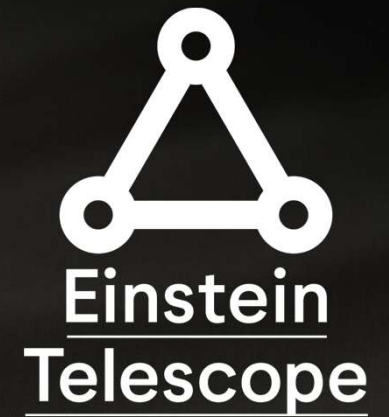


Groundwater modelling : new results and future works

Quentin Guillemoto, Philippe Orban, Frédéric Nguyen

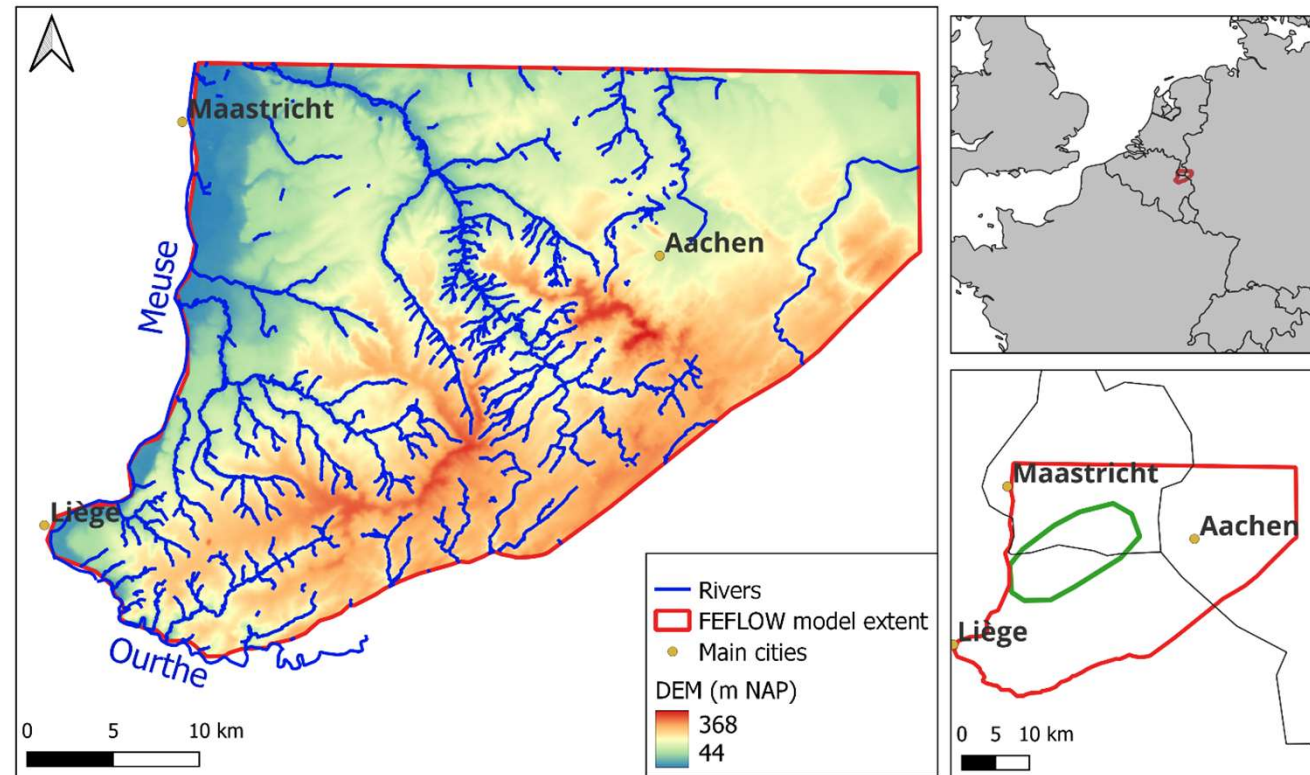
27/05/2025



Objectives of the model

- △ Open cross-border groundwater model for ecosystem service:
 - △ quantify quantitative impacts of ET tunnels implantations on groundwater
 - △ estimate groundwater inflows in tunnels

