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The Thiem team – Adolf and Günther Thiem, two forefathers of hydrogeology

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Abstract. Adolf and Günther Thiem, father and son, left behind a methodological legacy that many current hydrogeologists are probably unaware of. It goes far beyond the Dupuit–Thiem analytical model for pump test analysis, which is connected to their name. Methods, which we use on a day-to-day basis today, such as isopotential maps, tracer tests, and vertical wells, were amongst the many contributions which the Thiems either developed or improved. Remarkably, this was not done in a university context but rather as a by-product of their practical work of designing and building water supply schemes in countries all over Europe. Some of these waterworks are still active. Both Thiems were also great science communicators. Their contributions were read and applied in many countries, especially in the USA, through a personal connection between Günther Thiem and Oscar Edward Meinzer, the leading United States Geological Survey (USGS) hydrogeologist of the time.

1 Introduction

The name Thiem appears in many hydrogeological textbooks, most often in the context of the Dupuit–Thiem method, which is an analytical model for the evaluation of steady-state pumping tests (e.g. Batu, 1998; Kruseman and de Ridder, 2000; Bear, 2007; Kresic, 1997; Kasenow, 2010). Few hydrogeologists, however, are aware that there were two engineers of this name, father and son, Adolf and Günther Thiem. Both contributed much more to the current hydrogeological methods than just a somewhat outdated pumping test model. Their work laid the foundations for a range of diverse applications and methods still being used today, e.g. tracer tests, well construction, and isopotential maps, and was widely acknowledged even on an international scale, especially in the USA. They also planned and supervised the construction of many groundwater supply schemes in several European countries, some of which are still active today, although in a modernized form. The focus of this study is thus to investigate the scientific biography of both Thiems and how their contributions found their way into the international canon of methods.

2 Adolf Thiem

2.1 Biography

Adolf Thiem (Fig. 1) was born on 21 February 1836, under the full name of Friedrich Wilhelm Adolf Thiem in the town of Liegnitz (now Legnica, Poland) in the Prussian province of Silesia, where he obtained his high school diploma (Herfried Apel, personal communication, 2021; Anonymous, 1906). His family had been living in Liegnitz at least since the 18th century. His father was the eponymous Friedrich Wilhelm Adolf Thiem (born 1804), who married Johanna Natalie Julianne Thiem, née Küpper, in 1835. The family had a background of being craftsmen but were all self-employed; the father was a master plumber, the grandfather, Gottlieb Wilhelm, was a master nailsmith, and the great-great-grandfather, Johann, was a master cartwright. Adolf had a younger brother, Paul Thiem (born in 1841 in Liegnitz and died in 1883 in Munich), who also became an engineer. Adolf left his parents' house at the age of 14 for appren-

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ticeship and self-study (Vieweg, 1959). He never attended a university but became an autodidact. At the age of 25, he published his first paper in the influential *Journal für Gasbeleuchtung* (*Journal for Gas Lighting*; Thiem, 1861), where he introduces himself as an inspector at the gasworks of his hometown, Liegnitz, a job he still held at least into the following year (Thiem, 1862). In his 1864 paper in the same journal, he signs his name as the inspector of the gasworks of the much larger town of Munich (Thiem, 1864), a job he kept until 1865. The early papers already show his mathematical proficiency and his will to improve technical concepts (Thiem, 1861, 1864, 1866). Through contact with Nicolaus Schilling (1826–1894), founder of the now renamed *Journal für Gasbeleuchtung und Wasserversorgung* (*Journal for Gas Lighting and Water Supply*), based in Munich, he was recommended to Heinrich Gruner (1833–1906), a German engineer based in Basel, Switzerland, at that time. Gruner had mainly built gasworks until that point but wanted to expand into the water supply market and hired Thiem as an assistant in 1865 (Mommsen, 1962). Gruner introduced the aspiring Thiem to some fundamental French literature, including the works by Henry Darcy (1856) and Jules Dupuit (1854, 1863). His first work assignments led Thiem to the French town of Beaucourt, near Belfort, where he built spring captures and pipelines, and to Winterthur, Switzerland. After a bumpy start, Thiem proved to be an excellent technician, and in 1868, Gruner made him his partner and the head of the branch office in Dresden (Mommsen, 1962). The company was called Heinrich Gruner & Thiem, Ingen. und Unternehmer von Wasseranlagen (engineers and entrepreneurs of water schemes). Thiem was mainly tasked with obtaining a share of the quickly expanding market for water supply in Germany. Again, after a bumpy start, Thiem managed to acquire several contracts, mainly convincing his clients through his technical competence. One of the projects was for the historic mining town of Freiberg, Saxony, where he installed a dual system in 1871, consisting of a separate, spring-fed drinking water and service water network (Grahn, 1883, 1902). Gruner, however, was not equally happy, since Thiem showed much less enthusiasm for financial issues and the day-to-day supervision of the construction sites than for the technical details. Therefore, he decided to move to Dresden himself in 1873 to regain control (Mommsen, 1962). Together, they designed and built the water supply schemes for the cities of Zwickau (1875) and Regensburg (1875), both fed by springs. For the latter, they relocated their company to this town in 1874. In the newspaper announcements from this time, Thiem is mentioned as an Ingenieur von Kamburg, Sachsen-Meiningen (engineer from the city of Camburg, Duchy of Saxe-Meiningen), where he must have lived briefly. The Regensburg scheme was a technical challenge, since it involved capturing springs located in a river bed which needed to be protected from the river water itself. Additionally, the pipeline had to be laid through the bed of the Danube and Regen rivers, which they accomplished by the

Figure 1. Adolf Thiem around the year 1900 (Franke and Kleinschroth, 1991).

intensive use of divers (Thiem, 1877a; Mommsen, 1962). It was not unusual that such projects were financed by issuing stock for a designated public water supply company, in this case with a value of 1 028 400 German Marks, of which the Gruner and Thiem company assumed a substantial share of 340 000 Marks (Grahn, 1902). The project was so time-consuming that Thiem moved his family to Regensburg. He had married Luisa Thekla Groß (born in 1852 in Zöblitz and died in 1931 in Leipzig) in 1871 in Freiberg, while working there. All of his three children were born in Regensburg, i.e. Paul Adolf (1874–1907), Ernst Gerhard Günther (1875–1959), and Katharina Else (1876–?) (Mommsen, 1962; Hoffmann, 2017). Gruner and Thiem's first truly groundwater-based supply system was the one for the city of Augsburg (1873–1879). Groundwater head observations for this study were already plotted in the form of an isopotential map.

Pumping tests, using observation wells to investigate the aquifer response, were already performed by the German engineer Bernhard Salbach (1833–1894) in Halle, Germany, in 1866 (Houben, 2019). Thiem's significant improvement, first applied in Augsburg, was the comparison of the drawdown to predictions by the Dupuit–Thiem model, which he had published previously (Thiem, 1870; see below). This was probably the first pumping test subjected to a rigorous mathematical evaluation. Another pumping test in Strassburg, Alsace, received more attention since its results were published in much more detail (Thiem, 1876b). Through their work in Augsburg and Strassburg, Thiem had clearly set the standard for identifying and quantifying groundwater resources. But he also considered the basic engineering problems of water supply, e.g. the design of pipeline networks (Thiem, 1876a, 1883a, 1884a, 1885b, c, 1915).

The conflicts between Gruner and Thiem had not abated. Thiem considered himself to be the underappreciated and underpaid workhorse, and in 1876, the partnership was dissolved (Mommsen, 1962). Both, independently of each other, moved to Munich, where several concepts for a central water supply were being considered. Thiem favoured groundwater, based on an intensive investigation in the fluvial Gleisenthal aquifer and published a detailed report (Thiem, 1878). In the end, the city council selected a concept proposed by Bernhard Salbach, based on karst springs located 38 km away in the Alps, due to their high yield, pristine water quality, and the fact that the system was purely gravitational. This proved to be a wise decision, since the system is still the backbone of the city's water supply today. After the split from Gruner, Thiem successfully promoted himself by advertising the projects with Gruner as his own exploits. An irate Gruner felt obliged to publish a piece in a Munich newspaper, where he denounced Thiem as a mere assistant, whose responsibility had been to travel, acquire projects, take measurements, and prepare calculations, which then had to be submitted to Gruner (1876).

In 1886, following an invitation by the city mayor Otto Georgi, Thiem moved for the last time to Leipzig. In the first year, they lived in Kramerstraße but then moved into the newly built Haus Pommer at Hillerstraße 9 in 1887, which was to become the Thiem family residence at least until the late 1950s. His consulting company, which at the turn of the century was named A. Thiem & Söhne, Civilingenieure (A. Thiem and sons, civil engineers; Mommsen, 1962), became so successful that he had to rent a separate office in 1891, located at Thomaskirchhof 18, right in the city centre, which he later moved to Quaistraße 2 in 1902 (today Carl-Maria von Weber-Straße). The company employed up to 12 people, including his two sons. His older son, Paul Adolf, a graduated civil and mechanical engineer, died in December 1907, aged only 33, a few months before Adolf (Anonymous, 1908). Adolf Thiem was the leading planner of the groundwater supply scheme for several larger cities (Table 1), including his new hometown Leipzig, which was expanded in several stages (Thiem, 1881b, d, e, 1906, 1908).

Other cities in Germany that he was working for include – in alphabetical order – Biebrich, Blasewitz, Crimmitschau, Eilenburg, Essen, Frankenstein (Ząbkowice Śląskie, Poland), Greifswald, Harburg/Hamburg, Hirschberg (Jelenia Góra, Poland), Hohenstein, Kiel, Liegnitz (Legnica, Poland), Limbach, Magdeburg (Thiem and Fränkel, 1902; Thiem, 1904), Mansfeld, Markranstädt, Meerane, Metz, Mittweida, Oels (Oleśnica, Poland), Plauen, Posen (Poznań, Poland), Warmbrunn (Cieplice Śląskie-Zdrój, Poland), Wismar, and Zeitz (Grahn, 1902; Anonymous, 1906; Dyck, 1986). His expertise was also valued abroad (Anonymous, 1906, 1952; Dyck, 1986) and, in addition to the entries in Table 1, led him to work in Romania (Bucharest, Czernowitz, Klausenburg/Cluj-Napoca), Scandinavia (Åbo/Turku, Finland; Malmö, Sweden), and Brazil (Porto Alegre). His work was not restricted to studies of aquifers and wells but also encompassed the hydraulics of pipeline networks, the improvement of pumps, the development of water treatment techniques (especially iron removal), and even the construction of water towers, e.g. the still-existing tower in Strasbourg from 1878, which is the first with a semi-spherical wrought iron tank (Thiem, 1876b, 1877a, 1878, 1880c, 1883a, 1884a, 1885b, 1896, 1897a, 1894b, 1898b, 1915, 1929q; Grahn and Thiem, 1885). He briefly worked on inland navigation, in particular on the hauling of cargo vessels on the Hohensaaten–Spandau canal near Berlin, and he presented the work he did there at a conference in Paris in 1892 (Thiem, 1892c). Curiously, his home base is given as Eberswalde. He offered his clients the full package, ranging from groundwater exploration to the planning and construction of wells and pipeline networks, water treatment plants, and storage tanks, including economic considerations (Thiem, 1884b). He was probably one of the first to use the term "sustainability" (Nachhaltigkeit) in the context of groundwater (Thiem, 1881a). He had observed the groundwater levels in observation wells located along the Leipzig–Grimma train track over the course of 15 years. The relatively stable drawdowns led him to the conclusion that the drawdown caused by the extraction for the Leipzig water supply had become stable and extraction was thus sustainable (Thiem, 1881a).

In 1892, Thiem received the honorary title of Königlich Sächsischer Baurat (Royal Saxon building officer). Probably in 1899, he received the Königlich Sächsischer Verdienst-Orden (Royal Saxon Order of Merit) and, as of 1900, he proudly added the title Ritter 2c (knight, second class) to his entry in the Leipzig address book. A striking feature of his work ethic was that he never took out any patents in order to foster the advancement of science (Anonymous, 1906, 1952). When asked about it by his pupils, he would smile and answer the following:

> Dies ist für die Allgemeinheit und nicht für mich alleine da (this is for the public and not for me alone). (Anonymous, 1952)

However, this claim is not entirely true, since he registered at least one patent on a water valve that would automatically close after a sudden pressure loss, e.g. caused by a pipeline rupture (Thiem, 1894a). On his 70th birthday, he was honoured by a page-long biographical sketch in the *Journal für Gasbeleuchtung und Wasserversorgung*, which states his role as founding father of hydro(geo)logy (Anonymous, 1906). Adolf Thiem died after a short but severe illness at the age of 72 in Leipzig on 2 May 1908 (Anonymous, 1908). He was buried there in the Südfriedhof (cemetery) in an honorary grave that still exists (Fig. 2). It is only a few metres away from the still active Probstheida waterworks and its impressive water tower, which Thiem designed shortly be-

Table 1. Main water supplies planned and built by Adolf Thiem (English names in parentheses).

Name of city	Name of city today	Comment	References
Freiberg		1871, with Gruner	Grahn (1883, 1902)
Zwickau		With Gruner	Grahn (1902), Mommsen (1962)
Regensburg		With Gruner	Thiem (1877a)
Augsburg		With Gruner	Gruner and Thiem (1874), Mommsen (1962)
Strassburg	Strasbourg, France	Then Germany	Thiem (1876)
München (Munich)		Not built	Thiem (1877b, 1880d, 1914)
Nürnberg (Nuremberg), also Fürth			Thiem (1879a, 1881a)
Riga		Then Russia, today Latvia	Salm (1893), Thiem (1883b, 1888e)
Leipzig			Thiem (1881b, e, 1883c, 1885a, 1889, 1890a, b, 1891, 1892a, 1892b, 1906, 1908, 1911)
Gera			Thiem (1884c), Grahn (1902)
Stralsund		Not built	Thiem (1888d)
Malmö, Sweden		1890, with Johan Gustaf Richert	Svensson (2013)
Potsdam			Thiem (1892d)
Charlottenburg		Now part of Berlin	Thiem (1897a, 1913a)
Mainz		Including Laubenheim	Thiem (1897b, c), Grahn (1902)
Dessau		1897	Grahn (1902), Pfeffer (1906)
Breslau	Wrocław, Poland	Then Germany	Anonymous (1902)
Prag (Prague)	Praha, Czech Republic	Then Austria–Hungary	Anonymous (1903)
Braunschweig (Brunswik)			Grahn (1902), von Feilitzsch (1904)
Waldenburg	Wałbrzych, Poland	Then Germany	Lummert (1905)
Landeshut	Kamienna Góra, Poland	Then Germany	Thiem (1909)

fore his death. In 1912, the city of Leipzig named a street after him (Thiemstraße), which still bears this name today and leads to the Probstheida waterworks (Fig. 2). Several important German hydrologists, such as Emil Prinz, Max Rother and his son, Günther Thiem, were his pupils. In Germany, his legacy was recognized and kept alive, as evidenced by several commemorative articles (Thiem, 1929q; Prinz, 1936; Anonymous, 1949, 1952, 1958; Vieweg, 1958a, b, 1959; Dyck, 1986; Engemann, 1989). As late as 1956, his seminal 1870 publication was reprinted (Thiem, 1956).

