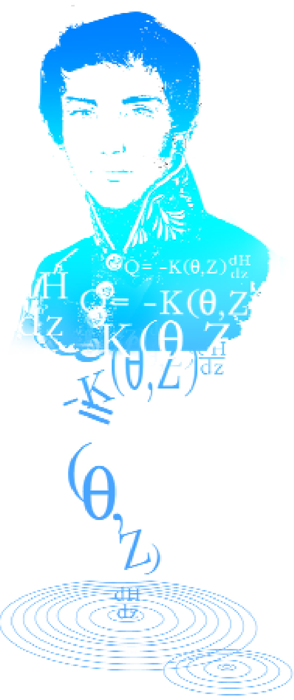

DARCY DAY
About Darcy’s life and work
Modern applications of the Darcy’s law

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About Darcy's life and work • Technical sessions, new tools

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Vie et travaux de Henry Darcy

Life and work of Henry Darcy

Conférences invitées

Invited conferences

DARCY 31

Henry Darcy's Public Fountains of the City of Dijon

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Abstract

An unabridged English translation of Darcy's 1856 book, now a rare book available in few libraries, makes it possible for hydrogeologists to experience Henry Darcy's activities and insights first-hand. Darcy's book describes the construction of Dijon's water supply system in 1840, the sand experiments that led him to formulate Darcy's Law, among numerous other topics.

As an engineer in the Corps of Bridges and Roads, Darcy fulfilled his life's dream of providing abundant clean water for his native city of Dijon. The book describes his research into Dijon's 400-year history of surface and ground water projects and his planning and execution of all aspects of Dijon's water supply system. Darcy calculated the population's daily water needs and selected a spring to supply the necessary amount of water to Dijon via a 12-km aqueduct. He built two reservoirs, 13 km of pipes, and 120 street fountains in the city. The fountains supplied free water for domestic purposes, street flushing, and fire fighting.

Introduction

Henry Darcy (1803-1858) wrote The Public Fountains of the City of Dijon as a guide for engineers involved in the construction of water supply systems. He wrote the book in the 1850s, long after he had built Dijon's water supply, but before water supply systems were common in European cities.

In planning the Dijon water supply system in the 1830s, Darcy investigated the sources of water available to the city, estimated the city's water needs, and chose an abundant spring located in an adjacent village. Darcy designed and built a 12.7 km aqueduct to Dijon and two reservoirs within the city. He designed and built a network-type internal distribution system to deliver water to 120 street fountains. At the completion of the project, Dijon ranked second only to Rome in terms of water quality and quantity. Within the walls of Dijon, street fountains were no farther than 100 meters apart, meaning that no one had to walk more than 50 meters to obtain water. At the time, water fountains in Paris were spaced at an average interval of 270 meters.

Because Darcy's book is a how-to manual for engineers, it contains discussions of a number of topics unrelated to the Dijon project. Darcy discusses rivers, ponds and lakes as water supply sources; his understanding of artesian wells; pipes and pipe making; and natural and artificial filtration of river water, among other topics. In Darcy's day, sand filters were used to filter river water. Because the filters were so large, it was difficult for a city to find space to build them. Darcy's research into a way to make filters smaller led to the sand experiments described in Darcy's Law.

Darcy's concern for the poor shows in his discussions of the importance of numerous street fountains located so that poorer citizens would not put be off by the length of the journey to obtain water.

Darcy's father died when he was about 14, leaving the family in difficult straits. Henry and his brother were excellent students, and their mother "put forth great effort" with the city of Dijon to obtain money to educate them. During his childhood Darcy had been sickened by the only water available and had promised himself to put an end to this situation if ever he were in a position to do so (Darcy, 1957). After Henry completed his education and entered the Corps of Bridges and Roads, the city of Dijon requested that he be assigned to his native city. Shortly after returning to Dijon in 1827, Darcy began working on his plan, and by 1832 he was gauging the Rosoir Spring, which he would later divert to Dijon.

The book is divided into four parts and an appendix. The four parts are further divided into chapters. The English translation contains the 28-plate atlas of engineering drawings that was originally published as a separate volume.

Part One

Part One is a description of the historical water situation of Dijon. Chapter 1 is an account of the Darcy's research on old fountains in the city. His friend the city archivist helped him determine which springs Dijon had used as water sources during the previous four centuries.
In Chapter 2, Darcy examines the Suzon, an intermittent stream that flowed through Dijon. Darcy investigated the widespread belief that prior to 1830 it had been a perennial stream. Based on his review of the archives, Darcy concluded that the Suzon had been an ephemeral stream for at least 450 years.
The Suzon also presented a more difficult problem. Its streambed, which passed through the city, was a convenient refuse dump for many city dwellers. One of the goals of Darcy's water distribution system was to construct a cover over the sewer and flush it out. Darcy accomplished the sanitization of the Suzon sewer in 1847, seven years after the completion of the aqueduct. Darcy discusses this project in more detail in Part Four.
Part One Chapter 3 is entitled The Rosoir Spring, the name of the spring Darcy diverted to Dijon. This long chapter contains numerous topics. Darcy describes the source of Dijon's drinking water as private wells and wells along the city streets that tapped into alluvium saturated by fluid from adjacent permeable-wall cesspools. Darcy discusses the mid19th century view of the relative purity of well water, cistern water, pond (stagnant) water, river water and spring water, concluding that spring water was preferable. He provides a chemical analysis of water collected from a well in a private house and a water analysis of the Rosoir water from 1850. Darcy enumerates the potential sources of water for Dijon, which included several springs, a nearby river, and an artesian well. He calculates the amount of water needed for a city water supply, including domestic needs, manufacturing, public buildings, fire suppression, street cleaning, public fountains and gardens. Darcy determines the per capita water requirement to be 150 liters per day, 90 liters for domestic and industrial purposes, and 60 liters for street flushing. He then eliminates various sources that do not provide enough water, or provide water that is too hot in summer, or water that is too expensive because it must be raised from a riverbed. Darcy shows that the Rosoir Spring provides abundant pure cool water that will remain cool until it reaches the street fountains because of the insulation provided by underground aqueduct. Darcy discusses water quality in terms of what water should contain: atmospheric air, carbonic acid, sodium chloride and calcium carbonate, and states that it should also dissolve soap well. He discusses iodine, goiter and cretinism. He describes the gauging of the Rosoir Spring in 1832-33. The Rosoir Spring flows from Jurassic limestone and discharges 4,000 to 12,000 liters per minute depending on the season.
In a section on the origin of springs Darcy notes that by 1850 most people believed springs to be fed by infiltrated rain water, and discusses historical views on the origin of springs, inclu-

ding Descartes' idea of underground fires and huge stills beneath the earth's surface. Darcy provides a classification of springs and discusses the history of springs-seekers, from the Greeks to his French contemporaries. He describes methods of creating artificial springs.
A significant portion of Chapter 3 is dedicated to artesian wells. An artesian well had been dug in Dijon in the early 1830s, but it didn't flow above the ground surface and didn't provide enough water to supply the city, so Darcy rejected it as a water supply source. During Darcy's time, it was evidently believed that water circulated in pipe-like voids under the earth's surface. Darcy also recognized that many artesian wells flow from sandy layers under an impermeable layer. Darcy understood that friction resulting from water movement consumes hydrostatic head, or pressure, as he called it. Darcy understood that it was possible to increase the discharge of an artesian well by lowering its discharge point, and calculated that it was also possible to increase its discharge by increasing the diameter of the well. He also understood that as the number of artesian wells from a single source increases, the discharge of the wells decrease.

Part Two

Part Two describes the construction of the aqueduct and the internal distribution system. In Chapter 1, Darcy describes the masonry aqueduct he built between the Rosoir Spring and Dijon. Construction of the aqueduct began in March 1839 and was completed in September 1840. The aqueduct is 12.7 km long between the pavilion that covers the spring and the Porte Guillaume reservoir in Dijon (Fig. 1). For the most part, the aqueduct is 0.60 m wide and 0.90 m high, and is covered by one meter of soil. Manholes are located every 100 m. The spring is located on the bank of the Suzon stream upstream of Dijon, and the aqueduct crosses the Suzon stream three times on the way to Dijon. The aqueduct also passes through three villages where water is diverted from the Dijon aqueduct to provide for the villages. Just before reaching Dijon, the aqueduct becomes a viaduct to cross an area of low topography. In the text, Darcy provides details about the slope and cross section of the aqueduct and details of all the work involved and all costs for material and labor.

In Chapter 2, Darcy discusses the internal distribution system, which consists of two reservoirs and a system of cast iron pipes that branch out into all neighborhoods of the city to provide water to street fountains and private concessions. The main artery connects the two reservoirs, distributor pipes branch off the main artery, and service pipes branch perpendicularly off the distributors to serve the street fountains. Darcy used masonry tunnels and trenches for the pipes, depending on the importance of the street above the pipe. The pipes connect at distribution tanks to form a grid system.
The Porte-Guillaume reservoir (Figure 2) is located at the end of the aqueduct and the beginning of the main artery of the internal distribution system. Darcy brought water into the Porte Guillaume reservoir through a vertical pipe in the central well of the reservoir. At a certain height, the water flowed through some openings and down a stairwell to fill the reservoir. This height was the head that controlled water flow and pressure and maintained maximum water pressure throughout the city. Darcy also discusses the problem of air expansion in the reservoir, and the means he devised to minimize this problem.

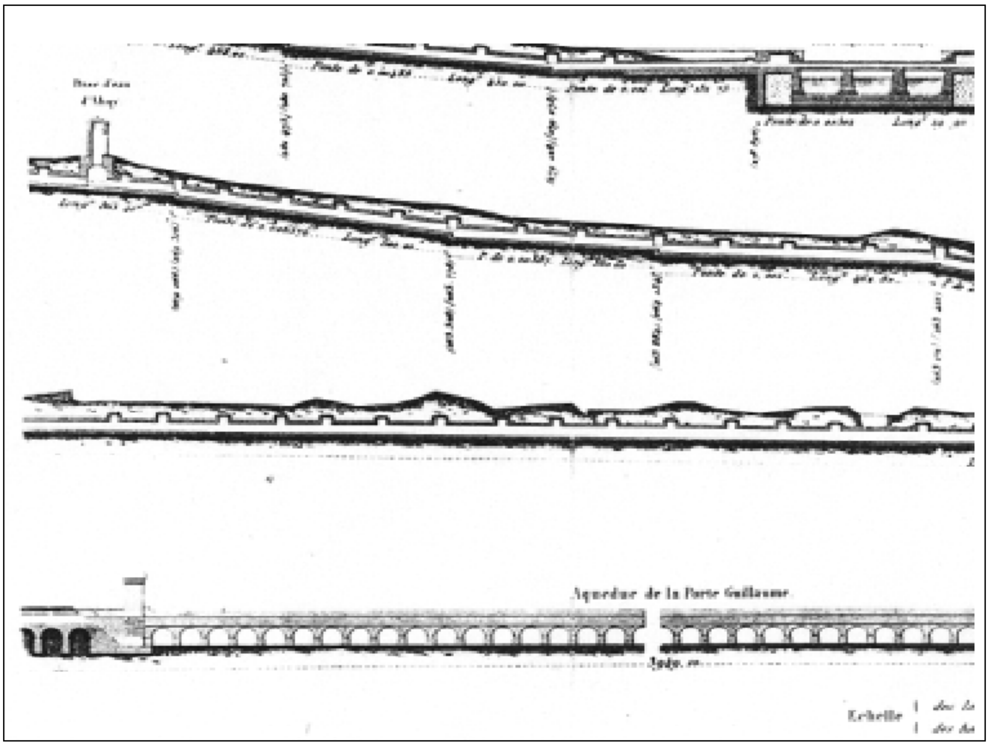

Figure 1. Profile of the Aqueduct that conveys the Rosoir Spring water to Dijon, Plate 2.

The Porte-Guillaume reservoir is circular in shape, and is covered by one meter of soil. The reservoir capacity is 2313 m^3. Reducing the water supply to the amount strictly necessary for the inhabitants, which Darcy estimated at 20 liters per person, or 540 m^3 per day, the reservoir could supply enough water for four or five days. Darcy constructed an entrance structure on top of the reservoir, which is still there today.

Darcy knew that more storage capacity was required, primarily because an aqueduct repair could easily last more than four or five days. He built a second reservoir, rather than one larger reservoir, to prepare for the possibility that the main artery would require repair. By building the Montmusard Reservoir on a hill at the other end of the main artery, Darcy ensured that all points in the city could be supplied by interconnecting pipes. In addition, Darcy saw

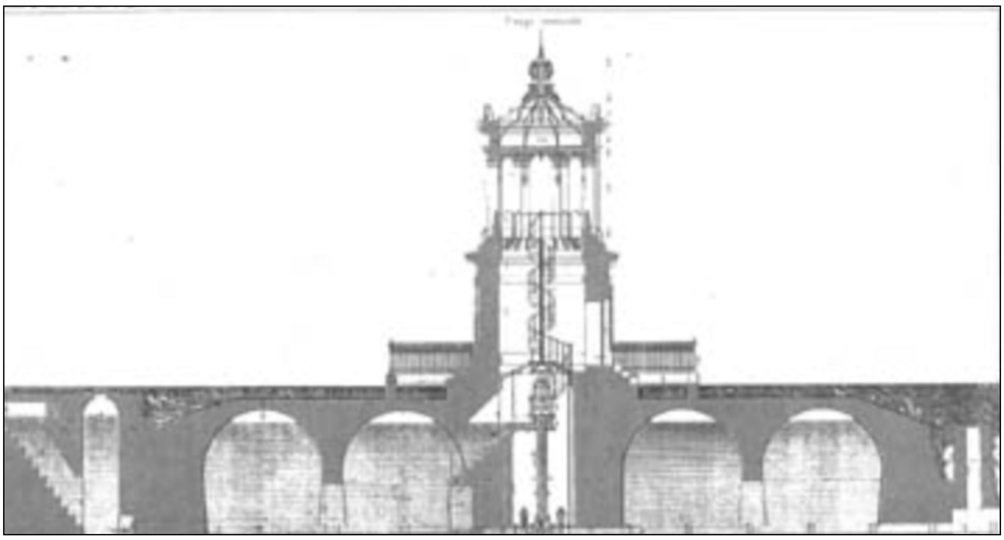

Figure 2. Cross section of the Porte Guillaume Reservoir, Plate 11.

that supplying the main artery from both ends made it possible to furnish a much larger amount of water than if it were served by only one end. Another reason Darcy gives for constructing the second reservoir is the possibility that the Porte Guillaume reservoir may need repair. In that case, the springs themselves could not supply enough water for street watering during the hot summer when domestic water use would be high, but with the water from the Montmusard Reservoir, it would be possible to do so.
The Montmusard Reservoir is rectangular and is located underground, covered by one meter of soil. Its capacity is 3177 m^3. All flow in the city pipes was suspended every night while the Montmusard Reservoir was being filled.
Chapter 2 also contains a detailed discussion of all components of the distribution system. He provides the calculations for the jets of the fountain he built at the Place Saint-Pierre, which still flows today. He also provides a detailed description of the street fountains, all of which have now disappeared.

Part Three

Part Three presents experiments that Darcy conducted on the aqueduct and distribution system. Chapter 1 discusses experiments on water flow in the aqueduct that conveys water from the Rosoir spring to Dijon. Chapter 2 deals with experiments on water flow in the conduit system. The first three sections of Chapter 2 summarize Darcy's memoir Recherches experimentales relatives au mouvement de l'eau dans les tuyaux [Experiments on Water Movement in Pipes] that was published in 1857.

Part Four

Part Four contains a discussion of the administrative and legal questions involved in the construction of the water supply system. These included the expropriation of the spring, the opposition mounted by the owners of mills located downstream of the springs, the purchase of land the aqueduct would cross, the sanitizing of the Suzon sewer within the city, and private water concessions.
Because the Rosoir spring was located within the jurisdiction of a nearby village, the question of water rights had to be resolved. The question was settled in favor of the City of Dijon by edict of the King on 31 December 1837. The city compensated the state and the village for the spring. Darcy proposed a water distribution formula that gave the inhabitants of the villages between the springs and Dijon 150% of the per capita water allocation of a Dijon resident. The claims of the mill owners were finally resolved by the payment of simple damages rather than expropriation costs.
Darcy was in charge of the land purchases for the aqueduct. He hired an expert to handle the negotiations. He says of this process, "the discussions were conducted with so much calm and sincerity on the part of the expert that the landowners exhibited such moderation that I was obliged to increase the amount of the indemnities claimed by one of the communes. From that time forward, so many landowners felt confident of us that they sent us the acts of sale, signed blank. Not a single opposition was raised, and there were five hundred fifty-six parcels."

Appendices

The Appendix contains eight notes, designated by the letters A through H.
Appendix A is a list of springs located near Dijon. Darcy probably made this inventory as a part of the process of selecting a water supply source.

Appendix B is a contract dated 6 December 1445 between the City of Dijon and Pierre Belle, a carpenter from the neighboring village of Talant. In this contract, the carpenter agrees to bring the waters of the Montmusard Spring to the Porte Saint-Nicolas, one of the old city gates of Dijon, through an aqueduct constructed of hollowed-out logs.

Appendix C is a discussion of the water supply systems of London, Paris, Brussels, Lyon, Bordeaux, Nantes, Besançon and Nîmes in the 1800s. In this note, Darcy also discusses his adaptation of the Pitot tube to make it easier to use in gauging water flow in rivers and streams.

