Henry Darcy (1803–1858): Immortalised by his scientific legacy

Craig T. Simmons

Keywords Profiles · History of hydrogeology · Henry Darcy · Darcy's Law · France · Dijon

Introduction

Darcy's Law is the fundamental equation describing the flow of fluid through porous media including groundwater. It forms the quantitative basis of many science and engineering disciplines including hydrology, hydrogeology, soil science, civil engineering, petroleum engineering and chemical engineering. The year 2006 marked the 150th anniversary of the publication of Henry Darcy's most famous text *Les Fontaines Publiques de la Ville de Dijon* (*The Public Fountains of the City of Dijon*; Darcy 1856). Buried in its depths was Note D, an appendix that contained the famous sand column experiments and the discovery of Darcy's Law–a discovery that marked the birth of quantitative hydrogeology.

This article describes the many contributions Darcy made to hydraulics, including Darcy's Law. But what many hydrogeologists may not realise is that Darcy made other contributions to science and engineering that are possibly less familiar. He was the first to describe aquifer resistance, he furnished the very first evidence of the fluid boundary layer, he made major contributions to pipe hydraulics as evidenced by the joint naming of the commonly used Darcy-Weisbach pipe friction equation, he clearly understood the nature of laminar/turbulent flow regimes and recognised the similarity of his law to Poiseuille flow. Many of these experimental observations were facilitated by improvements Darcy made to the Pitot tube that both yielded its modern design and allowed for more accurate measurements of the pipe fluid flow velocity distribution. Finally, not only did Darcy discover Darcy's Law, he was the first to combine it with continuity to develop the falling head permeameter solution that is still used today. He also applied that unsteady solution to the analysis of spring discharge. Whilst Darcy is immortalised by Darcy's Law, it is clear that his scientific legacy extends beyond it.

Darcy's contributions to engineering science are described in this article. A brief historical account of Darcy's life is provided in order to place them within the necessary critical historical context and to provide some accompanying insights on Darcy's life, personality and motivations. A detailed description of Darcy's contributions to science and engineering is then presented. A number of excellent papers written recently by Brown (2002a, 2002b, 2003) form the basis for this analysis. Finally, a brief discussion of hydrogeology in the post-Darcy years shows that Darcy's Law was applied almost immediately after its discovery to the problem of radial flow to a well, first treated by Dupuit (1863). It is here that Darcy's Law was first applied to a hydrogeologic problem that resembles a modern day aquifer analysis. The use of Darcy's Law in formalising the foundations for modern day quantitative hydrogeology is also described. It is shown how these early fundamental contributions followed as either a direct consequence of Darcy's Law or the immediate application of it.

Darcy's life: a brief historical perspective

Henry Philibert Gaspard Darcy was born on 10 June 1803 in Dijon, France, and died in Paris on 3 January 1858. He spent most of his life stationed in his native town of Dijon working as an engineer. A large body of available literature provides compelling evidence in support of the claim that Darcy was a great scientist, engineer and a selfless citizen. There have been a number of historical analyses that lend insight into Darcy's work and times (e.g., de Caudemberg 1858; Marsaines 1858; his great-nephew, Paul Darcy 1957; Hubbert 1969; Freeze 1983; Freeze 1994; Philip 1995; Brown 2002a; Simmons 2003; and Bobeck 2003) and some recent reviews/commentaries of Bobeck's recently released complete English translation of *Les Fontaines* (Bobeck 2004) by Simmons (2004) and Sharp and Simmons (2004). Copies of Darcy's original 1856 monograph are very rare, and few scientists have ever seen it but the new translation fills that void. Bobeck (2006) describes insights gained into the personality of Henry Darcy from the English translation (Bobeck 2004). Numerous examples clearly illustrate "Darcy's intellectual curiosity, his compassion for the poor, his fairness and

Received: 26 November 2007 / Accepted: 7 April 2008

Some material was originally published in *Aquifer Systems Management: Darcy's Legacy in a World of Impending Water Shortage*, edited by: Laurence Chery and Ghislain de Marsily. ISBN:9780415443555. Published by: Taylor & Francis, The Netherlands, 2007. Reprinted with permission from the publisher.

C. T. Simmons (✉)
Flinders University,
GPO Box 2100, Adelaide, SA 5001, Australia
e-mail: craig.simmons@flinders.edu.au

 DOI 10.1007/s10040-008-0304-3

dedication to community service, perseverance in the face of health problems, modesty and lack of self-interest, and youthful exuberance" (Bobeck 2006). Answers to even the most basic questions such as what did Darcy look like can be found in the literature cited above. Two reproductions of Darcy–one of the young Darcy at age 18 at the L'Ecole Polytechnique, Paris in 1821 and the other of the mature Darcy–are shown in Fig. 1. Darcy was 1.69 m tall, had light brown hair, blue eyes and a cleft chin (Brown 2002a). And what of Darcy's name? As Philip (1995) points out, everything he uncovered in his visit to Dijon, Darcy's native town, clearly used the English spelling Henry and not Henri, and Darcy not d'Arcy. Brown and Hager (2003) noted that Henry Darcy's first name is commonly spelled Henri, while his last name sometimes appears as d'Arcy. They conclude that original source material shows that the correct spelling is "Henry Darcy" and that the "Henry" spelling was his from birth, while the "Darcy" spelling was adopted in his youth and kept throughout his life. Indeed, it is this anglicized form that appears on the title pages of the famous *Les Fontaines* report (see Fig. 2), on Darcy's tombstone and his great-nephew Paul Darcy uses it in the title of his Darcy biography and throughout that text (Freeze 1994).

It is useful to highlight some of the key points in Darcy's life and the timelines associated with both his major engineering projects and scientific discoveries. These important previous accounts provide strong evidence that Darcy's somewhat short life of 54 years may be characterised by at least three distinct periods: (1) the early educative years (early 1810s to mid 1820s) that establish Darcy's strong technical background in engineering, mathematics and physics, followed by, (2) a longer period (mid 1820s to late 1840s) of engineering service where Darcy carried out major engineering projects, including the design and construct of the town's water supply in Dijon. This is the period in which Darcy clearly rose to prominence, and then (3) the final years of Darcy's life (early 1850s to his death in 1858) where Darcy's failing health leads to a clear shift towards research and to completing the writing of much of his life's work.

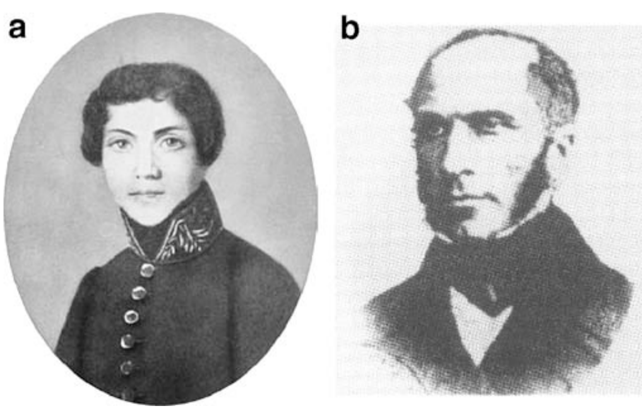
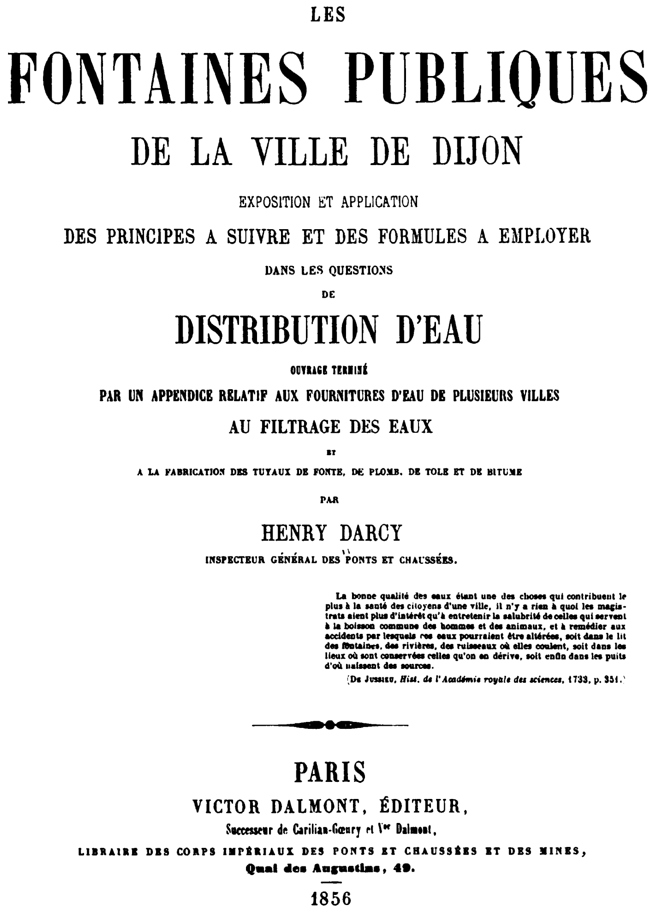


Fig. 1 **a** Henry Darcy in 1821. (P. Darcy 1957). **b** Henry Darcy in the later years of life. Portrait by F. Perrodin from the collection of the Bibliothéque Municipale de Dijon (from Philip 1995; Brown 2002a)



LES

FONTAINES PUBLIQUES

DE LA VILLE DE DIJON

EXPOSITION ET APPLICATION

DES PRINCIPES A SUIVRE ET DES FORMULES A EMPLOYER

DANS LES QUESTIONS

DE

DISTRIBUTION D'EAU

OUVRAGE TERMINÉ

PAR UN APPENDICE RELATIF AUX FOURNITURES D'EAU DE PLUSIEURS VILLES

AU FILTRAGE DES EAUX

ET

A LA FABRICATION DES TUYAUX DE FONTE, DE PLOMB, DE TOLE ET DE BITUME

PAR

HENRY DARCY

INSPECTEUR GÉNÉRAL DES PONTS ET CHAUSSÉES.

La bonne qualité des eaux étant une des choses qui contribuent le plus à la santé des citoyens d'une ville, il n'y a rien à quoi les magistrats aient plus d'intérêt qu'à entretenir la salubrité de celles qui servent à la boisson commune des hommes et des animaux, et à remédier aux accidents par lesquels ces eaux pourraient être altérées, soit dans le lit des fontaines, des rivières, des ruisseaux où elles coulent, soit dans les lieux où sont conservées celles qu'on en dérive, soit enfin dans les puits d'où naissent des sources.

(De Jussieu, *Hist. de l'Académie royale des sciences*, 1733, p. 351.)

PARIS

VICTOR DALMONT, ÉDITEUR,

Successeur de Carilian-Gœury et V[ve] Dalmont,

LIBRAIRE DES CORPS IMPÉRIAUX DES PONTS ET CHAUSSÉES ET DES MINES,

Quai des Augustins, 49.

