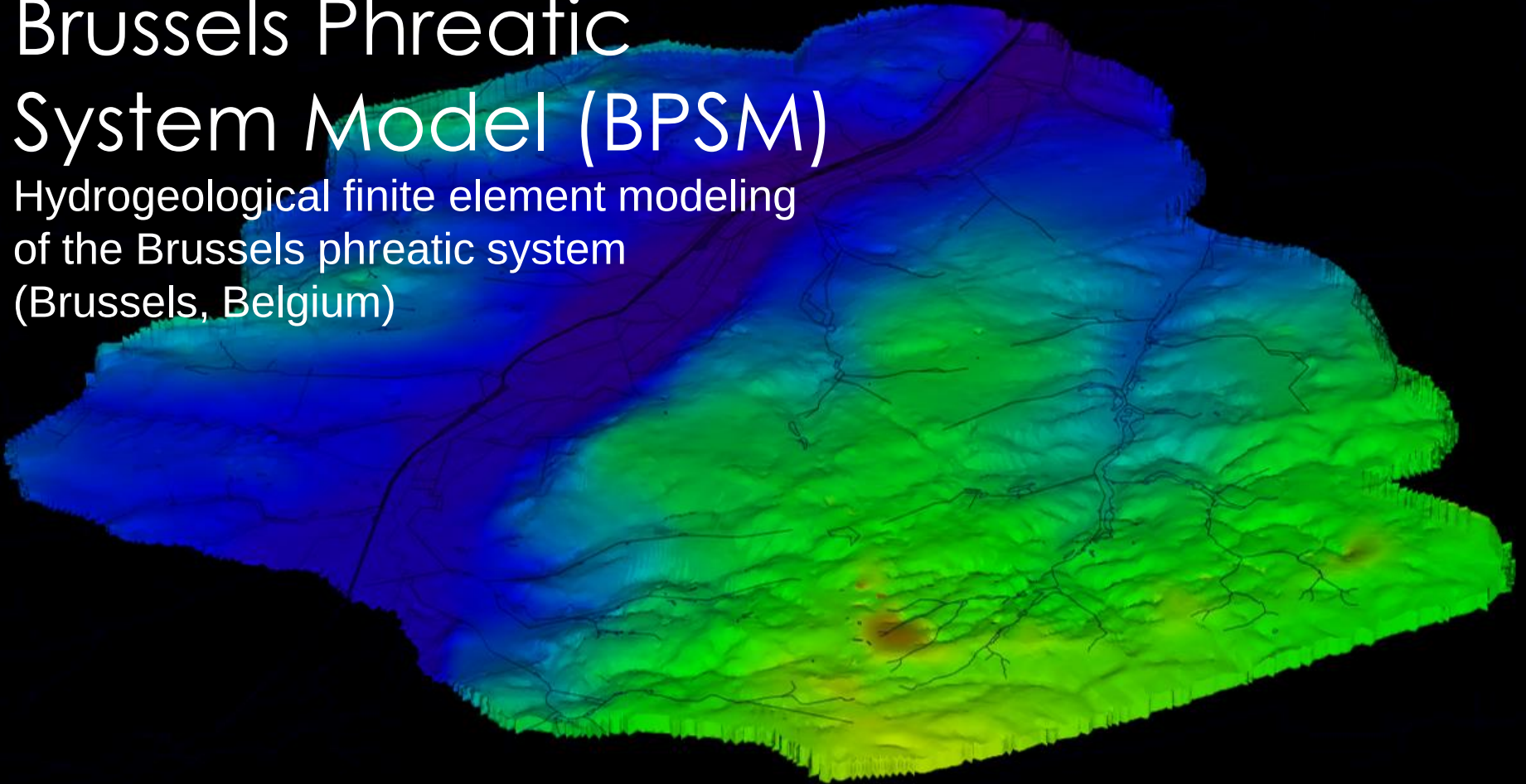


Brussels Phreatic System Model (BPSM)

Hydrogeological finite element modeling
of the Brussels phreatic system
(Brussels, Belgium)



Mathieu AGNIEL

Hydrogeologist

Bruxelles Environnement

magniel@environnement.brussels





CONTENTS

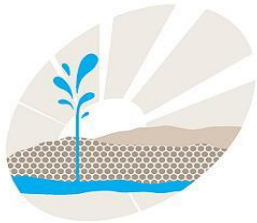
- Introduction
- Conceptual model
- Numerical model
- Calibration
- Uncertainty analysis
- Sensitivity analysis
- Results



INTRODUCTION

GROUNDWATER MANAGEMENT / OBJECTIVES

Groundwater constraints



Catchments



Urban development



Ecosystems



Soil &
groundwater
pollution



Geothermal
energy

Working strategy



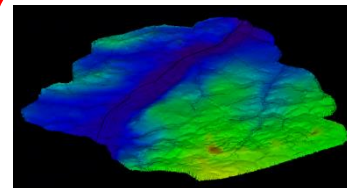
measurement



data
collection



analysis



modelling/
forecast



OBJECTIVES



strategy/
expertise

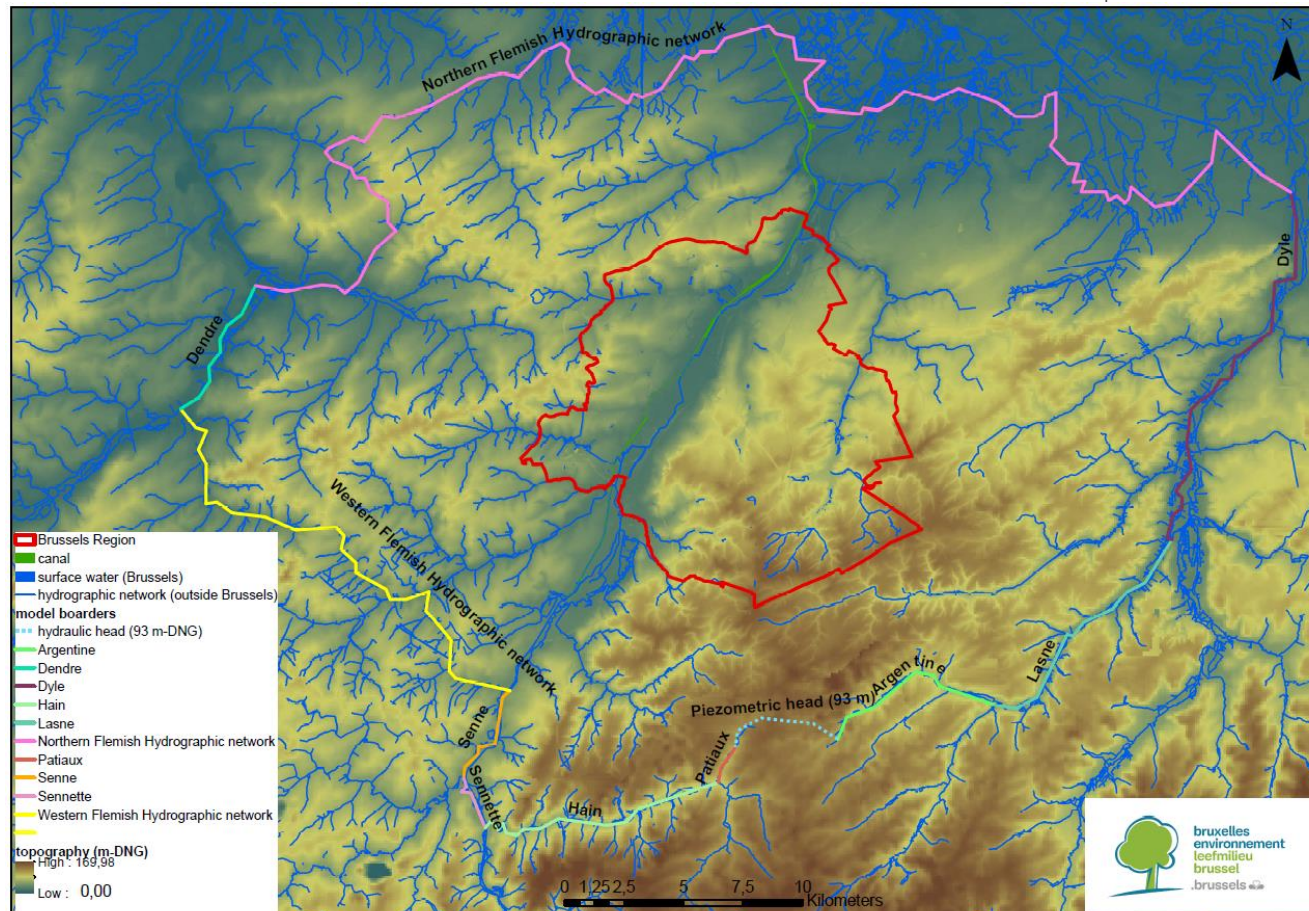
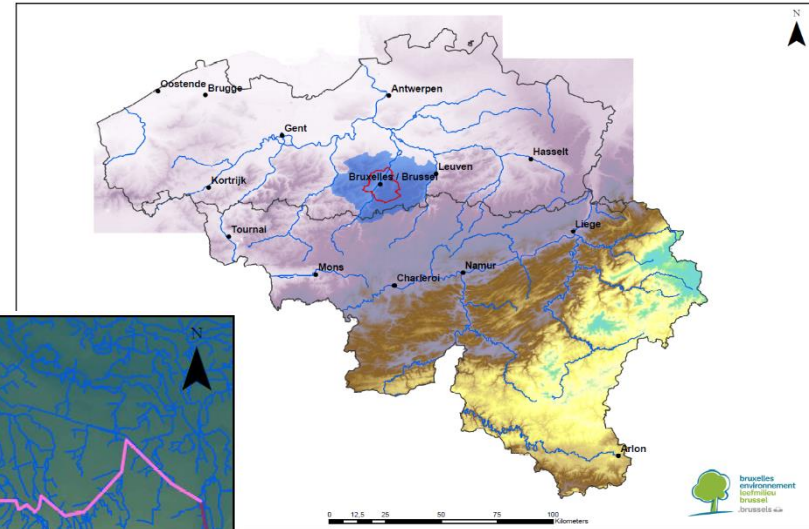


data
diffusion



CONCEPTUAL MODEL

STUDY AREA





CONCEPTUAL MODEL

HYDROGEOLOGICAL CONTEXT / VERTICAL DISCRETIZATION

Ere	Unités Stratigraphiques (US/RBC)	Unités Hydrogéologiques (UH/RBC)		Type	Layer
IV (Cénozoïque)	US/RBC_11 Remblais	UH/RBC_1 Système aquifère du quaternaire	UH/RBC_1a Système aquitard quaternaire superficiel	aquitard	1
	US/RBC_12 Couverture limoneuse				
	US/RBC_13 Argiles alluviales				
	US/RBC_14 Limons, sables et graviers alluviaux		UH/RBC_1b Aquifère des limons, sables et graviers alluviaux	aquifère	2
III (Cénozoïque)	US/RBC_21 Sables de Diest	UH/RBC_2 Système aquifère sableux perché			3
	US/RBC_22 Sables de Bolderberg				
	US/RBC_23 Sables et argiles de Sint-Huilbrechts-Hern				
	US/RBC_25 Sables de Maldegem (membre de Onderdale)				
	US/RBC_31 Argiles de Maldegem (membre de Urseel et Asse)	UH/RBC_3 Aquiclude des argiles de Urseel et Asse		aquiclude	4
	US/RBC_41 Sables de Maldegem (membre de Wemmel)	UH/RBC_4 Aquifère des sables de Wemmel, Lede, Bruxelles et Vlierzele			5
	US/RBC_42 Sables de Lede				
	US/RBC_43 Sables de Bruxelles				
	US/RBC_44 Sables de Gent (membre de Vlierzele)				
	US/RBC_51 Argiles de Gent (membre de Merelbeke)	UH/RBC_5 Aquiclude des argiles de Gent		aquiclude	6
	US/RBC_61 Sables et argiles de Tielst	UH/RBC_6 Aquitard des sables et argiles de Tielst		aquitard	7
	US/RBC_71 Argiles de Kortrijk (membre d'Aalbeke)	UH/RBC_7 Système aquitard des sables et argiles de Kortrijk	UH/RBC_7a Aquiclude des argiles de Aalbeke	aquiclude	8
	US/RBC_72 Sables et argiles de Kortrijk (membre de Moen)		UH/RBC_7b Aquitard des sables et argiles de Moen	aquitard	9
	US/RBC_73 Argiles de Kortrijk (membre de Saint Maur)		UH/RBC_7c Aquiclude des argiles de Saint-Maur	aquiclude	Bottom
	US/RBC_81 Sables de Hannut (Membre de Grandglise)	UH/RBC_8 Système aquifère des sables du Landénien	UH/RBC_8a Aquifère des sables du Landénien	aquifère	hors zone modélisée
	US/RBC_82 Argiles de Hannut (Membre de Lincent)		UH/RBC_8b Aquiclude des argiles du Landénien	aquiclude	
II (Mésozoïque)	US/RBC_91 Craies de Gulpen	UH/RBC_9 Système aquifère des craies du Crétacé et du socle Paléozoïque	UH/RBC_9a Aquifère des craies du Crétacé	aquifère	
I (Paléozoïque)	US/RBC_92 Socle Paléozoïque		UH/RBC_9b Système aquifère du socle Paléozoïque	aquifère/aquitard	