Appendix D, entitled “Filtration” contains an account of the experiments that led Darcy to formulate Darcy’s Law. Darcy cites London and Glasgow as cities that practiced artificial filtration. The disadvantage of artificial filtration is the large surface area required for the filtration beds, 4,000 square meters in the case of one filtration bed in London. Darcy proposes a modification to decrease the size of filtration beds by increasing the discharge of the filter, using a taller column of water or negative pressure under the filter. This leads Darcy into the discussion entitled, “Determination of the Laws of Water Flow through Sand” and his description of the experiments he conducted in Dijon in 1855 with Engineer Ritter.

In Appendix E, Darcy discusses the methods he used to gauge the Rosoir Spring.

In Appendix F, Darcy discusses methods for drawing a constant volume of water from a variable level channel.

Appendix G is a discussion of pipe strength and fabrication of cast iron, lead, sheet metal and bitumen pipes. Sheet metal pipes covered with bitumen were a new invention in the 1850s.

Appendix H contains additional information on water flow in the Rosoir Aqueduct.

Conclusion

In this brief overview of Darcy’s book, I have had to leave out numerous topics that Darcy discusses. The reader of Darcy’s entire book will encounter many treasures not mentioned in this article, including a discussion of the cisterns of Constantinople and an ingenious fire-suppression plan for Dijon’s Theater.

Darcy is also responsible for Dijon being located on the main rail line between Paris, Lyon and Marseille. In addition, he was a city councilor and a founder and administrator of social service organizations that sought to lend a hand to those like him who had had difficult beginnings (Darcy, 1957). After his unexpected death in Paris, his body was brought back to Dijon by train, and the entire city gathered at the train station to show their respects. The City of Dijon renamed the location of the Porte Guillaume Reservoir to Place Darcy in his honor.

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DARCY 119

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

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Abstract

This paper discusses Henry Darcy's distinguished contributions to science and engineering. In addition to Darcy's Law, Darcy made major contributions to pipe hydraulics and pipe friction coefficient analyses that are acknowledged in the joint naming of the Darcy-Weisbach pipe head loss equation. He also furnished the very first evidence of the fluid boundary layer. Darcy combined his law with continuity to develop the first falling head permeameter solution that we use today and he applied it in the analysis of spring discharge. His work on open channel flow with Bazin and his breakthroughs in pipe friction research were made possible through improvements he made to the Pitot tube used for measuring point water velocity. This paper will demonstrate the Darcy made numerous contributions to the study of hydraulics. Whilst Darcy is immortalised by Darcy's Law, it is immediately evident that his scientific legacy extends beyond it.

1. 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 marks the 150th anniversary of the publication of Henry Darcy's most famous text "*Les Fontaines Publiques de la Ville de Dijon*" (T*he 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 paper 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 we are possibly less familiar with. 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 we still use 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.

This paper provides an account of Darcy's contributions to engineering science. It does so by beginning with a brief historical account of Darcy's life (Section 2) 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 (Section 3). 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 immediate post-Darcy years (Section 4) 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 we first see Darcy's Law applied to a hydrogeologic problem that resembles a modern day aquifer analysis.

2. Darcy's Life: A brief historical perspective

Henry Philibert Gaspard Darcy was born on 10th June 1803 in Dijon, France, and died in Paris on 3rd 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., Caudemberg 1858; Marsaines 1858; his great-nephew, Paul Darcy 1957; Hubbert 1969; Freeze and Back 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. From all of these accounts, we have been able to learn some interesting things about Henry Darcy and to answer even the most basic questions such as what did Darcy look like? Two reproductions of Darcy – one of the young Darcy at age 18 at the L'Ecole Polytechnique in 1821 and the other of the mature Darcy are shown in Figure 1. And just to give a little Darcy trivia for a moment, we also know that Darcy was 1.69m 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. It appears that Darcy's name was always Henry and never Henri but that he was born with the surname d'Arcy but it changed in his teen years (see section 2.1). The subject of Darcy's name has been dealt with by Brown and Hager (2003) and provides conclusive evidence to support this claim. Indeed, it is this anglicized form that appears on the title pages of the famous "*Fontaines Publiques*" report (see Figure 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: (i) the early educative years (early 1810's to mid 1820's) that establish Darcy's strong technical background in engineering, mathematics and physics, followed by, (ii) a longer period (mid 1820's to late 1840's) 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 finally, (iii) the final years of Darcy's life (early 1850's to his death in 1858) where Darcy's failing health sees a clear shift towards research and to completing the writing of much of his life's work.

Figure 1a. Henry Darcy in 1821. (P. Darcy, 1957)

Figure 1b. Henry Darcy in the later years of life. Portrait by F. Perrodin from the collection of the Bibliotheque Municipale de Dijon (from Philip, 1995; Brown, 2002a).

2.1 The early educative years (mid 1810's - 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 it deeply. According to Henry Darcy V (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 (2003) described this man as a "republican brute" who in return for the loan demanded that their surname be changed from d'Arcy to the anglicised form Darcy, a wish that Agathe complied with in order to provide her sons with an education.
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 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 the 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 practicing engineers for careers in the Corps. It both supported and expected excellence and Darcy's 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, we can be sure that Darcy learned the state of the art in fluid flow, mathematics and physics. We also know from Brown (2002a) that 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 suggests that Darcy was a good, but not the best student.

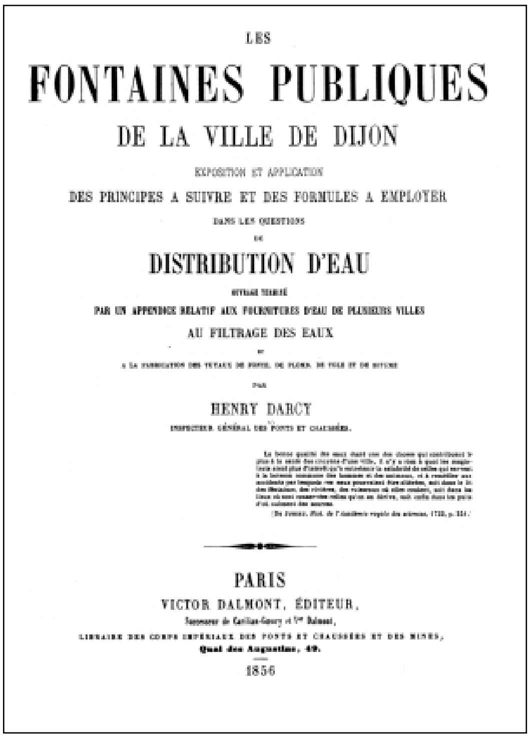
2.2 Darcy's engineering years and his rise to prominence (1826-1848)

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 16th 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 Means of Providing Necessary Water to the City). On March 5, 1835, the Munipical Council approved his plans with no revision, and on March 31, 1837, the Dijon water project was declared a public utility by a royal ordinance. On March 21, 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 water supply development in Paris that was achieved by the mid 1860's. 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 1.3km stretch of the Suzon, a small stream that acted as an open sewer through the centre of Dijon (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 four kilometre tunnel at Blaisy which began in January of 1845 and of which Darcy completed about one third of the tunnel 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. 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 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).


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.

PARIS

VICTOR DALMONT, ÉDITEUR,

Successeur de Carilian-Gœury et Vor Dalmont,

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

Quai des Augustins, 49.

1856

Figure 2. Darcy's famous 1856 "Fontaines Publiques" report (from Hubbert, 1969).(P. Darcy, 1957)

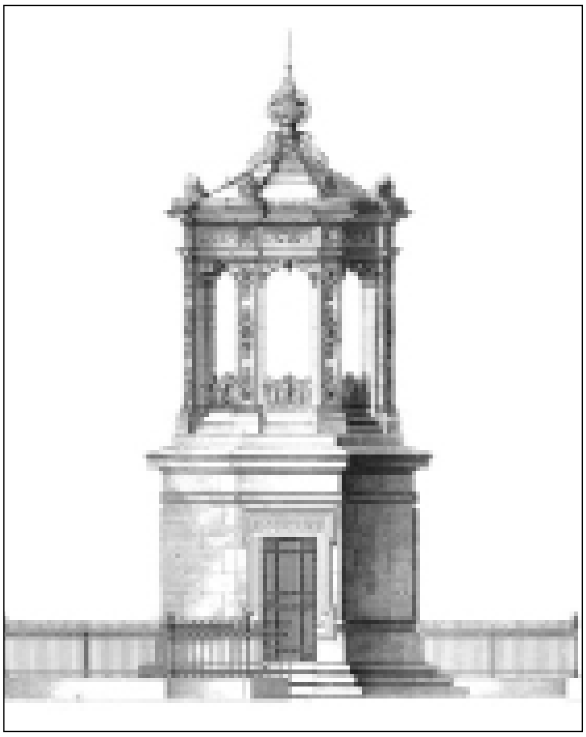


Figure 3. Darcy's design of the tower at Porte Guillaume reservoir (Darcy 1856, Plate 9). The tower and reservoir are still standing today.

2.3 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 December 20 1848, Darcy was transferred to Paris and appointed as Chief Director for Water and Pavements. On December 2, 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 Caudemberg (1858) attributed to 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 last few years of Darcy's life would see Darcy make some major scientific discoveries – what we might now call 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. 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 January 3 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 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 square Château d'Eau, the location where the waters of the Rosoir spring enter Dijon, was officially renamed Place Darcy – a decision arrived at unanimously and immediately 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" (Darcy and Bazin, 1865). Also published posthumously, this publication would be Darcy's last.

3. Darcy's everlasting 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 legacy more fully. As scientists and engineers, we 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 included 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.

3.1 Observations of aquifer resistance (Darcy, 1834)

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 Means of Providing Necessary Water to the City). In it, Darcy described tests conducted in the groundwater system at Place Saint-Michel on August 6, 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). 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.

3.2 *The Darcy-Weisbach Equation, Boundary Layers, Laminar/Turbulent Flow (Darcy, 1857)*

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 1840's, Darcy initiated, designed and completed a comprehensive experimental program intended to improve the estimation of the Prony pipe friction coefficients (Darcy, 1857; Brown, 2002a; Brown 2002b) that was largely conducted in the period 1850-1854, although his report "*Recherches Expérimentales Relatives au Mouvement de l'eau dans les Tuyaux*", (Experimental Research Relating to the Movement of Water in Pipes) was published later in 1857 (Darcy, 1857).
At the time, the Prony equation (Eqn.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.

$$h_L = \frac{L}{D}(aV + bV^2)$$ The Prony Equation (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*, the velocity of the flow *V*, 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 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 (Eqn 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 (Eqn.3) at high velocities (Brown, 2002a; Brown 2002b). As noted by Brown (2002b) the pipe friction equation proposed by Darcy took the form:

$$h_L = \frac{L}{D}\left[\left(\alpha + \frac{\beta}{D^2}\right)V + (\alpha' + \frac{\beta'}{D})V^2\right]$$ The Darcy Pipe Friction Equation (2)

where *α, β, α', β'* 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 (Eqn 3) that is commonly used today.

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

where f is usually called the Darcy friction factor and is a complex function of the relative roughness and Reynolds number 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 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 often 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 1/4 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 details 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, page 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 *decreases continuously as the*

degree of polish increases. But the reduction nevertheless is far from appearing proportional to the degree of polish obtained. In vain one would say that the influence of asperities inappreciable to the eye persists for the fluid molecules; that explanation would not seem at all satisfactory. In effect, the term in 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 its similarity with Poiseuille's Law (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 the constant circular cross-section. Darcy later showed that his newly proposed pipe friction formula reduced to the Poiseuille's linear equation (Eqn. 4) at low flow and small diameters, namely,

$$Q = kD^4 \frac{h_L}{L}$$ Poiseuille's Law (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). Here we see the clear recognition that at low flows (i.e., laminar) flows, a linear relationship holds between flow and head loss. Indeed, Darcy clearly understood that such a linear relationship held in slow flow, small diameter pipes. 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 gradien*t". He later showed explicitly that his newly proposed pipe friction formula would reduce to equation (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 (1797-1884) had begun to understand the differences between low and high velocity flows in capillary tubes (what we would now call laminar and turbulent flows), Darcy had extended those insights into real pipes and to pipes of larger (general) diameters. All available documentation clearly 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.

3.3 Les Fontaines and Darcy's Law (Darcy, 1856)

"*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).

3.3.1 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 writeup of what is now considered by many to be his most famous text on the construction of the municipal water supply of Dijon, "*Les Fontaines Publiques de la Ville de Dijon*"(*The Public Fountains of the City of Dijon*) (Darcy, 1856). This is Darcy's "*swansong*", Darcy's attempt to write a thesis in the style of the day at a time of deteriorating health. In it, 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) and for which Bobeck was awarded the prestigious 2004 S. Edmund Berger Prize for Excellence in Scientific and Technical Translation, which is presented by the American Foundation for Translation and Interpretation (www.afti.org). Patricia Bobeck's amazing translation of Les Fontaines Publiques de la Ville de Dijon opens a window into the world of engineering science in the early 19th 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 8m^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 3,177m^3). The entire engineering design contained some 13.5km of distribution lines. It supplied 141 public street fountains spaced 100m 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 Figure 3, at ''*Chateau d'Eau*'' at La Porte Guillaume (Darcy 1856, Plate 9).

In this text, Darcy also clearly emphasised the importance of science in providing and understanding our water resources. In Darcy's time, hydrogeology was still arguing about the Greek water cycle which moved water from the sea to the continents and Father Paramelle's famous book "*The art of discovering springs*" (1856, 1859), with no mention of Darcy's work, was the best seller, not Darcy's (de Marsily, 2003). Darcy's discussions of Father Paramelle's exploration for springs and the ancient Greek hydrologic cycle are well written and perceptive. Darcy dedicates a significant number of pages to a gentlemanly debunking of his methods and dismissed dowsing as a cult (Sharp and Simmons, 2004).

Les Fontaines Publiques de la Ville de Dijon begins with Darcy's introduction on the need for a good watersupply, 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 15th to the 19th centuries, a discourse on springs and the rationale for choosing 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: A. Springs in the Dijon area; B. A 15th century contract for Dijon water; C. Water supply systems for various cities, including London and Paris; D. Filtration, which includes the famous Darcy column experiments; E. Weir gauging; F. Extracting constant volumes of water from a varying-level stream channel; G. Pipe fabrication methods; and H. Flow in the Rosoir aqueduct.

3.3.2 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 titled "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….*". Whilst filtration methods and galleries were becoming a common practice at the time, it was clear that filter clogging posed the major operational concern at that time. Critically, there had been no attempt to quantitatively analyse filtration hydraulics. 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 in 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 (October 29/30, November 6, 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 (February 17 and 18, 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. It is said that Darcy's experiments were conducted in an unnamed hospital courtyard. The apparatus used is shown in Figure 4 (plate 24, Figure 3 of the original monograph) and consisted of a vertical column 2.50m 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 0.35m. The experiments were performed using siliceous sand from the Saône River, and each experimental series had a different sand packing. Packing height varied from 0.58m (Series 1) to 1.70m (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 coarsest 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*"), that 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 that large (but random) fluctuations allowed average height of mercury to be measured to the nearest 5 mm, and thus allowed the water pressure to be determined to about 13cm. 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.

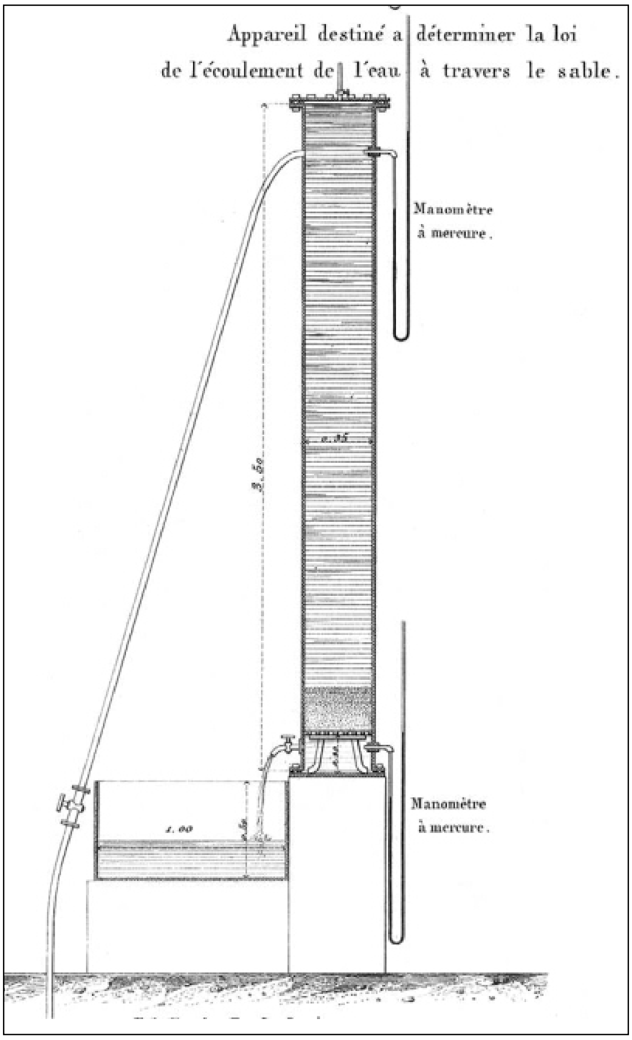


Figure 4. Darcy's original sand column apparatus (Darcy 1856, Plate 24, Figure 3).

The duration of the experiments varied between 10 and 30 minutes, 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 we now call 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 4th 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 and only a few days in the hospital courtyard, quantitative hydrogeology as we know it 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 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, who successfully confirmed that this was indeed the case. Darcy then stated his law (exactly as it is written in Eqn. 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 ± h_o to yield, in general terms:

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

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. Eqn 4 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 we use 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 probably 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.

