WATER RESOURCES RESEARCH, VOL. 38, NO. 7, 1106, 10.1029/2001WR000727, 2002

Henry Darcy and the making of a law

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Received 19 June 2001; revised 28 November 2001; accepted 13 February 2002; published 17 July 2002.

[1] Henry Darcy was a distinguished engineer, scientist, and citizen who is remembered for his many contributions in hydraulics, including Darcy's law for flow in porous media. While he has been given full credit for the finding, little insight has been available on the process of his discovery. It is shown that his discovery was the logical result of a lifetime of education, professional practice, and research. Darcy understood both its significance and its relationship to the broader fields of hydraulics and groundwater hydrology. Besides the discovery of Darcy's law, he was the first to show that significant flow resistance occurs within aquifers, the first to recognize the law's similarity to Poiseuille flow, and the first to combine the law with continuity to obtain a solution for unsteady flow. *INDEX TERMS:* 1719 History of Geophysics: Hydrology; 1829 Hydrology: Groundwater hydrology; 5114 Physical Properties of Rocks: Permeability and porosity; *KEYWORDS:* Darcy's law, Corps of Ponts et Chaussées, Dijon, France

1. Introduction

[2] In 1856, Henry Philibert Gaspard Darcy (1803–1858), in a report on the construction of the Dijon, France, municipal water system, published a relationship for the flow rate of water in sand filters [*Darcy*, 1856]. In terms only slightly different from his own, Darcy's law was given as

$$Q = AK\frac{(h_1 + z_1) - (h_2 + z_2)}{L}, \qquad (1)$$

where Q is the volume flow rate, A is the area of porous media normal to the flow, K is the hydraulic conductivity, h is the pressure head (pressure divided by the specific weight), z is the elevation, L is the length of the flow path, and the subscripts 1 and 2, designate the up and downstream positions, respectively. The term within the parentheses is the hydraulic or piezometric head. A photo of Darcy taken late in his life is shown in Figure 1.

[3] Equation (1) has of course been generalized by many writers to allow for differential solutions, vector analysis, unsaturated flow and multiphase flow. Likewise, the equation's theoretical basis and applicability in several fields has been well defined. Conversely, little has been published on the process of the discovery. This deficiency may be explained in part by the facts that Darcy lived 150 years ago, copies of his writings are difficult to obtain, and little has been translated from the French. Even native French speakers have difficulty interpreting terminology inconsistent with modern usage wrapped in old flowery prose. However as will be shown, Darcy was a person of unusual ability who had worked in the field for decades. His discovery was the logical conclusion of a lifetime of education, professional practice and research.

[4] Several writers have previously addressed Darcy's life. *Marsaines* [1858] and *Caudemberg* [1858] published detailed obituaries based on firsthand accounts. Both are excellent documents, but each suffers from a lack of historical perspective. *Tarbé de St-Hardouin* [1884] and *Fancher* [1956] based their short biographies on Marsaines' account, while in turn most recent publications are based on them. *Hubbert* [1969] reviewed Darcy's experiment, while *Rao* [1968] summarized Darcy's major contributions to hydraulics. R. Freeze in the work of *Freeze and Back* [1983] performed a partial translation of *Darcy* [1856] as part of an excellent collection of early groundwater papers. An interesting nontechnical perspective on Darcy's times was presented by *Freeze* [1994] that incorporated new material translated from *Darcy* [1957]. P. Darcy was a great nephew of Henry's and may be the Colonel Darcy referred to by Fancher. The biography does not appear on any book list and was found by Freeze in a Dijon bookstore. P. Darcy's work contains a considerable amount of interesting personal and historical information, but the author was obviously not technically trained. *Philip* [1995], using archival material from the Dijon Bibliothéque Municipale, rebuked Dijon for forgetting her native son. Of final note, *Brown et al.* [2000] have presented a brief summary of his work and reexamined the spelling of his name.

[5] Using a limited number of source documents, previous writers have clearly shown that Darcy was a great engineer and citizen, but they have shed little light on the process of his discovery. However, by examining the French, English and American technical publications of the day, we can discern what Darcy knew, when he knew it and how his work related to the developing sciences. An exhaustive search was made to find any publication by Darcy, and all identified were reviewed and referenced here. Likewise, all cataloged Darcy biographies were examined and any that contain original material have been cited. Other authors, in particular *Rouse and Ince* [1957], have been used to identify the other relevant publications of the nineteenth century. Original source material was given highest value, but current theoretical insight is also applied to infer missing information when necessary. While the story is

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Figure 1. Portrait of Henry Darcy by F. Perrodin, from the Collection of the Bibliothéque Municipale de Dijon.

incomplete, enough of the plot can be deduced to outline the path that was followed. Sometimes the text is vague, but the equations and data leave little to debate.

2. Formative Years

[6] Darcy was born 10 June 1803 in Dijon, France. His father, Jacques Lazare Gaspard was a tax collector, and his mother was Agathe Angelique Serdet [*Darcy*, 1957]. Located southeast of Paris, Dijon is the former capital of the Duchy of Burgundy. It has a long notable history and many beautiful historic buildings. It was, and remains, the center of the great Burgundy wine region, and is capital of the Department of Côte d'Or. However, at the start of the nineteenth century it was a provincial backwater and had a population of less than 30,000. At the national level, the brutality of the French Revolution was over and France was entering a period of relative prosperity fueled by the industrial revolution. While the country could hardly be described as being stable as it proceeded through a series of governments, rulers and revolts, education was supported and the bourgeoisie grew in size and influence.

[7] Darcy's father died when he was 14, but his mother assured his education by borrowing money for tutors and by obtaining a city scholarship for him to attend college. In 1821, Darcy entered L'Ecole Polytechnique, Paris. The Polytechnique was created during the French Revolution in 1794 with the mission to replace several small Royal schools with a comprehensive three-year program in all branches of engineering [*Bradley*, 1998]. The curriculum emphasized math, science, engineering and hands-on laboratories. The latter was considered innovative at the time. All students took military studies, and the school was the primary source of the officers for Napoleon's very effective artillery corps. Gaspard-Marie Riche de Prony (1755–1839) had been the school's primary guiding intellect since 1800, and the Polytechnique had taken a central role in all areas of French science and engineering education by the time Darcy enrolled. Likewise, its student body usually played a part during periods of civil unrest and had manned the street barricades more than once.

[8] Darcy's short student record from the Polytechnique provides a glimpse of him at this time (C. Billoux, École Polytechnique Bibliothéque, Paris, Responsable du service des archives, letter dated 24 October to G. Brown, 2000.) He was 1.69 m tall ($5'–6^1/_2''$), had light brown hair with bangs, blue eyes and a cleft chin. Within the student corps, he obtained the level of Sergeant Major. That and his class rank of 12 out of 64 at the Polytechnique, and 8 out of 15 who proceeded to the Ecole des Ponts et Chaussées indicates he was a good, but not the best student.