Thiem's contributions to the growing field of hydrogeology were also noted outside Germany, already during his life-

Figure 2. The left panel shows the grave of honour of the Thiem family at the Südfriedhof in Leipzig. The gravestone is an erratic block found during the construction of the neighbouring monument (Völkerschlachtdenkmal) commemorating the decisive Battle of Leipzig against Napoleon in 1813. The right panel is a road sign of Thiemstraße (Straße means street) in Leipzig (photos: Georg Houben).

time. His work for the water supply of Leipzig was considered important enough to be presented at the world exhibition in Chicago in 1893 (Hillger, 1893). In their 1899 book on groundwater flow, Franklin Hiram King and Charles Sumner Slichter cite seven of Adolf Thiem's papers, including those on tracer tests and other German papers by Lueger and Hagen (King and Slichter, 1899).

2.2 Contributions to pumping tests

The analytical model describing the radial flow of groundwater to a well embedded in a horizontal circular island aquifer is sometimes called the Dupuit model, after Jules Dupuit (1863), sometimes the Thiem model, after Adolf Thiem (1870) or Günther Thiem (1906), and sometimes the Dupuit–Thiem model. It is therefore important to compare the seminal contributions. After an analysis of open-channel flow, in chapter VIII of his 1863 publication, Dupuit turned his attention to flow in permeable soil (*Du mouvement de l'eau travers les terrains perméables*). Based on his work on open-channel flow, Dupuit stated that the slope of a groundwater table should follow a parabolic equation of the type of Eq. (1):

$$i = \alpha \cdot Q + \beta \cdot Q^2, \quad (1)$$

where i is the slope, Q is the flow rate, and α and β are coefficients. This is basically identical to the later Forchheimer equation (Forchheimer, 1901). However, Dupuit realized that the velocity term $\beta \cdot Q^2$ could be ignored due to the commonly very low flow velocities of groundwater. Assuming a radial symmetry and a horizontal aquifer, he then derived the fundamental equations describing groundwater flow to a well at steady state, for both the water table and artesian aquifers. Thiem (1870) had clearly read Dupuit's paper, as he duly cites it and ends his paper with a literal quote in French from Dupuit. Günther Thiem claimed that his father had actually been a friend of Dupuit, which is technically possible since Dupuit died in 1876, well after the 1870 publication by Adolf (Thiem, 1951a). There is, however, no other evidence that both knew each other, apart from Günther's claim. Thiem's paper follows parts of the outline of Dupuit's chapter VIII closely. So, was Thiem just a copycat? Not quite! In his equations, Dupuit used two heights of the water table above the impermeable aquitard, namely (1) h_0 in the well itself at the well radius r_0 (la hauteur de l'eau dans le puit) and (2) H at the outer radius of the cone of influence (la hauteur de l'eau extérieure) at a radius R (le rayon du massif filtrant). While the choice of these two points was sufficient for the mathematical derivation, they were both a rather poor choice from a practical point of view. The water levels in the well were often affected by additional, non-laminar head losses caused by the well tubing itself, something which Dupuit was aware of (see below) but chose to ignore. He also gave no practical hints on how to obtain the outer limit. He only realized that the value for the outer radius is of limited influence as it appears in a logarithmic term ($\log(R/r_0)$). As such, the equations were of limited practical use and were not taken up by practitioners.

It was Adolf Thiem's merit to have grounded the Dupuit equation in the real world. He used two observation wells located within the cone of depression at different radii, r_1 and r_2, thus avoiding the problems of turbulent losses in the well and of finding the radius of influence. While Dupuit (1863) takes precedence for the mathematical derivation (Ritzi and Bobeck, 2008), Thiem (1870) and his later papers (e.g. Thiem, 1876b) converted the method into a practical tool and popularized it. It is thus justified to call the method the Dupuit–Thiem model. Remarkably, his first-ever paper on groundwater became a classic. For the confined case, it takes the form of Eq. (2):

$$h_2 - h_1 = \frac{Q}{2 \cdot \pi \cdot K_{\mathrm{aq}} \cdot B} \cdot \ln\left(\frac{r_2}{r_1}\right), \quad (2)$$

with h_1, h_2 being the head at radial distance r_1, r_2 (L), Q being the pumping rate ($\mathrm{L^3\,T^{-1}}$), K_{aq} being the hydraulic conductivity ($\mathrm{L\,T^{-1}}$), B being the constant thickness of confined aquifer (L), and r_1, r_2 being the radius from the well axis, with $r_1 < r_2$ (L).

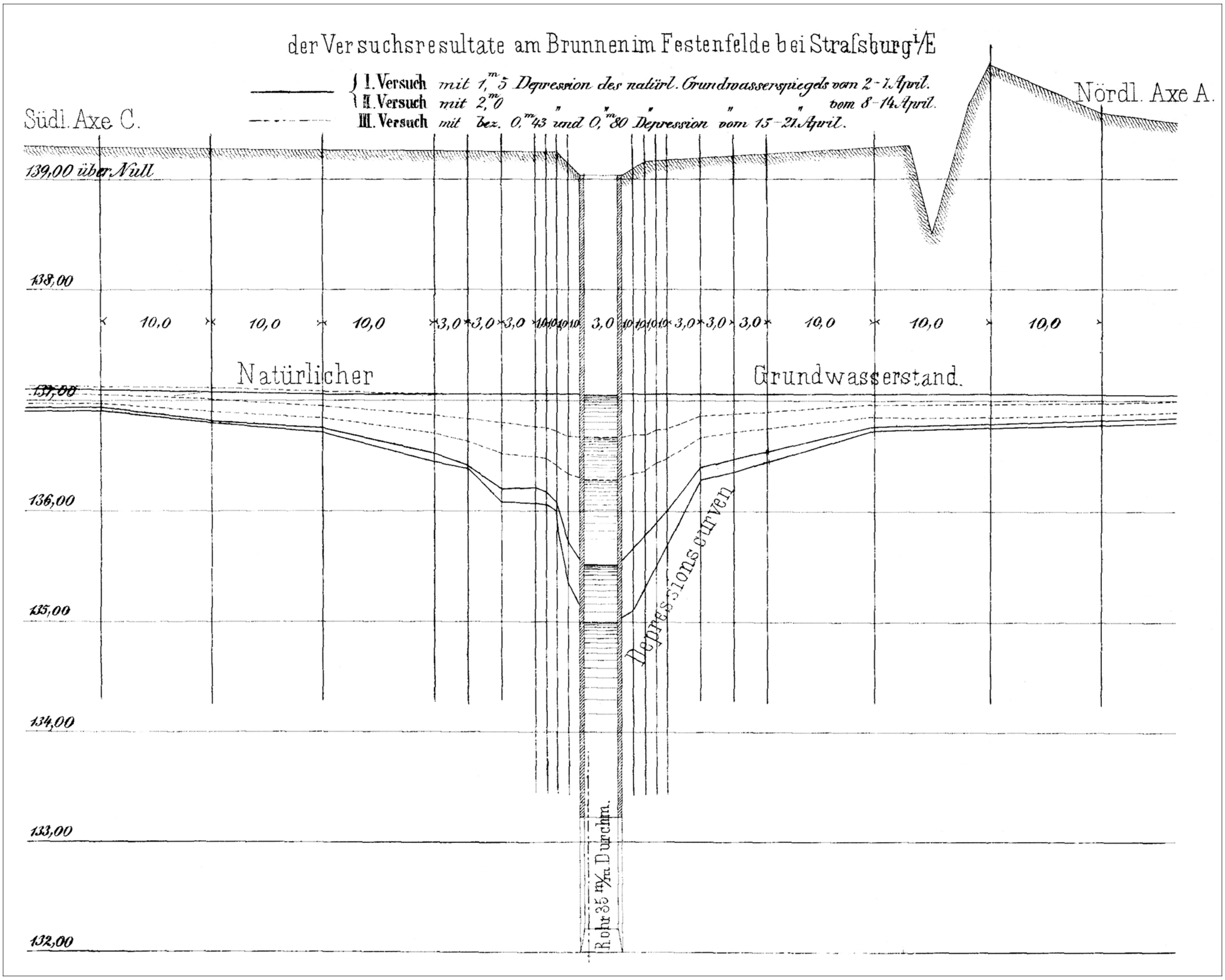


Figure 3. Sketch of the cones of depression for different flow rates obtained during pumping tests in Festenfeld near Strassburg, Alsace. The vertical black lines are the logarithmically (10, 3, and 1 m spacing) arranged observation wells (Thiem, 1876b). Note: Natürlicher Grundwasserstand is the natural groundwater level; Rohr is the well diameter of 35 mm; Depressionskurven is the pumping level curves; Versuch is the test; Versuchsresultate is the test results; über Null stands for above (French) sea level; Südl./Nördl. Axe is the southern/northern axes.

Although the first well-documented pumping test in Germany was performed in 1866 in Beesen near Halle (Saale) by Bernhard Salbach (Houben, 2019), Adolf Thiem's work defined some of the standard procedures. Already for his first pumping tests in Augsburg, Strassburg, Alsace, und Munich, he developed several approaches that are still in use today (Thiem, 1876b, 1879a, 1880a). To delineate the geometry of the cone of depression and the radius of influence, he installed several observation wells, both perpendicular and parallel to the estimated flow direction of groundwater (Fig. 3). For this purpose, he mostly used Abyssinian wells (Norton tubes), sturdy prefabricated well tubes, usually of 50 mm inner diameter, which could be rammed into the ground and recovered – if necessary – afterwards. They were spaced more closely to the well and further apart from it (Fig. 3). He also insisted on installing observation wells outside of the radius of influence to study the influence of natural variations in the groundwater levels, e.g. the ones caused by varying river water levels. By default, not only the drawdown phases for different pumping rates (Fig. 3) but also the recovery phase was observed (Thiem, 1876b). Another regular procedure was measuring the groundwater temperature during the test and taking water samples for later analysis. Already in Strassburg 1874/1875, he used a Locomobile mit Centrifugalpumpe, a submerged centrifugal pump driven by an external steam engine (Thiem, 1876b). The drive shaft of the pump was probably connected to the engine via a belt, like a primitive drive shaft pump.

Adolf Thiem used one procedure, which is not common anymore – he increased the depth of the pumping well during the test to find productive zones (Thiem, 1876b), as he had realized early on that thin layers of high conductivity provide a disproportional yield of water (van Lopik et al., 2020). He was also probably the first to notice – and quantify – the difference between horizontal and vertical hydraulic conductivity. From the results of his pumping test in Strassburg, he determined a value of eight for the ratio of horizontal to vertical conductivity (Thiem, 1876b). This is remarkably similar to the default value of 10 recommended in most textbooks today. During his exploration of the hydrogeology around Leipzig, Thiem realized the concept of multi-aquifer systems, i.e. the presence of several aquifers stacked on top of each other and separated by aquitards (Thiem, 1881a). He referred to these individual aquifers as Grundwasseretagen (groundwater floors/levels).

Dupuit (1863) had realized that flow in pipes connected to the well, e.g. a riser pipe, can cause additional head losses. To address this, he brought back a velocity term from his studies on pipe flow and added it as a second term, very similar to the one shown in Eq. (3). Again, Thiem (1870) follows him in this, adding a velocity term in the slightly different form of the well-known Darcy–Weisbach equation (Eq. 3). Interestingly, Dupuit (1863) references his previous work as the source for the velocity term, and Thiem (1870) calls it a "well-known equation" without citing any reference. Both thus ignore the contribution by Julius Weisbach (1845).

$$h_2 - h_1 = \frac{Q}{2 \cdot \pi \cdot K_{\mathrm{aq}} \cdot B} \cdot \ln\left(\frac{r_2}{r_1}\right) + f_{\mathrm{D}} \cdot \frac{L_{\mathrm{B}}}{4 \cdot r_{\mathrm{b}}^5 \cdot \pi^2 \cdot g} \cdot Q^2, \quad (3)$$

with f_{D} being the Darcy friction coefficient, L_{B} being the length of borehole (L), r_{b} being the radius of casing/screen (L), and g being the acceleration of gravity ($\mathrm{L\,T^{-2}}$).

Dupuit (1863) realized that he could use the velocity term to investigate the relative influence of pipe flow on well hydraulics. He retroactively studied two wells in Grenelle and Passy, both near Paris. Again, Thiem (1870, 1879b) converted Dupuit's theoretical approach into a practical tool, the step-discharge test, which is still being used today. Therefore, he simplified Eq. (3) to the following:

$$H - h = A \cdot Q + B \cdot Q^2, \quad (4)$$

with H being the head in well at zero flow (L), h being the head in well while pumping (steady state) (L), Q being the pumping rate ($\mathrm{L^3\,T^{-1}}$), A being the aquifer loss coefficient ($\mathrm{T\,L^{-2}}$), and B being the well loss coefficient ($\mathrm{T^2\,L^{-5}}$).

This equation is still the main model to interpret step-discharge tests today. In his pump tests, Thiem plotted the drawdown s as a function of different pumping rates Q and could identify the presence and quantify the contribution of the velocity term or, in other words, the non-linear laminar and turbulent losses of the well itself (Houben, 2015a, b). If the $s - Q$ pairs plotted on a straight line, then the flow was laminar and the velocity term negligible. Any deviations from a straight line could then be attributed to additional well losses and quantified. Therefore, Thiem usually employed several pumping rates during his tests, plotted the resulting drawdown curves, and evaluated the contribution of non-laminar flow (e.g. Thiem, 1876a, b, 1879b, 1880a).