1856

Fig. 2 Darcy's famous 1856 *Les Fontaines* report (from Hubbert 1969)

The early educative years (mid 1810s–1826)

Darcy's father, Jacques Lazare Gaspard was a tax collector, who died in 1817 when Darcy was only 14 (Darcy 1957). Darcy's mother, Agathe, did not have the means to finance her two sons' studies but she clearly valued a good education deeply. According to Henry Darcy V (Darcy 2003), she obtained a scholarship from the city of Dijon and a loan from her brother-in-law who was also her children's tutor. Henry Darcy V described this man as a "republican brute" who advised the children to give up the particle and to transform d'Arcy into Darcy which they did. But why a surname change? It is possible that the surname change was just like that of many other people of the day who changed their surname–a result of the French Revolution and the increasing challenges faced by the nobility. Indeed, a good number of noble men were hanged or guillotined. It is possible that, like many others at that time, a surname change removed associations with the "old regime", made life easier and afforded opportunities that would otherwise be forsaken.

In 1821, Darcy entered L'Ecole Polytechnique, Paris, and commenced science and engineering studies that would set the stage for his distinguished career. Jean Baptiste Joseph Fourier (1768–1830) held a Chair at the L'Ecole Polytechnique and in 1822 published his *Théorie*

DOI 10.1007/s10040-008-0304-3

analytique de la chaleur (*The Analytic Theory of Heat*) while based in Paris. It is therefore possible that Fourier taught Darcy his heat law and that the earliest seeds of Darcy's Law may have been planted at this point. In 1823, at the age of 20, he was admitted to L'Ecole des Ponts et Chaussées (School of Bridges and Roads), Paris. This was the academic schooling arm of Le Corps des Ponts et Chaussées, "an elite fraternity of engineers that had influential status in mid-nineteenth century France" (Freeze 1994), that was first created in 1716 with a mission to support the construction of infrastructure throughout France. The school was created by decree of the Royal Council in 1747 to train students and practising engineers for careers in the Corps. It both supported and expected excellence. Darcy's career progression was usual for the better students at the time and would shape the course of the rest of Darcy's life (Brown 2002a). A list of the schools' graduates and teaching staff reads like a cast of science, mathematics and engineering stars and includes Antoine Chézy (1718–1798), Louis Marie Henri Navier (1785–1836), Gaspard Gustave de Coriolis (1792–1843), Arsene Jules Emile Juvenal Dupuit (1804–1866) and Henri Emile Bazin (1829–1917), to name just a few. Coriolis also taught at the Polytechnique during Darcy's residence (Brown 2002a). In these early educative years, Darcy learned the state of the art in fluid flow, mathematics and physics. Based on his class rank of 12 out of 64 at the Polytechnique, and 8 out of 15 who proceeded to L'Ecole des Ponts et Chaussées, Brown (2002a) suggests that Darcy was a good, but not the best, student.

Darcy's engineering years and his rise to prominence (1826–1848)

Darcy joined the Corps as an engineer upon graduating in 1826 and spent most of his working life with them stationed in Dijon. According to Freeze (1994), Darcy and other prominent scientists and engineers attained public recognition and status in their tenure working there. Initially, Darcy was assigned by the Corps to a position in the Department of Jura but shortly thereafter, at the specific request of the Prefect of Côte d'Or, was transferred to Dijon in 1827. He was assigned to perform a preliminary feasibility study of the Dijon public water supply first proposed by Hugues Sambin, the sixteenth century architect of Dijon. Darcy substantially completed this task in the period 1828–1834 and in 1834 published *Rapport à M. le Maire et au Conseil Municipal, de Dijon, sur les Moyens de Fournir l'Eau Nécessaire à cette Ville* (*Report to the Mayor and the Town Council of Dijon on the Methods of Providing Necessary Water to the City*; Darcy 1834). On 5 March 1835, the Municipal Council approved his plans with no revision, and on 31 March 1837, the Dijon water project was declared a public utility by a royal ordinance. On 21 March 1839, work began on the Dijon water project and on 6 September 1840, water was delivered to the reservoir at Porte Guillaume, just some 535 days later (Brown 2002a). Darcy had transformed a provincial capital rid with filth and squalor into a city with one of Europe's best water supply systems by about 1840. It was purported to be second only to Rome at the time and occurred well in advance of even the water-supply development in Paris that was achieved by the mid 1860s. Work on the delivery and distribution system continued until 1844 when the Dijon water supply was largely completed. In May 1840, Darcy was appointed Chief Engineer for the Department of Côte d'Or at the young age of 37. Darcy's rise to prominence had begun.

At around this time, Darcy was also involved in the construction of a number of road projects, navigation works and bridges. These included two major structures over the Saône River (Marsaines 1858), his project to cover a 1.3-km stretch of the Suzon, a small stream that acted as an open sewer through the centre of Dijon (de Caudemberg 1858) and his important work on the design and initiation of the component of the Paris-Lyon railroad that passed through the Côte d'Or (Darcy 1957). This involved the construction of the 4-km tunnel at Blaisy which began in January of 1845 and of which Darcy had completed about one third before a private corporation took over the project in April of 1846 (Brown 2002a). The Blaisy Tunnel is still used today by the TGV, the high-speed train that connects Paris and Dijon. As noted by Brown (2002a), the tunnel equalled the longest existing tunnel at the time.

Brown (2002a) describes the awards that followed and Darcy's rise to prominence in the period 1834–1848. They are also described by Philip (1995). These included a letter from the Under Secretary of State and Director of Public Works (Dumay 1845) that praised his work. Darcy was awarded the Legion of Honor by King Louis Philippe on 31 August 1842. He accepted a gold medal from the Municipal Council and a laurel wreath from the workmen when the project was completed in 1844 but he waived all fees. It is believed that an identical bronze version of the original medal was awarded to Darcy at that time. It is an heirloom of the living Darcy descendents but the whereabouts of the gold original are unknown (Pierre Darcy de Moltke Huitfeldt, personal communication, 2006). To this author's knowledge, the original medals have not previously been reproduced in the literature. Recent photographs taken by this author of the front and reverse sides of the original medal are shown in Fig. 3.

As described by Philip (1995), "Darcy, with great vision and skill, designed and built a pure water supply system for Dijon, in place of previous squalor and filth. Dijon became a model for the rest of Europe. Darcy selflessly waved fees due to him from the town, corresponding to about $1.5 million today. Medals were struck recognizing his skill and selflessness; and a monument celebrates his great work". The translated inscription on Darcy's tomb expresses the strong sentiment felt in Darcy's time (Philip 1995), "He conceived the project, made all the studies, pursued to the end the execution of the works to which Dijon owes the creation and the abundance of its public waters. Doubly benefactor of his native town through his talent and his selflessness". The translation to "selflessness" here is arrived at from the

 DOI 10.1007/s10040-008-0304-3

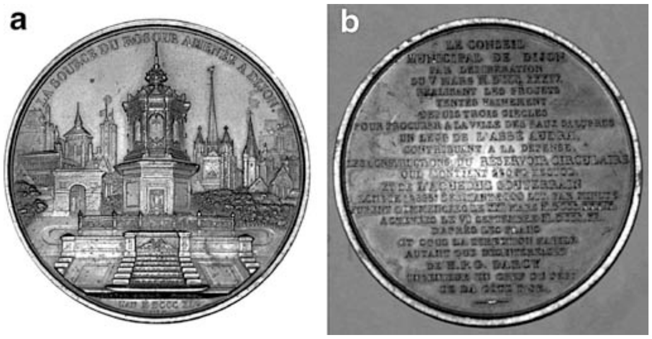


Fig. 3 Photographs, **a** front and **b** reverse, of the original medal awarded to Darcy by the municipal council. The tower at Porte Guillaume reservoir is evident on the front side design. Photographs taken by the author in 2006 and reproduced courtesy of Pierre Darcy de Moltke Huitfeldt

French word *désintéressement*, and Philip notes that the word means "the total putting aside of one's own selfish interests". Philip also notes that the word *désintéressement* appears many times in Darcy documents and that the literal translation *disinterestedness* would be too weak a translation. Darcy did, however, accept one final reward for his work. In 1846, the Municipal Council resolved "The town will provide free to M. Darcy, during his life, in the house which he occupies, the quantity of water from the public supply required for all the needs of his family and household" (Philip 1995).

Research excellence in Darcy's final years (1848–1858)

It was not all fun and joy for Darcy. He suffered political persecution and in the later years of his life his health deteriorated. In 1848, a revolution brought on by an economic depression saw the French constitutional monarchy ruled by King Louis Philippe replaced by a provisional republican government. At only 45 years of age, Darcy was suspended from duties since he was considered "dangerous for the new state of things" (Darcy 1957) and apparently had too much influence in Dijon for the new Commissioner's liking (Brown 2002a). Darcy was at the height of his career, and was deemed the hero of his fellow citizens (Philip 1995). According to Philip (1995), in Darcy's very success lay his downfall. Philip (1995) notes that despite the fact that Darcy was totally apolitical and had over the years given generously of his own money to set up workers' cooperatives, the Second Republic saw him as dangerous and a reactionary collaborator with the ancient regime. Darcy lost his offices and was banished from Dijon in 1848. In that period, Darcy was appointed to Bourges to work on the Berry canal project and prepared plans for a new project to provide drainage and irrigation over the Sologne region. Soon after the formation of the Second Republic, however, and the election of Louis Napoleon on 20 December 1848, Darcy was transferred to Paris and appointed as Chief Director for Water and Pavements. On 2 December 1852, the Second Republic was officially ended and the Second Empire formed. President Louis Napoleon Bonaparte became Emperor Napoleon III. It appears that Darcy was now "politically rehabilitated but his days were numbered" as Philip (1995) puts it. Darcy's health was failing. A nervous disorder accompanied by symptoms of meningitis had been noticed as early as 1842, and he suffered a very bad period of health while directing the works at Blaisy (Darcy 1957; Brown 2002a) that de Caudemberg (1858) attributed to a railcar accident during the construction of the Blaisy tunnel. Darcy lost consciousness during a conference in Paris in 1853.

In April 1850 Darcy travelled to England to collect data and information on the practice of English road construction (including the paving of streets with layers of crushed rock called macadam) that was published quickly upon his return to Paris (Darcy 1850). The report was highly regarded and Darcy was promptly promoted to the rank of Inspector General, 2nd Class, in April of 1850 (Brown 2002a). At around this time, Darcy also consulted on the City of Brussels' municipal water system, for which he received the Order of Leopold. This most significant new appointment as Inspector General provided Darcy with major research opportunities, particularly as his new position brought with it command of the large hydraulic installation at Chaillot (Brown 2002a).

