



Eight centuries of groundwater supply in Liège : from coal exploitation to cutting-edge hydrogeology in chalk and limestone aquifers

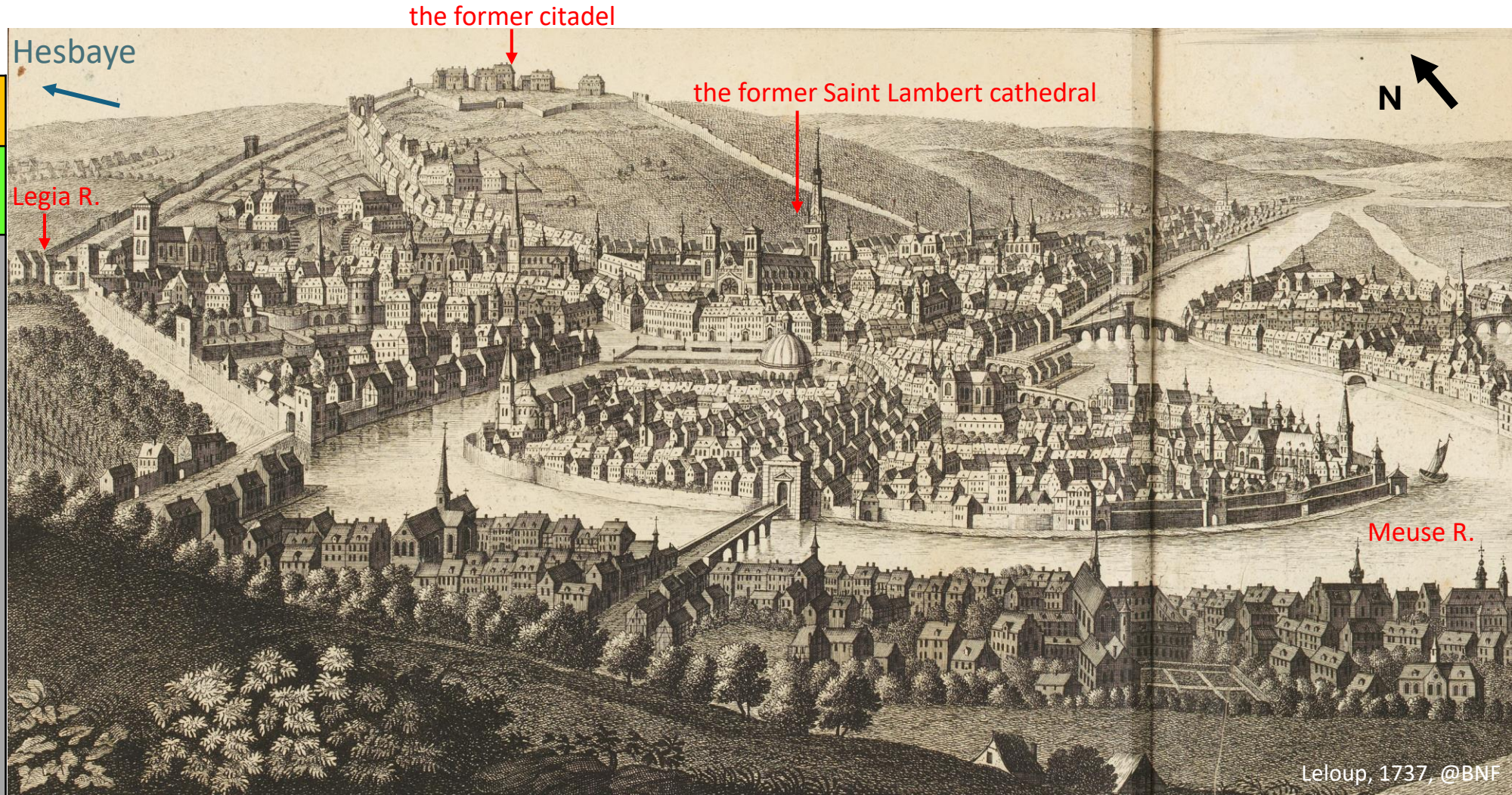
Annick Anceau & Alain Dassargues

Geologica Belgica Luxemburga scientia & professionis
Online webinar, 24 February 2025



Schematic geology of Liège

Cenozoic
Upper Cretaceous
folded Upper Carboniferous bedrock



View and perspective of the city of Liège and its surroundings from the heights between St Gilles and Avroy



Meuse River



Vue et perspective de la Ville de Liege et ses environs prise de hauteur entre S^t. Gilles et sur avroy.

Leloup, 1737, @BNF



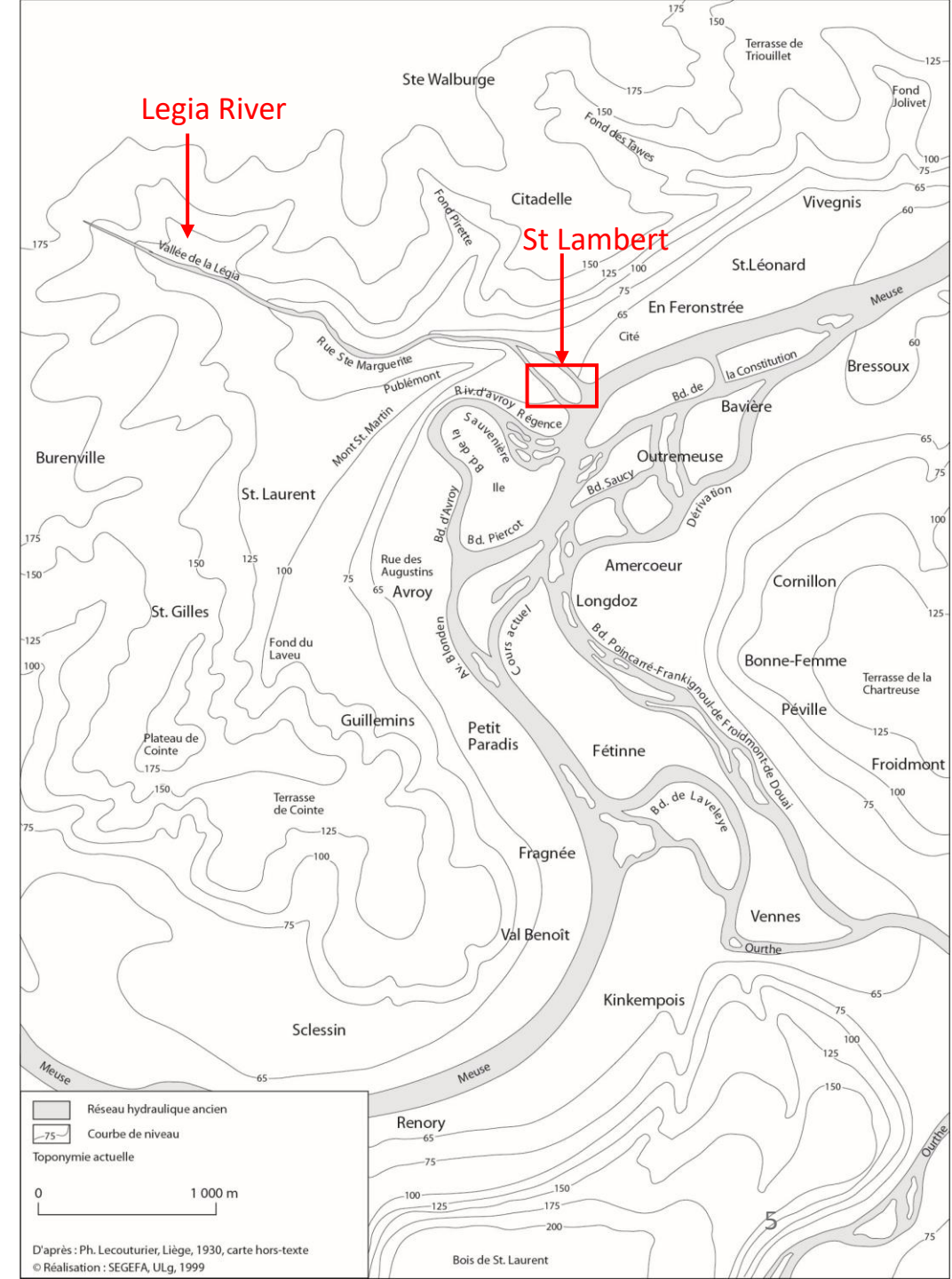
Alluvial plain of the Meuse River



Legia River

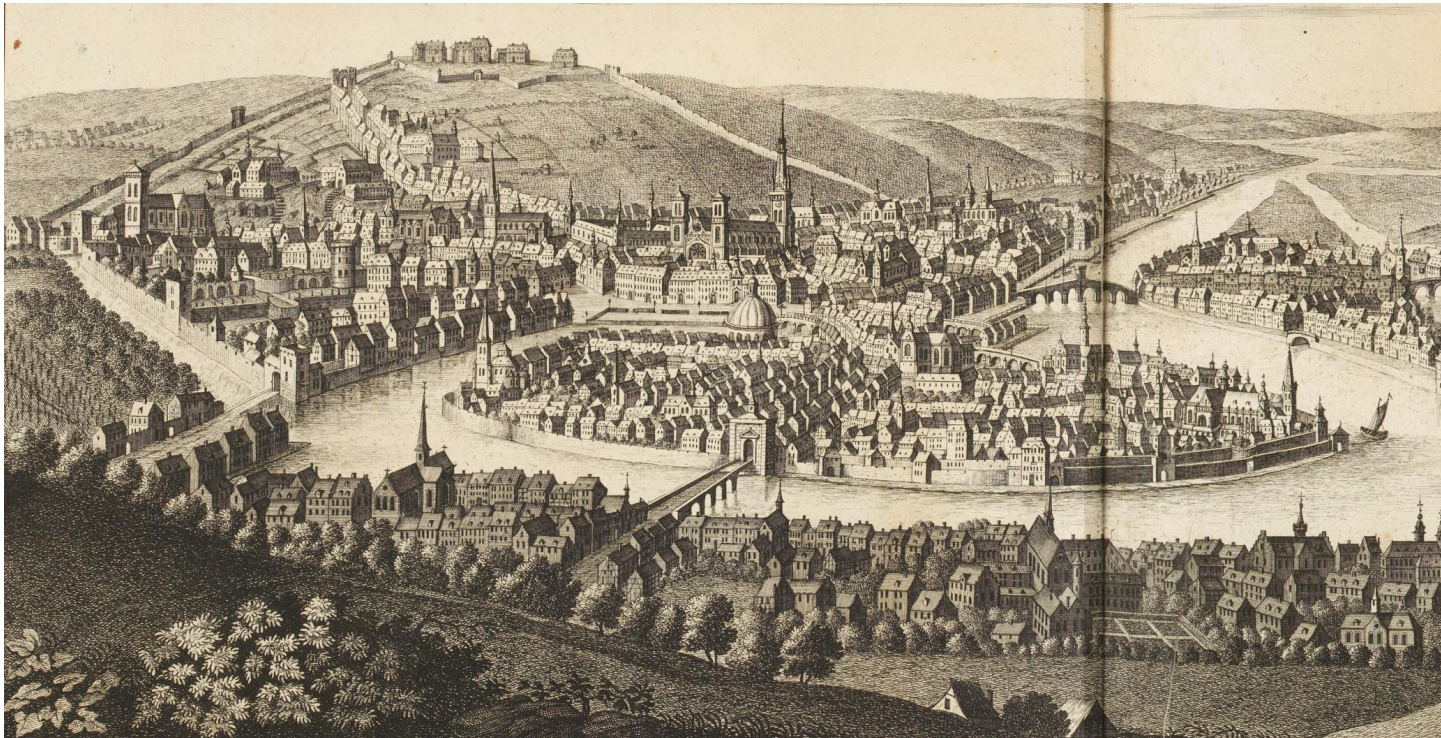


(Musée de la Vie wallonne)



Coal mining began in Liège in 1195

- collecting coal blocks from coal seams on the hillslopes
- then shafts and galleries dug
... until they were abandoned



(Agricolae, 1657)

Drainage galleries

Dewatering

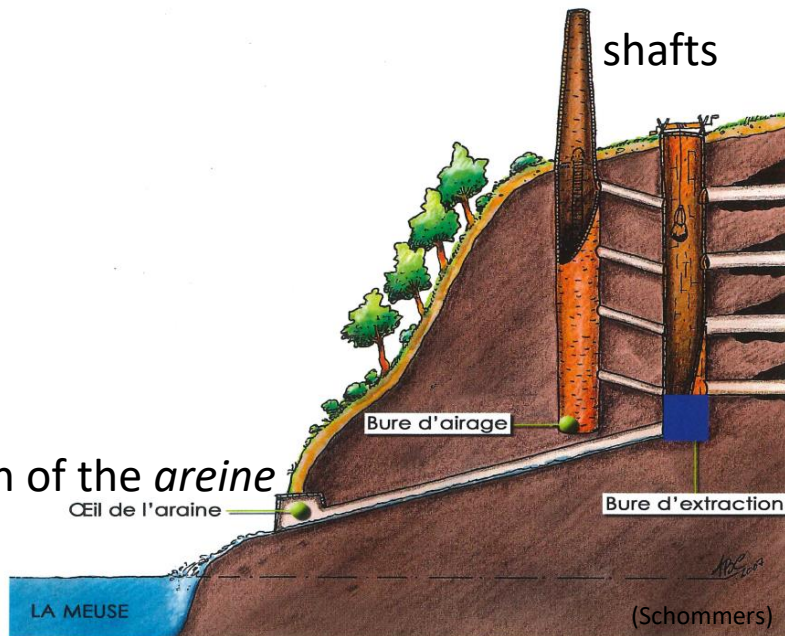
- buckets and tanks, manually or with horses
- drainage galleries from **13th century**
= *areine*, *arène*, *araine*,
lareine, or *lharaine*



(Agricolae, 1657)



mouth of the *areine*



mouth of the *areine*

Œil de l'araine

Bure d'extraction

Bure d'airage

shafts

LA MEUSE

(Schommers)



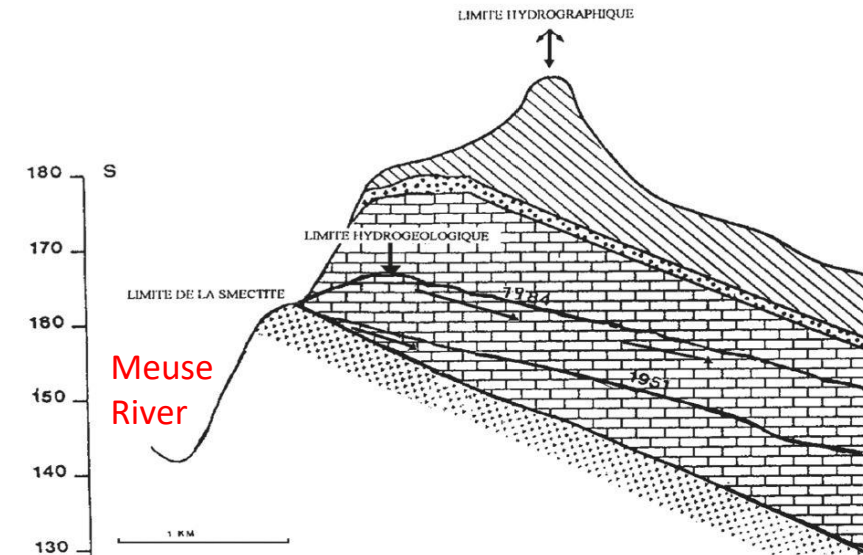
Areines franches and *areines bâtardes*

- *Areines franches* = drinking water supplying public and private fountains of the city
 - only **four** gallery network
 - protected by very strict laws
 - only flowing water sources until 1680
- *Areines battardes* = waters from the other drainage gallery networks fed directly into the rivers