Adolf Thiem realized that removing fines from the aquifer at high pumping rates can improve its hydraulic conductivity and thereby discovered the principle of well development (Thiem, 1876). In some cases, he took this to the limit and beyond. In the course of a pumping test in Strassburg, Alsace, the highest pumping rate of $136\,\mathrm{L\,s^{-1}}$ ($490\,\mathrm{m^3\,h^{-1}}$) induced such a high degree of suffusion that the ground around the well subsided, and the well tubing was deformed (Thiem, 1876).

The method for a pumping test evaluation after Adolf Thiem (1870) remained one of the most important hydrogeological tools for several decades. It was intensively discussed and applied in the USA (Wenzel, 1932, 1933, 1936; Wenzel and Fishel, 1942; Meinzer, 1934), which can be traced back to the good contacts of Günther Thiem to the leading United States Geological Survey (USGS) hydrogeologist of its times, Oscar Edward Meinzer (see Sect. 4). The Dupuit–Thiem method was not without flaws: as a steady state method, it commonly required long times until the drawdown had become stable and needed two observation wells. The transient method by Theis (1935), which does not require steady drawdown and can do with one observation well, was the first serious challenger but remained problematic due to the use of type curves, which was both tedious and a bit subjective. Only its later simplification by Cooper and Jacob (1946) relegated the Dupuit–Thiem method to the second place.

Nevertheless, the Dupuit–Thiem equation can still be found in many textbooks (e.g. Batu, 1998; Kruseman and de Ridder, 2000; Bear, 2007; Kresic, 1997; Kasenow, 2010). Due to its geometrical set-up and simple mathematics, it is often used to teach students how to derive analytical models for groundwater flow (e.g. Hendriks, 2010). It is still helpful for the design of water wells and the planning of construction dewatering (Houben, 2015a, b). For pumping tests, it has become a niche method when steady-state pumping test data are available (Misstear, 2017). The Dupuit–Thiem equation forms the basis for several later analytical models, including the old but still commonly used Forchheimer (1901) model, which describes the contribution of non-linear flow processes in the flow towards wells (Houben, 2015a, b). The Forchheimer equation consists of two terms; the first is the Dupuit–Thiem equation, which describes the linear laminar losses. The second term describes the non-linear laminar losses. Until today, the Dupuit–Thiem equation is used as a base case for validation or as quality control for more advanced analytical models (see Tügel et al., 2016, for examples). Despite its simplicity and high age of 150 years, to this day, the Dupuit–

Thiem equation is still an important method for groundwater professionals worldwide.

Prior to the full development of vertical wells, many hydrologists used backfilled drainage trenches instead, which could be of substantial length and depth (Houben, 2019). While working for the water supply of Winterthur, Switzerland, with Heinrich Gruner, Adolf Thiem considered such an option (Thiem, 1870). Therefore, he adapted his equation for well flow to a linear sink. Despite its simplicity, it only considered the height of the water table from the constant head boundary to the drain in a 2D projection (Thiem, 1870). This was probably the first model for horizontal wells.

2.3 Contributions to well design

The first pumping wells Thiem had used were shaft wells of large diameter, e.g. in Strassburg. They were difficult and expensive to build and often displayed poor performance. He realized that he could overcome these problems by developing the concept of the Norton wells (Abyssinian wells) further, which he had used as observation wells during his pump tests. In 1881–1883, for the waterworks of Naunhof (Leipzig), he increased their diameter to 150 mm, which still allowed them to be rammed into the subsurface. At first, he tried to emulate the shaft wells by installing so-called Ringbrunnen (ring wells), a central collector shaft surrounded by up to 20 individual rammed vertical wells, aligned on a circle with a radius of 10 m from the shaft (Engemann, 1989). The vertical wells were drilled first and then partially excavated down to the depth of the pipeline towards the central collector (Fig. 4). The latter still proved to be a difficult and expensive construction, and the many wells tended to interfere with each other. The Ringbrunnen were operational until 1926 (Engemann, 1989).

Later, he installed vertical well galleries connected to a central siphon pipeline. This concept proved to be much more useful and cost-effective and became the standard. However, the vertical wells caused a lot of trouble due to corrosion, sand intake, and incrustations, which often led to their complete failure to deliver water after only a few years. Thiem even equipped his wells with a noose, attached to the bottom, which could be used to pull out the whole well (Fig. 5). Later, a detachable screen was tried (Thiem, 1925a). Thiem introduced cast iron as a material for the screen and casing, which was more corrosion resistant than the forged iron used before. Since the slots in the cast or forged iron screens were – due to technical reasons – quite wide (often up to 1 cm), sand control was a critical problem. Many wells filled with sand eroded from the aquifer quite quickly. The solution used by Thiem was to wrap fine metal meshes around the screens, which, however, were prone to blockage by the very sand they were supposed to retain and by corrosion and incrustations. Due to their small diameter and the described clogging processes, the yield of the early Thiem wells was quite small, often in the range of a few cubic metres per hour. Therefore, Thiem had to install 225 of them for the first well field of Leipzig in 1883 and 300 for a later one (1907) in the same town (Thiem, 1925a). Thiem kept tinkering with the well design, e.g. by simplifying the design (Fig. 5), increasing the diameter to 150 mm (1907 in Leipzig), installing rubber seals, and introducing copper pipes, which were lighter, easier to manufacture and much more corrosion-resistant, although more expensive. For the Nuremberg waterworks, the tedious and problematic metal meshes were replaced by an artificial gravel pack, a technique that had already been used for horizontal drains (Thiem, 1879; Houben, 2019). In Nuremberg, Thiem (1879a) proposed a gravel pack of four layers with gradually increasing grain size towards the well (2, 4, 8, and 15 mm). The well itself was made from perforated brickwork.

Thiem also found time to study the flow of groundwater towards wells under laboratory conditions. In 1879 and 1882, Gustav Oesten had presented sand tank experiments on the groundwater flow to vertical, partially penetrating, wells installed at two different depths in a square box (Oesten, 1879a, 1882a, b, c). Using colour tracers, he correctly observed that the highest flow velocities occurred around the screen. For a short screen installed at a shallow depth, he found that coloured water from the bottom of the aquifer did not flow to the well (Oesten, 1882a). He thus postulated an interface separating a pumping affected from a not affected area. Only a deeper placement of the screen induced flow from below. Adolf Thiem was very unhappy with this and stated in his rebuttal that his previous theoretical work had already clarified how water should flow around a well (Thiem, 1879d, 1882). However, he still felt obliged to perform his own sand tank experiments, which he called "demonstratio ad oculos" (Latin for "demonstration to the eyes"). At first, he used a square box but later a wedge-shaped sand body to simulate the convergent flow towards the well. The main objection of Thiem to the experiment of Oesten (1882a) was that Oesten infiltrated water through a small trench at the surface of the box. As this did not represent the reality of flow to wells, Thiem allowed water to be infiltrated from one side over the entire thickness of the sand and the water level in this reservoir was kept constant by an overflow (basically a constant head boundary). The well was simulated by a little sieve body from which water was extracted. The images indicate that the bottom of the well was probably not closed. The well screen only covered the uppermost third of the saturated aquifer thickness. The flow paths were visualized by injecting small volumes of coloured water at different depths at the inflow side. This conclusively showed that water from below the screened interval also entered the well, inducing a vertical flow component close to the well and elevated inflow rates at both the top and the bottom of the screen. Thus, Thiem had conclusively demonstrated the flow field around a partially penetrating well. Oesten responded to the rebuttal (Oesten, 1882b), claiming rather unconvincingly that Thiem

Figure 4. Construction of a Ringbrunnen at Leipzig–Naunhof, around 1887. The upper left panel shows the drilling of vertical wells. The upper right panel provides a view of the radial pipelines connecting the vertical wells (visible at the end) to the central collector shaft. In the lower left panel, Adolf Thiem is visiting the construction site (third from left, lower row). Also present is Hermann Credner, head of the Saxon Geological Survey, and Max Rother (left panel), one of Thiem's pupils (photos: Stadtarchiv Leipzig).

had not sufficiently considered the influence of capillarity, but the case was settled.

Unbeknown to many well designers, Adolf Thiem defined one of the most critical and most criticized values, i.e. the maximum permissible entrance velocity. Many textbooks and international standards on well design cite a value of $0.03\,\mathrm{m\,s^{-1}}$ ($0.1\,\mathrm{ft\,s^{-1}}$; e.g. Campbell and Lehr, 1973, Driscoll, 1986, and Sterrett, 2007). Keeping the entrance velocity below this value is said to curb head losses, maintain fully laminar flow conditions, prevent suffusion of sand particles, minimize incrustation build-up, and even control corrosion. The value is sometimes attributed to Bennison (1947), who, however, presented neither theoretical concepts nor experimental or field data to back up his claim. It is very likely that this value goes back to experiments executed by Adolf Thiem, while he was designing wells and their gravel packs for the Nuremberg waterworks (Thiem, 1879a). Thiem understood that the flow velocity of groundwater is the critical parameter that controls particle mobilization and thus sand intake. Therefore, he investigated the minimum vertical flow velocity required to keep grains of different diameters in suspension. At velocities below, the grains would not be transported. For sand grains up to a grain diameter of 0.25 mm, he obtained maximum flow velocities of $0.028\,\mathrm{m\,s^{-1}}$, under which no transport would take place, which is basically the recommended value above. The value found its way into the influential German textbooks by Smreker (1914b) and Thiem's pupil Emil Prinz (1919) and the monograph by Günther Thiem (1928a). It is quite probable that USA hydrologists became aware of this value from the

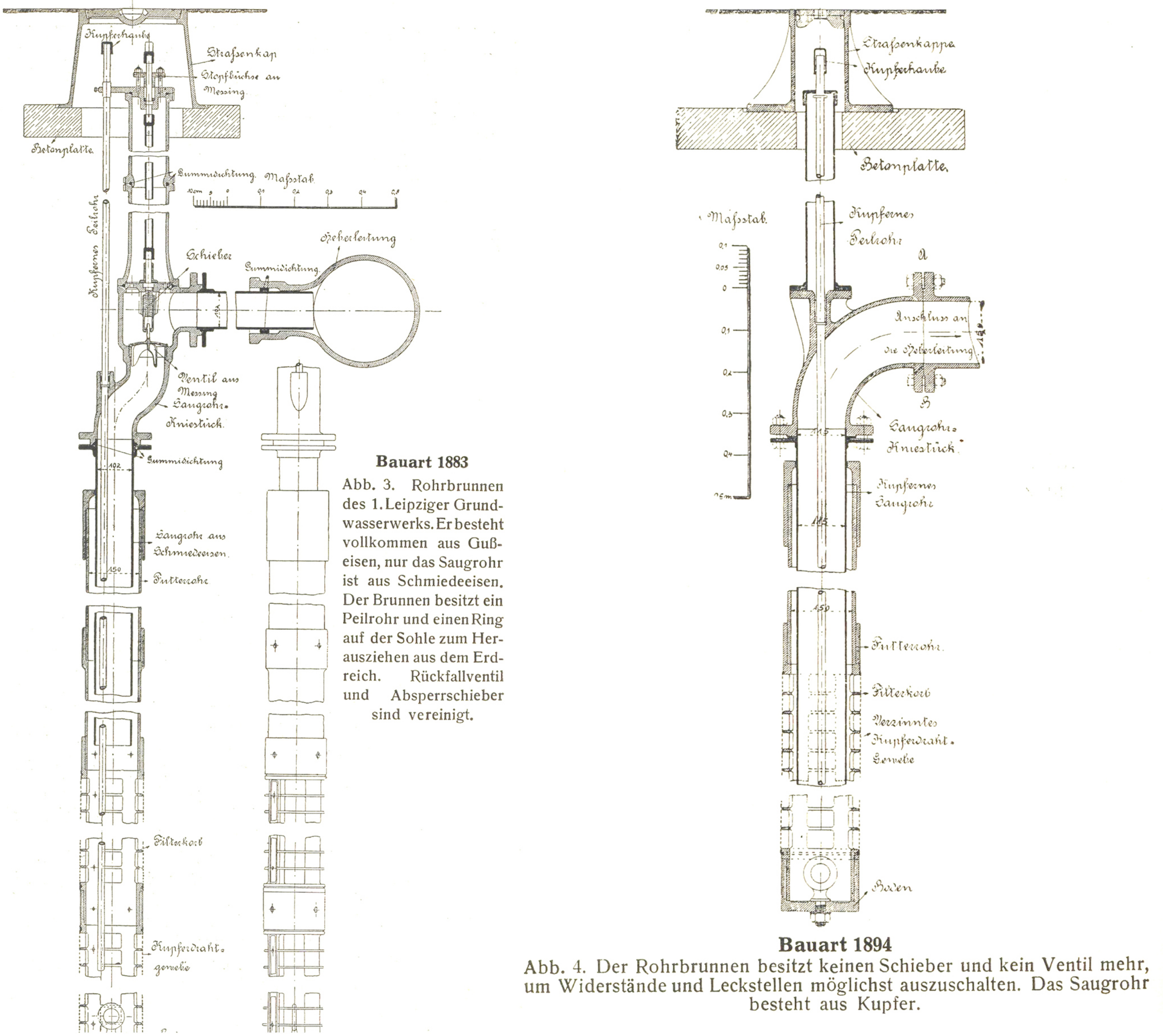


Figure 5. Well designs by Adolf Thiem used in Leipzig. On the left-hand side is the first design from 1883, including a cast iron screen and a riser pipe from wrought iron. On the right-hand side is a simplified design from 1894, with the backflow valve omitted and the suction pipe now made of copper (Thiem, 1925a).

German literature and through personal exchanges between Oscar Edward Meinzer of the USGS and Günther Thiem (see below) and adopted it without further questioning.

For the water supply of the town of Greifswald, located at the German Baltic coast, Adolf Thiem built a rather unusual construction in 1890 to extract groundwater. He had found an artesian aquifer of 6 m thickness under a confining layer of 5 m of glacial till (Houben, 2019). Instead of wells, he had a trench of 9 m depth and 450 m length constructed, equipped with two strings of perforated stoneware tubes of 500 mm diameter each, installed at different depths and then backfilled. He also had an impervious underground cutoff wall installed to impound the groundwater, allowing it to flow towards the town by gravity alone. Unfortunately, this most likely very expensive construction never lived up to the expectations. The yield was very low, at 10.8 $m^3\,h^{-1}$, and soon had to be augmented by additional vertical wells.