The shift to research in the last few years of Darcy's life would see Darcy make some major scientific discoveries–what might now be called the Darcy scientific legacy. Importantly, Darcy's research efforts had been inspired by many years of engineering service and indeed, it is clear that Darcy's research was directly developed for engineering purposes. In the period 1850–1854, Darcy designed and implemented an experimental program intended to improve the estimation of the Prony pipe friction coefficients (Darcy 1857). Darcy's work on pipe friction was substantially completed in the period 1850–1854. In the period between its submission to the French Academy of Science in 1854, and its ultimate publication in 1857, Darcy's health was failing. In 1855 he returned to Dijon and requested release from all active duties except research. His wish was granted. In his final two years, Darcy gave full attention to his experimentation. In Dijon, he worked on two sets of experiments, those with Bazin on the Bourgogne Canal and the famous column experiments with Ritter in the unnamed hospital laboratory. In this period he wrote *Les Fontaines*, arguably his "swansong" thesis completed just two years before he died (Brown 2002a). In 1857, Darcy was unanimously elected to hold the prestigious Chair of the French Academy of Sciences, a position held previously by the great mathematician Cauchy but the position was not long-lived. Darcy died on 3 January 1858, at the age of 54. He had apparently fallen ill with pneumonia on a trip to Paris, no doubt brought on by the lingering effects of his many years of poor health (Freeze 1994). Darcy (1957) notes he was "carried off by pleurisy aggravated by angina". His body was taken by rail to Dijon where he was given a state funeral. The day immediately after his death, the square Château d'Eau, the location where the waters of the Rosoir spring

DOI 10.1007/s10040-008-0304-3

enters Dijon, was officially renamed Place Darcy–a decision arrived at unanimously by the Dijon Municipal Council.

Darcy's work on improvements to the Pitot tube that yielded its modern design (Darcy 1858; Brown 2003) were published posthumously in 1858. His protégé at the Corps, Henri-Emile Bazin (1829–1917), an engineer some 26 years Darcy's junior, published the results of open channel flow experiments originally designed with Darcy in their report titled *Recherches Hydrauliques, Enterprises par M.H. Darcy* (Darcy and Bazin 1865). Also published posthumously, this publication would be Darcy's last.

Darcy's contributions to science and engineering

While the previous section sets out the major path of Darcy's life within a historical context and the important points in the Darcy timeline, it is important to examine Darcy's scientific and engineering work more fully. Scientists and engineers are the beneficiaries of Darcy's scientific legacy–a legacy that not only included his well known law of water flow through sand, but also many other important contributions to hydraulics that are outlined below. As an engineer, Darcy's research contributions were clearly inspired by a life of engineering excellence and driven by a deep desire to solve practical and useful engineering problems that he had encountered along the way.

Observations of aquifer resistance

In 1834, Darcy published his report *Rapport à M. le Maire et au Conseil Municipal, de Dijon, sur les Moyens de Fournir l'Eau Nécessaire à cette Ville* (*Report to the Mayor and the Town Council of Dijon on the Methods of Providing Necessary Water to the City*; Darcy 1834). In it, Darcy described tests conducted in the groundwater system at Place Saint-Michel on 6 August 1830. Darcy noted that the groundwater supply would not be sufficient to meet Dijon's needs and recognised that a clean water supply for Dijon would necessarily involve more conventional surface-water methods (Dumay 1845; Brown 2002a). de Caudemberg (1858) describes the efforts made by a society of subscribers and the Municipal Council in hopes of repeating Molut's successful artesian well in Paris (Brown 2002a). It is likely that this outcome would probably have been seen as a major disappointment. However, it was within this failed pump test that Darcy made an important new observation–that the aquifer being pumped provided significant resistance to flow, an apparently new discovery (Brown 2002a). Darcy noted that the amount of water yielded by the well was less than would be expected even when friction losses within the pumping well were accounted for. According to Brown (2002a) Darcy correctly concluded, "The comparison of these figures shows that the source did not provide to the pump what the head and the diameter of pipe made it possible to provide, or in the least, the difference was absorbed by filtration" i.e., aquifer losses. It appears that Darcy may have been making a connection here between real aquifer processes and the filtration mechanics in a filter bed since he used the term "filtration" explicitly here and again later in Note D of the famous *"Les Fontaines"* text (Darcy 1856) in which Darcy's Law was discovered. In numerous places throughout the 1856 text, it is clear that Darcy understood that the aquifer could provide significant resistance to flow.

The Darcy-Weisbach equation, boundary layers, laminar/turbulent flow

Pressure drop during internal pipe flow is one of the most important considerations in designing a fluid flow system. Building upon his interest in pipe flow that had grown whilst working on the Dijon water system throughout the 1840s, Darcy initiated, designed and completed a comprehensive experimental program intended to improve the estimation of the Prony pipe friction coefficients (Darcy 1857; Brown 2002a, 2002b). This work was largely conducted in the period 1850–1854, although his report *Recherches Expérimentales Relatives au Mouvement de l'Eau dans les Tuyaux*, (*Experimental Research on the Movement of Water in Pipes*) was published later in 1857 (Darcy 1857).

At the time, the Prony equation (Eq. 1) was the widely accepted pipe flow resistance equation used to calculate head losses in pipes (and open channels using different empirical coefficients) but was one that was prone to error since the empirical and recommended pipe friction coefficients did not account for pipe roughness.

$$h_L = \frac{L}{D}\left(aV + bV^2\right) \text{ The Prony Equation} \tag{1}$$

where h_L is the head loss due to friction calculated from the ratio of the length to internal diameter of the pipe L/D, V is the velocity of the flow, and a and b are two empirical friction coefficients that account for friction. The Prony friction coefficient values were debated, but they were believed not to be a function of pipe roughness (Brown 2002b).

Darcy's new results showed that the pipe friction factor (and hence head loss) was a function of both pipe roughness and pipe diameter. Indeed, his new formulation provided a much better estimation of losses. Darcy proposed an equation (Eq. 2) that was similar to the Prony equation with friction coefficients that were a function of pipe diameter D, and which reduced to the version now known as the Darcy-Weisbach equation (Eq. 3) at high velocities (Brown 2002a, 2002b). As noted by Brown (2002b), the pipe friction equation proposed by Darcy took the form:

$$h_L = \frac{L}{D}\left[\left(\alpha + \frac{\beta}{D^2}\right)V + \left(\alpha' + \frac{\beta'}{D}\right)V^2\right] \tag{2}$$

The Darcy Pipe Friction Equation

DOI 10.1007/s10040-008-0304-3

where α, β, α', $\beta'$are friction coefficients. He noted that the first term could be dropped for old pipes and at higher velocities to yield an equation that looks similar to the Darcy-Weisbach equation (Eq. 3) that is commonly used today.

$$h_L = f\frac{L}{D}\frac{V^2}{2g} \text{ The Darcy} - \text{Weisbach Equation} \tag{3}$$

where f is usually called the Darcy friction factor and is a complicated function of the relative roughness and Reynolds number (Reynolds 1883), and g is acceleration due to gravity. It may be evaluated for a given set of hydraulic conditions by the use of various empirical or theoretical correlations, or it may be obtained from published charts referred to as Moody diagrams, after Lewis F. Moody (1880–1953). A detailed historical account of the Darcy-Weisbach equation has been given by Brown (2003) and the reader is referred to that for further details. It is interesting to note from that account, however, that it was actually Julius Weisbach (1806–1871) who first proposed the current form of the Darcy-Weisbach equation in 1845 (Rouse and Ince 1957) but it was Darcy's work that identified surface roughness as an important parameter in fluid flow and introduced that concept to the science of fluid dynamics. The friction factor term f is therefore usually called the "Darcy f factor", although Darcy did not propose it in that form. It was actually J.T. Fanning (1837–1911) who first combined Weisbach's equation with Darcy's improved estimates of the friction factor (Brown 2002b). Since Fanning worked in terms of radius instead of diameter in his friction analyses, the Fanning f values are one quarter of the Darcy f values. Darcy's contribution to understanding of pipe flow friction losses and the improved Prony pipe friction coefficients is acknowledged in the joint naming of the Darcy-Weisbach equation.

In his 1857 report, Darcy also made the first accurate measurements of turbulent pipe velocity distributions and provided the very first evidence of the existence of the fluid boundary layer (Darcy 1857) which were made possible using his improved Pitot tube designs. Whilst limitations in technique inhibited detailed measurements of the boundary layer in quantitative terms, Darcy began to suspect the existence of the boundary layer when he compared results in both smooth and rough pipes. In a translation by Rouse and Ince (1957, p. 170) it is immediately clear that Darcy correctly suspected that the fluid boundary layer was the cause of the variation between smooth pipe and fully rough flows: "If one uses very smooth pipes, of lead, recovered with glazed bitumen, etc, the coefficient of V^2 does not appear to correspond only to the resistance caused by the asperities, but also to that produced by the fluid layer next to the boundary".

Darcy also recognised the similarity of his pipe friction formula with Poiseuille's Law (Poiseuille 1841) developed by Jean Louis Marie Poiseuille (1797–1869), an experimentally derived physical law concerning the voluminal laminar stationary flow of incompressible uniform viscous liquid through cylindrical capillary tubes with constant circular cross-section. Darcy later showed that his newly proposed pipe friction formula reduced to Poiseuille's linear equation (Eq. 4) at low flow and small diameters, namely,

$$Q = kD^4\frac{h_L}{L} \text{ Poiseuille's Law} \tag{4}$$

where Q is the volumetric flow rate of the liquid and k is an empirical coefficient that lumps constants with a second order equation for the temperature dependent viscosity (Poiseuille 1841). Darcy clearly understood that a linear relationship between flow rate and head loss held when slow flows occurred in small diameter pipes (i.e. under the conditions of laminar flow). According to Brown (2002a) Darcy wrote, "Before seeking the law for pipes that relates the gradient to the velocity, we will make an observation: it appears that at very-low velocity, in pipes of small diameter that the velocity increases proportionally to the gradient". He later showed explicitly that his newly proposed pipe friction formula would reduce to Eq. 4 at low flow and small diameters. Darcy noted that this was a "rather remarkable result, since we arrived, Mr. Poiseuille and I, with this expression, by means of experiments made under completely different circumstances". Darcy had made the important connection between real pipes and capillary tubes, "My formula seems to contain the link that unites the laws of water flow in a pipe of any diameter and in a capillary pipe" (Darcy 1856, Note G). He had probably already made a connection, based upon the expected slow speed of water flow through sand, between his work on pipes and his work in sand columns. Indeed, a footnote in his 1857 report notes the similarity to his 1856 results for flow in sand columns. Similarly, Darcy's 1856 report noted the similarity of his sand column results with his (laminar flow) pipe results. Whilst workers such as Poiseuille and Hagen had begun to understand the differences between low and high velocity flows in capillary tubes (what are now called laminar and turbulent flows), Darcy had extended those insights into real pipes and to pipes of larger (general) diameters. All available documentation shows that Darcy understood the differences in the flow regimes and the subsequent limitations and applicability of his findings. There can be no doubt that Darcy clearly understood how pipe diameter and flow velocity affected his results. Whilst, according to Brown (2002a), it appears that Darcy had discovered "the kernel of the truth" by 1854, it was not until the work of Osborne Reynolds (1842–1912) in 1883 that the differences between laminar and turbulent flow were truly quantified.

