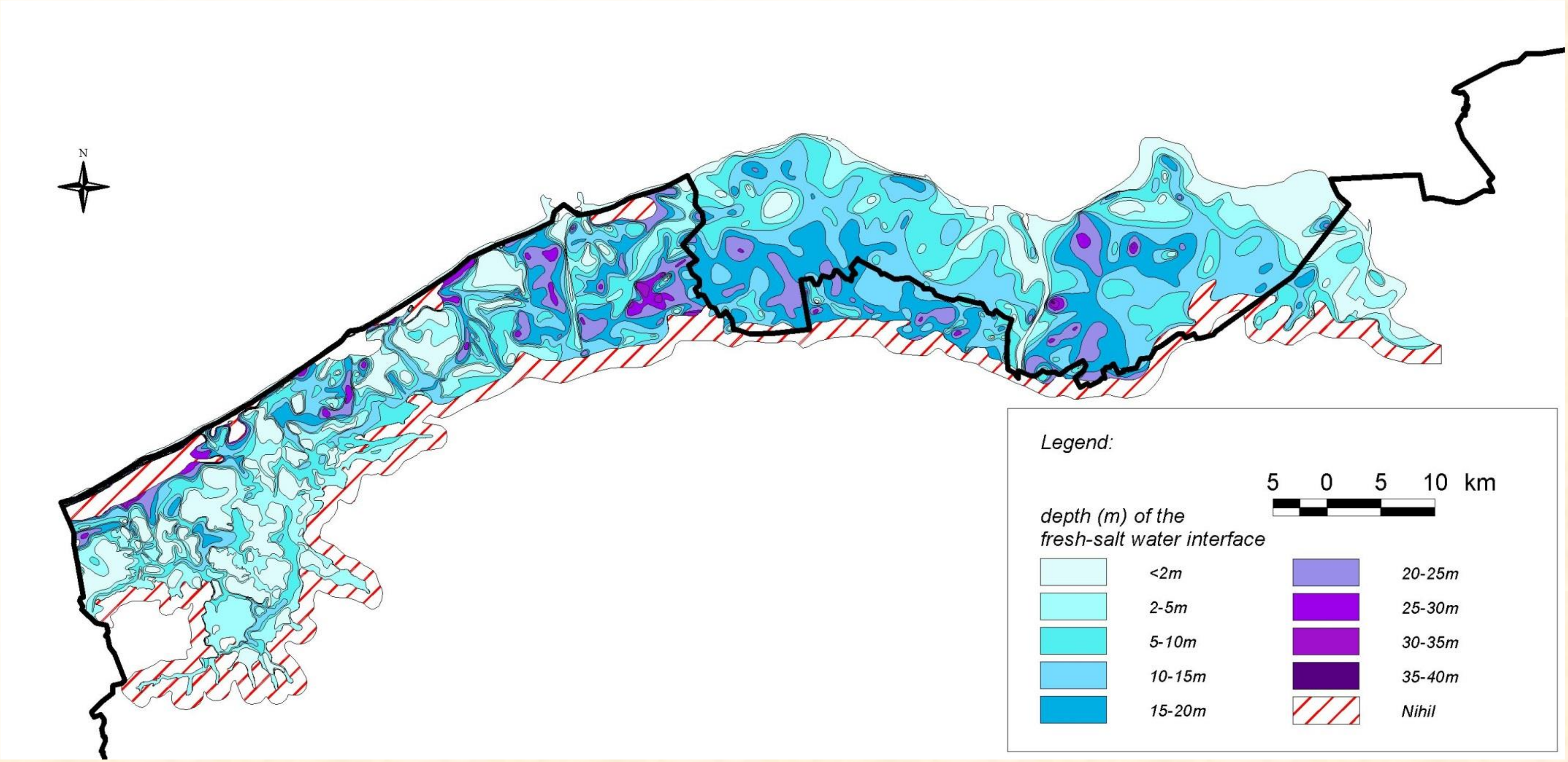


GROUNDWATER SAMPLING

GROUNDWATER ANALYSIS

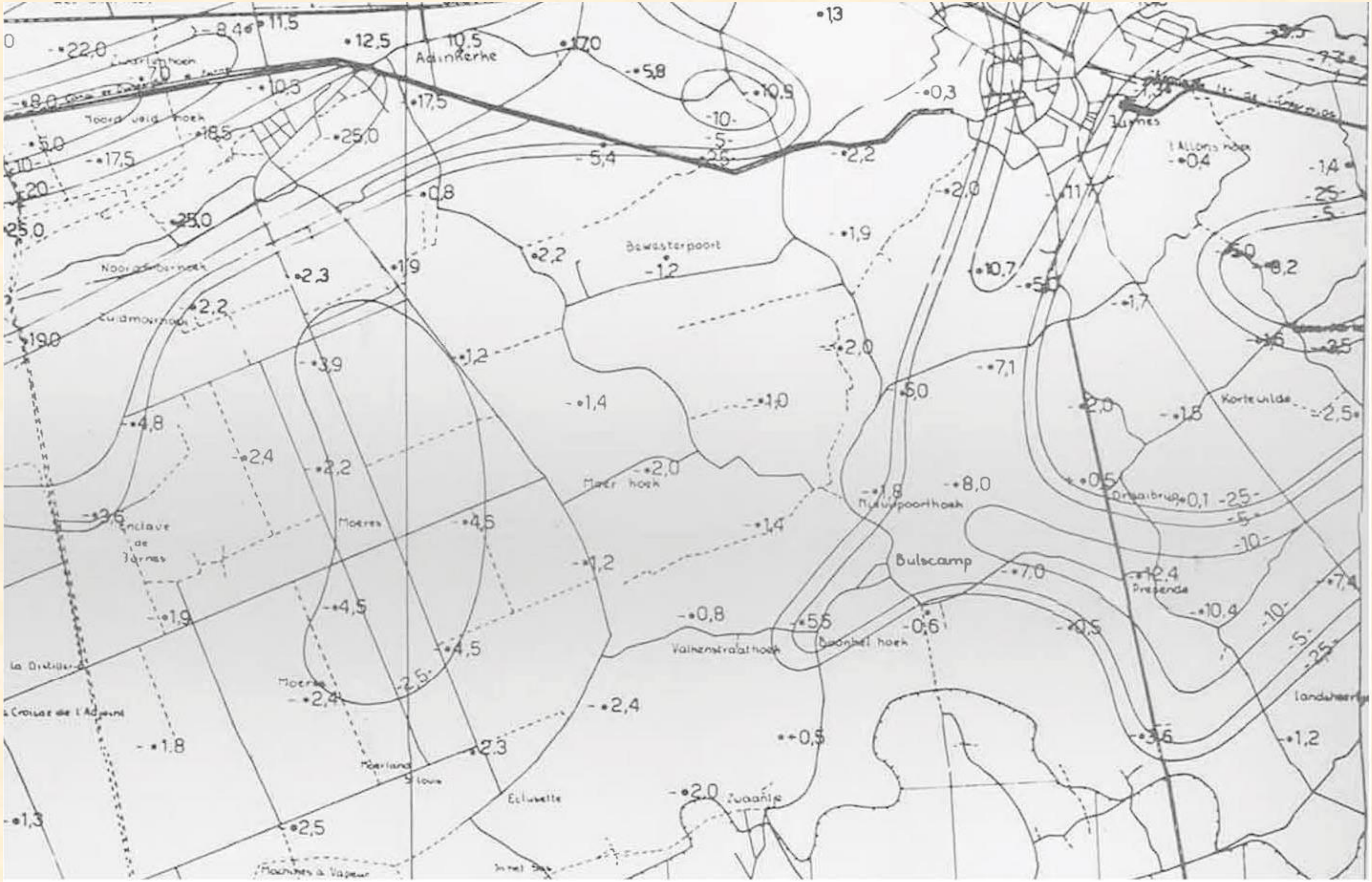
GROUNDWATER ANALYSIS

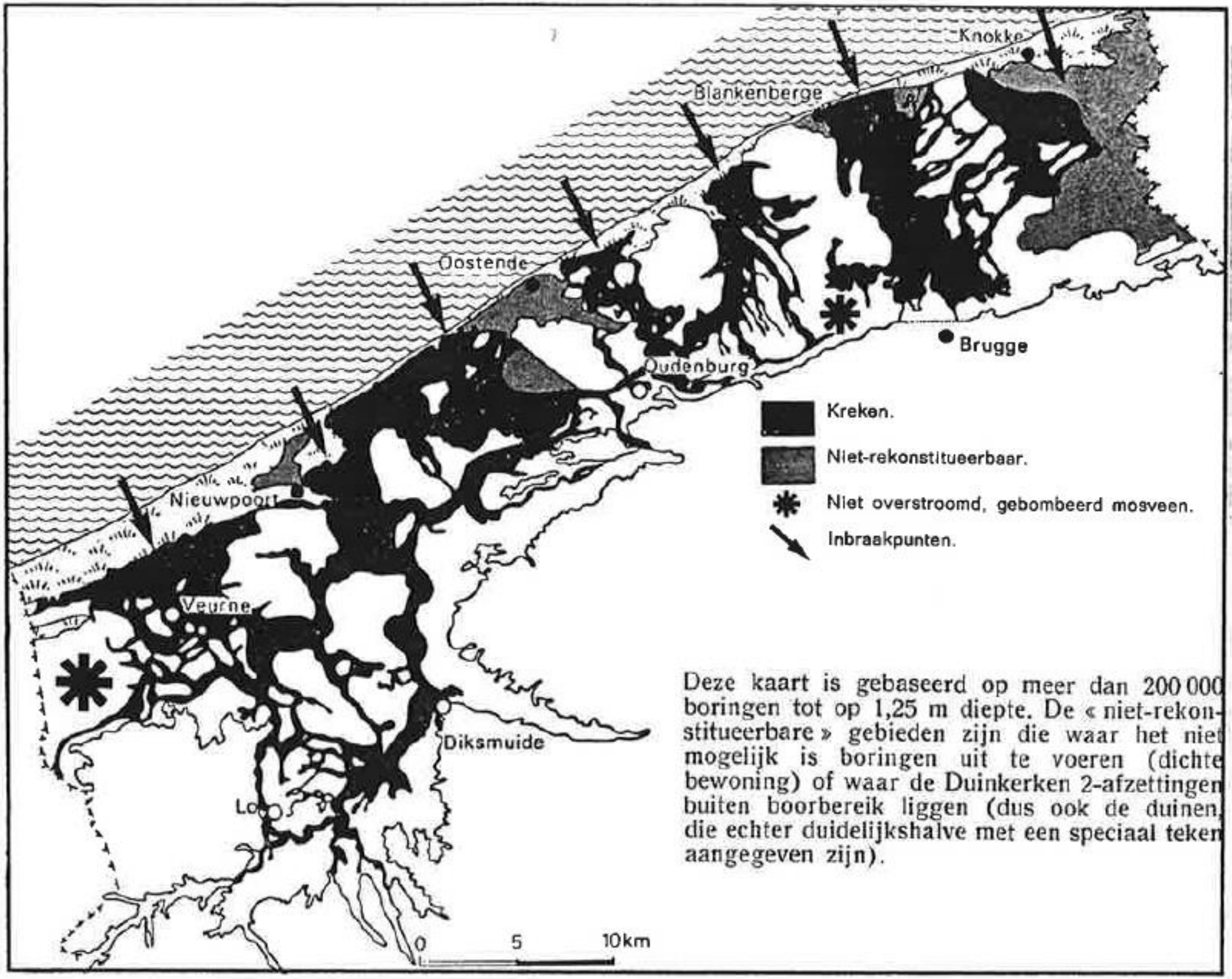
DEPTH OF FRESH/SALT WATER INTERFACE



For Belgian coast alone: based on > 1700 VES

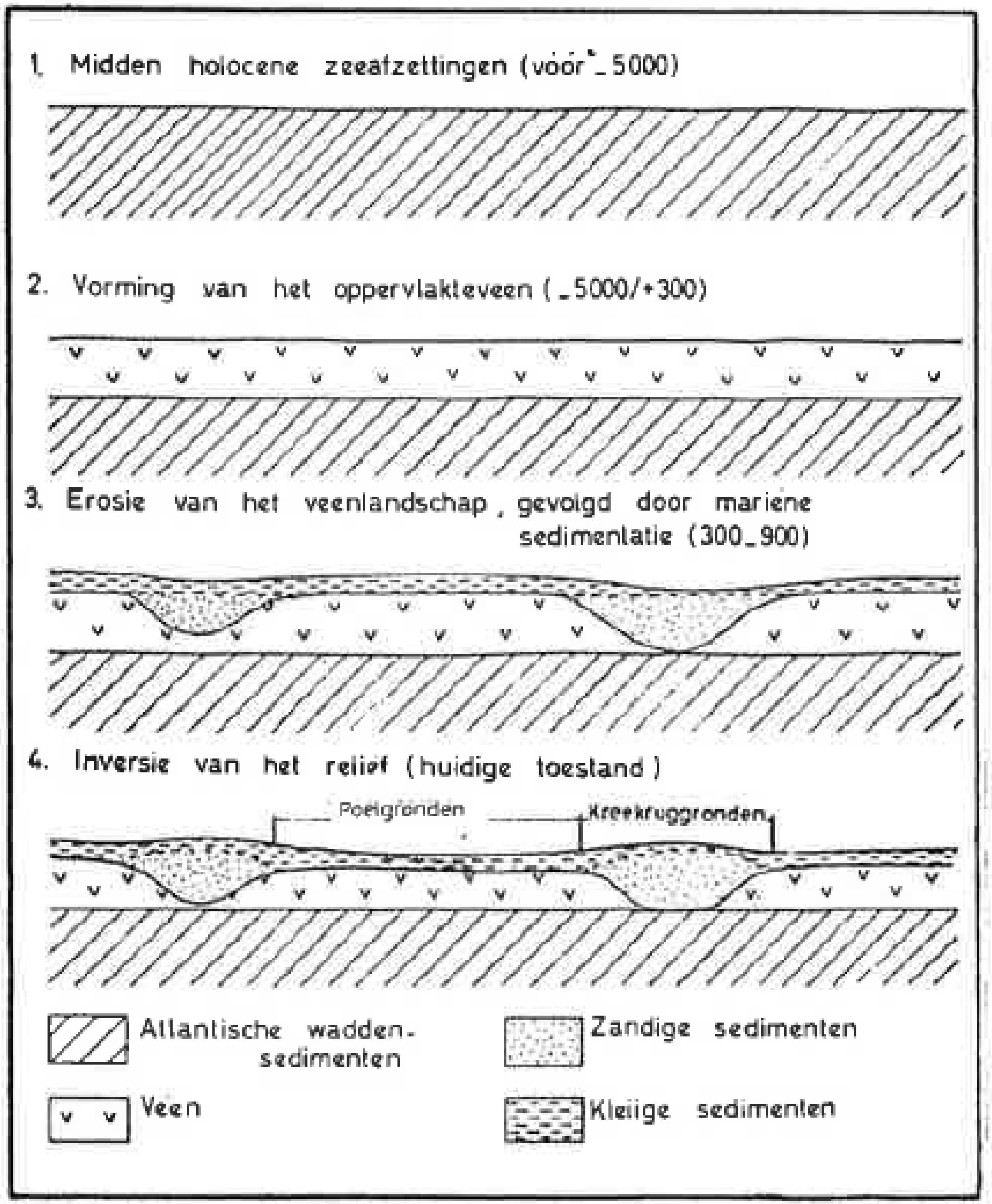
UNIVERSITEIT GENT
Laboratory for applied Geology and Hydrogeology
Krijgslaan 281- S8, B-9000 Ghent



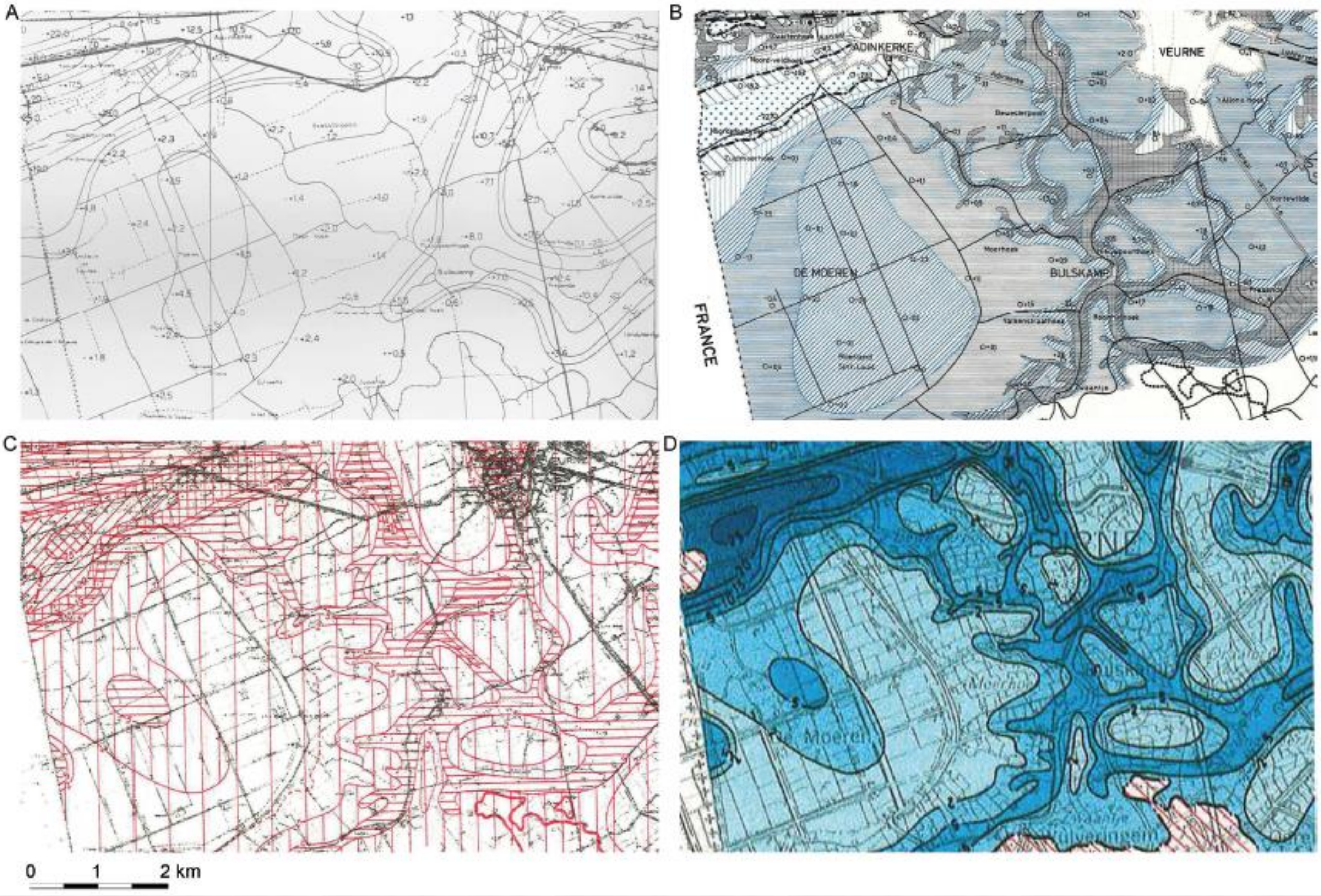


UNIVERSITEIT GENT

Creek systems based on 200 000 drillings for soil mapping



Inversion of topography of creek systems (Tavernier, 1947)


A
B
C
D
ADINKERKE
VEURNE
DE MOEREN
BULSKAMP
FRANCE
Moeren
0 1 2 km

MAPPING THE FRESH-SALT INTERFACE BY GEOPHYSICAL PROSPECTION

DC resistivity electrical method: used since late 1930s (e.g. Belgian coastal plain: De Breuck et al., 1974, 1989)