2. Darcy knew 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 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 nor theoretically as a bundle of capillary tubes. This would follow very shortly after 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 we know that such approaches are at the heart of current challenges faced by hydrogeologists in difficult concepts such as the REV, matters of hydrogeologic scaling and dealing with heterogeneity in the subsurface.

4. The rise of the linear gradient laws: Interestingly, the early to mid 19th century saw the birth of the entire suite of linear gradient laws including Fourier's heat conduction law (1822), Ohm's law for electricity (1827), Poiseuille's Law (1841), and Fick's Law (1855) for molecular diffusion. 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 (1768-1830), a French Professor and academic. 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.

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 combing 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 Figure 5, 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.

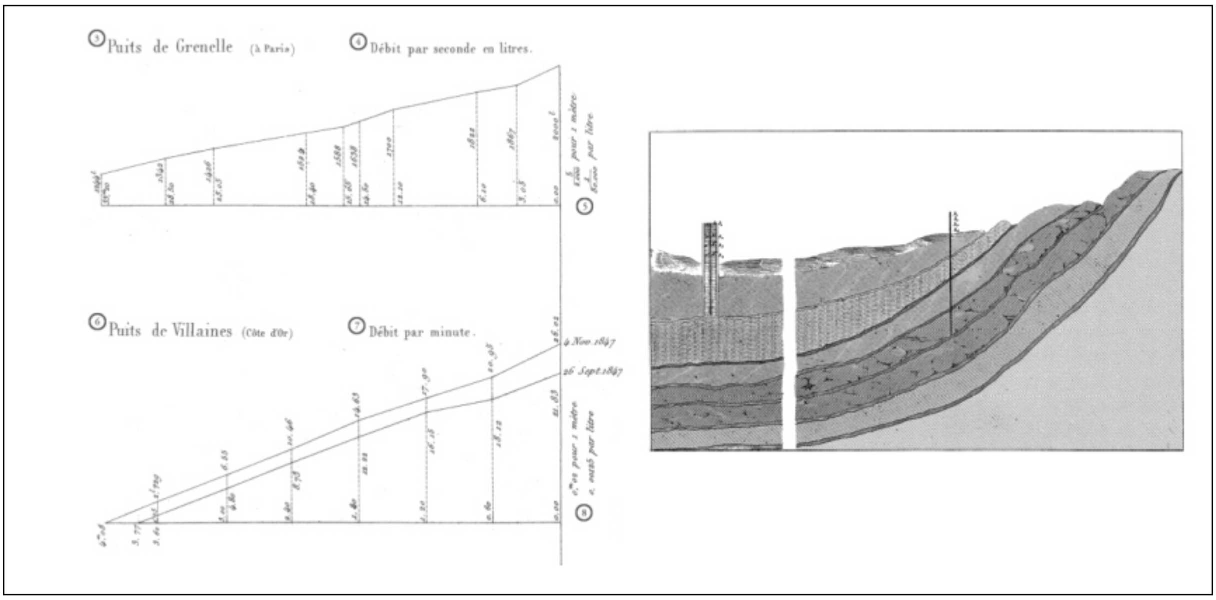


Figure 5. Darcy's measurements of artesian spring flow and his linear observations (Darcy 1856, Plate 22).

3.4 Improvements to the Pitot Tube (Darcy, 1858)

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 that points straight down into the field (to measure static pressure) and a second tube that has a 90 degree 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 Darcy (1856). Darcy's 1858 publication "Relative à quelques modifications à introduire dans le tube de Pitot" (Some modifications introduced to the Pitot tube) was published posthumously shortly after his death and reflected several years of work gradually perfecting its design over the period 1850-1857.

4. Hydrogeology in the immediate post-Darcy years

It would be just seven years before Darcy's Law was applied in what we might now call 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 with a free surface. 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). Both Darcy's work and that of Dupuit inspired other investigations in water supplies, soils and engineering geology. As early as 1870, the German Adolf Thiem had modified Dupuit's formula to allow for the calculation of aquifer hydraulic properties using a pumping well and observing the resulting decline in water table in adjacent wells (Thiem, 1887). The Austrian Philipp Forchheimer (1852–1933) applied Laplace's equation and potential theory to groundwater problems by recognising the similarity between groundwater flow and heat flow (Forchheimer, 1886). A well known American geologist, T. C. Chamberlin further developed the relationships between groundwater and its host geologic formations in his pioneering report "The Requisite and Qualifying Conditions of Artesian Wells" (Chamberlin, 1885) – the first groundwater report published by the United States Geological Survey. In it, Chamberlin provided a theoretical basis for the scientific study of groundwater which prompted a boom in groundwater exploration in the United States. It is interesting to note that Darcy's work on artesian wells and springs (Darcy, 1856) predated Chamberlin's by some thirty years.

5. 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*". We should remember Darcy as 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 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. We as 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. But Darcy lives on forever and his contributions are everlasting. Indeed, Darcy is immortalised by Darcy's Law and his scientific legacy.

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DARCY 120

Darcy, the water in Dijon and something in the air

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1. Public fountains

On the 31st of October 1833, Henry Darcy who was then an engineer of Bridges and Roads (Ponts et Chaussées) in Dijon, wrote to the Mayor of the city:

"In your letter of April 17, 1832, you asked me to compile a report on the various ways in which water could be conveyed in Dijon.
I have the honour of informing you that my work is finished: I will present it to you as soon as you so desire".
The report was presented to the City Council on the 15th of December 1833.
That is how it all began.

Today, when we have water on every floor, in the kitchen, the bathroom, the lavatory we have difficulties understanding the magnitude of what Darcy accomplished: "deviate" the water from the Rosoir spring and bring it to
- the "public fountains";
- the wash-houses,
- the horses' watering troughs, etc.
which he caused to be installed in his native city.

Over a century and a half later, how should we view this work carried out in an environment so very different from our own,
- where there was no electricity, no petrol-powered engines nor, of course, tap- water?
- when hydrogeology (the science of groundwater) did not exist and geology itself was hesitantly constructing its identity.

2. Wells

Water for the citizens of Dijon before Darcy

So far, the city had been getting its water mainly from its wells. Around 1750, there were over one hundred public wells accessible to everybody, randomly placed in squares and streets, sometimes in such a way as to hinder the traffic. And there were many more in private courtyards or even inside the houses. Those that can still be seen today (in the courtyard of the Hôtel de Vogûé, at the entrance to the Archaeological Museum) now count as historical landmarks.
Unfortunately, although these wells provided easy access to water, it had long since said goodbye to its quality. One of the reasons being that the wastewater was discharged nearby. The modern word "pollution" may not have been used at the time but its manifestations were certainly present.

Projects that always came to nothing

Nevertheless, many suggestions had been made: springs in the Suzon valley, springs in the Ouche valley, among others.
In the 18th century there had been a plan to "elevate" the water from the Ouche. But to elevate river water was no small enterprise. It could only be done through the motive force of the river itself. This procedure had been used in Paris ever since Henry IV had ordered the construction, on the Seine, of the

“Pump at the Samaritaine” which was driven by a mill-wheel. At the end of the 18th century steam pumps were installed, for example, at the foot of the Chaillot hill in Paris.
In 1827, the mayor of Nevers had equipped the city with a steam engine that would force the water of the Loire river into a reservoir 32 m higher up but the pump proved to be weak and whimsical and only the hospitals, the garrison and a few institutions were supplied ( ).
In Dijon the use of steam was proposed in 1825 but the cost of the installation, maintenance and fuel for the machines gave food for thought.

The artesian well

All these ideas remained at the stage of vague intentions because of lack of in-depth studies, technical possibilities or simply of financial means.All ideas? All but one, the most astounding one: but this idea was in the air.
A subscription society planned to drill an artesian well and on March 2, 1829 the City Council voted a budget and decided on the location of the well: the Saint-Michel Square.
It seems that no preliminary study had been made but artesian wells were in fashion; Darcy devoted an entire chapter to them in his 1856 publication on the Public Fountains in Dijon.
From 1820 to 1840 the number of artesian wells increased: 12 Paris, 8 in Saint-Denis, 3 in Mulhouse, others in Le Havre, Tours, Strasbourg, La Rochelle, Perpignan. In addition to the failures including the one in Dijon. ( )
In 1833, the drilling began in Paris of what was to become, in 1841, the well-known artesian well in the rue de Grenelle, after 7 years and 2 months of work and unforeseen events. In Dijon, the work extended over only three and a half years but the well was shallower: 155 m instead of 600.
Unfortunately, the structure of the ground was less favourable and consequently, the results did not meet the expectations. The water did rise to 2 metres “below the paving of the square” whereas the water level in the surrounding wells was over 9 metres below it, but it was still necessary to pump and the resulting flow rate was too weak to be usefully exploited.
Darcy was not fooled by the artesian-well craze which had led to this failure in Dijon.

3. Guillebot cross-section

The Côte d’Or geology

In fact, at the time very little was known about the mysterious fate of water underground, and there was no precise knowledge of what the underground of the country was like.The first geological map of the Côte d’Or region with the first cross-section that gives an idea of the Dijon underground was not published until 1852, only a short time before the book by Darcy (1856) on the “public fountains in the city of Dijon”, but long after the first water-supply network was created in Dijon (1840).

Darcy certainly learned of the work undertaken to draw a map of the Côte d’Or region. The author, Mining Corps Engineer Guillebot de Nerville, had, between 1840 and 1848, been in charge of the Mineralogical Services of the Côte d’Or region. As they both worked in the same city, it was inevitable that Darcy and Guillebot would meet.
In his book from 1856, Darcy describes the underground terrain in the Dijon area. He follows verbatim the nomenclature of Guillebot de Nerville. However, none of it is used to understand the Rosoir spring nor to draw up the plans that led to the arrival in 1840 of the water in the Porte Guillaume reservoir.
Darcy’s project was that of an engineer, not of what we today call a hydrogeologist.
We shall try to follow his reasoning.

In the footsteps of Darcy

On the origin of springs

“There is nobody today who, if asked about the origin of fountains, would not staunchly answer that they are the product of rainwater infiltration”, wrote Darcy in 1856 in his chapter “On the origin of fountains” (p. 109).

He added: “But this idea only gained credence after several centuries and ancient philosophers offered curious explanations of this phenomenon whose origin appears obvious to us today”.
Then he quotes Ecclesiastes (verse 7): “the water from the fountains, rivers and streams runs into the sea and still its level does not change”.
“What mysterious mechanism regulates this level?… They have imagined underground conduits. The sea gives back to the fountains and to the sources of rivers the volume it has received from them”.
Here Darcy dwells on the “mechanisms” that had been imagined to explain both the return of the water and the elimination of the salt in the sea water.

Concretely, Darcy distinguished three types of springs (1856, p. 112).
1 - The first ones: “in impervious terrain”; not worth discussing because too mediocre.
4 - Rosoir block
2 - The second ones: “When an impervious rock covered by a permeable formation crops out either on the slope or the bottom of a valley, one understands that, at this point, there must be a more or less abundantly flowing spring: such is the origin of the Rosoir fountain”…. However, this explanation has to be qualified.
3 - The third case is that of a “permeable layer enveloped by impervious formations which constitute its top and bottom.
The water flows as if in a conduit and a natural artesian spring wells up if a well-placed fracture in the top layer allows the water to reach the surface”.
A conduit is, in fact, a notion of a hydraulic engineer.

4. Darcy, the engineer.

Let us return to the second type of spring concerning which Darcy concluded: “such is the origin of the Rosoir fountain”. This conclusion is somewhat hasty and simplistic without any real attempt at explaining the behaviour of the water in the “permeable rock”.
In fact, Darcy’s measurements, experiments and calculations concerned:
- how to bring the water from Rosoir to Dijon and distribute it to the fountains in the city,
- but not the behaviour of the water upstream in what he called, rather vaguely, “the permeable rock” which to us is the aquifer.

For example, the technology of “network” distribution, the one finally chosen in Dijon, was much more complex than the “linear” one preferred till then. It was, however, quite approximate and Darcy had to work on his type curve calculations to achieve it ( ).
On the other hand, when one reads Darcy, one does not discern any difference between porous media (sand and gravel), for which his work was seminal, and fractured media, also said to have “large-scale permeability”, of which limestone, i.e., our karstic aquifers, are the main examples: which is precisely the case of the Rosoir spring.

Conquering the water

From another point of view, Darcy’s project can be seen as the very first step in what one might call “conquering the water”, a slow conquest that proceeded throughout the 19th century.
According to a survey made in France in 1882 ( ):
- only 19 cities possessed a water supply system in 1820;
- 23 cities acquired one between 1820 and 1840, including Dijon;
- between 1840 and 1882, there were a further 326.

This was still the gathering stage: i.e., water was taken where it was seen to flow out of the ground.

5 - Aqueduct

Darcy’s great achievement was that after having eliminated the inadequate options (artesian wells, the Neuvon spring, etc.), the uncertain or overly costly solutions (elevation of the Ouche water), he proved, figures in hand, that it was feasible to “divert” the Rosoir water. Divert it and bring it to Dijon simply

through gravity by means of an aqueduct built of good cut stone, a material that was commonly used and available at the time (stone from Is and Chanceaux, etc.)
Simply through gravity … Provided that its route had been carefully calculated and the slope regulated: here to prevent the flow from accelerating, there to increase it in order to keep it from freezing. It only remained to calculate the cost of constructing and maintaining the "the masonry structure surrounding the spring" (Darcy did not speak of tapping) and of the aqueduct.
The water itself was still a free gift from heaven.

Darcy tells us that the Rosoir spring flowed freely "at the foot of a high forested hill (elevation 200 metres), on a rocky slope, on the very banks of the Suzon into which it discharged directly.

6 - The spring pavilion

The steep, forested hill is still there. The rocky slope is partly covered by moss and ivy. As to the spring, it would remain unnoticed by the many walkers in the Parc de Jouvence if it were not for the protection zone that surrounds it, carefully closed and sign-posted.
And the two strange square pavilions built of stone from Is-sur-Tille, grey with age, on each side of the dry river bed. Do the walkers suspect that they mark the first crossing of the Suzon by an "underground siphon" of the aqueduct that Darcy built to convey the water from the Rosoir to the Porte Guillaume reservoir?

7 - Map at the time of Darcy

After Darcy

At the time Dijon had some 25 000 inhabitants and covered only part of the alluvial plain of the Suzon at its confluence with the Ouche.

8 - Sainte-Foy

- The population grew as did its needs; the spring of Ste-Foy, upstream in the Suzon valley, already part of Darcy's project, was therefore added to the Rosoir Fountain and later, the Fountain du Chat.
- Furthermore, the city spread beyond the alluvial plain and climbed up the slopes of Montchapet to the west and Montmusard to the east.

9 - Marmusots

It was not until 1900 that the Marmusots reservoir, was built at Talant, on the boundary of the Dijon municipality. It was also called the Morcueil reservoir because it received water from the Morcueil spring, situated between Fleurey and Pont-de-Pany, with the help of the "elevation plant" at Chèvre-Morte. This plant was then powered by the motive force of the Ouche; later it was driven by steam (a piston engine, now retired but still in existence).
The continuing upward growth of the city, both westwards and eastwards, and the ever higher housing developments were preceded, or followed, by the installation of new reservoirs at increasing elevations; today, the height record is held by the Chaumont reservoir on the hill to the west of Talant.

10 - Higher and higher

- Darcy and Montmusard 1840 …. 254 m
- Marmusots 1903 …. 292 m
- Victor Hugo 1933 …. 318 m
  Bocage 1935

Marcs d'Or 1936 at equilibrium with Marmusots
Valmy 1959
- La Motte Giron 1952 …. 392 m
Charme d'Aran 1958 …. 329 m
Rente de Chatenay 1971 …. 334 m
- Chaumont 1974 …. 399 m
Upper Valmy 1978, at equilibrium with Charme d'Aran.

The needs are different as well.

Cars that are cleaned with a hose have taken the place of the horses that had to be watered.
Around 1900 the washtubs made the public wash-houses obsolete before the arrival of washing machines, bathrooms, lavatories, etc.
The industrial use of water changed and increased.
Then came the sewers which advantageously replaced the disposal into the Suzon (Darcy and the mayor Victor Dumay had considered this question, but that would be another research subject).

11 - Map of the country surrounding Dijon

Therefore, more and more water was needed. The springs, those in the Suzon valley as well as the one at Morcueil were no longer sufficient.

This marks then end of the gathering stage. It became necessary to drill wells and pump.
- This was first done nearby, in the alluvia of the Ouche, but always upstream of the city in order to avoid the risks of contamination and to use the facilities of the Chèvre-Morte plant.

12 - Côte d'Or resources

Finally, at greater distance, thus at greater cost, in the Saône alluvia at Poncey-lès-Athée and later at Flammarens. It must be remembered that the Saône is the major water resource for the Côte d'Or region before the one represented by rainfall.

What is left today of Darcy's work?

13 - The Darcy reservoir

14 - The Montmusard reservoir

In and around Dijon, there are the Darcy square, the park and, although they are now empty and in retirement, the two Darcy reservoirs: the one at Porte Guillaume, which is today called the Darcy reservoir, behind the waterfall which it no longer feeds and that of Montmusard in the boulevard de Strasbourg marked by its neo-gothic tower - two monuments intimately linked to the landscape and to the history of Dijon.

