

Groundwater

Historical Note/

The First Potentiometric Map

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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 (Daubrée 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 (Daubrée 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 exploitation) 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 Liège (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; Gümbel 1875; Thiem 1876; Darton 1909).

Regional and Historical Context

International 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, based on the existing methods for mining drainage, 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 “foggaras” in North Africa as early as 500 years B.C. Some of them extended over several kilometers, as in arid areas in China, Afghanistan, and North Africa (Tolman 1937).

Other contributions made to the field of hydrogeology in the first half of the 19th century were by Belgrand (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. Duperoy's seminal contributions to the theory of groundwater flow started in 1848 with a book on the

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movement of groundwater (Dupuit 1848). In France, from 1832 to 1853, the Abbé Paramelle was a famous expert in groundwater exploration and prospection using a distinctive conceptual approach for understanding local hydrological conditions linked to topographic and geological controls (Bobeck and Sharp 2019).

The technique of drilling boreholes arrived in the United States from England around 1820. Having learned from the artesian boreholes in France, many artesian aquifers were drilled in the U.S. starting in the 1880s (Parker 1986). Also, in the 19th century, dewatering of mines was practiced, as in Belgium, the UK, the Czech Republic, and many other European regions (Muzikar 2013).

Darcy's law in 1856 opened new avenues for formulating groundwater flow problems with equations, which can be solved for given boundary conditions and parameters (de Vries 2007). Dupuit (1863) and Thiem (1870) proposed 2D horizontal groundwater flow simplifications that can be used respectively in confined and unconfined aquifers. Boussinesq (1877) and Forchheimer (1886) combined Darcy's law and the mass conservation principle yielding the Laplace groundwater flow equation, mathematically analogous to the heat diffusion equation previously proposed by Fourier (de Vries 2007).

In the UK, Lucas proposed in 1874 a scheme for the improvement of London's water supply (Mather 2004), consisting of digging galleries in the Cretaceous chalk. Although the galleries were never practically implemented, it is astonishing how this work on the hydrogeology of the Chalk aquifer appears similar (at least for the lithology, the recommended methods and the way of describing the hydrogeological conditions) to what was described in earlier work of Gustave Dumont (see below) for Liège in 1856. Interestingly, the Lucas (1874) report included the first British map showing potentiometric contours (Mather 2001).

In Belgium, in 1851, the Brussels water supply was based mainly on shallow boreholes in Ypresian and Lutetian sands (Daubrée 1887). In The Netherlands, from 1852, Amsterdam was supplied groundwater from coastal dunes using drainage canals (de Vries 2007, 2013). Finally, in Germany, in 1892, Hamburg turned to artesian water from deep confined aquifers (Loehnert 2013). Hence, in the second half of the 19th century, many European cities chose to develop water resources from groundwater.

Brick (2013) mentioned that water table or potentiometric surfaces were originally represented explicitly in cross-sections from 1850 onwards (Clutterbuck 1850). Water table or potentiometric maps for unconfined and confined conditions were presented, first in Belgium by 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, Veeren (1893) and Pennink (1904) in The Netherlands and King (1899) and Darton (1909) in the United States.

In his influential book, Daubrée (1887) exemplified the relationship between geological structures and the presence and flow of groundwater by reproducing maps and cross-sections from different countries. Daubrée (1887) also notes that in mapping groundwater heads, it was observed that the groundwater divide was not everywhere corresponding to the topographical or surface water divide.