Regional hydrogeological model extent



Aquifer simulated

all the aquifers are simulated until lower Famennian

aquifers considered as connected

with different hydrogeological properties

| Ere | Système | Série | Etage | Groupe | Formation | Membre | Lithologie | Abréviation | Hydrogéologie |
|-------------|-------------|-------------|----------------|---------------------------------------------------------------------------------------|-------------------------------------------------------------|---------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|-------------|------------------------------------------------|
| CENOZOÏQUE | QUATERNAIRE | HOLOCENE | | | Alluvions Modernes | | Sables et graviers | AMO | Aquifère alluvial |
| | | | | | Dépôts Tourbeux | | Tourbières à sphaignes | TRB | Aquifère des tourbes |
| | PALEOGENE | OLIGOCENE | | | Dépôts Saboteux | | Sables quartzeux souvent micacés - Lentilles d'argiles sableuses | SBL | Aquifère des sables de remplissage |
| MESOZOÏQUE | CRETACE | SENONIEN | Maastrichtien | | Gulpen | | Craies glauqueuses, craies blanches avec silex noirs - Conglomérat à silex (SX) | GUL | Aquifère des craies du Crétacé |
| | | | Campanien | | Vaals | | Sables, silt et argiles glauqueux, à horizons indurés | VAA | Aquifère - Aquitard de Vaals |
| | | | Santonien | | Aachen | | Argiles siltieuses et sableuses, silt argileux, sables blancs à niveaux indurés, localement lentilles graveleuses | AAC | Aquifère des sables du Santonien |
| PALEOZOÏQUE | CARBONIFERE | NAMURIEN | Marsdenien | Houiller | | | Alternance de shales et de siltites, de grès argileux, de grès et de quartzites - Veines de charbon | HOU | Aquiclude à niveaux aquifères du Houiller |
| | | | Kinderscoutien | | | | | | |
| | | | Alportien | | | | | | |
| | | | Chokierien | | | | | | |
| | | VISEEN | Livien | Justenville | Selles | Calcaires - Niveaux à oolites - Cherts | SEI | JUS | Aquifère des calcaires du Carbonifère |
| | | | | | Lives | Calcaires - Nodules de cherts | LIV | | |
| | | | Moliniacien | Bay-Bonnet | Moha | Calcaires grossiers généralement oolithiques Cherts | MOH | | |
| | | | | | Tenragie | Calcaires fins à grossiers | TER | | |
| | | TOURNAISIEN | Ivorien | Bilstein | Dolomies de la Vesdre | Dolomies, dolomies crinoïdiques - Cherts et nodules siliceux | VES | BIL | Aquifère - Aquitard - Aquiclude de l'Hastarien |
| | | | | | Landeles | Calcaires fins à grossiers, crinoïdiques, dolomités au sommet | LAN | | |
| | | | Hastarien | Pont d'Arcote | Shales, calcschistes avec nodules calcaires | PDA | | | |
| | | | | Hastière | Calcaires moyens à grossiers - Calcaires argileux au sommet | HAS | | | |
| SUPERIEUR | Famennien | | Dolhain | Calcaires crinoïdiques et grès carbonatés - Intercalations de shales et siltites | DOL | ME | Aquifère des grès du Famennien | | |
| | | | Monfort-Evieux | Grès micacés feldspathiques, grès carbonatés - Shales - Siltites - Nodules carbonatés | ME | | | | |
| | | | Souverain-Pré | Calcaires argileux et noduleux | SVP | | | | |
| | | | Esneux | Grès fins plus ou moins argileux | ESN | | | | |
| | | | Hodimont | Siltites micacées - Nodules carbonatés | HOD | | | | |
| | | | Lambermont | Shales, siltites, calcaires, schistes nodulaires | LAM | | | | |
| FRANSIEN | | | Aisemont | Shales, calcschistes et calcaires organoclastiques | AIS | LH | Aquitard du Famennien - Frasnien | | |
| | | | | | | | | | |

Cretaceous aquifers (sands, chalk)

Houiller (Namurian)
(shales, siltstones, sandstones)

Famennian (limestones-sandstones)

Lower Famennian aquitard
(siltstones)

Table of hydrogeological units
Hydrogeological map. RUTHY and DASSARGUES, 2009.



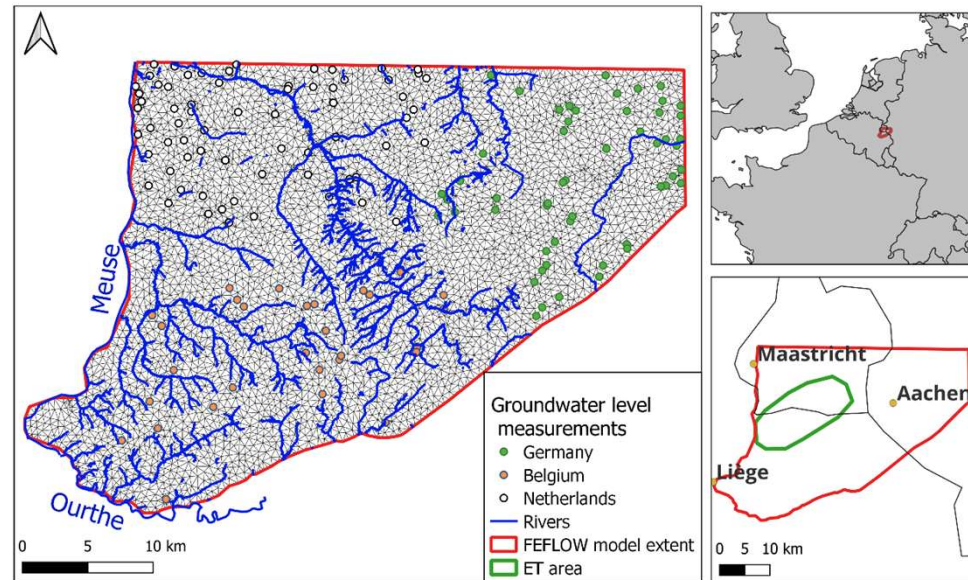
Numerical model

△ Feflow[®] hydrogeological flow model construction:

- finite element mesh
- steady flow model
- based on 2018 data

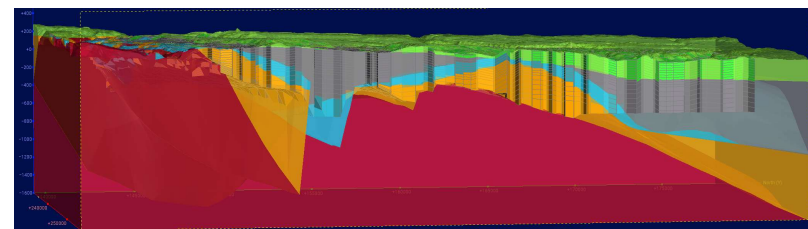
△ Regional database used in the model:

- groundwater water level observations, groundwater abstractions (Wallonia, Germany, The Netherlands)
- hydraulic conductivities
- topography
- geology



River network, groundwater level measurements and mesh of the finite elements model