15 - St-Pierre square

One must not forget the water spouts in St-Pierre square (Wilson square) although they are no longer fed by the 1840 reservoir.
Better still, a large share of the city water supply still comes from springs in the Suzon valley.
We must not forget the major achievement of Henri Darcy's work the tapping of the Rosoir spring which

still functions in an "environment" (a word unknown to Darcy) that has quite successfully retained its "natural" character, beneficial to the water quality.

16 - 2002 graphics

In a "normal" year, the Suzon valley springs (the Rosoir, "diverted" by Darcy, Ste-Foy whose addition he had foreseen and the Fontaine au Chat) provide around half of the Dijon consumption.
In 2002, a year of severe drought, they still contributed almost a third. For 2003 we are still awaiting the numbers.

17 - Rue des aqueducs

Another memory is called up by the name: the rue des Aqueducs. This is where the Rosoir water pipe arrived just before it entered the Porte Guillaume reservoir by an aqueduct above ground, built of stone, 148 m long and supported by 59 semicircular, 1.50 m high arches.
The aqueduct was dismantled in 1881 when the neighbourhood was redesigned and the cemetery built. It was replaced by an underground cast-iron siphon which was more unobtrusive and less costly to maintain. The masonry had, in fact, began to leak in several places where the women of the area were said to have built wash-basins to soak their laundry.

18 - Aqueduct

The feeder aqueduct still remains with many markers on the surface like the pavilion at the Moulin du Rosoir and especially, the aerial crossing of the Suzon which is very visible next to the bridge on the road from Ahuy to Messigny.
This is another historical landmark that deserves to be preserved.

In 2003, there remains, in particular, the fact that the Dijon water distribution network is indeed inherited from the network of "public fountains" and the decisive initiative taken by Henri Darcy in 1833.

> Under a different heading, at a global scale, for scientists:
> - there is Darcy's law on the flow of water,
> - and a measurement unit, the "darcy".
>
> This is a unit to measure the permeability, for example, that of sand.

19 - Experimental column

Take a layer of sand with a thickness of one centimetre.
Subject it to the pressure of a liquid:
whose viscosity is that of water at 20°C and
a pressure of one kilo per square centimetre (around one atmosphere).
If the sand lets through:
- every second,
- a cubic centimetre of liquid,
- per square centimetre of surface area,
- its permeability is one darcy.

That's how simple it is.

All this just because 200 years ago, Dijon had a serious water shortage.

Darcy, l'eau à Dijon et l'air du temps

Pierre RAT - Université de Bourgogne

Le 31 octobre 1833, Henry Darcy, alors ingénieur des Ponts et Chaussées à Dijon écrivait à Monsieur le Maire de la ville : « Par lettre du 17 avril 1832 vous m'avez invité à faire un rapport sur les différents moyens que l'on pourrait employer pour conduire des eaux à Dijon. J'ai l'honneur de vous prévenir que mon travail est terminé : je vous le soumettrai aussitôt que vous le désirerez.[1] » Le rapport fut présenté au Conseil municipal le 15 décembre 1833. C'est ainsi que tout a commencé.
Aujourd'hui, alors que nous avons l'eau à tous les étages, à la cuisine, à la salle de bain, aux toilettes, nous mesurons mal ce que fut la réalisation de Darcy : « dériver » l'eau de la source du Rosoir pour l'amener aux « fontaines publiques », aux lavoirs, aux abreuvoirs pour chevaux qu'il fit installer dans sa ville natale. Un grand siècle et demi plus tard, quel regard pouvons-nous porter sur cette œuvre, menée dans un contexte si différent du nôtre, alors qu'il n'y avait à Dijon ni électricité, ni moteur à essence ni, évidemment, d'eau au robinet ? Alors que l'hydrogéologie (la science des eaux du sous-sol) n'existait pas et que la géologie elle-même tâtonnait pour se construire. La connaissance géologique du sous-sol bourguignon, elle aussi, était balbutiante.

L'eau des Dijonnais avant Darcy

La ville, jusque-là, tirait l'eau surtout de ses puits. Vers 1750, on comptait une bonne centaine de puits publics, accessibles à tous, au hasard des places et des rues au point de gêner parfois la circulation. Et combien y en avait-il encore dans les cours privées, ou même à l'intérieur des maisons ? Ceux qui nous restent aujourd'hui (dans la cour de l'Hôtel de Vogüé, à l'entrée du Musée archéologique, ...) ont valeur de monuments historiques. Hélas, s'ils offraient une eau d'accès facile, la qualité, depuis longtemps, n'était plus au rendez-vous, d'autant plus que les eaux souillées se perdaient à proximité. Si le sens actuel du mot « pollution » n'était pas encore connu, le fait était bien là.

Des projets, toujours dans le vide

Pourtant, bien des suggestions avaient été faites : sources de la vallée du Suzon, sources de la vallée de l'Ouche. On avait aussi envisagé au 18e siècle « l'élévation » des eaux de l'Ouche. Mais, élever l'eau des rivières n'était pas une mince affaire. On ne pouvait le faire que par la force motrice de la rivière elle-même, procédé utilisé à Paris depuis qu'Henri IV avait fait construire la Pompe de la Samaritaine mue par une roue de moulin. À la fin du 18e siècle, on put ajouter des pompes à vapeur, au pied de la colline de Chaillot notamment. À Nevers, en 1827, le maire avait bien fait installer une machine à vapeur pour refouler de l'eau de la Loire jusqu'à un réservoir, 32 mètres en contre-haut ; mais la pompe à feu s'était avérée faible et capricieuse et seuls les hospices, la caserne et quelques établissements étaient desservis [2].
À Dijon, l'emploi de la vapeur fut proposé en 1825, mais le coût d'installation, d'entretien et d'alimentation des machines donnait à réfléchir.

Le puits artésien

Toutes ces idées étaient restées à l'état de velléités, faute d'études suffisantes, de possibilités techniques ou tout simplement de moyens financiers. Toutes ? Sauf une, et la plus surprenante; mais elle était dans l'air du temps.

1 Archives municipales de Dijon, liasse 3N.
2 GOUBERT (Jean-Pierre), La conquête de l'eau, Laffont, 1986 (« Pluriel »), p . 208.

Une société de souscription fit le projet de forer un puits artésien, si bien que, le 2 mars 1829, le conseil municipal dijonnais vota un crédit et fixa l'emplacement Place Saint-Michel. Aucune étude préliminaire ne semble avoir été faite, mais ces puits avaient alors la cote, l'idée était dans l'air, si bien que Darcy leur consacra tout un chapitre dans ses Fontaines publiques de la Ville de Dijon. De 1820 à 1840, note Jean-Pierre Goubert [3], le nombre s'en multiplie : 12 à Paris, 8 à Saint-Denis, 3 à Mulhouse, d'autres au Havre, à Tours, Strasbourg, La Rochelle, Perpignan. Sans compter les échecs, dont celui de Dijon. En 1833, débutait à Paris le forage de ce qui allait être, en 1841, le fameux puits artésien de Grenelle, après 7 ans et 2 mois de travaux et d'aléas. À Dijon, les travaux s'échelonnèrent sur 3 ans et demi seulement, mais le puits était moins profond : 155 m au lieu de 600. Hélas, la structure du sous-sol était moins favorable, aussi les résultats ne furent-ils pas à la hauteur des espérances. L'eau s'éleva, certes, jusqu'à 2 m « en contrebas du pavé de la place », alors que le niveau des puits du voisinage était à plus de 9 mètres au-dessous, mais il fallait encore pomper et le débit obtenu restait insuffisant pour une exploitation judicieuse. Darcy ne fut pas dupe d'un tel engouement pour les puits artésiens, soldé à Dijon par cet échec [4].

La géologie de la Côte d'Or

On ne connaissait alors pas grand chose du mystérieux destin souterrain de l'eau et rien de précis sur ce que pouvait bien être le sous-sol du pays. La première carte géologique de la Côte d'Or, avec la première coupe donnant une idée du sous-sol dijonnais, ne date que de 1852 : elle avait donc été imprimée peu avant la parution du livre de Darcy cité plus haut, mais nettement après la réalisation du premier réseau dijonnais de distribution d'eau (1840) [5].

Darcy eut certainement connaissance des travaux entrepris pour l'établissement de la carte de la Côte-d'Or. En effet, l'auteur, Guillebot de Nerville, ingénieur au Corps des Mines, avait été chargé, de 1840 à 1848, du Service minéralogique de la Côte-d'Or. Inévitablement, en fonction dans la même ville, Darcy et Guillebot de Nerville se sont connus. Dans son ouvrage, Darcy donne un relevé des terrains du sous-sol dijonnais qui suit mot à mot la nomenclature de Guillebot de Nerville. Rien de tout cela n'apparaît, ni pour comprendre la source du Rosoir, ni dans l'élaboration des plans qui ont abouti en 1840 à l'arrivée de l'eau au réservoir de la Porte Guillaume. Le projet de Darcy fut celui d'un ingénieur, non celui de ce que nous appellerions aujourd'hui un hydrogéologue.

Sur les pas de Darcy

De l'origine des sources

« Il n'est personne aujourd'hui qui, consulté sur l'origine des fontaines, ne réponde hardiment qu'elles sont le produit de l'infiltration des eaux pluviales. Mais cette idée n'a prévalu qu'après bien des siècles, et les anciens philosophes avaient donné d'étranges explications à ce phénomène dont l'origine nous paraît évidente aujourd'hui [6]. » Et de citer l'Ecclésiaste (verset 7) : « les eaux des fontaines, des rivières et des fleuves se jettent dans la mer, et cependant son niveau ne varie pas. » « Quel est donc le mystérieux mécanisme qui le règle ?... Ils ont imaginé des conduits souterrains. La mer rendait aux fontaines, aux sources des fleuves le volume qu'elle en avait reçu.[6] » Et Darcy de s'attarder sur les mécanismes imaginés pour expliquer et la remontée de l'eau et la dessalure à partir de l'eau de mer.

Plus concrètement Darcy distinguait trois sortes de sources [7] :

1 - les premières « dans les terrains imperméables ». Passons, elles sont plus que médiocres.

3 Op. cit. [1], p. 55.
4 Fontaines, chap. III.
5 La première carte géologique de la France, à l'échelle de 1/500 000, par Dufrénoy et Elie de Beaumont, ne fut publiée qu'en 1841.
6 Fontaines, p. 109.
7 Fontaines, p. 112.

2 - les deuxièmes : « Lorsqu'une roche imperméable recouverte d'une formation perméable vient affleurer soit le flanc, soit le fond d'un vallon, on comprend qu'il doit y avoir en ce lieu production d'une source plus ou moins abondante : telle est l'origine de la fontaine du Rosoir ». Toutefois cette explication est à nuancer.

3 - les troisièmes, dans le cas d'une « couche perméable enveloppée de formations imperméables qui lui servent de toit et de lit. Les eaux coulent comme dans un conduit et l'on obtient une source artésienne naturelle si une fracture heureuse du toit permet à l'eau de s'élever en surface » Un « conduit » c'est bien une image d'ingénieur hydraulicien !

Darcy ingénieur

Revenons à la deuxième pour laquelle Darcy concluait : « elle est l'origine de la fontaine du Rosoir », conclusion un peu rapide et simplificatrice sans véritable tentative d'explication du comportement de l'eau dans « la roche perméable ». En fait, les mesures, les expériences, les calculs de Darcy ont concerné l'amenée des eaux du Rosoir à Dijon et la distribution aux fontaines de la ville, mais non le comportement amont de l'eau dans ce qu'il appelait, d'une manière peu précise, « la roche perméable » et nous, aujourd'hui, l'aquifère. La technologie de la distribution « en réseau », qui fut finalement adoptée à Dijon, beaucoup plus complexe que celle de la distribution « en ligne », resta approximative, souligne Jean-Pierre Goubert, jusqu'à ce que Darcy ait établi les abaques de calcul.

De plus, dans la logique de Darcy, on ne voit pas de distinction entre les milieux poreux (sables, graviers), pour lesquels ses travaux ont fait école, et les milieux fissurés, dits encore « perméables en grand », dont les calcaires, nos aquifères karstiques, sont les principaux représentants ; ce qui est le cas précisément de la source du Rosoir.

La conquête de l'eau

D'un autre point de vue, on peut situer le projet de Darcy dans le tout début de ce qu'on a pu appeler la conquête de l'eau, une lente conquête réalisée au long du 19e siècle. Selon une enquête réalisée en 1882, en France 19 villes seulement possédaient une distribution d'eau en 1820 ; 23 s'en sont pourvues entre 1820 et 1840, Dijon étant du nombre. De 1840 à 1882, il y en eut 326.

On en était alors encore au stade de la cueillette : prendre l'eau là où on la voit sortir de terre. Le grand mérite de Darcy fut, après avoir éliminé les solutions insuffisantes (le puits artésien, la source de Neuvon...), les solutions incertaines ou trop onéreuses (élévation des eaux de l'Ouche), de démontrer, chiffres en main, la faisabilité de la « dérivation » du Rosoir. Dérivation et amenée à Dijon par simple gravité grâce à un aqueduc en bonnes pierres de taille, matériau parfaitement en usage et disponible à l'époque (pierre d'Is, pierre de Chanceaux, ...). Par simple gravité, à condition d'avoir bien calculé le tracé, réglé la pente, ici pour éviter que le courant ne s'emballe, là pour l'accélérer afin d'empêcher le gel. Il n'y avait donc qu'à envisager le coût de construction et d'entretien de « l'enceinte de maçonnerie qui environne la source » (Darcy ne parlait pas de captage), et de celui de l'aqueduc. L'eau elle-même restait un don gratuit du ciel.

La source du Rosoir sortait librement au pied d'un haut versant boisé (dénivellation 200 mètres), dans un abrupt rocheux, au bord même du Suzon dans lequel elle se déversait aussitôt. Le versant raide et boisé est toujours là. Quant à la source, elle passerait bien inaperçue des nombreux promeneurs du Parc de Jouvence s'il n'y avait ce périmètre de protection qui l'enserre, soigneusement enclos et signalé. Et ces deux curieux pavillons carrés, en pierre d'Is-sur-Tille patinée de gris, de part et d'autre du lit à sec de la rivière. Les promeneurs se doutent-ils qu'il s'agit du premier franchissement du Suzon, par un « syphon souterrain », de
l'aqueduc que Darcy fit construire pour conduire l'eau du Rosoir jusqu'au réservoir de la Porte Guillaume ?

Après Darcy !

Dijon comptait alors quelque 25.000 habitants et n'occupait qu'une partie du plat alluvial du Suzon à son confluent avec l'Ouche. La population s'est accrue et avec elle les besoins ; on a donc ajouté à la Fontaine du Rosoir, en amont dans le Val Suzon, la Source de Ste-Foy que Darcy avait déjà envisagée, puis la Fontaine au Chat.

De plus, la ville a débordé de la plaine alluviale pour s'élever sur les pentes de Montchapet à l'ouest, de Montmusard à l'est. Il fallut attendre 1900 pour que soit construit sur Talant, à la limite du territoire communal dijonnais, le réservoir des Marmusots, dit aussi de Morcueil car il recevait l'eau de la source de ce nom, située entre Fleurey et Pont-de-Pany, grâce à « l'usine élévatrice » de Chèvre-Morte. Celle-ci était alors actionnée par la force motrice de l'Ouche ; elle le fut ensuite par la vapeur (une machine à piston, aujourd'hui à la retraite, mais toujours existante). La montée continue de la ville, tant à l'ouest qu'à l'est, et la hauteur accrue des grands ensembles ont été suivies ou précédées par l'installation toujours plus haut de nouveaux réservoirs ; le record est tenu à ce jour par celui de Chaumont sur la butte à l'ouest de Talant.

Mais aussi, les besoins ont changé. Les autos que l'on nettoie au jet se sont substituées aux chevaux qu'il fallait faire boire. Vers 1900, la lessiveuse a rendu inutiles les lavoirs publics avant que n'apparaissent nos machines à laver. Salles de bains, toilettes, ... Les usages industriels aussi ont changé. Et puis il y a eu le tout-à-l'égout qui a heureusement remplacé l'évacuation par le Suzon (Darcy et le maire Dumay y ont pensé, mais ce serait un autre sujet d'étude). Il a donc fallu de plus en plus d'eau. Les sources, tant celles de la vallée du Suzon que celle de Morcueil, ne suffisaient plus. Fini le stade de la cueillette ! On dut forer des puits et pomper. D'abord à proximité, dans les alluvions de l'Ouche, mais en amont de la ville pour éviter les risques de contamination et où l'on bénéficiait de l'usine de Chèvre Morte. Enfin, plus loin, donc plus cher, dans les alluvions de la Saône à Poncey-lès-Athée puis à Flammerans. N'oublions pas que la Saône est la première ressource d'eau pour la Côte d'Or, avant celle qui provient des pluies.

Que reste-t-il aujourd'hui de l'œuvre de Darcy ?

Il y a, dans le paysage dijonnais, la place, le jardin Darcy, et même s'ils sont vides et maintenant à la retraite, les deux réservoirs de Darcy : celui de la Porte Guillaume, connu maintenant sous le nom de réservoir Darcy, derrière la cascade qu'il n'alimente plus, et celui de Montmusard, boulevard de Strasbourg, signalé par sa tour néogothique. Deux monuments indissociables du paysage et de l'histoire de Dijon. Sans oublier les jets d'eau de la place Wilson (place Saint-Pierre), bien qu'ils ne soient plus alimentés par le réservoir de 1840. Mieux, une forte part de l'alimentation de la ville se fait toujours à partir des sources de la vallée du Suzon.