3. Ponts et Chaussées

3.1. L'Ecole

[9] In 1823, Darcy was admitted to L'Ecole des Ponts et Chaussées (School of Bridges and Roads), Paris. The step from the Polytechnique to an "Ecole d'application" was the normal progression for the better students at the time, and it would shape the course of the rest of his life. First assembled in 1716, the Corps of Ponts et Chaussées had a mission to support infrastructure construction throughout the country. By decree of the Royal Council in 1747, the School was created to train both new students and practicing engineers for the Corps. As the first modern engineering school, it elevated engineers in France to the status of a profession. Together, the School and the Corps provided an environment that both expected excellence and furnished the support to achieve it. A list of the school's graduates and instructors reads like a who's-who of eighteenth and nineteenth century engineering and science. It includes, Prony, Henri de Pitot (1695–1771), Antoine Chézy (1718–1798), Louis Marie Henri Navier (1785–1836), Augustin Louis Cauchy (1789–1857), Jean-Baptiste Bélanger (1790–1874), Gaspard Gustave de Coriolis (1792–1843), Jean Claude Barre de Saint-Venant (1797–1886), Arsene Jules Emile Juvenal Dupuit (1804–1866) and Henri Emile Bazin (1829–1917) [*Coronio*, 1998]. Coriolis was also teaching at L'Ecole Polytechnique during Darcy's residence.

[10] When Darcy entered L'Ecole des Ponts et Chaussées, it was open to males from the whole of France, recruitment was by competitive examination, tuition was free, and students received a small fixed stipend. The total enrollment was about 65 and there were seven regular faculty [*Bradley*, 1998]. Some instructors were graduates of the school, who after a period of practice, had returned to pursue their own studies. The school's curriculum and its instructors' expertise are well known. First, following the tradition they created, every student had significant math instruction that included calculus. Consistent with the school name, the students had training in solid mechanics, bridge design and construction that was relatively sophisticated even by

today's standards. Prony was the school's longtime director and Navier was an instructor, so we may be certain the students learned the state of the art in fluid flow. On his death, Prony's library contained lecture notebooks on hydrostatics, hydrodynamics, navigation, irrigation and diversions [*Bradley*, 1998].

3.2. Theorical Foundations

[11] Hydrostatic and hydrodynamic theory had been well defined by eighteenth century mathematicians and scientists. First among them was Daniel Bernoulli (1700–1782), who showed that energy was conserved along a streamline in steady, incompressible, invisid flow, or in modern terms,

$$\frac{V^2}{2g} + h + z = const, \tag{2}$$

where V is the velocity. Following Pierre Simon Laplace's (1749–1827) earlier efforts, *Navier* [1823] presented a differential relationship for pressure and velocity in unsteady three-dimensional viscous flow. While additional work was necessary for the development of what we call the Navier-Stokes equations, the mathematical basis of ideal fluid flow was well developed and undoubtedly known to Darcy.

[12] Conversely hydraulics, the science of real flows, was not as advanced. The fluid friction between two points in a pipe or channel could be quantified by the empirical extension of equation (2) properly called the energy equation,

$$\begin{aligned} h_L = & \left(\frac{V_1^2}{2g} + h_1 + z_1\right) - \left(\frac{V_2^2}{2g} + h_2 + z_2\right) \\ & \cong (h_1 + z_1) - (h_2 + z_2), \end{aligned} \tag{3}$$

where h_L is the fluid friction or head loss between positions 1 and 2. Since they usually limited analysis to uniform (constant area) flow, the velocity terms would cancel, and the RHS was used without explanation. For design however, there were no reliable relationships to predict h_L in pipes, open channels or other flows. The most accepted relationship for pipe flow resistance was Prony's,

$$h_L = \frac{L}{D}\left(aV + bV^2\right), \tag{4}$$

where D is the pipe diameter, and a and b are empirical friction coefficients. A similar equation with different coefficients was used for open channel flow. At high flow velocities, the first order term was often dropped for computational convenience. Prony's equation was prone to error since the recommendations for the coefficient values did not account for the pipe roughness. The only practical link between hydrodynamics and hydraulics was the application of equation (2) to orifice and weir flow that the French called Torricelli's theorem,

$$V = \sqrt{2\,gH}, \tag{5}$$

where H and is the difference between a reservoir's water surface, z_1 and the orifice elevation, z_2. That relation was combined with continuity to give the orifice discharge,

$$Q = mA\sqrt{2\,gH}, \tag{6}$$

where Q is the volume flow rate, A is the orifice area and m is an empirical discharge coefficient that was calibrated for each device. The vertical integration of equation (5) also provided similar accurate relationships for weir flow and low head orifices.

[13] At that time in England, there was little if any quantitative understanding of fluid flow. The benchmark English document of the period, *Hydraulia* [*Matthews*, 1835], contains almost no quantitative analysis, with the exception of reporting French and English orifice and weir flow measurements. Matthews demonstrated that while the English had already completed several successful large water projects, they had little appreciation of hydraulic analysis and design. *Storrow* [1835], an American who trained at L'Ecole des Ponts et Chaussées, is credited for introducing Britain to the French work [*Straub*, 1964].

[14] Porous media and groundwater flow was even less well understood. Because of his familiarity with the American, English and French literature, Storrow's thesis may be considered an authoritative reference on the contemporary state of the art. His discussion of the large water filters built by the Chelsea and Greenock Waterworks Companies included flow rates, bed areas and supply heads. However, no attempt was made to quantify the resistance to flow in the sand. This is curious, considering he wrote at length on pipe friction. It appears that although water filtration was becoming standard practice, the notion of quantitatively analyzing the hydraulics of the systems had not occurred to the practitioners. This may have been due to their focus on the clogging and cleaning of the filters, which was the major operational concern.

[15] Groundwater research focused solely on artesian wells in carbonate aquifers, which is not surprising. Mechanical pumps were large, expensive and unsuitable for deep down hole applications. Furthermore, the traditional shallow well drawn with a bucket was known to be vulnerable to pollution. Thus only deep artesian wells were considered appropriate for water supply systems. Upslope recharge had been correctly identified by the American Lathrop in 1800 and the Frenchman *Garnier* [1822], as the source of the water in artesian wells. *Storrow* [1835] cited the former and translated much of the latter in his thesis. Those and other accounts from France and England lead him to state:

> It is only in calcareous rocks, then, that we should seek for rising springs. We have seen, that these springs may be found wherever a stratum containing fissures sufficient to give passage of water, is enclosed between two others which are water-tight; and if the intermediate stratum comes to the surface in the more elevated spots so as to receive water from rain, and from streams, and afterwards descends without there being any vent for the waters, we have only to pierce through the upper bed and give to these a free passage, and they will rise to the surface of the ground and sometimes even above it.

That and other sections makes it clear that while they understood the nature of confined aquifers, it was assumed significant volumes of water could only be transported over