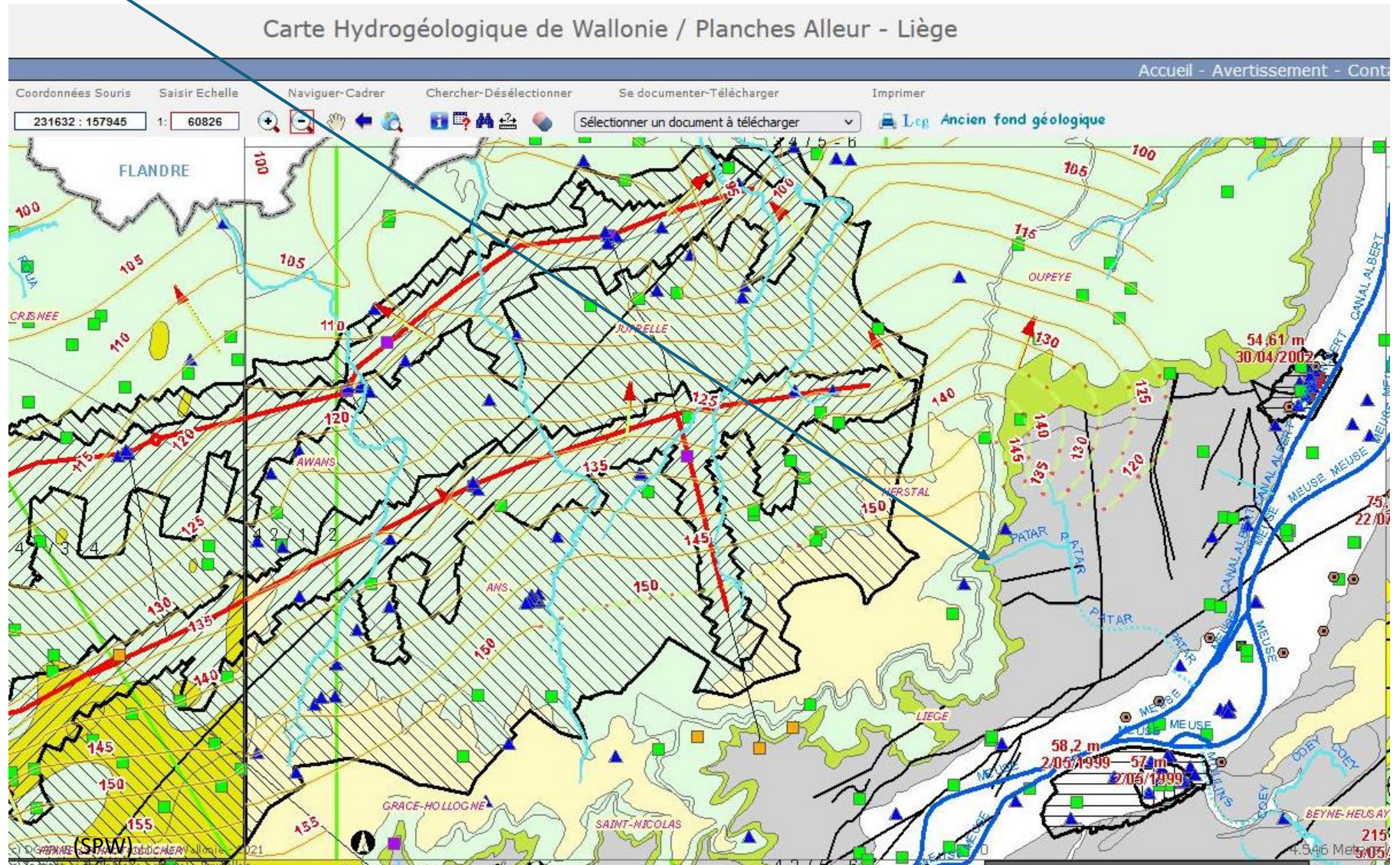


Fontaines Roland

- 1697: merging of two drinking water drainage galleries (or *areines franches*)
- Jean Roland built a new gallery to collect groundwater from the springs in the Cretaceous chalk at the top of the marly clay layer, northwest of Liège
- this gallery brought water from the Hesbaye aquifer to the city's mills and fountains, demonstrating an excellent knowledge of the underground



- the first Cretaceous formation: marly clay layer (= 'smectite')
- at the contact 'smectite' - chalk
 - ➔ springs along the hillslope
 - ➔ small streams flowing towards the Meuse River in Liège



Fontaines Roland

- five more galleries were built after into the chalk as an extension of the natural springs
- they fed public and private fountains
- company = the *Société des Fontaines Roland*





→ = 4 areines franches (Houiller)
 → = 5 "Roland" galleries (Crétacé)

PLAN
 indiquant la position
 DES ARÈNES ET DES GALERIES
 qui fournissent l'eau à la ville de
LIÈGE

(Dumont, 1856)



Until mid- 19th century

The drinking water came from:

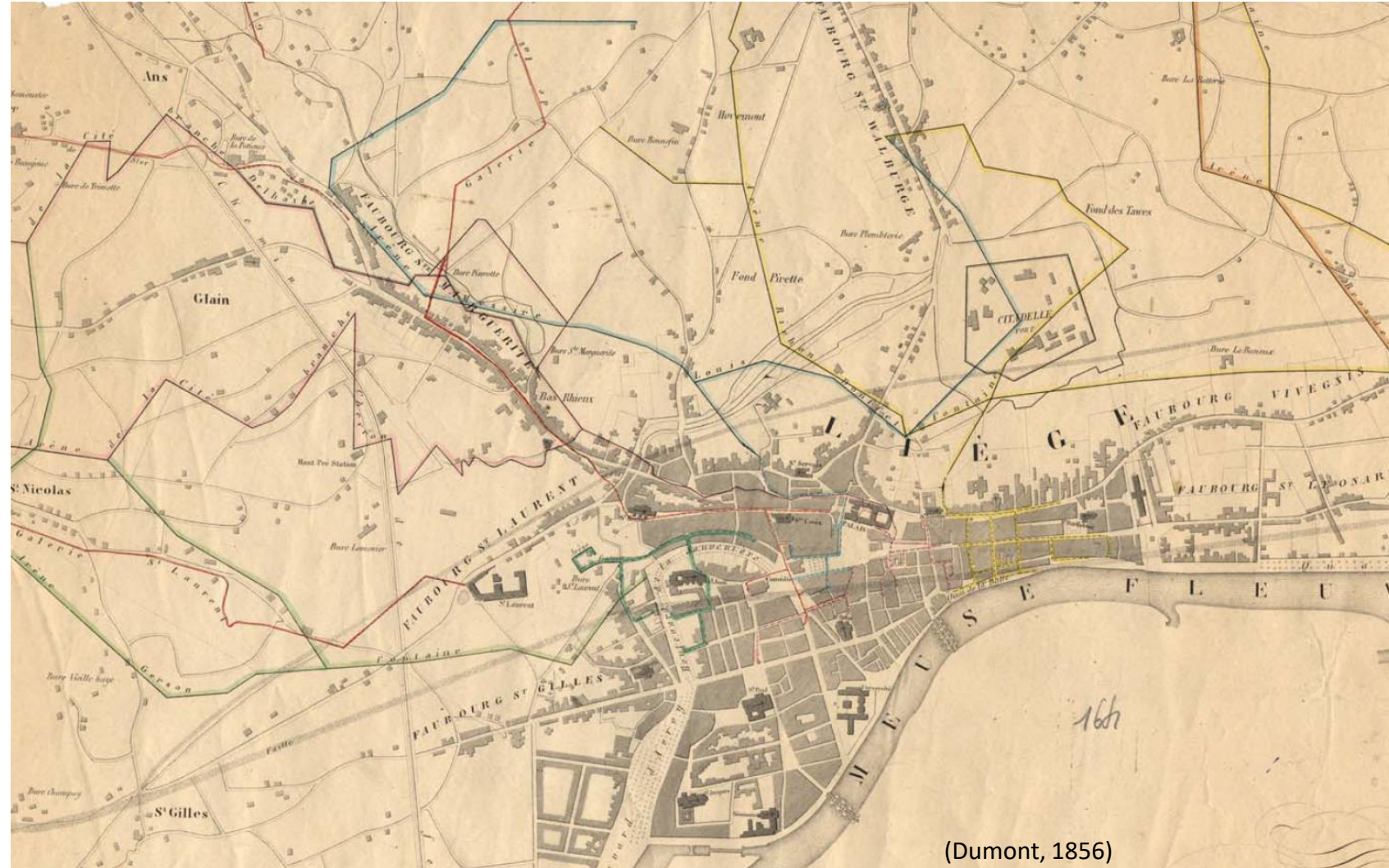
- Meuse River
- alluvial plain
- areines
- *Fontaines Roland galleries.*

LE GRAND PUIS
DE
PAIENPORTE



Mid- 19th century: the need for more water

In the 19th century, when the population of Liège grew to nearly 100,000 inhabitants, the drinking water supply from Meuse River, the alluvial plain, the *areines* and the *Société des Fontaines Roland* was insufficient in quantity and quality.



(Dumont, 1856)

© City of Liège, Ulysse Capitaine Library

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André Dumont: application of geology to groundwater research

- 1851, **André Dumont**, professor at University of Liège
- note about regional geological knowledge for groundwater exploration
- lithostratigraphy of the Cretaceous layers and Cenozoic deposits in Hesbaye
- hydrogeologic properties
- discharge and recharge zones
- marly clay layer could be considered impervious
- suggested that this aquifer could be pumped or ideally be drained for drinking water supply of Liège



Bulletins de l'Académie royale des Sciences, des Lettres et de Beaux-Arts de Belgique, 18/1, 1851

(47)

Fig. 5. Limbe vu de côté.

a. Lobes rotatoires.

b. Appendice du grand lobe.

Fig. 4^a. Œuf au moment de la ponte; on y voit encore la vésicule de Purkinje.

Fig. 4^b. Œuf dont le développement est plus avancé.

a. Point oculiforme.

b. Mâchoires.

Note sur une application de la géologie à la recherche d'eaux souterraines; par André Dumont, membre de l'Académie.

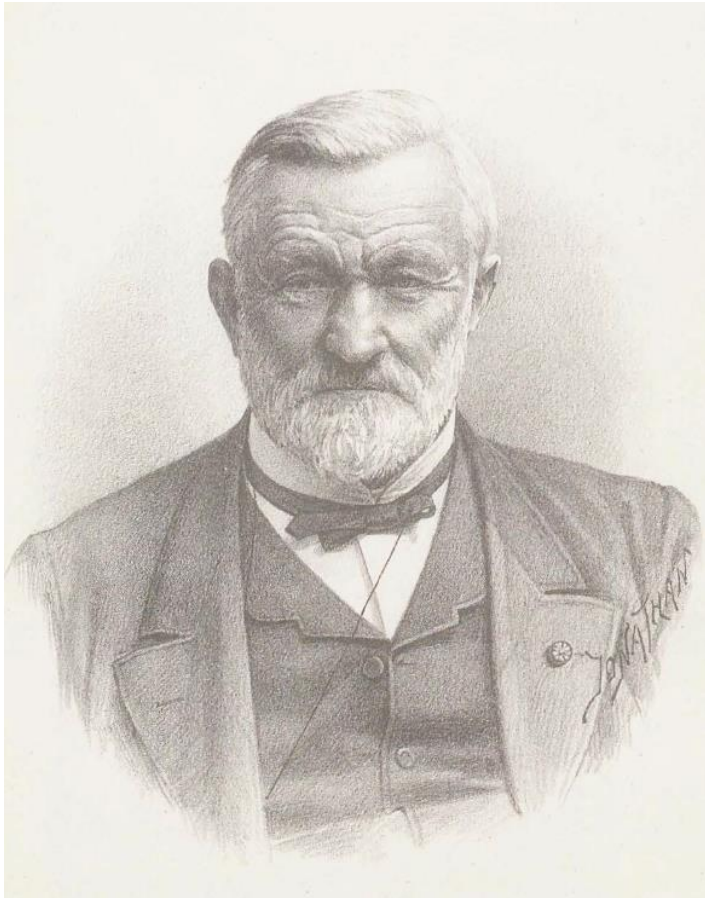
La quantité d'eau que donnent les fontaines de la ville de Liège, ayant, dans ces derniers temps, diminué d'une manière notable et étant devenue insuffisante pour les besoins de la consommation, la régence crut devoir nommer une commission pour rechercher les causes de cette diminution et les moyens d'y remédier, soit directement, soit par la découverte de nouvelles sources. La commission, à laquelle j'ai l'honneur d'appartenir, m'ayant chargé d'examiner cette dernière partie du problème, au point de vue de la science, j'ai rédigé la note suivante, qui montrera à quel point la connaissance géologique d'un pays est utile pour la solution des questions relatives à la recherche des sources ou nappes d'eaux souterraines (1).