New methods, e.g. **Airborne electromagnetic surveys**

HOWEVER: **how to compare both results?**

Measuring ΔV and I:

$$\rho = \frac{\Delta V}{I} G$$

Archie's law (1942) (for non-conductive rock matrix):

$$F = \frac{\rho_b}{\rho_w}$$

Patnode & Willie (1950) (when $1/\rho_m$ becomes important):

$$\frac{1}{\rho_b} = \frac{1}{\rho_m} + \frac{1}{F\rho_w}$$

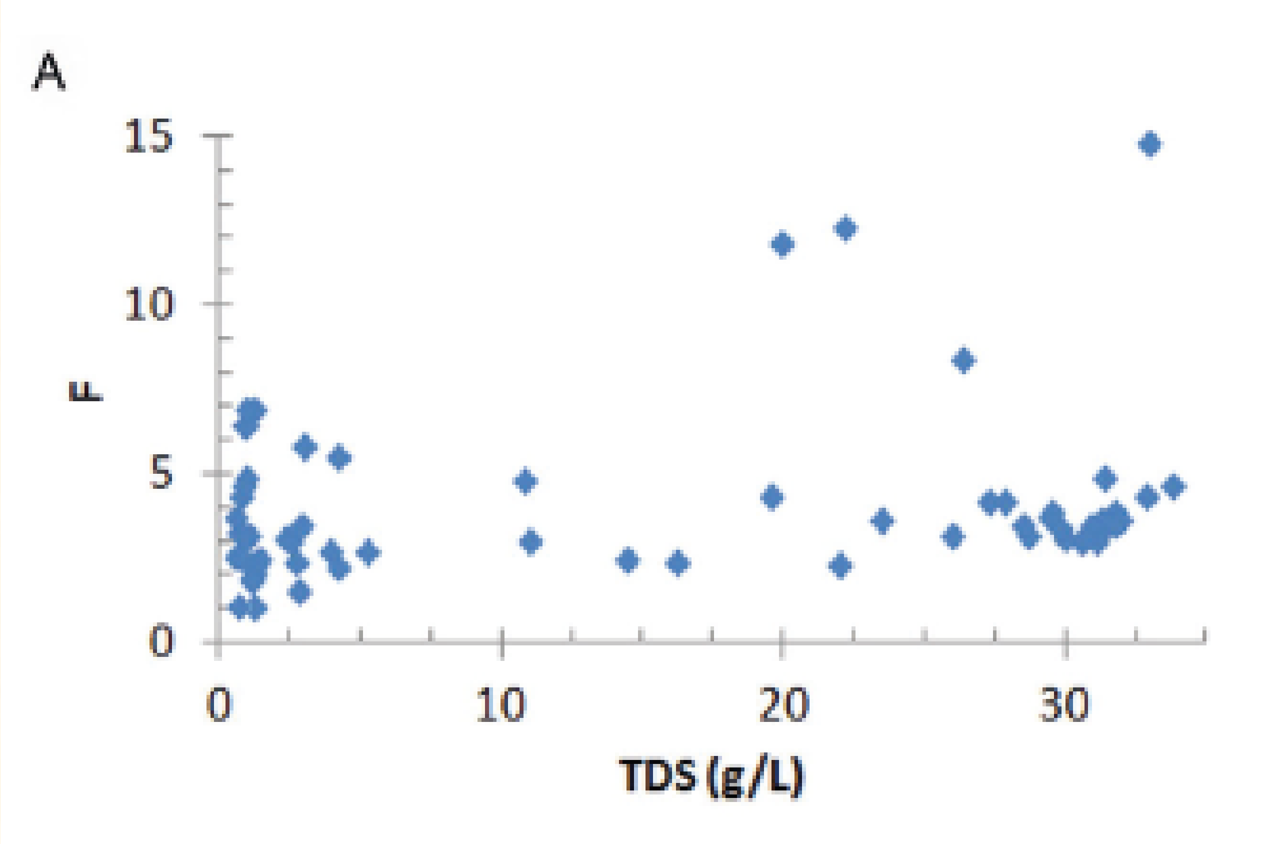
Relation TDS – pore water conductivity:

$$TDS = \frac{10 f_{11}}{\rho_w}$$

VES-interface: in general, in middle of transition zone of ρ_b

Studies in eastern coastal plain

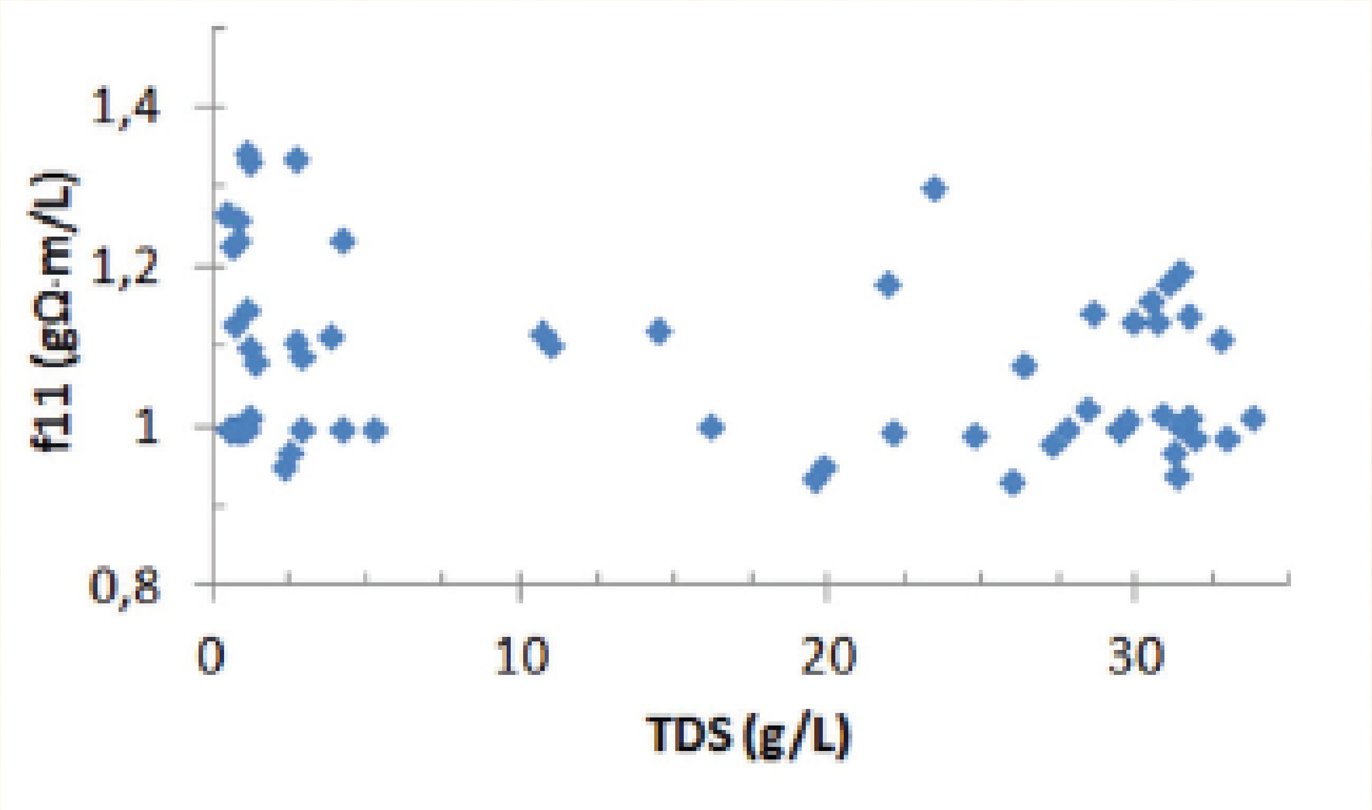
F determined by measurement of $\boldsymbol{\rho_w}$ (water samples) and $\boldsymbol{\rho_b}$ (LN log)



F varies between 1 and 15, with average of 4.4

Studies in eastern coastal plain

f_{11} determined from measured ρ_w (water samples) and TDS (lab analysis)



f_{11} varies between 0.9 and 1.4, with average of 1.07

Measuring ΔV and I:

$$\rho = \frac{\Delta V}{I} G$$

Archie's law (1942) (for non-conductive rock matrix):

$$F = \frac{\rho_b}{\rho_w}$$

Patnode & Willie (1950) (when $1/\rho_m$ becomes important):

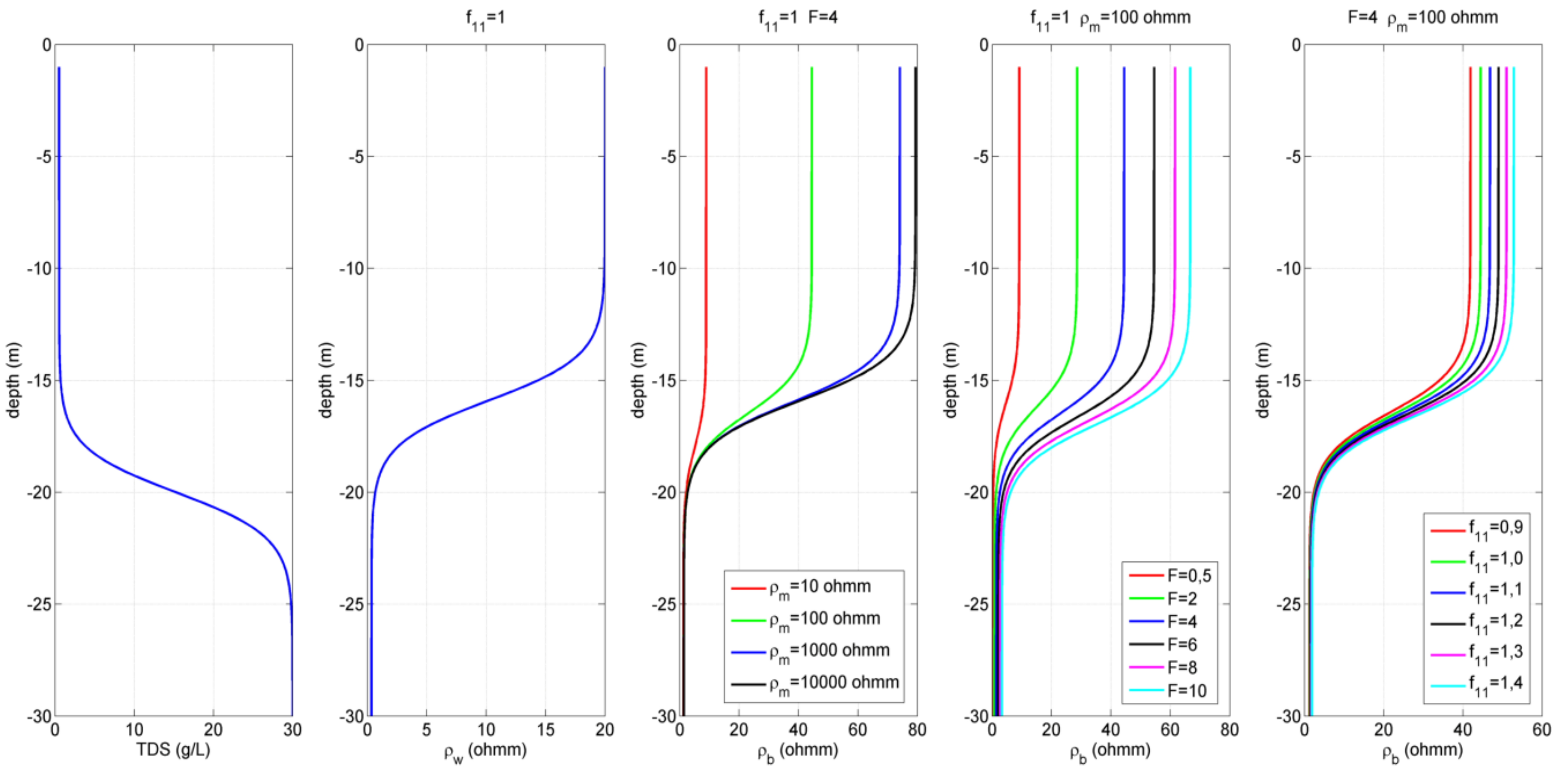
$$\frac{1}{\rho_b} = \frac{1}{\rho_m} + \frac{1}{F\rho_w}$$

Relation TDS – pore water conductivity:

$$TDS = \frac{10 f_{11}}{\rho_w}$$

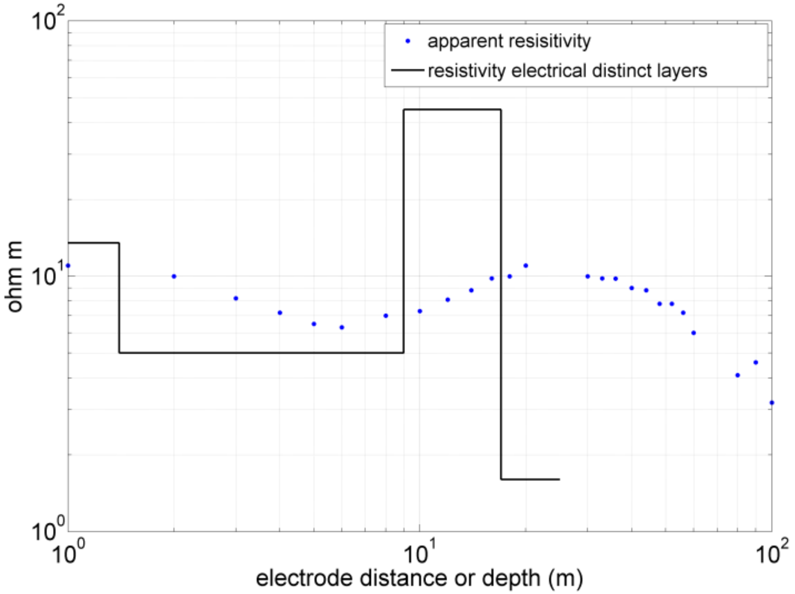
VES-interface: in general, in middle of transition zone of ρ_b

Hypothetical salinity profile and the resulting pore water and bulk resistivity as a function of depth for a range of values of F, ρ_m and f_{11}.



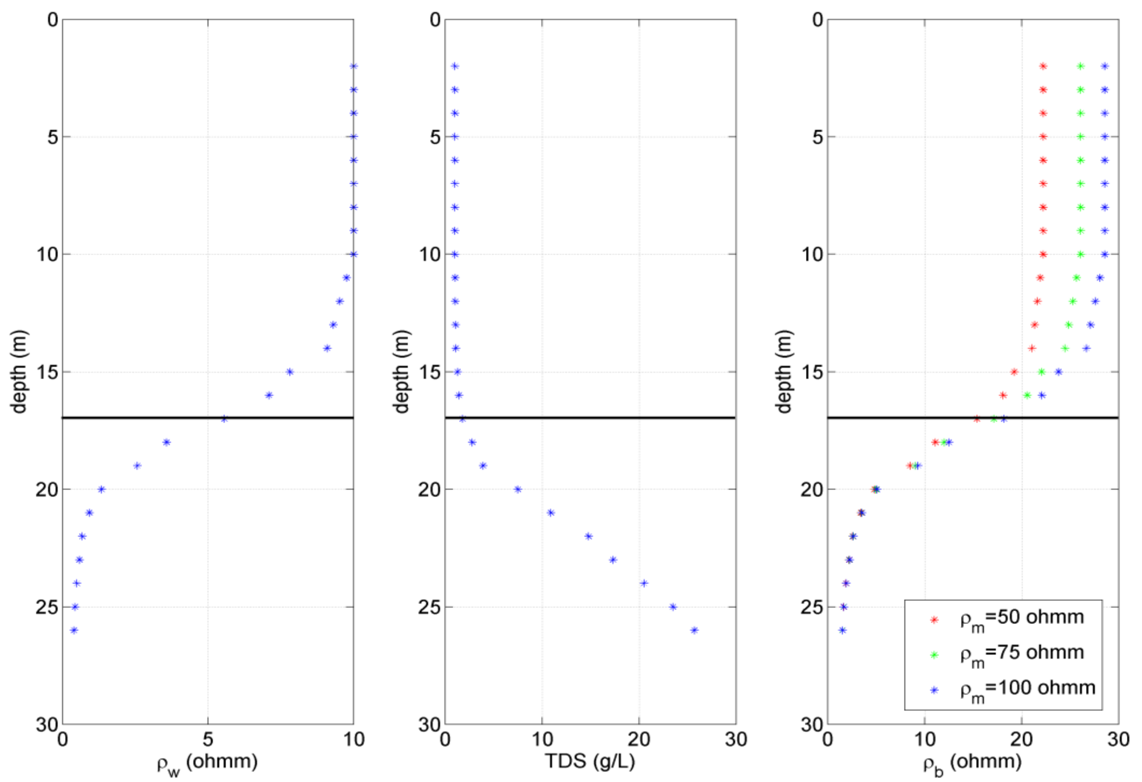
Transition zone in terms of ρ is shifted upwards compared to TDS!

(more with increasing ρ_m , decreasing F and increasing f_{11})



VES data and interpreted geological model for field example:
interface was found at 17 m.
(above: ρ_b is 45 Ωm; below ρ_b is 1.6 Ωm)

Measured pore water resistivity and calculated TDS and bulk resistivity as a function of depth.
VES interface at 17 m.



Plot of bulk resistivity below interface mapped by De Breuck et al. (1974) as a function of bulk resistivity above interface.

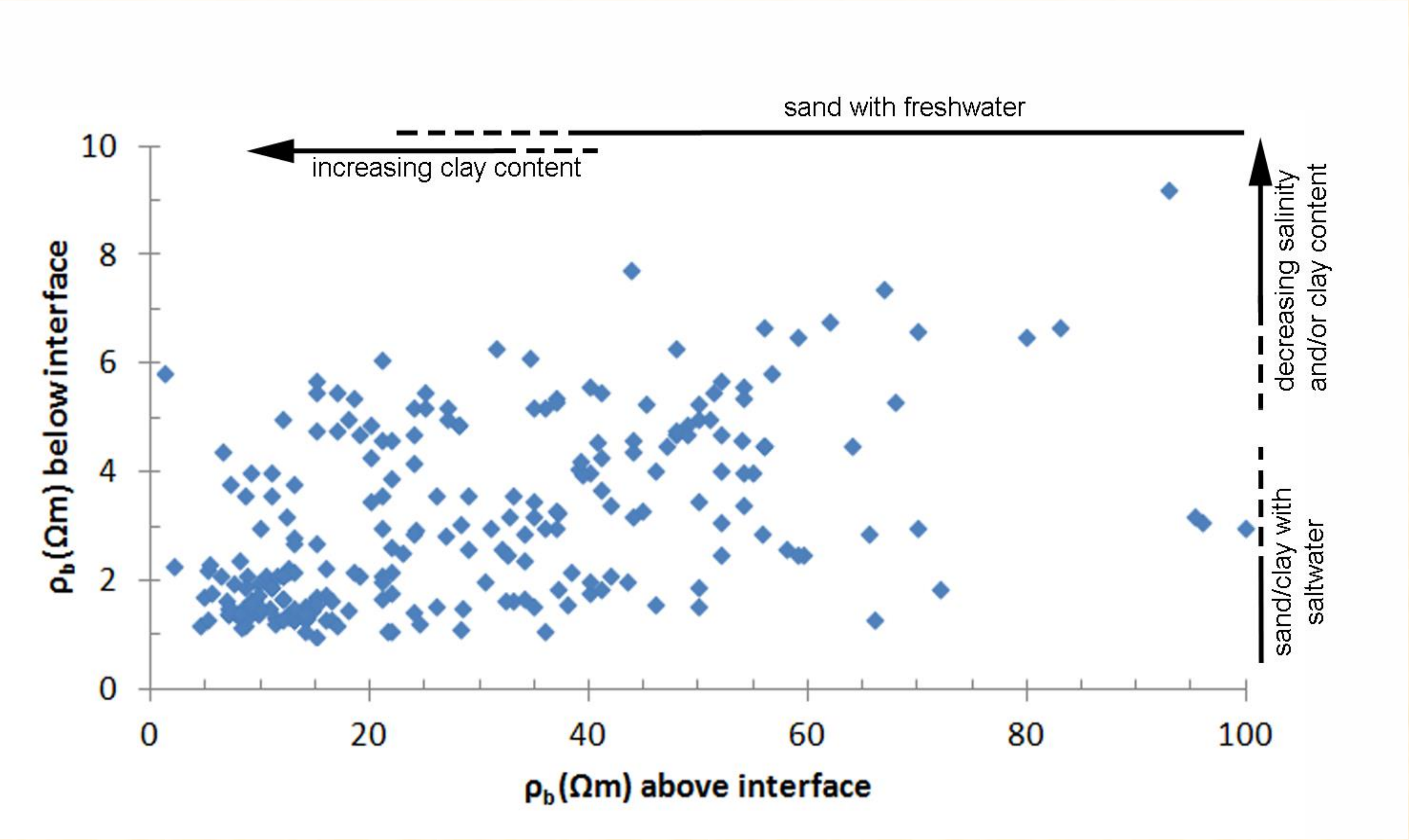
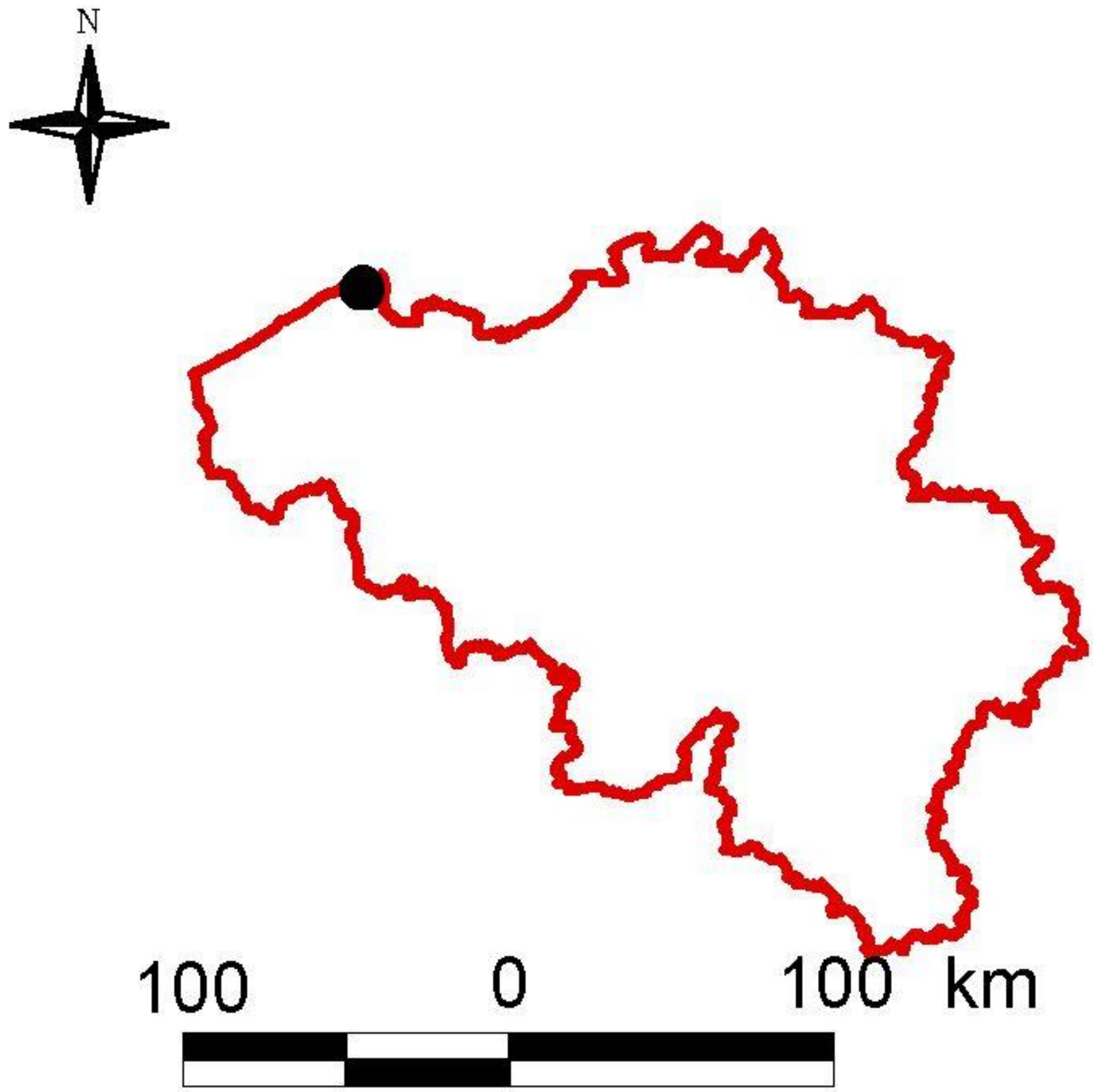