Les Fontaines and Darcy's Law

"A city that cares for the interest of the poor class should not limit their water, just as daytime and light are not limited" (Darcy 1856).

 DOI 10.1007/s10040-008-0304-3

An overview of Les Fontaines

Although work on the Dijon water supply was largely conducted in the period 1834–1844, it was not published until 1856. It is likely that Darcy's failing health prompted him to complete the write-up of what is now considered by many to be his most famous text on the construction of the municipal water supply of Dijon (Darcy 1856). Darcy noted that various books available at the time debated issues relating to water supply systems but that they did so theoretically and that "a publication that reports on the construction of a large distribution system would be of interest to engineers". Full details of this monograph are now readily accessible worldwide thanks to Patricia Bobeck's faithful English translation (Bobeck 2004) for which Bobeck was awarded the prestigious S. Edmund Berger Prize for Excellence in Scientific and Technical Translation by the American Foundation for Translation and Interpretation in 2004. Patricia Bobeck's translation of *Les Fontaines Publiques de la Ville de Dijon* opens a window into the world of engineering science in the early nineteenth century, as well as its challenges and implications for the present. There are many other fascinating pieces of scientific, social, and historical information throughout the monograph and the illustrative plates are amazing pieces of engineering artwork.

The original Darcy monograph was some 680 pages long and contained 28 plates of figures in a separate atlas. While much of the material in it addresses the Dijon water supply, Darcy also discussed several other topics including groundwater, sand filters and pipe manufacture. Darcy's monograph shows how he approached the design and construction of the Dijon water supply system by choosing the water source, building an aqueduct and designing the water distribution system. Darcy's design collected about 8 m^3/min at the Rosoir Spring, which was dug out to improve its flow. The system did not rely on pumps, as it was gravity driven. From the original Rosoir spring source, the water was carried some 12.7 km in a covered aqueduct to an enclosed reservoir located near the Porte Guillaume (holding capacity 2,313 m^3) and another reservoir at Montmusard (holding capacity 3,177 m^3). The entire engineering design contained some 13.5 km of distribution lines. It supplied 141 public street fountains spaced 100 m apart throughout Dijon that would supply abundant free water for domestic purposes (one fountain for every 200 people), for washing streets and sewers and in fire fighting. One of the most elegant reservoir entrances is shown in Fig. 4, at "Chateau d'Eau" at La Porte Guillaume (Darcy 1856, Plate 9).

In the 1856 text, Darcy also clearly emphasised the importance of science in providing and understanding water resources. In Darcy's time, hydrogeology was still arguing about the Greek water cycle which moved water from the sea to the continents. Interestingly, Father Paramelle's famous book *The Art of Discovering Springs* which was published in 1856, the same year as Darcy's work, was the best seller not Darcy's (de Marsily 2003). Unlike Darcy's engineering work, Paramelle's work is a much more descriptive and "naturalistic" contribution that

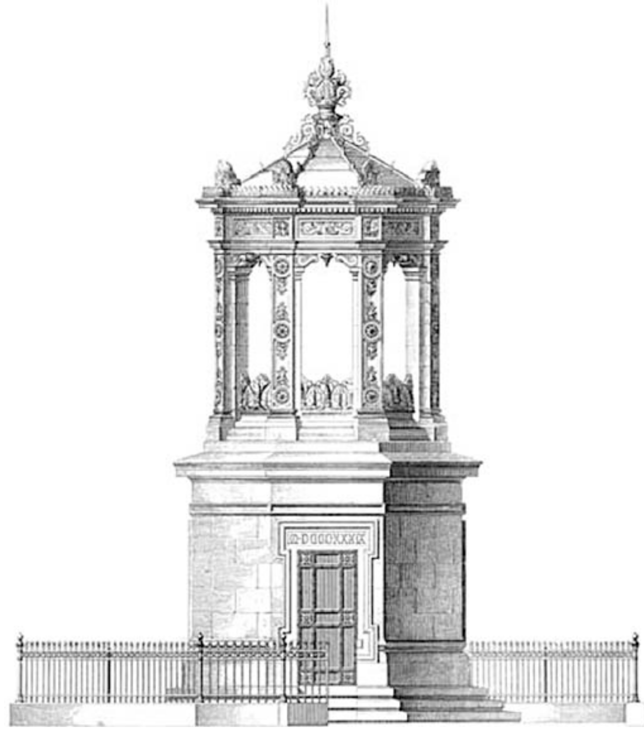


Fig. 4 Darcy's design of the tower at Porte Guillaume reservoir (Darcy 1856, Plate 9). The tower and reservoir are still standing today

is quite different to that of Darcy (1856). Darcy's discussions of Father Paramelle's exploration for springs and the ancient Greek hydrologic cycle are well written and perceptive. After what initially appears to be a significant number of pages dedicated to a gentlemanly debunking of Paramelle's methods and Darcy's dismissal of dowsing as a cult (Sharp and Simmons 2004), Darcy eventually saw some usefulness in Paramelle's observations and recognised him as a good geologist concerned with underground hydrography. In the end, it is clear that whilst Darcy did not agree with all the rules and methods provided by Paramelle to discover springs, he no longer dismissed him as a water dowser.

Les Fontaines Publiques de la Ville de Dijon begins with Darcy's introduction on the need for a good water supply, the requirements for achieving this supply, and the organization of the book into four parts. These are outlined as follows. Part 1: History of Dijon's water supply and research conducted from the fifteenth to the nineteenth centuries, a discourse on springs and the rationale for choosing the Rosoir Spring as the source of Dijon's water supply. Part 2: The design of the Rosoir aqueduct and water distribution systems, including pipes and pipe design, street fountains both for supply and public display, valves, and the two reservoirs, plus a cost analysis (Darcy intended his monograph to be a manual for future water supply projects). Part 3: Experiments on flow of water in the aqueduct and conduit systems. Part 4: Administrative and judicial issues. These are followed by eight appendices: (1) Springs in the Dijon area; (2) A

DOI 10.1007/s10040-008-0304-3

fifteenth century contract for Dijon water; (3) Water supply systems for various cities, including London and Paris; (4) Filtration (which includes the famous Darcy column experiments); (5) Weir gauging; (6) Extracting constant volumes of water from a varying-level stream channel; (7) Pipe fabrication methods; and (8) Flow in the Rosoir aqueduct.

The discovery of Darcy's Law

Darcy left his greatest gift buried in the depths of the report. Part 2 of Note D, in a subsection translated by Bobeck (2004) as "Determination of the laws of water flow through sand", contains the results of his famous column experiments. Freeze (1994) described their appearance as "hardly front and center". Here Darcy's motivations are clear. In presenting data concerning the discharge of filters in England, Scotland and France, Darcy's principal motivation for the column experiments is clarified when he writes "no general law can be deduced from this data, given that the nature and the thickness of the filtration sands are not comparable, that the heads are variable, and the water enters the equipment with different degrees of clarity. I have tried to use precise experiments to determine the laws of water flow through filters....". Water filtration methods and galleries were becoming an increasingly common practice at the time to improve water clarity (see Guillerme 1988 for a review) and, as a result, engineers were starting to think about the behaviour of filters (e.g., Génieys 1835). However, no general law governing their hydraulic behaviour had yet been discovered–a critical observation that helps understand the scientific landscape and historical context in which Darcy's Law was found. Darcy remarks on the need to "decrease significantly the surface area of artificial filters" and the section of Note D on modifications to apply to filters begins with the statement "Now I would like to discuss a method of significantly increasing the discharge of filters per given surface area and as a result, facilitating the construction of this equipment that until now has required sites so large that the very choice of them was one of the major difficulties of large-scale filtration". But one thing was still missing–a physical law that would express the relationship between filter volumetric capacity, filter dimensions (area and thickness), filter bed properties, and the hydraulic conditions under which the filter should be operated. With that motivation in mind, Darcy set out to unravel the universal porous media flow law–a flow law that he had suspected based on his earlier work on pipes.

It is interesting to provide some details on Darcy's column experiments, although full details are now readily accessible in Bobeck (2004). Brown (2002a) also provides a comprehensive analysis of the experimentation. Two sets of column experiments were performed in total. Set 1 (23 experiments) were conducted with the assistance of engineer Mr Charles Ritter (on 29–30 October and 6 November 1855) and Chief Engineer Mr Baumgarten repeated those experiments but the repeat tests are not reported. Set 2 contained an additional 12 experiments that were conducted by Mr Ritter alone (17–18 February 1856). The major difference between the experiments rested in the pressure conditions applied to the column. The first set was undertaken with the outlet at the bottom held at atmospheric pressure, and the second set was conducted with variable inlet and outlet pressures by methods that are not reported. A total of 35 experiments were reported. Darcy's experiments were conducted in an unnamed hospital courtyard. The apparatus used is shown in Fig. 5 (Plate 24, Fig. 3 of the original monograph) and consisted of a vertical column 2.50 m high (note here that the text suggests this dimension but that the original figure notes a vertical height of 3.5 m–perhaps this is an error or were there two column designs?) and with an internal diameter of 0.35 m. The experiments were performed using siliceous sand from the Saône River, and each experimental series had a different sand packing. Packing height varied from 0.58 m (series 1) to 1.70 m (series 4). The column was filled with water first and then sand was poured and packed into it. Brown (2002a) notes that the packing method used would have resulted in the coarsest

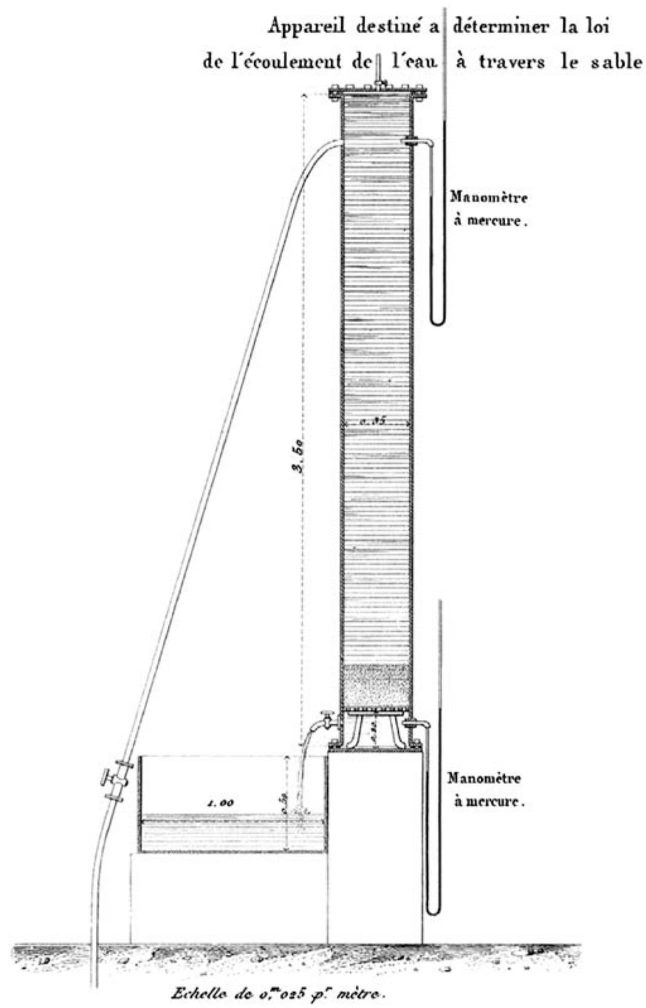


Fig. 5 Darcy's original sand column apparatus (Darcy 1856, Plate 24, Fig.3)

 DOI 10.1007/s10040-008-0304-3

particles settling at the bottom of each lift, but that since the experiments were run to equilibrium and the height of the sand was measured only at the end of each series of experiments ("after the passage of water had suitably packed the sand"), the packing method would not have altered any of Darcy's conclusions.