On sait que la vallée de la Meuse est creusée aux environs de Liège dans le terrain houiller et qu'elle est limitée

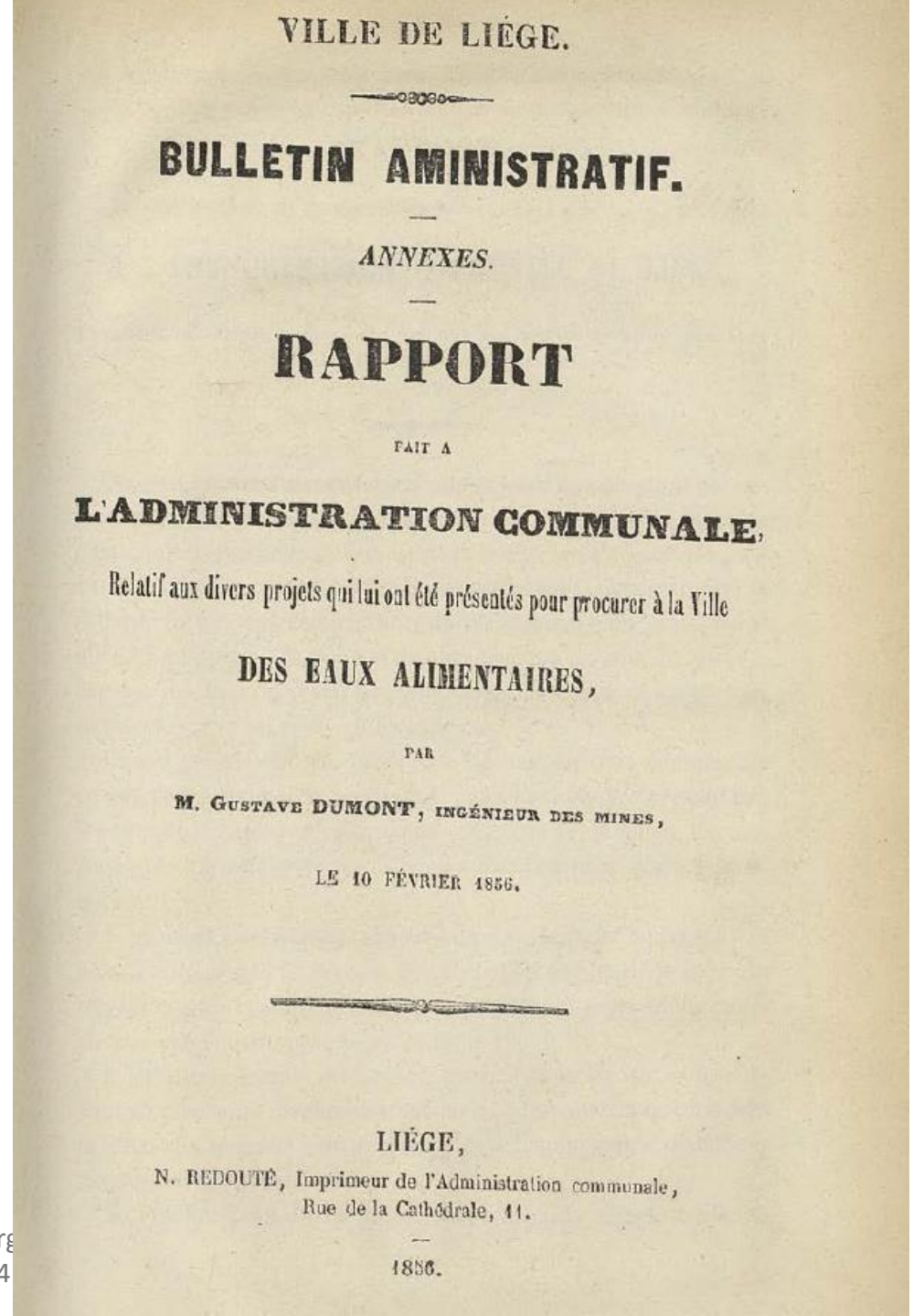
(1) Je compte un jour faire connaître l'étendue et la forme des divers bassins hydrographiques souterrains de la Belgique.



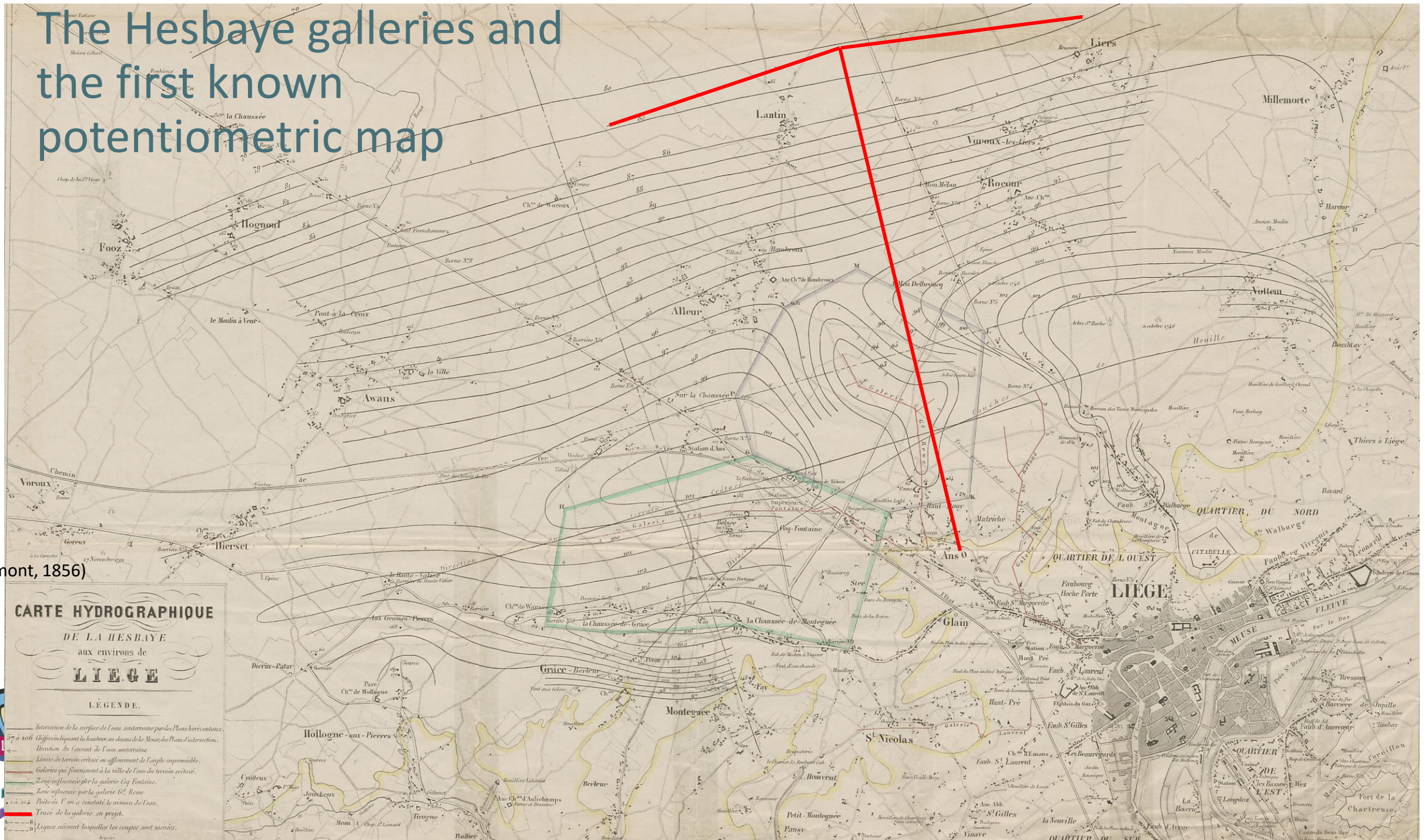
Mid- 19th century: the need for more water



Gustave Dumont



The Hesbaye galleries and the first known potentiometric map



(Dumont, 1856)

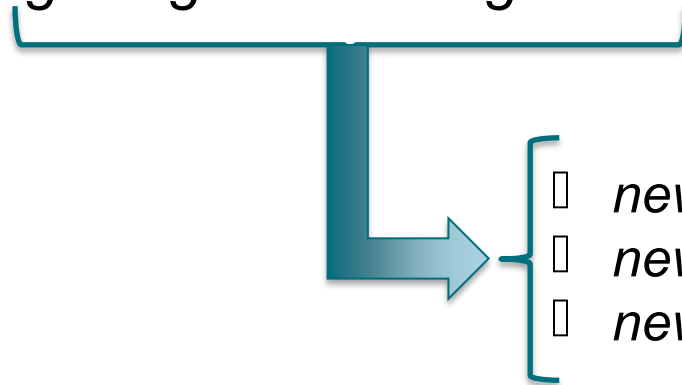


International context



- *19th century: progress and innovations in hydrogeology driven mostly by two main factors:*
 - *mining operations* *reached deeper zones and required complex drainage/pumping works*
 - *water supply* *providing safe and sufficient water supply in cities*

this brought geologists and engineers together



- *new ideas about actual groundwater resources*
- *new ways for pumping/drainage*
- *new ways for mapping/designing projects*



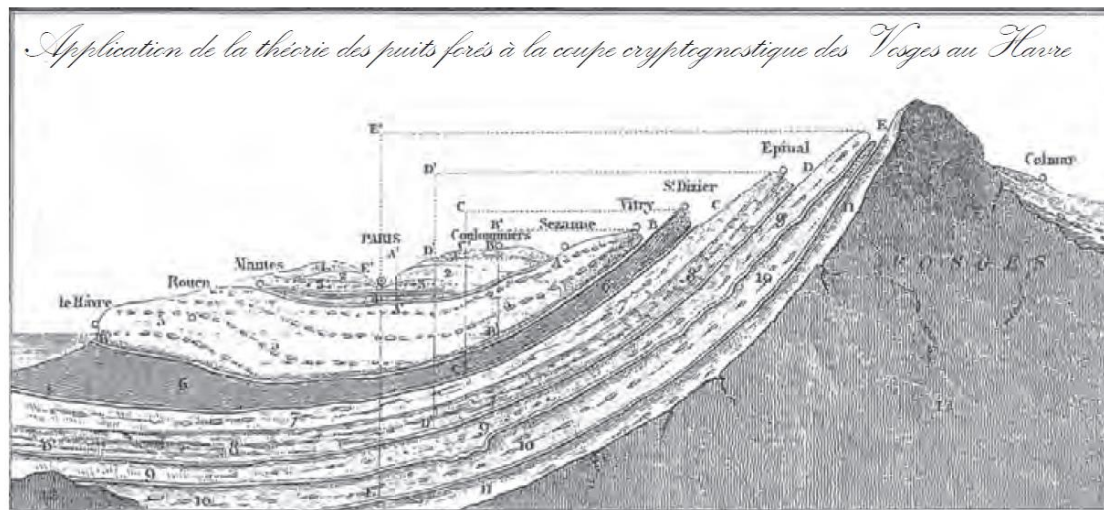
International context

- In UK, William Smith in 1827 rock properties and structures
↔ water-bearing vs water-confining

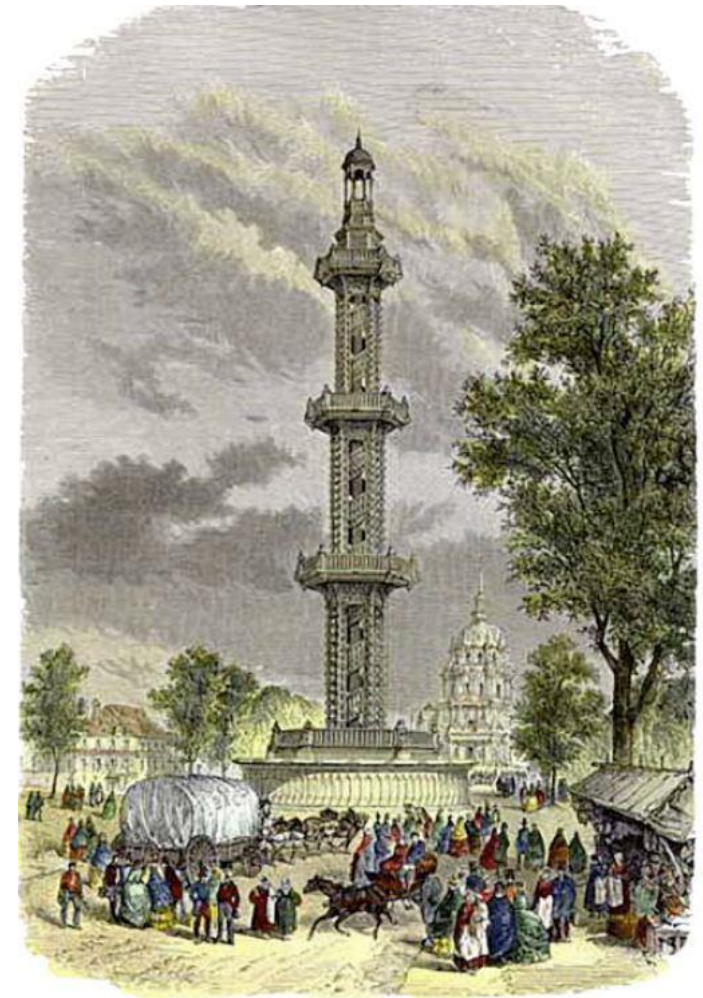


William Smith

- In France, Georges Mulot 1841 drilled the artesian well of Grenelle in Paris
below Tertiary confining marly and clayey layers



Artésianisme - Théorie d'Héricart de Thury (1829)



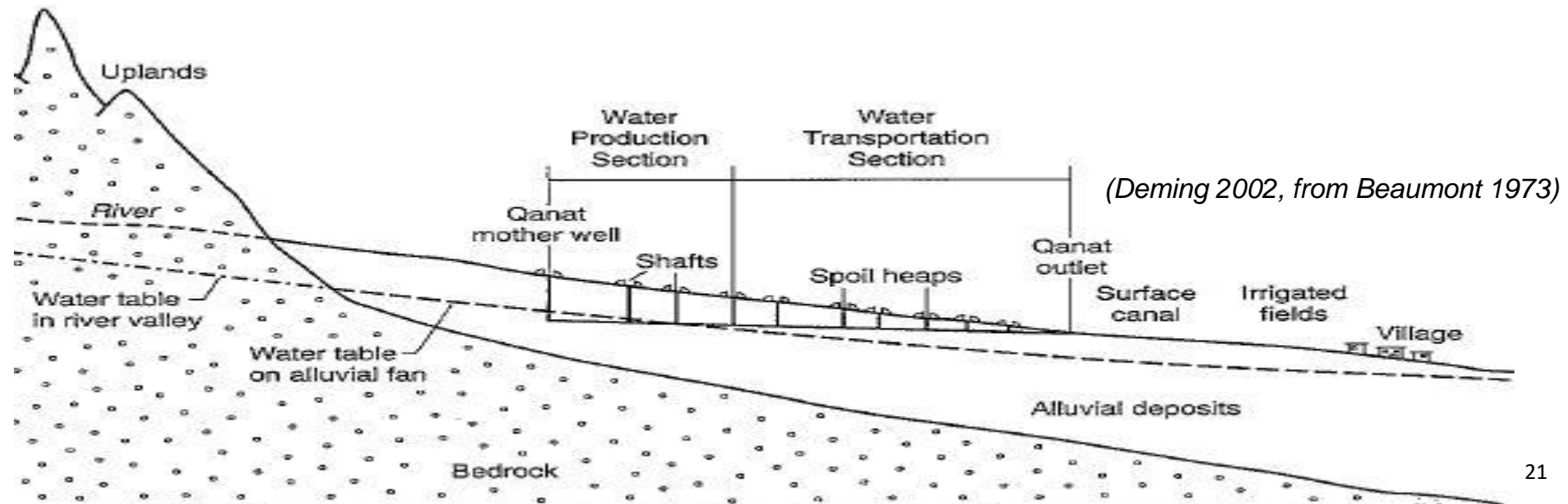
International context



✂ *In Europe, drainage galleries are used in mines*

✂ *But ... very ancient technique*

- *'qanats' in Persia (800 years B.C.)*
- *'foggaras' in North Africa (500 years B.C.)*
- *extended over several kilometers, in arid areas as in China, Afghanistan, ...*