2.4 Development of tracer test methods

Although reports on – sometimes involuntary – tracer experiments in karst aquifers predate the 19th century, Adolf Thiem played a crucial role in developing tracer experiments into a scientific instrument, especially for porous aquifers (Thiem, 1887a, 1888a). His first field tests were done in 1886 in the towns of Greifswald and Stralsund, located at the Baltic coast of Germany. He dissolved 75 to 100 kg of table salt (NaCl) in water and measured the breakthrough curves in several observation wells (Thiem, 1888a). Therefore, the chloride concentrations were determined via titration with silver nitrate, using potassium chromate as an indicator. During a tracer test in Plauen (Saxony), he observed five to six tracer peaks, which he attributed to the heterogeneity of the aquifer. To understand the fundamental processes of tracer migration, Thiem (1888a) performed laboratory experiments using a sand column of 4 m length. Based on his experiences, Thiem (1888a) was the first to postulate the following fundamental requirements for tracer chemicals: (1) non-reactive, (2) non-toxic, (3) cheap, and (4) easy and quantitative analysis.

2.5 Equipotential and hydrogeological maps

During his work in Augsburg with Gruner, Adolf Thiem made extensive use of Norton (or Abyssinian) wells, which are small but thick-walled pipe screens that could be rammed into the ground, to measure groundwater levels. Since they also determined the ground elevation of the observation wells, they were able to construct one of the world's earliest isopotential maps in 1873 (Mommsen, 1962; Dassargues et al., 2021). Strangely enough, Thiem considered the map produced for a later project in Strassburg, Alsace (now Strasbourg, France), as his first isopotential map, probably because he published a detailed account of this study in the *Journal für Gasbeleuchtung und Wasserversorgung* (Thiem, 1876b), which was widely received and acclaimed. Figure 6 shows a typical example of Thiem's clear graphical style, showing equipotentials based on observation wells, time series of groundwater levels, and cross sections showing aquifer thickness and water table.

Thiem immediately realized the influence of the water level of the neighbouring river Rhine on groundwater levels and thus constructed two equipotential maps, i.e. one for high and one for low river stages (Thiem, 1878). Due to its importance, the original drawing of the equipotential map was donated to the German Museum (Deutsches Museum) in Munich (Thiem, 1929q, 1941a), the most important technical collection of Germany. Unfortunately, it seems to have been lost during the war, as a request for it from the museum's archive department in 2020 by the authors led to no results. However, a copy is reproduced in some publications of Günther Thiem (1929q, 1931f, 1941a).

Mainly due to the increasing demand for mineral resources, geological mapping became an important task in Germany during the second half of the 19th century. The role of unconsolidated rocks as aquifers, however, was not overlooked. Adolf Thiem contributed a chapter "On the hydrology of the old river bed of the River Mulde near Naunhof" to the *Annotations on the Geological Map of the Kingdom of Saxony, section Naunhof*, Sheet 27 (near Leipzig), which is one of the first hydrogeological contributions to a geological map (Thiem, 1881c; Sauer, 1881; Sauer et al., 1906). The cooperation with geologists was thus no anathema to Thiem. It had been the geologist Hermann Credner (Fig. 4), head of the Saxon Geological Survey, who pointed Thiem towards Naunhof, where the second waterworks for Leipzig was installed in 1887, the largest and most modern groundwater works in Europe at the time (Credner, 1883; Thiem, 1892a, b; Heinker, 2005). Credner later supported Günther Thiem when he wanted to become a member of the German Geological Society in 1911.

2.6 Artificial groundwater recharge

Thiem quickly realized that not all aquifers were productive enough to satisfy the demand and that an augmentation via surface water might be useful (Thiem, 1898a). Early on, he studied bank filtration, e.g. in Fürth in 1880 and for the town of Essen, and recommended using temperature as a tracer to distinguish ground and surface water (Thiem, 1898a). He was also aware of the danger of colmation of the riverbed (Thiem, 1929q). For the water supply of Stralsund, Thiem had unsuccessfully proposed artificial groundwater recharge via drainage trenches (Thiem, 1888b), a concept already applied in Chemnitz in 1875, using trenches with an artificial sand bed (see the discussion in Thiem, 1898a; Houben, 2019). However, Thiem's Swedish pupil Johann Gustaf Richert (1857–1934) perfected the concept (Svensson, 2013). It was implemented for the first time in Göteborg (Gothenburg) in 1898. Richert published his experiences in a book in German (Richert, 1911), and the concept became quite popular in Germany after the turn of the century, especially in the Ruhr valley.

2.7 Construction dewatering

The construction of deep basements often requires working in the saturated zone and thus the control of groundwater. In the 19th century, this problem was – if not avoided altogether – tackled by encapsulating the construction site and sealing it off from the surrounding groundwater, e.g. by ramming sheet piles, injecting cement or freezing parts of the aquifer. These procedures were technically demanding, costly, and not always successful. Adolf Thiem realized that dewatering by verticals wells was a viable alternative since the well type he had developed could be installed cheaply and quickly, and his equations allowed him to dimension the dewatering scheme. In 1886, Thiem applied this concept, using a shaft well, for the first time, in the construction of the Leipzig water supply in Naunhof (Prinz, 1907; Thiem, 1929q, 1931f). Therefore, Thiem can be considered one of the founding fathers of construction dewatering.

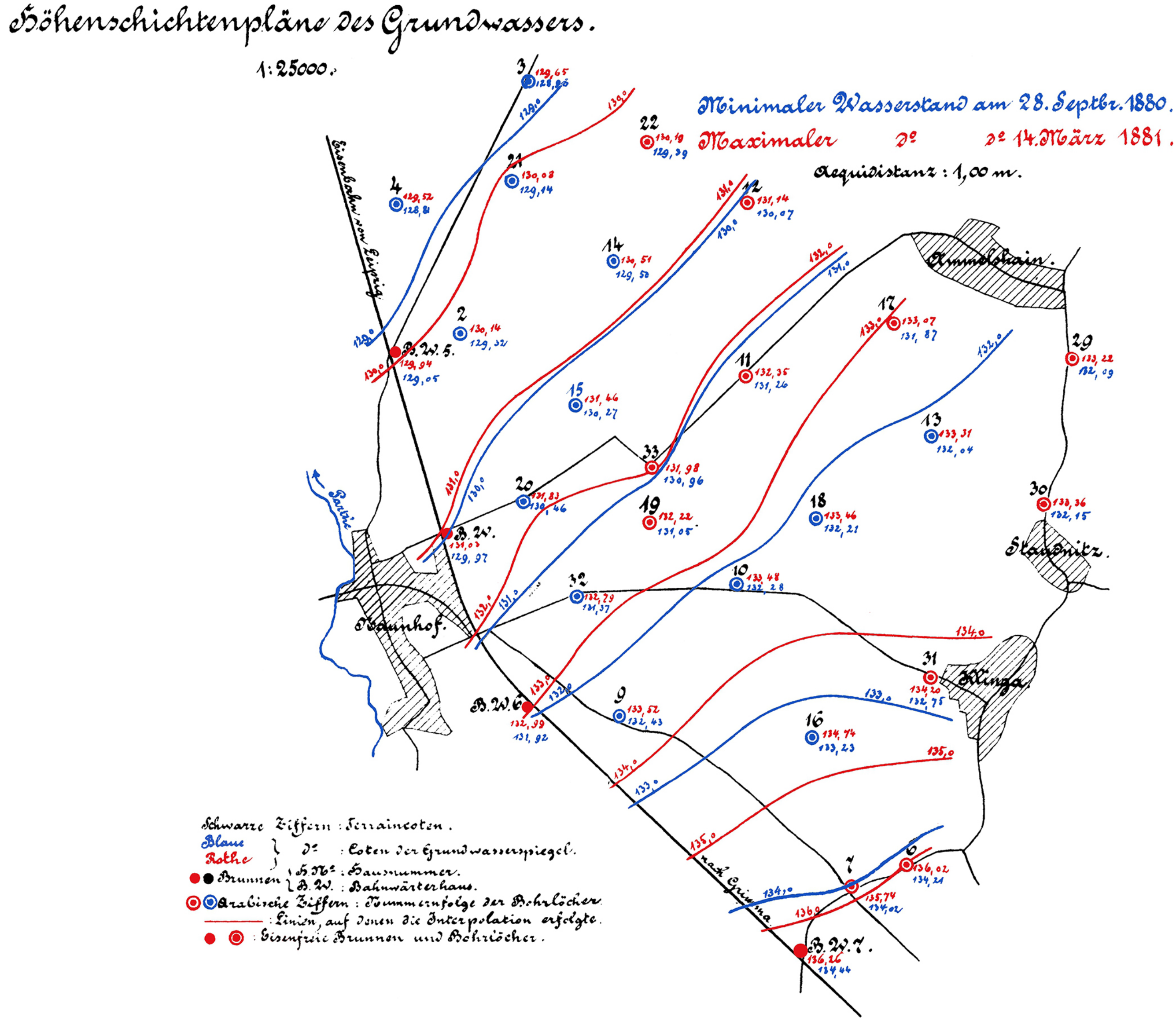


Figure 6. Isopotential map from the Leipzig–Naunhof study (Thiem, 1881e). The blue isopotentials are from 1880, and the red ones are for 1881. Black dots and numbers show the observations wells. The straight black line to the west is a train track, and the shaded areas are villages.

2.8 Scientific feuds

Thiem regularly attended conferences, e.g. those of the German Association of Water Professionals (DVGW), and was an avid contributor to the discussions (e.g. Thiem, 1880b, c, d, 1885c, 1888b, c). He did not shy away from voicing controversial opinions, which led to some prolonged scientific feuds.

The main opponent of Adolf Thiem was Oskar Smreker, who was born in 1854 in Castle Görzhof/Cilli, Austria–Hungary (now Celje, Slovenia), and who died in Paris in 1935. He was a graduate of the Swiss Technical University (ETH) in Zurich (1870–1874), where he, much later, in 1914, at the age of 60, received his doctorate on a groundwater-related study (Smreker, 1914a). In 1876, he was hired by Heinrich Gruner in Regensburg as a replacement for Adolf Thiem, after Gruner and Thiem had parted ways, but he was sacked in 1877 (Mommsen, 1962). After several years as an engineer in Germany and Italy, Smreker founded a successful company in Mannheim, Germany, in 1882 that designed and built many groundwater supply systems in Germany and abroad. Smreker published several papers (Smreker, 1878, 1879, 1881, 1883, 1907) criticizing both the work of Darcy (1856) and Thiem (1870, 1876b). He doubted the validity of the Darcy law – and the Dupuit–Thiem equation deduced from it – due to the supposed ignorance of the increase in velocity around a well. He even formulated his own non-linear law of groundwater movement and dared to use the results of Thiem's pumping tests from Strassburg to test it (Smreker, 1878). Adolf Thiem responded by citing ample literature based on both field and experimental data, which showed the validity of Darcy's law for practically all applications (Thiem, 1880c).

Even after Thiem had died in 1908, Smreker would not relent. In his 1914 doctoral thesis, several papers, and his textbook, Smreker still attacks the validity of Darcy's law and upholds his alternative law (Smreker, 1914a, b, 1915a, b, c, d, e). He argued that

> The Darcy law … fails completely when applied to the principle of groundwater abstraction, because the differences in velocities at the varying distances from the well are large. (Smreker, 1914b)

Several prominent authors, including Max Rother (1855–1928), Adolf Thiem's last collaborator, felt obliged to publish a defence of the Darcy law. In the middle of the First World War (WWI) and shortly afterwards, a war of papers ensued across several journals and countries and arguments flew back (Brix, 1915; Rother, 1915, 1916, 1919, 1920; Lummert, 1916a, b, 1917a, b; Hocheder, 1919) and forth (Smreker, 1915a, b, c, d, e, f, 1916a, b, 1918, 1919a, b, 1920a, b, c), with Smreker receiving support from Hache (1919) and Henneberg (1919). Based on an extensive experimental comparison of equations using a Darcy permeameter, which he calls "Thiem apparatus", Krüger (1918) found the best fit using a modified Smreker equation. Other authors, like Robert Weyrauch (1916), the Dutchman Jan Versluys (1915, 1919), the Austro–Hungarian J. Zavadil (1915) and Ferdinand Zunker (1920), tried to reconcile the approaches by investigating their limits. The latter also proposed a new equation based on experimental data. In 1919, the *Journal für Gasbeleuchtung und Wasserversorgung* had apparently had enough of the discussion and tried to declare it finished (Anonymous, 1919) but to no avail (Rother, 1920; Smreker, 1920a, b, c). Adolf's successor, his son Günther Thiem, participated only marginally in the feud (Thiem, 1920i, l). He probably did not want to compromise his role as neutral editor of his journal (Sect. 3.5). The feud lost steam in the early 1920s, after more than 40 years of struggle. Although several review papers had tried to declare Smreker's approach to be the correct one (Krüger, 1918; Hache, 1919), his struggle was in vain, and his equation fell into oblivion and is hardly cited today (Benedikt et al., 2018). Unbeknown to most participants of the feud, Philipp Forchheimer, who was only marginally involved in it (Lummert, 1916b), had already solved the problem in 1901 by proposing the law today known as Forchheimer law (Forchheimer, 1901). It expands on the Darcy law with a velocity term that can be used when flow velocities are high, e.g. in the vicinity of pumping wells. This fixes the deficiency of the Darcy law that Smreker had correctly identified. With low velocities, the Forchheimer equation reduces to the Darcy law, which thus remains valid for most situations. Smreker's feud with the Thiem school of thought must have been quite bitter, as Smreker mentions the hydraulic study of neither Adolf nor Günther Thiem in his otherwise excellent book (Smreker, 1914b). This is quite unusual for a time when there were few published studies available, and Thiem had already been recognized as the founding father of hydrogeology in Germany.

Another hydrologist who landed into trouble with Adolf Thiem was Gustav Oesten, a civil engineer and subdirector of the Berlin waterworks and later the author of an influential textbook on water supply that went through several editions (Oesten, 1904). He had published on the flow of groundwater to well screens based on sand tank experiments and interpreted them in a non-Darcian manner (Oesten, 1879a), which Thiem attacked in a quite sarcastic style (Thiem, 1879c; Oesten, 1879b). In 1882, Oesten published basically the same results in a different journal (Oesten, 1882a). Again, Thiem attacked his interpretations and even conducted experiments to prove his point (Thiem, 1882; Oesten, 1882b). Details can be found in Sect. 2.3.