The column was set up so that water flowed into the sand column from above through a pipe connected to the hospital water supply and vertically downward through the column before exiting from the lower outlet. The pressure at the two ends of the column was measured by a U-shaped mercury manometer which, under weak heads, resulted in almost complete quiescence of the mercury in the manometer and allowed measurement to the nearest millimetre, representing 26.2 mm of water. Darcy observed that, when operating under higher pressures, large (but random) fluctuations allowed the average height of mercury to be measured to the nearest 5 mm, and thus allowed the water pressure to be determined to about 13 cm. Here, Darcy observes that the fluctuations were due to "water hammers produced by the operation of the numerous street fountains at the hospital where the experimental apparatus was located"–an effect brought about by Darcy's own water supply that he had constructed some 15 years before the experiments were conducted. In each experiment, the extent of oscillations was noted. When the inlet and outlet pressure observations assured that the flow had become uniform, the discharge of the filter was noted for a certain time, and the average discharge per minute was determined.

The duration of the experiments varied between 10 and 30 min, and within each series, the mean discharge per minute was both varied and measured. The smallest value of volumetric discharge rate used was *Qlower*=2.13 l/min (in set 1, series 3, experiment number 1) and the highest value of *Qupper*=29.40 l/min (in set 1, series 1, experiment number 10). Darcy noted that the results "demonstrate that the discharge from each filter increased proportionally with the head". Darcy denoted Q as the "discharge per second per square meter", and I as the "head per meter of filter thickness" and noted that for each series, a straight line relationship existed between Q and I. However, between experiments, slightly different values of the coefficient Q/I (what is now called hydraulic conductivity) were observed. Here Darcy noted that the sand used was not consistently homogeneous. For the second series it was not washed; for the third series it was washed; for the fourth series, it was very well washed and had a slightly larger grain size. He then concluded, "Thus, it appears that for an identical sand, it can be assumed that the volume discharged is (directly) proportional to the head and inversely proportional to the thickness of the sand layer that the water passes through". And in those few words, quantitative hydrogeology as it is known today was born. Darcy had provided conclusive evidence that the water flow rate was a linear function of the total head loss across the filter bed and not just the difference in water pressure. The subsequent experiments in February 1856 were undertaken to ensure that the law could be generalised, and that the experimental conditions employed to develop the law covered the necessary and different pressure conditions that might be expected in an operational filter plant. Darcy had an extremely good understanding of hydraulics, and he would have known that the pressure would not have impacted his new discovery. He therefore let Mr Ritter conduct the second set of experiments alone in February 1856, which successfully confirmed that this was indeed the case (Brown 2002a). Darcy then stated his law (exactly as it is written in Eq. 5) for the very first time, noting that the pressure on the top of the layer was P+h (where P = atmospheric pressure and h is the height of water on the sand layer), and on the bottom of the layer was $P \pm h_o$ to yield, in general terms:

$$q = k\frac{s}{e}(h + e \pm h_o) \text{ Darcy's Law from Darcy (1856)} \tag{5}$$

where q is the volume of water discharged (per unit time), k is a coefficient that depends on the permeability of the layer, e is the thickness of the sand layer and s is its surface area. Equation 5 can easily be generalised in terms of general pressure heads and elevation heads at the inlet and outlet accordingly to yield, the more familiar version used routinely today. Furthermore, the Darcy unit of permeability (D) that is widely used in geology and petroleum engineering recognises that Darcy was the first to note that flow depended upon a permeability coefficient, a direct consequence of his experiments and the discovery of his law.

A number of interesting points follow from the column experiments that help to contextualise Darcy's Law and the process of his discovery:

1. *Darcy did not stumble on to his law, he suspected it.* His column experiments were carefully planned and meticulously executed. Darcy had a very strong understanding of the underlying fluid mechanics, informed by both his background education and the great experience he had already amassed in his pipe flow research. He had already made the connection between flow in real pipes and flow in smaller diameter capillary tubes at low flows and knew that his pipe formulae would reduce to Poiseuille's Law under the limiting (small pipe diameter, low flow i.e., laminar) conditions. Now all that remained was for the connection to be made with sand and Darcy did not leave that stone unturned. Indeed, when discussing his new law, Darcy notes clearly in footnote 4 of Note D, "I had already foreseen this curious result in my research on water flow in conduit pipes of very small diameters, when the water velocity did not exceed 10 to 11 centimeters per second". Darcy made the first clear connection between flow in sand and flow in small pipes at low velocities. He knew that his law and Poiseuille's Law were linear laws and most importantly, he understood why.

 DOI 10.1007/s10040-008-0304-3

2. *Darcy understood his discovery was new and significant.* This is noted by Darcy himself when he writes in his preface "I have not seen the documents that are included in Note D collected in any special book. In particular, to my knowledge at least, no one has experimentally demonstrated the laws of water flow through sand". Darcy's personal view on the significance of Note D is also enforced by the fact that he dedicates almost half the length of his preface to his entire monograph to a discussion on it.
3. *Capillary tube models of porous media and the representative elementary volume (REV)*. Whilst Darcy made the connection between capillary tubes and porous media, he did so primarily on the basis of flow speed and his expectation that flow in porous media would be slow (i.e., they would be laminar, like that in small pipes with small flow speeds). He did not treat the porous medium formally or theoretically as a bundle of capillary tubes. This would follow very shortly after in a work by Dupuit (1857) who, according to Narasimhan (2005), idealized a permeable medium to be a collection of small diameter tubes, and showed that Darcy's Law was a special case of Prony's equation, with inertial effects neglected. Interestingly, it can also be seen in Darcy's text that he assumed proportionality of flow with surface area, and was therefore applying the principles of continuum mechanics. For the conditions under which Darcy's Law was developed, this may have been entirely reasonable but such approaches are now known to be at the heart of current challenges faced by hydrogeologists in difficult concepts such as defining the REV and its appropriateness, matters of hydrogeologic scaling and dealing with heterogeneity in the subsurface.
4. *The rise of the linear gradient laws*. Interestingly, the early to mid nineteenth century saw the birth of the entire suite of linear gradient laws including Fourier's heat conduction law discovered in 1822, Ohm's law for electricity discovered in 1827, Poiseuille's Law discovered in 1841, and Fick's Law for molecular diffusion discovered in 1855. Darcy's Law was the last of the great linear law discoveries. Darcy only makes mention of Poiseuille's Law (which was obviously the most relevant one to him) but he likely knew of the others and indeed may have been taught by Fourier. According to Groenevelt (2003), it is likely that Darcy was aware of Fourier's work soon after it was published and certainly well before he conducted his famous laboratory experiments in 1856. However, with the exception of Poiseuille's Law, Darcy did not cite any of the other linear gradient laws in his 1856 report.
5. *Darcy understood the practical significance of his law and he applied it.* Darcy developed the first falling head permeameter solution in Note D by combining his law with continuity, and then applied it to "determine the law of progressive decreases of a spring from its maximum flow" and for "increasing their product by artificially lowering their level". His work on spring discharge and artesian wells (and the discovery of a linear relationship between discharge and spring discharge height) as shown in Fig. 6, combined with his previous pipe research and the sand column experiments, lead Darcy to believe that the linear relationship was reasonable for "laminar" flow conditions i.e., that the wells were either supplied by very small diameter open conduits, or by conduits that were filled with sand. However, because observation wells were expensive, only drawdown in the extraction well was observed, and radial flow was ignored. Darcy continued to think of groundwater flow in terms of linear conduit flow. However, what is critical here is that Darcy was now applying his theoretical concepts developed in both his pipe research and sand column experiments to practical field applications in natural geologic media and was using real field data.

Improvements to the Pitot tube

In 1732, Henri Pitot (1695–1771) created a simple instrument to measure fluid velocity that is called the Pitot tube. This device is lowered into a flow field and contains two tubes. A static tube points straight down into the field (to measure static pressure) and a second tube has a 90° bend at the bottom that faces directly into the flow (that measures total pressure = static pressure + dynamic pressure). When the device is lowered into the flow the pressure differential is recorded by observing the difference in the liquid level in the two tubes. The difference is the dynamic pressure component that relates to the speed of the flow. The Pitot tube is commonly used in aircraft speed determination and other pneumatic devices. The original Pitot design had several problems as outlined in Brown (2003) who provides an excellent account of the major developments Darcy made to the Pitot tube and notes that Darcy's contribution to the development of the device equalled or exceeded Pitot's initial work. He also notes that Darcy's final design for the instrument tip is reflected today in modern instrumentation and that it is appropriate to call the modern design the Pitot-Darcy tube. Darcy used evolving designs to make accurate measurements of point velocity within pipes (Darcy 1857) and in mapping isovels (lines of equal velocity) in open channels (Darcy and Bazin 1865). The Pitot tube also made an appearance in *Les Fontaines Publiques de la Ville de Dijon* (Darcy 1856) as is shown in Fig. 7. Darcy's 1858 publication *Note relative à quelques modifications à introduire dans le tube de Pitot* (*Note on modifications to be made in the Pitot tube*; Darcy 1858) was published posthumously shortly after his death and reflected several years of work gradually perfecting its design over the period 1850–1857.

Darcy's Law and the birth of quantitative hydrogeology

Considerable discussion on the history of hydrogeology may be found in previous works by Narasimhan (1998, 2005), Fetter (2004) and de Vries (2006). The intention

DOI 10.1007/s10040-008-0304-3

here is to provide important highlights on the evolution of groundwater science in the period following the discovery of Darcy's Law in order to illustrate how Darcy's Law was employed in the post-Darcy years to formalise the foundations for modern quantitative hydrogeology.