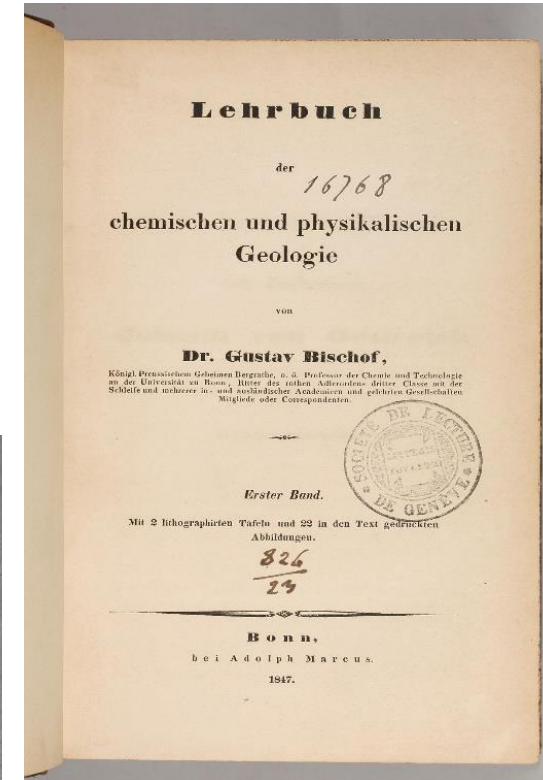
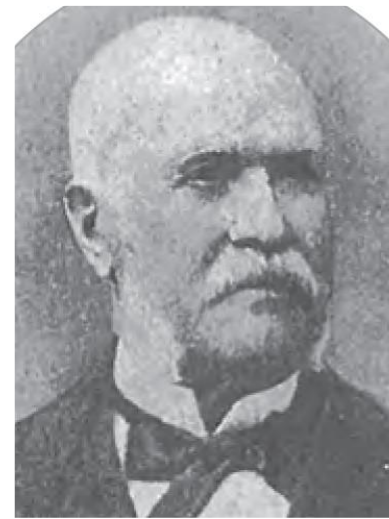


International context

- in France, Belgrand 1846
permeable ↔ impermeable
geological formations
applied in the Paris Basin

✂ in Germany, Bischof 1847
book about chemical and physical
geology, with groundwater aspects

✂ in France, Dupuit 1848
theory of groundwater flow movement

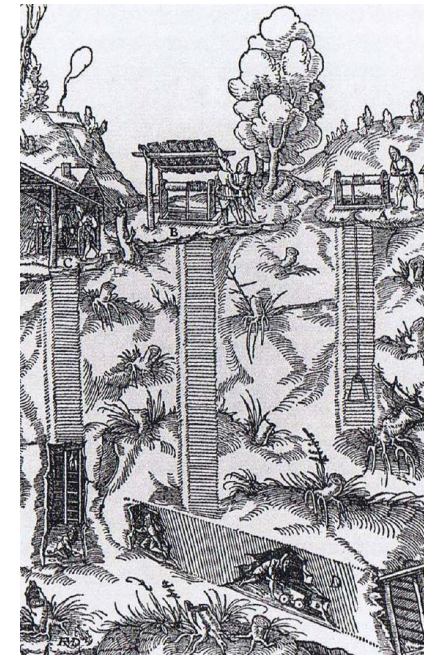
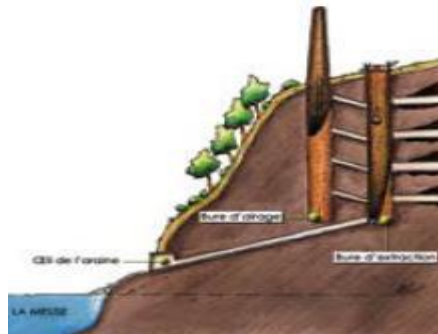


International context

- *In France, the Abbé Paramelle 1832-1853, expert in groundwater exploration and prospection based on a clever understanding of local hydrological, topographic and geological conditions*
- *More and more dewatering of mines in Belgium, UK, Czech Rep., and in many other European regions*



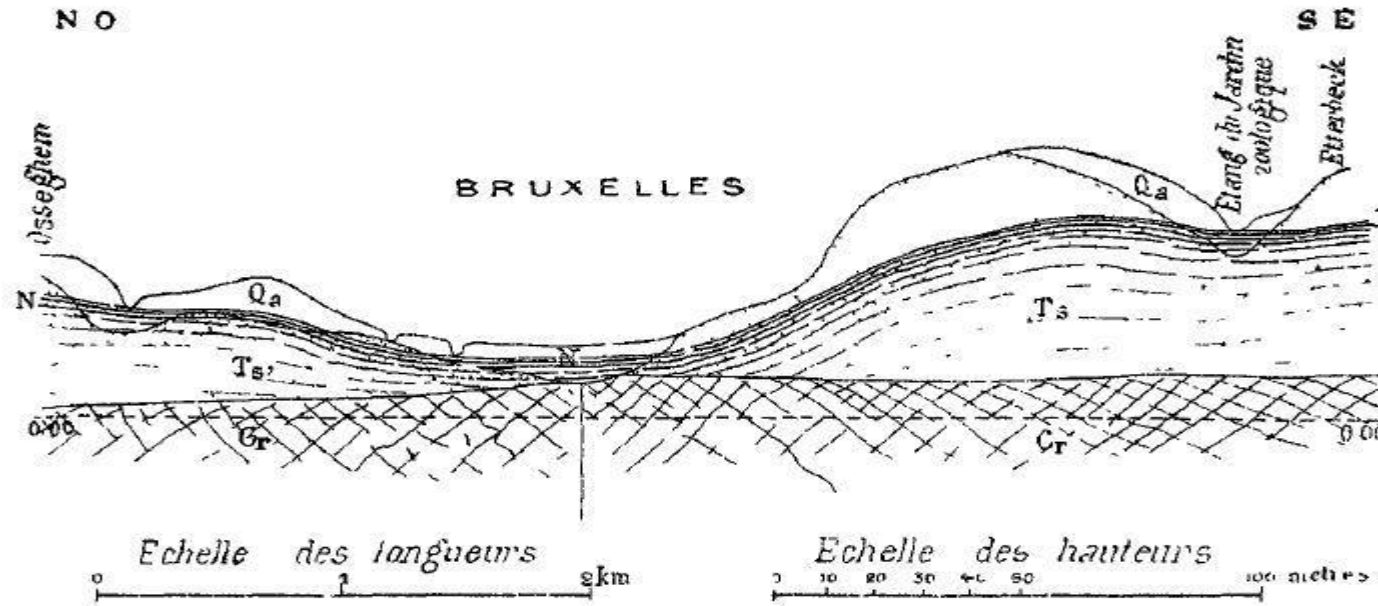
Figure 1. Abbé Jean-Baptiste Paramelle (undated photo from Paramelle family collection). Photo source: Spéleo-club de Paris, Mémoire #30.



International context



- in Belgium, in 1851, the Brussels water supply
→ from shallow boreholes in Ypresian and Lutetian sands

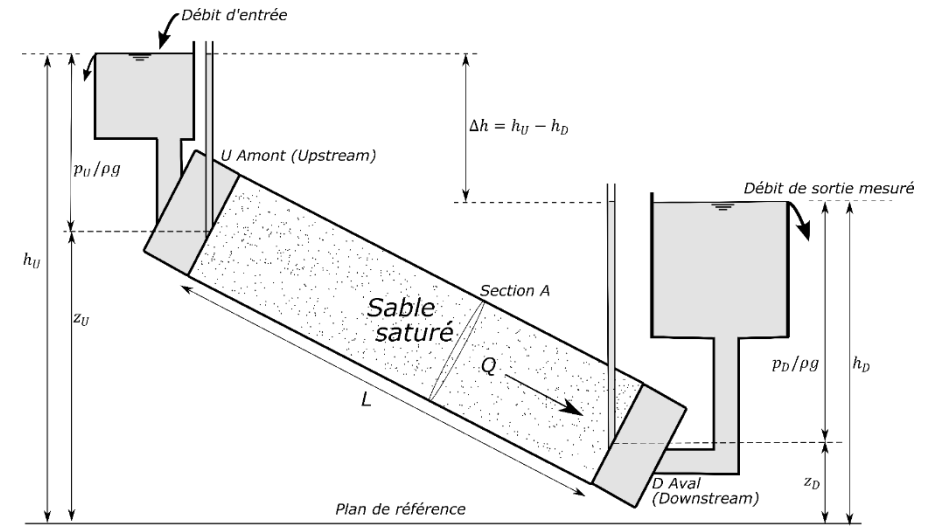
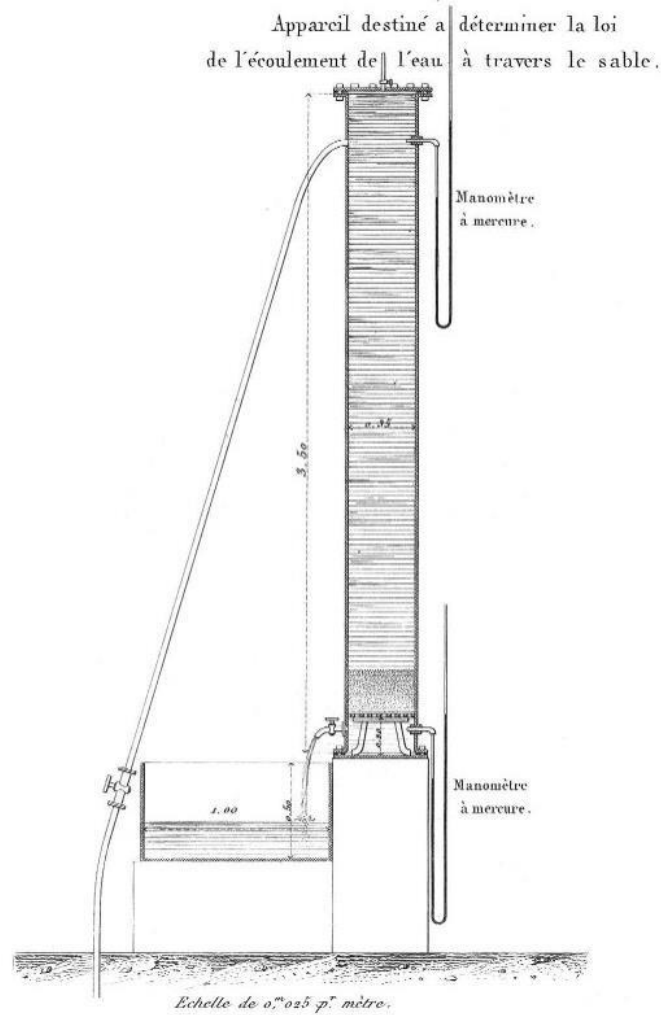


- ✂ in The Netherlands, from 1852, Amsterdam was supplied groundwater from coastal dunes using drainage canals





- *Darcy's law (1856): starting point of quantitative hydrogeology*

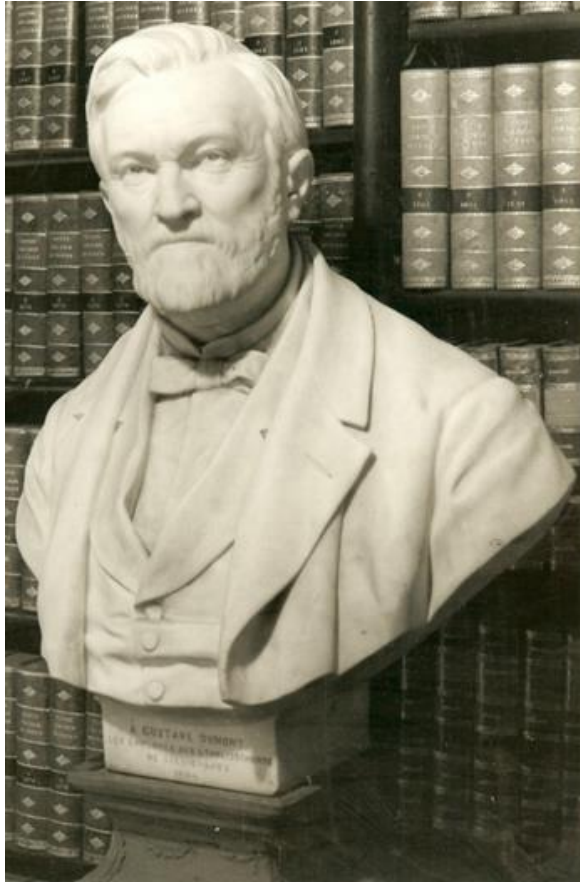


$$Q = KA \frac{\Delta h}{L}$$

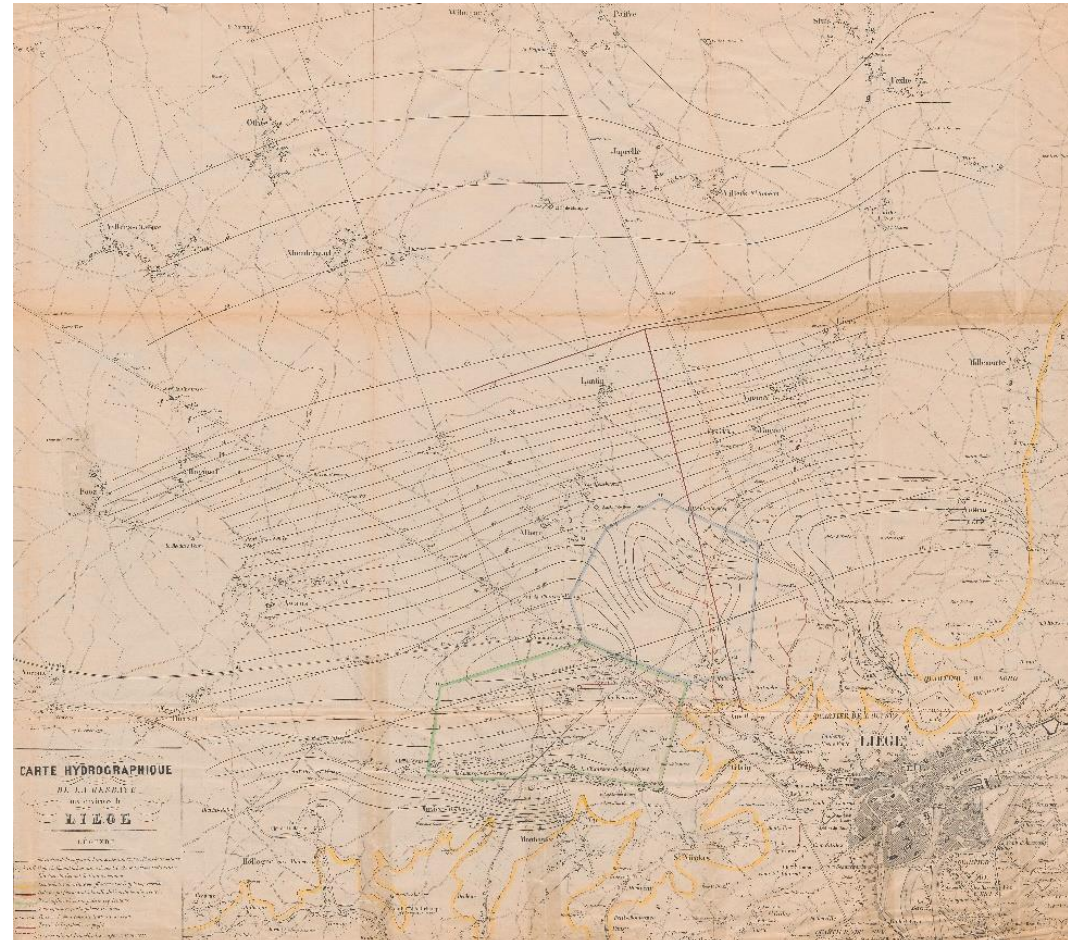




*BUT ... earlier in February 1856:
a first potentiometric map, in Liège (Belgium) by Gustave Dumont*