Regional Context: Dewatering of Mines and Liège Water Supply

The city of Liège, Belgium, is located in the alluvial plain of the Meuse River and on the slopes of the valley. In the valley, the alluvium lies directly on folded Carboniferous bedrock. On the hills to the Northwest of Liège, discordant Upper Cretaceous and Cenozoic deposits cover the bedrock and correspond to the eastern part of the Hesbaye plateau. Above the bedrock, the first Cretaceous formation is a low permeability marly clay layer currently named the Vaals Formation (lower Campanian), formerly known as the "*Smectite de Herve*" (Robaszynski et al. 2001). This formation is overlain by highly permeable upper Campanian and Maastrichtian chinks of the Gulpen and Maastricht formations (Thorez and Monjoie 1973; Delcambre and Pingot 2021). These chinks are partly covered by Cenozoic sandy sediments (Delcambre and Pingot 2021) and by loess (Dassargues and Monjoie 1993). At the contact between the Vaals and the Gulpen formations, springs appear along the hillslope forming small streams flowing towards the Meuse River in Liège (Dumont 1856; Gobert 1910). One of these streams is the Legia River, whose waters were used to activate mills as early as the 12th century.

Also in the 12th century coal mining began in Liège (de Crassier 1827; Fourmarier and Denoël 1930; Gaier 1988). The exploitation started with "collecting" coal blocks from the upper Carboniferous coal seams cropping out along the sides of the hills surrounding the city. After this early stage, shafts and galleries were dug until they were abandoned as soon as air ran out for the miners and were filled by water (de Crassier 1827; Fourmarier and Denoël 1930). Dewatering became a necessity (de Crassier 1827). Initially, the miners drained manually or with horses, using buckets and tanks (Gobert 1910; Gaier 1988). As early as the 13th century, the first drainage galleries were developed in Liège. Rapidly, they were pushed to a level of complexity and performance unmatched at that time in an urban environment (Gaier 1988). Drainage galleries, called "*areine*," "*arène*," or "*araine*" in Belgium, were built to lower the water levels occurring in the coal mines (de Crassier 1827; Gaier 1988) and had exit points at the lowest possible elevation so that the water could flow out into the Meuse River or the nearest stream in the valley (de Crassier 1827). Starting at its mouth, the drainage gallery was dug up to the first mine was reached, observing a minimum slope for gravitational flow (de Crassier 1827). After the first junction with mine works, the drainage gallery was progressed and linked to different mine shafts



Figure 1. Mouth of the Richefontaine drainage gallery network, one of the four “*areines franches*,” just before entering the drinking water fountains. Photo by A. Anceau, 20 September 2020.

by smaller drainage galleries or by voids left after the mining (de Crassier 1827). From the beginning of the 17th century, with the deepening of the mine works, a drainage gallery, higher in altitude, could be merged with another drainage gallery at a lower elevation. Such drainage connections supported coal mining and decreased the cost of the exploitation. Each drainage gallery consisted of a network of galleries dug into the rocks. Taking advantage of the valley topography, the drainage galleries dewatered mines mainly by gravity for five centuries (Gaier 1988, 2012).

The water of four main drainage gallery networks (called “*areines franches*”) was used as drinking water by supplying public and private fountains of the city (Figure 1), while the waters from the other drainage gallery networks (called “*areines bâtarde*s”) fed directly into the rivers (de Crassier 1827; Gaier 1988). This distinction already existed in 1586. The four “*areines franches*,” due to their water supply importance, were therefore protected by stringent laws (de Louvrex 1750). Until 1680, the *areines* were the only sources of flowing water in Liège (Gaier 1988).

In 1697, after merging a drinking water drainage gallery (i.e., *areine* of “Val St Lambert”) to a lower level drinking water drainage gallery (i.e., *areine* “de la Cité”), its contribution to the Legia River and the

fountains ceased. To maintain activities along this river and provide water supply, Jean Roland, who requested this merger of drainage galleries to improve the exploitation of his coal mines, was required to provide a new water source to replace the ceased source (de Crassier 1827). He built a new gallery to collect groundwater from the springs in the Cretaceous chalk at the top of the marly clay. This gallery was dug at great expense, bringing new water from the Hesbaye to the mills and the fountains of the city (de Crassier 1827). It was still in use when G. Dumont prepared his report (see Figure 2, “*Galerie de la Sté [Société] Roland*”) and was used for drinking water supply until 1992 (CILE 1995).