***Table** 1 The range of bulk resistivity for different natural materials (after De Moor and De Breuck, 1964, Marechal et al., 1957 and Marechal et al., 1970).*

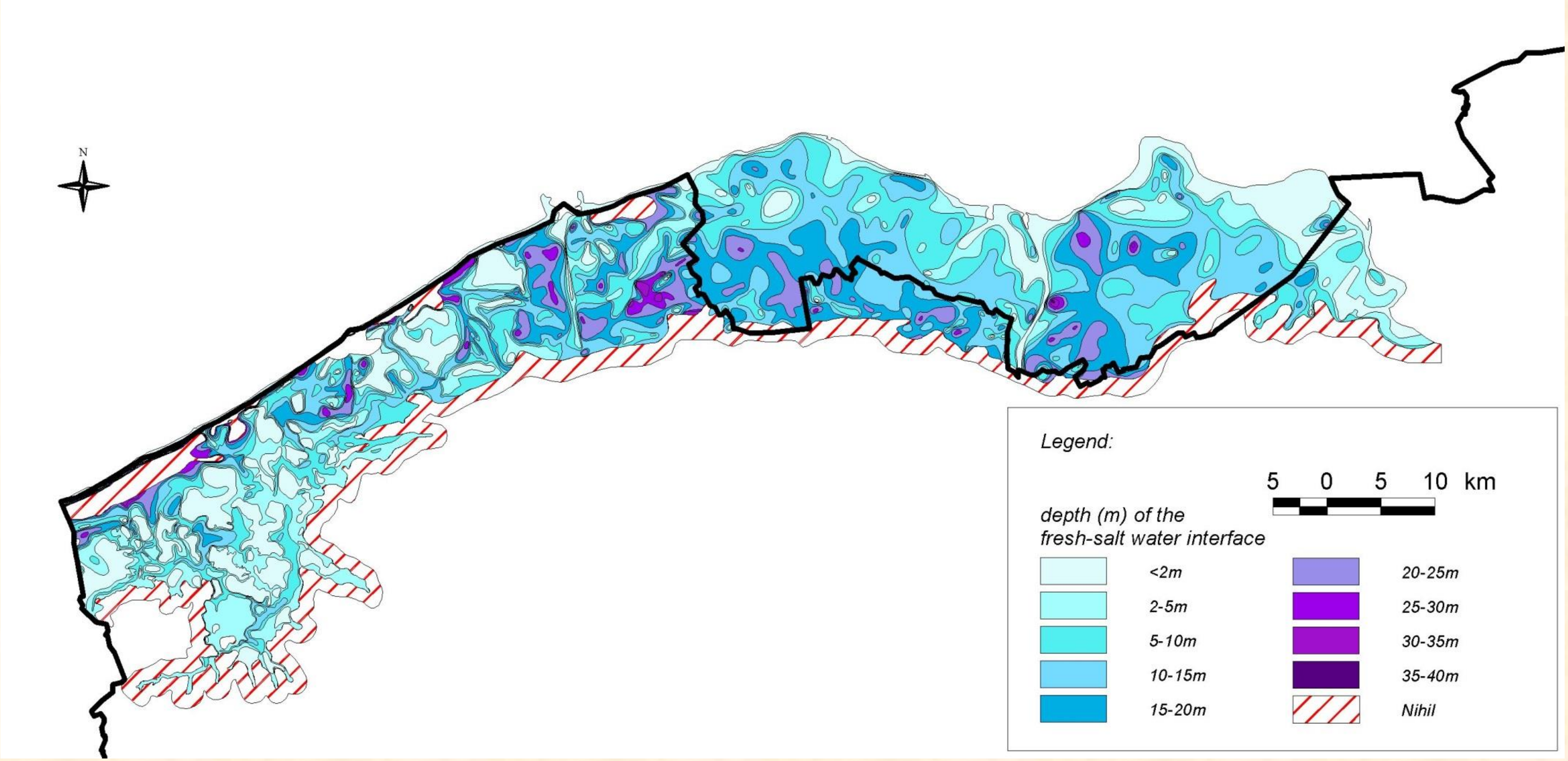
natural material	bulk resistivity ρ_b (Ωm)
dry sand	100 - 1000
sand with fresh pore water	40 - 100
loam with fresh pore water	25 - 40
arenaceous clay with fresh pore water	15 - 30
clay with fresh pore water	6 – 15
sediments with saline pore water	1 - 10

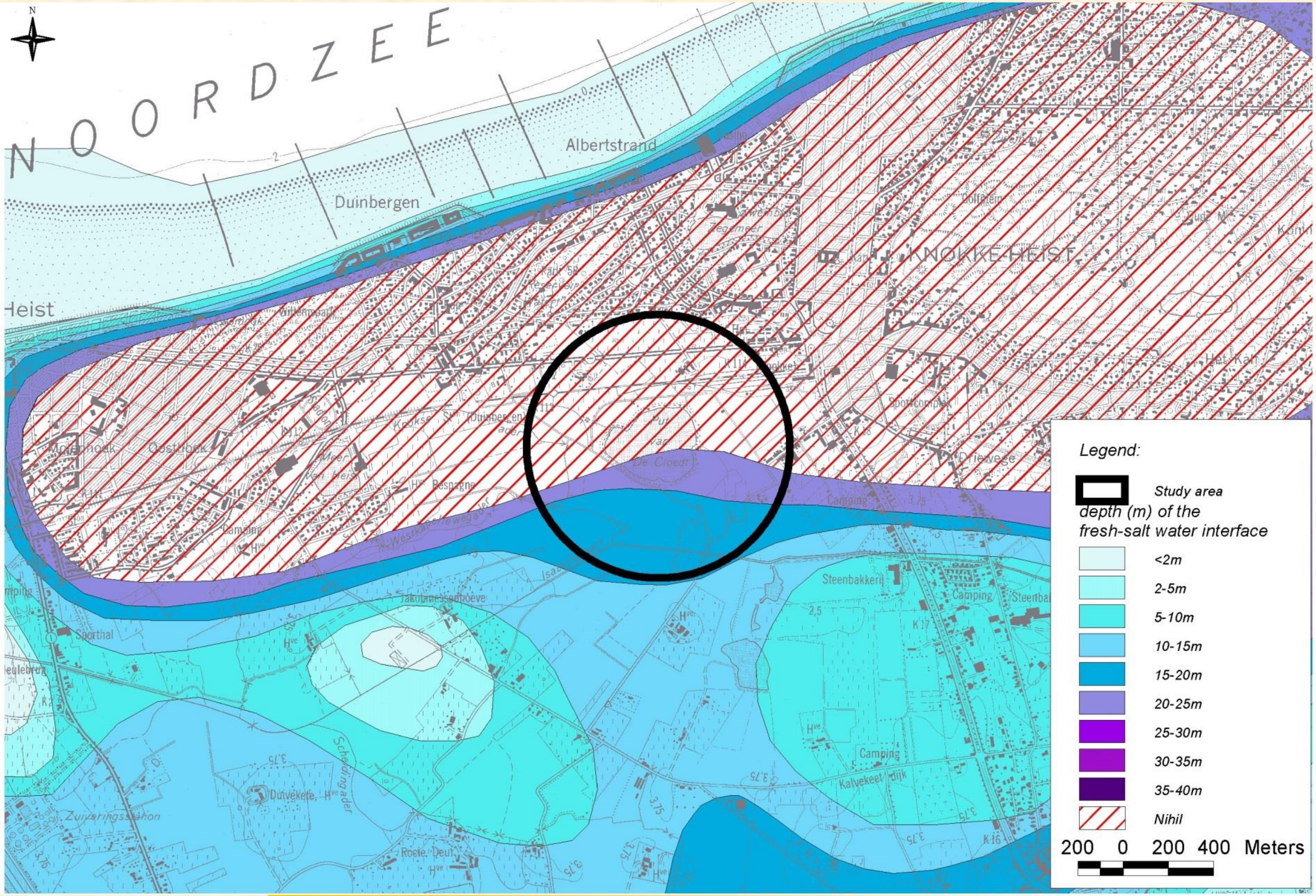
< 6 Ωm: clearly salinized sediments
< 3 Ωm: highly salinized sediments

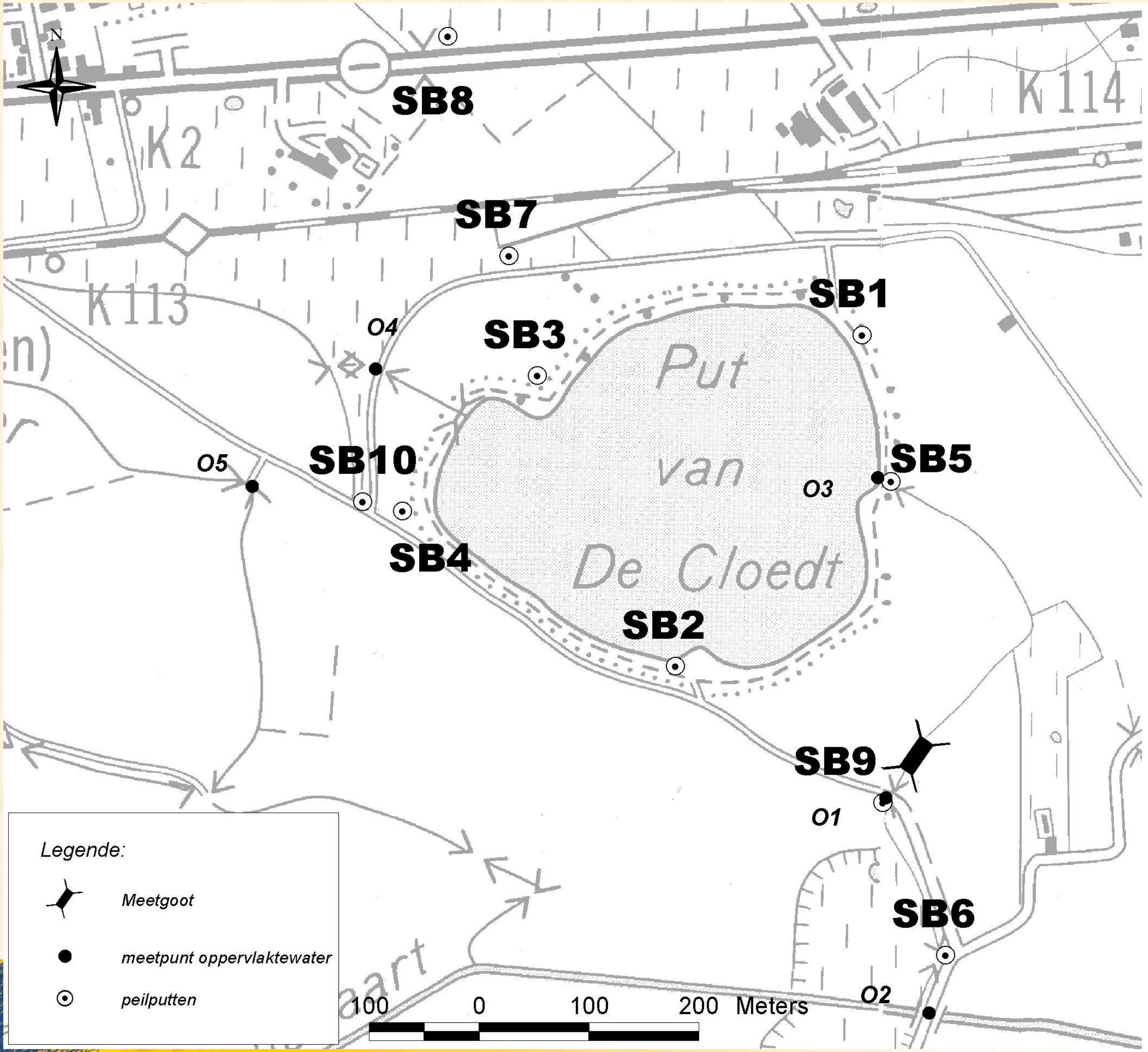
However, do not take 6 Ωm (or any resistivity value) as value for the interface!!!