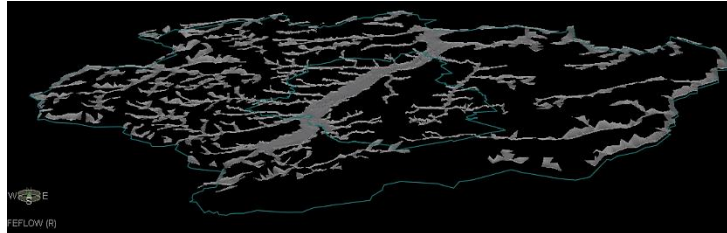


CONCEPTUAL MODEL

HYDROGEOLOGICAL CONTEXT / VERTICAL DISCRETIZATION

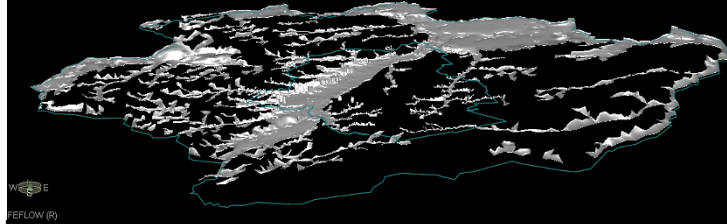
Layer 1

Alluvial clay
aquitard



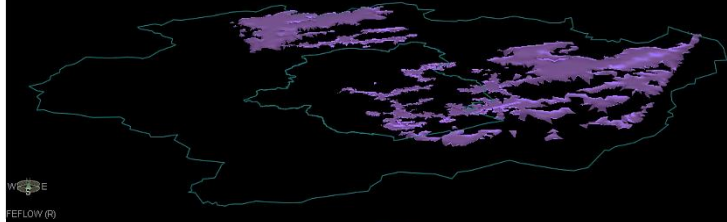
Layer 2

Alluvial silt,
sand & gravel
aquifer



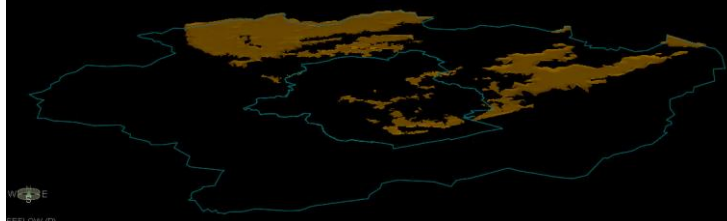
Layer 3

Perched
aquifer
system



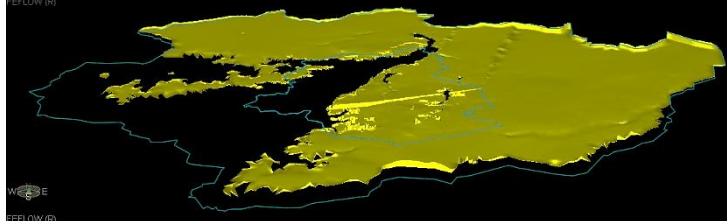
Layer 4

Ursel &
Asse
aquiclude



Layer 5

Brusselian
aquifer



Layer 6

Merelbeke
aquiclude



Layer 7

Tielt
aquitard



Layer 8

Aalbeke
aquiclude

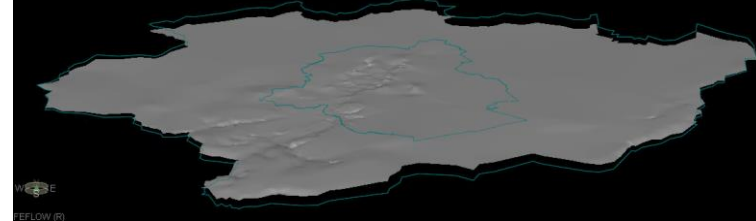


Layer 9

Moen
aquitard



Bottom





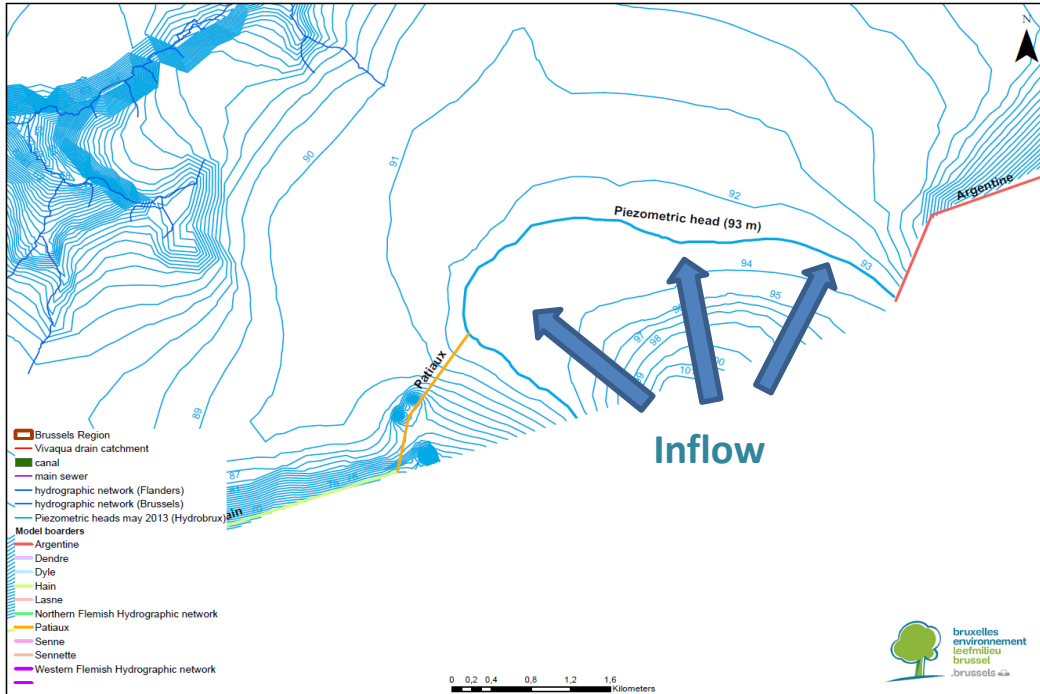
CONCEPTUAL MODEL

BOUNDARY CONDITIONS

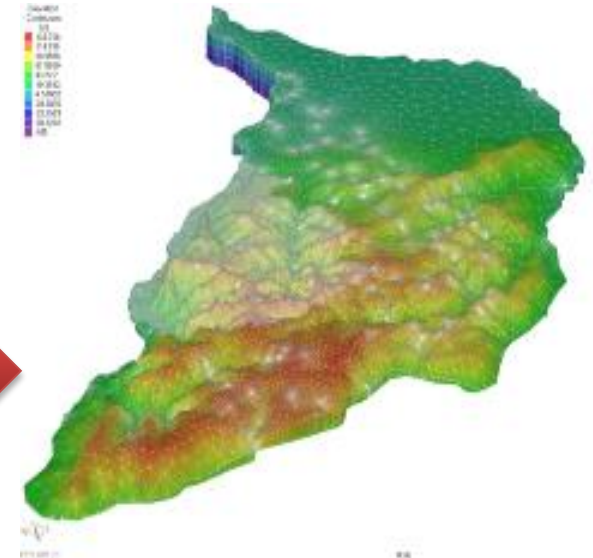
2nd kind (Neumann)

v_{darcy}
(m/j)

Southern boundary



HYDROBRUX (spring 2013)
(no longer operational)



(m³/j) (m²) (m/s) (m)

$$Q = A \times K \times i$$

v_{darcy}

Darcy flow velocity

(m/j)

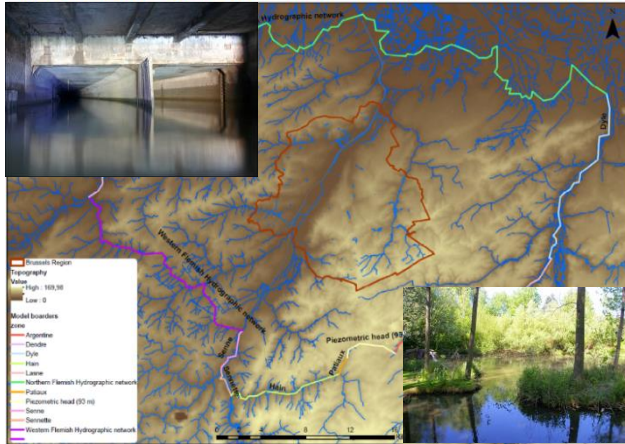




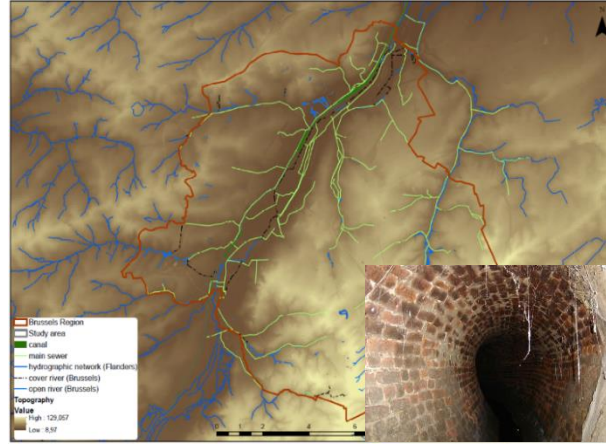
CONCEPTUAL MODEL

BOUNDARY CONDITIONS

Hydrographic network



Main sewers



3rd kind (Cauchy)

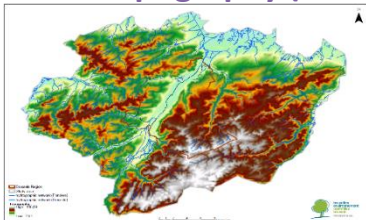
h_{ref} Φ_{in} Φ_{out}

(m) (1/s) (1/s)

Limnimeters



Raster topography (URBIS)