Ne négligeons donc pas la pièce maîtresse de la réalisation d'Henry Darcy, le captage de la source du Rosoir, toujours fonctionnel, dans un « environnement » (un mot que Darcy ignorait) qui a relativement bien gardé son aspect « nature », favorable pour la qualité de l'eau. En année « normale », les sources de la vallée du Suzon (le Rosoir « dérivé » par Darcy, Sainte-Foy dont il avait prévu l'ajout et la Fontaine au Chat) fournissent environ la moitié de la consommation dijonnaise. En 2002, année de sécheresse sévère, elles y ont encore participé pour près du tiers.

Un souvenir : la rue des Aqueducs. C'est là, en effet, qu'aboutissait la conduite des eaux du Rosoir, juste avant son entrée dans le réservoir de la Porte Guillaume, par un aqueduc aérien de pierre, de 148 m de long, porté par 59 arcades en plein cintre de 1,50 m de haut. L'aqueduc fut détruit en 1881, lors du réaménagement du quartier et le départ du cimetière, et remplacé par un siphon souterrain en fonte, plus discret et moins coûteux d'entretien. La maçonnerie,

en effet, présentait des fuites que, dit-on, les femmes du quartier avaient aménagé en lavoirs pour y tremper leur lessive.
Reste aussi l'aqueduc d'amenée avec plusieurs témoins en surface, comme ce pavillon au Moulin du Rosoir et surtout ce franchissement aérien du Suzon, bien apparent à côté du pont de la route d'Ahuy à Messigny. Autre monument historique qui mérite d'être conservé.
Il reste surtout, en 2003, que le réseau dijonnais de distribution d'eau est bien l'héritier du réseau des Fontaines publiques et de l'impulsion décisive donnée par Henry Darcy en 1833. Sur un autre registre, à l'échelle mondiale, pour les scientifiques : il y a la loi de Darcy sur l'écoulement de l'eau, et une unité de mesure, le "darcy". Une unité pour chiffrer la perméabilité, celle d'un sable par exemple. Prenons une couche de sable épaisse d'un centimètre. Soumettons-la à la pression d'un liquide : un liquide dont la viscosité est celle de l'eau à 20°, une pression d'un kilo par centimètre carré (à peu près une atmosphère). Si ce sable laisse passer, chaque seconde, un centimètre-cube du liquide par cm2 de sa surface, sa porosité est de un darcy. Et voilà, c'est tout simple !

Tout cela, parce qu'il y à 200 ans, Dijon manquait cruellement d'eau !

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DARCY 133

Henry Darcy et les fontaines publiques de la ville de Dijon

Eliane LOCHOT, conservateur en chef
des archives de la ville de Dijon

En 1856, le dijonnais Henry Darcy publie un ouvrage appelé à connaître une brillante renommée : "Les fontaines publiques de la ville de Dijon : exposition et application des principes à suivre et des formules à employer dans les questions de distribution d'eau". Comme le sous-titre l'indique, cette publication est la synthèse des recherches menées par ce brillant ingénieur en chef des ponts et chaussées pour résoudre la question de l'alimentation en eau potable de Dijon.

En 1832, une épidémie de choléra frappe le département de la Côte-d'Or et le conseil municipal de Dijon décide de confier une étude à Henry Darcy. Sa mission consiste à résoudre les difficultés techniques d'un approvisionnement en eau saine et suffisamment abondante pour une cité qui compte alors 25 000 habitants.

Dès 1834, la solution proposée par Darcy est retenue : dériver la source du Rosoir, située dans le Val-Suzon, et conduire l'eau à Dijon par un aqueduc souterrain de plus de 12 kilomètres de longueur en utilisant habilement le dénivelé.

Après deux années de travaux, les dijonnais se réjouissent le 6 septembre 1840 de voir l'eau de la source du Rosoir pénétrer dans le réservoir de la porte Guillaume (aujourd'hui réservoir Darcy). Très à l'avant-garde, la municipalité a également décidé d'aménager un vaste réseau de distribution d'eau. Il permet à chacun d'accéder gratuitement à l'eau grâce à des bornes-fontaines ou bien de disposer de l'eau à domicile en payant un abonnement. Les notions d'hygiène, de salubrité et de santé publiques sont essentielles.

L'ouvrage dont nous célébrons cette année, le 150ème anniversaire de la publication, présente non seulement les solutions techniques retenues par l'ingénieur mais est également le fruit de la réflexion d'un scientifique. Il a expérimenté puis théorisé sur le mouvement de l'eau dans les tuyaux. La célèbre note D sur l'écoulement de l'eau à travers le sable préfigure la loi qui prendra le nom de Darcy.

DARCY 134

Schéma directeur d'alimentation en eau potable du Grand Dijon

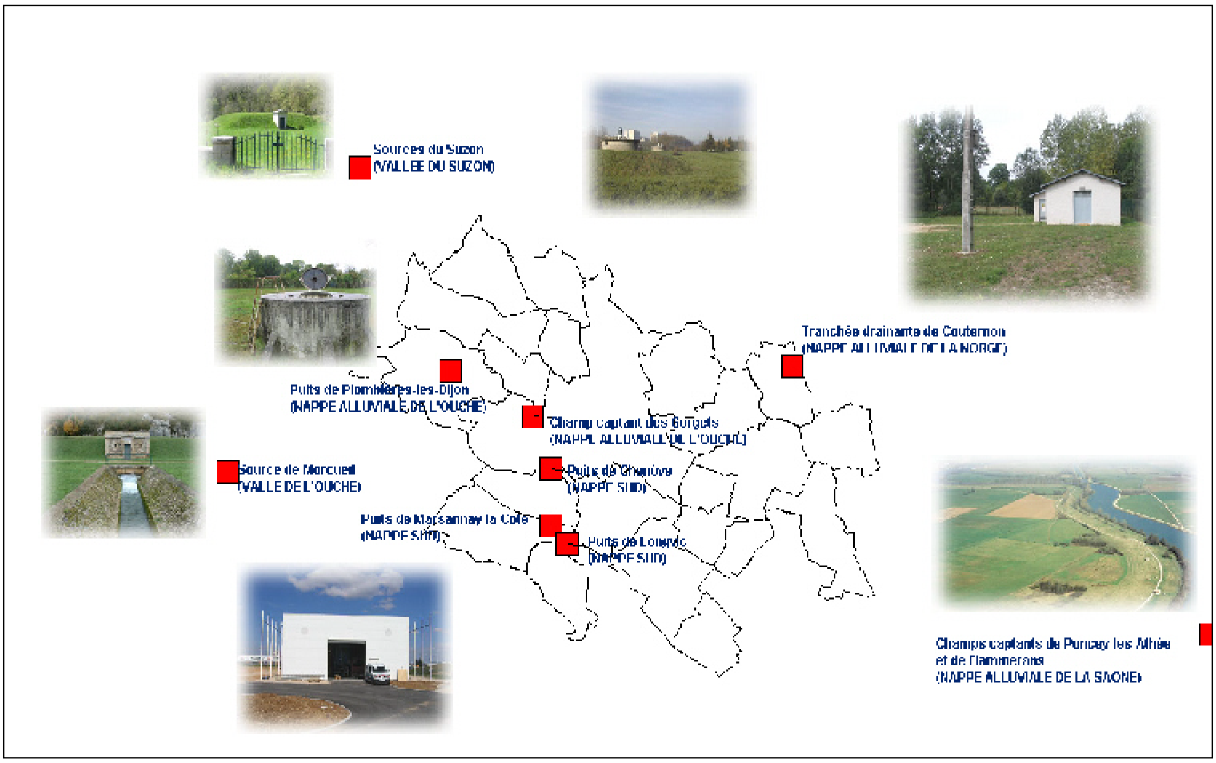
Jérôme de Dompsure,
responsable de la production d'eau potable à Lyonnaise des Eaux

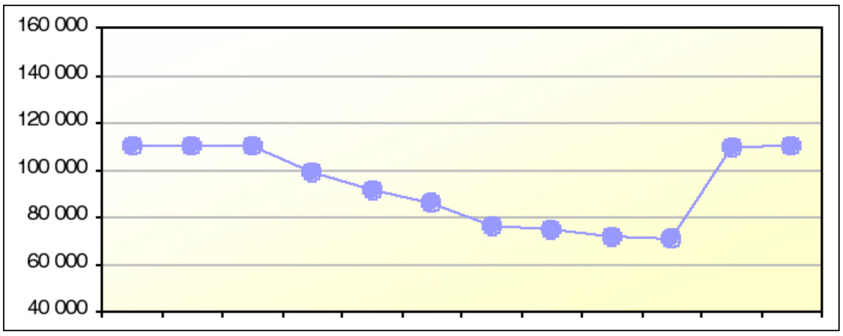
Pour la première fois, un schéma directeur de l'alimentation en eau potable a été réalisé en 2005 sur le périmètre de l'agglomération dijonnaise. Pour les 15 prochaines années, après avoir évalué les besoins en eau de l'agglomération dijonnaise (besoins actuels et nouveaux, induits par le développement économique de l'agglomération), l'objectif de cette grande étude était de permettre au Grand Dijon de définir un programme d'actions hiérarchisées afin d'orienter les investissements nécessaires à l'alimentation en eau potable d'une agglomération en expansion.

Les ressources de l'agglomération dijonnaise

Les ressources sont de nature très diverses et présentent des étiages sévères pour certaines: deux sources de type karstiques (Suzon et Morcueil) et quatre nappes (nappes alluviales de la Saône à Poncey-les-Athée, de l'Ouche à Plombières-lès-Dijon et à Dijon-Gorgets, de la Norges à Couternon et nappe sud à Chenôve, Marsannay-la-Côte et Longvic).

La capacité totale de production offerte par les ressources est comprise entre 71 000 m³/j en période d'étiage des sources (octobre) et plus de 110 000 m³/j en hiver. La ressource essentielle à l'agglomération est la nappe de Poncey-lès-Athée qui représente près de 60 % de la production en octobre et est la seule ressource importante avec une forte capacité d'extension.





Les besoins en eau de l'agglomération dijonnaise

L'analyse des consommations des cinq dernières années met en évidence trois tendances :

- une faible baisse des consommations sur la ville de Dijon (-1,4 % par an environ)
- une croissance sur les autres communes de l'agglomération (+ 2 % par an)
- des économies significatives chez les industriels

L'analyse de l'historique des consommations a également permis de mettre en valeur une évolution saisonnière des besoins. Le mois de plus forte consommation est le mois de juin, pour lequel les besoins du jour de pointe sont 30 % supérieur au besoin de pointe du mois de décembre.

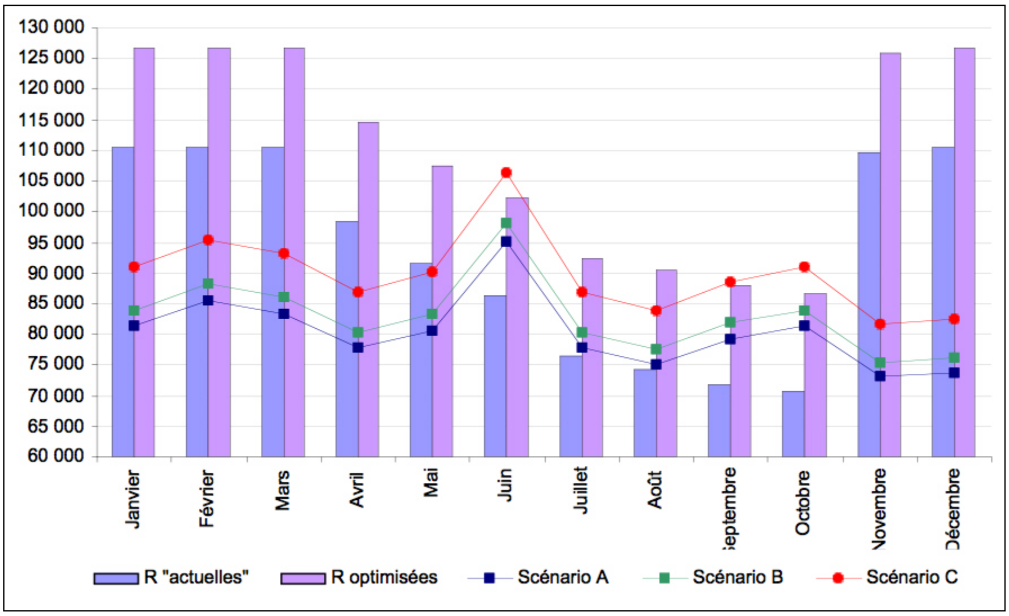
L'analyse des consommations futures a été réalisée pour chaque catégorie (domestique, industrielle, tertiaire) à l'aide des documents d'urbanisme de l'ensemble des communes. Ensuite trois différents scénarios ont été pris en compte simulant un développement de l'agglomération faible, moyen et fort. Ces scénarios prennent en compte les incertitudes liés aux mouvements de population dans l'agglomération ou sur le territoire du SCOT.

Les performances du réseau de distribution

Les pertes en eau représentent actuellement 25 % de la production d'eau. Le « rendement » des réseaux est en effet estimé à 75 % à l'échelle du Grand Dijon. Des économies significatives peuvent être réalisées, en particulier grâce aux actions engagées dans le cadre du programme « Eau Vitale » du SMD. A l'horizon du schéma directeur (2020), une économie de 2,2 millions de m^3 est envisagée.

Comparaison des besoins futurs et des ressources disponibles – Horizon 2020

A ces ressources (nommées R « actuelles » sur le graphique suivant) s'ajoutent 16 000m^3/j de gain de production attendus grâce à des travaux prévus, qui devraient se dérouler dans les années à venir. Ces travaux comprennent 14 000 m^3/j de production supplémentaire sur l'usine de Poncey-les-Athée, grâce à une optimisation du fonctionnement du champ captant. Il est prévu par ailleurs de poursuivre la mise en place d'unités de traitement sur la nappe sud : un filtre supplémentaire dans l'usine de Marsannay, mise en service fin 2005, ainsi qu'une nouvelle unité de production à Longvic, ces deux actions permettant un gain de 2000 m^3/j. ces ressources sont nommées « R optimisées » sur le graphique suivant.



Bilan besoins-ressources en 2020

Conclusion

Le bilan est très nettement excédentaire sur les mois de novembre à avril. En revanche, à l'étiage et particulièrement sur les mois de juin (plus forte consommation) et d'octobre (plus faible production), les ressources sont à peine satisfaisantes, voire insuffisantes pour répondre aux besoins en eau notamment en cas de crise à partir de 2010.

Seule l'amélioration progressive des rendements de réseau (objectif 80 % en 2020), permet d'obtenir un bilan satisfaisant pour les deux scénarios de croissance les plus faibles. Pour le scénario de croissance le plus fort, les ressources resteront un peu juste à l'horizon 2020. Une nouvelle ressource près de la Saône sera peut-être nécessaire.

Strategic Planning of the drinking water supply in Grand Dijon (agglomération of Dijon)

For the first time, a strategic planning of the drinking water supply was carried out in 2005 on the perimeter of the agglomeration of Dijon. For the 15 next years, after having evaluated the needs in drinking water for the agglomeration of Dijon (present and new needs, induced by the economic development of the agglomeration), the objective of this great study was to define an hierarchical action plan in order to direct the investments in drinking water supply of an agglomeration expanding.

The resources of the agglomeration of Dijon

The resources caracteristics are very diverse and present severe low water levels for some: two karstic sources (Suzon and Morcueil) and four tablecloths (alluvial tablecloths of the Saone River with Poncey-lès-Athée, Ouche River in Plombières-lès-Dijon and Dijon-Gorgets, of Norges River with Couternon and the only deep tablecloth with Chenôve, Marsannay-la-Côte and Longvic).

The total capacity of production offered by the resources lies between 71 000 m³ per day in period of low water level (October) and more than 110 000 m³ per day in winter. The resource essential for the agglomeration is Poncey-lès-Atheist who represents nearly 60 % of the production in October and is the only significant resource with a strong capacity of extension.

The requirements out of water for the agglomeration of Dijon

The analysis for the the five last years consumption highlights three tendencies:

- a weak fall of consumption within the city of Dijon (-1,4% per annum approximately)
- a growth on the other towns of the agglomeration (+ 2% per annum)
- significant economies among big consumers (industry)

The analysis of the history of consumption also made it possible to emphasize a seasonal evolution of the needs. The month of stronger consumption is June, for which the needs for the day of point are 30% superior with the need for point of December.
The analysis of the future consumptions was carried out for each category (domestic, industrial, tertiary) using the documents of urbanistic planning. Then three various scenarios were taken into account simulating a weak, average and strong developpement of agglomeration. These scenarios take into account uncertainties as the population move within the agglomeration or a larger territory (SCOT).

The performances of the distribution network

The water losses currently account for 25% of the production of water. Significant savings can be realized, in particular thanks to the actions engaged within the program "EAU VITALE" of the Grand Dijon. In the horizon of the strategic planning (2020), a saving in 2,2 million m³ is considered.

Comparison of the future needs and the resources available - Horizon 2020

To these present resources (named R "actuelles" on the above graph) are added 16 000m³ per day profit of production awaited thanks to a program of works, which should proceed in the years to come. These works includes 14 000 m³ per day additional production on the water station in Poncey-les-Athée, thanks to new wells in the collecting field. The resources after this program are named "R optimized" on the above graph.

Conclusion

The above graph shows an positive assessment from November to April. However during the low water period and particularly over June (stronger consumption) to October (weaker production), the resources are hardly satisfactory, even insufficient to satisfy needs in drinking water since 2010, particulary if a crisis event will occur. Only the progressive improvement of the performance of network (objective 80% in 2020), makes it possible to obtain a satisfactory assessment for the two weakest scenarios of growth. For the scenario of most extremely growth, the resources will remain a little right by 2020. A new resource near Saone River will be necessary at this time.