3 Günther Thiem

3.1 Biography

Günther Thiem was born under the full name Ernst Gerhard Günther Thiem on 11 October 1875, in Regensburg, Bavaria, where his father was working with Heinrich Gruner (1833–1906) at the time (Fig. 7). After his father had relocated to Leipzig in 1886, he attended the renowned Thomasschule, Germany's oldest public school, founded in 1212, which was right next door to his childhood home in the Hillerstraße. He started his academic career in 1895, studying philosophy at the University of Leipzig. In 1896, he changed to civil engineering at the Königlich Technische Hochschule (Royal Technical University) in Stuttgart to follow the classes of Robert Weyrauch (1874–1924) and Otto Lueger (1843–1911), with the latter being Germany's leading expert on water supply and the author of influential textbooks (Lueger, 1883, 1895). During semester breaks, Günther worked in his father's consulting company. Lueger, in his book *The water supply of towns* (Lueger, 1895), advocated for the use of springs and groundwater instead of surface water (Loehnert, 2013). However, some of his theoretical concepts were wrong; he followed the doctrine that groundwater under free water table conditions could not flow upwards (de Vries, 2006). In 1901, he reappeared in Leipzig with the title Regierungs-Bauführer (government building chief), which indicates that he intended to join the Saxon state administration. But this was not meant to be. Instead, he pursued his doctorate in Stuttgart (Sect. 3.2) and later took over the family consulting company after the rather sudden

Figure 7. Photos of Günther Thiem from around 1910 (left; Anonymous, 1910) and around 1940 (right; Thiem, 1941a).

deaths of his older brother in 1907 and his father in 1908 (Sect. 3.4).

Günther Thiem married Erna Carola Auguste Goelitz (1887–1976) in Marburg in 1909. They had three children, all born in Leipzig, called Auguste Luisa Ingeborg (born 1911), Anna Else Erika (born 1913), and Karl Wolf Gunther (1917–2015). The latter became a renowned art historian and head of the graphical collection of the state art gallery in Stuttgart (Hoffmann, 2017; Herfried Apel, personal communication, 2021). After the death of Adolf Thiem, Günther's family moved into the old Thiem residence at Hillerstraße 9, where they stayed at least until 1949 (according to an entry in the last available address book) but probably even longer until Günther's death and possibly beyond. Adolf's widow Thekla moved to the neighbouring Schwägrichenstraße, where she lived until her death in 1931. In the address book, she appears with the description "Privata", indicating that she was a wealthy widow who could afford to live from her inherited means.

3.2 Thiem (1906) doctoral thesis

Otto Lueger was also the advisor of Thiem's doctoral thesis, which Günther dedicated to his father (Thiem, 1906). It was probably one of the first doctoral studies solely dedicated to groundwater and was widely received in Germany and abroad. The doctoral thesis was remarkably short; it had 45 pages with three annexes providing 10 borehole descriptions, three tables with results of calculations, and eight plans or cross sections. The thesis had no formal reference list but referred in the text to publications of six authors (Darcy, Adolf Thiem, Slichter, Forchheimer, Dupuit, and Lueger). Verbatim quotes were referenced from Slichter and Dupuit in English and French, respectively. In the thesis, he presented the so-called ε-Verfahren (epsilon method). In essence, it was the Dupuit–Thiem pump test analysis method for obtaining the hydraulic conductivity. However, instead of using a hydraulic conductivity K, he defined ε, which he called the unit capacity, as the product of the K and a unit cross section normal to the groundwater flow. He derived and presented unconfined and confined flow to wells and equations for ε, i.e. the Dupuit–Thiem equations. He then applied this method by performing 10 pump tests to estimate the groundwater flow in a 6 km long section of the Iser river valley (now Jizera river) near its confluence with the Elbe river, close to the city of Altbunzlau (now Stará Boleslav, Czech Republic). The pumping tests were part of a study to develop groundwater resources for Prague, a project initiated by Adolf Thiem (Anonymous, 1903). The field investigation was executed in the first half of 1902. He showed that the Iser river is the receptor of the groundwater flow and that the higher the river bed is above the base of the unconfined aquifer, and the closer one is to the river, the more vertical upward flow there is, which was in contradiction to the ideas of his advisor Lueger (1895).

The last chapter of Thiem's thesis is probably one of the first published extensive analyses of groundwater–surface water interaction. Thiem explained and presented in clear figures how equipotential lines are differently oriented towards a river dependent on gaining or losing river conditions (Fig. 8). But also he showed how, during an infiltrating flood wave passing through the river, the equipotential lines change their curvature near the river. Hence, he recognized and described the process of bank infiltration and storage. During 5 months, in support of studying groundwater–surface water interactions, he observed groundwater levels in piezometers at different distances from the river at the 10 pump test locations. In one of the 10 locations, he suffered data loss due to the vandalism of his piezometer, apparently an issue of all times. By calculating the changing gradients, he observed, e.g. on 25 March 1902, that the high river water levels caused infiltrating conditions in the valley aquifer. Based on observed strongly changing gradients in the time frame of 48 h, he concluded that groundwater level observations during at least 1 year are required to obtain an average gradient with which the groundwater flow to the river can be estimated. He also extensively discussed the temporal changes in groundwater–surface water interaction and sources of extracted water under the influence of seasonal groundwater level variations and the regime of a well located near the river. In designing the well field, Thiem aimed to avoid extracting low-quality surface water. Hence, Thiem developed an analytical equation to estimate the required distance between the river and the well, based on phreatic flow between two assumed fully penetrating canals (representing the river and the well). In the same chapter, he discussed the different infiltration and recharge characteristics of the study area, which were low on the loamy valley soils and high on the sandy terraces. Moreover, he described the strongly delayed response of rainfall on the groundwater levels, warning that the delay is generally well underestimated.

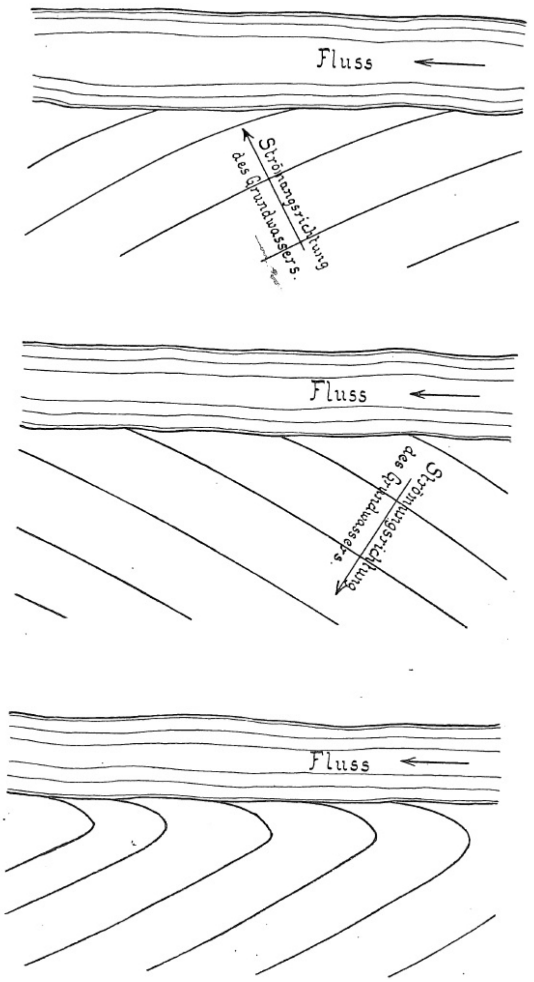


Figure 8. Groundwater–surface water interaction at the Iser (Jizera) river near Prague. At the top, the gaining conditions are shown. In the middle, the losing conditions are shown. At the bottom, the bank infiltration during river flood conditions are shown (Thiem, 1906). Note: Fluss is the river, and Strömungsrichtung des Grundwassers is the flow direction of groundwater.

The proposed ε-Verfahren never became widely popular under this name, despite being discussed in detail in the book by Prinz (1919) in German but also in French by Imbeaux (1921, 1930). The approach Günther Thiem proposed was actually not novel, as his father had essentially already published the derivation of the Dupuit–Thiem equation for estimating the hydraulic conductivity in 1870. Nevertheless, the 1906 doctoral thesis very clearly details and applies the method and is well cited – at least 521 times (Google Scholar, October 2020). Often the thesis is erroneously cited as the source of the Dupuit–Thiem model or Thiem equation (e.g. Wenzel, 1936; Meinzer and Wenzel, 1940), but this honour belongs to Adolf Thiem (1870), who has so far received only 30 citations. The clear exposition of the Dupuit–Thiem equation and Günther Thiem's support in transferring his method to the USA (see below) explain the erroneous citation.

3.3 Work overseas

After graduating in 1900, Günther Thiem went to the USA and worked in New York for the Hering and Fuller consulting company. One of the founders was the famous civil engineer Rudolph Hering (1847–1923), a member of the Hall of Fame of the American Water Works Association and the eponym of the Rudolph Hering Medal, which is awarded by the American Society of Civil Engineers for outstanding contributions to environmental engineering. Being of German descent, Hering had been sent by his parents to Dresden to attend school and university. Whether he came into contact with Adolf Thiem during this period remains unclear. One of Günther Thiem's projects in the USA was building the water supply for the city of Jersey, New Jersey. He also travelled to Egypt, India, and Ceylon (Sri Lanka) during this time (Thiem, 1915c, 1936c, 1955a). In 1903, he returned to Leipzig and became a junior partner in his father's company. While the bulk of the work there was in Germany, he was also involved in projects in Austria–Hungary, Switzerland, and Russia (details see below).

3.4 Consulting engineer

After the death of his older brother and father, Günther took over the consulting company in Leipzig in 1908, employing five to seven engineers and several technical staff (Anonymous, 1910). In 1911, he moved the offices to Marschnerstraße 13, in 1915 to Plagwitzer Straße 9, and, finally, in 1939 to Plagwitzer Straße 7 (today Käthe-Kollwitz-Straße), which was basically in the same corner house as his home in Hillerstraße 9. All mentioned buildings survived the war with minor damage, were nicely refurbished after the reunification, and still exist today (Fig. 9). Public water supply companies were his main clients. For them, he designed and supervised the construction of many water supply schemes in Germany and abroad (Table 2). Most of them were based on groundwater and a few on bank filtration, which he considered artificial groundwater (Thiem, 1919k). He also served on the city council of Leipzig (1913–1918 and 1921–1922). In 1912, he was appointed as Gerichtlicher Sachverständiger (surveyor appointed by the court). During the First World War, he served in the German army as a field engineer and published papers on military aspects, e.g. the construction and drainage of trenches (Thiem, 1915a, 1916e, 1917e), field water supply (Thiem, 1917a, 1919c), and the disinfection of water (Thiem, 1916d, 1918a, d, 1919c). For his efforts, he was awarded the Saxon medal of war merit (Kriegsverdienstkreuz), a fact that is curiously never mentioned in any of his later biographies (Anonymous, 1917).

After the war, he applied his skills in the growing field of lignite mining, which had major impacts on groundwa-

Table 2. Main water supplies planned and built by Günther Thiem (English names in parentheses).

Name of city	Name of city today	Comment	References
Prag (Prague), Altbunzlau, Czech Republic	Praha, Stará Boleslav	Then Austria–Hungary	Thiem (1906)
Landeshut	Kamienna Góra, Poland	Then Germany	Thiem (1909b)
Harburg		Today part of Hamburg	Thiem (1910a)
Wilhelmsburg		Today part of Hamburg	Thiem (1910c)
Leipzig		Expansion of previous schemes	Thiem (1910d, j, 1911a, b, 1912b, 1914c, 1915d, 1920g, 1922c, 1935a, d, f, 1957)
Czernowitz	Chernivtsi, Ukraine	Then Romania	Thiem (1910e, f, 1929c, n)
Magdeburg			Thiem (1910g, 1921b)
Mönchengladbach			Thiem (1911c)
St Petersburg, Russia			Thiem (1913b, c, 1929k, m)
Vaasa (Wasa), Finland		Then Russia	Thiem (1913e), Juuti and Katko (2006)
Meerane			Thiem (1914d)
Kempten			Thiem (1915e)
Aue			Thiem (1916c, 1923a)
Zeitz			Thiem (1919e, 1920f)
Danzig	Gdansk, Poland		Thiem (1919a, h, j)
Halle			Thiem (1919i, l, 1921a), Winterer (1919)
Mitau, Latvia	Jelgava		Thiem (1929e, n, o, r)
Posen, Poland	Poznań		Thiem and Matakiewicz (1923)
Zittau			Thiem (1929g, h, p)
Tampere (Tammerfors), Finland			Gagneur and Thiem (1928, 1929)
Wolmsdorf			Thiem (1930b)
Bautzen			Thiem (1931b, h, l)
Saaz, Czech Republic	Žatec		Thiem (1932b, c)
Reichenberg, Czech Republic	Liberec		Thiem (1933a, d, 1934a, 1939a)
St Moritz, Switzerland			Thiem (1933b, c, 1934b, c)
Samedan, Switzerland Dessau			Thiem (1936b, d) Thiem (1955b)

Figure 9. On the left is the corner house on Hillerstraße 9, and Plagwitzer Straße 7 is shown on the right (today named Käthe-Kollwitz-Straße). Günther Thiem had his offices at Plagwitzer Straße 9 (yellow building to the right) from 1915 and finally moved to Plagwitzer Straße 7 in 1939 (right). Hillerstraße 9 was the Thiem family residence, and Adolf and his family lived on the second floor from 1887, while Günther took over the residence in 1909 (photos: Georg Houben).

ter resources through the dewatering of the open-pit mines in central Germany and Bavaria (Thiem, 1920b, m, 1921c, 1922a, b, 1923d, 1924a, b, 1928d, 1929b, i, 1930b, 1935b, 1937d, 1938a, 1939b, 1940c, e, 1950, 1952). In his publications at this time, he introduced himself as Montanhydrologe (mining hydrologist) and tried to convince the mining engineers that geohydrology was an important contribution to their field. The industrial water supply also became important (Thiem, 1919k, 1920k, 1922e, 1924c, d, e, f, 1929l, 1931e, 1935d, e, 1937a). Building on the work of his father, he was also an important contributor to the improvement of the design and construction of vertical wells (Thiem, 1911d, 1916b, 1917d, 1919f, 1920c, d, j, 1923c, f, 1924h, 1925a, 1928a, d, 1929f, 1936a, 1938d, 1941b, 1942, 1951b, c, 1953c, d). Similar to his father, he investigated the hydraulic and economic aspects of pipeline networks (Thiem, 1910b, h, 1912b, c, 1915d, 1918c, 1919b, d, e, 1920a, 1924c, e, 1931b, c, i, n, 1932a, d, e, 1938b, c, 1954) and their maintenance (Thiem, 1914b, 1929d). Water treatment, especially the removal of ferrous iron, was a side issue (Thiem, 1910i, 1914d, 1915b, 1924d, 1928c, e, f, 1929a, 1931m). He also designed and, unlike his father, patented technical equipment, amongst them a device to measure groundwater levels (Thiem, 1908b), a detachable riser pipe (Thiem, 1911d), a water meter (Thiem, 1911e, f, 1912a), a device for screened wells that allow the injection of chemical reactants to dissolve incrustations (Thiem, 1931d), an acid-proof coating for metal well screens (Thiem, 1931j), a rubber pipe seal (Thiem, 1933d), a check valve with the wonderfully German name of Rückschlagklappenventil (Thiem, 1935c), and a gate valve (Thiem, 1937c).