Mesh sizes about 500 meters length



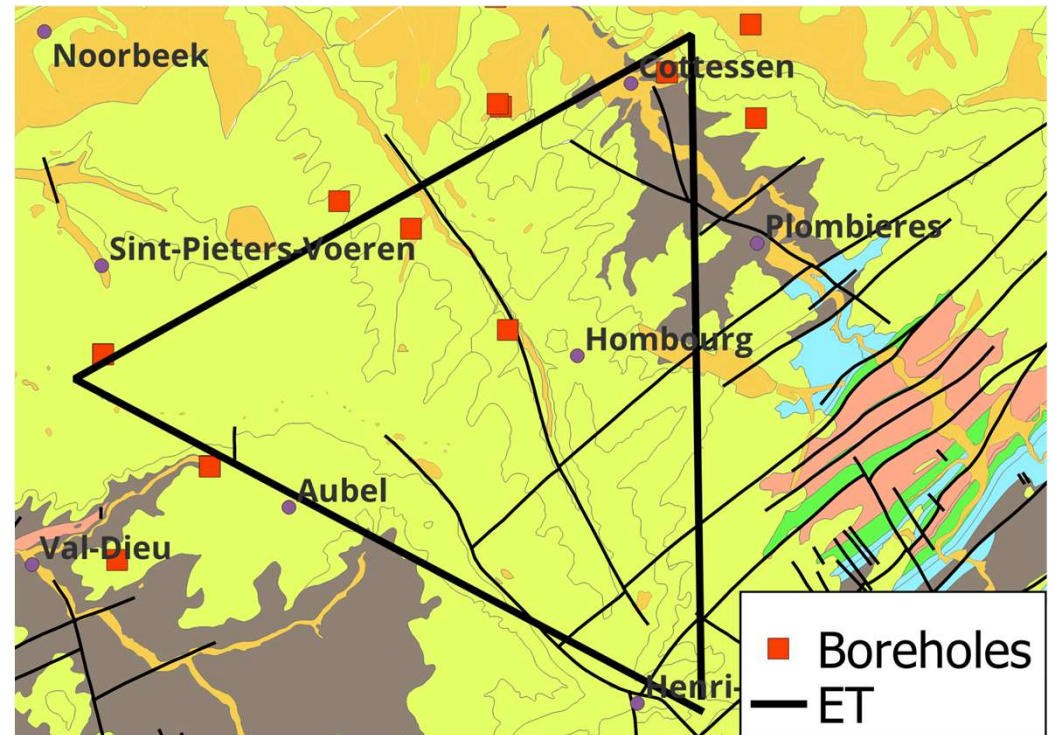
Hydrogeological model according to regional geological model



Recent improvements of the model

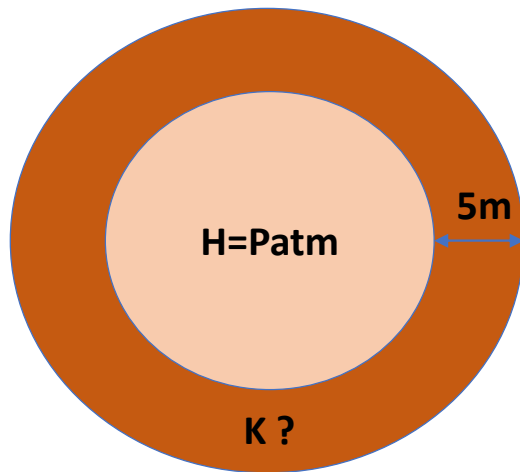
- △ Quantifying tunnels inflows using boundary conditions (3rd type)
- △ Better discretization of the tunnel surfaces in the regional model.
 - finer mesh near tunnels
 - 3D geometry imported into the regional model
- △ New position of the ET tunnels

New position of the ET triangle



Tunnel design simulated

Consideration of the grouting area



- △ Tunnel surrounded by ≈ 5 m of grouting area
- △ The hydraulic conductivity of the grouting area is adapted considering an acceptable inflow rate

**Expected volumes are of the order of 10 L / 100 m /min
(0.144 m³ / d / m)
(i.e. 4320 m³/d over 30 km of tunnel)**



Tunnel design simulated

3rd type boundary condition

The inflow is simulated as:

$$Q = Ar(h_{\text{ref}} - h)$$

A = relevant area (tunnel surface)

r = conductance (calculated from k_g and d)

h_{ref} = reference water level (atmospheric pressure)

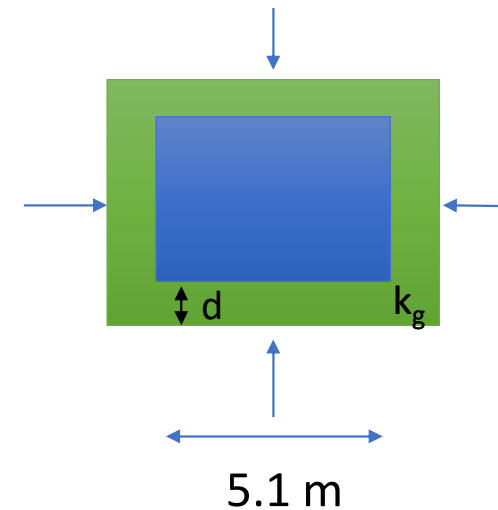
h = current hydraulic head in groundwater

The inflow rates are linked to the conductance:

$$r = k_g/d$$

k_g = grouting conductivity, d = grouting thickness

The 3D tunnel in the model



≈ 6.5m diameter tunnel surface



Numerical model calibration

△ Optimization of the objective function

$$\Phi = \sum_i w_i (h_i^{obs} - h_i^{sim})^2$$

Calibration with Pest software 50 pilot points/geological layers, considering prior hydraulic conductivities.