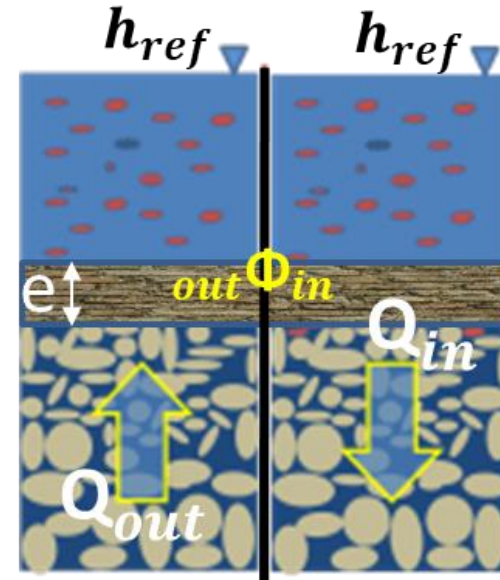
$$Q = A \times (h_{ref} - h_{aq}) \times \frac{K_{interface}}{e}$$

$\frac{(m^3/j)}{(m^2)} \times \frac{(m)}{(m)} \times \frac{(m/j)}{(m)}$

spring 2013
representative values

Φ_{in} or Φ_{out}
transfer rate
(1/j)

CALIBRATION





CONCEPTUAL MODEL

BOUNDARY CONDITIONS

VIVAQUA drain catchment

2013 annual declared flow rate ($\Rightarrow$ **m³/day** - **spring 2013** representative values)

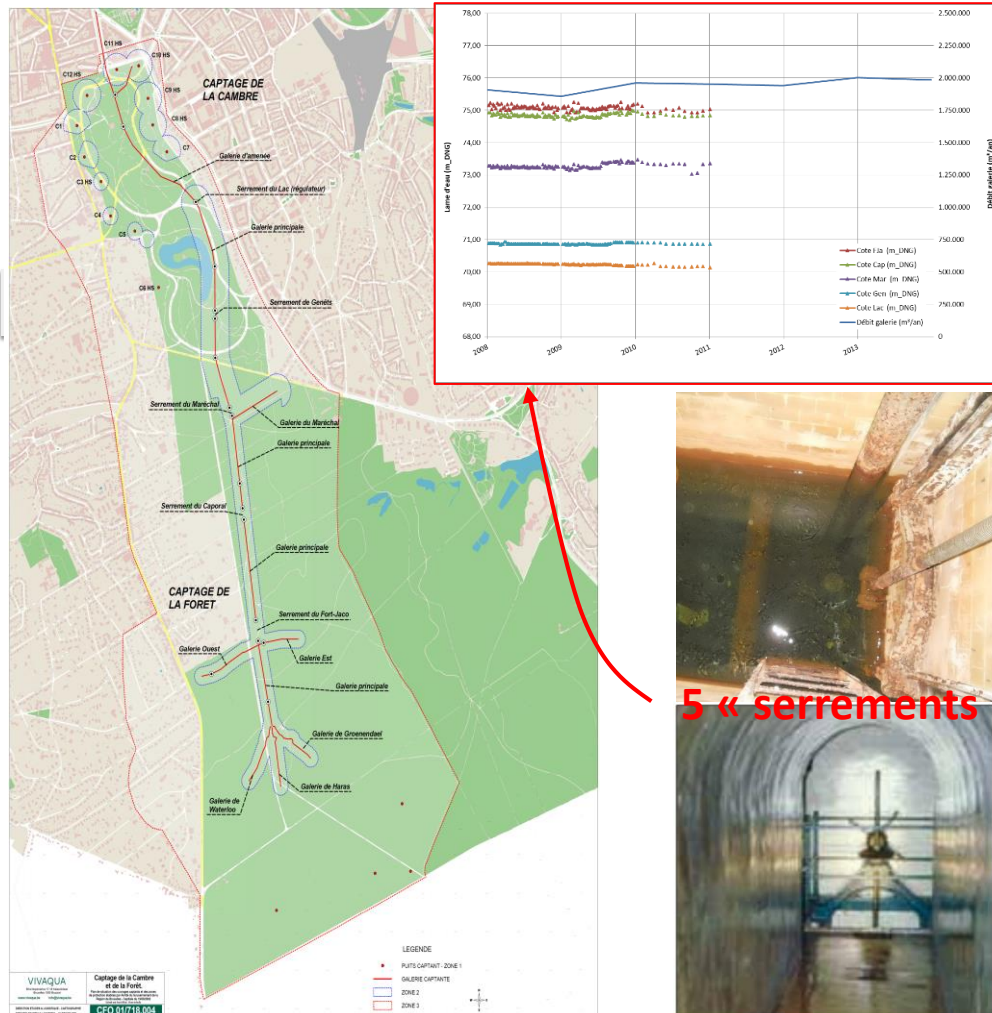
3rd kind (Cauchy)

h_{ref} Φ_{out}
(m) (1/s)

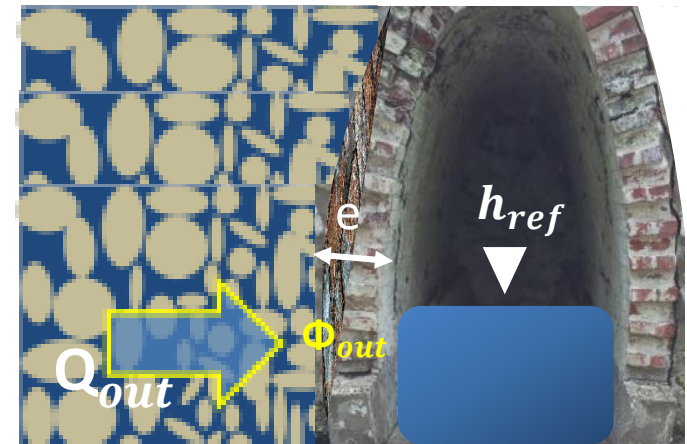
$$Q = A \times (h_{ref} - h_{aq}) \times \frac{K_{drain}}{e} \quad (m^3/j) \quad (m^2) \quad (m) \quad (m) \quad (m)$$

Φ_{out}
transfer rate
(1/j)

CALIBRATION



5 « serrements »





CONCEPTUAL MODEL

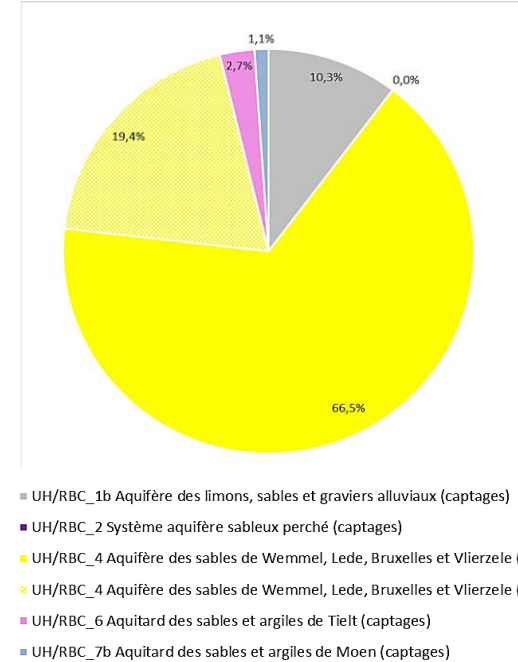
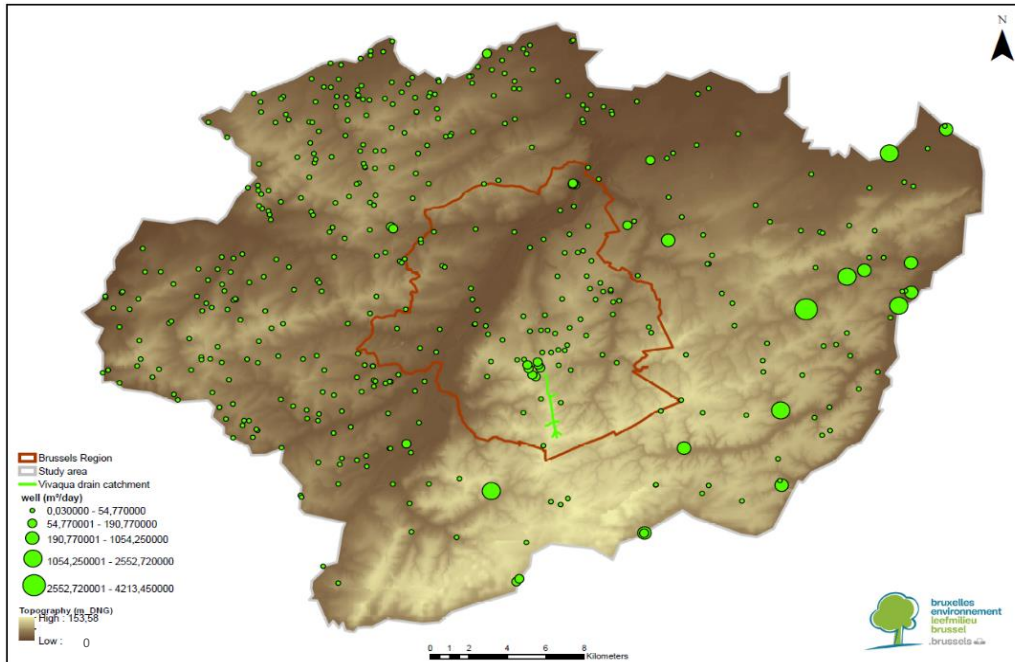
BOUNDARY CONDITIONS

Well condition

Q
(m³/j)

452 wells

2013 annual declared flow rates ($\Rightarrow$ **m³/day** - **spring 2013** representative values)



drinking water



industry



tertiary sector



other

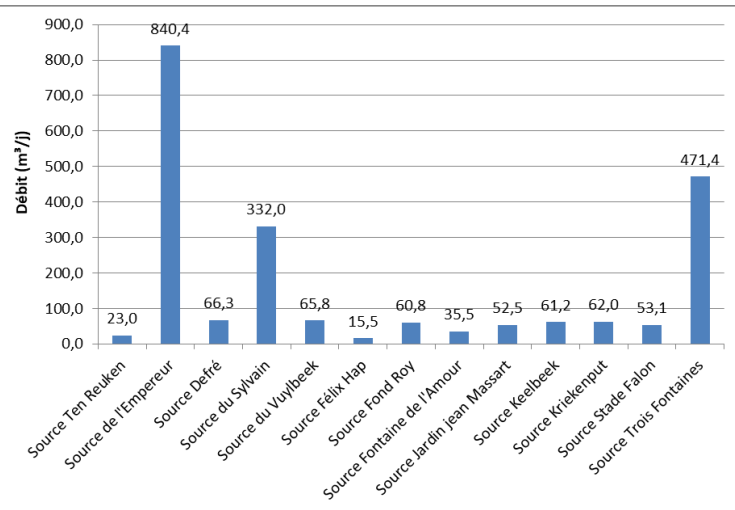


CONCEPTUAL MODEL

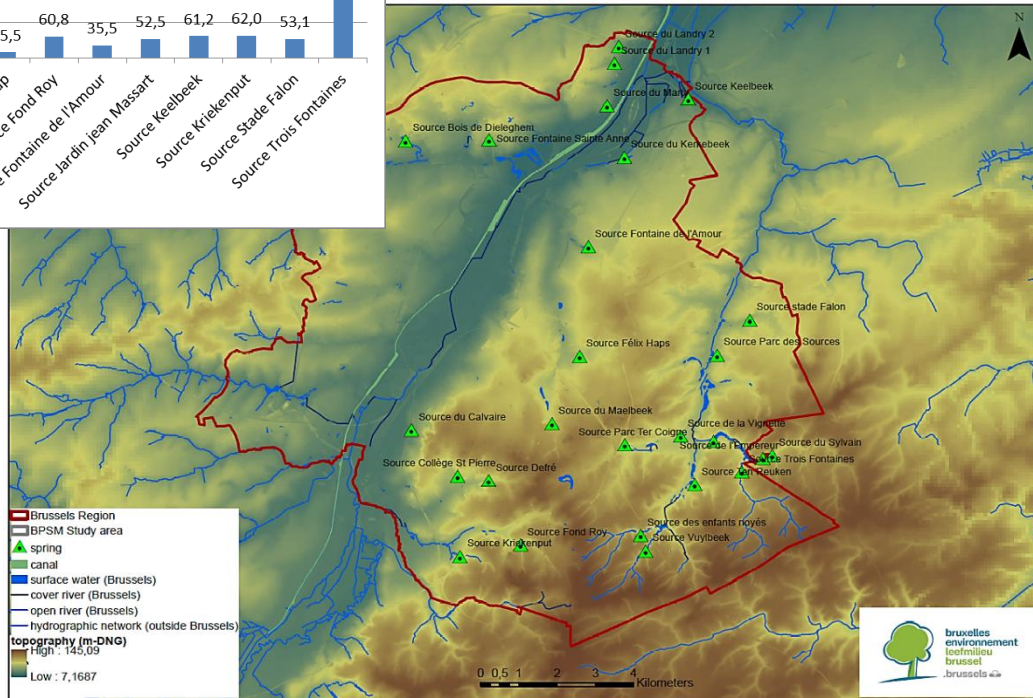
BOUNDARY CONDITIONS

26 Springs (Brussels)

Measured flow rates ($\Rightarrow$ **m³/day**
spring 2013 representative values)