With the discovery of Darcy's Law, groundwater flow problems could be formulated in mathematical models and solved for given boundary conditions (de Vries 2006). Indeed, it would be just seven years before Darcy's Law was applied for the first time in what one might now call the first modern aquifer analysis. Arsene Jules Emile Juvenal Dupuit (1804–1866) submitted a ground breaking report in 1863 (Dupuit 1863) that solved the radial flow equation for steady flow to a well in both an unconfined and confined aquifer. Dupuit was Darcy's associate and successor as Chief Director for Water and Pavements for Paris and Darcy's contribution was noted clearly by both Dupuit and the reviewers at the French Academy of Science (Brown 2002a). In Germany, Adolph Thiem and then later, Gunther Thiem, his son, carried out pioneering studies on groundwater flow to wells and collected extensive observational evidence and data in field based

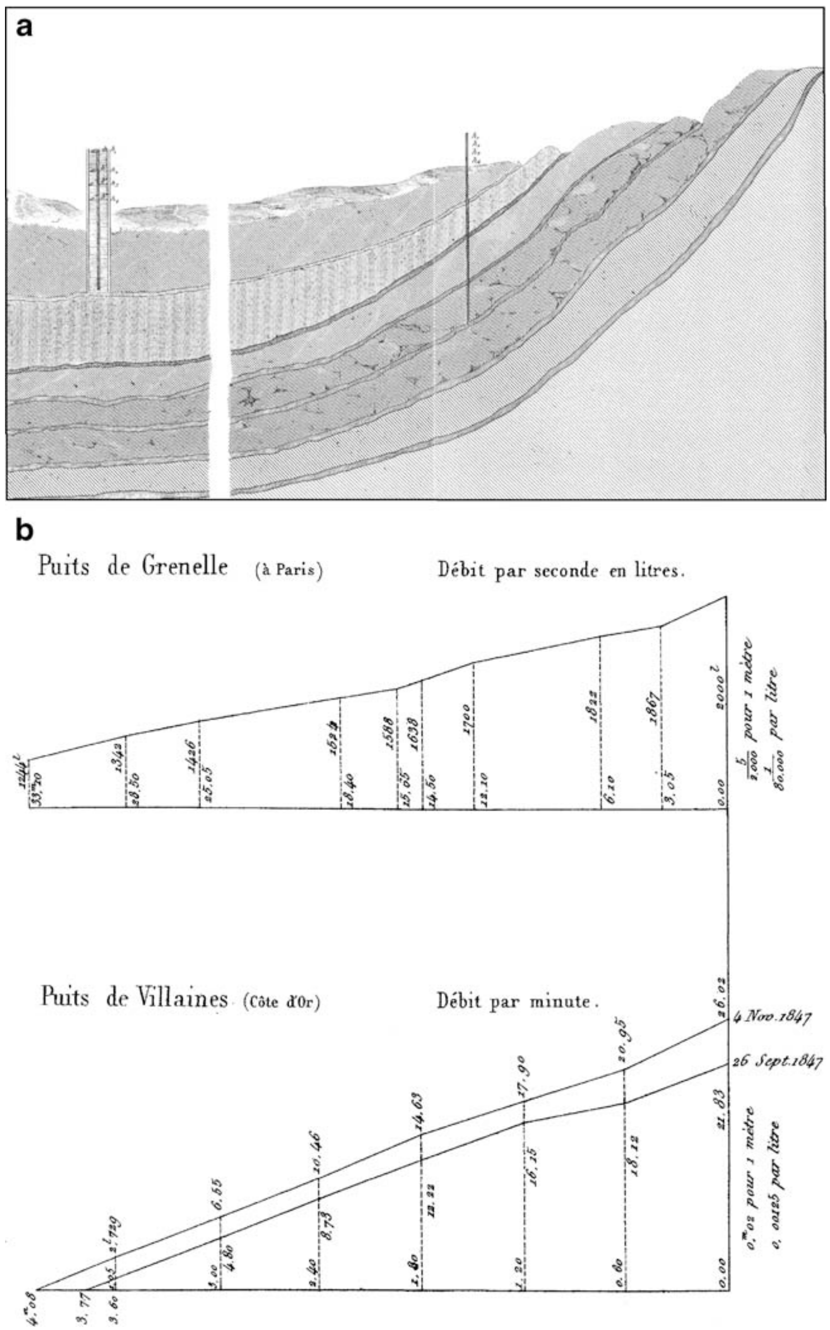


Fig. 6 Artesian well flow **a** Darcy's schematic of artesian flow measurements showing a geologic cross-section, and **b** flow rate measured as a function of the discharge elevation at two sites. A clear linear trend was observed in these and other data sets. (Darcy 1856, Plate 22)

 DOI 10.1007/s10040-008-0304-3

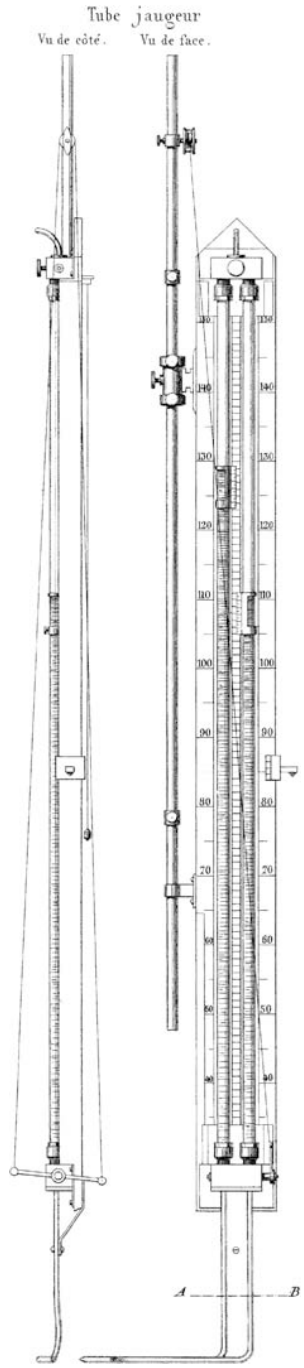


Fig. 7 The Pitot tube design used by Darcy in his 1856 report (Darcy 1856, Plate 23, Fig. 14)

settings. Although Adolph Thiem later became aware of Dupuit's work, it is understood that he independently derived the expressions for the steady radial flow of water in confined and unconfined aquifers (Narasimhan 1998; de Vries 2006). However, Thiem both knew of and utilised Darcy's Law. By using a pumping well and observing the resulting decline in water table in adjacent wells at steady state, Thiem (1887) essentially worked with a modified form of Dupuit's equations to calculate aquifer hydraulic properties. It is, however, Gunther Thiem (Thiem 1906) that is now widely recognized for his work with the steady state radial flow equation in a confined aquifer, although the solution was clearly derived much earlier by Dupuit (Narasimhan 1998). Unlike the earlier work of his father Adolph and that of Dupuit, Gunther focussed his efforts on advancing field based practice rather than in developing new theoretical work. He conducted pump tests in places such as the Rhine Valley in Germany in order to quantify aquifer hydraulic characteristics using real data.

Other important theoretical advances in groundwater hydrology were made in the nineteenth century by the French physicist Valentin Joseph Boussinesq (1842–1929), the Austrian hydraulic engineer Philipp Forchheimer (1852–1933) and the American Professor of Mathematics and collaborator with the United States Geological Survey (USGS), Charles S. Slichter (1864–1946). Boussinesq and Forchheimer were the first to realise that an analytical solution to a groundwater flow problem cannot be based on Darcy's Law alone and must also satisfy the continuity principle (de Vries 2006). In combination and under steady-state conditions, these yielded the well known Laplace Equation. Boussinesq, Forchheimer and Slichter all recognised the similarity between groundwater flow and heat flow and that the Laplace Equation would result in both cases under steady conditions. They used the Laplace Equation to solve steady state groundwater flow problems. As pointed out by Narasimhan (1998), Forchheimer was among the earliest to recognise the concepts of equipotential lines and streamlines in groundwater and he extended these concepts to generate flow nets as a means of quantitatively analysing steady flow fields, including groundwater flow to wells under varying geometric conditions. Forchheimer (1898) described steady state groundwater flow using the Laplace equation and used mathematical methods including conformal mapping to solve groundwater problems. The transient version of Forchheimer's Laplace Equation appeared in Boussinesq (1904). In the United States, Slichter (1899) was leading the way in the development of groundwater theory, again using steady state analyses of groundwater flow. He analysed the interference patterns between artesian wells and the effect of pumping on steady state regional groundwater flow. Completely independently, Slichter (1899) produced identical results to Forchheimer for the solution to steady state groundwater flow but he did not refer to Forchheimer (de Vries 2006). It is interesting that Slichter did not cite Forchheimer, although it is apparent he was familiar with some of the other important European studies at that time as he did cite Darcy, Dupuit and Thiem. Unlike earlier work which permitted horizontal groundwater flow only, Slichter made an important extension to include a vertical flow component. The preceding discussion makes it abundantly clear that Darcy's Law provided the critical foundation for subsequent quantitative contributions relating to groundwater flow made by workers notably including Dupuit, Thiem, Boussinesq, Forchheimer and Slichter during the mid- to late-nineteenth and early twentieth centuries.

 DOI 10.1007/s10040-008-0304-3

The late nineteenth century and early twentieth century would also see greater exploration of the relationship between groundwater and its host geologic formations. Field based studies continued to develop understanding of how geologic conditions control the occurrence, distribution and movement of groundwater. de Vries (2006) outlines some of these major groundwater exploration activities in Europe and the United States. Parker (1986) provides an overview of the early stage of hydrogeology in the United States from the mid-1770s to early 1900s. Despite its earlier origins in Europe, it is apparent that around the turn of the twentieth century there was a gradual shift in the centre of activity in groundwater research and investigation from Europe to the United States (Narasimhan 1998). The late nineteenth century saw a rapid growth in groundwater exploration in the United States associated with expansion and activity in the mid-western plains. A number of pioneering groundwater exploration studies were conducted in the late nineteenth century and early twentieth century (Chamberlin 1885; Darton 1905; Meinzer 1923a, 1923b). These were significant field based (rather than theoretical) investigations including noteworthy observational evidence, geologic characterisation, and descriptive discussion on the conditions governing the occurrence of groundwater. The first USGS groundwater report by Chamberlin (1885) on artesian wells did not cite Darcy or Thiem. Anderson (2005) also notes that Meinzer's later treatises on groundwater (Meinzer 1923a, 1923b) were largely qualitative discussions on groundwater occurrence and surprisingly omit any mention of the quantitative work of Darcy and Slichter.