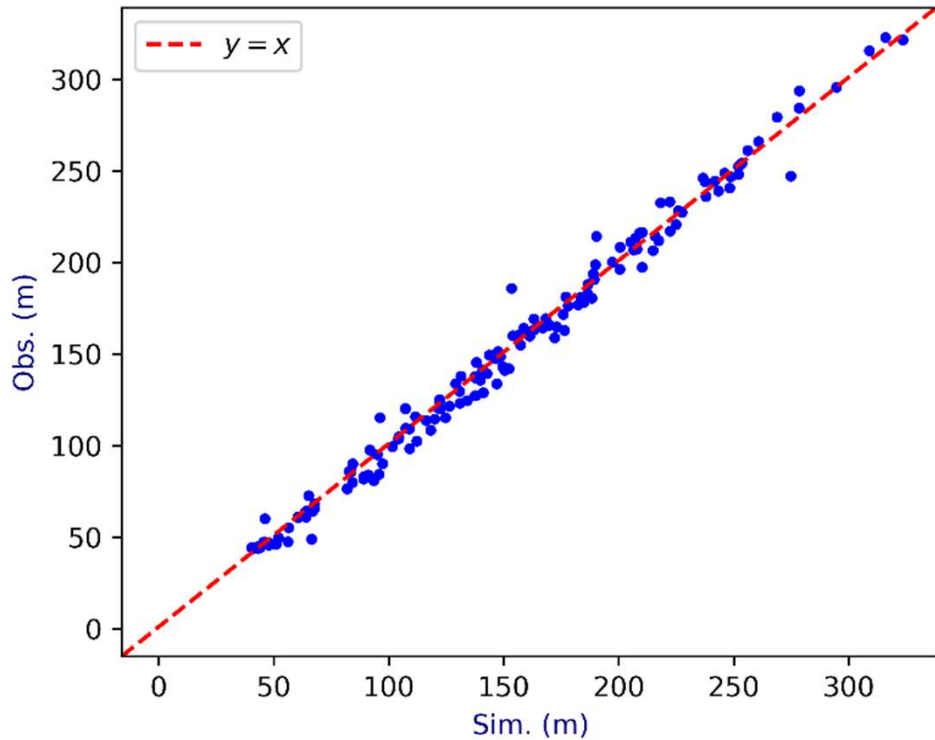
Ranges of hydraulic conductivity values estimations from expert knowledge and previous studies in the considered main geological unit allowed for the Pest estimation.

| Geological unit | Lower Limit | Preferred values | Upper Limit |
|---------------------------|---------------------|---------------------|---------------------|
| Cretaceous | $1.0 \cdot 10^{-7}$ | $1.0 \cdot 10^{-6}$ | $1.0 \cdot 10^{-3}$ |
| Namurian (Houiller) | $1.0 \cdot 10^{-8}$ | $1.0 \cdot 10^{-7}$ | $1.0 \cdot 10^{-5}$ |
| Visean and Tournaisian | $1.0 \cdot 10^{-7}$ | $1.0 \cdot 10^{-5}$ | $5.0 \cdot 10^{-3}$ |
| Famennian | $1.0 \cdot 10^{-7}$ | $1.0 \cdot 10^{-7}$ | $1.0 \cdot 10^{-5}$ |



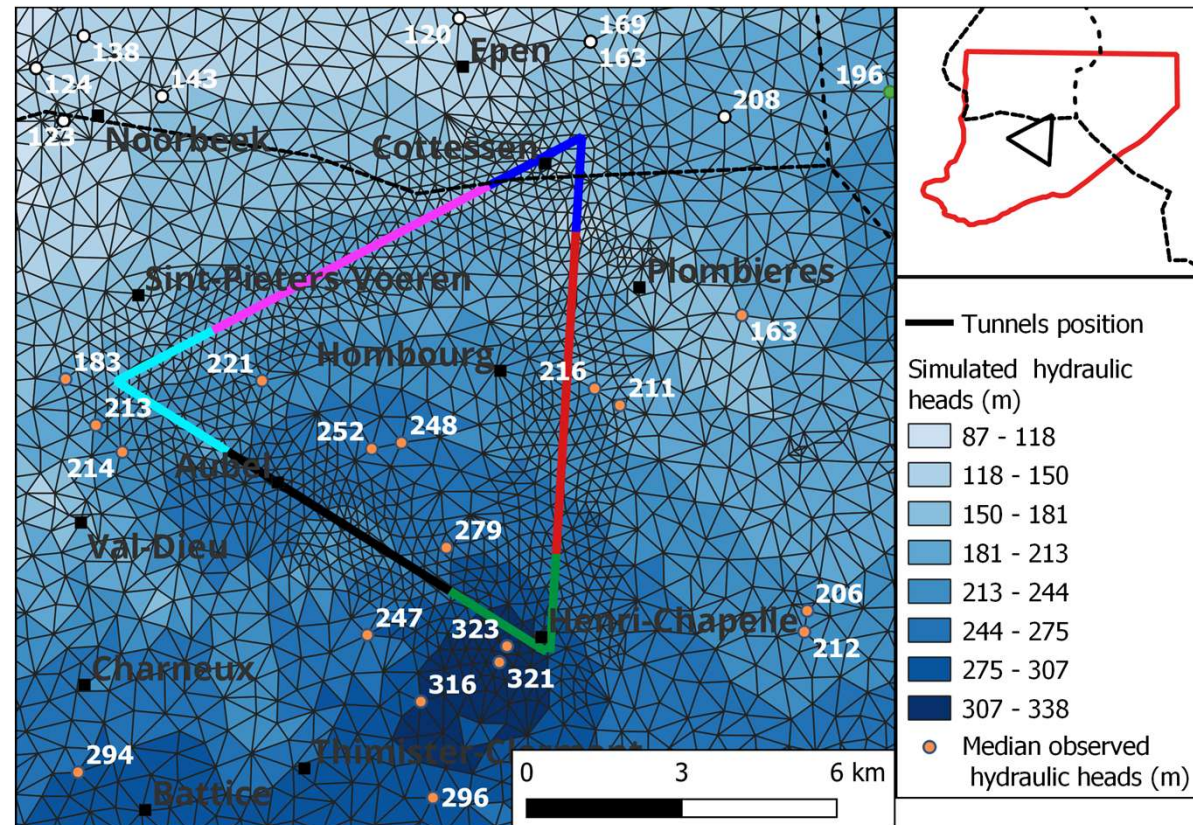
Calibrated numerical model

Observed and simulated natural hydraulic heads



Plot of groundwater level observations and groundwater level simulations.

$$\Phi = 15,887 \text{ m}$$



Tunnel inflow estimations

△ Calculations of ET impacts considering variations of the grouting area hydraulic conductivity.