Spring flow measurement



Well condition

Q

(m³/j)



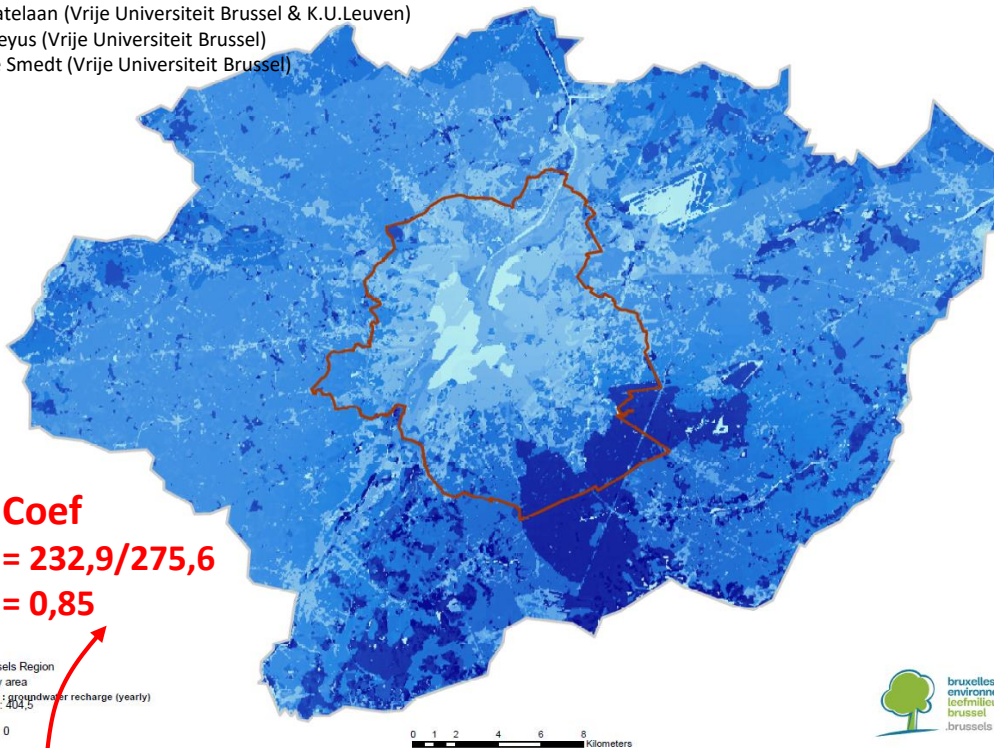
CONCEPTUAL MODEL

BOUNDARY CONDITIONS

Recharge

Flanders WetSpa hydrological model 20*20m (VUB, 2007)

O. Batelaan (Vrije Universiteit Brussel & K.U.Leuven)
Y. Meyus (Vrije Universiteit Brussel)
F. De Smedt (Vrije Universiteit Brussel)



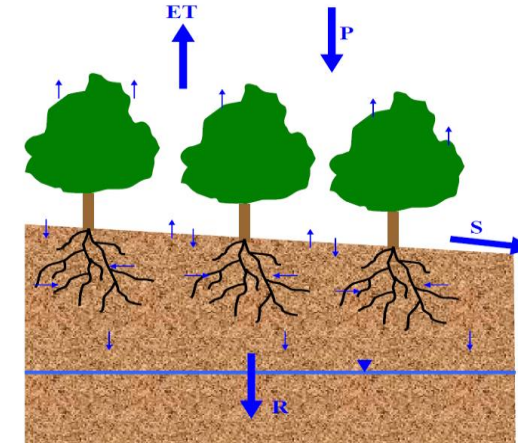
Coef
= 232,9/275,6
= 0,85

Model area (Thornwaite)
Pluviometry & ETP (2013),
Uccle, IRM
runoff + recharge = 232,9
mm/y

BPSM area (WetSpa)
runoff = 83,8 mm/y
recharge = 191,8 mm/y
runoff + recharge =
275,6 mm/y

Inflow on top model

R
(m/j)



Summer/winter/annual hydrological budget
Period 1833-1975

	Parameter	Min ¹	Max ¹	Gemiddeld ²	Std. Dev
Jaarlijks	Neerslag (P; mm)	654,4	1008,2	759,7	47,6
	Evapotranspiratie (ET; mm)	204,8	757,7	482,2	57,3
	Grondwatervoeding (R; mm)	-126,1	554,7	219,8	86,4
	Oppervlakkige afvoer (S; mm)	1,1	591,2	64,9	82,7
	Waterbalans (WB = P - ET - R - S; mm)	-	-	-7,2	-
	Fout op waterbalans (WB/ P; %)	-	-	-1,0	-
Zomer	Neerslag (P; mm)	335,6	517,0	389,6	24,4
	Evapotranspiratie (ET; mm)	102,9	626,0	366,8	56,8
	Grondwatervoeding (R; mm)	-188,6	193,1	-7,0	48,4
	Oppervlakkige afvoer (S; mm)	0,0	304,4	35,6	38,5
	Waterbalans (WB = P - ET - R - S; mm)	-	-	-5,8	-
	Fout op waterbalans (WB/ P; %)	-	-	-1,5	-
Winter	Neerslag (P; mm)	318,8	491,2	370,1	23,2
	Evapotranspiratie (ET; mm)	69,5	157,0	115,4	7,1
	Grondwatervoeding (R; mm)	0,0	381,7	226,9	59,4
	Oppervlakkige afvoer (S; mm)	0,23	365,3	29,3	53,4
	Waterbalans (WB = P - ET - R - S; mm)	-	-	-1,6	-
	Fout op waterbalans (WB/ P; %)	-	-	-0,4	-

Flanders area (WetSpa)

1. Volume per oppervlakte in de extreme rastercel
2. Totaal volume per oppervlakte van het volledige studiegebied

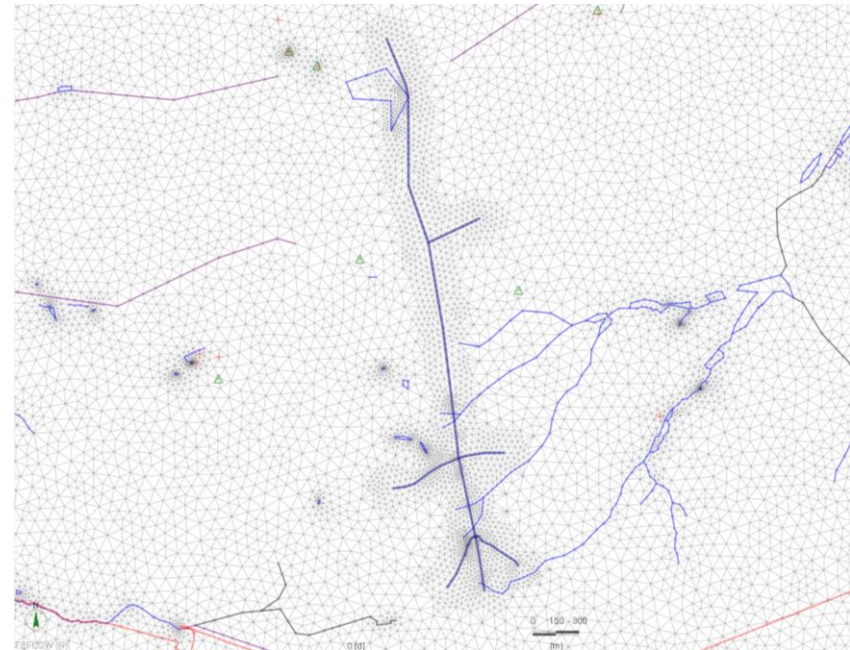
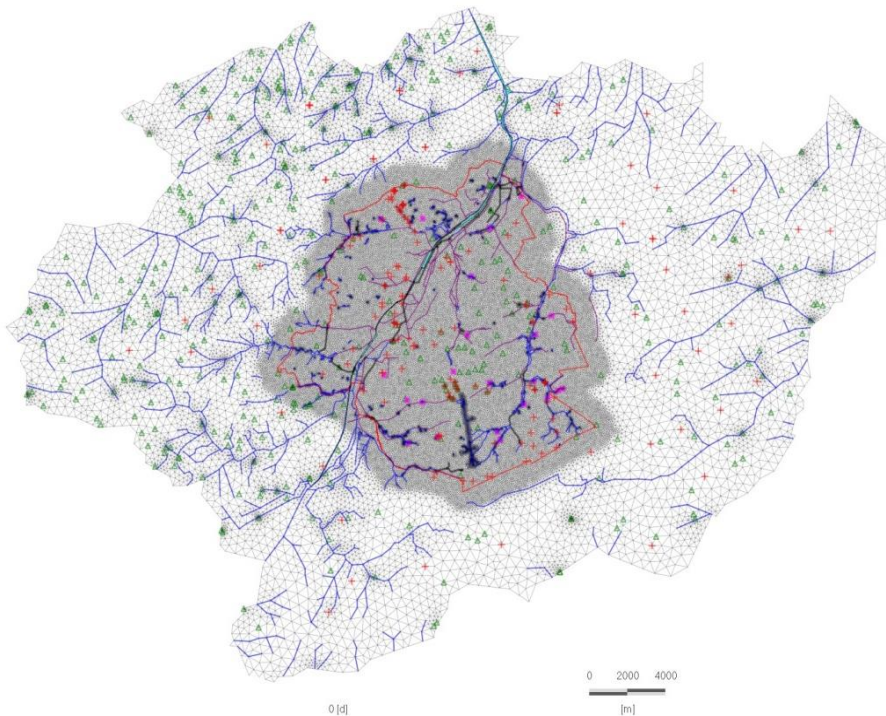
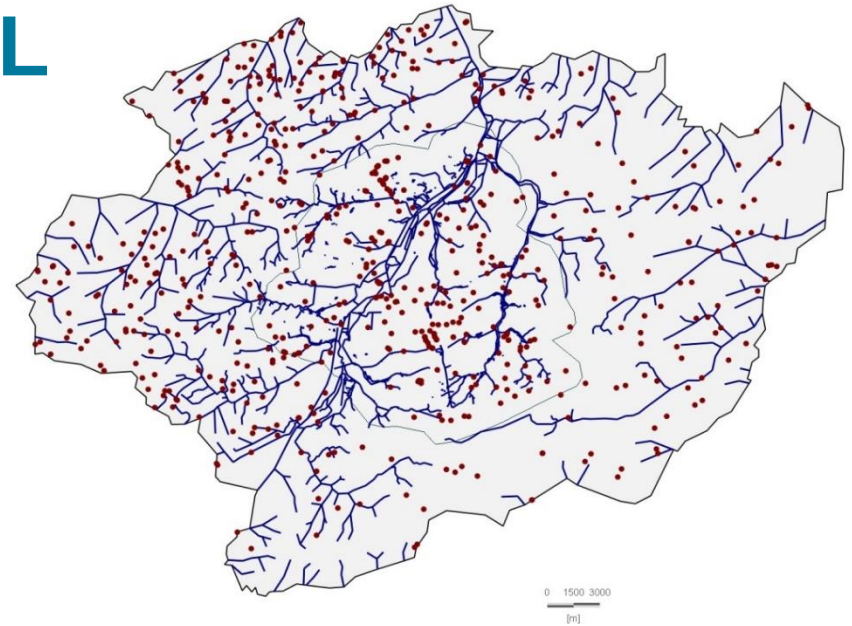