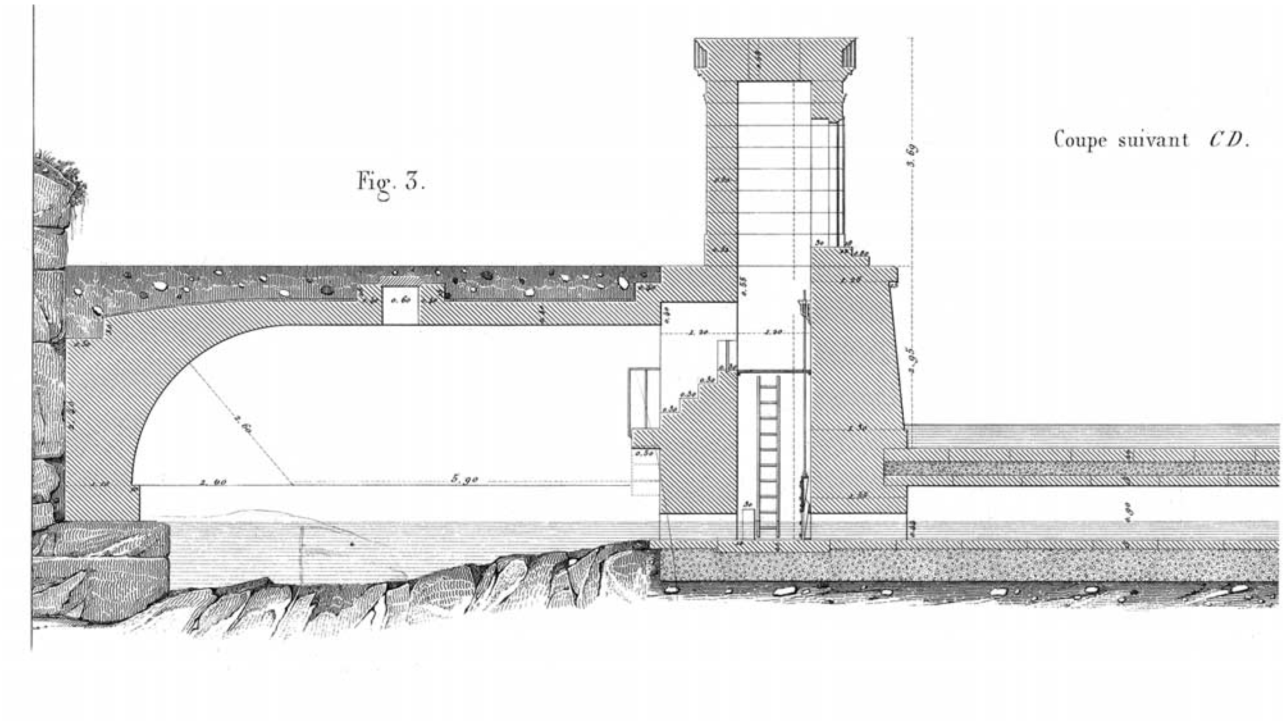

Figure 2. Section of Rosoir Spring Inlet Structure, covered aqueduct on the right. Detail from *Darcy* [1856, Plate 3].

long distances in relatively large, continuous open conduits within an aquifer.

3.3. Water for Dijon

[16] Darcy graduated in 1826 with a degree in Civil Engineering and was assigned by the Corps to the Department of Jura, but he was soon transferred home to Dijon. Dijon had perhaps the worst water in Europe [*Darcy*, 1957], and Darcy was quickly assisting in the drilling of a deep test well.

[17] *Caudemberg* [1858] provides an account of the effort made by a society of subscribers and the Municipal Council in hopes of repeating Molut's successful artesian well in Paris. Beginning in March of 1829 they started drilling near Place Saint-Michel. "On August 6, 1830, the probe, that had descended to 150.72 m, penetrated suddenly into void; or had reached a stream of undergroundwater, that flowed briskly up the pipe, but without springing to the surface." Attempts made to pump the well were disappointing. "Mr. Darcy noted himself that the source gave a water of excellent quality, but that, even while lowering the level to ten meters below the pavement of the square, it could only provide 500 liters per minute, a quantity insufficient for the city of Dijon, . . ."

[18] Soon after the disappointment of the well, and under his own initiative, Darcy set out to provide a clean, dependable water supply to the city from more conventional surface water sources [*Dumay*, 1845]. A number of proposals had been made in the past, but each had flaws. Darcy reviewed the previous designs and proceeded to develop a better solution. In 1834, he 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 Municipal Council of Dijon on the Means to Supply Water Necessary to this City) [*Darcy*, 1834]. His recommended design provided for the collection of 8 m^3/min at the Rosoir Spring, which required digging out the spring to improve its flow. The water was then carried 12.7 km in a covered aqueduct to an enclosed 5700 m^3 reservoir located near the Porte Guillaume and another reservoir at Montmusard. Pressurized distribution lines totaling 28,000 m were laid in underground galleries and delivered water to major buildings and 142 public street hydrants spaced 100 m apart throughout the city. The entire system was gravity driven and required no pumps. The completely enclosed spring shown in Figure 2 allowed direct distribution without filtration or treatment. One of the elegant reservoir entrances, or "Chateau d'Eau" is shown in Figure 3. It indicates the importance placed on the system by the community (and the French flair for monumental architecture).

[19] The 1834 work provides a glimpse of Darcy's professional ability and technical knowledge. In the first part, the reader is impressed by the thoroughness of his review of previous proposals and existing systems. Darcy clearly did his time in the library as he described efforts back to the fifteenth century. Similarly, he reported correspondence with French and English engineers that helped him determine system feasibility and design standards. In the second part of the report, he provided a comprehensive analysis of four project alternatives with cost estimates for construction and operation. Two options utilized spring sources, the third used filtered water from the Ouche, and the fourth the Saint-Michel well. Prony's relationships equation (4) were used to size pipes and channels, typically using a design flow 50% greater than required, while numerous flow rates were quantified using the appropriate orifice and weir flow equations.

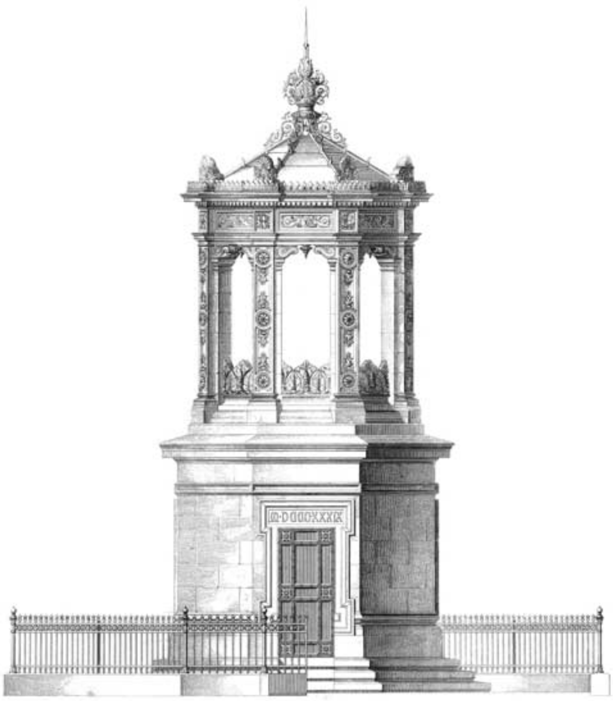

Figure 3. Chateau d'Eau, entrance to Porte Guillaume Reservoir. Detail from *Darcy* [1856, Plate 9].

[20] The discussions on filtering river water and the Saint-Michel well pump test reveal Darcy's understanding of porous media flow at that time. Both ''natural'' and ''artificial'' filters were in use elsewhere for clarifying surface water. Natural filters used large galleries constructed in alluvial deposits next to streams, while artificial filters were smaller, fully enclosed basins of various designs. Both types would normally use steam engines and pumps to overcome elevation differences between the supply and delivery points. All contemporary filters had problems with clogging and Darcy was clearly hesitant to use them in any design. He writes, ''I had to go through the preceding details to show how delicate the water purification operation is; English engineers are so thoroughly convinced of this, that if at any time that they can resort to spring waters, they advise companies to employ them, even with an increase in expenditure.''