△ Using the optimized model (one set of calibrated hydraulic conductivity)

Results of calculated inflow

| k_g (m/s) | Q m ³ /d |
|------------------------|---------------------|
| 1.00×10^{-8} | 45500 |
| 5.00×10^{-9} | 29000 |
| 1.00×10^{-9} | 7400 |
| 5.00×10^{-10} | 3800 |
| 1.00×10^{-10} | 776 |

} Expected inflows

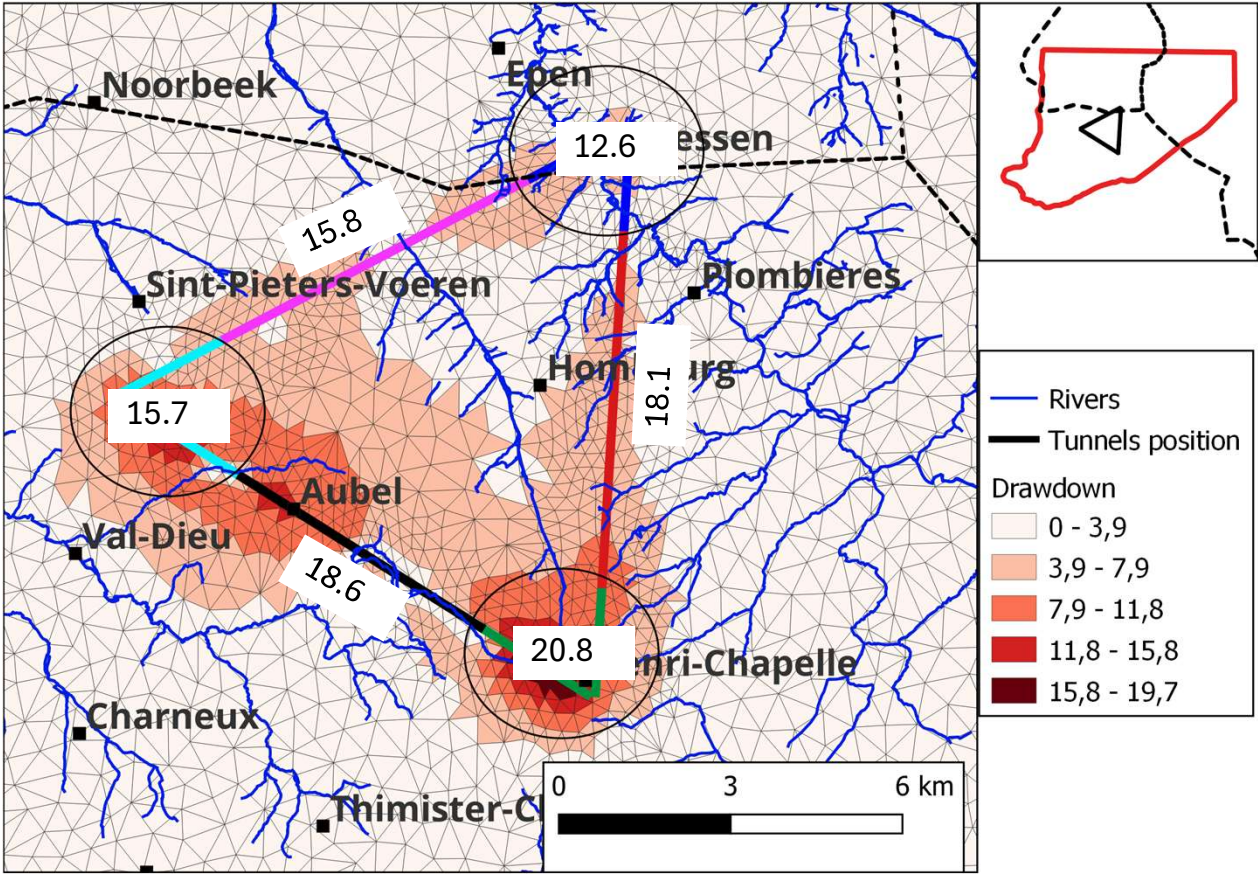


Drawdown and tunnels inflows

| k_g (m/s) | Q m ³ /d |
|------------------------|---------------------|
| 1.00×10^{-8} | 45500 |
| 5.00×10^{-9} | 29000 |
| 1.00×10^{-9} | 7400 |
| 5.00×10^{-10} | 3800 |
| 1.00×10^{-10} | 776 |

With a grouting conductivity of $K = 1.00 \times 10^{-9}$ and $Q = 7400 \text{ m}^3/\text{d}$ (mean total value of 17L/100m/min)

Inflow values (L/100m/min) at tunnel sections



Baseflow river decreases:

- Berwinne/Voer = 4.4 %
 - Berwinne at Val-Dieu = 8.5 %
- Gueul = 3.7 %

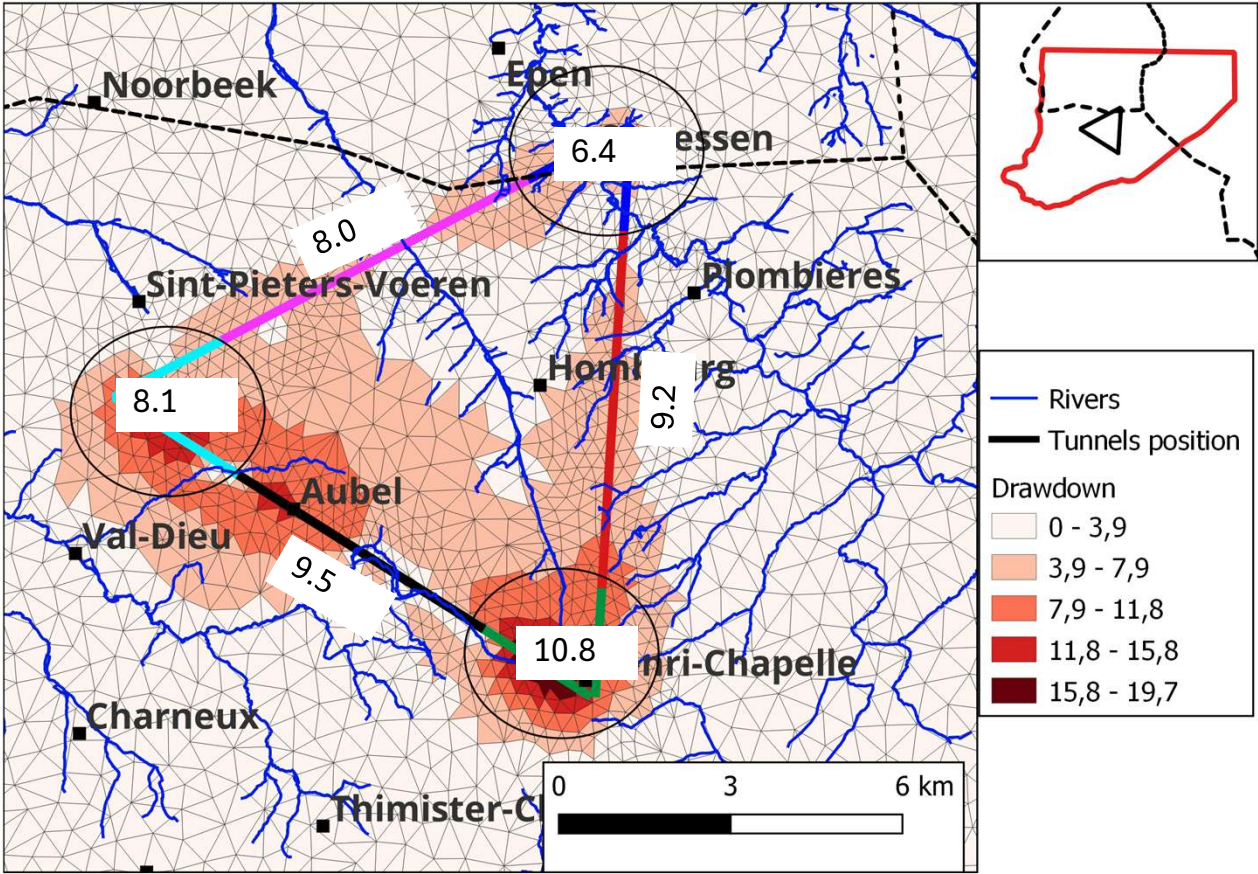


| k_g (m/s) | Q m ³ /d |
|------------------------|---------------------|
| 1.00×10^{-8} | 45500 |
| 5.00×10^{-9} | 29000 |
| 1.00×10^{-9} | 7400 |
| 5.00×10^{-10} | 3800 |
| 1.00×10^{-10} | 776 |

Drawdown and tunnels inflows

With a grouting conductivity of $K = 5.00 \times 10^{-10}$ and $Q = 3800 \text{ m}^3/\text{d}$ (mean total value of 8.8L/100m/min)

Inflow values (L/100m/min) at tunnel sections



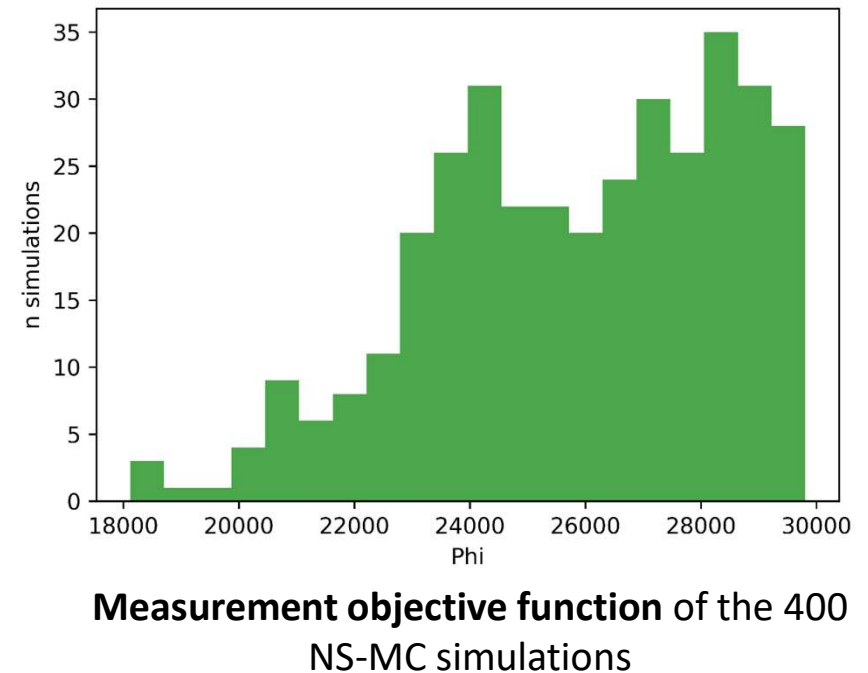
Baseflow river decreases:

- Berwinne/Voer = 2.2%
 - Berwinne at Val-Dieu = 4.3%
- Gueul = 1.9 %



Null-Space Monte-Carlo analysis

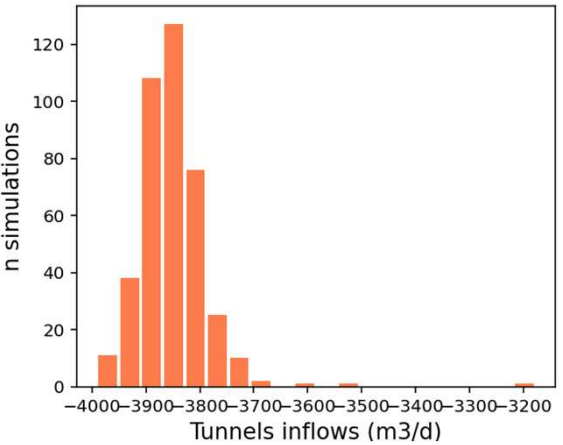
- △ Sensitivity analysis of the impact of groundwater levels taking into account different ranges of hydraulic conductivities
- △ 400 sets of hydraulic conductivities that cannot be estimated on the basis of the calibration dataset (Doherty et al., 2010)
- △ Hydraulic conductivity sets with acceptable Φ