After this first gallery, five more galleries were built and supplied water collected from the Cretaceous chalk to the city (Dumont 1856). These galleries were intentionally drilled into the chalk as an extension of the natural springs that marked the outcrop line of the Cretaceous clays (Detienne 1906). These six galleries, including the “Coq-Fontaine” and “Grand-Rèwe” galleries (see below), were still in use in 1855, as indicated on a map locating some *areines* and the six Cretaceous chalk galleries (“*Plan indiquant la position des arènes et des galeries qui fournissent l’eau à la ville de Liège*”) (Dumont 1856).

In the 19th century, when the population of Liège grew to nearly 100,000 inhabitants, the drinking water supply was insufficient in terms of quantity and quality (Van den Broeck and Rutot 1887). Most of the water supply for Liège was sourced from the alluvial deposits of the Meuse River (well water), the collecting galleries in the chinks at the top of the marly clay, and the drainage galleries at the foothills of the valley in the Carboniferous coal mining works (where the water quantity was inexorably declining) (Dumont 1856; Detienne 1906).

In 1851, André Dumont (1809-1857), professor at the University of Liège published a note about the application of regional geological knowledge for groundwater exploration (Dumont 1851). In this work, he presented a detailed description of the lithostratigraphy of the Cretaceous and Cenozoic deposits in Hesbaye (Geer basin) near Liège. He also described the hydrogeologic properties of these deposits, which dip slightly north-west with 5°, in great detail. Remarkably, he also identified the discharge and recharge zones of this aquifer and how its basement made of a marly clay layer could be considered an impervious base. In conclusion, he suggested that this aquifer could be pumped or ideally be drained for providing drinking water by a (gravity fed) aqueduct to the City of Liège located in the Meuse River valley at a lower elevation.

The Potentiometric Map of Gustave Dumont (1856)

In February 1856, Gustave Dumont (1821-1891) published the world’s first potentiometric map. It shows potentiometric levels (heads) of the unconfined Cretaceous chalk aquifer of the Geer basin near the City of Liège. The map appears in a report of 109 pages written in French, entitled “*Rapport fait à l’administration communale, relatif aux divers projets qui lui ont été*



Figure 2. The potentiometric map (named “hydrographic map”) of the Hesbaye aquifer as drawn by Gustave Dumont in his report, dated February 10, 1856 (Dumont 1856). As mentioned in French in the legend (lower left of the figure), the contours are “the intersection between the underground water surface with horizontal planes.” The red lines central in the map are the proposed excavations in the chalk for an aqueduct from “Ans” to “Lantin” (about 5 km in length) and two connected water supply galleries.

présentés pour procurer à la Ville des eaux alimentaires” (Report for the City of Liège’s Council about projects for providing drinking water) (Dumont 1856). This report was published in the “*Bulletin administratif de la Ville de Liège*” (Administrative bulletin of the City of Liège).

In 1855 a water commission of the City of Liège provided Gustave Dumont with 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. The official report includes the first potentiometric map (Figure 2) titled “*Carte hydrographique de la Hesbaye aux environs de Liège*” (literally “Hydrographic map of the Hesbaye region in the Liège area”). The map covers about 129 km² and has a scale of ca 1/20,500. It shows potentiometric contours every meter

from 54 m until 106 m, above the Meuse River. The contours were described as “the intersection between the underground water surface with horizontal planes” (literal translation from French). Dumont used the levels of 204 wells surveyed from March 18 to October 6, 1855 (Dumont 1856; Detienne 1906). The contour lines are hand-drawn and smoothly interpolated between the measured values in the different wells. The interpolated contours clearly show the influence of existing galleries in the area. For two of them, the Galleries “Coq Fontaine” and “Gd.[Grand] Rewe,” the map also delineates the capture zone (“*Zone influencée par la galerie*”) in respectively green and blue. The proposed galleries in the chalk consist of an aqueduct gallery (“*Galerie principale*”) in South-North direction from Ans to Lantin and two draining “lateral” galleries (“*Galeries latérales*”)