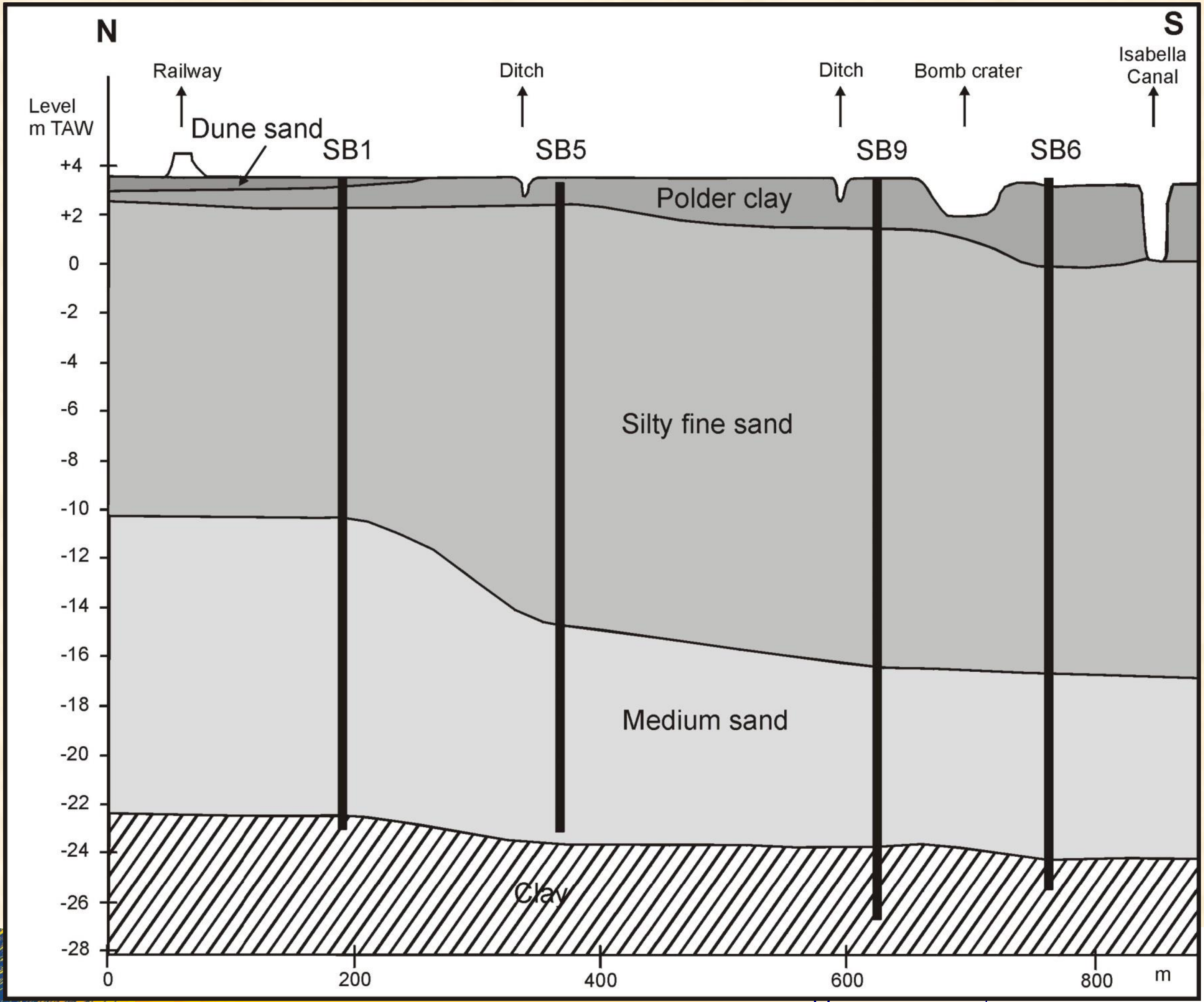

N
100
0
100 km

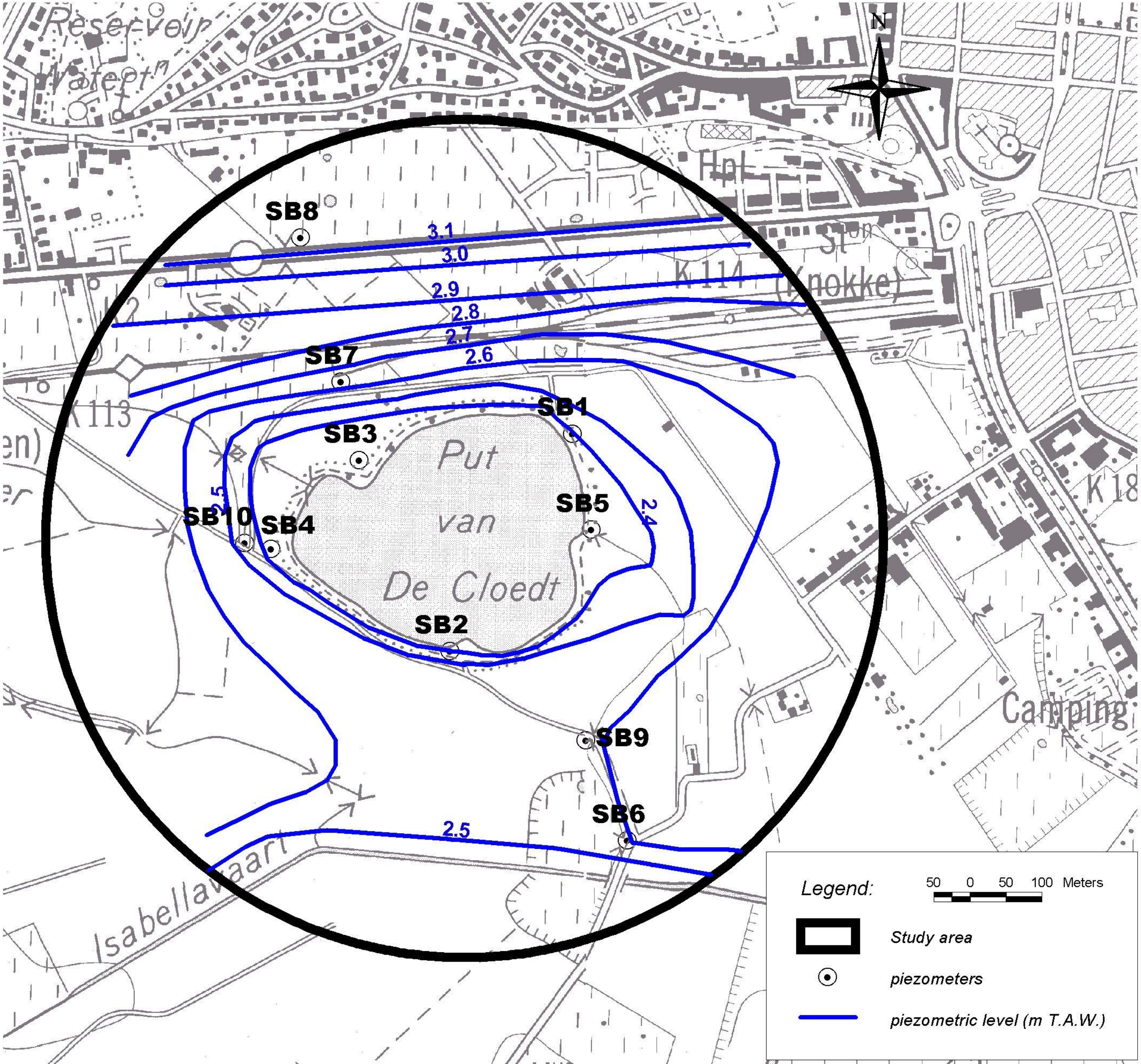
DEPTH OF FRESH/SALT WATER INTERFACE



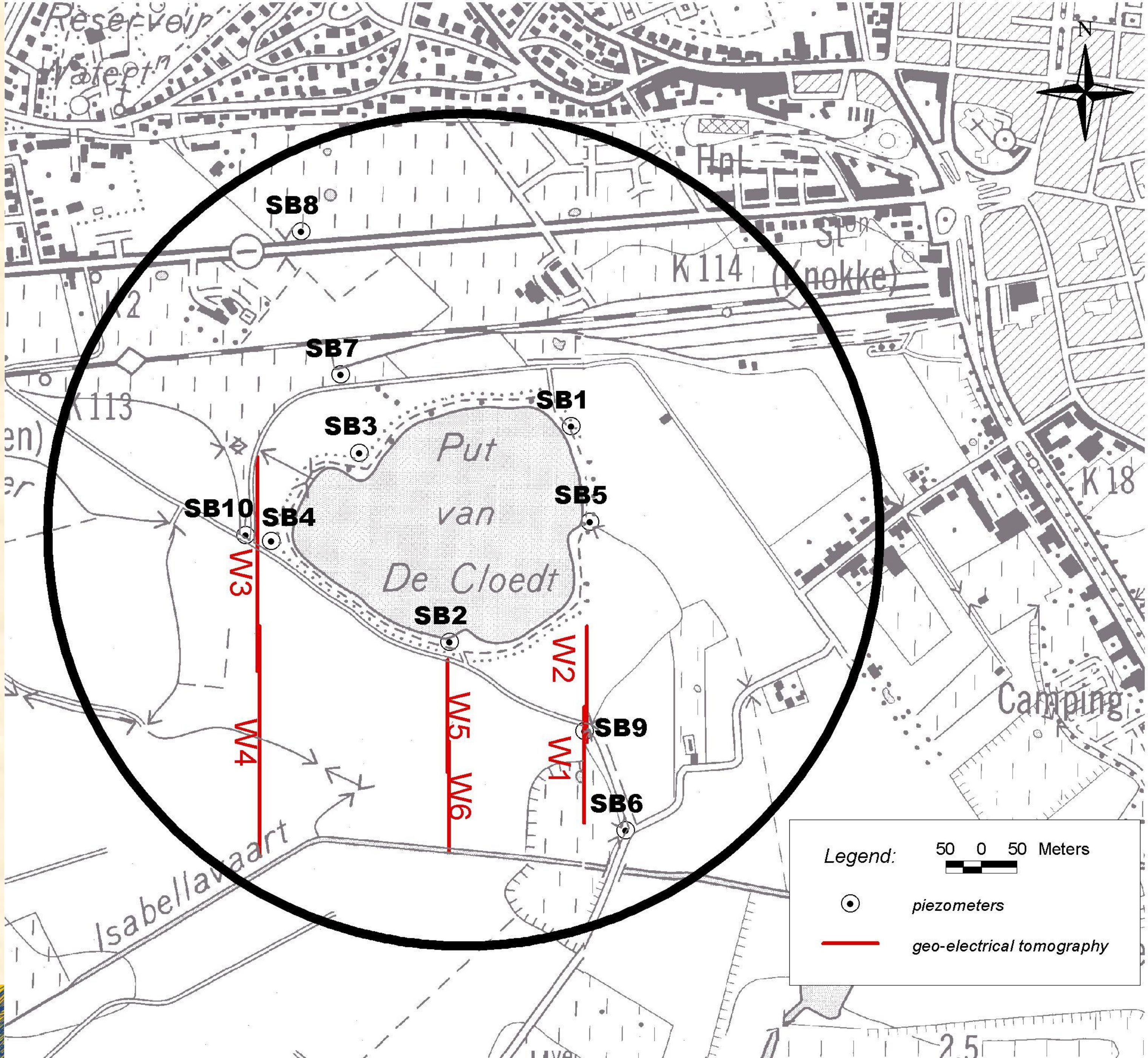

N
NOORDZEE
Albertstrand
Duinbergen
Heist
KNOKKE-HEIST
Legend:
Study area
depth (m) of the fresh-salt water interface
<2m
2-5m
5-10m
10-15m
15-20m
20-25m
25-30m
30-35m
35-40m
Nihil
200 0 200 400 Meters


N
SB8
K2
K114
SB7
K113
SB1
O4
SB3
Put
van
De Cloedt
SB10
O5
SB5
O3
SB4
SB2
SB9
O1
SB6
O2
Legende:
Meetgoot
meetpunt oppervlaktewater
peilputten
100 0 100 200 Meters

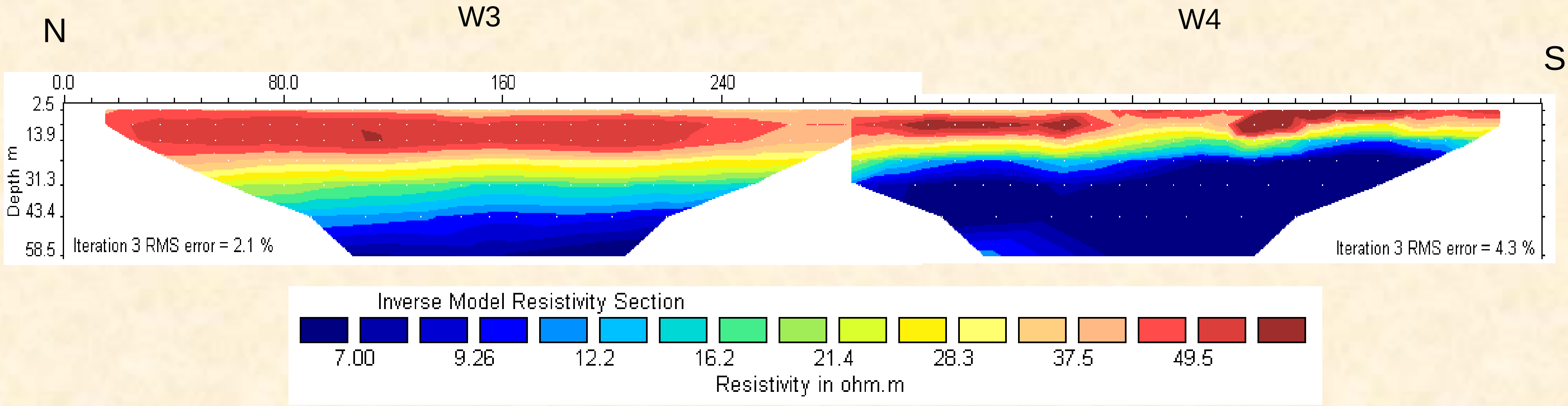

N
S
Railway
Ditch
Ditch
Bomb crater
Isabella
Canal
Level
m TAW
Dune sand
SB1
SB5
SB9
SB6
Polder clay
Silty fine sand
Medium sand
Clay
+4
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
0
200
400
600
800
m



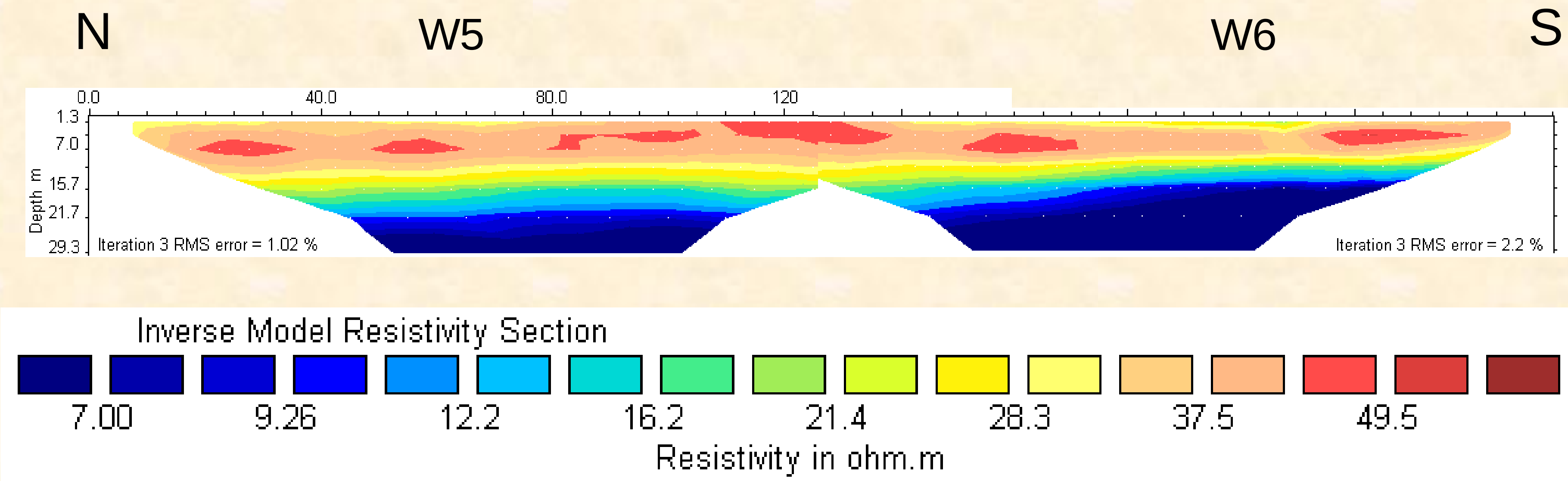
UNIVERSITEIT GENT

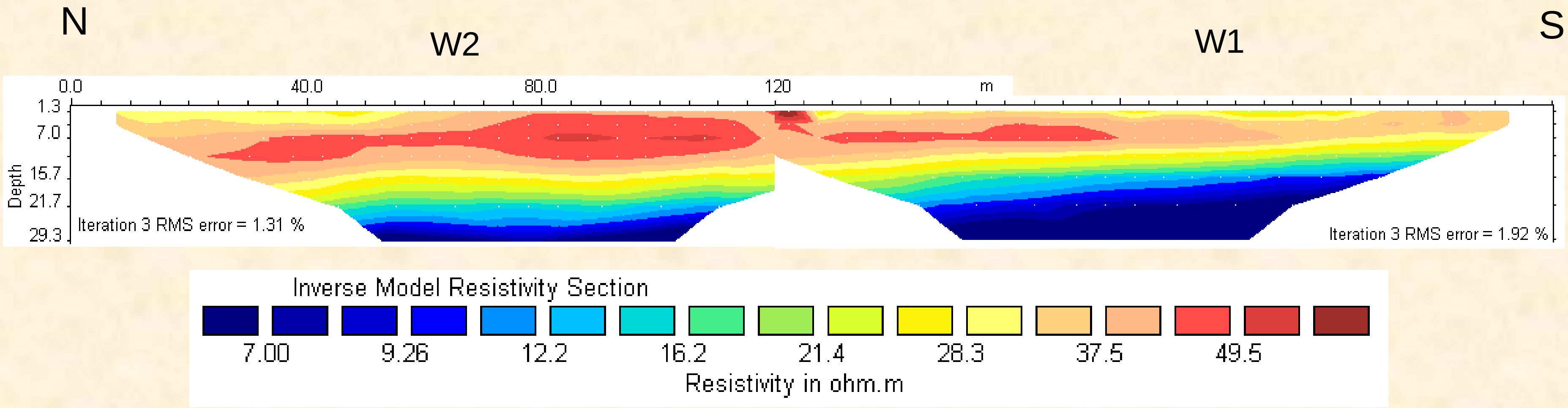


Put van De Cloedt
SB1
SB2
SB3
SB4
SB5
SB6
SB7
SB8
SB9
SB10
W1
W2
W3
W4
W5
W6
N
K 114
(Knokke)
K 113
K 18
Camping
Isabellavaart
Legend:
50 0 50 Meters
piezometers
geo-electrical tomography



N
W3
W4
S
0.0
80.0
160
240
2.5
13.9
31.3
43.4
58.5
Depth m
Iteration 3 RMS error = 2.1 %
Iteration 3 RMS error = 4.3 %
Inverse Model Resistivity Section
7.00
9.26
12.2
16.2
21.4
28.3
37.5
49.5
Resistivity in ohm.m


N
W5
W6
S
0.0
40.0
80.0
120
Depth m
1.3
7.0
15.7
21.7
29.3
Iteration 3 RMS error = 1.02 %
Iteration 3 RMS error = 2.2 %
Inverse Model Resistivity Section
7.00
9.26
12.2
16.2
21.4
28.3
37.5
49.5
Resistivity in ohm.m


N
W2
W1
S
0.0
40.0
80.0
120
m
1.3
7.0
15.7
21.7
29.3
Depth
Iteration 3 RMS error = 1.31 %
Iteration 3 RMS error = 1.92 %
Inverse Model Resistivity Section
7.00
9.26
12.2
16.2
21.4
28.3
37.5
49.5
Resistivity in ohm.m

DEDUCING WATER RESISTIVITY FROM FORMATION RESISTIVITY

Archie's law (1942) (for non-conductive rock matrix):

$$F = \frac{\rho_b}{\rho_w}$$

ρ_b is measured by LN-logging

In SWI studies, ρ_w strongly varies, and variation of F can be ignored

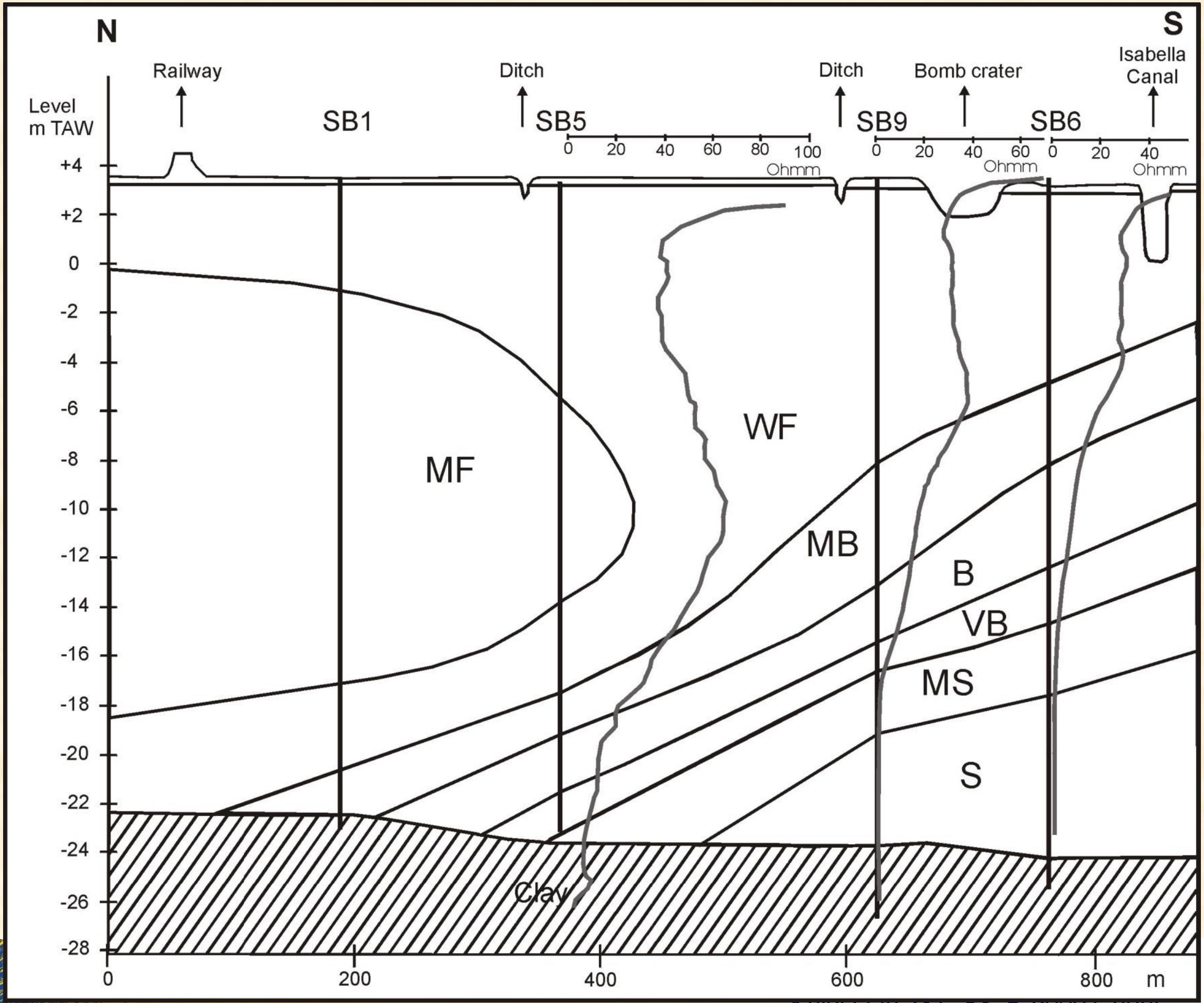
Based on a large database of measured ρ_b and ρ_w in Belgian coastal plain, and **average formation factor of F = 4** has been deduced:

$$4 = \frac{\rho_b}{\rho_w}$$

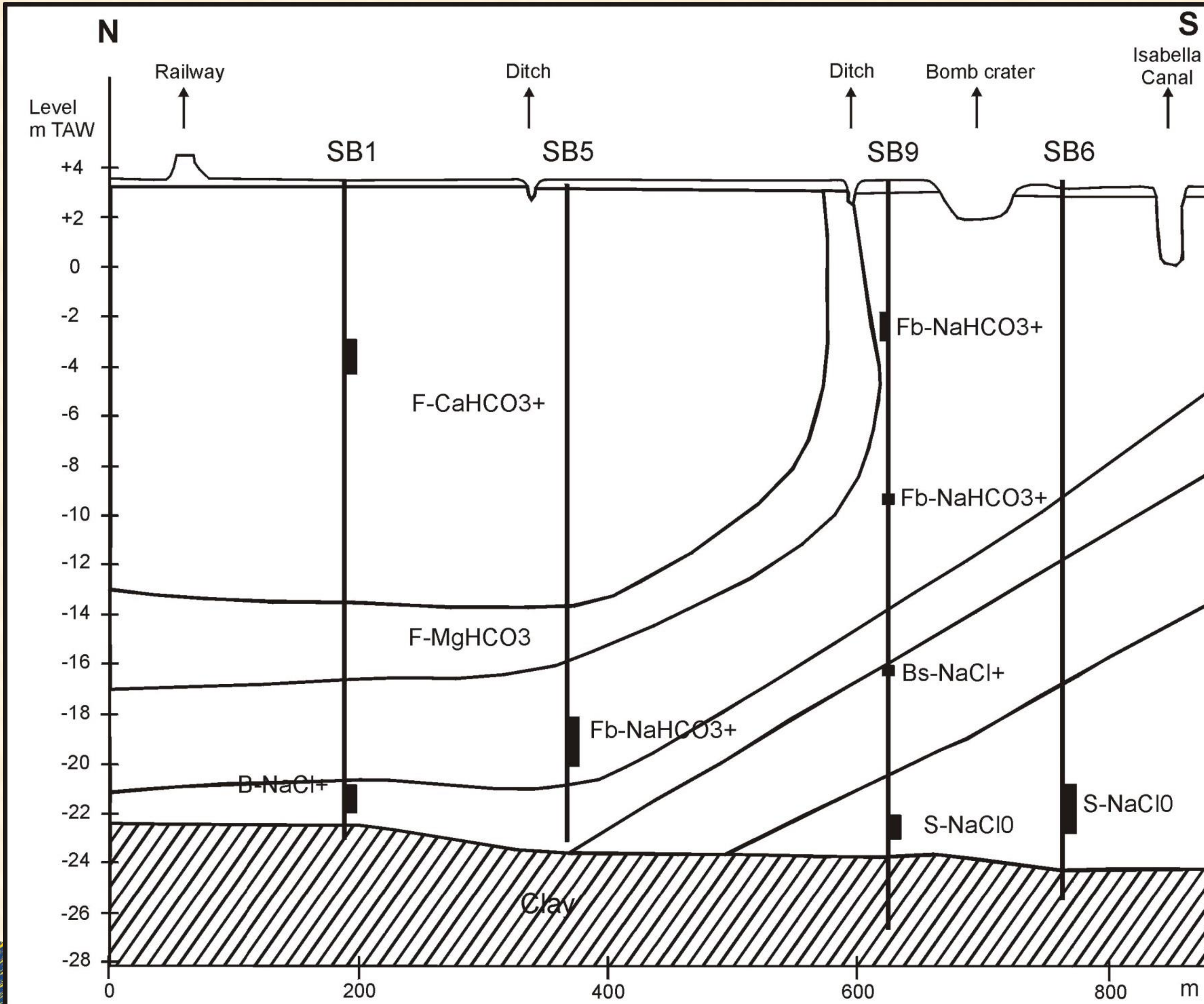
$$TDS = \frac{10 f_{11}}{\rho_w}$$ and assuming that $f_{11} = 1.0$

LN & SN LOGGING

Groundwater quality group	TDS (mg/l)	Groundwater resistivity ρ_w (ohm.m, 11°C)	Formation resistivity ρ_b (ohm.m, 11°C)
Very fresh (VF)	< 200	> 50	> 200
Fresh (F)	200 – 400	50 – 25	200 – 100
Moderately fresh (MF)	400 – 800	25 – 12.5	100 – 50
Weakly fresh (WF)	800 – 1600	12.5 – 6.25	50 – 25
Moderately brackish (MB)	1600 – 3200	6.25 – 3.13	25 – 12.5
Brackish (B)	3200 – 6400	3.13 – 1.56	12.5 – 6.25
Very brackish (VB)	6400 – 12800	1.56 – 0.78	6.25 – 3.12
Moderately salt (MS)	12800 – 25600	0.78 – 0.39	3.12 – 1.56
Salt (S)	> 25600	< 0.9	< 1.56


N
S
Railway
Ditch
Ditch
Bomb crater
Isabella
Canal
Level
m TAW
SB1
SB5
SB9
SB6
0 20 40 60 80 100
Ohmm
0 20 40 60
Ohmm
0 20 40
Ohmm
+4
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
MF
WF
MB
B
VB
MS
S
Clay
0
200
400
600
800
m


Atlas Copco
XAS 30
UGC 619


N
S
Railway
Ditch
Ditch
Bomb crater
Isabella
Canal
Level
m TAW
SB1
SB5
SB9
SB6
+4
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
Fb-NaHCO3+
F-CaHCO3+
Fb-NaHCO3+
F-MgHCO3
Bs-NaCl+
Fb-NaHCO3+
B-NaCl+
S-NaCl0
S-NaCl0
Clay
0
200
400
600
800
m

FACTORS DETERMINING GROUNDWATER COMPOSITION

- composition (and mixing ratio) of end members

- hydrodynamics → mass transport processes
  - advection
  - hydrodynamic dispersion (mixing)

- chemical reactions
  - within water phase
  - with gas phase (unsaturated zone)
  - with aquifer matrix

INTERACTION

HYDRODYNAMICS $\rightarrow$ **HYDROGEOCHEMISTRY**

$\leftarrow$

$\rightarrow$ both will tend to establish **new equilibrium**

$\rightarrow$ difference in **time scales**:

- hydrodynamic equilibrium is reached fairly quickly
- hydrochemical equilibrium may take very long to be reached

YET: in coastal aquifers: complicating factor: hydrogeochemistry influences hydrodynamics

INTEGRATED APPROACH IS FUNDAMENTAL!