Applications modernes de la loi de Darcy

Modern applications of Darcy's law

Conférences invitées

Invited conferences

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Permeability Measurements In Argillaceous Rocks At The Meuse/Haute-Marne Underground Research Laboratory, France

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Abstract

In November 1999 Andra began building an Underground Research Laboratory (URL) on the border of the Meuse and Haute-Marne departments in eastern France. The research activities of the URL are dedicated to reversible, deep geological disposal of high-activity, long-lived radioactive wastes in an argillaceous host rock.

When conducting permeability tests, it would be ideal to initiate them in the most stable pressure conditions possible. However, in very low-permeability clay formations (i.e. 10^{-13}-10^{-14} m/s), the pressure disturbances induced by drilling and testing take months or even years to dissipate. The main disturbances affecting transient pressure responses include technological effects due to the test equipment, drilling-history effects, thermal effects, physico-chemical and hydromechanical effects due to interactions between the test fluid and the formation, mechanical effects due to borehole-wall creep. All those effects need to be minimised during the operating phase, and should be taken into account when interpreting the measurements.

Introduction

Constituted as an autonomous public industrial establishment, by the Law of 30th December 1991, the French National Radioactive Waste Management Agency (Agence nationale pour la gestion des déchets radioactifs - Andra) is responsible for the long-term management of radioactive waste in France. Andra is also responsible for providing the French Parliament with sound scientific arguments as the basis for the debate to take place in 2006, concerning potential options for a HLW-LL waste disposal.
On 3rd August 1999, The French government authorised Andra to implement and operate the first French Underground Research Laboratory (URL) on a site straddling the Meuse and Haute-Marne departments, near the village of Bure (Meuse, France, figure 1).

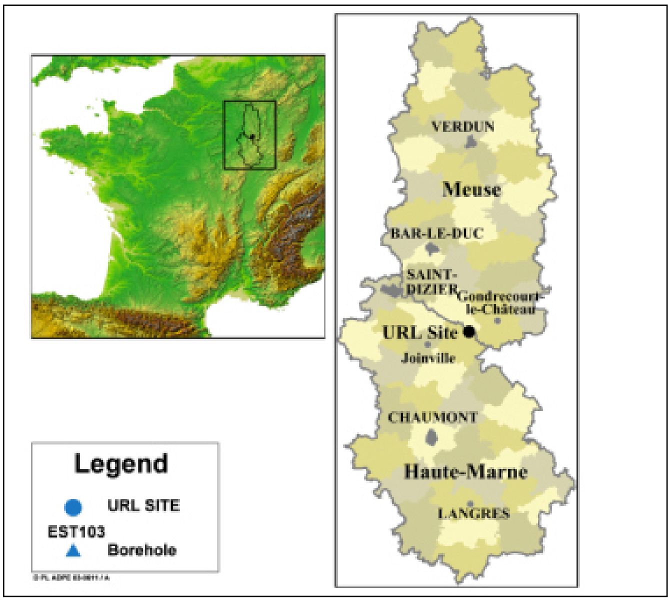

Figure 1: Location of the URL Meuse/Haute-Marne

The geological formation selected for this laboratory is a 130-meter thick argillaceous rock level, about 155 million year in age, the “Callovo-Oxfordian”

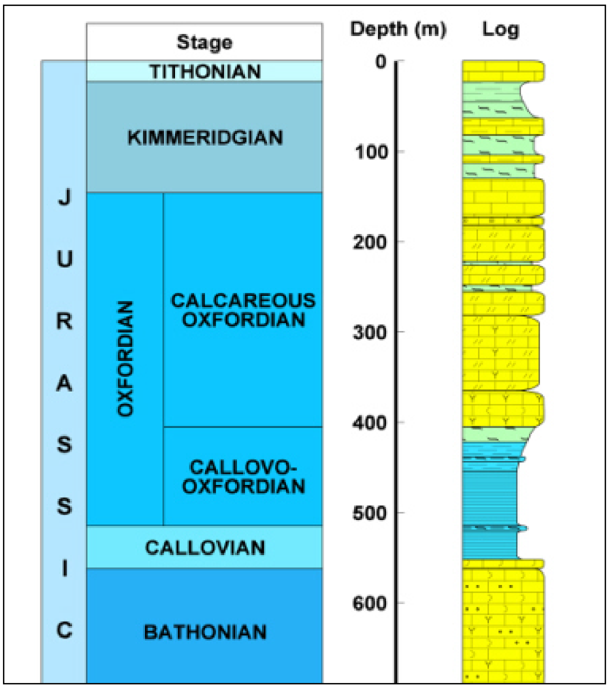

Figure 2: Simplified stratigraphic column

argillaceous rocks. This Callovo-Oxfordian clay rich layer is located between 400 and 600 meters depth (Figure 2) (Vigneron et al. 2005). In order to select the URL construction site and verify the existence and the physical characteristics of the host formation selected, an investigation phase was carried out from 1994 to 1996.

The work performed during this period was relatively conventional, using sedimentary investigation tools (surface mapping, seismic geophysics, borehole drilling and drill cores analyses) and relying as much as possible on former work performed in the scope of oil research. Nevertheless, from the outset, specific techniques for geochemical borehole monitoring and hydrogeological testing in very low permeability formations were implemented.

The objectives of the URL for the 1999-2005 years were mainly the in situ characterisation of the physical and chemical properties of this rock. This involved achieving a level of knowledge that may be used to develop disposal designs and perform safety studies. This work was carried out mainly from the shafts and experimental drifts, but also from deep boreholes drilled from the surface in the vicinity of the URL.

Studies and experimental work from deep boreholes and drifts cover three major aspects (Andra 2005a):

• Containment capability of the host formation

This containment capability comes from the specific physical characteristics of the rock, the physico-chemical characteristics of the interstitial fluids and their interaction with the rock. The fundamental physical characteristic is permeability. This property is studied through various specific tests (Distinguin et al. 2006). The chemical characteristics of the interstitial fluids condition the mobility of the various radionuclides likely to be found in the natural environment (Pearson et al. 2003). The studies focus on knowledge of the geochemistry of the interstitial fluids in equilibrium with the minerals in the rock and on the diffusion and retention capabilities of the radionuclides.

• Geomechanical properties - Creation of damaged and disturbed zones associated with drift excavation – assessment of sealing zone concept

The main purpose of the studies is to investigate how the rock reacts to the excavation of shafts and drifts, and the associated development of the damaged and disturbed zone (Tsang et al, 2004). The various geomechanical measurement campaigns conducted in the Callovo-Oxfordian formation from deep boreholes provided essential information on the natural stresses conditions: confirmed the amplitude of the minor horizontal component (sh), yielded the anisotropy ratio of the horizontal stresses and showed that the maximum major stress (s1) corresponds to the major horizontal stress (sH). The sealing of a drift is a major issue when considering the disposal construction and safety options (Andra 2005b). It involves designing systems to re-establish the original low permeability of the formation by overcoming potentially negative effects from the damaged zone surrounding the drifts and shafts.

• Regional knowledge of geological and hydrogeological properties of the host rocks and the surrounding aquifers.

Survey work focused on studying the deep hydrogeology of the sector. The aim of these studies is to evaluate the vertical and horizontal variability of the geological formation in order to evaluate an area where a deep disposal could be implemented.

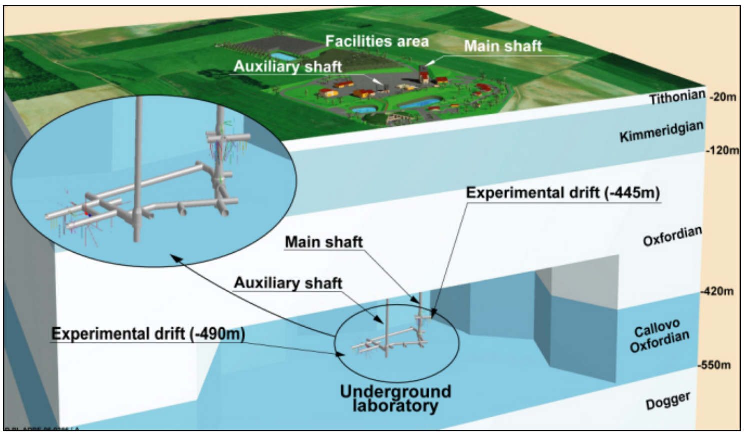

Figure 3: General layout of the underground drifts of the Bure URL

Overview of the experiments related to the containment properties carried out from drifts

The initial hydrogeological, geochemical and diffusion values used in the safety models and design files presented by Andra (Andra 2005c) were obtained through sample measurements or deep borehole measurements carried out during the period 1994 - 2004. Drift experiments carried out at 445 m and 490 m depth (Figure 3) provided new sets of values, usually more reliable, since they were obtained under much more controlled conditions, and therefore assumed to be more representative of the real values of the rock parameters taken into account in the files.

For the hydrogeological characterisation, the permeability programme in drifts relies on measurements made in boreholes equipped with permanent completions with five test intervals. These 200 to 400 cm^3 test intervals are filled with water of a composition close to that of the interstitial water in order to limit the chemical disturbance. In the experimental drifts, more than fifty tests were carried out from these boreholes. Due to the specific testing conditions of the URL, a single test could last up to three months.

For the geochemical characterisation of the interstitial water, gas and water samples are taken from two dedicated boreholes from the drifts. The aim of this experiment is to determine the chemical and isotopic composition of interstitial fluids in their natural initial state. The design of this experiment relied on measurements made on solid core samples taken for pore water extraction (Gaucher et al. 2004), and analyses and tests required for modelling water rock equilibriums (Parkhurst et al. 1999). The results were used to discuss the composition in major ions and the water/rock interaction mechanisms which govern the composition of the interstitial water. Figure 4 shows the results obtained after 113 days of synthetic water circulation and the evolution of its composition in major ions.

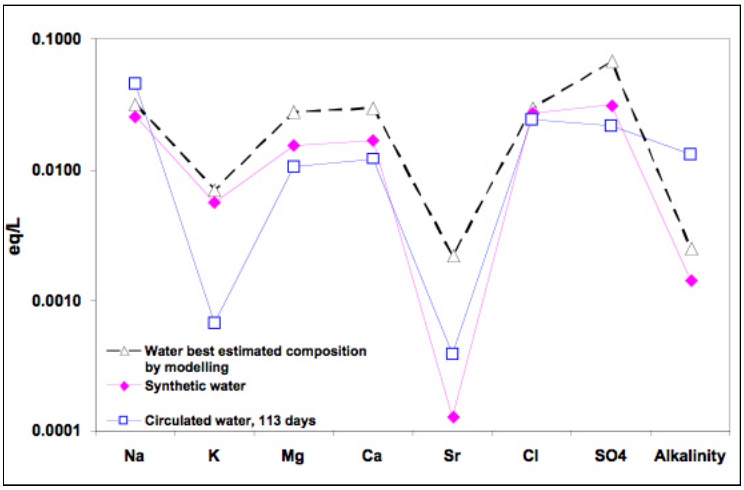

Figure 4: Pore water chemical composition obtained after 113 days of water circulation

For retention and diffusion properties, diffusion models determined from samples required confirmation. Tracer operations in six short boreholes were carried out from the drifts at 445 m and 490 m depth. The tests were designed to investigate the behaviour of, (i) inert HTO, (ii) anions: ^{125}I, ^{36}Cl,

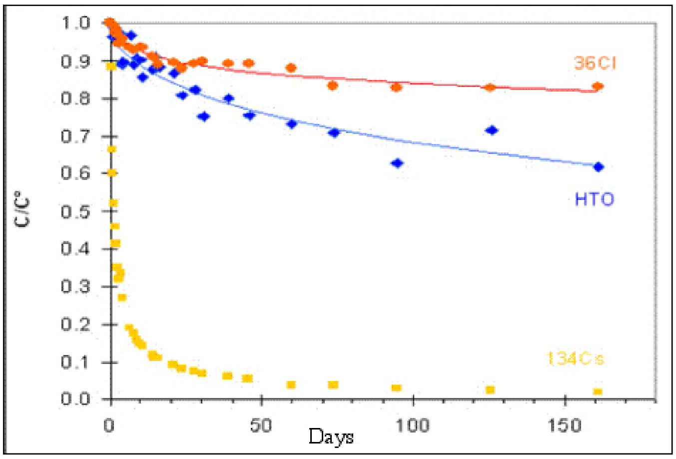

Figure 5: Evolution of tracer concentration in a diffusion borehole showing three behaviours: water (HTO), cationic retention (^{134}Cs) and anionic exclusion (^{36}Cl)

^{75}Se, (iii) cations: ^{22}Na, ^{134}Cs, ^{85}Sr. The decrease in tracer concentration was followed up through sampling and online gamma spectrometer. The first interpretations of the diffusion tests were based on the decrease in concentration of the tracers injected and showed the expected three types of behaviour (Figure 5). All this methodology had also been previously tested and validated at Mont Terri Rock Laboratory (Wersin et al. 2004; Van Loon et al. 2004).

Specific aspects of permeability in argillaceous rocks.

The permeability of a geological environment, a notion experimentally established by Darcy in 1856, describes the linearity between the water flow and the hydraulic head gradient. Thus, a macroscopic parameter assumes that the porous environment cannot be deformed, that the fluid does not interact with the solid skeleton of the environment and that the flow migration is laminar.

However, in predominantly argillaceous rock, owing to the H_2O molecule structure (Revil et al. 1998) which allows electrostatic links to occur with the crystalline structure of minerals, the interstitial water is found under different states: (i) adsorbed in the argillaceous minerals, (ii) adsorbed at the surface of argillaceous minerals – this water would be little or not at all mobile through hydraulic load gradient (Horsemann 1996) - and (iii) free between the minerals and argillaceous aggregates.

Thus, the interaction between water molecules and argillaceous minerals and the size of the pores brings us to question the validity of the Darcy law in such an environment. If the size of the pores is less than 10 nm, the structure of the water molecules in the double layer zone along the argillaceous layers eliminates convective transport (Horsemann 1996).

In the case of Callovo-Oxfordian argillaceous rocks, various methods for measuring porosity on samples (mercury, petrol, helium, nitrogen adsorption) and the images acquired trough autoradiography and SEM (Scanning Electron Microscope) were used to establish a conceptual model of the porosity of the environment. Below this 10 nm threshold, porosity is about 40%. (Figure 6) Therefore, the pore network allowing convective transport is above the percolation threshold and the Darcy law would be valid.

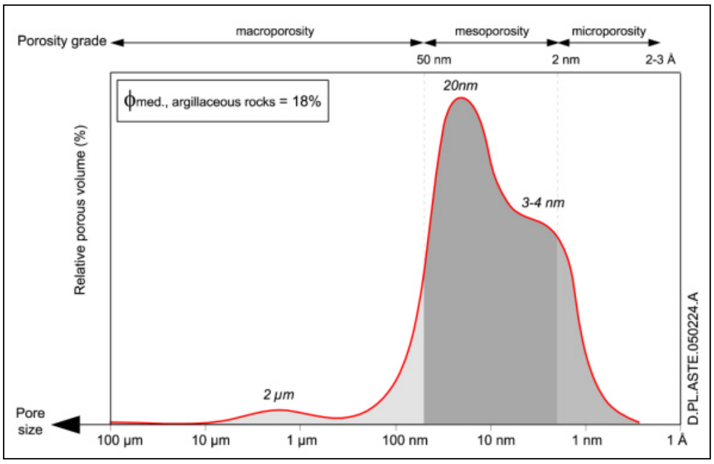

Figure 6: Pore size distribution in the Callovo-Oxfordian clay

From a methodological point of view, determining the permeability of argillaceous rocks is not an easy task when no migration can be observed. Therefore resistance to the migration of free water must be overcome. Concretely, this requires injecting a fluid under strong pressure gradient in order to be able to measure the flow in a steady migration state. However, the experimental protocols may generate artefacts:

- Excessive hydraulic head gradients may bring about (i) a change in porosity due to the decrease in actual stress, (ii) turbulent migrations, (iii) a migration of adsorbed water modifying the volume of water involved (Croisé 2004);
- Lack of equilibrium between a percolation fluid and the minerals injected in the argillaceous rocks, which may bring about dissolution processes - precipitation, or a change in thickness of the double layer.

The most commonly used method, according to different protocols, consists in inducing a temporary and limited disturbance of the fluid pressure and measuring its return to equilibrium (pulse test), which avoids having to apply excessive hydraulic gradients.
Short-term hydraulic tests were carried out in several deep boreholes of the studied sector prior to carrying out experiments in the underground laboratory. In the underground laboratory, a systematic pulse test measurement programme was carried out by monitoring the recovery of static pressure over several months.
In addition to these, in situ measurements, a set of laboratory measurements was performed on samples taken during the drilling of boreholes.
Three types of measurements were carried out including:

- A method consisting in interpreting the evolution of saturation profiles in an argillaceous rock based on its water sorption isotherm;
- A method for measuring the flow of Tritium traced water performed in association with diffusion measurements;
- Tests under steady and transient states using a rock mechanics laboratory cell.

Other indirect permeability measurements included either measuring the petro-physical characteristics of rock formations through geophysical methods, or performing a detailed analysis of pressure logs and stress profiles. For example, measurements performed with NMR (Nuclear Magnetic Resonance) probes (Klopff et al. 2004) provided a detailed description of the porosity, not only in terms of volume but also of geometrical structure.