Null-space Monte-Carlo

Range of hydraulic conductivities simulated in the 400 NS-MC simulations

| Geological zone | Mean K values (all elements) m/s | Mean variation factor [min – max] (all elements) (-) | Mean K values (around tunnels) m/s | Mean variation factor [min – max] (around tunnels) (-) |
|-----------------|----------------------------------|------------------------------------------------------|------------------------------------|--------------------------------------------------------|
| Cretace | 1.0×10^{-5} | 160 [5.7 – 7,499] | - | - |
| Houiller | 2.2×10^{-7} | 43 [11.2– 897] | 1.1×10^{-7} | 21 [14 .6 – 57.8] |
| Visean | 6.8×10^{-6} | 292 [9.1– 42889] | 3.8×10^{-6} | 59 [14.3 – 600] |
| Upper Fammenian | 4.8×10^{-7} | 47[5.6 – 920] | 3.9×10^{-7} | 42 [10.3 – 379] |



Computation of the 400 simulations considering the different scenarios

Scenario with $k_g = 5 \times 10^{-10}$ m/s

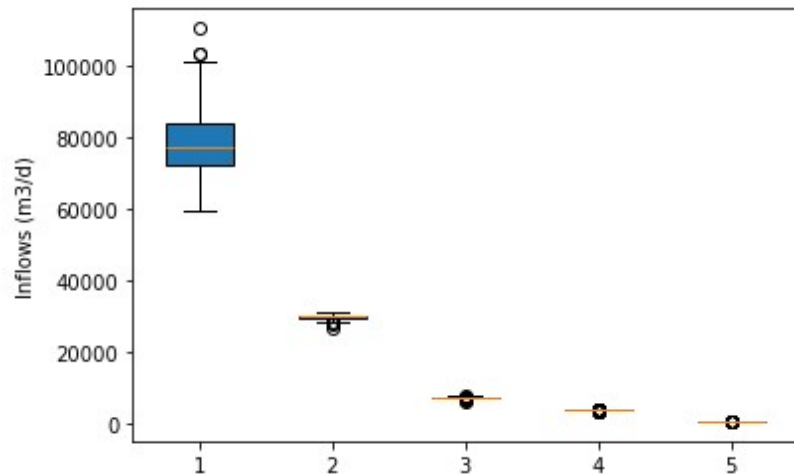
Scenarios of varying grouting hydraulic conductivity

| k_g (m/s) |
|------------------------------------------|
| 1.00×10^{-8} |
| 5.00×10^{-9} |
| 1.00×10^{-9} |
| 5.00×10^{-10} |
| 1.00×10^{-10} |



Null-Space Monte-Carlo analysis

Calculated inflow values for the 400 NS-MC simulations



Ranges of inflows considering the different scenarios (grouting area conductivity)

| Scenario | k_g (m/s) | Mean inflows (m3/d) |
|----------|------------------------|---------------------|
| 1 | 1.00×10^{-8} | 78100 |
| 2 | 5.00×10^{-9} | 29700 |
| 3 | 1.00×10^{-9} | 7396 |
| 4 | 5.00×10^{-10} | 3841 |
| 5 | 1.00×10^{-10} | 857 |

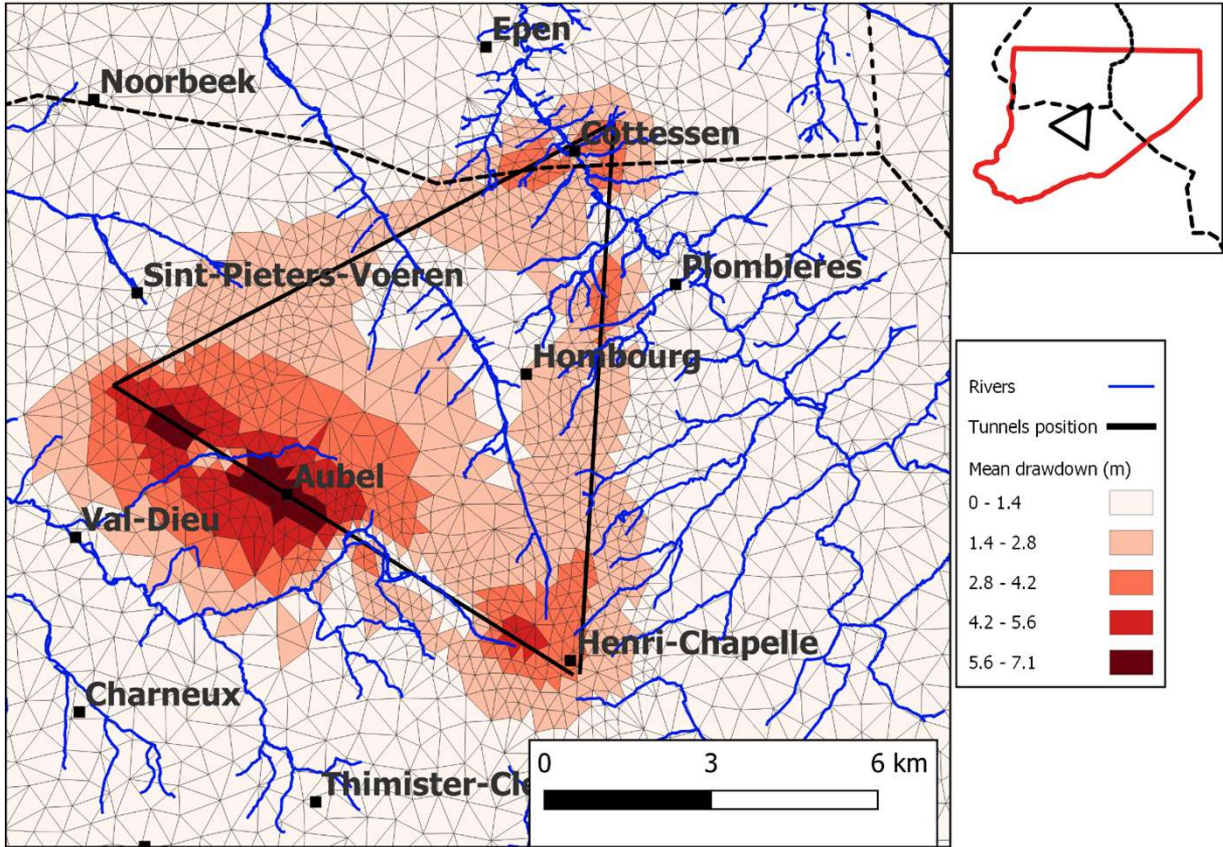
Mean inflows calculated from the different scenarios