NUMERICAL MODEL

MESH DESIGN



- **FEFLOW**, finite elements
- **Points** = springs, wells , observation points
- **Lines** = hydrographic networks, sewers, drain catchment

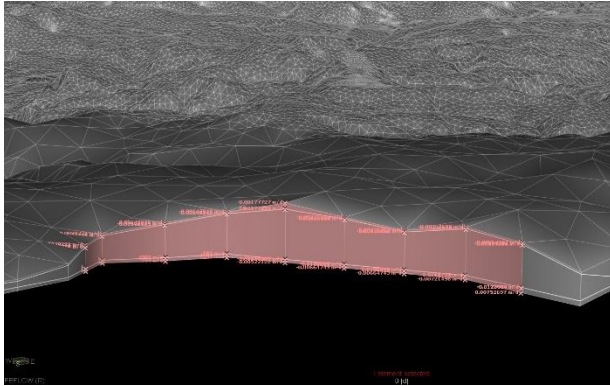




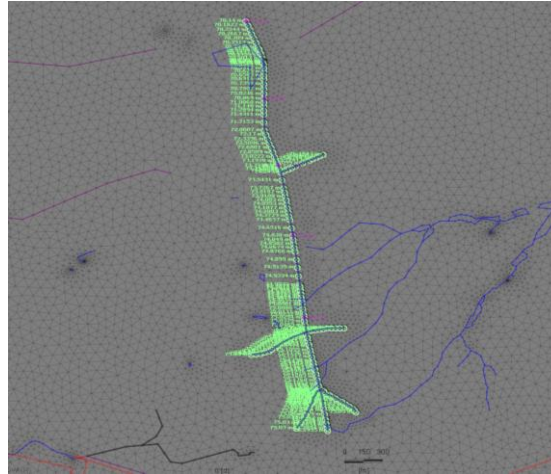
NUMERICAL MODEL

INPUT DATA IMPLEMENTATION

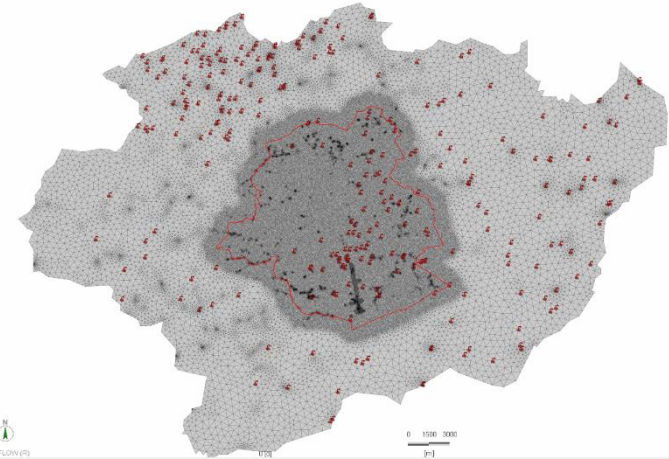
Southern border (V_{darcy})



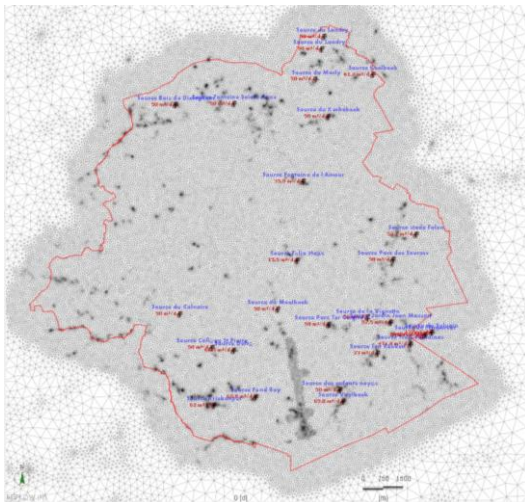
Drain catchment (h_{ref} , Φ)



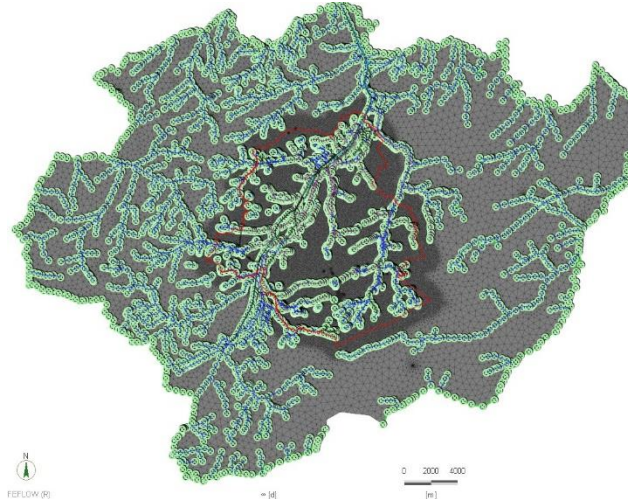
Wells (*Outflow*)



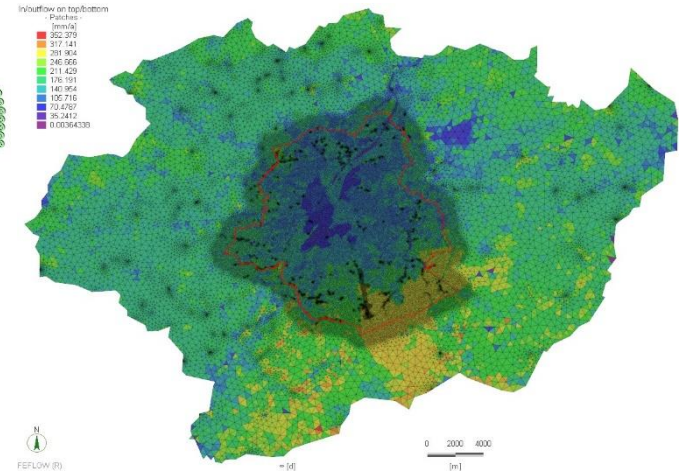
Springs (*Outflow*)



Surface water & sewer (h_{ref} , Φ)



Recharge (*Inflow*)





CALIBRATION

HYDRODYNAMIC PARAMETERS



Hydraulic conductivity (m/s)

$$K_h, K_z$$

Initial values : Bibliographic analysis

(pumping tests, scientific publications, studies, groundwater bodies characterisation in Flanders and Wallonia,...)



Pumping test

In/out transfer rate (1/s)

Initial values : Expert judgment

$$IN_{transfer\ rate}, OUT_{transfer\ rate}$$



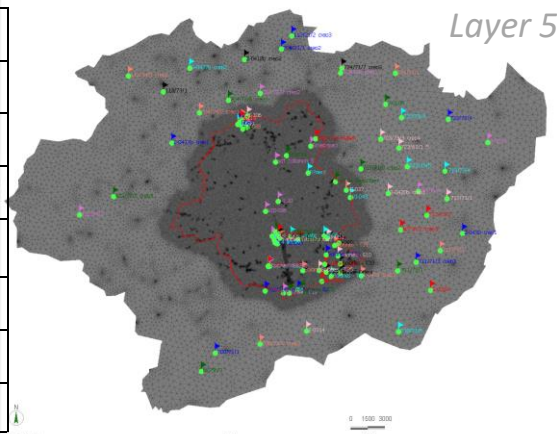
CALIBRATION

OBSERVATION POINTS

Piezometry (278 points)

174 Piezometers (spring 2013)

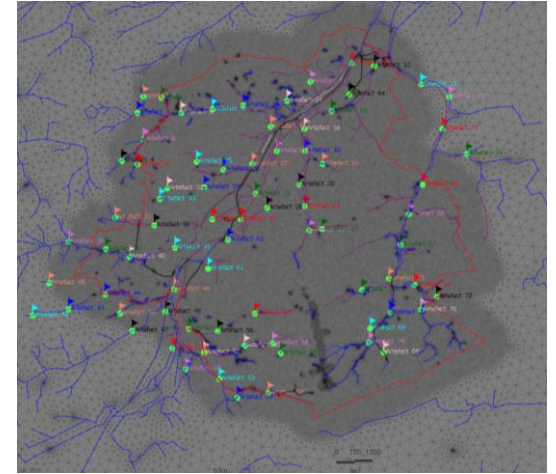
Unités Hydrogéologiques de la RBC (UH/RBC)	Layer	Total
UH/RBC_1 Système aquifère du quaternaire (argiles)	1	8
UH/RBC_1 Système aquifère du quaternaire (sables et graviers)	2	32
UH/RBC_2 Système aquifère sableux perché	3	5
UH/RBC_4 Système aquifère des sables de Wemmel, Lede, Bruxelles et Vlierzele	5	90
UH/RBC_6 Aquitard des sables et argiles de Tielt	7	21
UH/RBC_7 Système aquitard des sables et argiles de Kortrijk	9	18
TOTAL	-	174



Piezometric campaign

78 Artefacts

Open hydrographic network
=> from Raster topography (URBIS)



26 springs (Brussels)





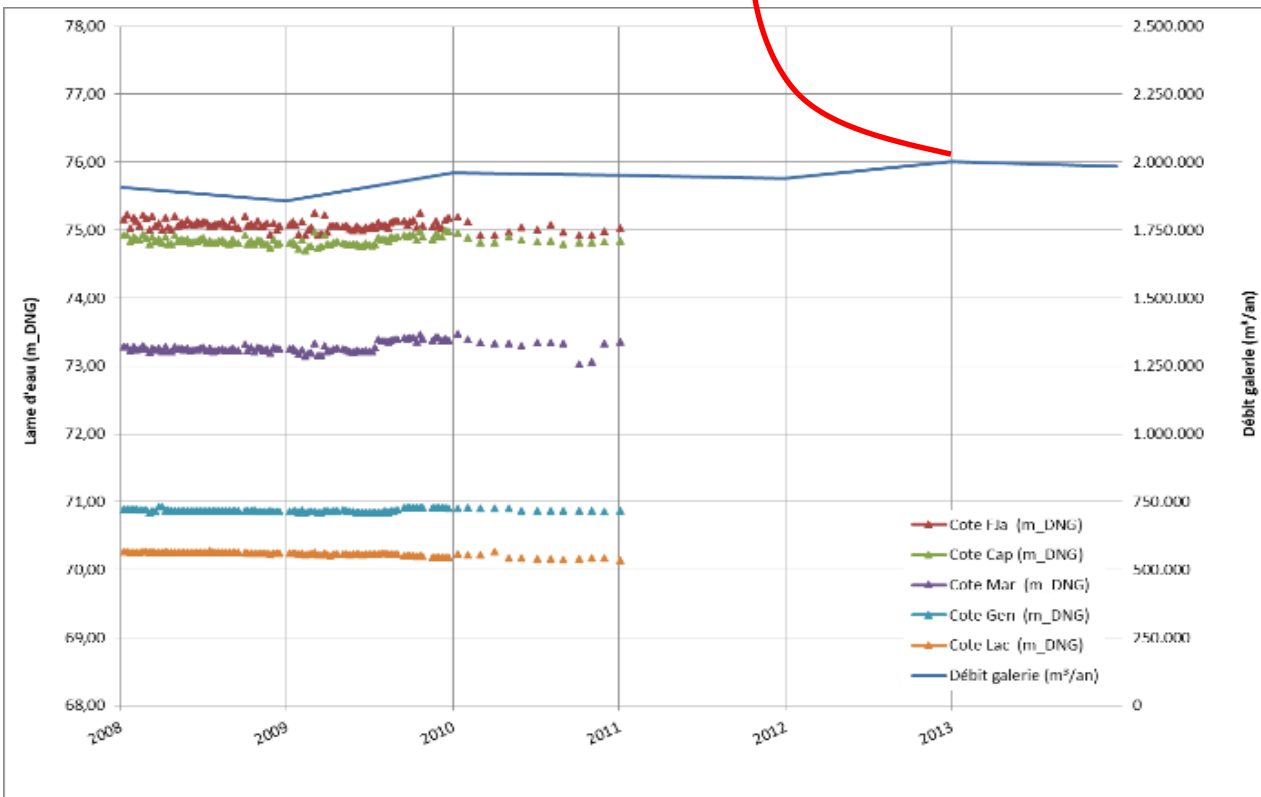
CALIBRATION

OBSERVATION POINTS

Drain catchment (*outflow rate*)