UNDERSTANDING NATURAL GROUNDWATER QUALITY CONTROLS

AQUIFER SYSTEM CHARACTERISATION

DATA AQUISITION
Observations / Measurements / Analysis / Tests
DATA (POST)PROCESSING
Visualisation / Statistical Analysis / Trend analyses

↓

SYSTEM ANALYSIS

↙ ↘

HYDRODYNAMICS

Groundwater flow cycles
Recharge / Discharge area's
Groundwater flow velocities
Well capture zones

HYDROCHEMISTRY

End memebers
Chemical processes
Sediment interaction

↘ ↙

**INTEGRATION
CONCEPTUAL MODEL**

↓

MODELLING

Three dimensional
Groundwater flow
Mixing / advection / dispersion
Hydrogeochemical

↓

APPLICATION

Prediction
Protection
Optimalisation
Management

In coastal aquifers

2 END MEMBERS:

recharge water:

infiltrating rain dissolving calcite

F-$CaHCO_3$0

seawater

S-NaCl0

SALINIZATION

- **advection** will bring the new saline end member in the aquifer, and both end members will move with groundwater flow

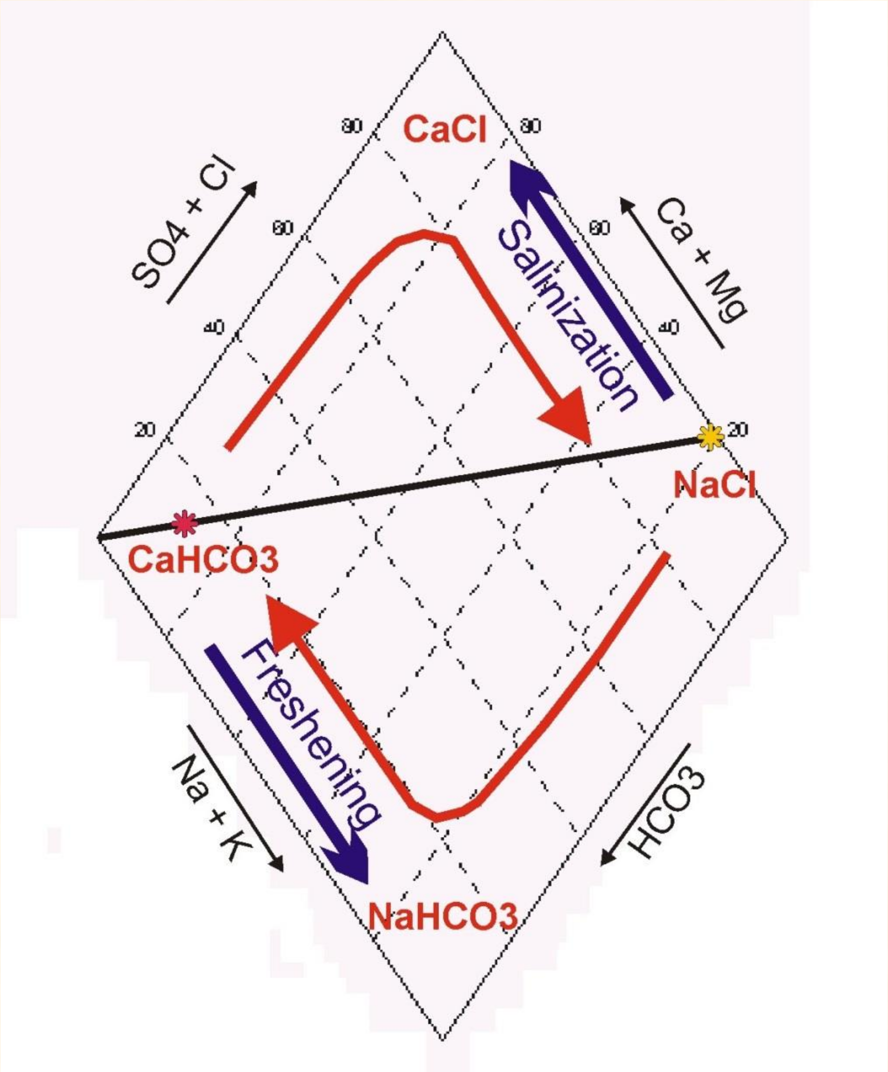
- at the interface, both end members will be mixed by **dispersion**

$$F \rightarrow F_b \rightarrow B \rightarrow B_s \rightarrow S$$

- the main chemical reaction will be cation exchange

$\Rightarrow$ deficit of marine cations (-)

$$CaHCO_30 \rightarrow CaCl- \rightarrow NaCl- \rightarrow NaCl0$$


CaCl
SO4 + Cl
Ca + Mg
Salinization
NaCl
CaHCO3
Freshening
Na + K
HCO3
NaHCO3
80
80
60
60
40
40
20
20

In coastal aquifers

2 END MEMBERS:

seawater

S-NaCl0

recharge water:

infiltrating rain dissolving calcite

F-CaHCO$_3$0

FRESHENING

- **advection** will bring the new fresh end member in the aquifer, and both end members will move with groundwater flow

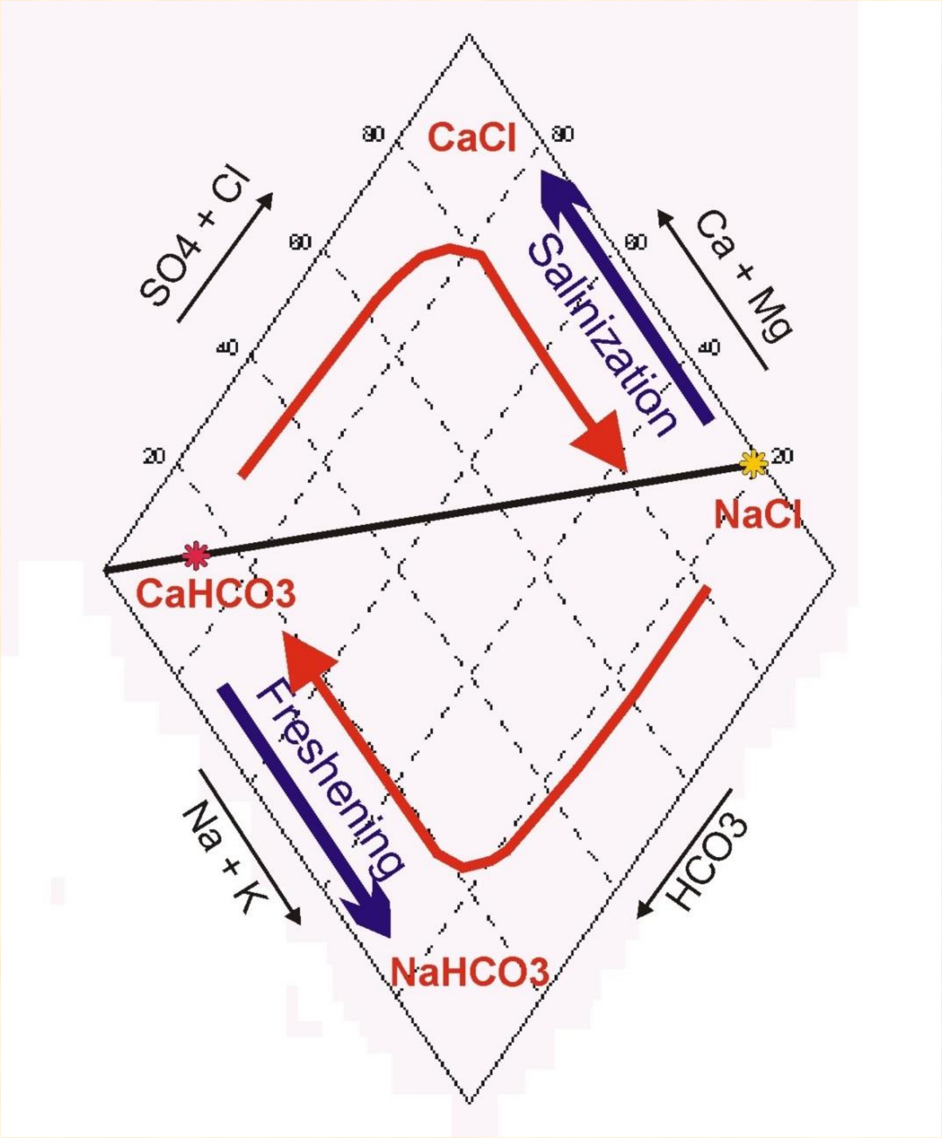
- at the interface, both end members will be mixed by **dispersion**

$$S \rightarrow B_s \rightarrow B \rightarrow F_b \rightarrow F$$

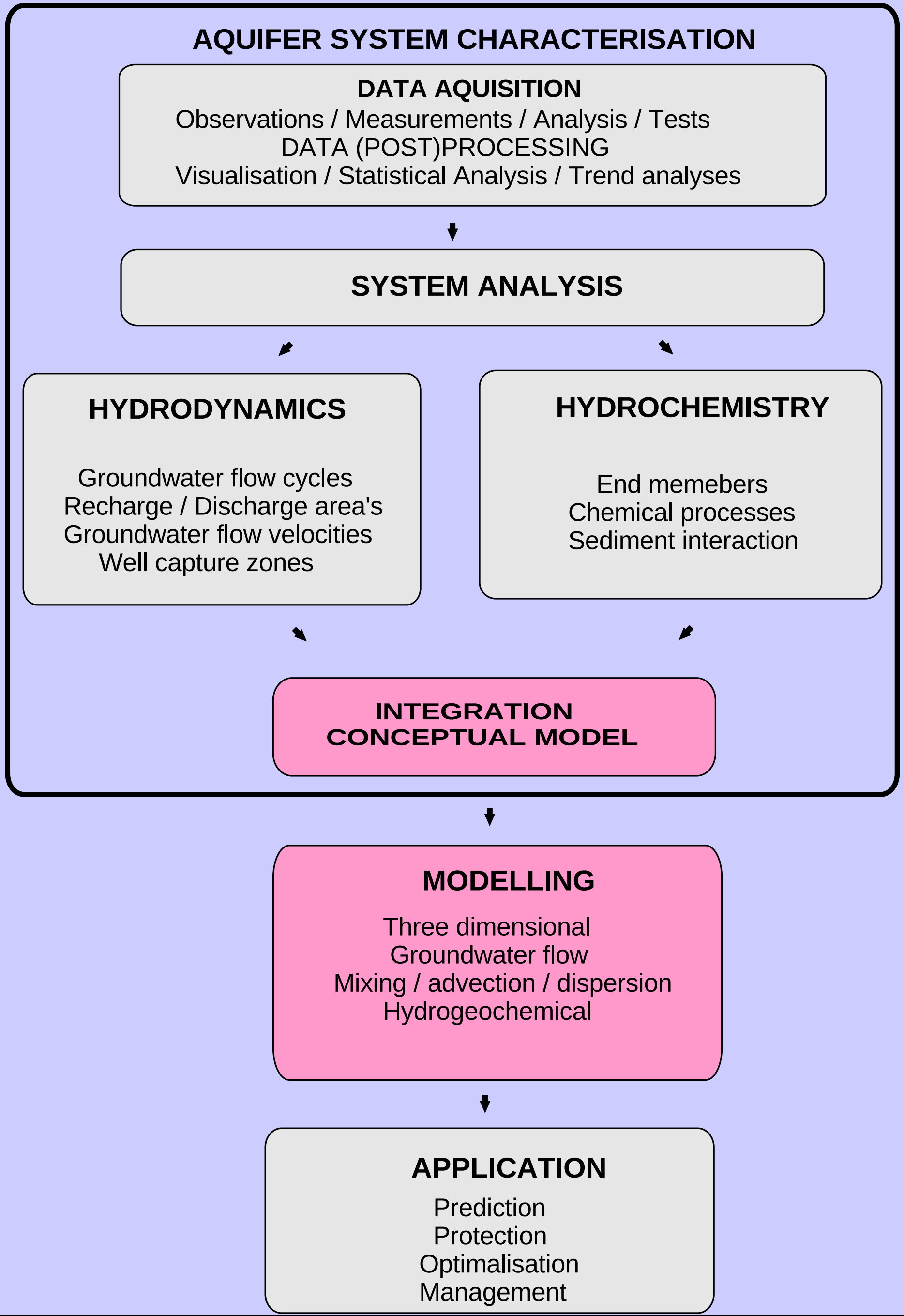
- the main **chemical reaction** will be cation exchange

$\Rightarrow$ surplus of marine cations (+)

NaCl0 → NaCl+ → NaHCO$_3$+ → MgHCO$_3$+ → CaHCO$_3$+ → CaHCO$_3$0


CaCl
SO4 + Cl
Ca + Mg
Salinization
80
80
60
60
40
40
20
20
NaCl
CaHCO3
Freshening
Na + K
HCO3
NaHCO3

UNDERSTANDING NATURAL GROUNDWATER QUALITY CONTROLS



MODELLING GROUNDWATER QUALITY

Groundwater quality
depends on

hydrodynamics	**hydrochemistry**
advection, mixing	**speciation,reactions**

coupled by
variable density flow

Groundwater quality models must contain:

- **flow model : advection**
- **solute transport model : mixing , dispersion**
- **hydro(geo)chemical model : reactions , speciation,..**

EVOLUTION OF SALT WATER INTRUSION MODELS

HYDRODYNAMIC MODELS

HYDROGEOCHEMICAL MODELS

NOW: COMBINATION

HYDRODYNAMIC MODELS

→ **incorporating density-driven flow**

1) **neglecting reactions**

- **sharp interface model: only advection**
  e.g. SHARP
- **solute transport models (2D, 3D): advection and dispersion**
  e.g. SUTRA, SEAWAT, MOCDENS3D, HST3D

2) **very simple approach for compositional changes: sink / source (sorption by means of K_d, degradation/decay)**
   e.g. MT3D, MT3DMS

HYDROGEOCHEMICAL MODELS

→ calculation of speciation and reactions
(not in mass balance models, e.g. BALANCE)

1) neglecting hydrodynamics
   e.g. WATEQ, MINTEQ, PHREEQE
2) very simple approach for hydrodynamics (1D)
   e.g. PHREEQM, PHREEQC

NOW: COMBINATION

→ full-scale reactive transport models (2D, 3D)
   e.g. PHAST

PHAST MODEL

- 3-dimensional multicomponent reaction-transport model

- simulates transient groundwater flow with geochemical reactions

- based on thermodynamic database for the geochemical calculations (extensible)

- combination of 2 existing models:

HST3D = the solute-transport simulator

PHREEQC = for the geochemical calculations

PHAST MODEL OF DEVELOPMENT OF

FRESH WATER LENS UNDER DUNE BELT

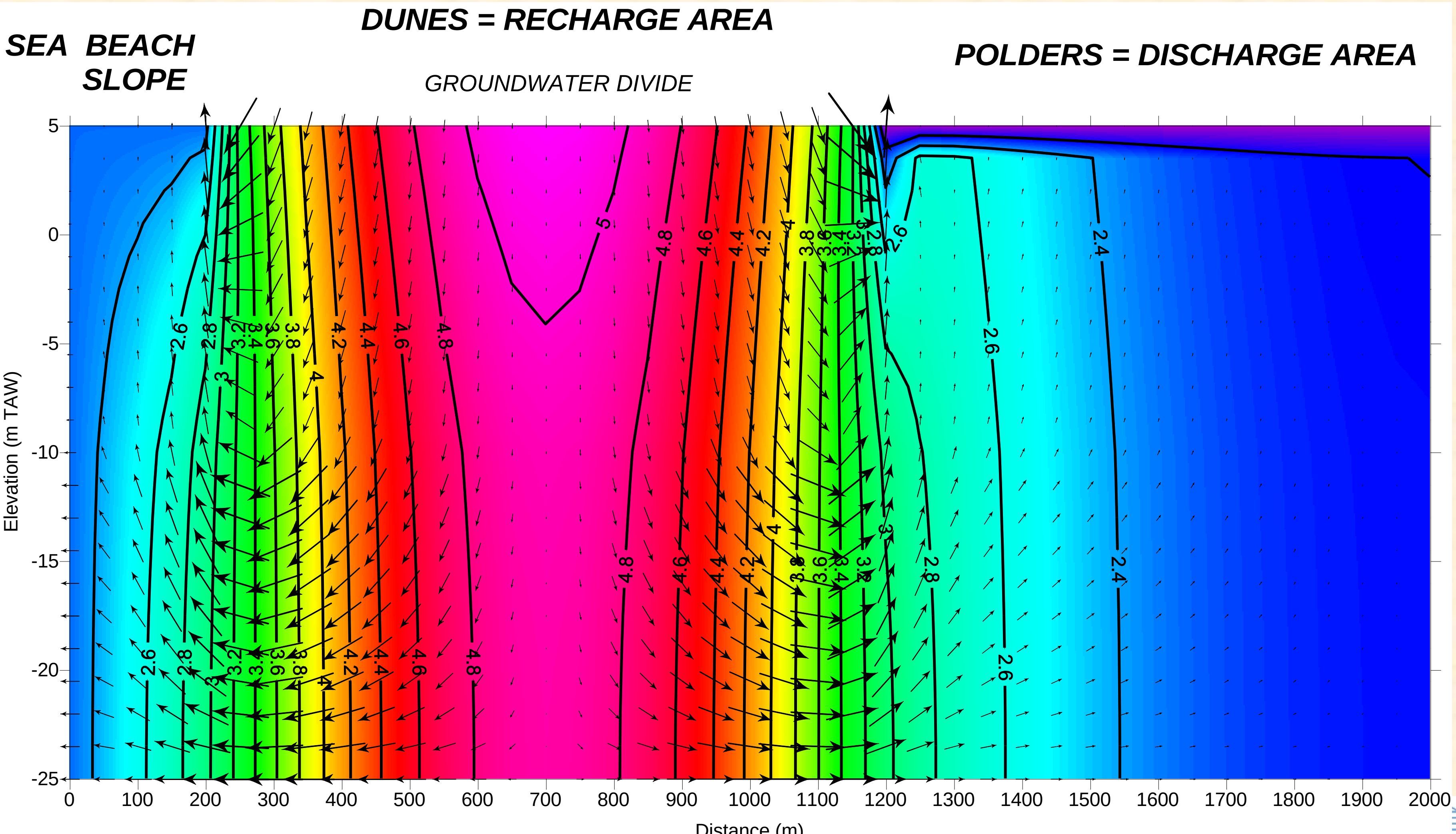
- schematic model : simplified geometry
- cross section = 2 dimensional
- aquifer = 30 m thick mainly sandy
- 2 km long, from beach, over dunes into polders
- initial situation = aquifer filled with seawater