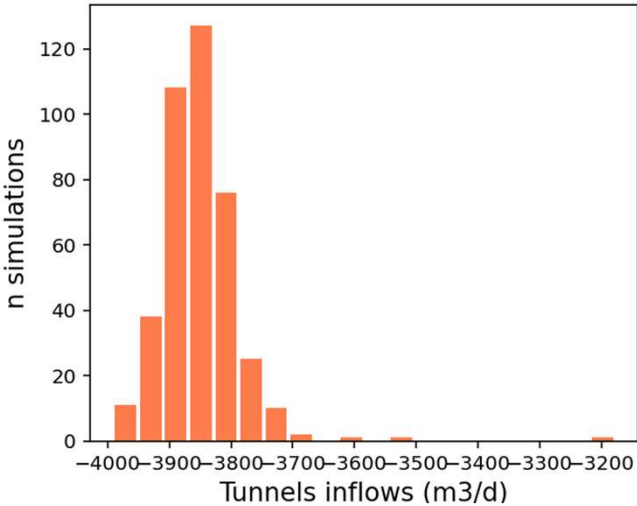
Null-Space Monte-Carlo analysis

Sensitivity analysis of the hydraulic heads through the 400 NS-MC scenarios

Mean drawdown

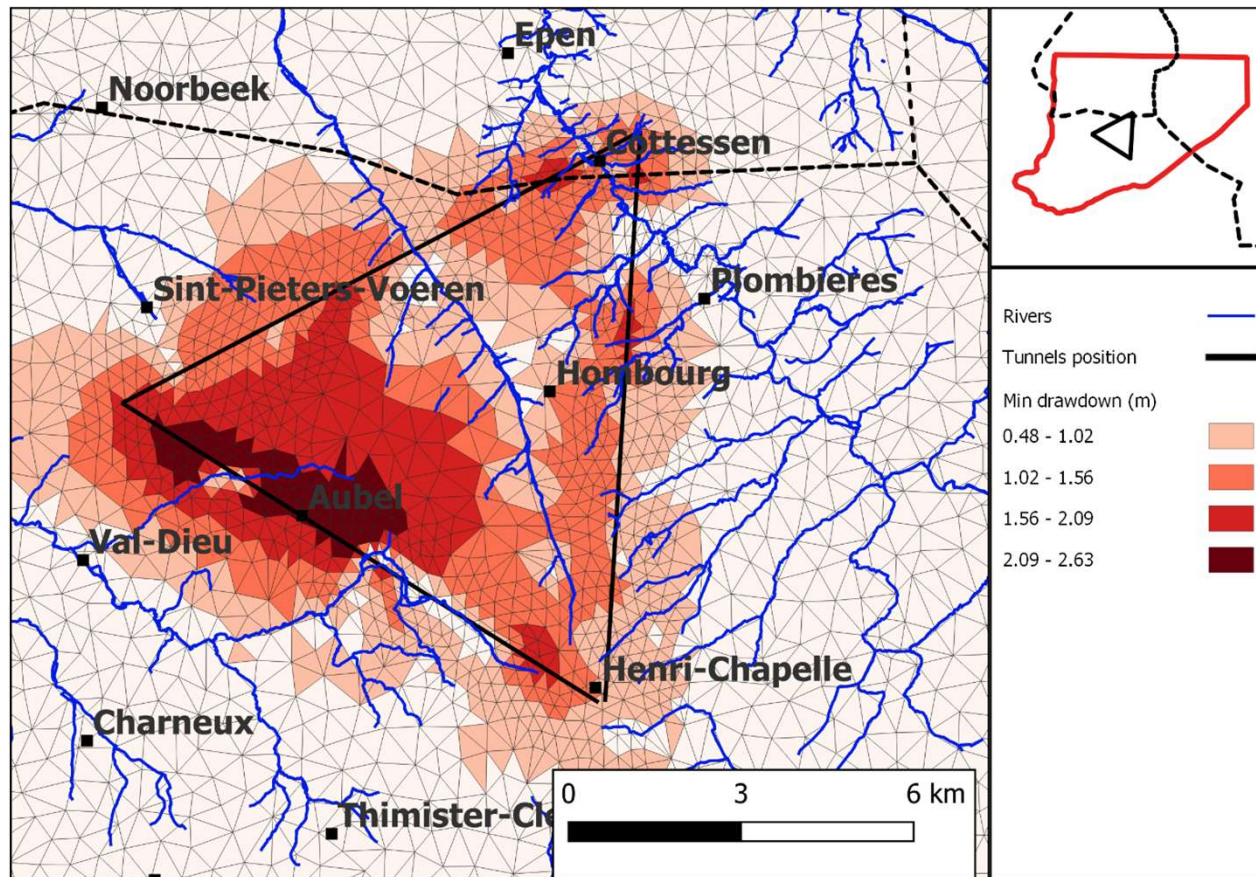


With an hydraulic conductivity of the liner of 5.00×10^{-10}



Null-Space Monte-Carlo analysis

Sensitivity analysis of the hydraulic heads through the 400 NS-MC scenarios
Minimum drawdown



With an hydraulic conductivity
of the liner of 5.00×10^{-10}



Conclusions & perspectives

- △ Results showed large impacts (>10m of drawdown) near the tunnels if hydraulic conductivity of the liner $> 5 \times 10^{-10}$ m/s. For all the scenarios, possible drawdown impacts are > 2 m.
- △ Hydraulic conductivity (and thickness, water pressure in the drainage system) of the grouting area are important to mitigate the impact on groundwater resources.
- △ Hydraulic conductivity (and thickness, water pressure in the drainage system) of the grouting area are important to mitigate the impact on groundwater resources.
- △ Local model developments (VUB and Uliège) are being developed to consider more precise geological configuration around the tunnels and caverns.



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Thank you for your attention

Einstein
Telescope