Due to his age, he did not serve in the Second World War (WWII) but contributed several short publications detailing the water supply for troops in the field, copying his work produced during WWI (Thiem, 1937b, 1940b).

Other cities that he worked for include Zwickau, Freiberg, Spremberg, Gera, Linz (Austria), and Suceava, Romania, then Austria–Hungary (Pöpel, 1956). Regarding his study in Mönchengladbach, he lists the prices for several of his hydrogeological investigations, including drilling costs and their duration (Thiem, 1911c). The investigations in Prague and Leipzig took about 200 d each and cost 51 000 and 30 000 German Marks. The study in Czernowitz took 67 d, while the one for Mönchengladbach required 150 d, both at the cost of about 15 000 Marks. To roughly convert these prices into Euros, one has to multiply them by 5.2. During his work in Switzerland in the early 1930s, he briefly became the technical director of the Hydrotechnik AG, Zurich (Thiem, 1933c).

3.5 Editor, publisher, and author

In 1914, Günther Thiem became the executive editor of the *Internationale Zeitschrift für Wasser-Versorgung* (*International Journal for Water Supply*), founded by the Internationaler Verband der Wassersachverständigen (International Association of Water Experts; Weber, 2020), the first international journal exclusively dedicated to hydrology. The journal was published through his own publishing company called Technischer Verlag Dr.-Ing. Günther Thiem. Rudolph Hering (USA), Édouard Imbeaux (France), Felice Poggi (Italy), and Johan Gustaf Richert (Sweden) acted as additional editors (Fig. 10). His contacts thus went further than the USA (see Sect. 4) and, despite all of the political problems, included the French-speaking world, e.g. through Édouard Imbeaux, whom he calls "... a dear old friend" in the letter shown in Fig. 11. Even in 1916, when the war between Germany and France was in its third year, Günther Thiem published a paper on the water supply for Nice, France (Thiem, 1916a). The friendship with Imbeaux outlasted the war, and as early as 1921, Imbeaux promoted the Thiem epsilon method in an article (Imbeaux, 1921). Contributions to the journal came from all over the world, including from leading USA hydrologists of the time, such as Charles Slichter (Slichter, 1915). Günther also republished several of his father's older publications (A. Thiem, 1914, 1915, 1918, 1920).

Interestingly, the 1917 issue of the journal still mentions all of the original foreign editors, although Germany was at war with France and Italy (Höfer von Heimhalt from Vienna and his former teacher Robert Weyrauch from Stuttgart had been added in the meantime). The journal was active throughout WWI but only published articles in German. In 1918, Günther Thiem realized that the term "international" in both the journal title and the name of the association was awkward during a time of war and dropped it. The names of Hering, Imbeaux, and Poggi disappeared as coeditors, while H. Peter from Zurich, Switzerland, was added. In mid-1919, the journal was renamed *Zeitschrift für Wasserversorgung und Abwasserkunde* (*Journal for Water Supply and Wastewater Science*). In 1920, he decided to give up the journal, and it was subsequently merged into the journal *Wasser und Gas*, which appeared until 1934, with Günther serving as the associate editor. He also worked in the same position for the *Kalender für das Gas- und Wasserfach* (a yearbook for the gas and water field), which appeared between 1921 and 1938. After WWII, Günther Thiem did reappear as editor of a journal. From 1951 to 1956 he was listed as a co-worker of the journal *Bohrtechnik, Brunnenbau* (*Drilling techniques, well construction*). Ironically, after his death in 1959, the East German government forgot to remove his now inactive publishing company from the public registry. Finally, in 2007, several years after the German reunification, the authorities finally deleted it.

Günther Thiem was a prolific author. He left a legacy of around 200 publications treating theoretical concepts, technical inventions, case studies from his consulting work, and promoting the general benefits of groundwater. He repeatedly published papers or booklets that summarized the gained knowledge on hydrogeology (e.g. Thiem, 1907, 1909a, 1913d, 1914a, 1917b, c, 1918b, e, 1919g, 1920e, h, 1922d, 1923e, 1925b, c, 1926a, b, 1927a, b, 1928b, 1929j, l, 1930a, c, 1931a, f, g, k, 1939c, 1940a, d, f, 1941a, 1951a, 1953a, b, 1955c; Thiem and Gagneur, 1929). His interest in international hydrological affairs is evidenced by several review articles on foreign water supply schemes, stretching as far as the former Soviet Union and Egypt (Thiem, 1915c, 1916a, 1923b, 1924g, 1936c). Many of his publications appear in a series published by himself, called *Thiems Hydrologische Sammlung* (*Thiem's Hydrological Collection*), a series of small booklets, which often are reprints of some of his papers published in journals. He was also a great communicator, whose oral explanations of by integrals supported hydrological calculations were even understandable for lawyers (Grahmann, 1960). This was often necessary since the quantitative methods introduced by both Thiems were initially often met with scepticism. As late as the early 20th century, a senior government official told Günther Thiem the following:

> Your whole hydrology is nonsense, I simply build well after well, until I obtain the desired quantity of water. (Thiem, 1911c)

Luckily, these random searches for groundwater, often aided by the use of the divining rod, were slowly overcome due to the persistent work and the publications by both Thiems. During his search for groundwater for the city of Bautzen, Günther actually hired two water diviners to compare their results to his drill holes, with the conclusion being that there were less than convincing results for the divining rods (Thiem, 1931b, h, l).

3.6 Honours

Like his father's work, Günther's contributions to Leipzig and Prague's water supply were considered important enough to be shown at the world exhibition in Brussels 1910, where he was even awarded a silver medal (Stoffers, 1910). The occasions of his 60th, 75th, and 80th birthdays in 1935, 1950, and 1955 were honoured by the publication of short biographies (Anonymous, 1935, 1950, 1955, 1956; Lang, 1950; Paavel, 1955; Herzner, 1955). Although not of working class background, Thiem was also honoured by the East German communists, who took over in Leipzig after WWII. In December 1952, they awarded him the somewhat peculiar title of Verdienter Techniker des Volkes (merited technician of the people), and he was one of the first to receive this honour (Henneberg, 1952). In the same year, he was appointed Ehrensenator (honorary senator) of the Hochschule für Bauwesen (University of Construction) in Leipzig (Schöne, 1959). Not to be outdone by their East German counterparts, Günther also received prices from West Germany. In 1956, the German Association for Gas and Water (DVGW) awarded him their highest honorary prize, the Bunsen–Pettenkofer-Ehrentafel (an Ehrentafel is a shield of honour; Anonymous, 1956), and the Technical University of Stuttgart commemorated the 50th anniversary of his doctorate by awarding him the golden doctoral diploma (Pöpel, 1956; Schöne, 1956). His death was mourned in both East and West Germany (Anonymous, 1959a, b; Schöne, 1959; Grahmann 1960).

4 Günther Thiem and Oscar Edward Meinzer

The work by Adolf Thiem had already been noted in USA literature (e.g. King and Slichter, 1899), but it was Günther who popularized the Thiem methods abroad, especially in the USA. Trying to understand the background of why, generally in the USA literature (Ritzi and Bobeck, 2008), the Dupuit–Thiem equation is called the Thiem method after Thiem (1906), and why it became so popular, we investigated the contacts between Günther Thiem and USA scientists, especially Oscar Edward Meinzer.

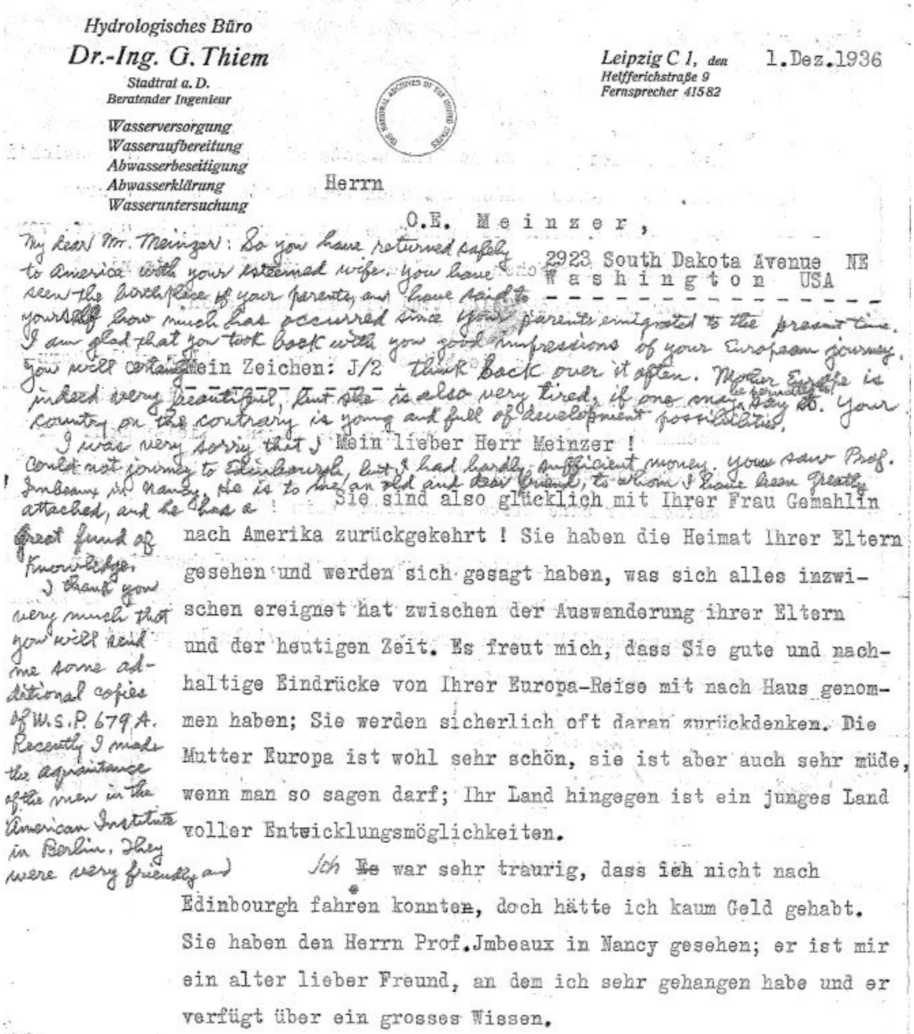
Nr. 18/19 Leipzig, den 16. September/1. Oktober 1917 4. Jahrgang

Internationale Zeitschrift
für
Wasser-Versorgung
ВОДОСНАБЖЕНІЕ
WATER-SUPPLY / ACQUEDOTTI صوجلب واساله‌سی APPROVISIONNEMENT d'EAU

Unter Mitwirkung von:
Rudolph Hering, Neu-York | Dr. Hoefer von Heimhalt, Wien | Dr. E. Imbeaux, Nancy | Felice Poggi, Mailand | Dr. J. G. Richert, Stockholm | Dr.-Ing. R. Weyrauch, Stuttgart

herausgegeben von Dr.-Ing. G. Thiem, Leipzig
Zeitschrift des Internationalen Verbandes der Wassersachverständigen.
Techn. Verlag der Int. Zeitschrift für Wasserversorgung, Leipzig, Plagwitzer Str. 9, Fernruf 13782. Postscheckkonto Leipzig Nr. 51547.

Figure 10. Header of the *Internationale Zeitschrift für Wasser-Versorgung* (1917), showing the international co-editors and the journal title in different languages.



Hydrologisches Büro
Dr.-Ing. G. Thiem
Stadtrat a. D.
Beratender Ingenieur

Wasserversorgung
Wasseraufbereitung
Abwasserbeseitigung
Abwasserklärung
Wasseruntersuchung

Leipzig C 1, den 1.Dez.1936
Helfferichstraße 9
Fernsprecher 41582

Herrn
O.E. M e i n z e r ,
2923 South Dakota Avenue NE
W a s h i n g t o n USA

Mein Zeichen: J/2

Mein lieber Herr Meinzer !

Sie sind also glücklich mit Ihrer Frau Gemahlin nach Amerika zurückgekehrt ! Sie haben die Heimat Ihrer Eltern gesehen und werden sich gesagt haben, was sich alles inzwischen ereignet hat zwischen der Auswanderung ihrer Eltern und der heutigen Zeit. Es freut mich, dass Sie gute und nachhaltige Eindrücke von Ihrer Europa-Reise mit nach Haus genommen haben; Sie werden sicherlich oft daran zurückdenken. Die Mutter Europa ist wohl sehr schön, sie ist aber auch sehr müde, wenn man so sagen darf; Ihr Land hingegen ist ein junges Land voller Entwicklungsmöglichkeiten.

Ich ~~Es~~ war sehr traurig, dass ich nicht nach Edinbourgh fahren konnte, doch hätte ich kaum Geld gehabt. Sie haben den Herrn Prof.Jmbeaux in Nancy gesehen; er ist mir ein alter lieber Freund, an dem ich sehr gehangen habe und er verfügt über ein grosses Wissen.

My dear Mr. Meinzer: So you have returned safely to America with your esteemed wife. You have seen the birthplace of your parents and have said to yourself how much has occurred since your parents emigrated to the present time. I am glad that you took back with you good impressions of your European journey. You will certainly think back over it often. Mother Europe is indeed very beautiful, but she is also very tired, if one may be permitted to say so. Your country on the contrary is young and full of development possibilities.
I was very sorry that I could not journey to Edinbourgh, but I had hardly sufficient money. You saw Prof. Imbeaux in Nancy. He is to me an old and dear friend, to whom I have been greatly attached, and he has a great fund of knowledge.
I thank you very much that you will send me some additional copies of W.S.P. 679 A. Recently I made the acquaintance of the men in the American Institute in Berlin. They were very friendly and

Figure 11. The first page of a typewritten letter by Günther Thiem, with a handwritten translation by Oscar Edward Meinzer (USGS, 1936–1940; Thiem to Meinzer, 1 December 1936).