[21] While Darcy computed pump horsepower and coal requirements for one alternative design using a natural filter, he made no explicit estimation of filter head losses. Instead, the required filter area was estimated based a rule of thumb with a fixed supply head. Similar to *Matthews* [1835], the filter operation was never decomposed into its various components. Thus the concept of fluid friction within the sand was never directly distinguished.

[22] Details of the Saint-Michel well construction were not explicitly reported. However, by piecing together various comments, it is believed that the well had solid casing with a short length of open hole at the bottom. A 0.11 m inside diameter pipe was dropped down 152 m and used as the intake of a steam powered piston pump. Well drawdown could have been measured in the annulus between the casing and the pump pipe. Darcy reported drawdowns of 1.8, 3.8 and 5.8 m for flows of 125, 272 and 575 L/min respectively. No mention was made of pumping duration or temporal variations, so it appears he believed them to be steady state values. Darcy deduced that significant resistance to flow was occurring in the aquifer, an apparently new discovery. He showed this by quantifying what the flow rate would have been if the drawdown was only result of the pipe friction in the pump intake pipe using the relation,

$$Q = 20.73\sqrt{\frac{HD^5}{L}}, \tag{7}$$

While not explicitly explained in the text, equation (7) combines continuity with a simplified version of equation (4) where the first order term has been dropped. Head loss is assumed equal to the well drawdown, (h_L = H). The numerical coefficient is equal to $\pi/4\sqrt{b}$ and L was set as the pipe length less the drawdown (152.3 - H). Theoretical flows of 534, 810 and 984 L/s were computed when the head loss was set equal to the measured drawdowns. He rightly 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.'' Darcy's calculations are reasonable when compared to the Darcy-Weisbach equation (discussed latter) and showed that only about one half of the drawdown was friction in the pump pipe.

[23] Darcy's analysis of the well was correct up to this point, but he then displays the contemporary theoretical limitations. He refers to the source of the water as a reservoir and states, ''... it seems to me that the reservoir is separated from the artesian well by natural conduits that offer resistance to the flowing water, ...''. The resistance is later quantified, ''By calling *d* the diameter of the opening of the natural conduit, the volume of water that enters the artesian well is given by the equation,

$$Q = 3.48\ d^2\sqrt{H}, \tag{8}$$

where H represents the height due to the velocity with which the fluid enters the well.'' Again, while not explicitly stated, the reference to ''height due to the velocity'' clearly shows equation (8) is simply the orifice equation, equation (6) with m = 1, and the numerical constants combine to produce the coefficient shown, for which Darcy provided no justification or reference. Finally, using equation (7), equation (8), and inelegant but reasonable logic, Darcy concluded that even if the well were enlarged, the aquifer resistance would not allow the required flow at a practical drawdown.

[24] Darcy's use of equation (8) left an important fact unstated, which is demonstrated by one simple observation. The drawdown data along with the zero point fits the linear regression Q = *79 H*, with a correlation coefficient, R^2 = 0.99. I believe he was too thorough not to have observed the linear trend of his data, but can only speculate on his reasons to disregard it. Given that he only used the highest flow rate data to evaluate the system, he may have chosen to ignore the low flow data thinking that it wasn't in the region where the second order term of equation (4) dominates. Similarly, he may have doubted limited observations when

they diametrically opposed the established theory. Possibly, the most pragmatic reason is he may not have wanted to start an argument on a side issue of a nonviable alternative when his first priority was to win project approval for the Rosoir Spring option. The negative assessment of the well's potential output was already in direct conflict of an earlier report by Arnollet (?-1856), the Chief Engineer of the Department of Côte-d'Or [*Dumay*, 1845]. In any case, the linear relationship is problematic. Steady state well drawdown is a function of both the linear loss in the aquifer and the second order turbulent losses near the well casing and in this case, up the pump pipe. For the three flows, Reynolds numbers ranged from 16,000 to 74,000 indicating turbulent flow in the pipe. It can be concluded that either the data was in error, flow was not steady state, or a variable such as the pump intake pressure ignored.

[25] A final observation can be made on the 1834 report. While not intended to be a thesis in the style of the day, it compares well against both Matthew's and Storrow's works that were published a year later. The Dijon Municipal Council published 400 copies, and undoubtedly many ended up in the hands of practicing engineers.

3.4. Rise to Prominence

[26] From 1834 to 1848 Darcy advanced professionally as he carried out a number of significant projects. His preferred plan for Dijon's water supply was approved by the Municipal Council with no revision on March 5, 1835. On December 31, 1835, a Royal ordinance declared the Dijon water project a public utility, which allowed for land acquisition. Work began in March of 1838, and on 6 September 1840, water was delivered to the reservoir at Porte Guillaume, 535 days later. The construction of the covered aqueduct in that period implies an impressive average daily rate of 24 m/d. Work on water distribution and delivery components continued until 1844, when the project was substantially completed.

[27] Honors were soon to follow. In 1836, his work was praised in a letter from the Under Secretary of State and Director of Public Works [*Dumay*, 1845]. On 7 May 1840 Darcy was appointed Chief Engineer for the Department of Côte-d'Or, which carried with it a seat on the Municipal Council. After recommendation by the Prefect of Côte-d'Or and the Minister of the Interior, on 31 August 1842 he was awarded the Legion of Honor by King Louis Philippe. Perhaps he took his greatest satisfaction at the project completion when he accepted a gold medal from the Municipal Council and a laurel wreath from the workmen. Finally in 1845, he was admitted to the Dijon Society of Science, Art and Letters.

[28] During this time, Darcy was also supervising the construction of road projects, navigation works and several bridges, including two major structures over the Saône [*Marsaines*, 1858]. Another very popular project was his covering 1.3 km of the Suzon; a small stream that acted as an open sewer through the center of Dijon [*Caudemberg*, 1858]. His most difficult and controversial project was the design, approval and initiation of the segment of the Paris-Lyon railroad passing though the Côte-d'Or [*Darcy*, 1957]. As in the water project, Darcy reviewed several previous proposals and came up with his own improved design that relied on the construction of a four-km tunnel at Blaizy. The bore equaled the longest existing tunnel at the time and was proposed only after test excavations and consultations with the noted geologist Elie de Beaumont (1798–1874). After a difficult and politically charged approval process, Darcy began construction in January of 1845 and completed about one third of the tunnel before a private corporation assumed the project in April of 1846. Darcy left no known record of his experiences. However, the tunnel must have provided him direct observations of geology and water seepage processes that few of his contemporaries had experienced.

[29] Several researchers were advancing hydraulic theory during this period. Of particular interest was the work done by Jean Louis Poiseuille (1799–1869). He measured friction losses in 0.029 to 0.142 mm capillary tubes over a range of conditions and developed an empirical relationship for flow,

$$Q = kD^4 \frac{h_L}{L}, \tag{9}$$

where k is an empirical coefficient that lumps constants with a second order equation for the viscosity as a function of the temperature [*Poiseuille*, 1841]. The most important aspect of Poiseuille's results was the accuracy of equation (9). While the restriction to small tubes and low velocities was realized, it was the first fluid-friction equation to achieved modern precision. An analytical derivation of Poiseuille flow based on Newton's viscosity law was not accomplished until 1860 [*Rouse and Ince*, 1957].