Factors which affect hydraulic tests

When conducting a short-term packer test, the ideal would be to carry out permeability tests in the most stable pressure conditions possible. However, in very low-permeability clay formations (i.e. 10^{-13}-10^{-14} m/s), the pressure disturbances induced by drilling and testing take months or even years to dissipate.
The main disturbances affecting transient pressure responses when testing such formation in a deep borehole include:

- Technological effects due to the test equipment: irreversible deformation (particularly that of packers at the contact with the formation) and reversible deformation controlled by equipment elasticity (test tool compressibility varying with pressure);
- Drilling-history effects: i.e. impact of hydraulic pressure conditions different from the formation pressure prior to the hydraulic test (e.g. drilling phase, geophysical logging, etc.);
- Thermal effects due to circulating or injecting fluid with a significantly different temperature from the formation temperature;
- Chemical effects due to interactions between drilling and formation fluids;
- Physico-chemical and hydromechanical effects due to interactions between the test fluid and the formation (clay hydration, swelling);
- Mechanical effects due to rock decontainment, borehole-wall creep.

All those effects need to be minimized during the operating phase, and should be taken into account when interpreting the measurements.

It has been recognized that hydraulic heads estimated in such formations, based on short-term packer tests, are marred by non-negligible uncertainties related to the above mentioned disturbance processes. However the permeability estimated with this technique as been proved to be reliable for characterizing near borehole conditions, assuming that the causes of disturbance (i.e. borehole history, temperature changes) are measured and accounted for in the analyses.
From the drifts only long term tests (one month or more) are carried out allowing a significant reduction of this disturbance factors. However, the construction of the drift itself could create a significant change in local hydro and geomechanical conditions.

In situ permeability measurements

Testing tools and measurement strategy
Three types of equipments, based on different concepts and methodologies, are applied on the Bure Site for permeability and head measurements in deep boreholes (Delay et al. 2004). The first testing tool is the single or double packer test equipment applied during or at the end of the drilling phase. It is a conventional test tool used in the petroleum industry. This equipment consists of a packer tool assembly. Inflation of the packers is controlled from the surface (both packers can be inflated together or separately). As stainless steel is being used for the tubing as well as for the hydraulic lines, the test zone compressibility is low ($\sim 1 \cdot 10^{-091}$/Pa). The test interval can be connected and isolated from the surface with a down hole shut-in tool. This valve can be activated with minimal water displacement in order to avoid pressure perturbations in the test interval. In very low permeable environment, solicitations to the test interval are performed with pulse tests or slug tests, thereby modifying the water level in the 2 7/8 (7.3 cm) tubing and opening up the shut-in valve. Finally, pressure and temperature in the test interval, as well as below and above the interval, are continuously monitored

The second tool, called Electromagnetic Pressure Gauge (EPG), is a monitoring equipment used in the petroleum industry and adapted to Andra's requirements (Soulier and Lemaître 1993). Such equipment is used for long-term monitoring of the formation pressure and temperature. The advantage of this system is its ability to perform measurements in a down hole isolated interval completely protected from external disturbances (i.e. without any influence from the upper/lower parts of the borehole). The test interval, about ten meters long, is totally isolated from upper borehole influences (Figure 7). A permanent packer inflated with cement is placed above the gauge then the upper section of the well is filled with a very-low-permeability cement plug (8.25 μ Darcy). Thanks to an independent down hole power supply, measurements can be carried out over several years with data transmitted to the surface by electromagnetic waves. The pressure sensor has a measurement range of 0 - 13.78 MPa, 10^{-4} % full-scale accuracy, and $2 \cdot 10^{-4}$ % full-scale resolution over three years (full-scale resolution = 3 kPa) (Cecconi et al. 2004). The life-time of the latest EPG installed by Andra in 2004 is expected to be more than 10 years. Thus, this tool measures at early time the pressure recovery from highly disturbed conditions (i.e. influence of drilling as well as testing and subsequent cementation activities) towards the initial formation pressure reached after several months. While late time data provide a direct reading of the formation pressure, early and middle-time data provide transient pressure measurements interpreted in terms of permeability. Andra has installed five EPG gauges at 420 to 540 m depth, 2 of them sealed one above the other in a single borehole.

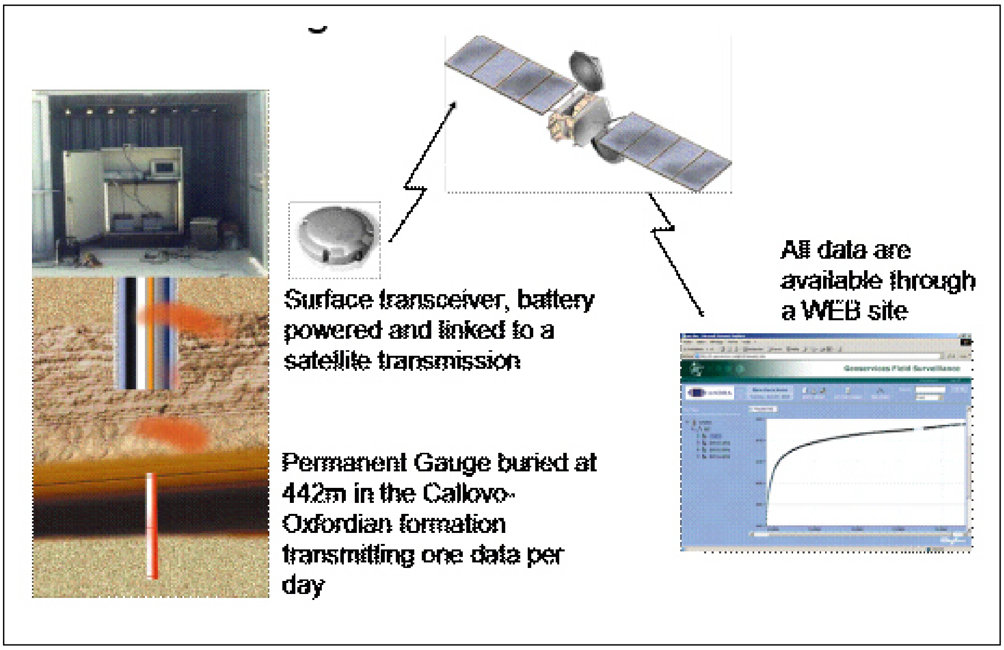

Figure 7: General set up of an electromagnetic pressure monitoring system

The third tool, multipacker equipment (Eldred 1995) was first developed for hydrogeological monitoring of aquifers. This equipment measures the pressure and temperature in several packer-isolated intervals in a single borehole. Pumping tests and water sampling can also be performed in each of the packed-off intervals. The PVC system installed at Bure is less rigid than the stainless steel EPG system, which contributes, besides the larger test interval volume, to a higher well-bore storage coefficient. Another constraint is that this equipment requires the borehole being filled with freshwater for installation, which is critical in argillaceous formations. However its main advantages are its active testing and monitoring capabilities as well as the amount of intervals for investigating formation properties (i.e. head or permeability profiles along a single well). The equipment installed in the Callovo-Oxfordian at Bure consists of 11 measuring chambers installed over 165 meters at 410-575 m depth.
For the drifts, only permanent multipacker equipments are used. They are installed in 101 or 86 mm diameter boreholes. The lengths of the boreholes are generally between 15 and 20 meters. The boreholes are cored using air as drilling fluid, which ensures good stability. The completion is installed immediately after drilling and a specific procedure for removing air and filling the tests intervals with synthetic water is carried out. One equipped borehole consists of five chambers.

Measurement Strategy

The measurement strategy relies on the successive use of short-term packer tests associated with in-situ long-term monitoring techniques.
Initial short-term packer tests provide a first estimate of the formation properties (permeability and head). More specifically, the tests are conducted under the following conditions: a 24 to 72 h test procedure designed to obtain the borehole-formation flow model as well as the near hole and the “undisturbed” formation permeability.
Thus the test procedure includes typically:
- An initial passive pressure recovery and;

• An active pulse test, followed by the continuation of the global pressure recovery.

This procedure is designed to provide an order of magnitude of hydraulic conductivity, but it is in most cases unable to provide a sufficiently precise value of the initial head. Various borehole configurations: orientation (vertical, inclined), nature of fluids (polymer-based mud, water, oil-based mud, diesel oil) have been tested and provided similar results.

Long-term monitoring equipments, such as EPGs or multipacker equipment, are then installed in the boreholes to measure accurately the pore water pressure. Furthermore the transient pressure recovery from the post drilling conditions toward equilibrium at static conditions provide excellent long-term data to determine the borehole-formation flow model as well as the corresponding formation permeability. As the static pressure is no longer estimated from transient data but measured at late time, the permeability determined from long-term data is estimated to be more accurate than the permeability obtained from short-term tests.

Interpretation methods

All short-term packer tests conducted during the 2003-2004 campaign were analyzed according to two approaches based on the same conceptual model, an analytical approach and a numerical approach with the nSIGHTS Code (Roberts 2002). nSIGHTS is a radial numerical model developed for Sandia National Laboratories in support of the WIPP Site program (Kessel 2005). nSIGHTS is capable of taking into account large spectra of formation and well situations. Optimization of the parameters is done by inverse modelling. Through the analytical approach, it was possible to derive the best preliminary hydraulic parameters (model type and transmissivity) and to use them as the input parameters for the numerical analysis. Two independent numerical analyses were performed as follows:

• The first phase of numerical interpretation (i.e. 1994-1996 campaign) was carried out at early-middle time by using the results of the analytical interpretation as input parameter sets. Parameters were then optimized by a non-linear regression in order to identify the best parameter set (formation transmissivity, storage and pressure) (Figure 8).

• The second phase of numerical interpretation was carried out at late time (i.e. 2004) by using that second parameter set, and the stabilized formation pressure as measured from the long-term monitoring system (Figure 9).

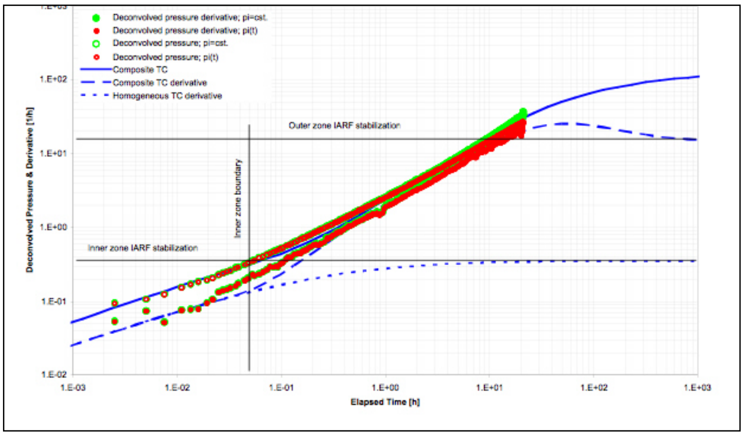

Figure 8: Interpretation of a short term pluse test

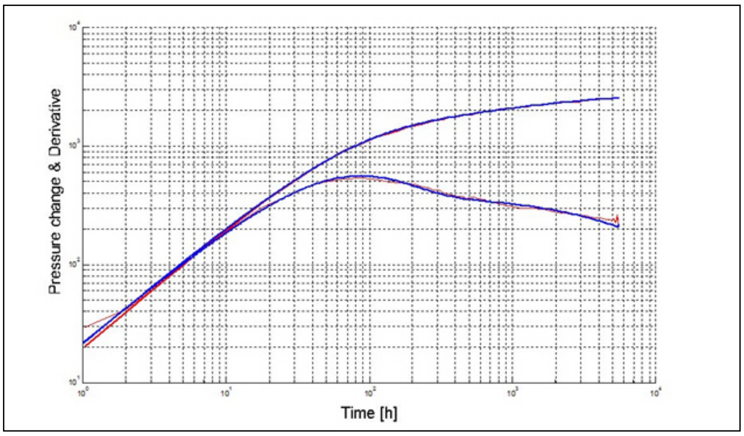

Figure 9: Interpretation of the recovery period of an EPG

Laboratory measurements on samples

Permeability tests on samples were carried out as a complement to in situ tests. Indeed, it was not always technically feasible to test the formations in situ, and experimental measurements on samples can be carried out over longer periods of time. However, samples are considerably disturbed by the conditions under which they have been taken and conditioned. Laboratory tests assume a good control of the conditions under which the samples were taken, of the mechanical confinement and saturation as well as a minimal cohesion of the samples.

Permeability estimates of the argillaceous rocks through the interpretation of water sorption/desorption isotherms and hydric profiles

In the case of mass transfer in the partially saturated argillaceous rocks, permeability can be determined according to the saturation level, assuming that the evolution of their global diffusivity is known.
Two different experimental devices were built on this principle.
The first one uses a conventional oedometrical frame in which a cell containing the samples and consisting of superimposed steel rings is placed. Based on a given hygrometry degree, the sample is resaturated through injection at the base. The hydric profile for a determined resaturation period is obtained by cutting the sample according to the rings. The permeability is worked out from several profiles for different periods of time, for a given sorption-desorption curve (Robinet 1995).
In the second case, the sample is placed under controlled relative humidity in a sealed containment covered with an isothermal lid. Pressure applied around the sample is modified, which induces a variation in the sample mass. The evolution kynetics of the mass is monitored through frequent weighing on a microscale. The permeability to fluid is calculated through inverse method by working out the mass transfer equation in a non-saturated environment.
The results obtained from samples taken in deep boreholes show a very low and relatively homogeneous permeability over the formation as a whole. Values range between $1\ 10^{-14}$ and $4\ 10^{-14}$ m/s .

Permeability measurements through Tritium traced water flow

This method for assessing permeability relies on the diffusion tests carried out with Tritium traced water. Following the diffusion tests, after the steady state was reached, a difference in pressure was applied between the upstream and downstream cavities of the diffusion cells. An increase in the fluid flow was observed in the downstream cavity. This increase was interpreted as a result of water migration through the sample.
However, although the order of magnitude of 10^{-14} m/s obtained through these tests as permeability values of the argillaceous rocks seem plausible, problems related to the equipment and certain analysis hypotheses question the reliability of these results.

Permeability measurements with a geomechanical cell

The tests are carried out on cylindrical test tubes, cut in a piece of core and stored in a cell immediately out of the borehole in order to maintain the mechanical confinement. Thus, the argillaceous rock retains most of its original water (usually over 95% saturation). In some cases, a blind hole is drilled in the axis of the test tube to obtain a radial flow.
Permeability measurements are carried out parallel or vertical to the stratification. The geomechanical load makes it possible to recover the original in situ state of stress of the test tube. However, even in drained conditions, it increases the pore pressure: the hydromechanical coupling is higher when the permeability is low and the overpressures resulting from the applied mechanical stress are long to dissipate or become homogeneous inside the test tube. Water in chemical equilibrium with the rock is used as injection fluid.

Two types of tests were carried out:

- Steady state tests (stationary),
- Transient state tests of the pulse-test type.

Steady state tests were only carried out with the radial injection device. Since the measured flows were extremely low, relatively high gradients were applied.

Results of tests on samples

These devices underwent cross-comparison tests in the framework of the ForPro (ForPro 2003) Research Group. Interpretation of the tests was based on the Hsieh (Hsieh et al. 1981) analytical solution either directly from graphs (in adimensionnal form), or through inverse method. The storage coefficient can only be determined if the pressure is close to stabilization (which requires carrying out the tests over a significantly longer period of time).
Permeability measurements on core samples were carried out parallel and perpendicular to the bedding planes in order to obtain estimates for the permeability anisotropy. The permeability estimates obtained are of the same order as those obtained through short-term tests carried out with straddle packers and long-term pressure logs. Estimates for vertical permeability range between $2.4.10^{-16}$ m/s and $1.5.10^{-12}$ m/s. Horizontal permeability estimates on samples range between $9.1.10^{-15}$ m/s and $7.6.10^{-13}$ m/s.

Conclusions

The means used by Andra since 1994 to determine the hydraulic properties of the Callovo Oxfordian argillaceous rocks have demonstrated their robustness in terms of the complementarity of methods and their implementation, as well as the coherence of results.
Four distinct methods contributed significantly to determining the permeability in Callovo-Oxfordian argillaceous rocks.
In situ investigations in deep boreholes tested great heights (metric or decametric) in order to obtain the bulk properties of the environment according to a horizontal plane, mostly parallel to the bedding. In terms of complementary, in situ investigations carried out in the underground laboratory experimental drifts provided values of the vertical and horizontal permeability of the argillaceous rocks at a more local scale (decimetric chambers). Laboratory measurements on samples, mostly carried out according to the vertical orientation, only tested reduced heights (below 0.1 m).
The permeability of the Callovo-Oxfordian formation obtained through in situ measurements ranges between 10^{-14} m/s and 10^{-12} m/s. Most values range between 5.10^{-14} m/s and 5.10^{-13} m/s. Permeability measured through in situ investigations is of the same order as that obtained through laboratory measurements on samples, even though the values obtained from the latter are more scattered. At this stage, no significant anisotropy has been observed.

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Aquifers imagery and permeability estimation using proton Magnetic Resonance Soundings

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Abstract

In this paper, we present hydrogeological parameters that can be measured with the magnetic resonance sounding method (MRS). This non invasive surface geophysical method meets a growing interest in the scientific and earth sciences engineering communities. It has been used for years now, both for water resources prospecting all around the world and to obtain additional information to the classical method for improving the management of aquifer. Limits of the method are presented and illustrated from numerical models and case histories.