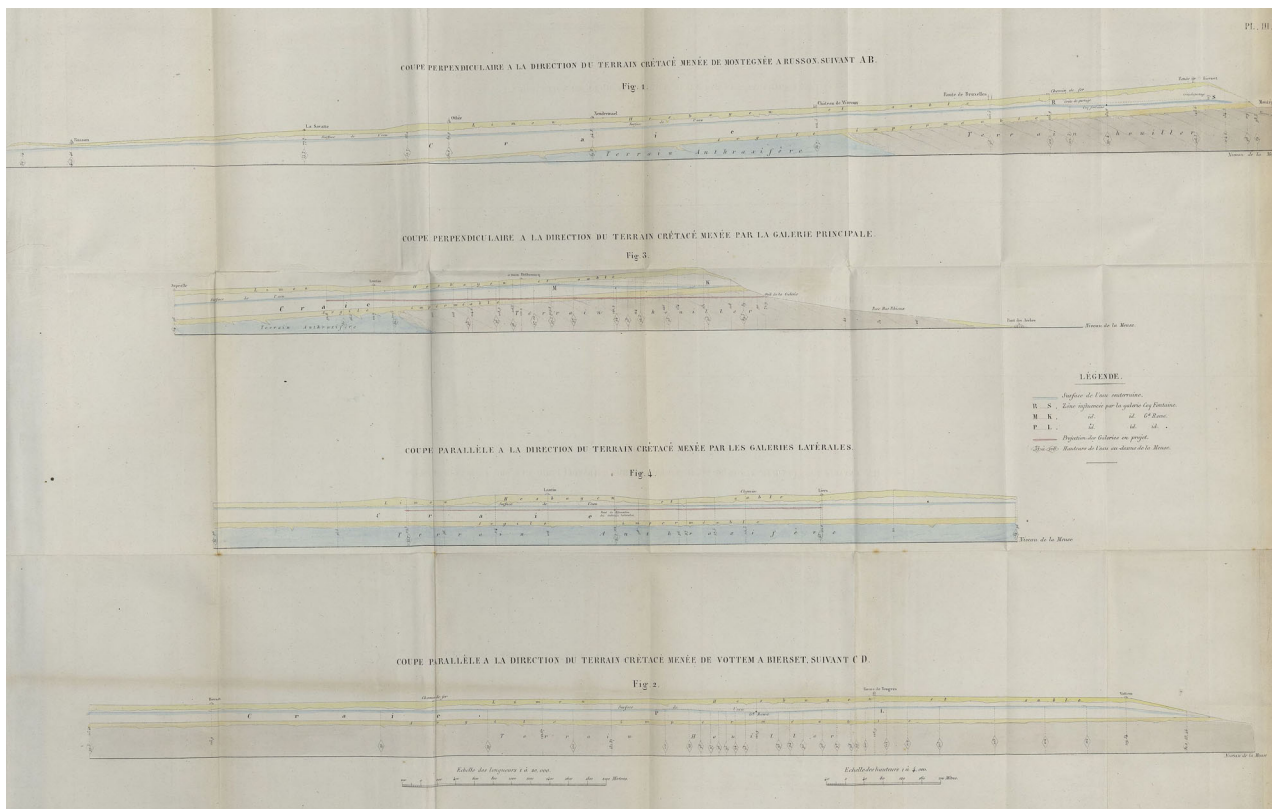


Figure 3. Cross-sections accompanying the potentiometric map (Dumont 1856). The first cross-section (top) is drawn orthogonally to the direction of the chalk layers. The second cross-section (second from the top) is also drawn in that direction and is located along the proposed aqueduct gallery. The third cross-section (third from the top) is in the parallel direction of the chalk layers following the two proposed “lateral” galleries, and the fourth cross-section (bottom) is also in the parallel direction of the chalk layers but located upstream.