flow rate (2013) = 2.002.478 m³/year

➡ 5436,2 m³/day



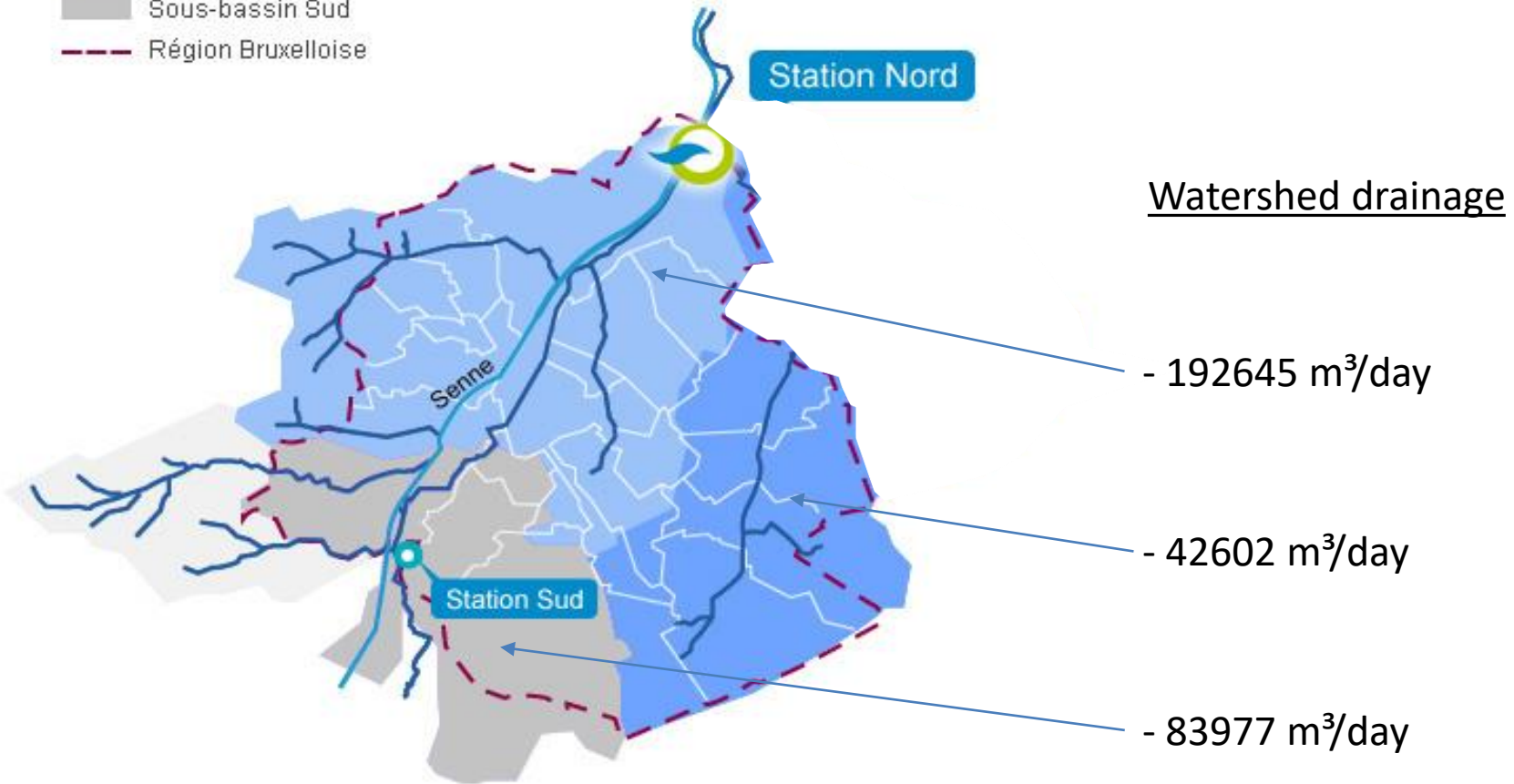


CALIBRATION

OBSERVATION POINTS

Hydrographic network/Main sewers drainage (outflow rate)

- Sous-bassin Nord
- Sous-bassin de la Woluwe
- Sous-bassin Sud
- Région Bruxelloise





CALIBRATION

STEADY STATE - RESULTS

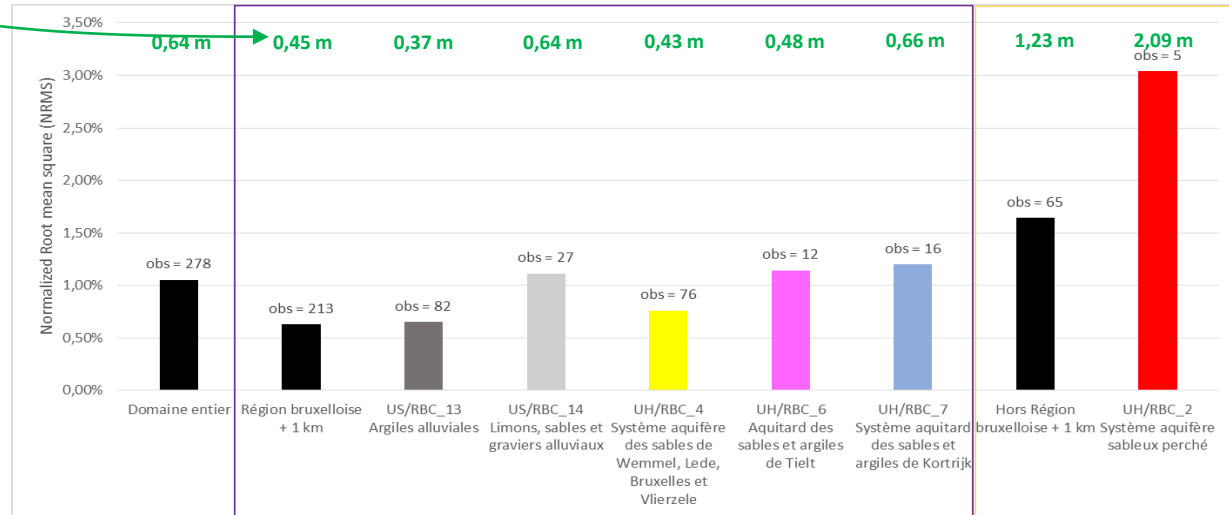
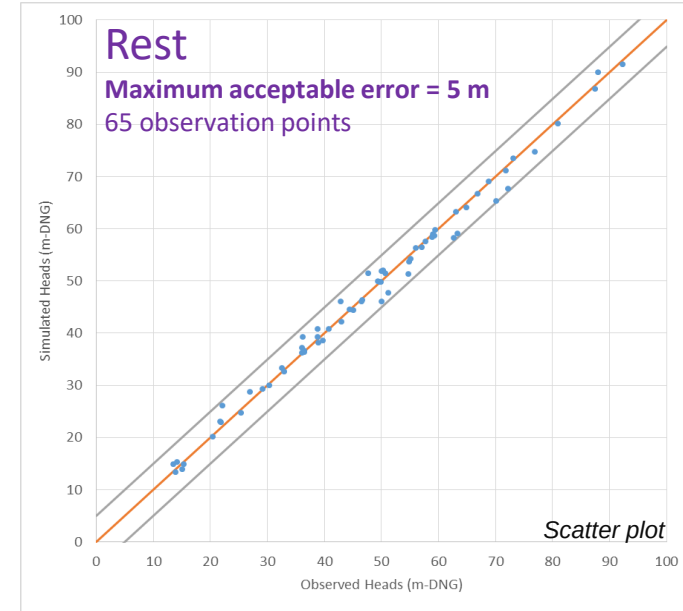
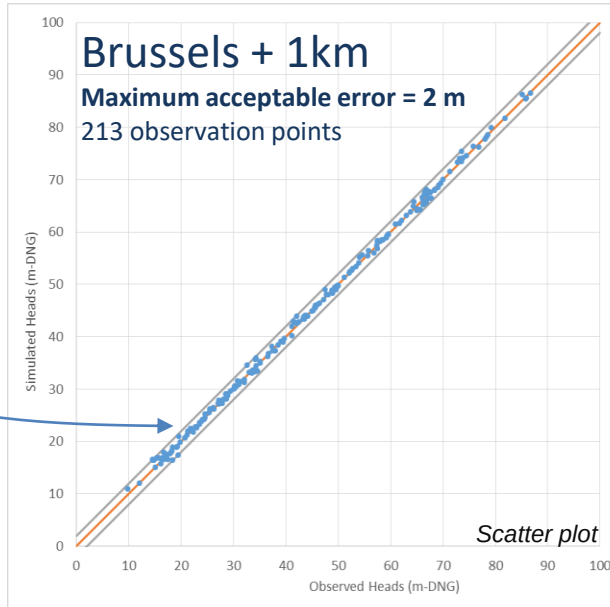
Piezometry

Error max.

Global errors

$$\text{Mean difference} = \frac{\sum_1^n |e_i|}{n}$$

$$\text{NRMS} = \frac{\sqrt{\frac{\sum_1^n (e_i)^2}{n}}}{x_{\max} - x_{\min}}$$





CALIBRATION

STEADY STATE - RESULTS

VIVAQUA drain catchment (outflow rate)

$Q_{\text{sim}} = 5444 \text{ m}^3/\text{day}$

Error = 0,14 %

Hydrographic network/Main sewers drainage (outflow rate)

Watershed (STEP)	Drainage flowrate Observation (m ³ /day)	Drainage flowrate Simulated (m ³ /day)	Error (%)
Woluwe	-42.602	-50.366	18,23%
Senne Sud	-83.977	-92.251	9,85%
Senne Nord	-192.645	-173.819	-9,77%