Charles Vernon ("CV") Theis, former district geologist and division scientist at the USGS Office of Ground Water from 1930 until his official retirement in 1970, was interviewed by John Bredehoeft in 1985 (Theis, 1985; Bredehoeft, 2008). CV was at that time already 85 years old. Although he took time to respond, his mind was still sharp, and he remembered details quite clearly (Bredehoeft, 2008). Bredehoeft asked CV about the pumping test in Grand Island, Nebraska, run by the USGS (Wenzel, 1932, 1933, 1936). Theis replied that Meinzer had gone to Europe to meet Günther Thiem, who had been using pumping tests for water supply, and "brought back the idea and to really try it out". He said that "it was the only one at that time [in this country], . . . , well, no, who was it that presumably made some sort of a pumping test in Pennsylvania?". He also related that "this was just before Hitler's time and Meinzer was sending back to Thiem various baskets of food because Thiem was having a hard time there". The food baskets were most likely sent after the war, since Thiem was a successful businessman before it.

The Grand Island pumping test was planned in 1930 under the supervision of Oscar Edward Meinzer, who had been the geologist in charge of the Office of Ground Water of the USGS since 1912. The measurements took place in summer 1931; the results were described in short in Wenzel (1932, 1933) and fully documented in Wenzel (1936). The goal of the two performed pumping tests was "to ascertain the accuracy of the Thiem method and to investigate the possibilities of determining specific yield by a pumping test" (Wenzel, 1936). Wenzel's publications in 1932 and 1936 both have "The Thiem method for determining permeability of water-bearing materials . . . " in their title and described the method extensively. Meinzer (1932) also explained the method; it is likely that he presented the method already at a meeting of the Society of Economic Geologists in New York City on 29 December 1928.

> Mimeographed copies of the paper in abbreviated form had been sent to the members prior to the meeting. The paper has been revised and enlarged for the present publication (Meinzer, 1932).

Both Meinzer and Wenzel referred to Adolf Thiem and particularly the Thiem (1887a) tracer test paper but not to the Thiem (1870) paper. However, Meinzer (1934) also referenced Adolf Thiem (1870).

> He introduced field methods for making tests of the flow of ground water and applied the laws of flow in developing water supplies. Under his influence Germany became the leading country in supplying the cities with ground water. The results of his work appeared in a number of papers, the first in 1870.

Hence, we may assume that Meinzer had been, at least since 1928, aware of the Thiem method based on Thiem (1906, 1870). The Wenzel (1936) "Water-Supply Paper 679-A" effectively established the Thiem (1906) method as a standard for the permeability assessment of pumping tests and received broad uptake. In the acknowledgement of Wenzel (1936), Leland Wenzel thanks Günther Thiem for his criticism of the manuscript, which shows the existence of contact between Thiem and the USGS at least during the 1930s.

It took between 66 and 30 years after, respectively, Thiem (1870, 1906) until the Thiem type of pumping test was introduced and made popular in the USA. Although Meinzer and Hard (1925) and Meinzer (1928) realized the importance of compressibility and elasticity of aquifers in the 1920s, the dominant groundwater flow theory was steady state and dictated by the Dupuit–Thiem model until Theis published his transient solution in 1935 (Theis, 1935; Deming, 2002). The slow acceptance of the Theis equation (in part by Meinzer) meant that, by 1936, the USGS "Water-Supply Paper 679-A" could still widely introduce and popularize the Thiem method in the USA.

To investigate in more detail the contacts between Günther Thiem and the USGS, we requested a search of the USA National Archives, resulting in about 42 pages of relevant correspondence, mainly between Günther Thiem and Oscar Edward Meinzer dated between 1 December 1936 and 23 August 1940 (USGS, 1936–1940). The correspondence consists of 17 letters from Thiem to Meinzer and one to John Adam Fleming, 13 letters from Meinzer to Thiem, one from Fleming to Thiem, one from the chief clerk to Thiem, and a copy of a publication about Thiem (Anonymous, 1935). Thiem writes in German to Meinzer, while Meinzer writes back in English. However, it is clear that both have a good command of the other language. Of the 17 letters by Thiem, only three seem to have been translated. The first letter (USGS, 1936–1940; Thiem to Meinzer, 1 December 1936) appears to have been translated by Meinzer himself in handwritten notes on the letter from Thiem (Fig. 11). The second and third translated letters (USGS, 1936–1940; Thiem to Meinzer, 23 April 1938 and 31 July 1939) are typewritten, with the likely purpose of transferring them to a colleague. Some remarks by Thiem concerning the (upcoming) war in Europe received particular interest and are translated in English on the original letters in Meinzer's handwriting.

> I hope that more peaceful time will soon come and that the scientific exchange will no longer be obstructed. (USGS, 1936–1940; Thiem to Meinzer, 3 November 1939)

In the following year, he wrote

> We all hope that the light of peace will come to Europe from America. Then I will actually make my trip to America which I have had to give up. (USGS, 1936–1940; Thiem to Meinzer, 28 February 1940)

It follows from the letters that one or more letters are probably missing and that there might have been correspondence before the first letter (USGS, 1936–1940; Thiem to Meinzer, 1 December 1936). In this first letter (Fig. 11), Thiem wrote, as translated by Meinzer,

> So you have returned safely to America with your esteemed wife! You have seen the birthplace of your parents and have said to yourself how much has occurred since your parents emigrated to the present time. I am glad that you took back with you good impressions of your European journey. You will certainly think back over it often. Mother Europe is indeed very beautiful, but she is also very tired, if one may be permitted to say so. Your country on the contrary is young and full of development possibilities. (USGS, 1936–1940; Thiem to Meinzer, 1 December 1936)

Thiem further wrote that he was sorry that he could not travel to Edinburgh (for the 1936 International Union of Geodesy and Geophysics – IUGG – General Assembly), as he had hardly any money. Thiem noted that Meinzer travelled to Nancy, France, to see Thiem's good old friend Imbeaux, a former president of the Commission on Subterranean Water of the International Association of Scientific Hydrology (IASH)–IUGG. Thiem thanked Meinzer for sending some additional copies of "Water-Supply Paper 679-A" (i.e. Wenzel, 1936). He also wrote the following:

> Recently I made the acquaintance of the men in the American Institute in Berlin. They were very friendly and lovable, and my wife had to see the institute. These gentlemen also want to get me some copies of this paper. The demand for it is great, especially from many geological institutions in Germany that are not able to send money because of governmental restrictions. (USGS, 1936–1940; Thiem to Meinzer, 1 December 1936)

In closing the letter, Thiem remarked the following:

> Please tell your esteemed wife many heart greetings from me and my wife. It was a fine afternoon when you took tea with us. Many thanks for the journey[1] photos. I find them excellent and they will be for me a dear reminder. May you keep real well, and have a happy Xmas; and don't forget your old professional comrade, who greets you many times. (USGS, 1936–1940; Thiem to Meinzer, 1 December 1936)

Oscar Edward Meinzer was born on 28 November 1876, on a farm near Davis, Illinois (Sayre, 1948, 1949b). He was one of six children of William and Mary Julia Meinzer, born in Karlsruhe, Germany. His grandparents and parents emigrated to escape a culture which they considered oppressive.

> This may have directly influenced Meinzer's future religious convictions, independent thought, hatred of war, and industriousness. (Reuss, 2000)

The European travel of Meinzer took place in 1936. He travelled to the IUGG Assembly at Edinburgh, Scotland, but he also visited hydrologists in Germany, the Netherlands, and France (Meinzer, 1936, includes a four-page trip report; however, it was not published, and we have not been able to obtain a copy; Waring and Meinzer, 1947; Sayre, 1949a). In the interview with Theis, CV must have been confused about Meinzer bringing back the idea of doing a Thiem method pumping test from this trip, as the pumping test was executed in 1931, and as there is no indication that Meinzer made a trip to Europe earlier than 1936 (Sayre, 1949a). Meinzer was the first chairman (1930) of the Hydrology Section of the American Geophysical Union (AGU), which served as the American National Committee of the IUGG (Meinzer, 1931). He was also, from 1936–1948, president of the Commission on Subterranean Water of the IASH-IUGG, from 1947–1948, president of the AGU, and as such, he was active in the organization of the IUGG 1936, 1939, and 1948 assemblies. He anticipated a second trip to Europe to attend the Oslo 1948 IUGG meeting before he passed away (Sayre, 1949a).

Most of the correspondence of Thiem and Meinzer, between 23 April 1939 and 23 August 1940, related to the possible participation of Thiem and contribution by Thiem to the IUGG 7th Assembly, Washington, DC, 4–15 September 1939. Thiem asked Meinzer for an invitation to participate in the assembly (USGS, 1936–1940; Thiem to Meinzer, 23 April, 1938) as, normally, these invitations only went to the official institutes and not to independent hydrological scientists like him. Thiem also expressed his concern about whether the German government would provide him with the necessary foreign currency (USGS, 1936–1940, Thiem to Meinzer, 7 January 1939). Meinzer replied that he is happy to note that Thiem and his wife are definitely planning to come to the USA.

> We will do all that we can to make your visit pleasant and profitable

and

> As you know, Mr Wenzel has done a large amount of work on different methods of determining permeability and flow of ground water so that your contact with him will be mutually helpful. (USGS, 1936–1940; Meinzer to Thiem, 24 May 1938 and 23 January 1939)

He sends a copy of the last letter to Vladimir Frolow and John Adam Fleming, with the latter being the General Secretary of the American Geophysical Union and organizer of

[1] Here Meinzer makes an (understandable) translation error. The original in German reads "reizenden", which means "lovely"; however, Meinzer confuses it with "reisen", which means "to travel".

IUGG 1939 Assembly, and adds the following message to John Adam Fleming:

> Dr. Thiem indicates his intention to come to the Washington meeting and to bring his wife with him, provided he can make the necessary arrangements with the German government. It is obvious to me that he does not stand in very well with the official representatives of Germany but we in this country esteem him very highly. (USGS, 1936–1940; Meinzer to Thiem, 23 January 1939)

Meinzer asked Thiem to contribute to question no. 3 of the International Commission on Subterranean Water, "Determination of runoff and physical conditions of the flow of underground water in natural or altered ground, the flow being natural or induced", of the forthcoming meeting (USGS, 1936–1940; Meinzer to Thiem, 28 November 1938). This question was coordinated by Leland Wenzel of the USGS. Thiem submitted, via the official channel of Werner Koehne of the *Landesanstalt für Gewässerkunde* in Berlin (Koehne, 1939), his written contribution of *Berechnete und beobachtete Grundwassermengen* (Thiem, 1939c, 1940d). Meinzer's reaction was as follows:

> Your paper on Question No. 3 with introduction by Dr. Koehne was received a long time ago and is being pre-published for the Washington meeting. Mr. Wenzel and I have read it in part and he will include it in his general report. We find it very interesting. (USGS, 1936–1940; Meinzer to Thiem, 29 June 1939)

In July 1939, Thiem reported to John Adam Fleming, who forwarded a translation to Meinzer, about his suffering for weeks:

> My health has not yet fully improved, for I am suffering in my right knee from rheumatism of the joints so that I cannot bear much weight on it. Also I have trouble going up stairs. . . . You cannot imagine how much my refusal (of your invitation) distresses me. (USGS, 1936–1940, Thiem to Fleming, 31 July 1939)

Meinzer replied as follows:

> I regret very much that the condition of your health will prevent your attending and taking part in the meetings of the Union. As you know, I had anticipated with pleasure meeting you again and discussing with you personally hydrologic problems of mutual interest.

He also noted that he translated Thiem's assembly paper into English for use at the meeting (USGS, 1936–1940; Meinzer to Thiem, 31 August 1939).

Meinzer reported, three days after the Washington meeting, the following to Thiem:

> . . . although most of the European delegates were not able to attend the meeting in Washington, a considerable number of representative delegates from different countries were nevertheless able to attend and the meeting was very successful. In the Commission on Subterranean Water a total of 55 papers were in hand in either printed or typewritten form, and these were effectively reviewed by the general reporters. The relatively few authors who were present were called upon to present their own papers at greater length. The only one of the officers of the Association who was able to attend was Vice-President Slettenmark who served efficiently as the President during the meetings. President Lutschg's Presidential address, which was submitted in German, was translated and presented by Mr. Slettenmark in the English language. It was accompanied by beautiful lantern slides. We all regretted that you and the other German delegates were not able to attend. (USGS, 1936–1940; Meinzer to Thiem, 18 September 1939)

Wenzel (1939) provided a summary of the contributions of question no. 3, while Meinzer (1939) reported on question no. 2: "Definitions of the different kinds of subterranean water". Official reports of the assembly, which took place under the emerging cloud of WWII, are provided in Chapman (1939) and Fleming (1940) as follows:

> On 30 August, when the European political crises was at its height, it was decided . . . that the Assembly should be held as scheduled but that its activities should be confined to scientific matters only.