nearly orthogonally to the aqueduct. The outcrop of the impermeable layer at the base of the aquifer is also mapped in yellow (“*Limite du terrain crétacé ou affleurement de l’argile imperméable*”). In small arrows normal to the contour lines, Dumont indicated on the map the groundwater flow direction (in the legend “*Direction du courant de l’eau souterraine*”). The report also presented different vertical cross-sections in the Hesbaye aquifer showing groundwater levels, allowing comparison with the bottom and top of the different sub-layers in the chalk aquifer (Figure 3). The layout of the first cross-section (Figure 3—top) is indicated on the potentiometric map (Figure 2), its direction is orthogonal to the direction of the chalk layers (“*Coupe perpendiculaire à la direction du terrain crétacé menée de Montegnée à Russon suivant AB*”). The second cross-section (Figure 3—second from the top) is in the same direction as the location of the proposed aqueduct gallery (“*Coupe perpendiculaire à la direction du terrain crétacé menée par la galerie principale*”). The third cross-section (Figure 3—third from the top) is in the parallel direction of the chalk layers following the two proposed “lateral” galleries (“*Coupe parallèle à la direction du terrain crétacé menée par les galeries latérales*”). The fourth cross-section (Figure 3—bottom) is indicated on the potentiometric map (Figure 2), in the parallel direction

of the chalk layers (“*Coupe parallèle à la direction du terrain crétacé menée de Vottem à Bierset suivant CD*”).

Gustave Dumont adequately combined his engineering expertise with the excellent geological work published 5 years earlier by his cousin André Dumont (Dumont 1851). He thus delivered a well-balanced report with a strong quantitative approach.

He delineated the Geer and the Meuse hydrological basins accurately; estimated effective recharge from precipitation; reported seasonal variations of the aquifer water levels; derived groundwater flow directions; indicated local discharges or overflow springs; and warned about the difference between dynamic and static measured groundwater levels. He also explained that the hydraulic gradient is low where the hydraulic conductivity is high and vice-versa and that the chalk is an anisotropic and fractured medium, with local dissolution creating enlarged fissures and even possibly conduits. He described the Hesbaye groundwater quality by identifying the main inorganic constituents. He also provided some arguments for optimizing a future network of galleries. For example, he advised to dig the galleries in a parallel direction to the “lines of equal value of water head” rather than in the perpendicular direction (steepest gradient direction), even if galleries in this perpendicular direction will still be necessary as aqueducts to bring the water by gravity to the



Figure 4. One of the “lateral” galleries in the Cretaceous chalk of Hesbaye still in use for the water supply of the City of Liège by the Public Water Company of the Liège area (“Compagnie Intercommunale des Eaux de Liège” CILE). Photo by Serge Brouyère.

City of Liège. He discussed the “influenced” zones of the future galleries and how to optimize their depth in the aquifer for avoiding too strongly induced drawdowns in the many existing wells used for agricultural purposes. Moreover, he elaborated on how the water flow in the future network of galleries could be blocked by a simple dam in the aqueduct at a location away from the valley and avoiding any local flooding as the water would be kept in the chalk aquifer itself.

The study was particularly innovative as it was not only driven by the needed feasibility and efficiency of the project but also by an estimation of the potential impacts (i.e., on the groundwater levels in private wells of the farmers in the Hesbaye region). The whole report is of a remarkable scientific and technical quality for its time, keeping in mind that Darcy’s law was not published until later that year.

Following the conclusions of Gustave Dumont, the aqueduct, also called “main gallery” (*galerie principale*) in the report, and “lateral” galleries were dug in the following years and extended later in a few additional steps. With more than 40 km of water supply galleries in the chalk, it currently constitutes one of the most important drinking water sources for the City of Liège (Dassargues and Monjoie 1993; Brouyère et al. 2004) (Figure 4).