(Photo by Damien Pirlot de Corbion)



(Dumont 1856)

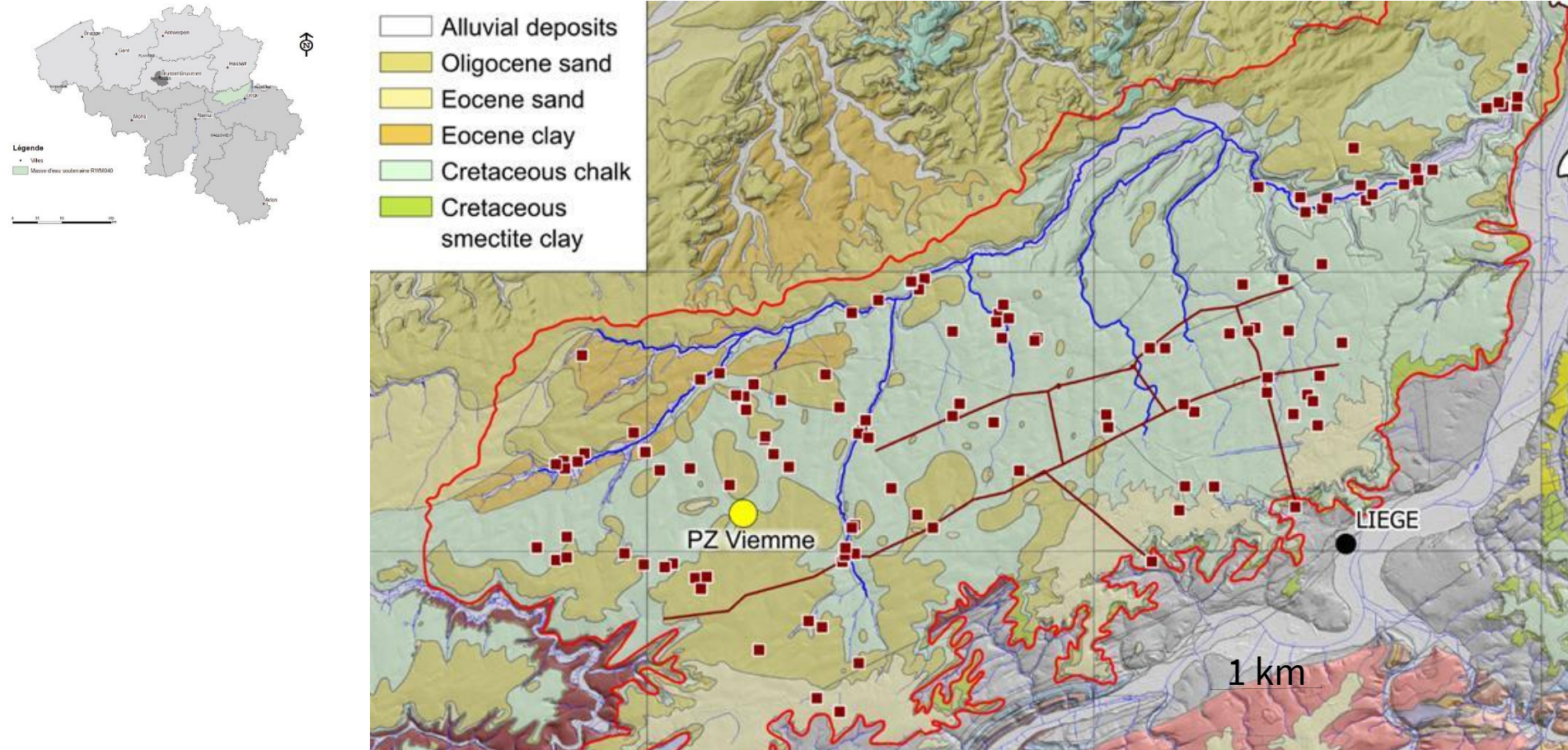
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Regional context



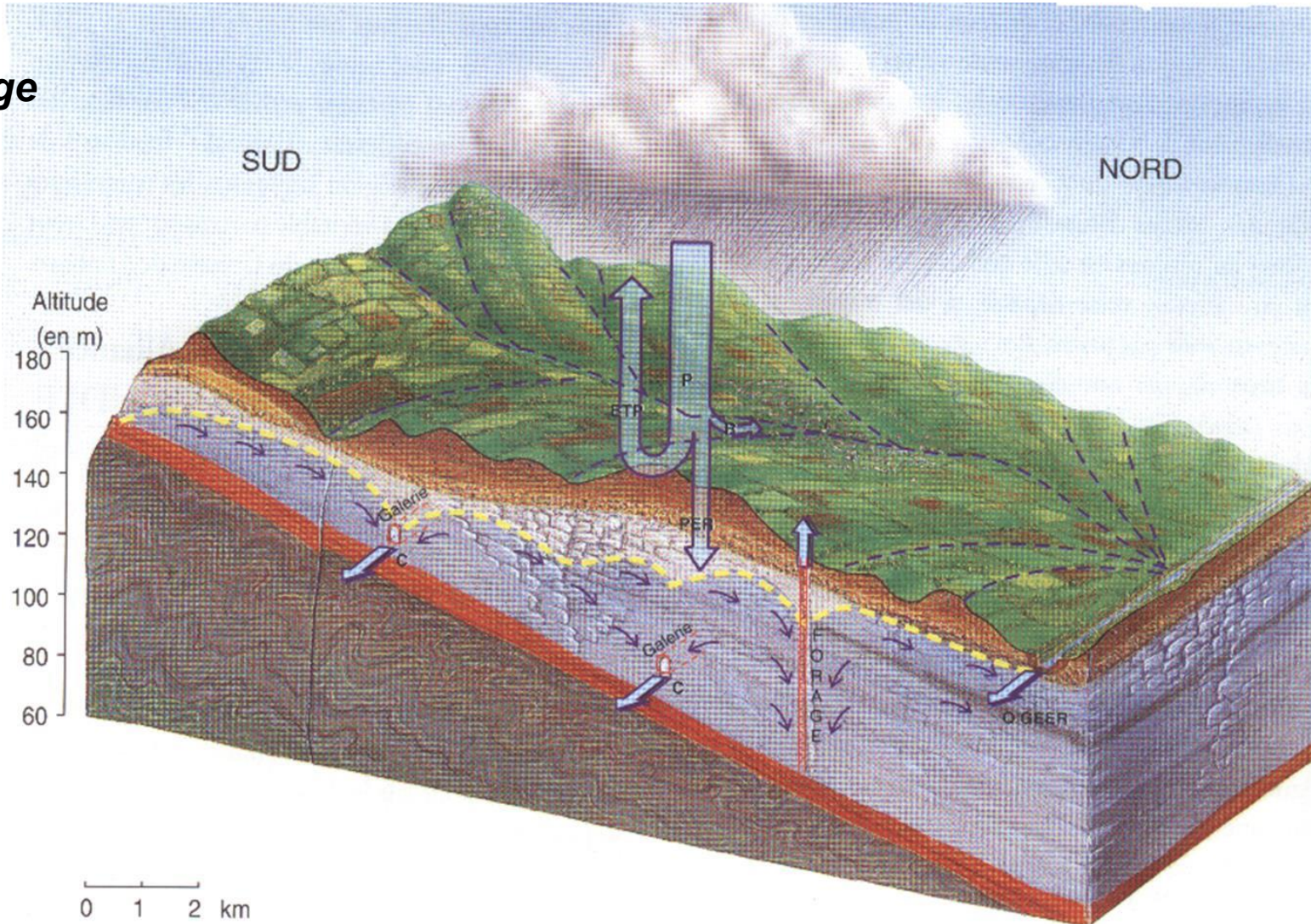
- Liège (Belgium) → in the alluvial plain of the Meuse River but also on the slopes of the valley
- in the valley, the alluvium lies directly on folded Carboniferous bedrock.
- on the hills, discordant Upper Cretaceous and Cenozoic deposits cover the bedrock (eastern part of the Hesbaye plateau).



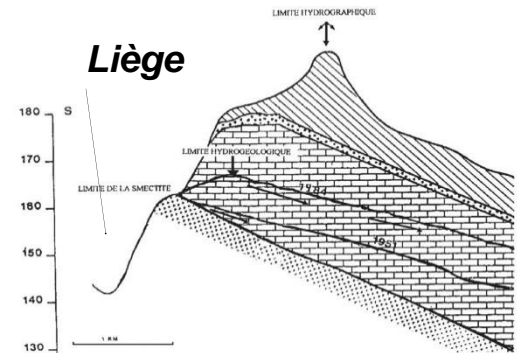
Regional context



Liège



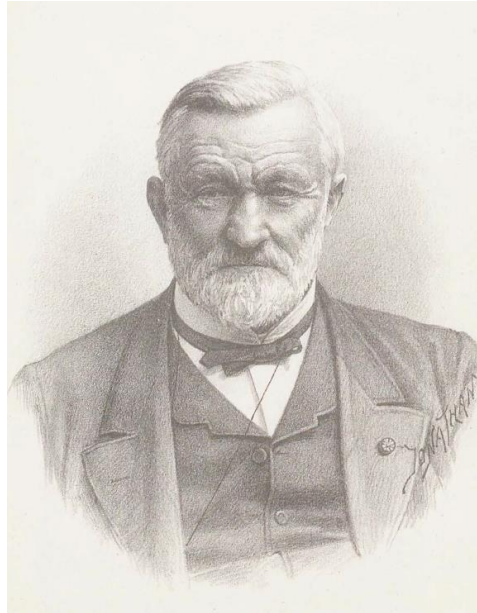
Liège



The potentiometric map of Gustave Dumont (1856)

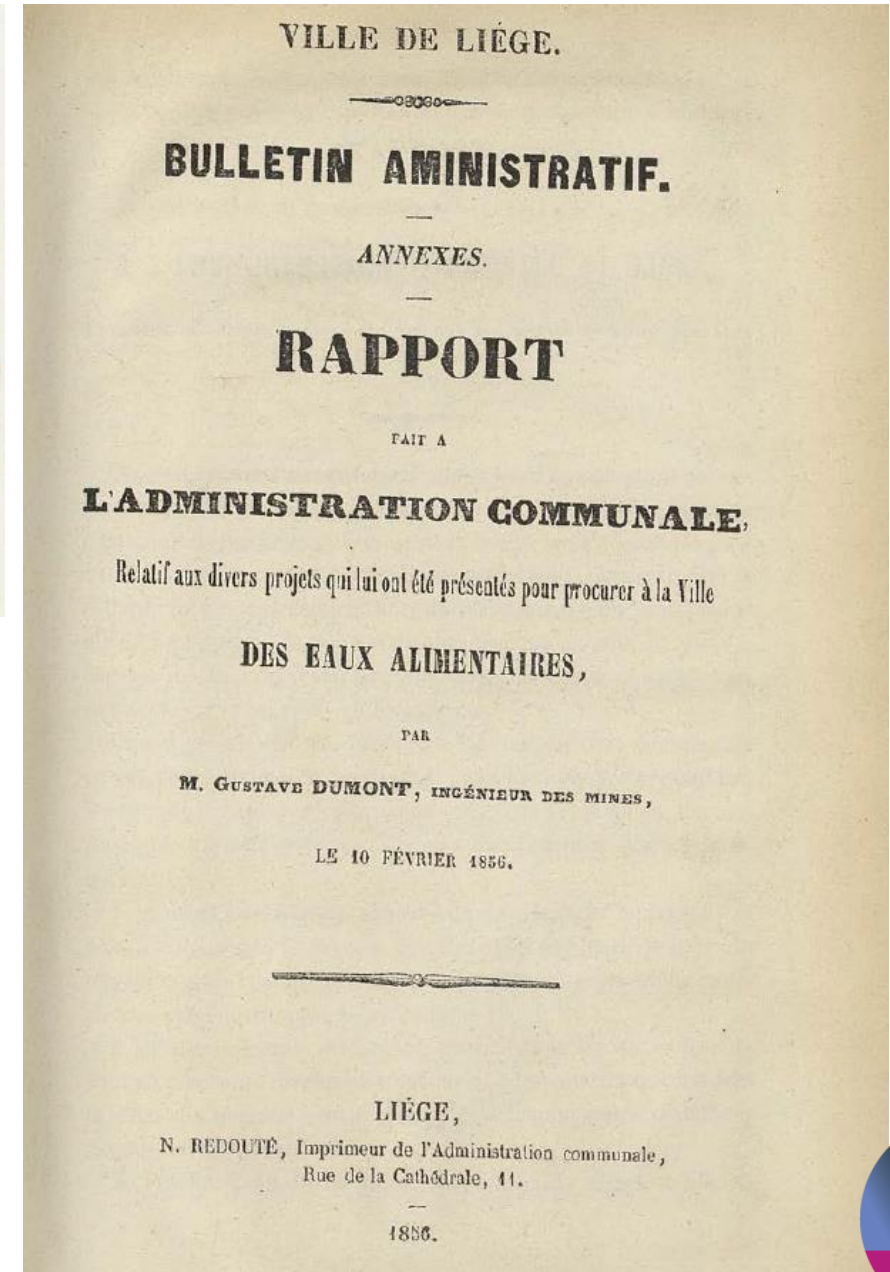


- 1855 **Gustave Dumont** has the task to study the feasibility and impact of an optimized network of water supply galleries in the Cretaceous chalk aquifer in the underground of the 'Hesbaye' region near Liège