In addition to the earliest application of Darcy's Law in deriving pump test formulae (Thiem 1906), it is useful to examine the continued dissemination of Darcy's Law into contemporary field based hydrogeology. In particular, it is interesting to consider when Darcy's Law began to be explicitly used to determine groundwater flow rates in field based settings. The earliest field based groundwater exploration work in the United States and the description of principles describing the occurrence of groundwater conducted by workers including Chamberlin, Darton, Mendenhall and Meinzer was largely observational in nature. There is, however, clear evidence that some of these early workers were beginning to think about, measure and compute groundwater flow rates in natural aquifer systems. Some very useful insights on early applications of Darcy's Law to determine groundwater flow rates are provided by Anderson (2006) who presents an excellent historical note on the educator and consultant Daniel W. Mead. She notes that an early textbook in hydrology (Mead 1919) contains a noteworthy chapter on groundwater (including a section on Darcy's Law) as well as two chapters on geology. In fact, in this book there is a table that is titled "Results of some observations on the flow of ground water" (Mead 1919, Table 45, p. 417). The earliest field application cited in that table is by E.L. Rogers from the Eng. Rec., Vol. 25, 1892, p. 435. The locality is not given and the material is "average sand" with a rate of 14.5 ft/day. The next earliest entry in the Mead (1919) table is by N.H. Darton, referencing the 18th annual USGS report, Sect, IV, 1896–97, p. 609 in the Dakota Sandstone with a rate of 14.5–29.0 ft/day. Presumably these early workers used Darcy's Law to make the calculation. Interestingly, Mead does not list the gradient for either of these entries as he does for some of the later entries. He talks about computing flow using Darcy's Law (he actually refers to it as Darcy's "formula") and gives an example calculation. Anderson (2006) notes the important section in Mead's text on Darcy's Law including a discussion of Slichter's related work on groundwater velocity measurements. She notes that Mead cites Slichter's work at length (e.g., Slichter 1899), relating Slichter's experimental formulas to Darcy's Law and identifying hydraulic conductivity in Darcy's Law as the "transmission constant". A closer examination of the report by Slichter (1905) titled *Field measurements of the rate of movement of underground waters* reveals that Slichter was clearly aware of Darcy's Law. He described it in physical terms in Chapter 1 of that report but did so without any direct mention of Darcy. He did, however, point out that he had previously dealt with the general laws governing the flow of water through a mass of sand or gravel in an earlier USGS report published in 1902. Darcy's work is presumably cited in that earlier report. Importantly, Slichter (1905) noted that earlier measurements he had made in the summer of 1901 to determine groundwater flow rates in the vicinity of the Arkansas River in the United States "constituted the first direct determinations of the rate of flow of ground water that had been made in this country". By this it may be implied that the earlier observations by workers such as Darton and Rogers employed an indirect method to calculate groundwater flow rates, presumably using Darcy's Law.

It is important to note that the application of Darcy's Law in groundwater flow measurements posed problems for earlier workers such as Slichter who were clearly struggling with the idea of hydraulic conductivity–both in terms of how to measure it and what it meant in physical terms. It is clear that they regarded hydraulic conductivity as a puzzling empirical constant that was dependent on porosity (Anderson 2006). This is immediately apparent in Table 1 of Slichter (1905) which presents "transmission constants" in tabular form for different soil types, soil particle diameters and porosity. The caption of Table 1 in Slichter (1905) reads "Transmission constants from which the velocity of water in sands of various effective sizes of grain can be obtained". Slichter also provided a nomograph method for estimating transmission constants using information related to the soil porosity, hydraulic gradient and diameter of the soil grains. It is clear that Chapter 1 and the nomograph method in Slichter (1905) were developed in order to apply Darcy's Law. However, the nomograph method was unnecessarily complicated and required all sorts of contortions to be performed involving soil grain diameter, porosity and hydraulic gradient in order to determine the transmission constant. In reading both Mead (1919) and Slichter (1905), it is immediately clear that early workers did not know how to assign hydraulic conductivity in calculations based upon

 DOI 10.1007/s10040-008-0304-3

Darcy's Law. As a result, they tried to directly measure groundwater velocity in aquifers rather than to use Darcy's Law (what might be called an indirect method because it requires knowledge of both hydraulic conductivity and hydraulic head gradient in order to compute groundwater flow speed). Slichter (1905) developed a device called an "underflow meter" to make direct measurements of groundwater flow velocity and direction, thereby avoiding the need for the difficult intermediate step using Darcy's Law which introduced problems associated with the uncertainty in hydraulic conductivity. The method essentially resembled that of a modern day tracer test. Furthermore, early workers knew that groundwater velocities could vary significantly within an aquifer. As noted by Anderson (2006), Slichter made measurements of groundwater velocity in a buried river channel and Mead used those measurements to illustrate that velocity "varies greatly in accordance with the materials, the porosities and the contour of the underground channel". Mead also expressed considerable uncertainty and scepticism about calculations of groundwater velocity based on Darcy's Law (Mead 1919; Anderson 2006). After reading these works, one is left wondering why Slichter did not conduct a pumping test and apply the Thiem equation to obtain field based estimates of hydraulic conductivity.

Indeed, it would be some two or so decades later before large-scale pumping tests would first be carried out in groundwater resource investigations in the United States. Bredehoeft (2008) notes that the USGS conducted a series of pumping tests in the 1930s in Nebraska, the first two conducted near Grand Island in 1931. Bredehoeft states that, according to Charles V. Theis in a personal interview, these tests were the first full-scale pumping tests in the United States. Fascinatingly, in that interview, Theis noted that Meinzer, who was head of the USGS Groundwater Division from 1912 to 1946, had been communicating with Gunther Thiem in Germany about pump tests. Indeed, we know that Thiem was already running pump tests in the Rhine Valley. Leland K. Wenzel (the USGS Groundwater Division's theoretician) conducted a serious evaluation of the limitations of the Thiem method using pump test data from Grand Island using drawdown data from 80 observation wells (Wenzel 1932, 1936). Since the Grand Island pump tests were the first full-scale pump tests in the United States, it is likely that the analysis of the Grand Island pump test data by Wenzel was the first serious attempt to determine aquifer hydraulic characteristics in field-scale settings in the United States. As a result of the Grand Island pump tests, the data were now available to apply the Thiem equation. It was also becoming clearer that the only available equation for interpreting a pump test at this time, the steady state Thiem equation, could not adequately explain field based pump test observations. The Thiem equation would, however, form a conceptual basis for the critical extension of pump test theory to nonsteady state conditions and the vital inclusion of a compressible porous medium (Theis 1935)–a true breakthrough in well hydraulics. Bredehoeft (2008) notes that after Theis' paper (Theis 1935) was published Meinzer asked Wenzel to reinterpret the data from the Nebraska tests using Theis' new theory and to extract the storage coefficient, which was in that particular case the specific yield (Wenzel 1942). This was a most important publication since it described in great detail the various methods that could be used for interpreting pump test data. Theis' groundbreaking contribution would in turn provide the basis for all pump test theory that followed under more generalised conditions by other workers (see Narasimhan 1998).

At around the same time of Theis' discovery, M. King Hubbert (1903–1989) developed an underlying theoretical foundation for the Darcy equation and introduced the concept of the force potential (gh) (Hubbert 1940). He examined Darcy's Law using the Navier-Stokes theory and emphasised that Darcy's Law is a macroscopic law. Hubbert also noted the limits of validity of Darcy's Law and established the foundations for the study of regional groundwater systems. That paper and others outlined above are still considered definitive by today's standards.

This body of papers formalised the foundations for quantitative hydrogeology and groundwater hydraulics and set the stage for the rapid growth in the number of groundwater papers that began to be published in the 1960s. Such papers spanned many areas of groundwater hydrology including aquifer hydraulic characterisation and dynamics (including groundwater flow rates and directions), computer modelling, the prediction of contaminant transport, and the continued quantitative assessment of groundwater resources. These later developments in modern day quantitative hydrogeology have their earliest origins in work on flow nets and pump tests and on subsequent analyses that followed as either a direct consequence of Darcy's Law or the immediate application of it.

Epilogue

Freeze (1994) reflected upon Darcy's life "I can see his path through life in its various roles: as a successful young student; as a fraternal brother in the Corps des Ponts et Chaussées; as a young engineer of such renown that he is asked to design the water supply for the city of Dijon; as the administrator of a large regional engineering office; as a respected leader of the community; as a victim of political pressure in a time of tumult; and as a research scientist who made lasting contributions to mankind". Darcy was a man who gave selflessly to his native people of Dijon to give them free and abundant clean water, which Darcy himself valued just as much as daytime and light. His work on the Dijon water supply would shape the rest of his life and see him rise to prominence in the Corps. Darcy's distinguished engineering years inspired his final research years. His research was aimed at solving practical and useful engineering problems. In the last few years of his life and despite his rapidly deteriorating health, Darcy unrelentingly pursued his research interests. He worked feverishly on several major research projects that were no doubt inspired by unresolved questions

 DOI 10.1007/s10040-008-0304-3

brought about by his engineering projects–his sand-column experiments, his improvements to Prony's pipe friction equation, his improvements to the Pitot tube for measuring point water velocity and his work with Bazin on the open-channel hydraulic experiments. Darcy's Law gave birth to modern quantitative hydrogeology. Scientists and engineers are the beneficiaries of a scientific legacy that includes Darcy's Law but that is not limited to it. It is a legacy created by a distinguished engineer and research scientist who in his short life of 54 years achieved many great things. Darcy lives on forever through his scientific and engineering contributions. Indeed, Darcy is immortalised by Darcy's Law and his scientific legacy.

Acknowledgments I would like to thank Professor G. O. Brown for many very informative exchanges over the years about Darcy and the history of hydrogeology. Thank you to P. Bobeck for her translation of Darcy's original 1856 report that has afforded us all a wealth of accessible new insights about Darcy's work and his law and for generously sharing her Darcy knowledge with me. I have also benefited from personal communication with many colleagues about this current work and the history of hydrogeology more generally. I thank M. Anderson, G. de Marsily, J. Sharp, T. N. Narasimhan and P. Renard for their very helpful comments. Thank you to F. Phillips, A. Davis and D. Stephens for providing supporting information that assisted in the preparation of this article. A. Freeze, S. Barles and C. Voss provided constructive reviews of this manuscript. Thank you to G. de Marsily, G. de Marsily, P. Brunner, T. Graf, M.-T. Schafmeister, M. Larocque, P. Bobeck and J.-J. Risler for assistance in translation matters pertaining to the text and references. Earlier historical accounts by J. R. Philip and R. A. Freeze inspired me to learn more about Henry Darcy and the history of hydrogeology. Finally, my sincere thanks to the living Darcy descendents in France, especially Henry Darcy V and his brother Pierre Darcy de Moltke Huitfeldt and their families. My personal contact with them continues to influence my writings on Darcy and has brought about new insights and information that were not contained in previous written accounts; I thank them for allowing us all to learn more about Henry Darcy.