[30] However, the understanding of porous media flow was not progressing, which is best demonstrated by *Dupuit* [1854]. He discussed the natural filters at Toulouse and described several small household artificial filters. Similar to *Darcy* [1834], he carried out no explicit calculation on the natural filter losses. He also calculated artificial filter flow using an orifice discharge analogy based on equation (6). In the analysis, A and m were always kept lumped together. Again, the use of an orifice equation in filter flow was not justified by reference or experiment. More important to note is that the lumping of the area and resistance terms indicates that Dupuit was not applying continuum concepts. That is, he was only thinking of a discrete filter and not the flow within the porous media. Darcy's contemporary biographers have attributed the use of orifice equations such as equations (6) and (8) in the description of filter flow to English engineers [*Marsaines*, 1858; *Caudemberg*, 1858]. That may well be the case, but *Darcy* [1834] and *Dupuit* [1854] are the only known published examples of their use.

3.5. A Shift to Research

[31] In February of 1848, the Government of Louis Phillipe collapsed under the pressure of a failing economy. The constitutional monarchy was replaced by a provisional republican government that was a mix of monarchists, bourgeois republicans and socialists. Darcy was soon suspended from duties, since he was considered "dangerous for the new state of things" [*Darcy*, 1957]. Apparently, he had too much influence in Dijon for the new Commissioner's comfort. The Dijon Municipal Council, the Corps, and L'Ecole Polytechnique protested his removal, but all it

accomplished was an appointment to Bourges to work on the Berry Canal. At his new assignment, Darcy proceeded to prepare a draft plan for a massive new project to provide drainage and irrigation over the Sologne region [*Caudemberg*, 1858]. However, after the formation of the Second Republic and the election of Louis Napoleon, Darcy was transferred to Paris and appointed Chief Director for Water and Pavements.

[32] He soon traveled to England to interview engineers and gather data on street pavements; a topic he apparently had been working on since at least 1847. (Darcy's English was probably very good since he had required English classes at L'Ecole des Ponts et Chaussées and his wife, Henriette Carey (1808–1875) was Anglo.) It is reasonable to expect that Darcy also took the time to visit the British water-supply engineers he had previously corresponded with and view their facilities. On his return, he quickly published a lengthy and highly regarded paper on English road construction practice [*Darcy*, 1850] and was promptly promoted to the rank of Inspector General, 2nd Class, in April of 1850. As Inspector General, he reviewed and reported on Corps projects being carried out throughout the country. Somehow during this period he also consulted on the Brussels, Belgium municipal water system, for which he received the Order of Leopold.

[33] Darcy's new position brought with it command of the large hydraulic installation at Chaillot, which provided a major research opportunity. He initiated and completed a comprehensive experimental program intended to improve the estimation of the Prony pipe friction coefficients [*Darcy*, 1857]. (His interest in pipe flow originated during the construction of the Dijon water system and he had carried out limited experiments in the 1840s.) The pipe hydraulics results are a topic unto itself that cannot be done full justice here. In short, he ran tests on various types of pipes from 0.012 to 0.50 m diameter over a large velocity range. The results greatly improved friction estimates by showing the wall roughness influenced the friction loss. He also provided the first accurate measurement of turbulent pipe velocity distributions and furnished the first evidence for the existence of the fluid boundary layer. His contribution is acknowledged in the co-naming of the Darcy-Weisbach pipe friction formula given by,

$$h_L = \frac{fL}{D}\frac{V^2}{2g}, \tag{10}$$

where f is usually called the Darcy friction factor and is a complex function of the relative roughness and Reynolds number. Some references will name equation (10) simply "Darcy's equation". In all fairness, it was Julius Weisbach (1806–1871) who first proposed the exact form of equation (10) in 1845 [*Rouse and Ince*, 1957]. Darcy proposed an equation similar to (4) with friction coefficients that were functions of D, and showed it reduced to a dimensionally inhomogeneous form of equation (10) at high velocities.

[34] Darcy completed the pipe flow report in 1854. Since it contained significant new theoretical material, it was submitted to the French Academy of Sciences for review and publication, which took 3 years. The report shows he clearly appreciated that fluid friction is a function of both the fluid velocity and the conduit size. Of even greater relevance is his observation that in small pipes and low velocities the hydraulic gradient (h_L/L) is proportional to the flow rate. He 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." Later he showed explicitly that his newly proposed pipe friction formula would reduce to equation (9) at low flow and small diameters. He 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." It would remain for Osborne Reynolds (1842–1912) [*Reynolds*, 1883] to fully quantify the occurrence and differences between laminar and turbulent flow. However by 1854, Darcy had discovered the kernel of the truth, and he probably had made the connection to flow in sands. In fact, a footnote that appears to have been added just before printing cites the similarity to his 1856 sand column results.

[35] During this period, Darcy's strength was failing. He had chronic poor health that *Caudemberg* [1858] attributed to injuries resulting from a railcar accident during the Blaisy tunnel construction. In 1855, he was granted release from all duties except research, after which he returned to Dijon for recuperation, writing and the initiation of an open-channel hydraulics study.

3.6. Fontaines

[36] During the time between the submission of the pipe report and its publication, he completed his most famous text, *Les Fontaines Publiques de la Ville de Dijon* [*Darcy*, 1856]. *Fontaines* weighs in with 680 pages and 28 plates of illustrations, and is clearly a compilation of years of work. While much of the material directly addresses the Dijon water supply, Darcy also discussed several unrelated topics including groundwater, sand filters and pipe manufacture. Due to his deteriorating health, he probably decided to make it his final thesis on water supply.

[37] Chapter III of Part 1 is devoted entirely to artesian wells and shows Darcy had again been consulting French and English experts in the field, in addition to gathering his own data. Several topics are discussed including geology, water quality, well development, sand production, and recharge from precipitation. Building on his 1834 report, he predicted well drawdown as a function of well-pipe friction and aquifer filtration losses, and showed how it would vary depending on which process dominated. This time, however, his theoretical hypotheses were compared to detail field data. Ten examples of artesian well production rates are presented, where the flow was measured as a function of the discharge elevation. Figure 4 shows his schematic of the measurement and one of his data sets taken in 1847. Flow was measured volumetrically as the discharge point was raised above the ground surface. In the chart, flow in liters per minute are plotted vertically against the elevation plotted horizontally (with increasing elevation drawn to the left.) Two different measurement dates are shown in this example. A clear linear trend in flow is evident in this and the other data sets. In this case, the linear trend is reasonable as Darcy noted the pipe losses were in the region

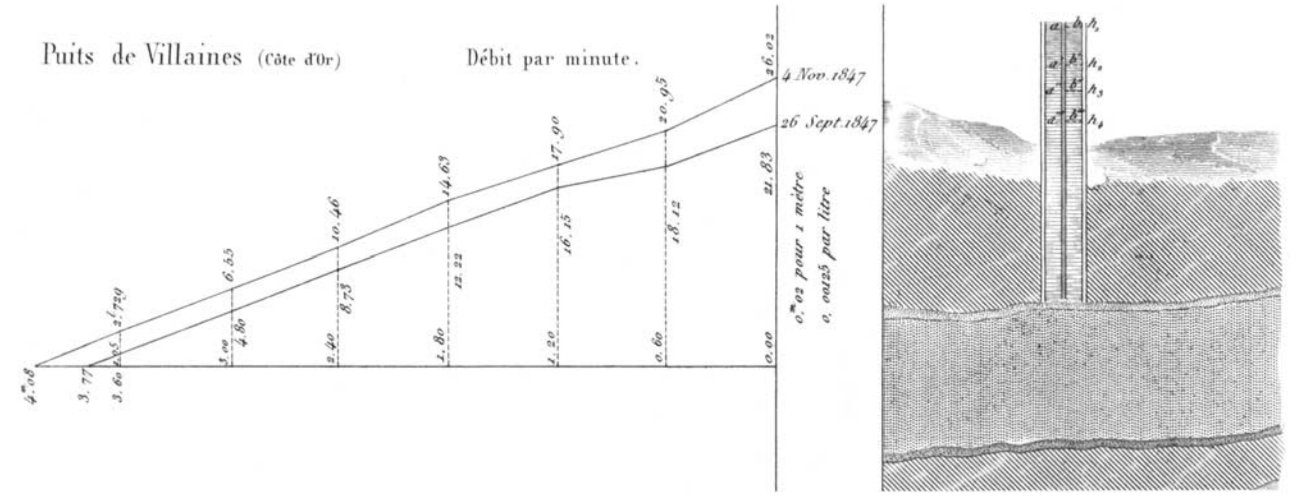

Figure 4. Spring flow measurements. Detail from *Darcy* [1856, Plate 22].