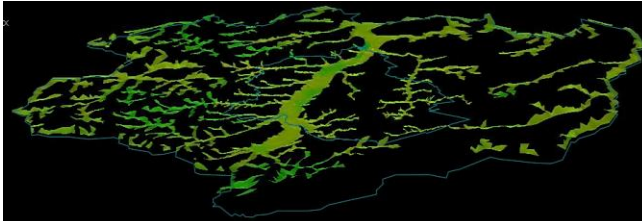
CALIBRATION

STEADY STATE - RESULTS

Calibrated hydraulic conductivities

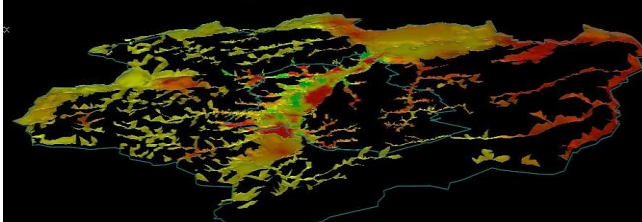
Layer 1

Alluvial clay
aquitard



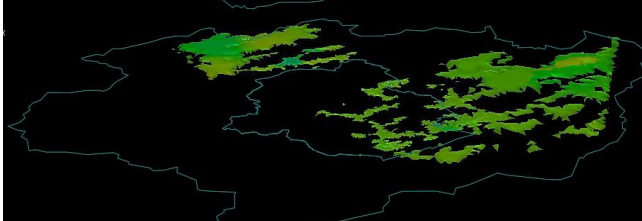
Layer 2

Alluvial silt,
sand & gravel
aquifer



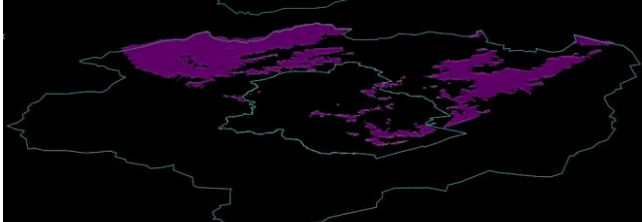
Layer 3

Perched
aquifer
system



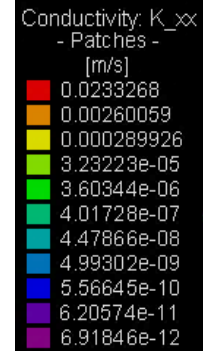
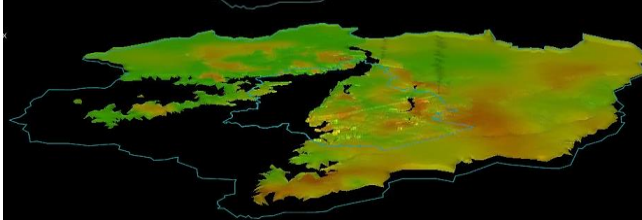
Layer 4

Ursel &
Asse
aquiclude



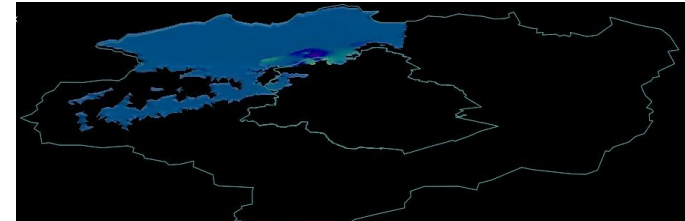
Layer 5

Brusselian
aquifer



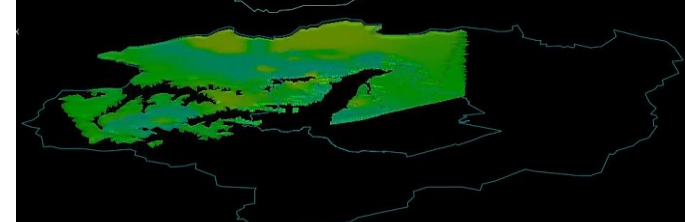
Layer 6

Merelbeke
aquiclude



Layer 7

Tielt
aquitard



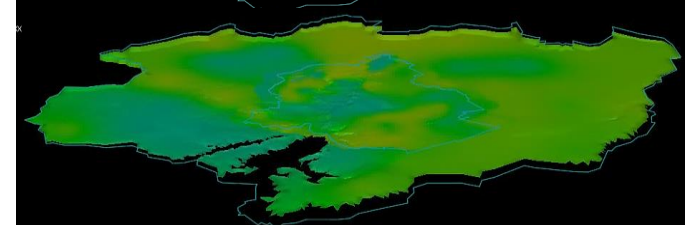
Layer 8

Aalbeke
aquiclude



Layer 9

Moen
aquitard

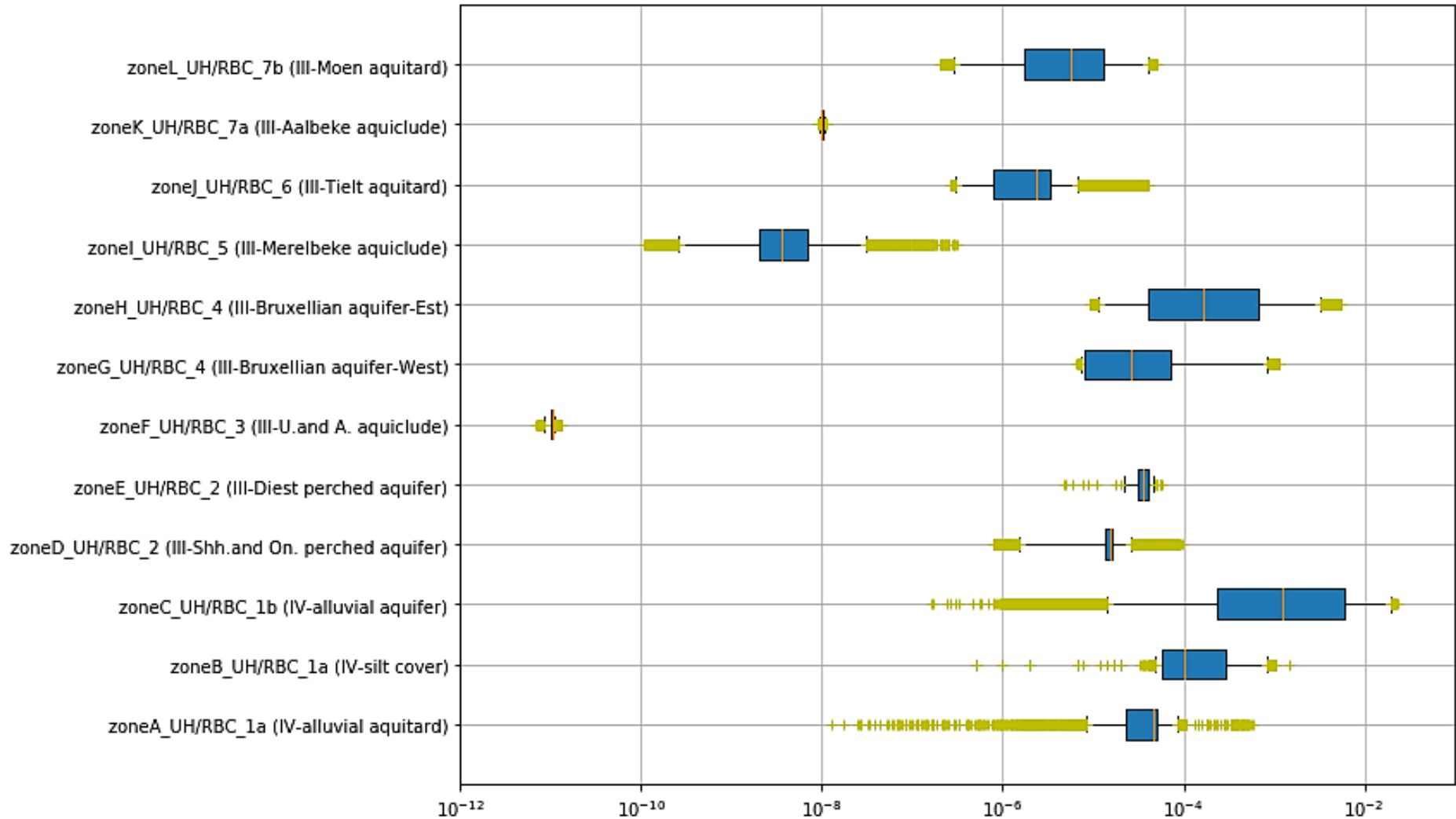




CALIBRATION

STEADY STATE - RESULTS

Calibrated hydraulic conductivities

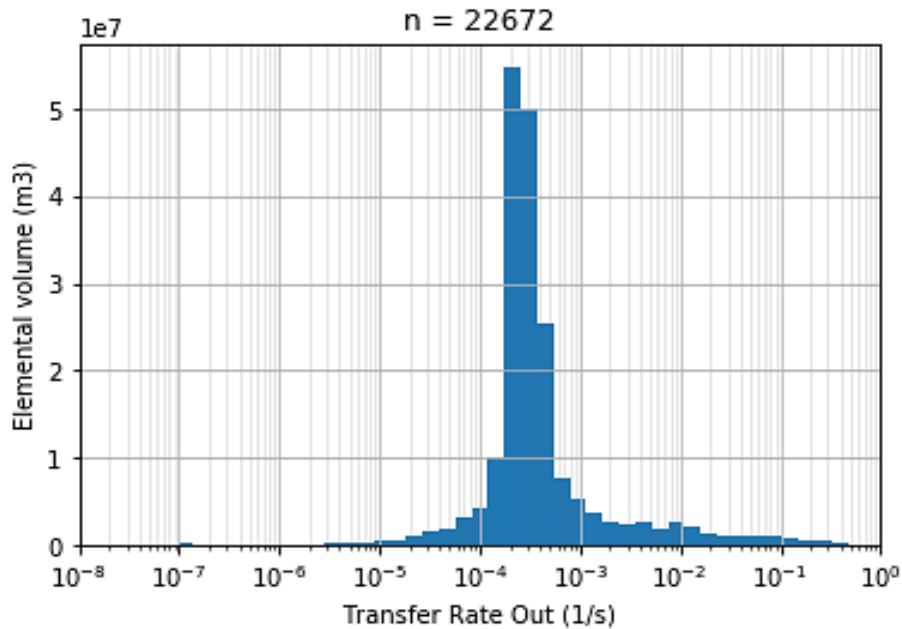




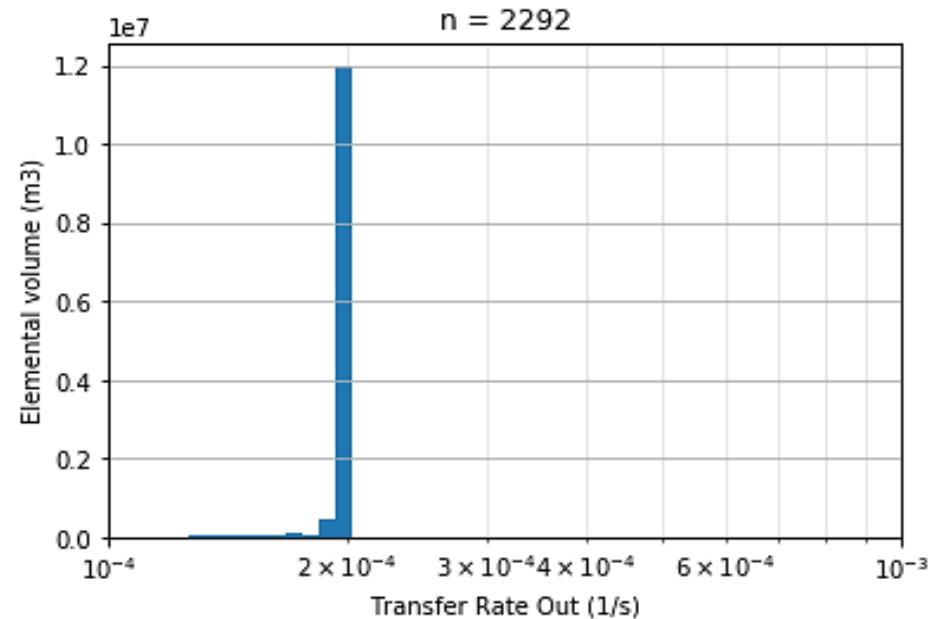
CALIBRATION

STEADY STATE - RESULTS

Calibrated transfer rates (conductances)



River / Main sewers drainage
(outflow rate)