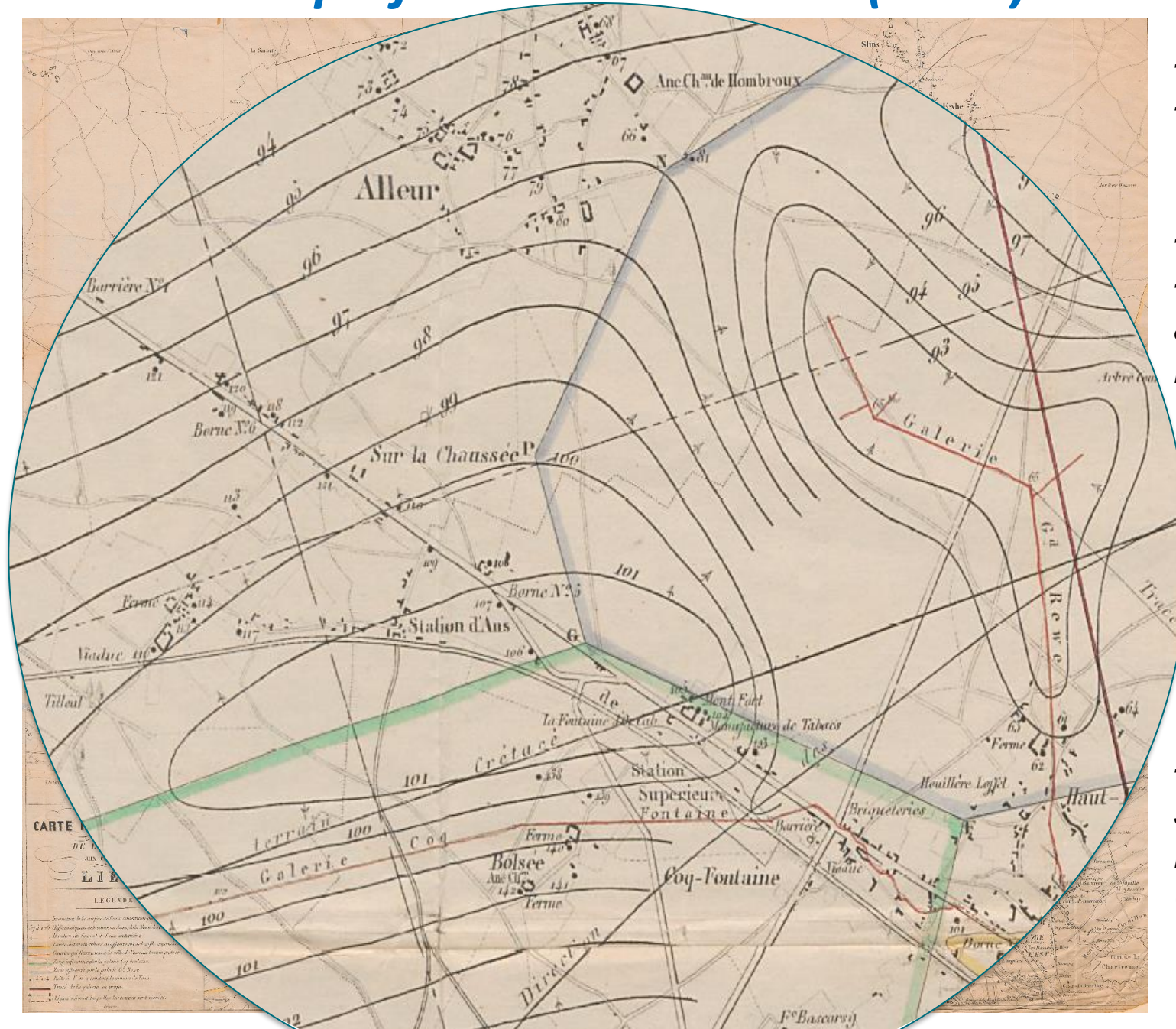


✂ February 1856:
official report, 109 pages, in French
with the world's first potentiometric map !

titled 'Carte hydrographique de la Hesbaye aux environs de Liège' (literally 'Hydrographic map of the Hesbaye region in the Liège area')



The potentiometric map of Gustave Dumont (1856)

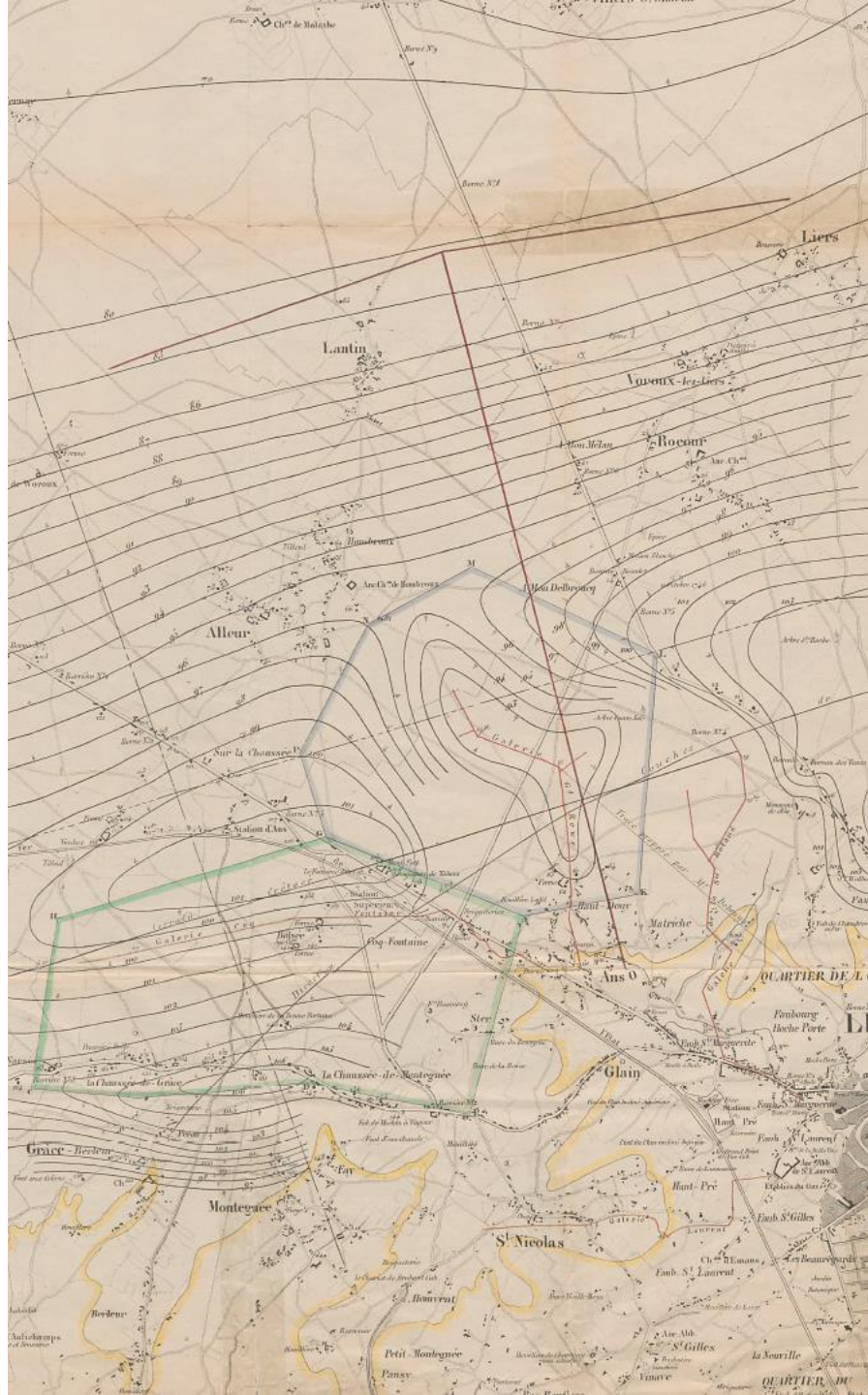


- 129 km²
- scale of 1/20,500

- contours every m
- 54 m until 106 m above the Meuse River (ref level)

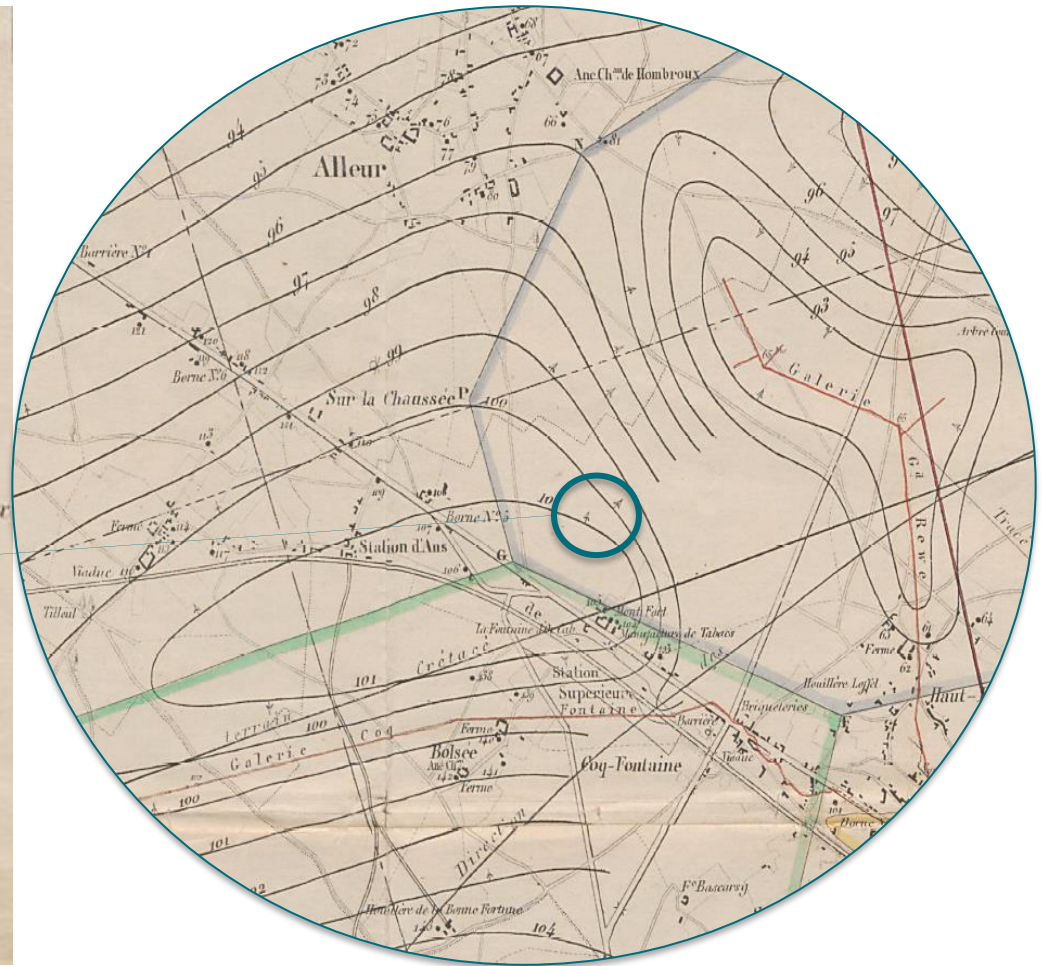
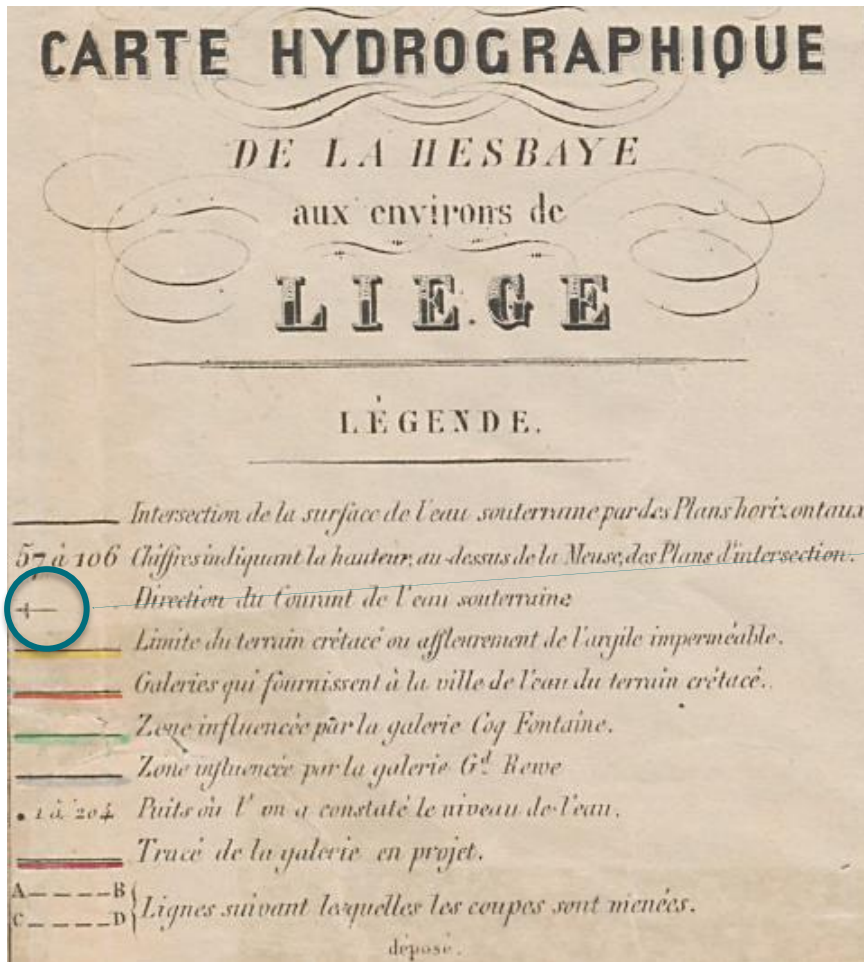
- 204 wells surveyed from March 18 to October 6, 1855





- contours described as ‘the intersection between the underground water surface with horizontal planes’ (literal translation from French)
- hand-drawn contour lines interpolated between the measured values
- influence of existing galleries in the area
- for two of them, the map also delineates the capture zone
- proposition of an aqueduct gallery and two draining ‘lateral’ galleries
- the outcrop of the base of the aquifer mapped in yellow





small arrows normal to the contour lines



groundwater flow direction
(in the legend 'Direction du courant de l'eau souterraine')

Pioneering nature of the work of Gustave Dumont



- combined engineering expertise with excellent geological work
➡ **well-balanced report** with a strong quantitative approach
- ✂ delineated the Geer and the Meuse **hydrological basins**, showed **flow directions** + local **discharges** or **springs**
- ✂ estimated **effective recharge** and **seasonal variations** of the water levels
- ✂ warned about **dynamic and static** measured groundwater levels
- ✂ explained that **hydraulic gradient** is low where hydraulic conductivity is high and vice-versa
- ✂ explained **chalk**: anisotropic and fractured medium + local dissolution features
- ✂ described **groundwater quality** (main inorganic constituents)
- ✂ provided arguments for **optimizing a future network** of galleries



Pioneering nature of the work of Gustave Dumont



- *advised to dig the **draining galleries in a parallel direction** to the ‘lines of equal value of water head’ + **aqueducts** to bring the water by gravity to the City*
- ✂ *discussed the ‘**influenced’ zones**’ + how to optimize their depth in the aquifer for avoiding impacts in the many existing wells used for agriculture*
- ✂ *elaborated on how the water flow could be blocked by a **simple dam in the aqueduct** at a location away from the valley and avoiding any local flooding*