of Equation 9, or in modern terms, the pipe flow was laminar. Similarly, since each data set was collected relatively rapidly, the aquifer cone of depression would not have changed, thus the net hydraulic gradient would remain proportional to the discharge elevation. These data, his previous pipe research, and the sand column experiments to follow led Darcy to conclude that the wells were supplied by conduits that were either filled with sand or very small in size.

[38] By only measuring well drawdown, Darcy was not able to observe the cone of depression that would be expected even in a fractured aquifer. Thus he continued to think of linear conduits and not radial flow. This limitation is understandable since the difficulty of drilling would have made observation wells out of the question. However, Darcy by then clearly understood that most groundwater occurred within a porous matrix. He wrote, "We understand that drilled wells more often bring to the surface water that has infiltrated through layers of sand than water circulating in natural cavities. In fact, the vertical section of the latter is necessarily limited, whereas water-bearing sands may have an almost infinite surface area."

[39] Appendix, Note D contains Darcy's review and analysis of water treatment filters. Only a small portion has been republished by *Hubbert* [1969] or translated by R. Freeze [*Freeze and Back*, 1983]. The first part reviews existing natural and artificial filters in England and France, as he had done previously [*Darcy*, 1834]. This time, however, the analysis includes flow per unit area of the bed, indicating Darcy was now applying continuum concepts to filters. He next demonstrated the application of his law, the proof of which was to follow, to artificial filters with vertical flow. With its first introduction, he again noted the similarity of the law to flow in small pipes with low velocities.

[40] The best was held for the end of Note D; the column experiments. Starting late in 1855, Darcy, with the assistance of Charles Ritter, completed the two sets of tests. Set 1 consisted of four series, with each series having a different sand packing. For each series, three to ten different experimental trials were performed at increasing flow rates. The inlet pressure was varied for each experiment while holding the outlet at atmospheric pressure. Set 2 was carried out in early 1856 by Ritter on a single sand packing and both inlet and outlet pressures were varied. In total, 35 trials were reported.

[41] Darcy's apparatus is shown in Figure 5. It was a vertical steel pipe with an inside diameter of 0.35 m and sealed on both ends by bolted flange plates. A total height of 2.5 m was reported in the text, but it is dimensioned on the illustration as 3.5 m. At the bottom, an outlet reservoir was created by supporting a set of screens 0.2 m above the bottom. An inlet reservoir was created by leaving a void between the sand and the column top, and a tap at the top allowed air to be bled from the system. Water was supplied directly from the hospital house line on the left, which induced considerable oscillations as users elsewhere turned faucets on and off. Flow was from the top down, and the discharge was determined by timing the effluent accumulation in a volumetric box one-meter square at the bottom. Mercury U-tube manometers mounted on the right allowed the calculation of the hydraulic head-on either side of the sand. Both supply and effluent lines had valves to allow control. In the set 2 experiments, the outlet pressure was set at both positive and negative gage pressures by unrecorded methods, the details of which may only be conjectured. It would be a simple matter to pressurize the outlet by restricting the outlet valve, while dropping the discharge pipe to a lower position with the valve wide open could produce a relative suction at the filter base. However, suctions up to 3.6 m of water were reported. Thus the column must have been elevated greater than the one-meter shown, or a vacuum pump used.

[42] Each test used Saône River sand with various degrees of washing. Darcy described the packing process: "The sand was placed and packed in the column, which beforehand had been filled with water, so that the sand filter voids contained no air, and the height of sand was measured at the end of each series of experiments, after the passage of water had suitably packed it." Packing height was varied from 0.58 to 1.71 m. (In Figure 5, however, the sand packing is shown as only 0.25 m.) A test run consisted of setting the inlet valve, allowing the column to reach equilibrium, reading the manometers and measuring the flow over 10 to 25 minutes. The only serious apparatus