HYDRODYNAMICS

- DUNES = recharge of aquifer
- POLDERS = discharge to polder drains
- SHORELINE and BEACH SLOPE = defined heads

PHAST MODELLING OF DUNE BELT FRESHENING

HYDRAULIC HEADS and GROUNDWATER FLOW



UNIVERSITEIT GENT
Krijgslaan 281- S8, B-9000 Ghent

HYDROCHEMISTRY

MODEL INPUT

- **including main chemical components**

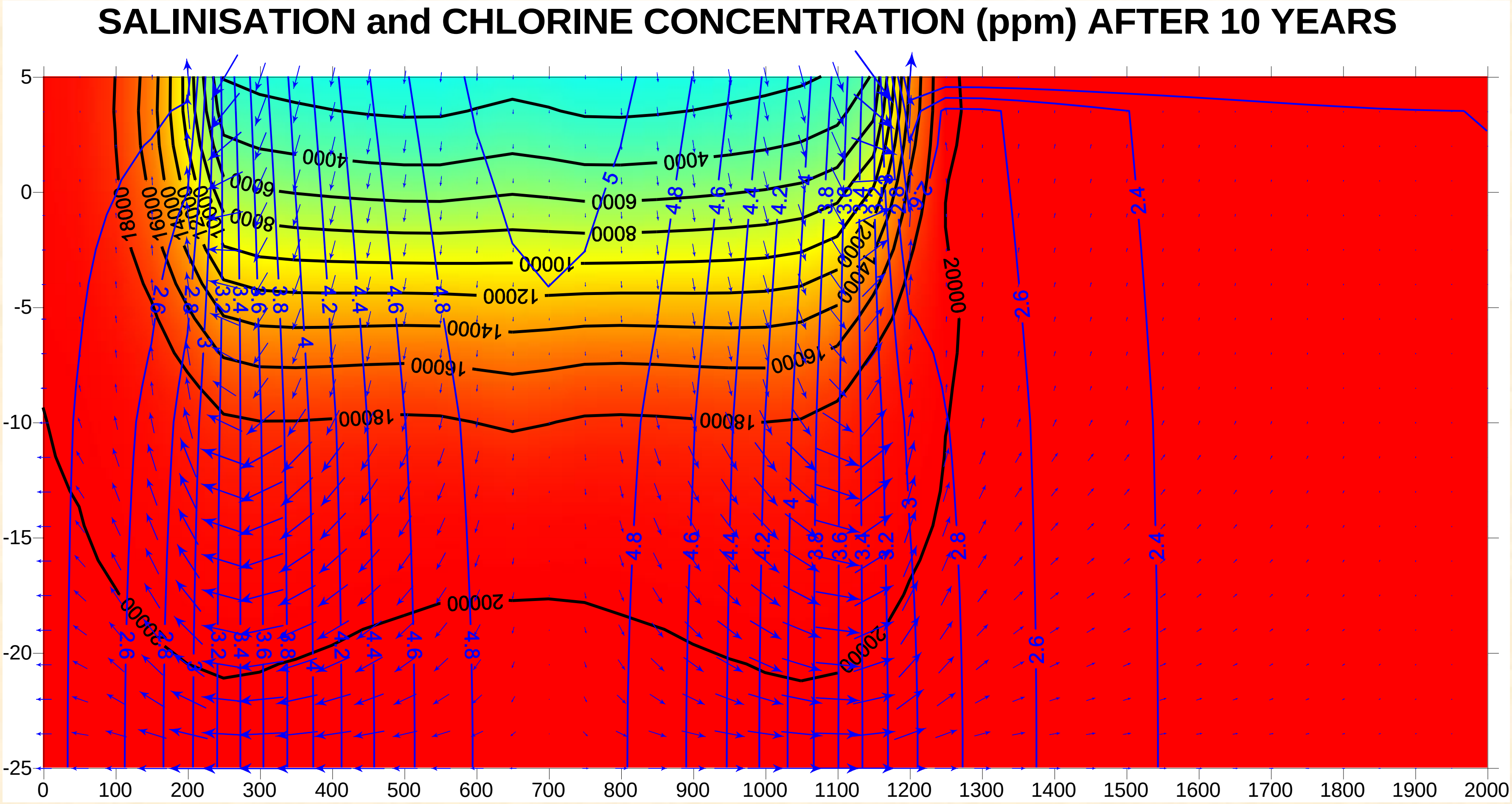
- main cations (Na,K,Mg,Ca) and anions (Cl,SO4,HCO3)
- pH

- **including main processes**

- advection, mixing, dispersion
- cation exchange
- calcite dissolution

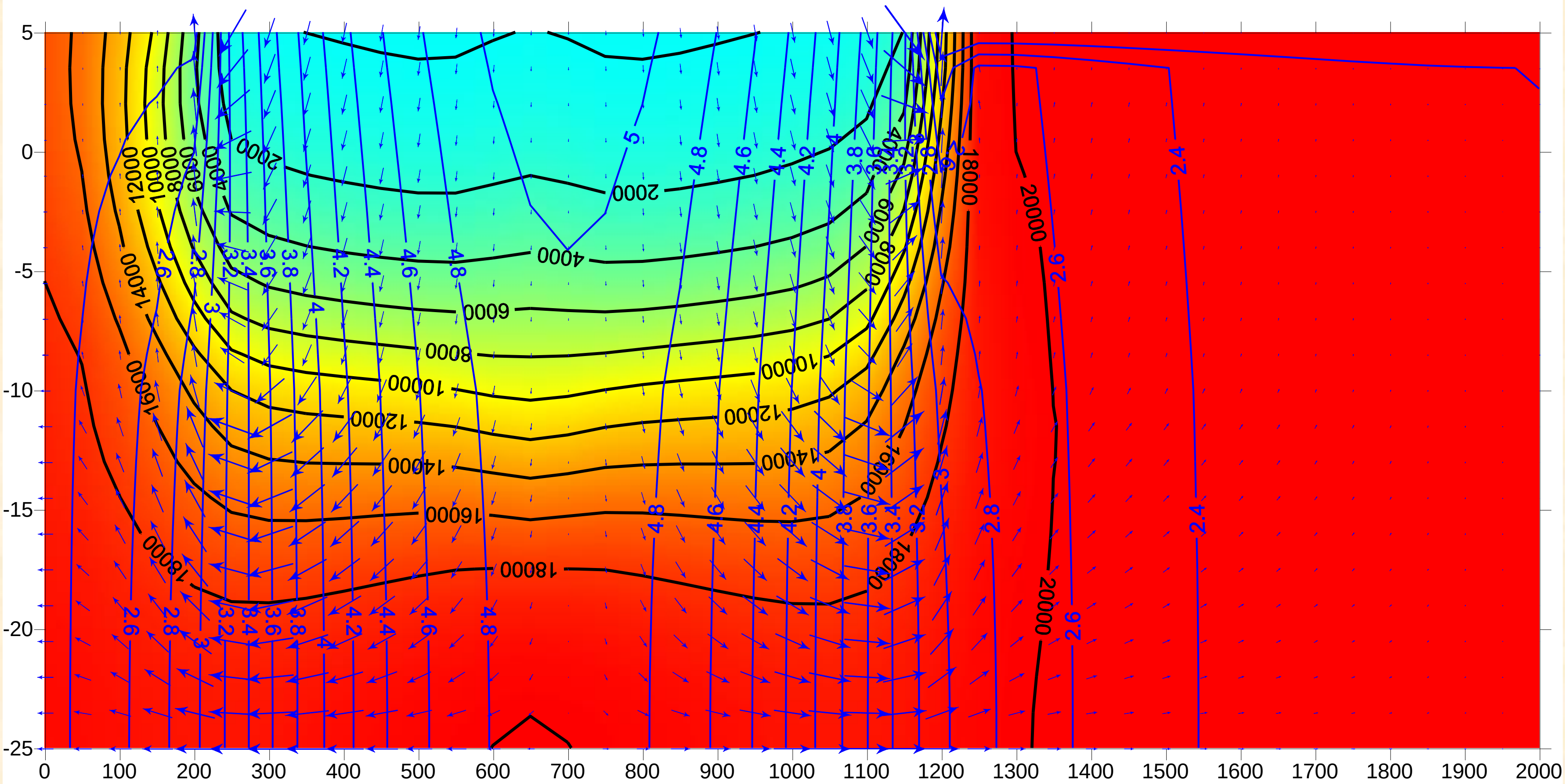
MODEL OUTPUT

- salinity based on Cl-concentrations
- element concentration distributions
- species concentration distributions
- relative ion distributions
- watertypes (STUYFZAND) calculated from ion concentrations
- exchanger species (ions adsorbed on exchanger)
- mineral saturation indices
- pH

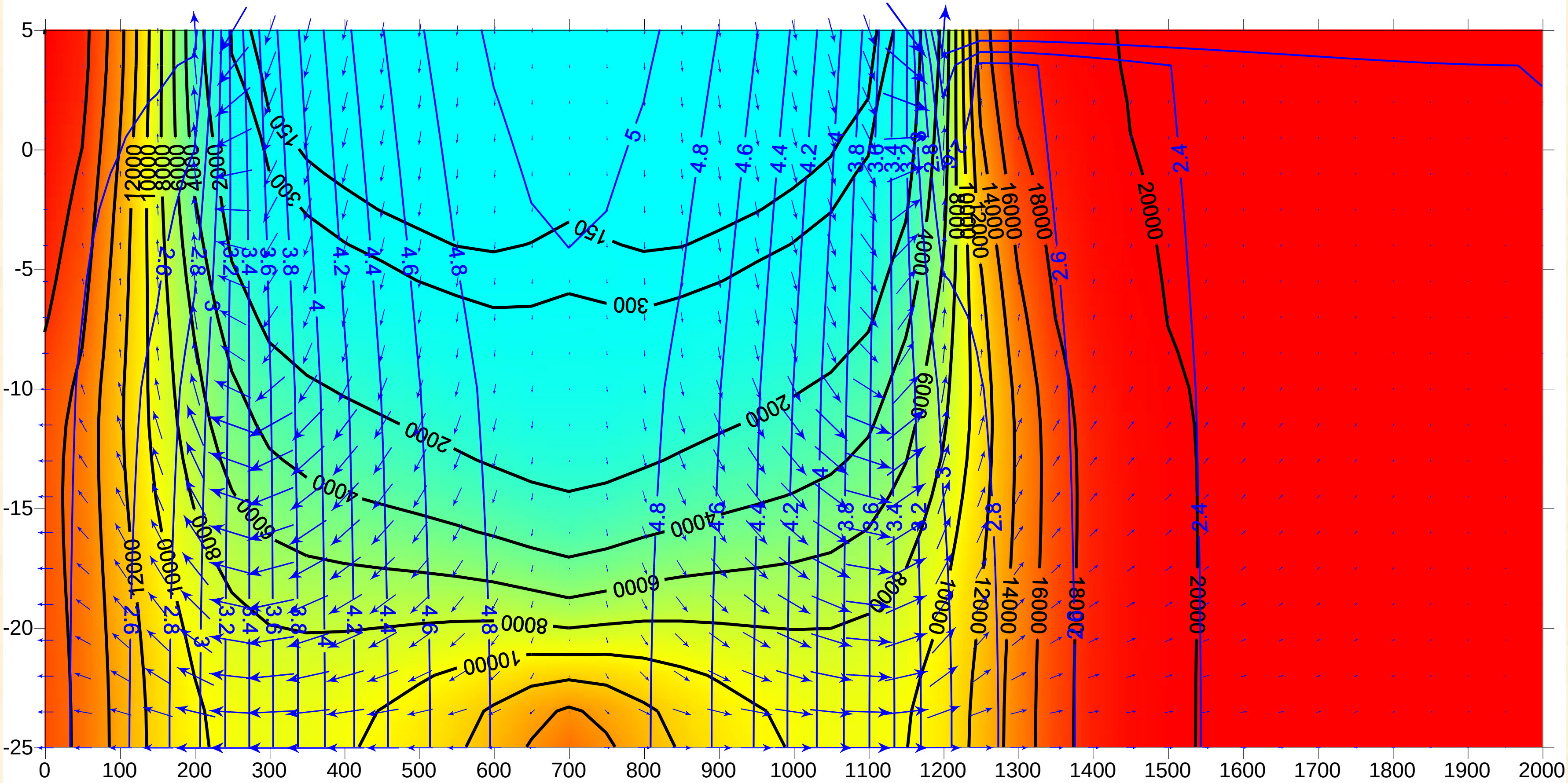


Laboratory for applied Geology and Hydrogeology
Krijgslaan 281- S8, B-9000 Ghent

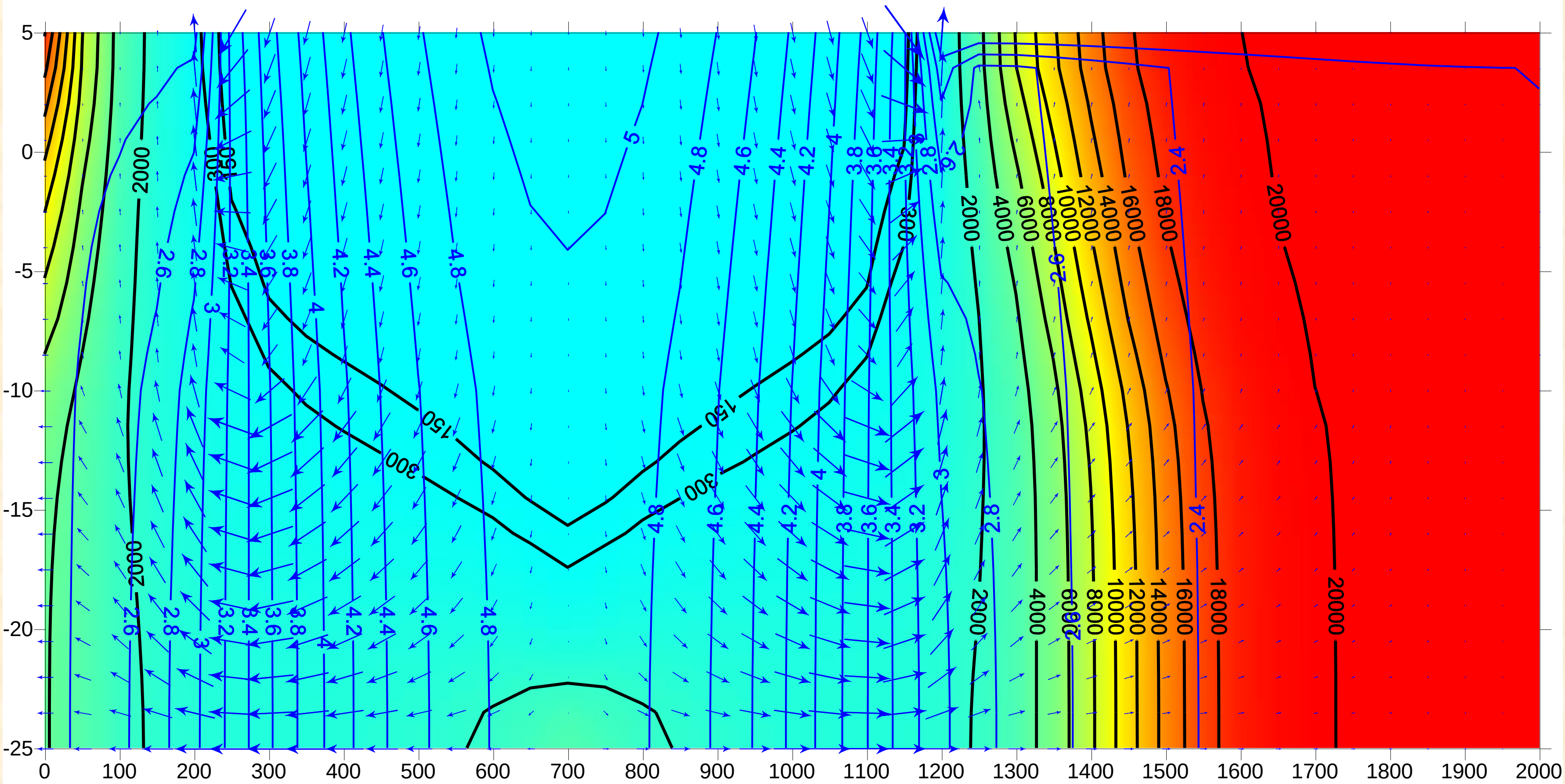
SALINISATION and CHLORINE CONCENTRATION (ppm) AFTER 20 YEARS



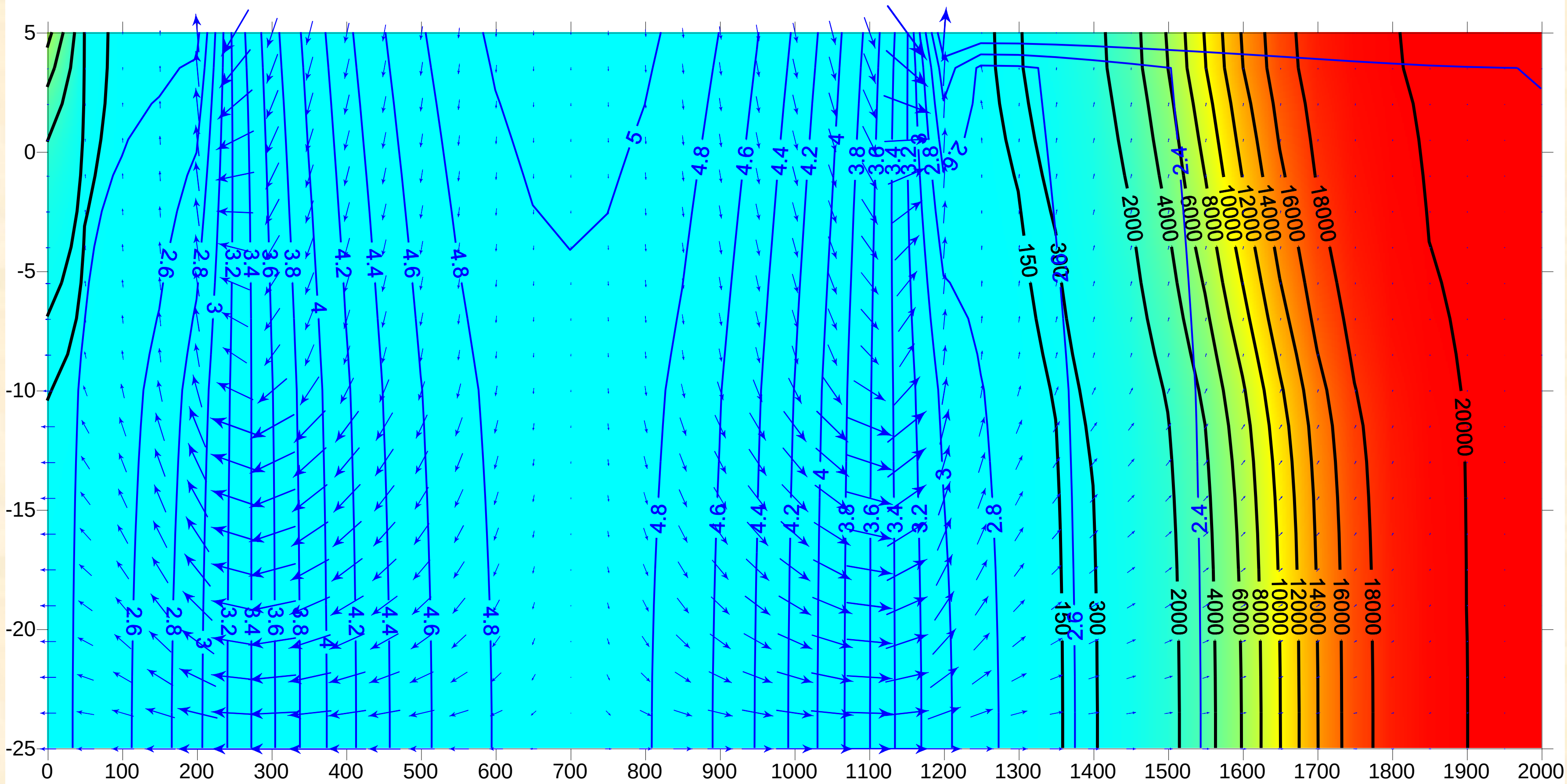
SALINISATION and CHLORINE CONCENTRATION (ppm) AFTER 50 YEARS