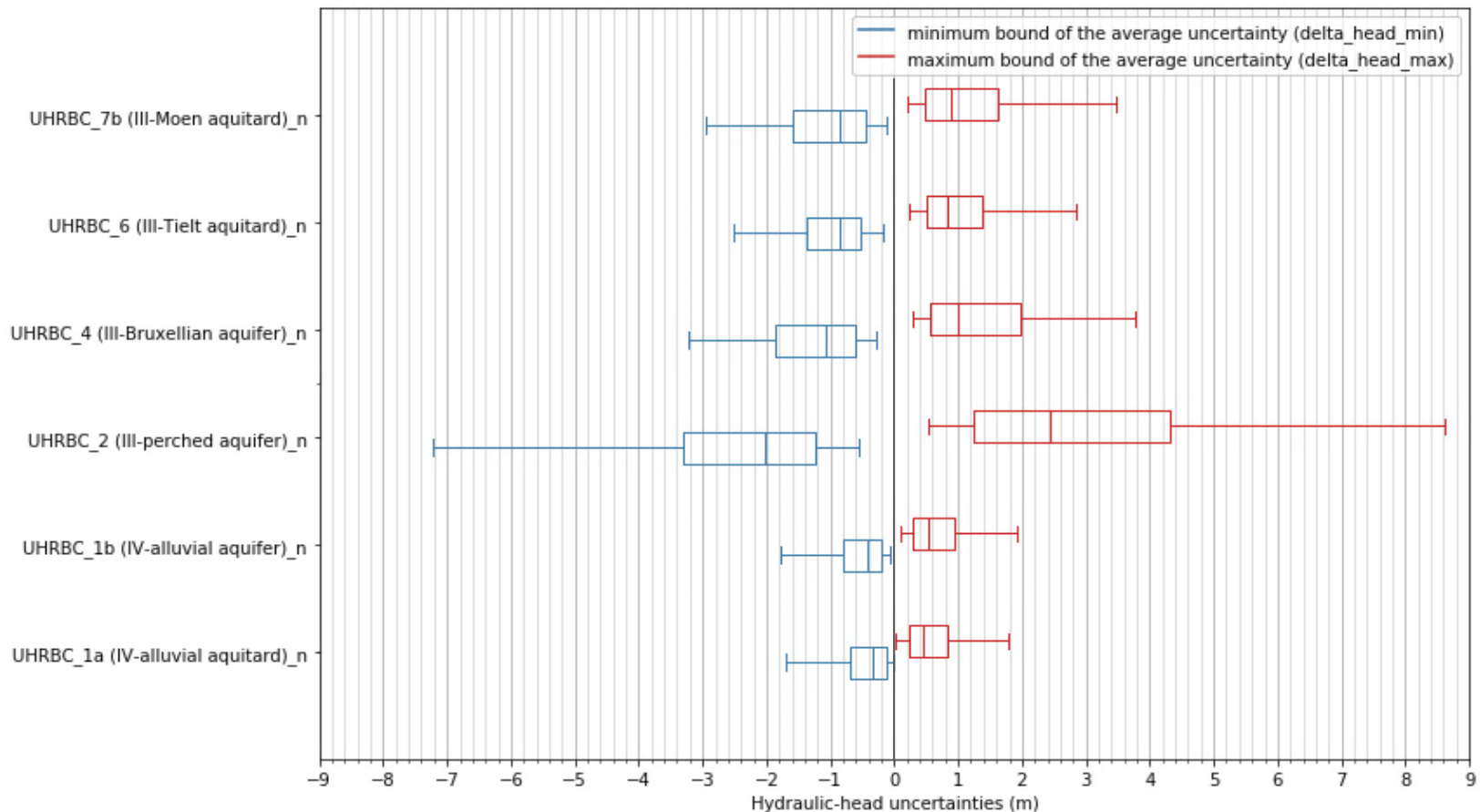
VIVAQUA Drain catchment
(outflow rate)



UNCERTAINTY ANALYSIS

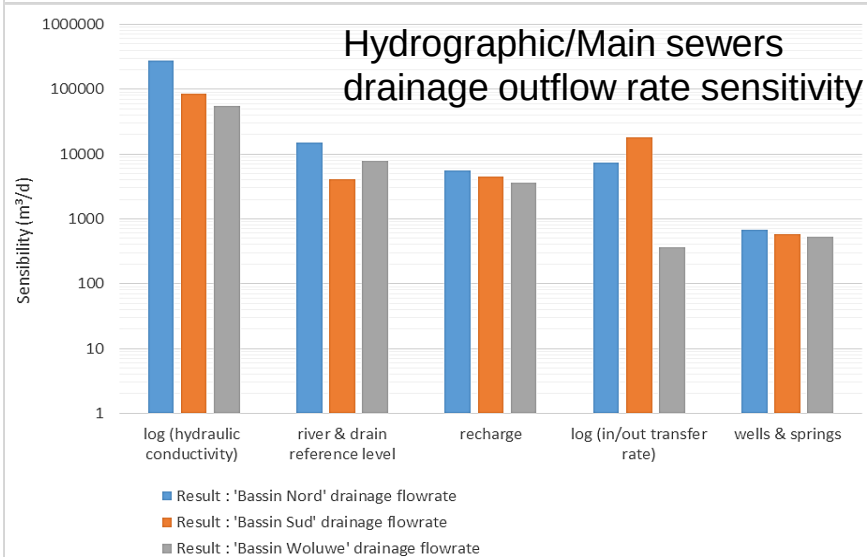
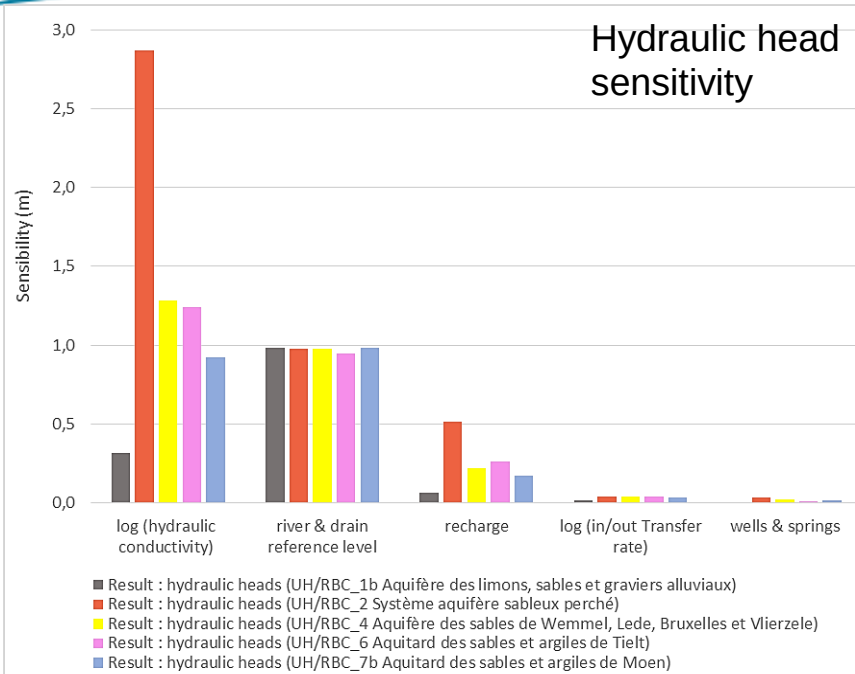
MONTE CARLO ANALYSIS

Automatic
approach

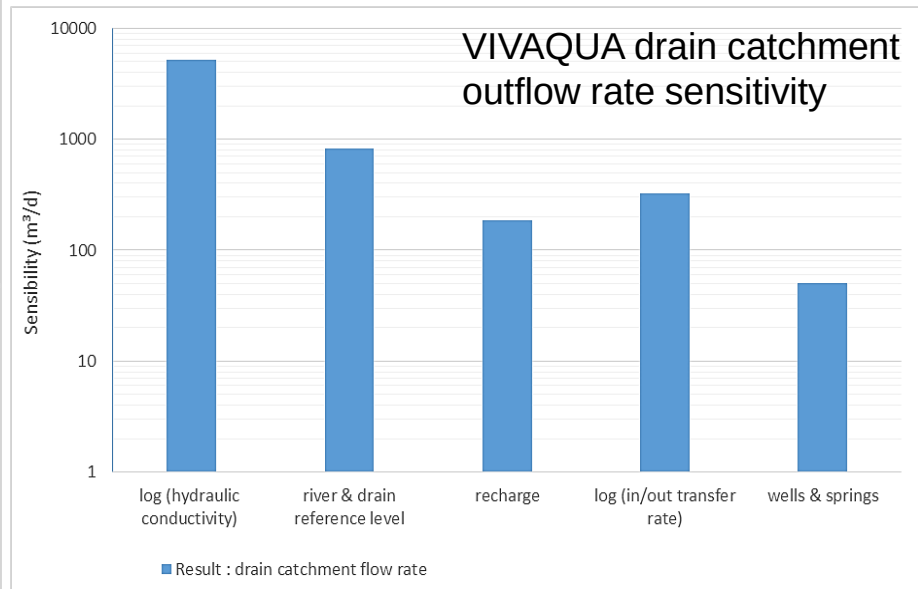




SENSITIVITY ANALYSIS



Automatic approach





RESULTS

PIEZOMETRIC MAPS

Dataset for diffusion (Brussels region) :

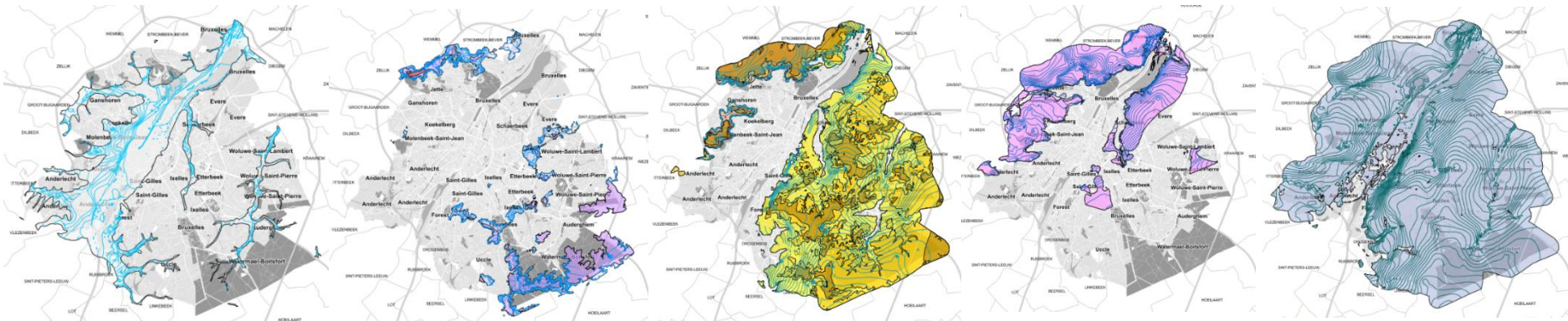
UH1b Quaternary confined aquifer (Alluvial silt, sand & gravel aquifer)

UH2 Sandy perched aquifer system

UH4 Wemmel, Lede, Brussel en Vlierzele sand (Bruxellian)

UH6 Tielt sand and clay aquitard

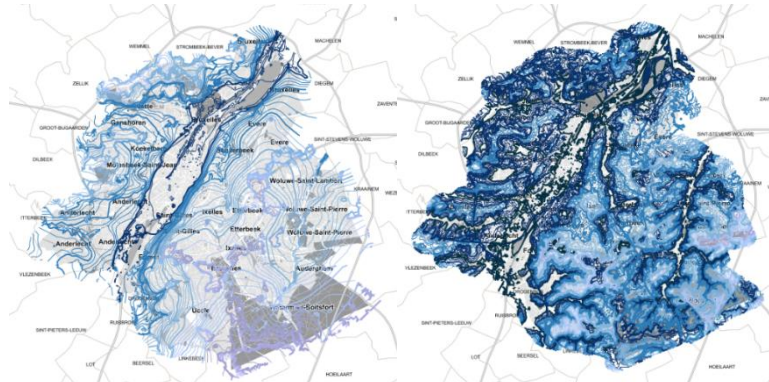
UH7b Moen sand and clay aquitard



Characteristics:

Isolines = 2 m

May 2013 reference period



Phreatic heads (m-DNG)
Phreatic depth (m)



RESULTS

HYDROGEOLOGICAL BUDGET