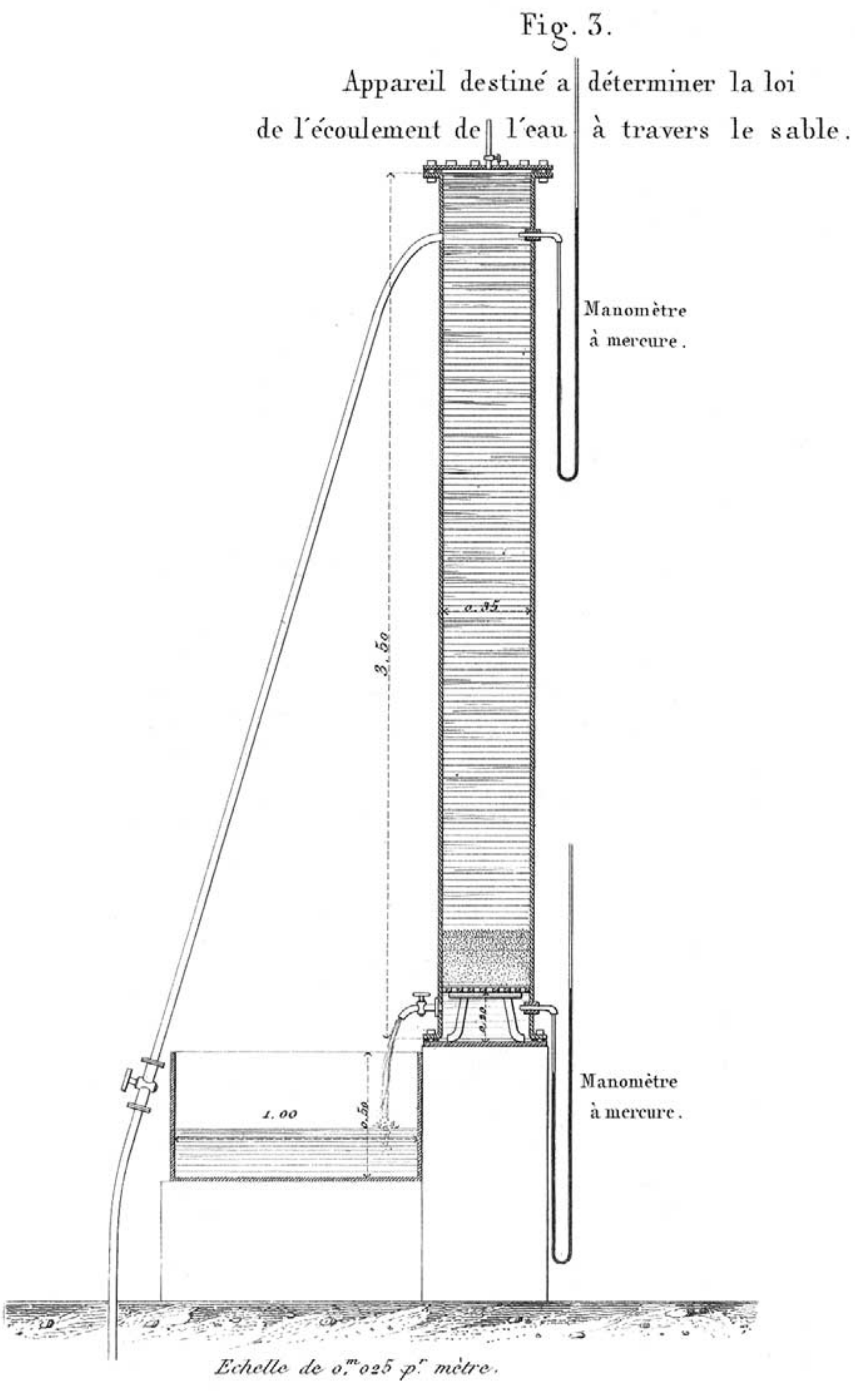

Figure 5. Column apparatus [*Darcy*, 1856, Figure 3, Plate 24].

concern was the use of an unregulated supply, for which Darcy had no alternative. Dropping the sand into the water filled column probably allowed it to segregate by size fraction with the coarsest particles on the bottom of each lift. It would also produce a low packing density subject to compaction. However, since he waited for equilibrium before taking any measurement and measured the filter height after the experiment, any compaction would not have impacted his conclusions.

[43] In set 1, the flow rate varied from 2.13 to 29.4 L/min, while the head loss ranged from 1.11 to 13.93 m. The results lead Darcy to observe, "It thus appears that for sand of comparable nature, one can conclude that flow volume is proportional to the head loss and inversely related to the thickness of the layer traversed." He then proposed equation (1), calculated conductivity values in units of L/m^2 s (10^{-3} m/s) and noted that they varied due to the difference in the sand used. For set 2, Darcy again noted the near

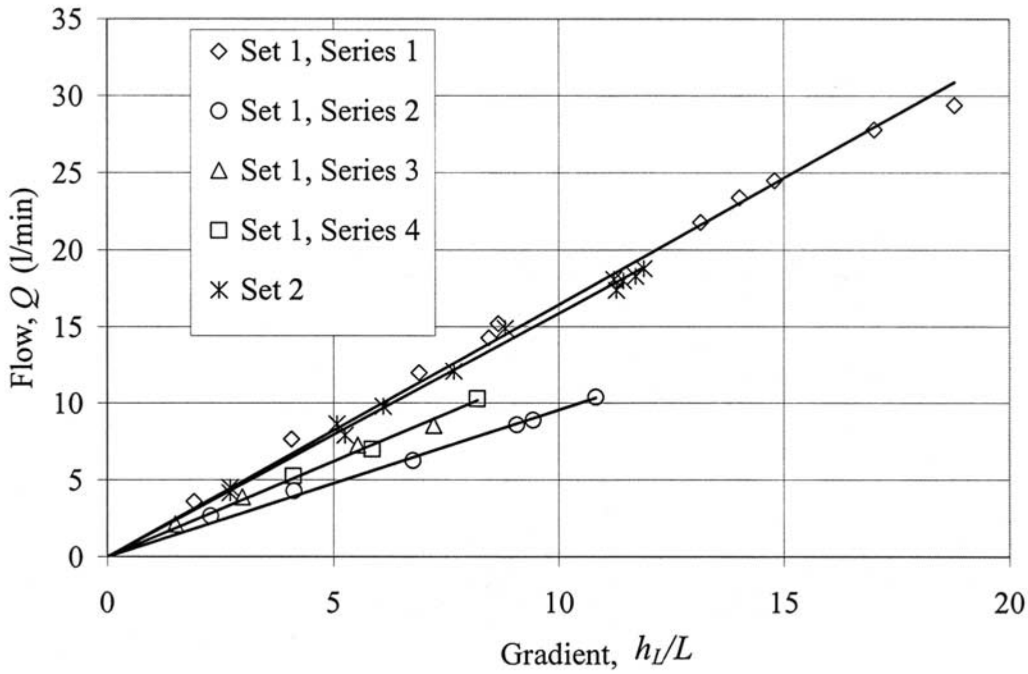

Figure 6. Darcy's sand column experimental results. Lines show best linear fit.

constant value of Q/h_L, consistent with the other experiments. Thus he showed conclusively that the flow was a linear function of the head loss across the filter bed and not the actual water pressure.

[44] Figure 6 plots Q versus the gradient, h_L/L and a least squares linear fit for each set. As can be seen, the data are quite good and the linear regression, R^2 is greater than 0.98 for each. Comparing the measured conductivity with the type of sand does not provide a clear trend. This would support the hypothesis that there was grain segregation during filling. Independent checks of his reported data confirm his calculations with one exception. As noted by *Freeze* [1994], in set 1, series 4 the conductivity should be 0.209 instead of the 0.332 L/m^2 s reported. There is another possibility for the apparent error. The filter height may have been 2.70 m instead of the recorded 1.70 m. A 2.70 m bed height is consistent with 0.322 L/m^2 s and seems a more reasonable experimental variation from the earlier series, but it would require a total column height of 3.5 m as shown on the plate.

[45] Even with careful translation, Darcy's writings can be easily misinterpreted for a variety of reasons. Like other authors of this period, he used the words pressure, load and charge rather imprecisely and the reader must infer from the equations if he meant pressure head, hydraulic head or head loss. The text and figures also contain a number of editorial errors, which may be due to Darcy's poor health or the distance between Dijon and the Paris publisher. However, his equations and analysis were completely correct and he introduced many of the concepts we use today including, the conductivity, "a coefficient dependent on the permeability of the layer," and the Darcy flux, v, defined as "$Q/A = v$".

[46] Darcy ended the appendix with a solution for the unsteady flow through a filter with a declining depth of water on the upper surface and a constant atmospheric pressure on the bottom. He would use the solution in the following section, Note E, which attempted to explain the behavior of artesian wells. His solution is now known as the falling head problem, and consisted of combining (1) with continuity, expressing head and time as differentials to allow for the temporal reduction in flow, separating variables and integration. The result rearranges to the modern convention is

$$\ln\left(\frac{y+L}{y_o+L}\right) = -\frac{K}{L}(t-t_o), \tag{11}$$

where y is the depth of water above the filter, t is the time and the subscript o indicates the initial variable values. Darcy's solution anticipates the solution for a falling head permeameter and other problems of this type. More importantly, he was the first to apply equation (1) to unsteady flow.

[47] Unexpectedly, on 3 January 1858, Darcy died of pneumonia while on a trip to Paris. He had just been elected to the French Academy of Sciences and his last work, which presented the first modern design for the Pitot tube, was published posthumously [*Darcy*, 1858; *Brown*, 2001]. While Darcy's death was tragic, his research was continued and built on by others in the Corps. His protégé, Bazin expanded and completed the open channel investigations [*Darcy and Bazin*, 1865]. In 1861, Dupuit an associate and successor as Chief Director for Water and Pavements for Paris, submitted a groundbreaking report [*Dupuit*, 1863].