So,

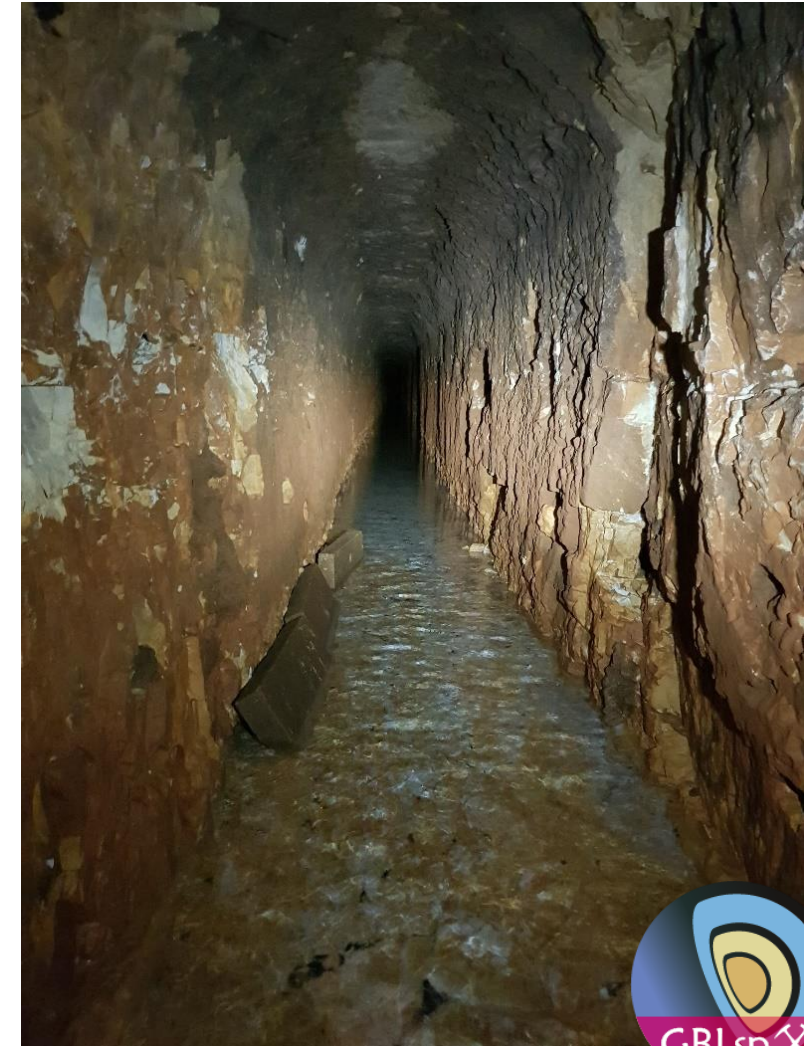
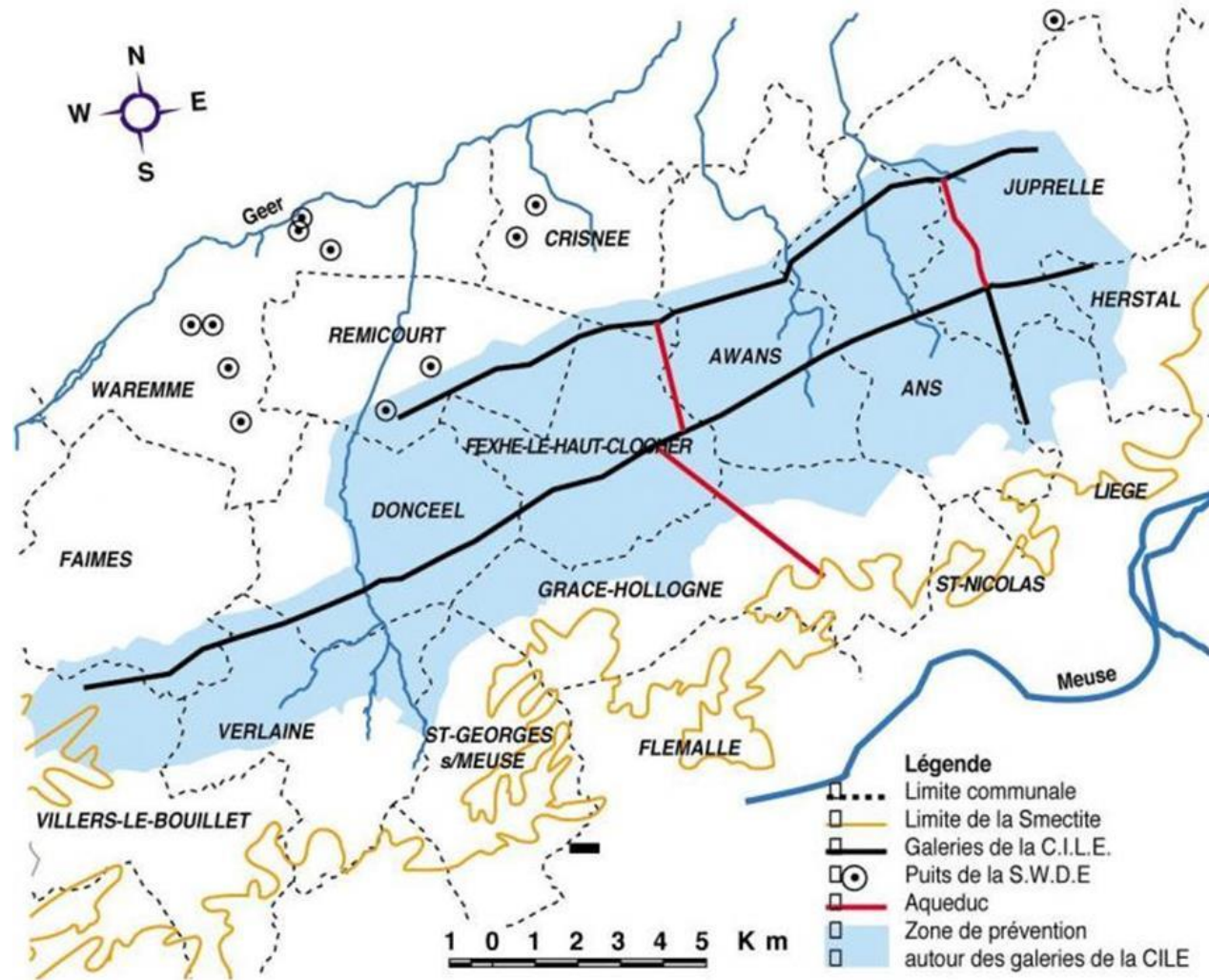
- ✂ ***innovative study** (feasibility, efficiency, potential impacts)*
- ✂ ***a remarkable scientific and technical quality** for its time !*

(keeping in mind that Darcy’s law was published later that year)



Nowadays, the galleries...

- aqueduct + lateral' galleries dug in the following years and extended later
- now more than 40 km of water supply galleries in the chalk
- one of the most important drinking water sources for the City of Liège



International context

*Gustave Dumont in 1856,
followed by*

- *Delesse (1858, 1862) in
France,*



International context



*Gustave Dumont in 1856,
followed by*

*✂ Delesse (1858, 1862) in
France*

✂ Lucas (1874) in the UK

proposed a scheme for London's water supply

- consisting of digging galleries in the Cretaceous chalk
(but never practically implemented)*
- very similar work (lithology, methods and description of
the hydrogeological conditions)*
- was reported as the first British map showing
potentiometric contours (Mather 2001)*



International context

- *Gustave Dumont in 1856, followed by*
 - *Delesse (1858, 1862) in France*
 - *Lucas (1874) in the UK*
 - *Gümbel (1876) and Thiem (1876) in Germany*

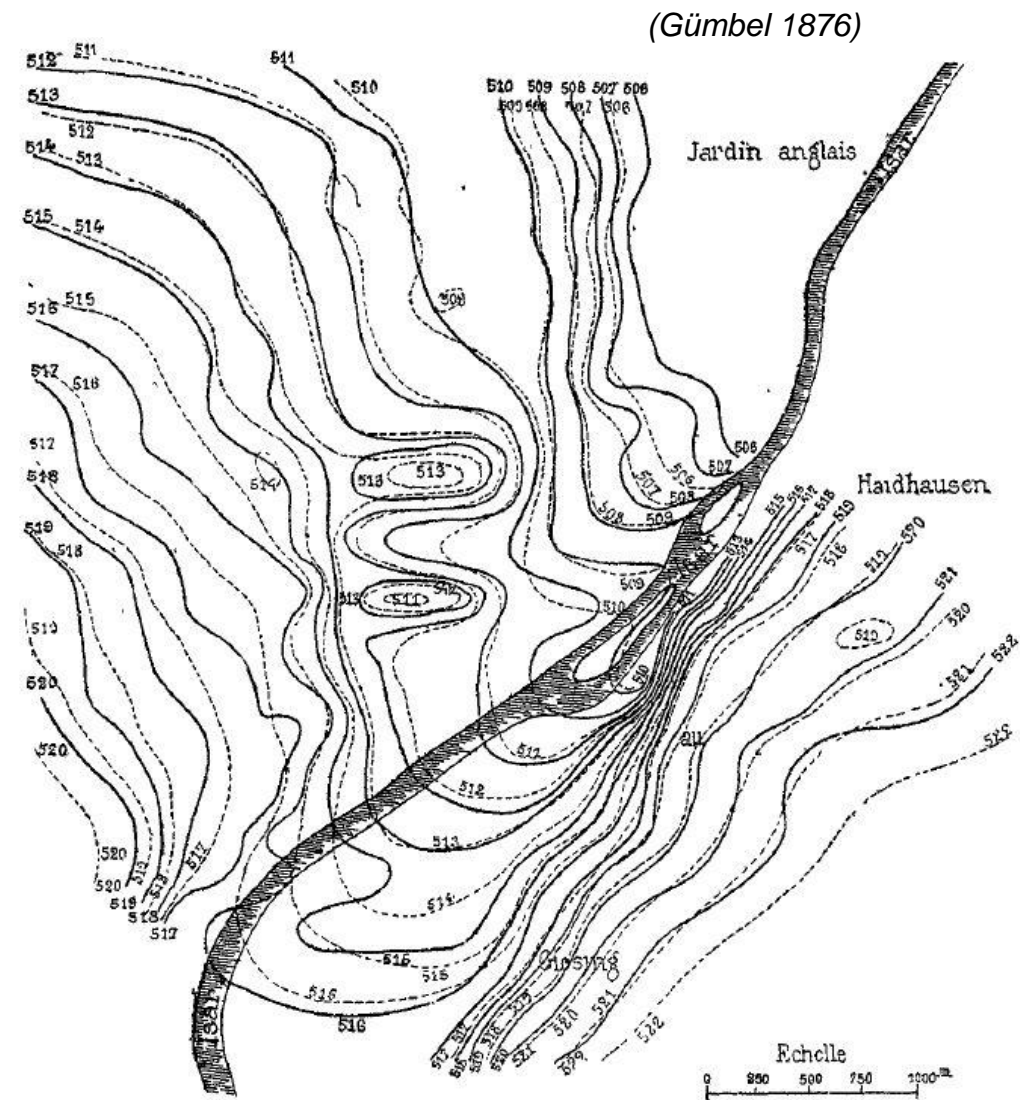


Fig. 15. — Plan de Munich avec les courbes horizontales des eaux phréatiques lors de leur état le plus haut (29 avril 1876) et de leur état le plus bas (29 décembre 1876), d'après M. le docteur C. W. Gumbel. Les courbes pleines sont relatives à la première date et les courbes pointillées à la seconde. Les chiffres de chaque courbe expriment en mètres leur cote au-dessus de la mer. L'échelle qui est indiquée en kilomètres est de $\frac{1}{200.000}$.

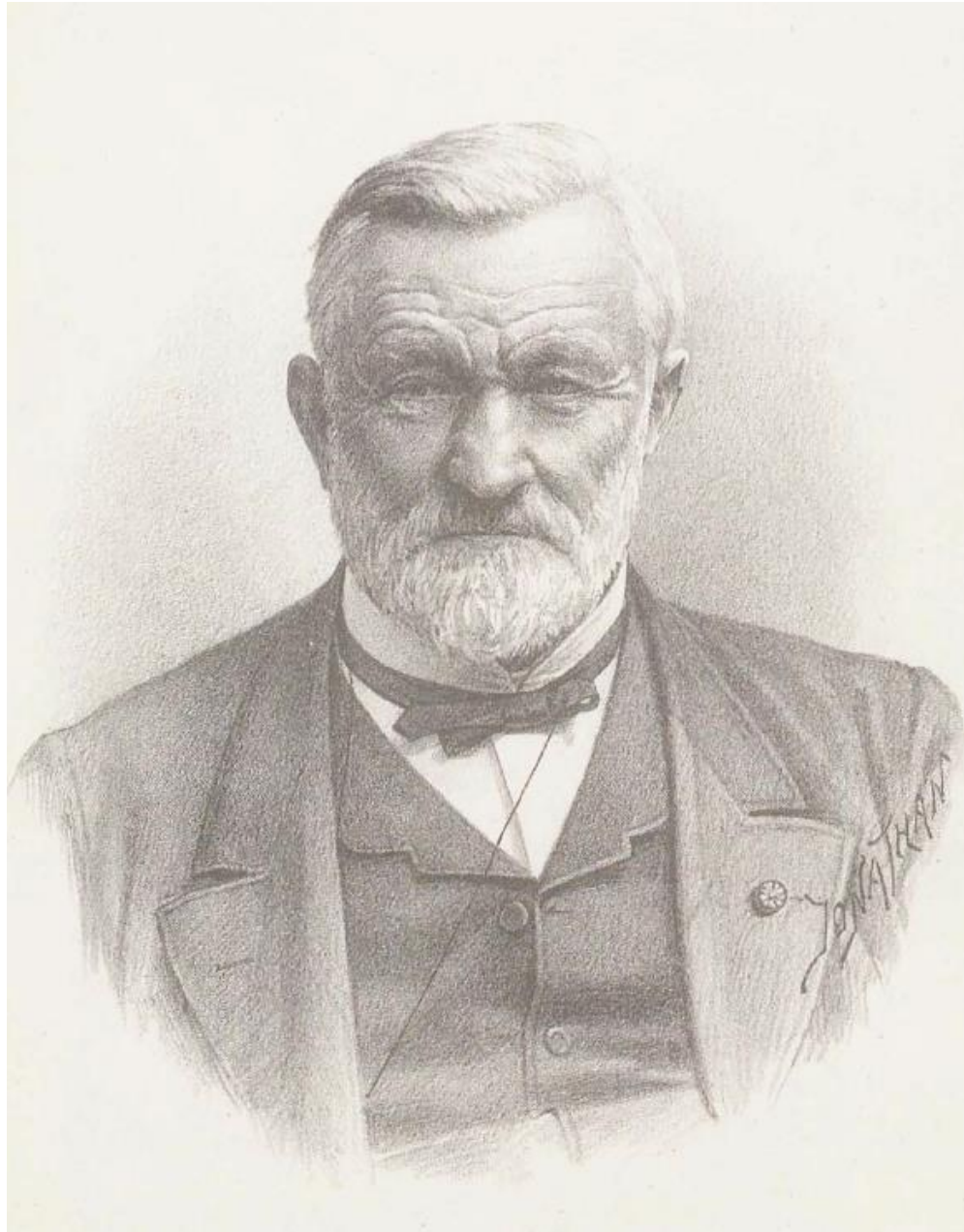


International context

- *Gustave Dumont in 1856, followed by*
 - *Delesse (1858, 1862) in France,*
 - *Lucas (1874) in the UK (Mather et al. 2004),*
 - *Gümbel (1875) and Thiem (1876) in Germany,*
 - *Veerren (1893) and Pennink (1904) in The Netherlands*
 - *King (1899) and Darton (1909) in the US.*

(King 1899)





- *this first potentiometric map ever was published by Gustave Dumont and referenced by Prinz (1919), Meinzer (1934) and Parker (1986), but ...has been largely forgotten in the mean time*



Meinzer (1934)

mastered. This attitude was challenged by M. L. Fuller in 1908 in his paper, "Summary of the controlling factors of artesian flows."⁴⁰ We now recognize that the hydrology of artesian water is a complicated subject that offers a large field for further investigation. Until recently attention has been directed mainly toward the static or structural conditions, with neglect of the hydraulics or dynamics of artesian water, although Chamberlin recognized what we may perhaps call the dynamic principle, and, indeed, considered that his original contribution lay in the recognition of this principle.