The IUGG President la Cour closed the assembly with the following words:

> . . . it has been an extremely important meeting, furthering our science and showing to the world a battlefield where only victory can be recorded because even the overthrow of a theory is a victory for truth. (Fleming, 1940)

In January 1940, Thiem wrote to Meinzer that he had received a package with extensive documents of the meeting in Washington and that now he really regretted that he could not participate. He also noted that he translated the question no. 3 report of Wenzel (1939) into German and would publish it in a German professional journal (USGS, 1936–1940; Thiem to Meinzer, 6 January 1940), which he indeed did (Wenzel, 1940). He continued as follows:

> It is for me a special recognition that the Thiem method for the estimation of the hydraulic conductivity of the subsurface and its water discharge

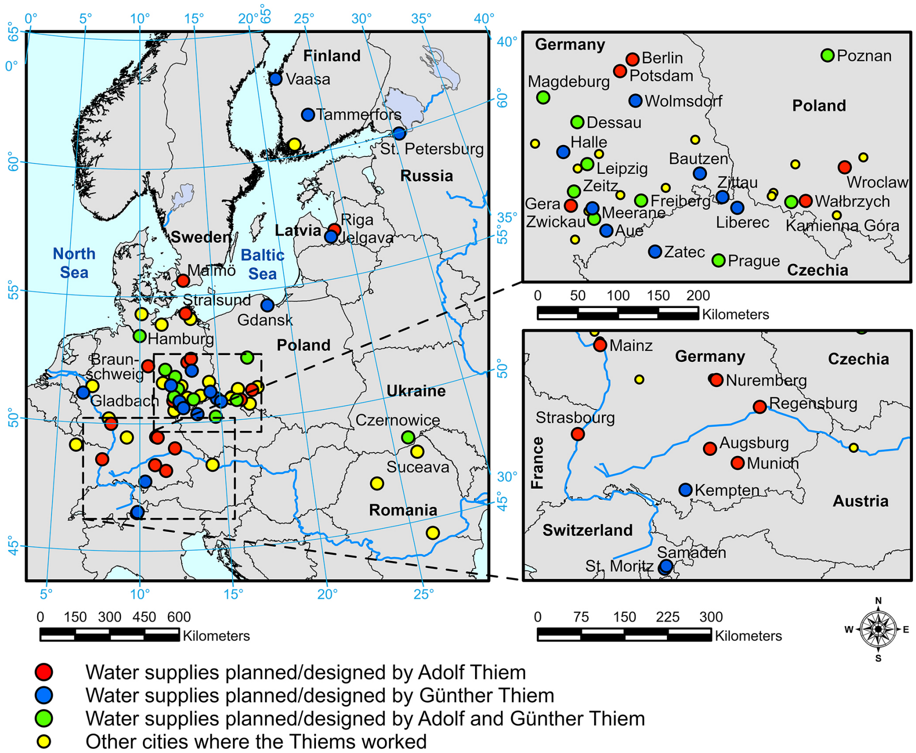


Figure 12. Map of waterworks planned and designed by Adolf and Günther Thiem (data credits: Europe NUTS 0 Boundaries from Esri; Michael Bauer Research GmbH; rivers/lakes from ArcWorld).

> in your country is applied. Do you think, that it later would be suitable to present myself in America to undertake there hydrological investigations for groundwater supply for cities based on my method? I would be very willing to come to America. I would like to ask you to tell me to whom I should direct myself in this case or do you think that your office could take on the negotiation for my appointment as expert? However, these questions can only be discussed with successful prospect when normal times in Europe, let alone in the world, have set in again. (USGS, 1936–1940; Thiem to Meinzer, 6 January 1940)

Meinzer replied to Thiem that he would like to have a copy of the translated report and wrote the following:

> We would be glad to have a visit from you at any time. However, I would not wish to encourage you as to the prospects of obtaining professional work in this country. You might be able to make a success of such an undertaking but there are so many difficulties in establishing oneself in a new country that I do not feel at all sure as to the success that you might have. (USGS, 1936–1940; Meinzer to Thiem, 1 February 1940).

Meinzer was friendly, but he definitely discouraged Thiem from working in the USA.

The last letter in the correspondence is from Thiem to Meinzer in August 1940. Meinzer translated the following lines:

> Your friendly letter of 17 April was received by me on 20 August . . . I suppose you will not receive my letter till Christmas. Therefore I will already today wish you a merry Christmas. My wife and I send our best greetings to you and your wife. Auf Wiedersehen either in America or Europe. Yours Dr. Engineer G. Thiem. (USGS, 1936–1940; Thiem to Meinzer, 23 August 1940).

It is not known if the correspondence ceased or continued during or after WWII. However, in 1946, shortly after WWII ended, Meinzer retired as geologist in charge of the Office of Ground Water. He died rather suddenly on 14 June 1948, while taking an afternoon nap, aged 71 (Sayre, 1948).

In the 1949 address book of Leipzig, Thiem is listed as the Beratender Ingenieur für Wasser und Abwasser, Stadtrat a.D. (consulting engineer for water and waste water, former member of the city council) and still living in Hillerstraße 9. According to Grahmann (1960), Günther Thiem was active until his death in Leipzig on 31 August 1959, aged 83.

Figure 13. The Probstheida waterworks, Leipzig, planned and designed by Adolf Thiem. The picture at the top shows an aerial view, with the water tower (foreground left) and water storage cellars with grass cover. The tower of the Völkerschlacht monument is visible in the background, and the small tower to its left is part of the chapel of the Südfriedhof where the Thiem family grave is located. The bottom left image is of the water tower in its original shape, around 1907. The roof was damaged in World War II and rebuilt in a simplified form. The lower right image shows the inside of water storage cellar (photos: Leipziger Gruppe, with permission).

5 Conclusions

Forevermore, the name Thiem will be connected to the Dupuit–Thiem equation, the first practical model for pump test analysis. However, father and son Thiem were far more prolific contributors to the canon of methods currently used in hydrogeology than most people know. All of their method development was done out of practical need, which arose during their many projects, while devising solutions for the many problems they were facing when building water supply schemes from scratch. This is even more remarkable since it was done while running a successful consulting business and planning many water supply schemes all over Europe, which today can be found in Germany, Poland, the Czech Republic, Austria, Switzerland, France, Finland, Sweden, Latvia, Romania, Ukraine, and Russia (Fig. 12). The infrastructure they planned and designed is a lasting legacy, since some of their waterworks are still active today after often more than 100 years, albeit in modernized form (Figs. 13 and 14). A few buildings have been preserved as protected monuments, e.g. in Leipzig and Suceava. The most striking buildings are, of course, the water towers, e.g. in Leipzig (Probstheida, Möckern, and Großzschocher), Markranstädt (1895), Liebertwolkwitz (1904; now used for housing), Oleśnica (1898, then Oels), and Strasbourg (1878; now a museum of voodoo).

While most of the Thiem methods, such as isopotential maps, tracer tests, and screened vertical wells were devised by Adolf Thiem, who was a true explorer and inventor, it was Günther's role to perfect and propagate them, despite the turmoils of two world wars and several regime changes. Considering the cumbersome communication channels of the late 19th and early 20th century and the language barriers of that time, it is amazing to see that both Thiems were in close contact with many leading scientists from Europe and abroad. The field was small, and the members were well aware of the work of others, and publications in different languages did not seem to be a barrier. Especially Günther's contacts to Oscar Meinzer of the USGS led to the introduction of their methods into the repertoire of English-speaking hydrogeologists. Meinzer's international contacts and his (German) language skills have played a crucial role in the exchange of the strongly developing science of groundwater hydrology.

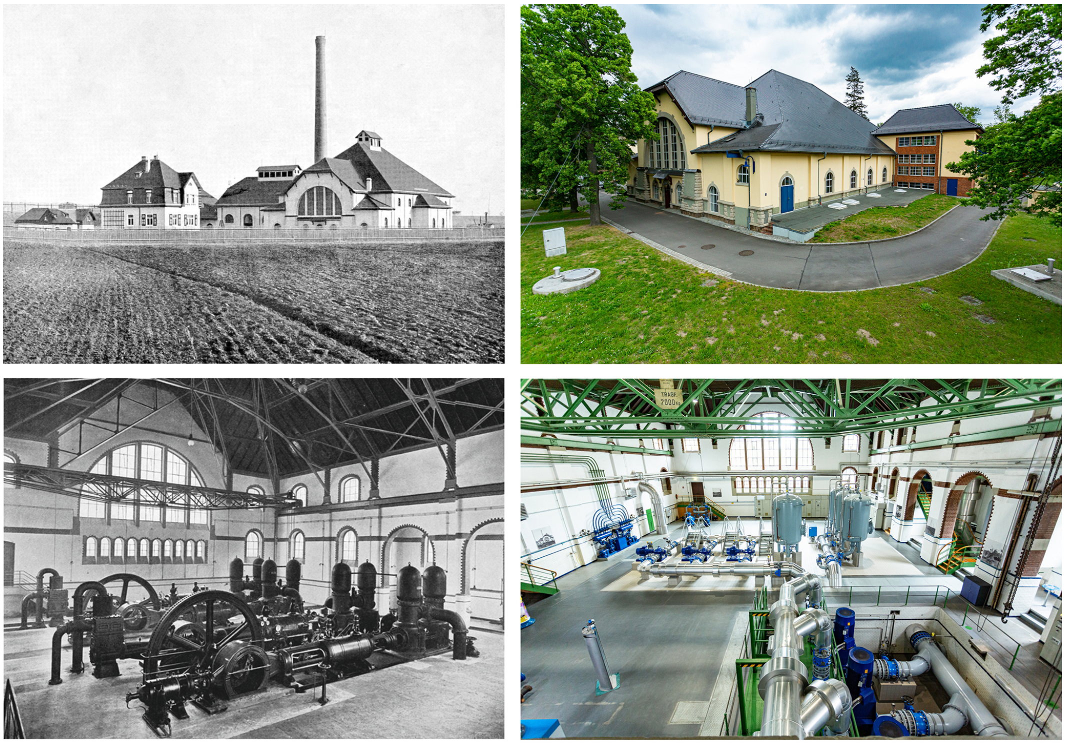


Figure 14. Buildings and pumps of the Canitz waterworks then and now, in Leipzig. On the left are the original buildings, as planned and designed by Adolf and Günther Thiem, around 1912. On the right are pictures of how they look today (photos: Leipziger Gruppe, with permission).

Both Adolf and Günther Thiem were highly concerned with the practical applicability of their theoretical work and with presenting it in a way that non-experts could follow their arguments. In his study for the water supply of Riga, Adolf Thiem stated that

> Es war mir nicht darum zu tun, Behauptungen und Schlüsse lediglich vom Standpunkt des Fachmannes aufzustellen, sondern ich beabsichtige vielmehr, auch dem außerhalb des Fachs stehenden Leser den logischen Gang der Untersuchungen klarzulegen und ihn so in die Lage zu versetzen, meine Methode kritisch prüfen zu können. (It was not my intention to present my claims and conclusions solely from the point of view of an expert but to clearly show to a reader, who is not from the field, the logical structure of my investigations, enabling him to critically judge my method). (Thiem, 1883b)

The engineering work of the Thiems can only be understood in the light of the social and technical problems arising during the late 19th and the early 20th centuries. Increasing population, industrialization, and urbanization had increased the water demand but – at the same time – had negatively affected water quality. Groundwater came into focus as a safe, reliable and often abundant resource to overcome both the demand for a sufficient quantity of water and for improved hygiene by better water quality. However, little was known about this mysterious underground resource. The Thiems reacted to this societal problem by adapting current technology but also by innovation, e.g. the development of new techniques and methods. One example is the vertical well, for which they improved the design continuously over several decades and paved the way towards the modern-day wells. At the same time, they were early adopters of new technology (e.g. the pumps driven by steam engines used in pumping tests) and new, mass-produced materials (e.g. steel and copper used for wells). Both Thiems were also great educators, and their wealth of publications and presentations shows their tireless dedication to the improvement in the delivery of water supply.

In the 19th century, the German states and German-speaking countries saw a professionalization of the engineering industry, the development of an independent technical educational system, and increasing specialization of engineering disciplines (König, 2016; Weber, 2020). Professional organizations developed strongly and published many specialized journals (Weber, 2020). Günther Thiem's editorial activity is a great example of this broader trend in the engineering discipline. Engineers were trained at Technische Hochschulen (institutes of technology), and all other professions were trained at universities, which had a much

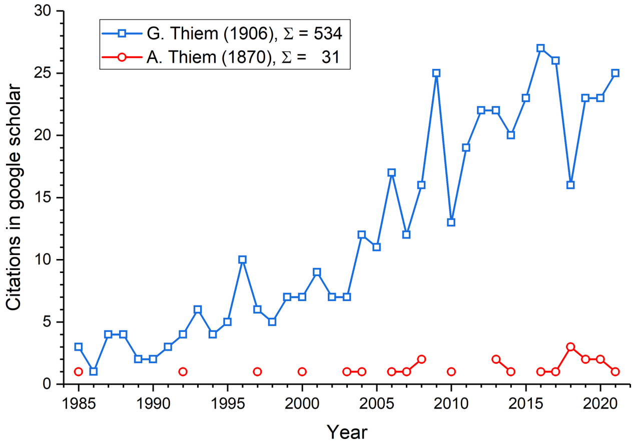


Figure 15. Citations of the two seminal papers by Adolf and Günther Thiem (Thiem, 1870, 1906), according to Google Scholar (https://scholar.google.com/, last access: 17 May 2022).

longer tradition. The role of the Technische Hochschulen was to provide a labour force for the strongly developing industry (Picon, 2004). Only around the year 1900 were the Technische Hochschulen allowed to confer doctorates (König, 2016). While Adolf Thiem was an autodidact, Günther Thiem was one of the first (1906) to receive a doctorate in groundwater hydrology from the Königlich Technische Hochschule (Royal Technical University) in Stuttgart. Hence, the engineering work of the Thiems was in response to the rapidly changing times in which they were living. However, equally, they benefitted strongly from the developing engineering profession and approaches, providing opportunities for experimenting and creating solutions for societal problems.

The lives and work of Adolf and Günther Thiem are not only documented in their legacy of references, of which we have tried to collect and list as many as possible. Several museums hold collections containing reports, letters, and photographs. These include the archives of the Deutsches Museum (https://www.deutsches-museum.de/en/library/searches/, last access: 24 June 2021), the Sächsisches Staatsarchiv (Saxon State Archive), Dresden, and the Museum der Leipziger Stadtgeschichte (Museum of City History), Leipzig.

Although many hydrogeologists today are using the methods developed by the Thiems, albeit often unbeknown to them, the Thiems' legacy is not forgotten. According to Google Scholar (https://scholar.google.com/, last access: 17 May 2022), the 1906 doctoral thesis of Günther Thiem has been cited 534 times, usually as a reference for the Thiem method for pumping tests. Figure 15 shows that its citations have increased steadily over the last few decades, and the paper can well be considered to be a cornerstone of hydrogeological literature. It should be noted that the almost linear increase in its citations is a mirror image of the continuous rise in the number of groundwater-related publications over the last decades, which have experienced annual growth rates of around 10 % since the late 1970s (Jia et al., 2020). Nevertheless, the fact that such an old publication can keep up with the high modern pace of citations is a testimony to its importance. Ironically, Adolf Thiem's seminal 1870 paper, which contains the actual Thiem equation, only stands at 31 citations and only pops up randomly, often in the literature from Germany (Fig. 15).

Data availability. No data sets were used in this article.

Author contributions. Both authors searched for, collected, and evaluated the historic literature by and on the Thiems. Both GH and OB wrote parts of the paper. OB identified and evaluated the communication between Günther Thiem and Oscar Meinzer (e.g. Fig. 11) and prepared the map (Fig. 12). GH collected and evaluated technical reports written by the Thiems (e.g. Figs. 3, 5, 6) and visited and photographed sites the Thiems worked on in Leipzig (Figs. 2, 9).

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