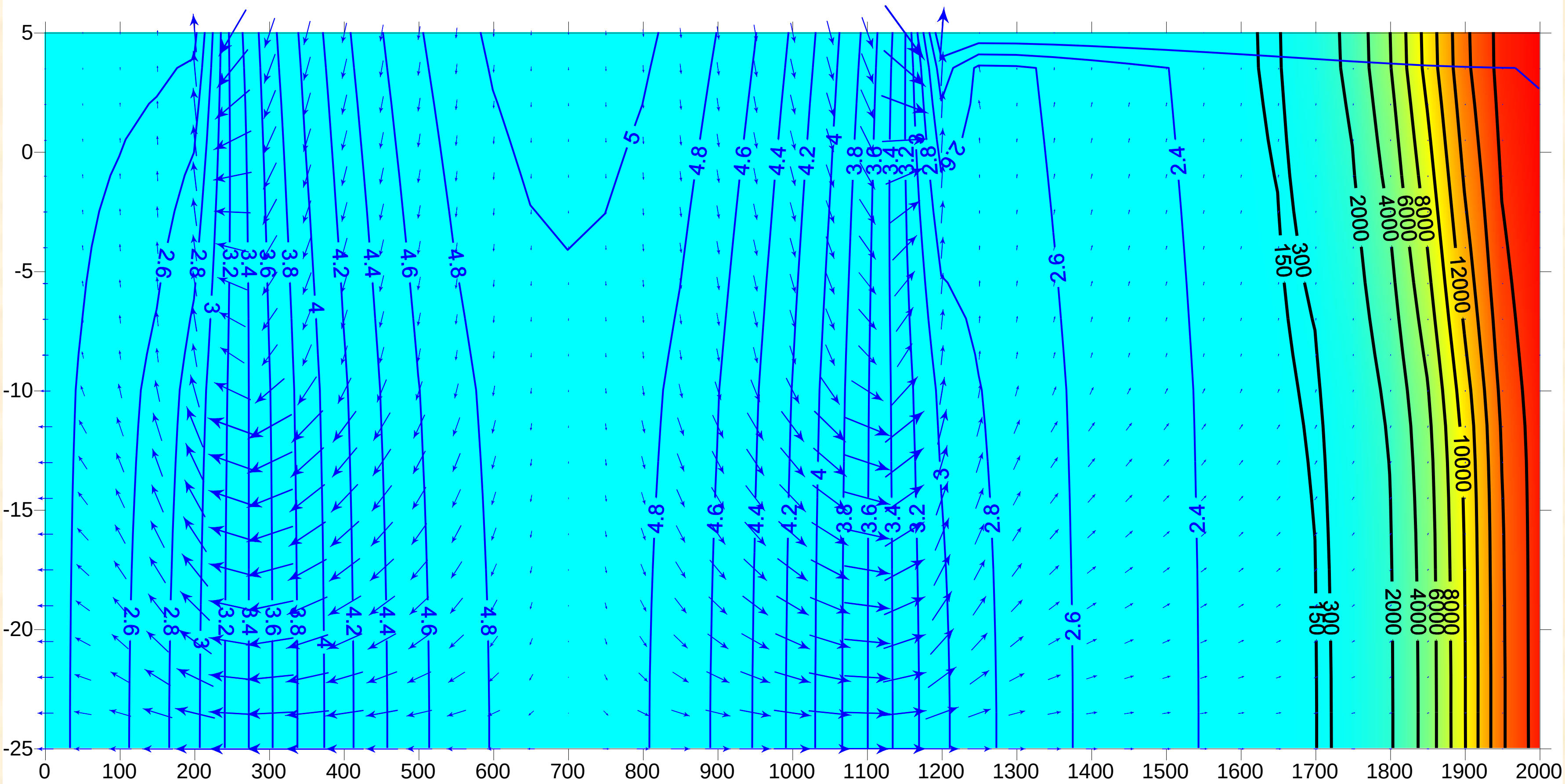
SALINISATION and CHLORINE CONCENTRATION (ppm) AFTER 100 YEARS

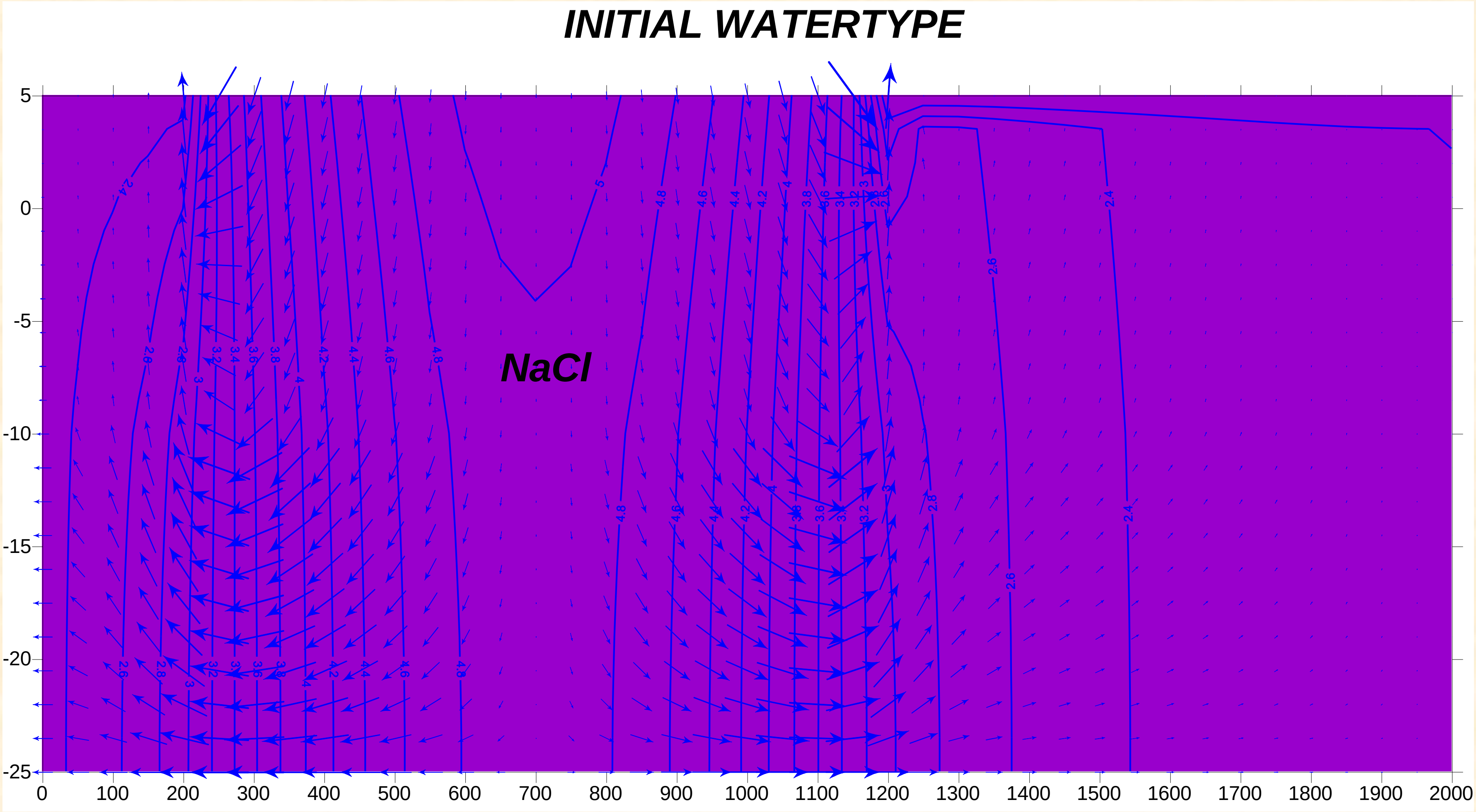


SALINISATION and CHLORINE CONCENTRATION (ppm) AFTER 200 YEARS

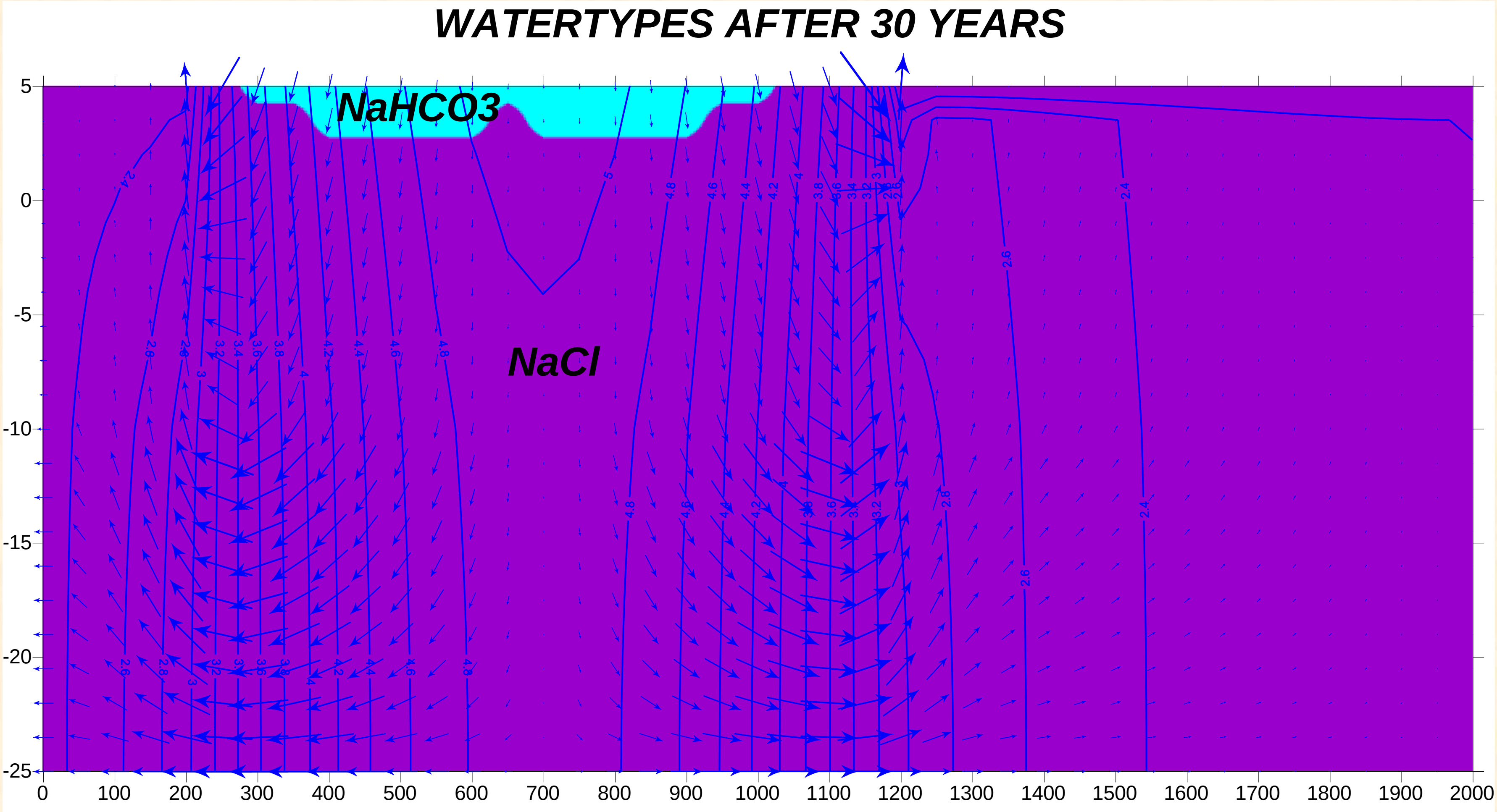


SALINISATION and CHLORINE CONCENTRATION (ppm) AFTER 500 YEARS

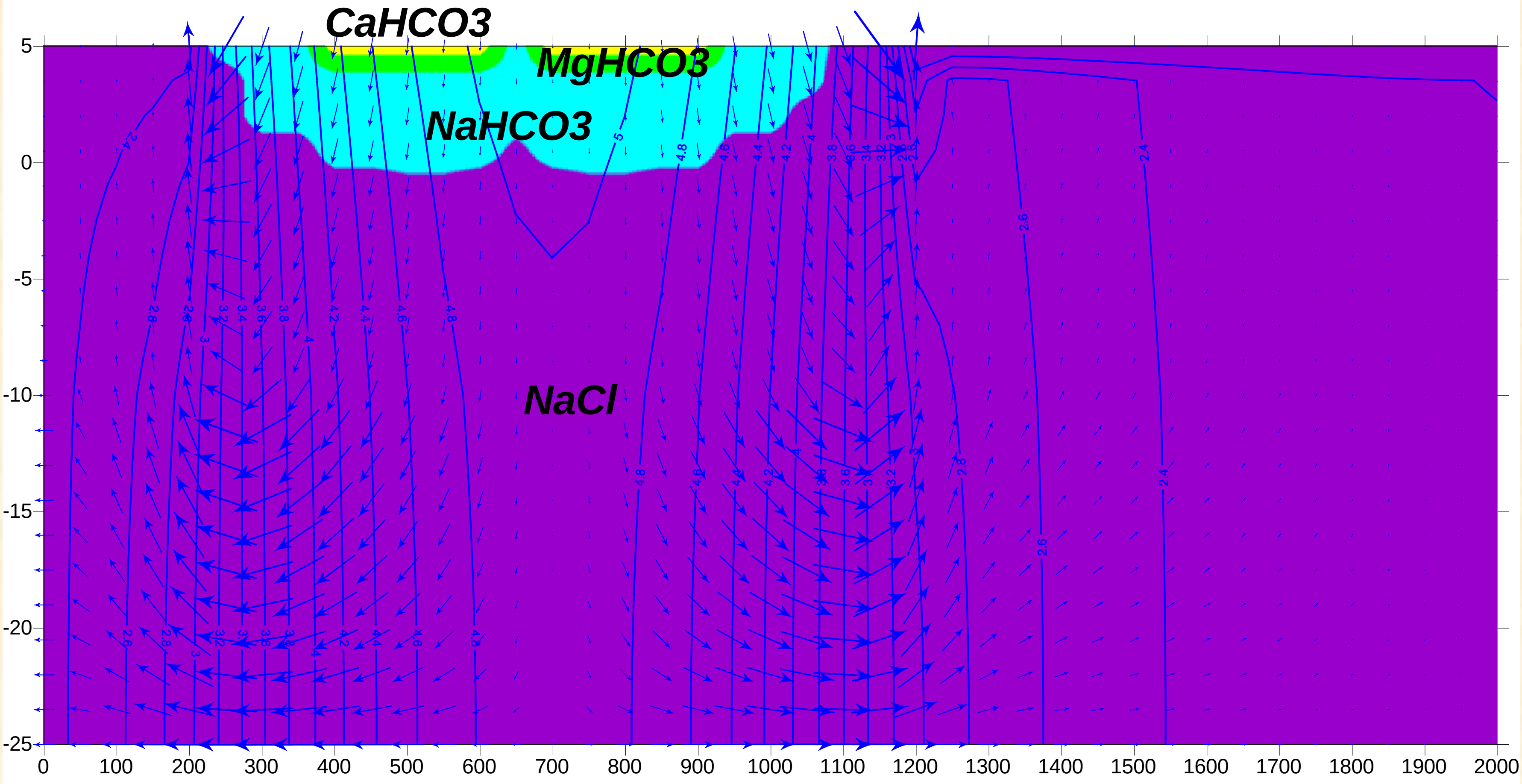




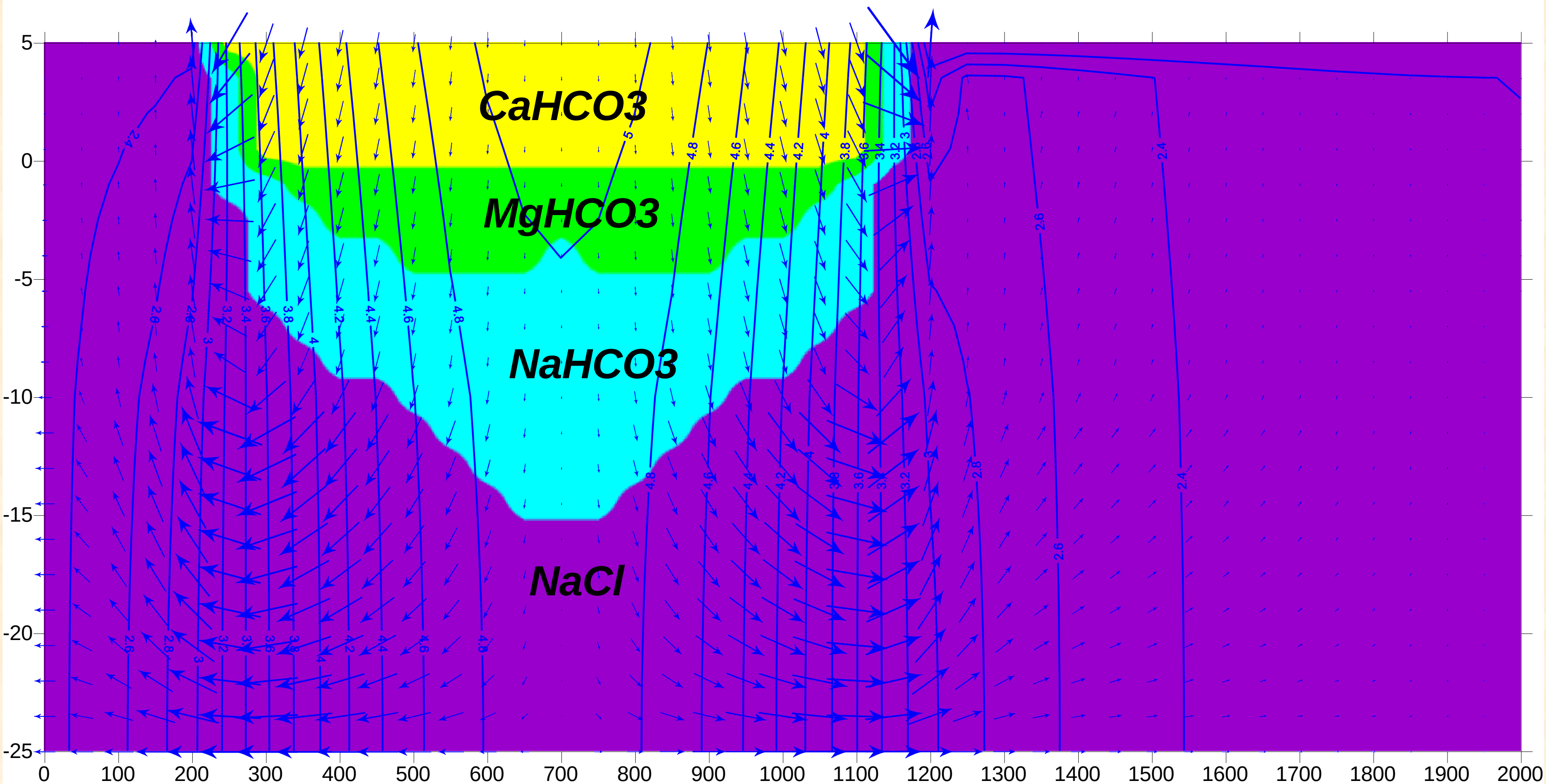
UNIVERSITEIT GENT
Laboratory for applied Geology and Hydrogeology
Krijgslaan 281- S8, B-9000 Ghent


WATERTYPES AFTER 30 YEARS
NaHCO3
NaCl
5
0
-5
-10
-15
-20
-25
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