Rock pressure was assumed by Thales about 650 B.C., and later by Pliny, as the agency for elevating the sea water to the levels of the springs. In modern times rock pressure has been suggested by different investigators as a cause of artesian head, and there has been unprofitable argument between the champions of this theory and the defenders of the orthodox hydrostatic theory. Recent critical interpretation of the behavior of wells has led us to recognize that the artesian water supports a part of the load of the overlying rocks and that many of the water-bearing formations have measurable elasticity; however, this concept of rock pressure supplements the hydrostatic theory without displacing it.⁴¹

Development of the principles relating to water tables and pressure-indicating surfaces.—The concepts of the zone of saturation and of the water table, as the upper, free-water surface of that zone, developed later than the concept of the artesian basin. In a sense the early scientific thought on ground water was deficient with respect to the third dimension. It was generally considered that the water from the surface percolates downward till it reaches an impermeable bed and then percolates laterally over the upper surface of that bed to its outcrop. This concept was amplified by the recognition of artesian structures in which the water becomes confined between two impermeable beds. More recently the concept has been developed, step by step, of a zone of saturation, with large storage capacity, performing the functions both of a huge reservoir and of a very intricate system of conduits.

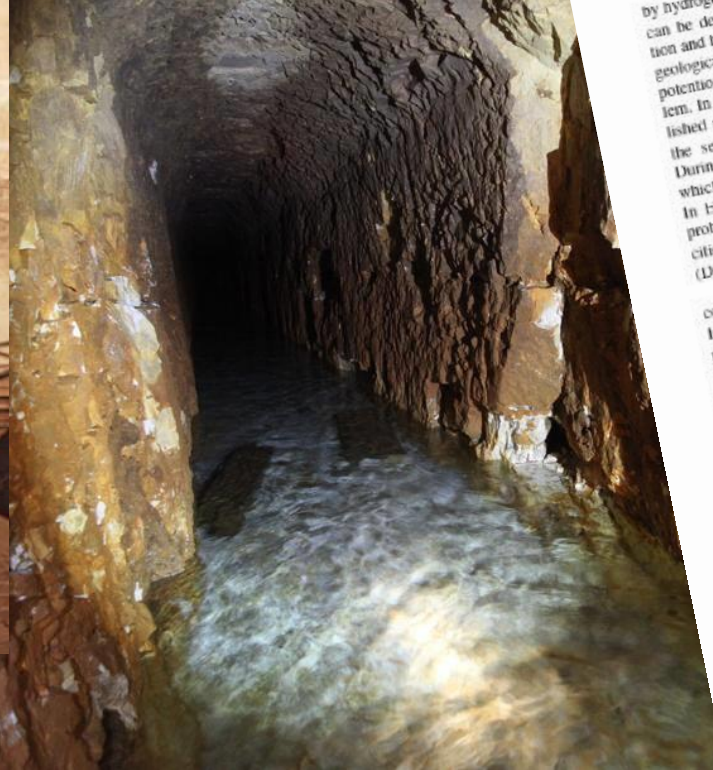
The simple concept of the water table has developed rather tardily, although a good contour map of the water table was published by Gustave Dumont⁴² in 1856. Gradually we are coming to recognize the

⁴⁰ FULLER, M. L. U. S. Geol. Survey Bull. 319: 1908.

⁴¹ MEINZER, O. E. *Compressibility and elasticity of artesian aquifers.* Econ. Geol. 23: 263-291. 1928.

⁴² DEMONT, GUSTAVE. *Les eaux alimentaires de la ville de Liège, 1856.*





Groundwater

Historical Note/

The First Potentiometric Map

by Alain Dassargues¹, Okke Batelaan², and Annick Anceau³

Introduction

Nowadays, potentiometric maps are commonly used by hydrogeologists. They contain information from which can be deduced, among others, groundwater flow direction and hydraulic conductivity variations. In most hydrogeological studies that deal with groundwater flow, the potentiometric head is the main variable of the problem. In the historical development of hydrogeology, published and documented potentiometric maps appeared in the second half of the 19th century (Daubree 1887). During this period, important developments were made, which allowed quantification of groundwater resources. In Europe, these advances are related to the increasing problems encountered by most of the big and mid-sized cities to provide clean water to the growing population (Daubree 1887).

Darcy's law, published in 1856 (Darcy 1856), can be considered the starting point of quantitative hydrogeology. However, the actual progress in hydrogeology, at the time, primarily resulted from scientific and technological innovations induced by two determining factors: first, the mining operations (mostly linked to coal exploration) reached deeper zones and required complex drainage/pumping

works; second, providing safe and sufficient water supply in cities brought geologists and engineers together, and from their cross-experiences, new ideas and quantification methods emerged. In this international and regional context, it appears that the first (known) published potentiometric map was drawn by Gustave Dumont in 1856 in Liege (Belgium). This map, although referenced by Prinz (1919), Meinzer (1934) and Parker (1986), has been largely forgotten but is older than other works of the same nature generally mentioned in the groundwater literature (Delesse 1862; Lucas 1874; Gumbel 1875; Thiem 1876; Darton 1909).

Regional and Historical Context

Interdisciplinary collaboration between geologists and engineers practically first appeared in the work of William Smith in 1827 (Meinzer 1934), who connected rock properties and structures to the perception of the water-bearing vs. water-confining roles of layers (de Vries 2007).

In 1841, Georges Mulot drilled the artesian well of Grenelle below Tertiary confining marly and clayey layers in Paris (Margat et al. 2013). Artesian wells have undoubtedly triggered further groundwater development and exploration of similar conditions (Jiang et al. 2020). In other situations, groundwater production from drainage galleries was developed. Drainage galleries were known for centuries as "qanats" in Persia as early as 800 years B.C. (Butler 1933; Deming 2002) and as "loggaras" in North Africa as early as 200 years B.C. Some of them extended over several kilometers, as in arid areas in China, Afghanistan, and North Africa (Totman 1937).

Other contributions made to the field of hydrogeology in the first half of the 19th century were by Bégout (1846), who distinguished between permeable and impermeable geological formations as applied to groundwater, and by Bischof (1847), who published a book about chemical and physical geology, including groundwater aspects. Dupuit's seminal contributions to the theory of groundwater flow started in 1848 with a book on the

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Article impact statement: This historical note is bringing to the groundwater community very interesting information about the first known potentiometric map.

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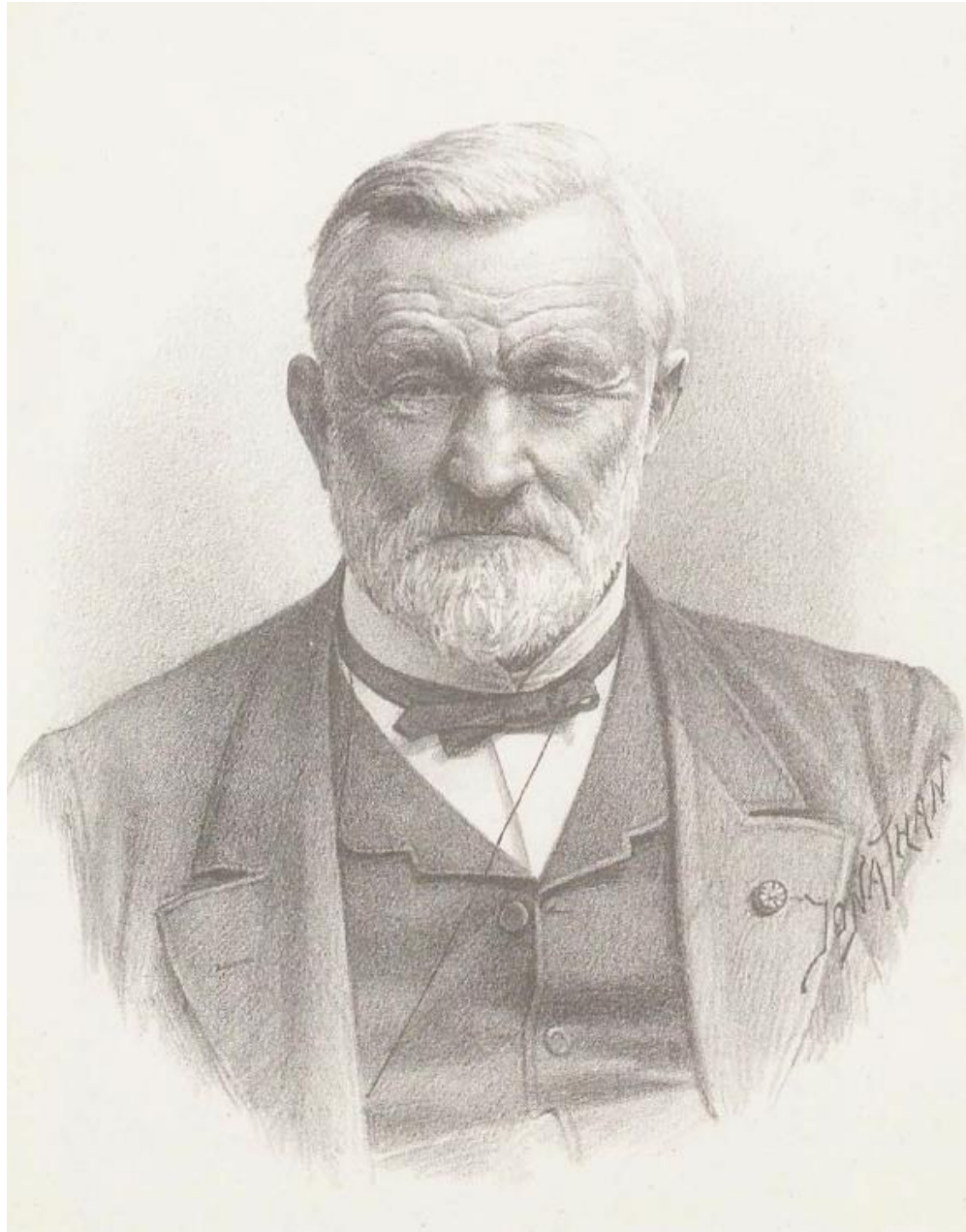
The Cretaceous Chalk of Hesbaye/Haspengouw:

a permanent object of research, example of the last 35 years



- the second (and first with FEM) regional groundwater model in Belgium (Dassargues et al. 1988; Dassargues et al. 1991, Dassargues 1993, Dassargues & Monjoie 1993)
- nitrate transport studies and local modelling in the saturated zone (Biver & Dassargues 1993; Biver & Dassargues 1994; Biver et al. 1995)
- groundwater flow and solute transport (tracer tests and modelling) in the saturated and partially saturated zones with double porosity (Dassargues et al. 1996; Brouyère et al. 2000; Brouyère 2001; Brouyère et al. 2004)
- many local geophysical investigations, tracer tests, and modelling for protection zones delineation (Hallet 1999, Hallet et al. 2000; Dassargues & Hallet 2000; Brouyère & Dassargues 2002; Brouyère et al. 2005)
- regional modelling of nitrate transport including remediation schemas and economical constraints (Orban et al. 2006; Orban et al. 2010)
- first regional integrated flow model for studying the impact of climate changes on the groundwater reserves, including uncertainty assessment (Brouyère et al. 2004; Goderniaux et al. 2009; Goderniaux 2011; Goderniaux et al. 2011; Goderniaux et al. 2015)
- study of trends for nitrates, pesticides (Battle-Aguilar et al. 2006; Battle-Aguilar et al. 2007; Hakoun et al. 2017)
- new groundwater flow model for studying the impact of extreme drought conditions (Goderniaux et al. 2021; Hutzemakers et al. 2024; Hutzemakers et al. in press)
- studying the potential of artificial recharge (MAR) (Glaude et al. in press)





- *outstanding work having largely participated to the birth of quantitative hydrogeology and before the publication of Darcy's law*
- ✂ *early steps of geological engineering, crossroads between mining engineering and geology*
- ✂ *the 'Liege school of Hydrogeology' was born !*
- ✂ *the main driver is to supply sufficient and good quality water for growing cities*

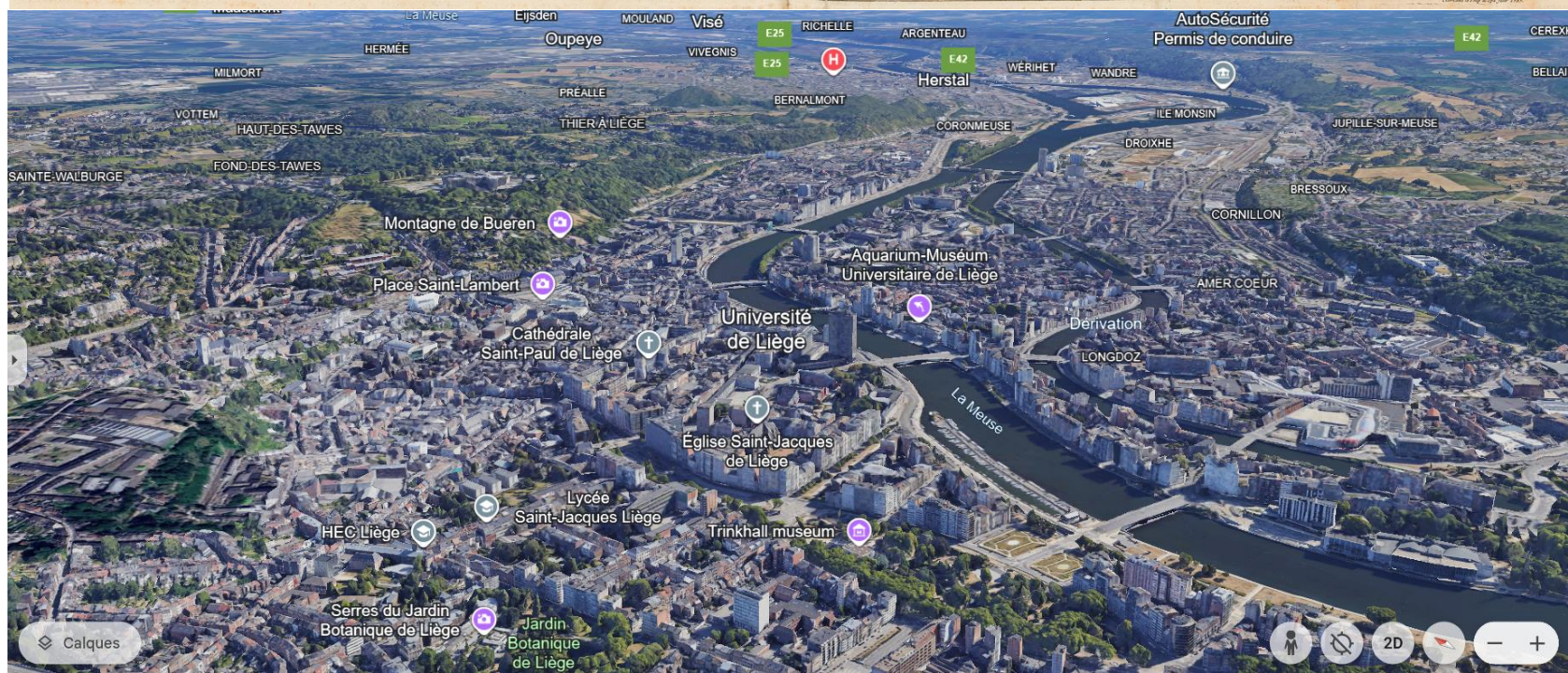
Conclusion



1737



2024



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