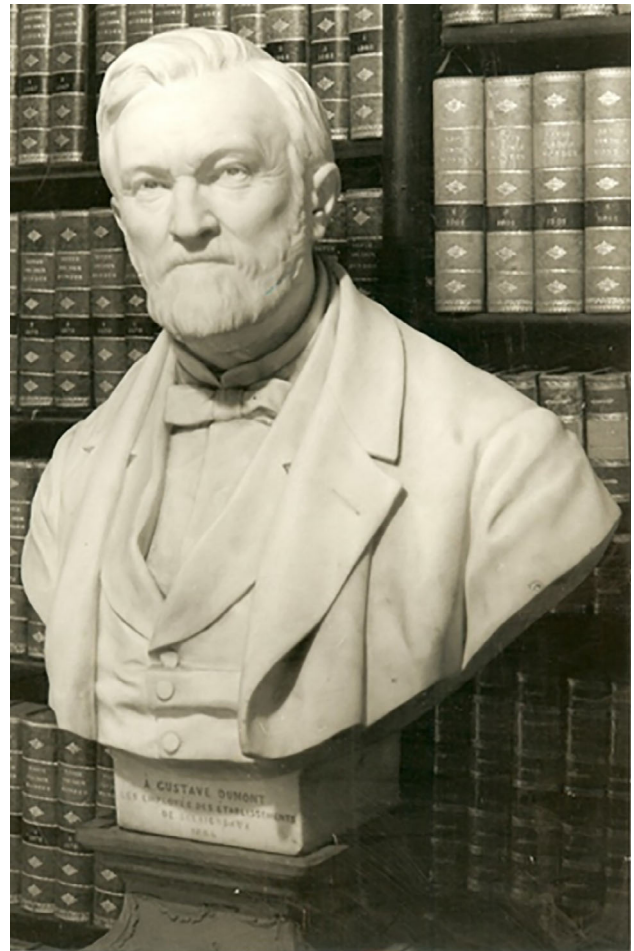


Figure 5. Gustave Dumont. The foot of the bust reads: “A Gustave Dumont les employés des établissements de Sclaigneaux 1884” (To Gustave Dumont the employees of the industry of Sclaigneaux 1884). Photo by Damien Pirlot de Corbion.

Gustave Dumont (Figure 5) was born May 15, 1821 and was the cousin of André Dumont, the famous geologist who was the first to map the geology of Belgium in detail (Fayn 1864). He graduated as a mining engineer in 1845 (Le Roy 1869) and was admitted to the Mine Administration in 1846. Gustave Dumont worked for this administration in the provinces of Mons, Namur and finally Liège until 1855. Then, he took a leave of absence from the Administration and worked on the drinking water supply project for the City of Liège, resulting in his Dumont (1856) report (Anonymous 1891). In 1871, he also published an important report on land subsidence induced by coal mining in the City of Liège (Dumont 1871). Dumont never went back to the Administration as he developed (from 1848 onward) his own industrial activity in the production of zinc, lead and silver in Sclaigneaux near Andenne in Belgium. At the end of his life, this metallurgical company was significant. It supplied more than 90% of lead and silver produced in Belgium. Dumont had become a renowned industrialist and businessman. In 1869 he received the Belgian Royal award of Knight in the Order of Leopold for the design

of the drinking water supply system for the City of Liège. He died on April 25th, 1891 at the age of 69 (Anonymous 1891).

Conclusions

In February 1856, the first potentiometric map ever was published by Gustave Dumont.

Gustave Dumont, a mining engineer, reported to the City Council of Liège (Belgium), on a feasibility study for a large drinking water production project based on galleries in an unconfined chalk aquifer. The first potentiometric map included in this report showed contours described as “the intersection between the underground water surface with horizontal planes.” Dumont used the groundwater levels of 204 wells surveyed in 1855. He hand interpolated the measured values, added flow directions and capture zones of galleries.

This outstanding work of Gustave Dumont has to be seen as part of the birth of quantitative hydrogeology and slightly precedes the publication of Darcy’s law later in the same year. The second half of the 19th century is typified by the early steps of geological engineering, in which expertise was developed at the crossroads between mining engineering and geology. Quantitative hydrogeology was rising through different ways and schools, combining a thorough understanding of geology with hydraulic engineering. These interactions were required to solve the practical problems related to industrial/mining developments and to supply sufficient and good quality water for growing cities.

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Data Availability Statement

The report and the potentiometric map of G. Dumont are made available online: <http://hdl.handle.net/2268.1/9420>

Authors' Note

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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