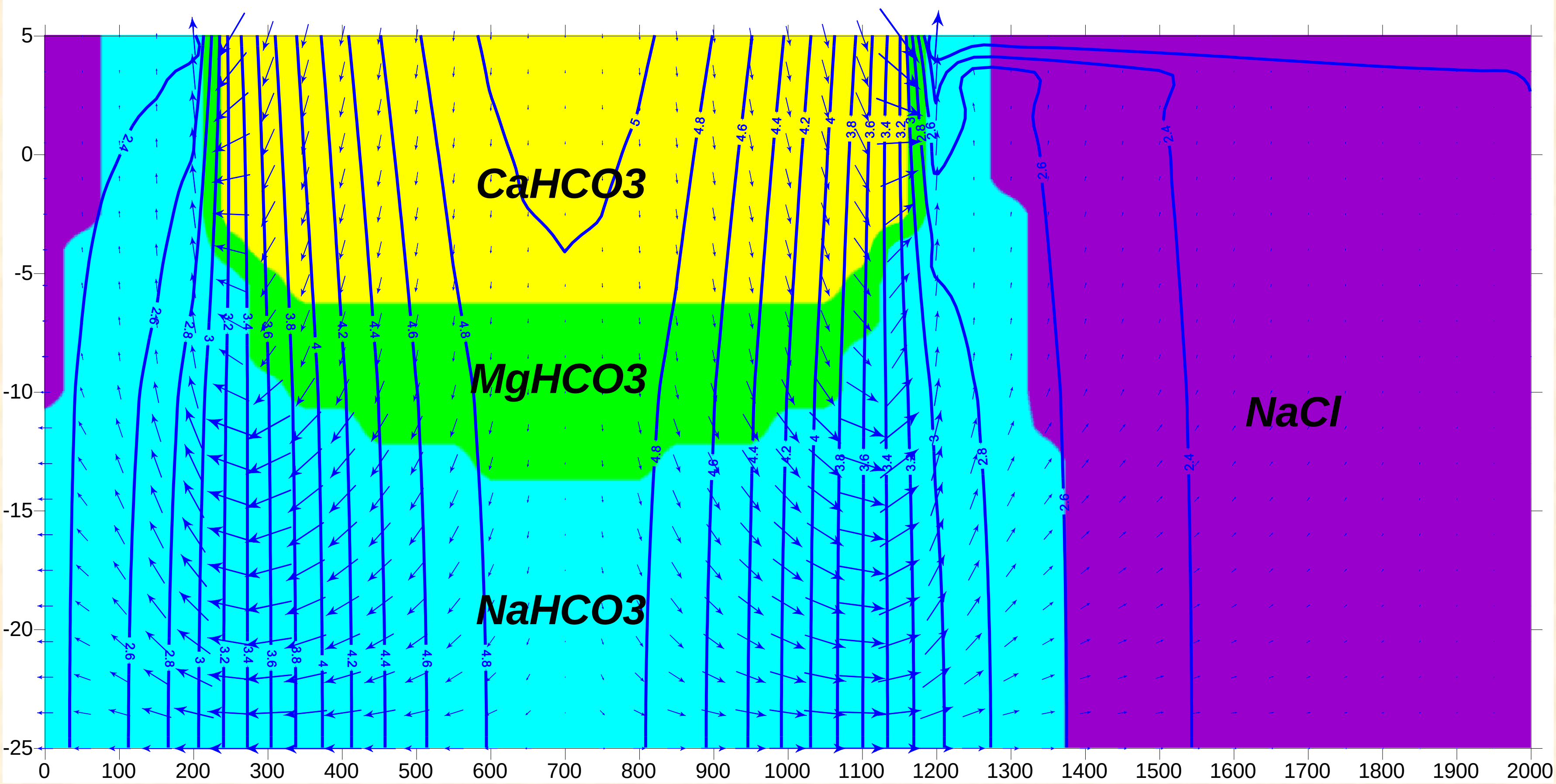
WATERTYPES AFTER 40 YEARS

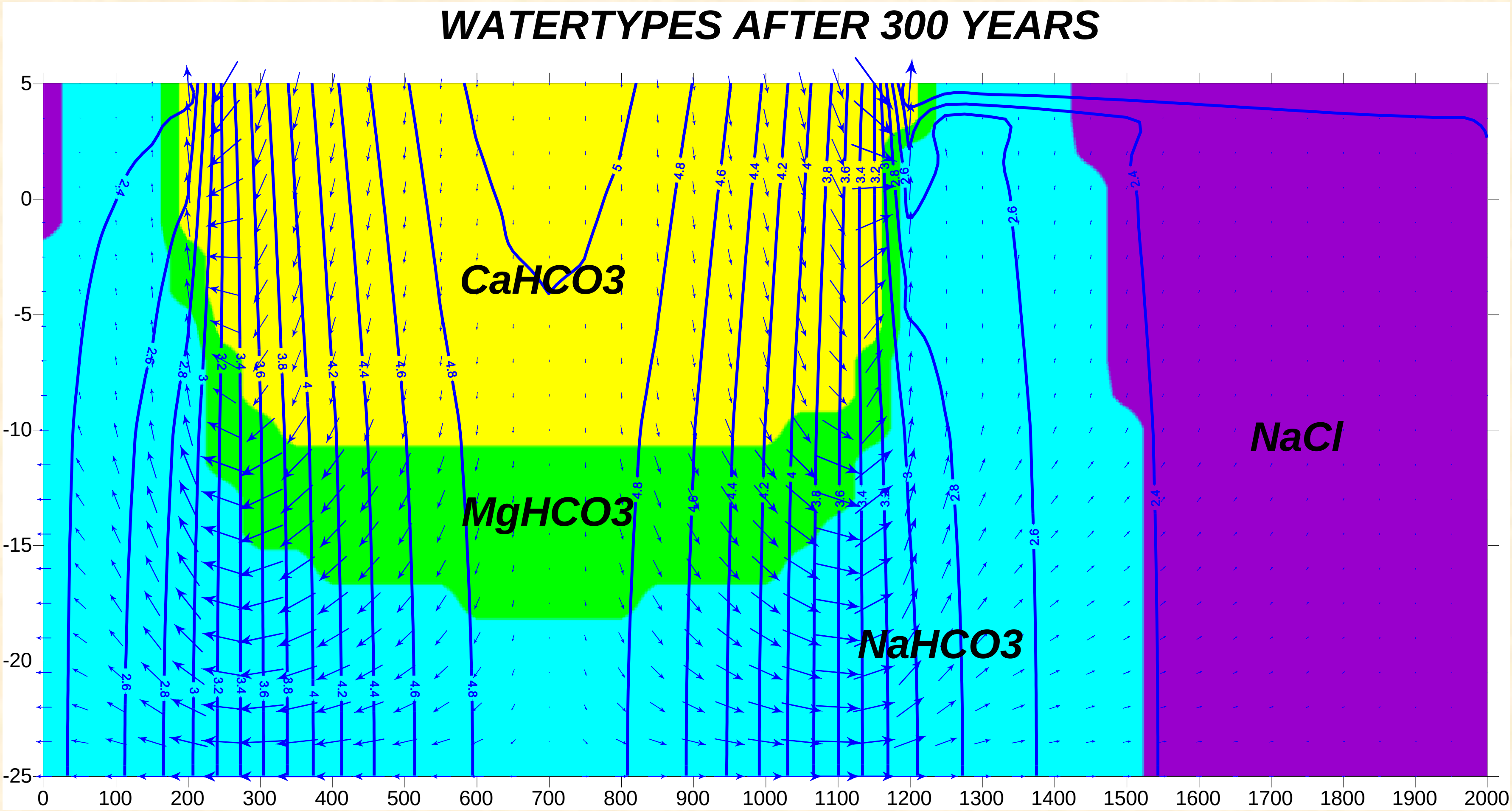


WATERTYPES AFTER 100 YEARS

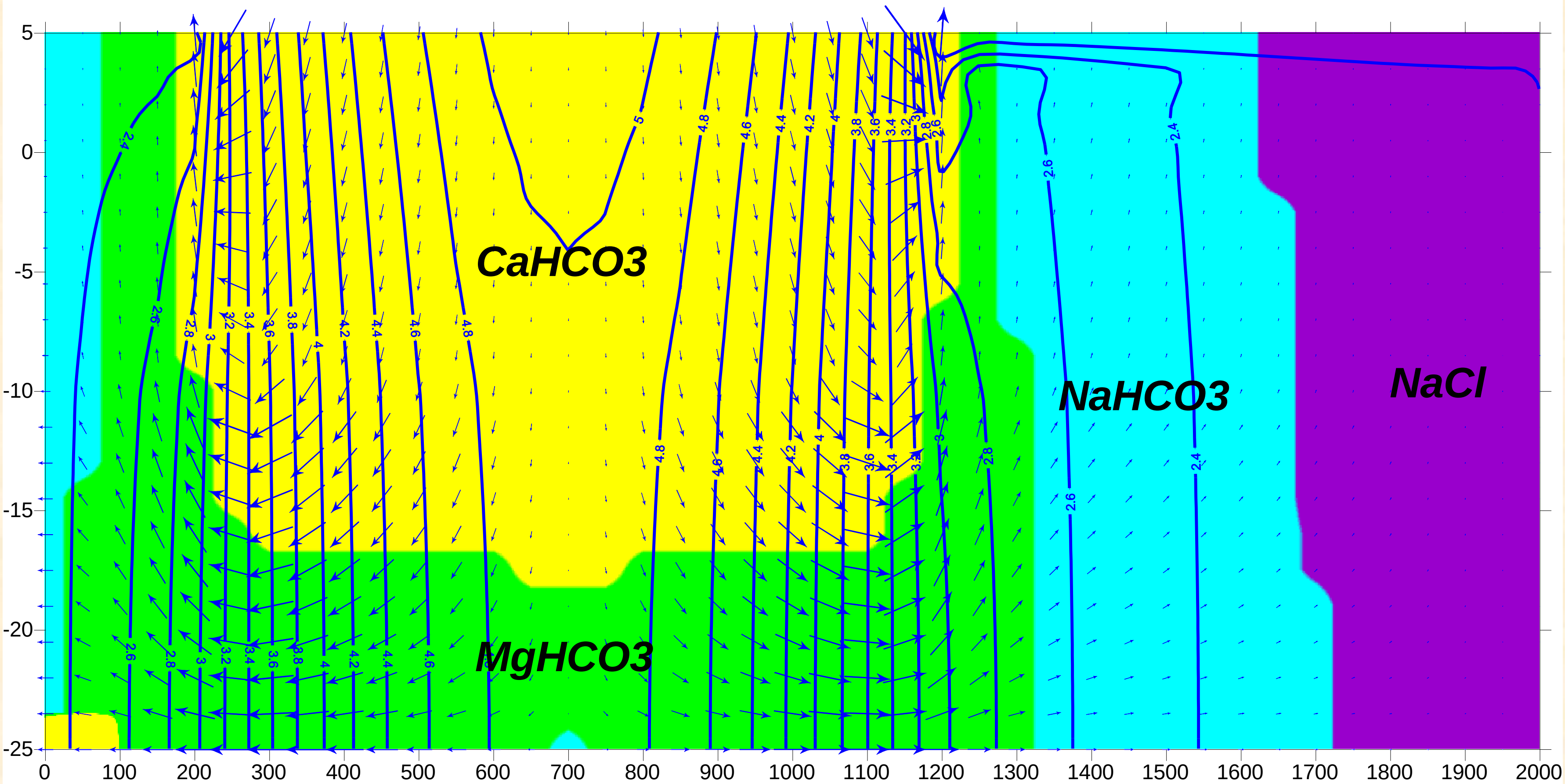


WATERTYPES AFTER 200 YEARS

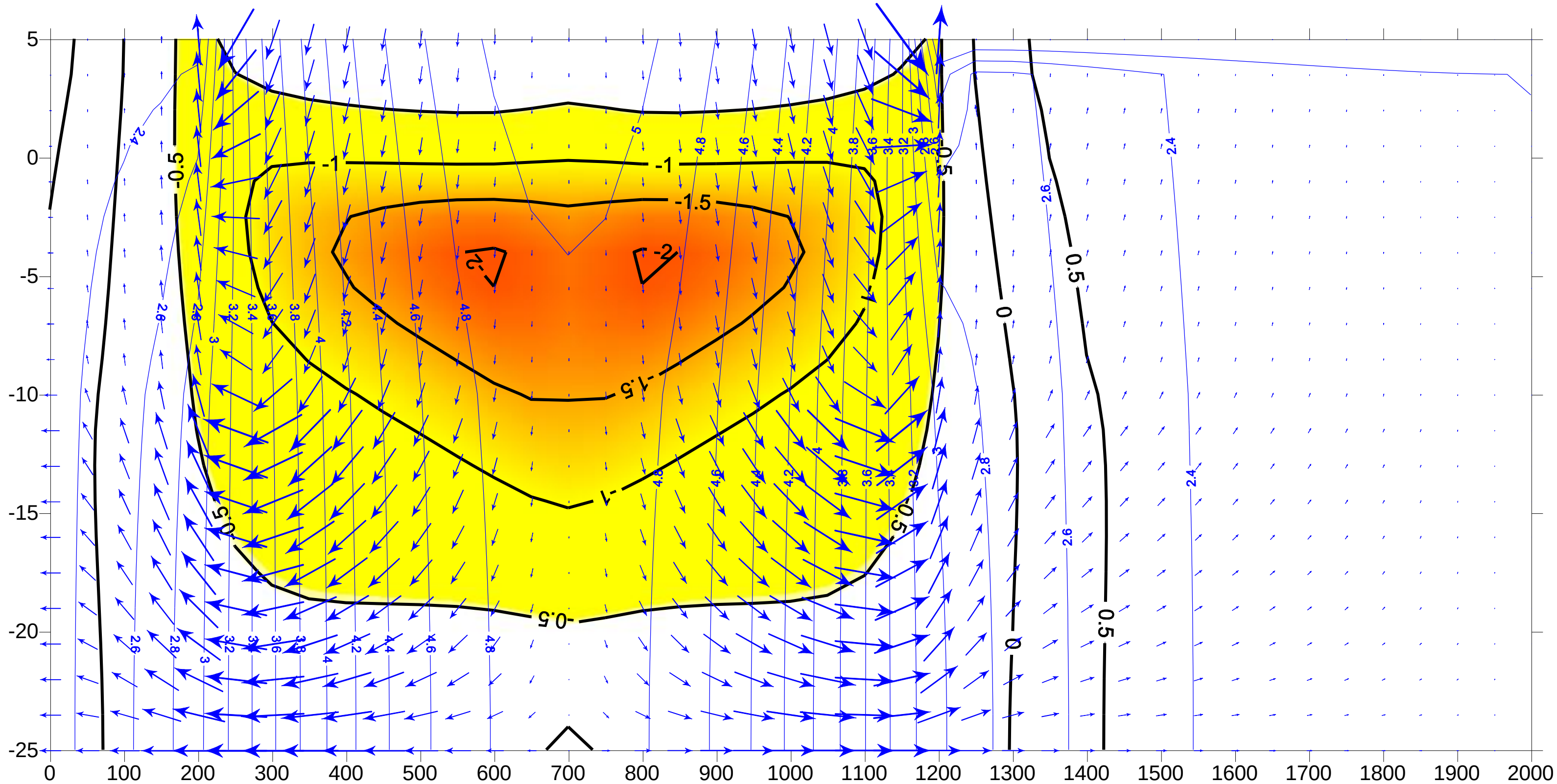


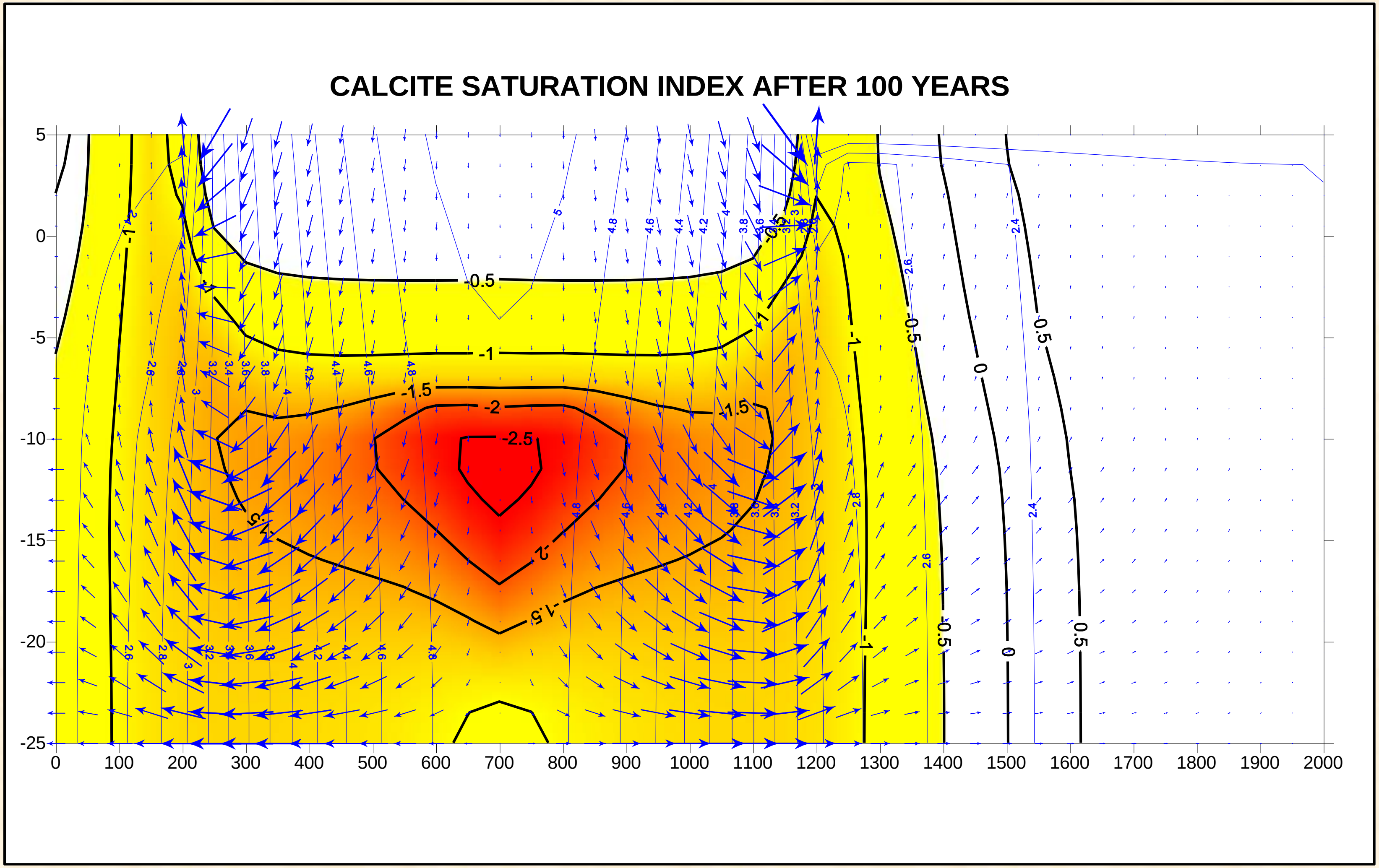

WATERTYPES AFTER 300 YEARS
CaHCO3
MgHCO3
NaHCO3
NaCl
5
0
-5
-10
-15
-20
-25
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

WATERTYPES AFTER 500 YEARS



CALCITE SATURATION INDEX AFTER 50 YEARS

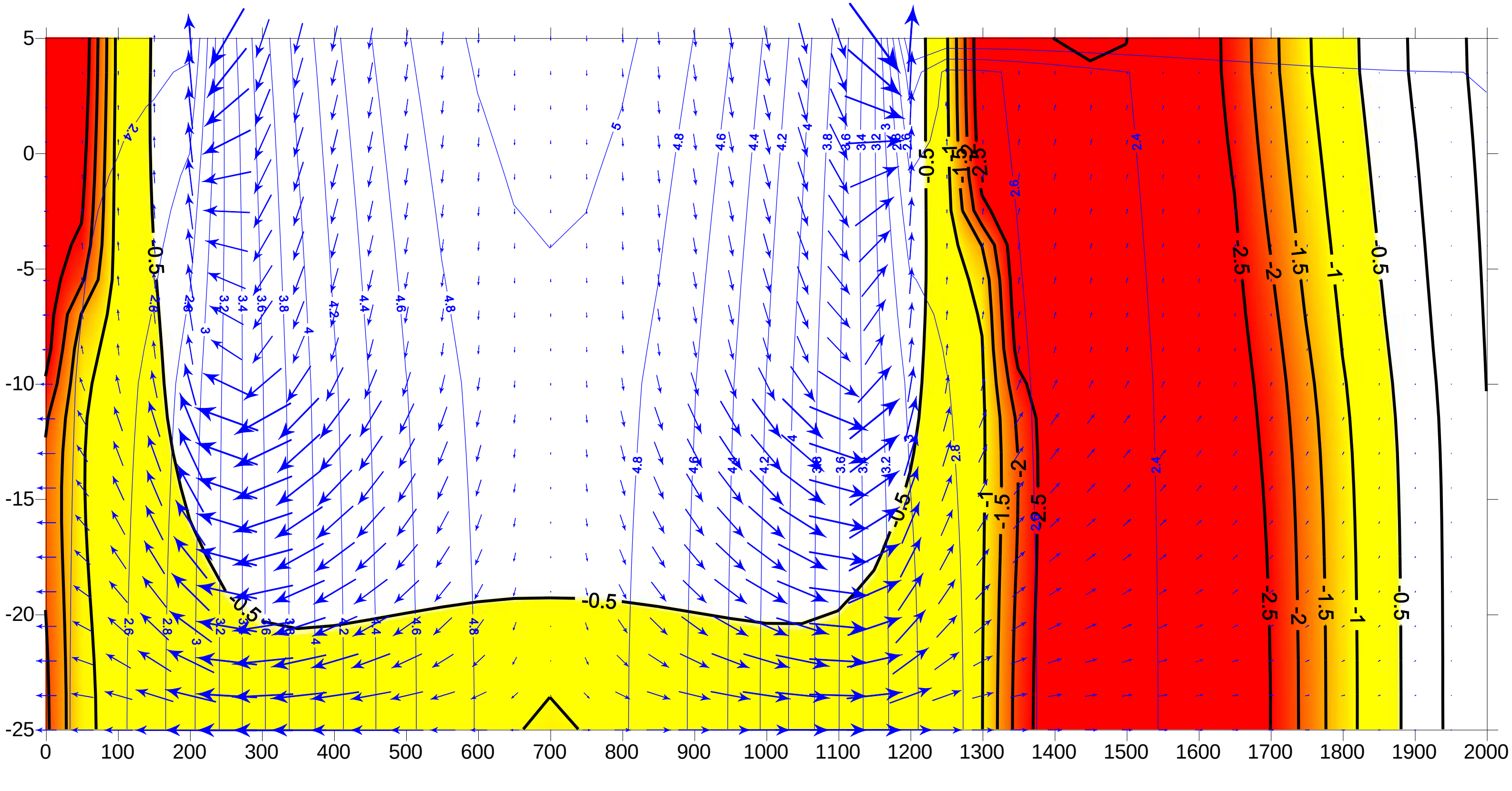




UNIVERSITEIT GENT

Laboratory for applied Geology and Hydrogeology
Krijgslaan 281- S8, B-9000 Ghent

CALCITE SATURATION INDEX AFTER 500 YEARS



These powerful models combine

- **full-scale hydrodynamics** (2D, 3D)

- **full-scale hydrogeochemistry**: full spectrum of chemical reactions (acid-base reactions, complexation reactions, sorption reactions, mineral dissolution/precipitation reactions, gas dissolution, redox reactions)

The conceptual model,

confirmed by simulation

leads to system understanding,

which allows for prediction and management