References

Anderson MP (2005) Wisconsin roots of ground water hydrology. Ground Water 43(1):142–145

Anderson MP (2006) Daniel W. Mead: pioneer educator, ethicist, and consultant. Ground Water 44(2):319–322

Bobeck P (2003) Henry Darcy and the public fountains of the city of Dijon. In: Brown G (ed) Proceedings of the Darcy Memorial Symposium, World Water and Environmental Resources Congress, vol 10, American Society of Civil Engineers, Philadelphia, PA

Bobeck, P, trans (2004) The public fountains of the City of Dijon by Henry Darcy (1856). Kendall/Hunt, Dubuque, IO, USA, ISBN 0–7575–0540–6. Available Online via www.pbobeck.com. Cited March 2008

Bobeck P (2006) Henry Darcy in his own words. Hydrogeol J 14 (6):998–1004

Boussinesq J (1904) Récherches théoriques sur l'écoulement des nappes d'eau infiltrées dans le sol [Theoretical research on groundwater flow in unconfined aquifers receiving direct infiltration]. J Mathématiques Pures Appliquées 10:5–78:363–394

Bredehoeft JD (2008) An interview with C.V. Theis. Hydrogeol J 16(1):5–9

Brown GO (2002a) Henry Darcy and the making of a law. Water Resour Res 38(7). doi:10.1029/2001WR000727

Brown GO (2002b) The history of the Darcy-Weisbach equation for pipe flow resistance. In: Fredrich A, Rogers J (eds) Environmental and water resources history. American Society of Civil Engineers, Reston, VA, pp 34–43

Brown GO (2003) Henry Darcy's perfection of the Pitot tube. In: Brown GO, Garbrecht JD, Hager WH (eds) Henry P. G. Darcy and other pioneers in hydraulics: contributions in celebration of the 200th birthday of Henry Philibert Gaspard Darcy. American Society of Civil Engineers, Reston, VA, pp 14–23

Brown GO, Hager WH (2003) Note: spell it "Henry Darcy". In: Brown GO, Garbrecht JD, Hager WH (eds) Henry P. G. Darcy and other pioneers in hydraulics: contributions in celebration of the 200th birthday of Henry Philibert Gaspard Darcy. American Society of Civil Engineers, Reston, VA, pp 1–3

Chamberlin TC (1885) Requisite and qualifying conditions of artesian wells. US Geol Surv Ann Rep 5:131–173

Darcy H (1834) Rapport à M. le Maire et au Conseil Municipal, de Dijon, sur les Moyens de Fournir l'Eau Nécessaire à cette Ville [Report to the Mayor and the Town Council of Dijon on methods for providing necessary water to the city]. Douillier, Dijon, France

Darcy H (1850) Rapport à M. le Ministre des Travaux Publics, sur le pavage et le macadamisage des chaussées de Londres et de Paris [Report to the Minister of Public Works on the paving and macadamizing of roads in London and Paris]. Ann Ponts Chaussées Ser. 2, 10:1–264

Darcy H (1856) Les Fontaines Publiques de la Ville de Dijon [The Public Fountains of the City of Dijon]. Dalmont, Paris

Darcy H (1857) Recherches Expérimentales Relatives au Mouvement de l'Eau dans les Tuyaux [Experimental Research on the Movement of Water in Pipes]. Mallet-Bachelier, Paris

Darcy H (1858) Note relative à quelques modifications à introduire dans le tube de Pitot [Note on modifications to be made in the Pitot tube]. Ann Ponts Chaussées Ser. 3, 15, 351–359

Darcy H (2003) Henry Darcy: Inspecteur général des ponts et chaussées [Henry Darcy: Inspector General of Bridges and Roads], by Henry Darcy (V). In: Brown GO, Garbrecht JD, Hager WH (eds) Henry P. G. Darcy and other pioneers in hydraulics: contributions in celebration of the 200th birthday of Henry Philibert Gaspard Darcy. American Society of Civil Engineers, Reston, VA, pp 4–13

Darcy H, Bazin H (1865) Recherches Hydrauliques, Enterprises par M. H. Darcy [Hydraulic research conducted by Mr. H. Darcy], Imprimerie Nationale, Paris

Darcy P (1957) Henry Darcy: Inspecteur Général des Ponts et Chaussées [Henry Darcy: Inspector General of Bridges and Roads]. Imprimerie Darantiere, Dijon, France, pp 1803–1858

Darton NH (1905) Preliminary report on the geology and underground water resources of the central Great Plains. US Geol Surv Prof Pap 32

de Caudemberg G (1858) Notice sur M. Henri Darcy, extract from Mémoires de l'Académie de Dijon [Obituary of Mr. Henry Darcy from Mémoires de l'Académie de Dijon). Loireau-Feuchot, Dijon, France

de Marsily G (2003) About Darcy's law. Abstracts with programs (Annual Meeting), vol 35, Geological Society of America, Boulder, CO, p 448

de Vries JJ (2006) History of groundwater hydrology. In: Delleur JW (ed) The handbook of groundwater engineering. 2nd edn. CRC, Boca Raton, FL, USA

Dumay V (1845) Notice Historique sur L'Établissement des Fontaines Publiques de Dijon [Historical notes on the construction of the Public Fountains of Dijon]. Frantin, Dijon, France

Dupuit AJEJ (1857) Mémoire sur le mouvement de l'eau à travers les terrains perméables (Essay on the movement of water through permeable terrains). C R Hebdomadair Séanc Acad Sci (Paris) 45:92–96

Dupuit AJEJ (1863) Études théoriques et pratiques sur le mouvement des eaux dans les canaux découverts et à travers les terrains perméables [Theoretical and practical studies on the movement of water in open channels and through permeable terrains], 2nd edn. Dunod, Paris

 DOI 10.1007/s10040-008-0304-3

Fetter CW (2004) Hydrogeology: a short history, part 2. Ground Water 42(6):949–953

Forchheimer P (1898) Grundwasserspiegel bei Brunnenanlagen [Water levels in wells]. Zeitsch Österr Ing Architek Vereins 44:629–635

Freeze RA transl (1983) Determination of the laws of flow of water through sand. Partial translation of Part 2 in Note D from The Public Fountains of the City of Dijon by Henry Darcy (1856). In: Freeze RA, Back W (eds) Physical hydrogeology. Benchmark Papers in Geology, vol 72, Wiley, New York, pp 14–20

Freeze RA (1994) Henry Darcy and the fountains of Dijon. Ground Water 32:23–30

Génieys R (1835) Clarification et dépuration des eaux (publication posthume) [Water clarification and purification (posthumous publication)], Ann Ponts Chaussées 1er sem. 1835, pp 56–76

Groenevelt PH (2003) The place of Darcy's law in the framework of non-equilibrium thermodynamics. In: Brown GO, Garbrecht JD, Hager WH (eds) Henry P.G. Darcy and other pioneers in hydraulics, vol 310, American Society of Civil Engineers, Reston, VA

Guillerme A (1988) The genesis of water supply, distribution, and sewerage systems in France, 1800–1850. In: Tarr J, Dupuy G (eds) Technology and the rise of the networked city in Europe and America. Temple University Press, Philadelphia, PA, pp 91–115

Hubbert MK (1940) The theory of ground-water motion. J Geol 48 (8):785–944

Hubbert MK (1969) The theory of ground-water motion and related papers. Hafner, New York

Marsaines C (1858) Notice nécrologique sur M. Darcy, Inspecteur Général des Ponts et Chaussées [Obituary of Mr. Darcy, Inspector General of Bridges and Roads]. Ann Ponts Chaussées Ser. 3, 15, 90–109

Mead DW (1919) Hydrology: the fundamental basis of hydraulic engineering. McGraw-Hill, New York

Meinzer OE (1923a) The occurrence of ground water in the United States with a discussion of principles. US Geol Surv Water Suppl Pap 489

Meinzer OE (1923b) Outline of ground-water hydrology with definitions. US Geol Surv Water Suppl Pap 494

Narasimhan TN (1998) Hydraulic characterization of aquifers, reservoir rocks, and soils: a history of ideas. Water Resour Res 34(1):33–46

Narasimhan TN (2005) Hydrogeology in North America: past and future. Hydrogeol J 13:7–24

Parker GG (1986) Early stage of hydrogeology in the United States, 1776 to 1912. J Am Water Resour Assoc 22(5):701–716

Philip JR (1995) Desperately seeking Darcy in Dijon. Soil Sci Soc Am J 59:319–324

Poiseuille JL (1841) Recherches expérimentales sur le mouvement des liquides dans les tubes de trés-petits diamétres [Experimental research into the movement of liquids in pipes of very small diameter]. Comptes Rendus, Acad. des Sci., Paris

Reynolds O (1883) An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous and of the law of resistance in parallel channel. Philos Trans R Soc 174:935–982

Rouse H, Ince S (1957) History of hydraulics. Iowa Inst. of Hydraul. Res., Univ. of Iowa, Iowa City, IO, USA

Sharp J, Simmons CT (2004) The compleat Darcy: new lessons learned from the first English translation of Les Fontaines Publiques de la Ville de Dijon. Ground Water 43(3):457–460

Simmons CT (2003) Happy 200th birthday Mr. Darcy and our thanks for your law! A tribute editorial celebrating the life and times of the father of our science, Henry Darcy (1803–1858). Hydrogeol J 11(6):611–614

Simmons CT (2004) Book review of "The Public Fountains of the City of Dijon" Henry Darcy, 1856, English translation by Patricia Bobeck. J Int Geosci (Episodes) 27(4):307–309

Slichter CS (1899) Theoretical investigations of the motion of ground waters. US Geological Survey 19th Annual Report, part 2, US Geological Survey, Reston, VA

Slichter CS (1905) Field measurements of the rate of movement of underground waters. US Geol Surv Water Suppl Pap 140

Theis CV (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground water storage. Trans Am Geophys Union 16:519–524

Thiem A (1887) Verfahren für Natürliche Grundwassergeschwindigkeiten [Methods to evaluate natural groundwater velocities]. Polyt Notizblatt 42:229

Thiem G (1906) Hydrologische Methoden [Hydrologic methods], Gebhardt, Leipzig, Germany

Wenzel LK (1932) Recent investigations of Thiem's method for determining permeability of water bearing materials. Trans Am Geophys Union 13:313–317

Wenzel LK (1936) The Thiem method for determining permeability of water bearing materials and its application to the determination of specific yield: results of investigations in the Platte River valley, Nebraska. US Geol Surv Water Suppl Pap 679A

Wenzel LK (1942) Methods for determining permeability of water bearing materials. US Geol Surv Water Suppl Pap 887

 DOI 10.1007/s10040-008-0304-3