Fig. 69.

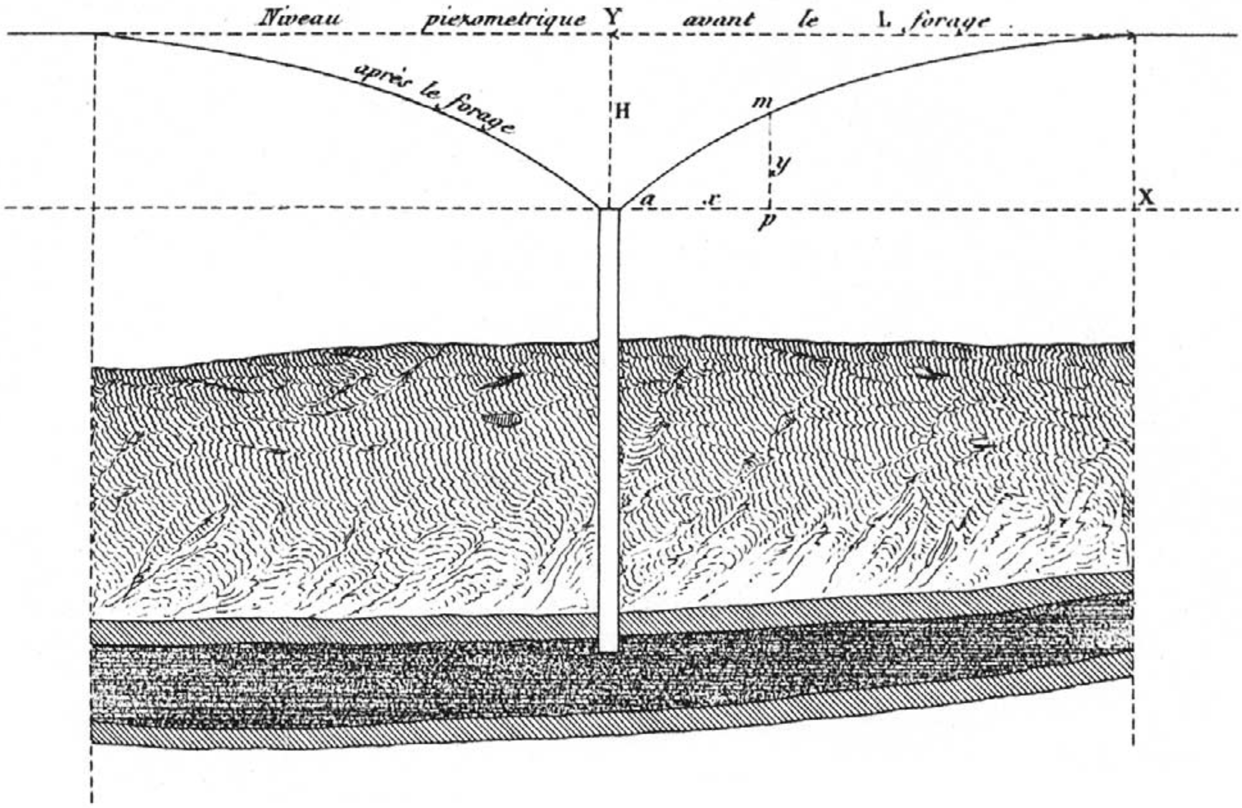

Figure 7. Dupuit's solution for radial flow [*Dupuit*, 1863, Figure 69] (History of Hydraulics Collection, Iowa Institute of Hydraulic Research).

This work expanded on an earlier edition of the same title. Principle among its new findings was the solution for steady radial flow to a well, using Darcy's law. One of Dupuit's illustrations of aquifer drawdown is presented in Figure 7. Dupuit had thus overcome the overly simplified assumption of discrete groundwater conduits, and had introduced modern aquifer analysis. Both Dupuit and the Academy of Sciences reviewers cited Darcy's contribution.

4. The Path

[48] With only a modest interpretation of the historical record, Darcy's journey toward discovery of the law can now be reconstructed. It started in 1830 with the Saint-Michel well test. He was a young engineer, who applied a crude pipe friction formula and deduced an unknown process was occurring, i.e., resistance to flow in the aquifer. His introduction to porous media continued as he exchanged letters with practicing engineers regarding the treatment of surface water with sand filters, and he completed at least one filter design. By this point, he made the connection between filters and aquifers since he described both as filtration. However, his limited analysis used the erroneous orifice analogy, which was probably acquired from one of his correspondents. Nevertheless, an interest in filter losses must have been aroused. In the 1840s, he began collecting data on artesian aquifers and deduced the linear relationship between flow and well drawdown. Additionally, his tunnel project brought him into contact with at least one leading geologist and gave him detailed insight into geology and seepage in general.

[49] In the early 1850s everything came together. His pipe flow research confirmed Poiseuille's law at low flows, and his responsibilities as Inspector General provided additional opportunities to review designs and operating water systems throughout France. Finally, his extended stay in England and the consultation on the Brussels water supply may have produced the final motivation to bring modern design concepts to filter systems. When he returned to Dijon, the column experiments were probably already conceived, designed and their results anticipated. The first set of experiments confirmed a linear relation between flow and gradient. He was done. I believe the second experimental set was only intended to provide additional proof for the practitioners. With his theoretical knowledge of hydraulics, he would have already known that the magnitude of the water pressure would have no impact; only the gradient of hydraulic head mattered. Thus he let Ritter conduct them while he continued on to other matters.

5. Concluding Comments

[50] The proceeding has demonstrated Henry Darcy's experiments were designed and carried out to prove a relationship that he probably already suspected. His tests were simple, but carefully performed and theoretically complete. With the falling head problem, he provided the first analytical solution to unsteady, saturated flow. Thus he both discovered the law and showed how to use it. It should also be observed that Darcy knew Note D was a significant new finding. He devoted almost a full page in the introduction to describing its results. In comparison, some sections of greater length were only given one or two sentences. He knew the law fit the experimental data well, that it was consistent with Poiseuille flow, and that it could also be used to understand groundwater hydraulics. He of course couldn't have known it would be applicable to so many problems not yet encountered, in fields of study not yet conceived.

[51] His discovery was the logical result of a lifetime of education, professional practice and research. Darcy started as a good student, developed into an excellent engineer, and ultimately became one of the premier water researchers of all time. Darcy's personal qualities have not been addressed, since they have been pointed out by most of his other biographers. In brief, he was an outstanding citizen who always placed the public good above his own interests. He repeatedly overcame personal and professional obstacles and always answered the call of service. The water resources community could hardly hope for a better icon to honor with one of our most important governing equations.

[52] **Acknowledgments.** Several persons provided valuable assistance in this effort. Cornelia Mutel and Kathryn Hodson of The University of Iowa; Margaret Bradley, Parthenay, France; Catherine Masteau of l'Ecole National des Ponts et Chaussées; and Claudine Billoux of l'École Polytechnique helped locate source documents. Allan Freeze was kind enough to supply a copy of Paul Darcy's work. Most noteworthy was Patricia Bobeck, Austin, Texas, who provided her unpublished translation of Paul Darcy's book and additional help. Translation assistance was provided by Jürgen Garbrecht of the USDA-ARS, El Reno, Oklahoma, and Bruno Cateni of Oklahoma State University. Finally, the suggestions of two anonymous reviewers were welcome.

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