Basic principles

Magnetic Resonance Sounding (MRS) is based on the measurement of the nuclear magnetic resonance signal which is produced by the hydrogen proton of water molecules after they have been stimulated by an alternative electromagnetic field at a specific frequency (the Larmor frequency). It uses the same basic principles as Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance logging (NMR) widely used respectively in medicine and in petroleum well-logging. It differs by the investigated volume (tens of cubic meters instead of cubic centimetres or millimeters) and the use of the natural geomagnetic field as a static field (instead of artificially created fields).

The MRS signal oscillates at the Larmor frequency and its amplitude decreases with time. Its initial amplitude, E_0 and the relaxation time constant T_2^* are related to respectively the water content, W and the mean pore size in the saturated aquifer. But T_2^* is also influenced by the local inhomogeneities of the magnetic field and a more reliable parameter (T_1) can be obtained using an excitation sequence composed of two electromagnetic stimulation pulses.

T1 is linked to the mean pore size of saturated aquifer as follows: T1≈ p V/S (1) ; V being the volume of water saturated pores, S the pore surface and Ú the capacity of pore surface to induce relaxation.

In the non-saturated zone, the MRS response could be intuitively predicted considering that water volume, V or content, W increase with saturation while pore surface, S remains constant. Thus, initial amplitude E_0 and relaxation time constants should increase with saturation.

Aquifer detection

Because MRS signal is generated by water hydrogen protons, it is specifically linked to the presence of water in the ground. It is today the only geophysical method which allows an unambiguous detection of water bearing structures. When used in a combined methodology with electric-electromagnetic mapping method for locating and delineating subsurface structure and geometry, MRS provides significant advantage as it helps to distinguish electrically conductive anomalies due to high clay content from those due to water content increase.

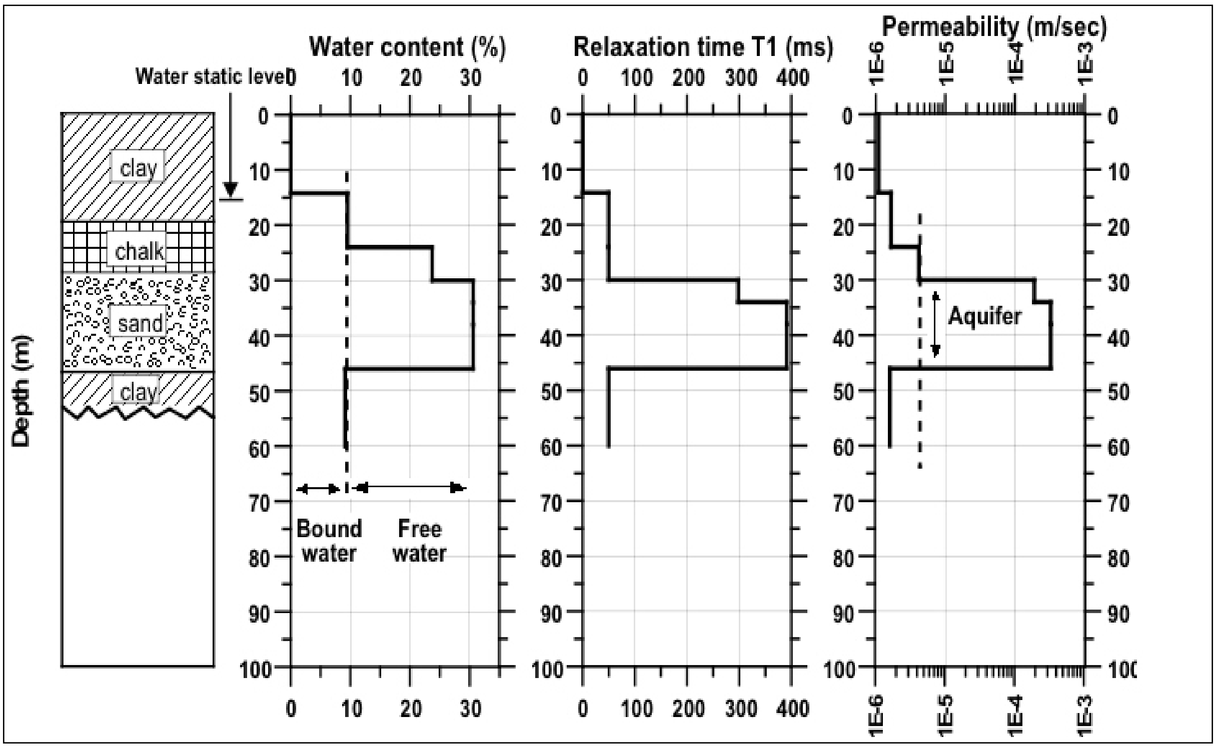

Figure 1: Borehole information and MRS results near Chuisnes (Beauce, France) studied site (transmissivity is 4.7e-3 m^2/s, with a similar estimation from pumping test and MRS)

Aquifer geometry

MRS data are inverted using 1D (layered earth) model providing a vertical log of water content. As a result, geometry of the saturated aquifer can be accurately defined (Figure 1). Aquifers are distinguished from aquitard zones. The top and bottom of the saturated alterite aquifer estimated by MRS and boreholes information were compared favourably in Burkina Faso prospected sites for village water supply (Vouillamoz, 2005).

MRS allows detection of top of saturated zone of the aquifers. Hence, water table is estimated in case of unconfined aquifer. Nevertheless, because MRS is not sensitive to pressure inside the saturated zone then only the top of confined aquifer is detected while the hydraulic head can't be estimated.

As other surface geophysical methods it is a non invasive method and it makes it possible to investigate large areas at reasonable cost and density of measurements is not practically limited. It was used to map the water table in unconfined chalk and sand aquifer over the

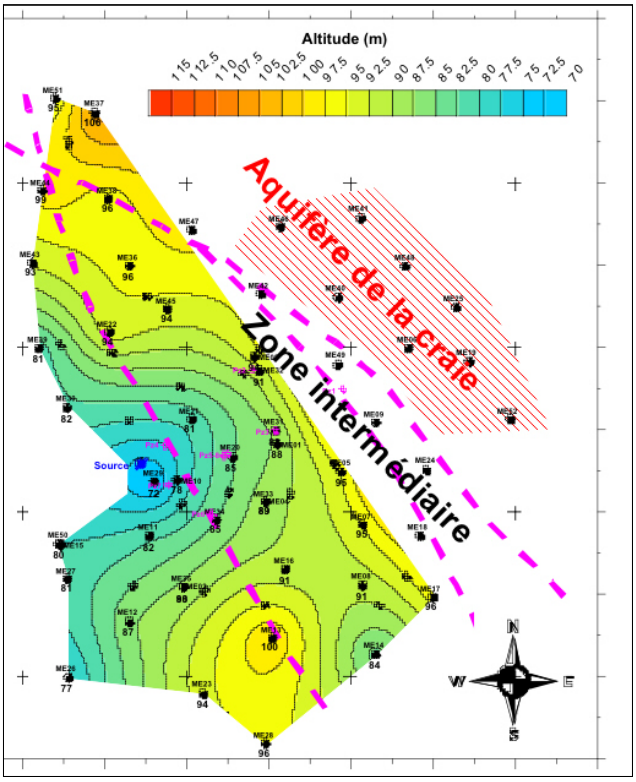

Figure 2: Water table elevation mapping using MRS over the “Cuisien” sand aquifer catchment of Montreuil-sur-Epte (Paris Basin)

Montreuil sur Epte experimental catchment (Paris basin). It is better than interpolation within a borehole network because it can detect lateral variation due to faulting, lenses, etc …. This information can be reliably extended outside the validation zone of the boreholes. MRS water table determination correlated with piezometers made it possible to map water level over the whole Montreuil catchment (Figure 2) and then helped to define its boundaries.

Nature and heterogeneity of aquifer

Type of water bearing material is characterized not only by the water content, but also with the decay time of the MRS signal (Table 1). Shorter is the decay time and smaller the pores are. In a known geological context, if media have noticeable variations in terms of MRS parameters then MRS response is an indicator of the nature of the medium. It makes it possible to separate the response of sand aquifer from chalk for example such as it was observed and confirmed over the Montreuil-sur-Epte catchment (Figure 3). The thickness variation of the sandy aquifer is moreover in good agreement with the borehole information.

Decay Time (ms)	*Aquifer material*
< 30	Sandy clay
30 – 60	Silt, very fine sand
60 – 120	Fine sand
120 – 180	Medium size sand
180 – 300	Coarse grain sand with gravels
300 – 600	Gravels
600 – 1000	Free water (lake, karstic conduit)

Table 1: MRS parameters for various geological media

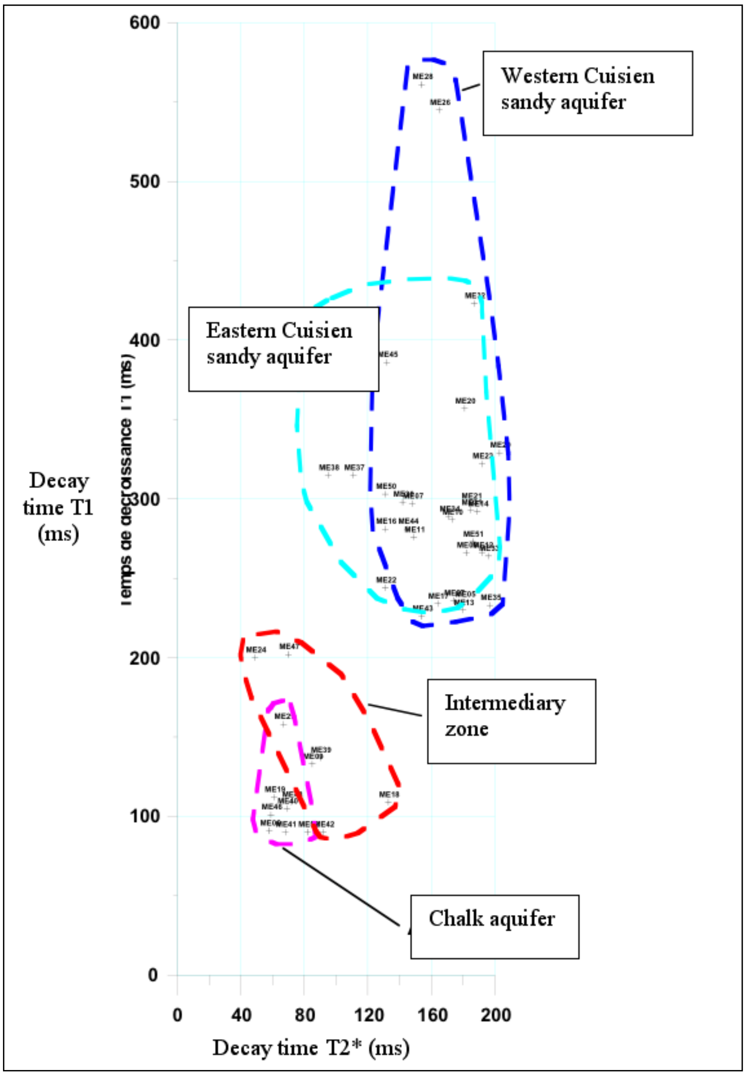

Figure 3: MRS Discrimination between chalk and sandy aquifers in Montreuil-sur-Epte study area

Hydrodynamic characterization

Because MRS data is linked to water filled pore size, hydraulic conductivity can be estimated using empiric models (Legchenko *et al.*, 2002, 2004) combining MRS parameters. For example an MRS hydraulic transmissivity can be defined such as:

$$T_{RMP} = C' \cdot (w \cdot \Delta z) \cdot T_1^2$$

where w is the MRS water content, Δz the saturated aquifer thickness, and T_1 the decay time of MRS signal. A calibration constant *C'* is used and varies with the medium properties. An empirical approach is used to overcome the problems of, on one hand, the not connected water which is detected by MRS but doesn't contribute to hydraulic conductivity, and, on the other hand, the part of moving water not detected by MRS but which contributes to transmissivity. Calibration should be first performed and consists in a comparison of pumping tests estimation of transmissivity with MRS estimation. Then, a reliable hydraulic characterisation can be achieved within the same hydrogeological setting even where no boreholes are available.

In the Beauce aquifer, such a methodology was developed and nowadays MRS is commonly used before drilling to discriminate the most favourable drilling site among a set of location previously selected with conventional hydrogeological criteria. Over the last years, several sites were prospected and drilled and a good correlation in transmisivity estimation was observed with MRS result.

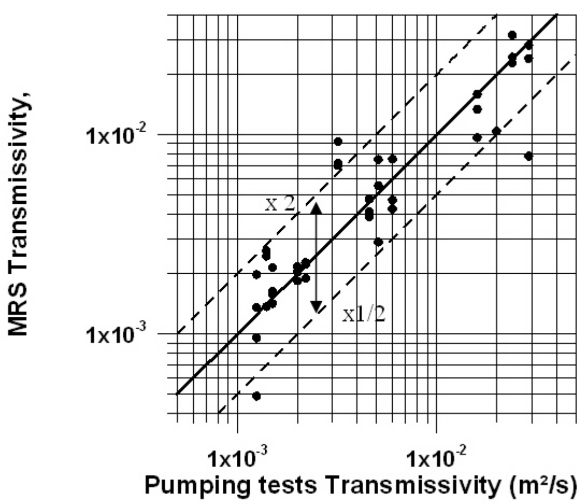

Figure 4: Correlation between MRS transmissivity and pumping test estimation for different borehole sites of the Beauce aquifer. The uncertainly on calibrated transmissivities is considered to be within the ratio of 2.

Comparison of MRS result with pumping test characterization of aquifer is particularly relevant because the investigated volume for both methods is similar. MRS investigated volume is roughly a vertical cylinder with the loop size diameter. There is no scaling effect between the two methods. MRS moreover is not affected by the problem of quality of connection between the borehole and the water flow (drilling crossing a clay lens, missing a fracture network, etc…).

Limits of applicability

MRS investigation depth is linked with the loop size (maximum depth is generally about 100 m with the biggest usual square loop of 100m side). Investigation depth furthermore decreases in highly electrical conductive medium. If the loop size and power are instrumental limit, electrical conductivity imposes a physical limit related with the electromagnetic skin depth (skin depth is around 110 m for a 100 Ω.m material, but only 35 m for 100 Ω.m and 11 m for 1 Ω.m).

But the main limit often encountered is due to electromagnetic noise close to urban area and power-lines. It is generally convenient to work at more than 200m from power lines (and 400m in case of high tension lines). The vulnerability is site dependent because the MRS signal amplitude may vary by a ratio of 100 depending on water content. Different filtering strategies have been developed to decrease the noise: stacking, digital filtering of industrial harmonic frequency and analogical filtering with remote reference loop. The efficiency of filtering varies from sites to sites because of the nature of the noise source. Generally, it is a matter of time to obtain a sufficient signal to noise ratio, resulting in sounding duration varying from 2 h up to 10 hours.

It is noticeable that magnetic rocks influence the PMR phenomenon and may shorten the decay of signal below the instrumental threshold. It is both an instrumental and a methodological limitation. Future device may be available for use even in magnetic environment as volcanic areas. But today, MRS can not work in such environment.

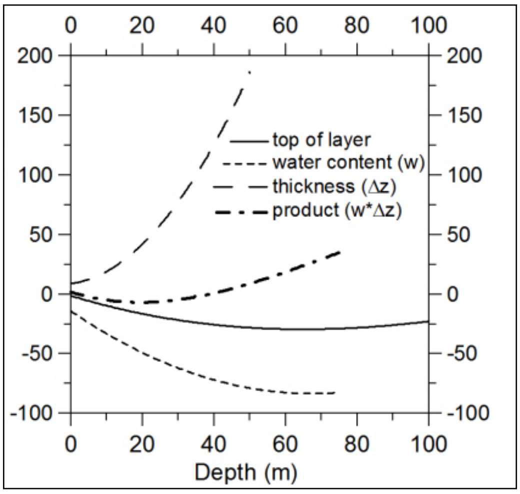

*Figure 5: Numerical study of MRS parameters resolution (from Legtchenko et al., 2004). Signal of a 10 m thickness layer with 20% of water content was modelled for a 100 m square loop. Inversion provides top of layer, water content (w), thickness (Dz) and product (w*Dz). Error on parameter P is estimated as:*

As well as for many geophysical methods of investigation from the surface, because of the integrative property of MRS, it is not always possible to characterize individually each layer in case of multi-layered aquifer. Responses from aquifers centred at the same depth with equivalent volume of water (product of thickness by water content) are similar. A numerical study was performed to underline the accuracy of MRS results. The top of the first aquifer and the water volume are reliably estimated (Figure 5). This explains why the aquifer transmissivity is faithfully estimated whereas the log of permeability is poorly defined without a priori information. Layers geometry input from geology or geophysics have to be used to reduce the number of free parameters in the inversion process. It increases accuracy of inversion results and lead to reliable estimation of water content log and permeability with depth.

Two striking results

Groundwater reserves mapping in weathered hard-rock aquifers in Brittany, France

MRS provides a quantitative estimation of the water content. Coupled with geometrical aquifer modelling, it has been used to create a map of groundwater reserves over a 270-km^2 study area in a weathered basement setting. Most of the reserves are contained in a stratiform multi-layer aquifer whose geometry is influenced by the weathering front. The depths to the interfaces determined by PMR are considered and validated by comparison with the geometrical approach. Water contents and decay times of the PMR signal for each weathered layer are compared with the hydrogeological model. The results of the study show a decrease in water content from the top downwards for the three main aquifer layers (respectively: unconsolidated alterite, and an upper and a lower fissured zone). The groundwater reserves (80% in the fissured zone and 20% in unconsolidated alterite) represent approximately three years of average infiltration (Wyns et al. 2004).

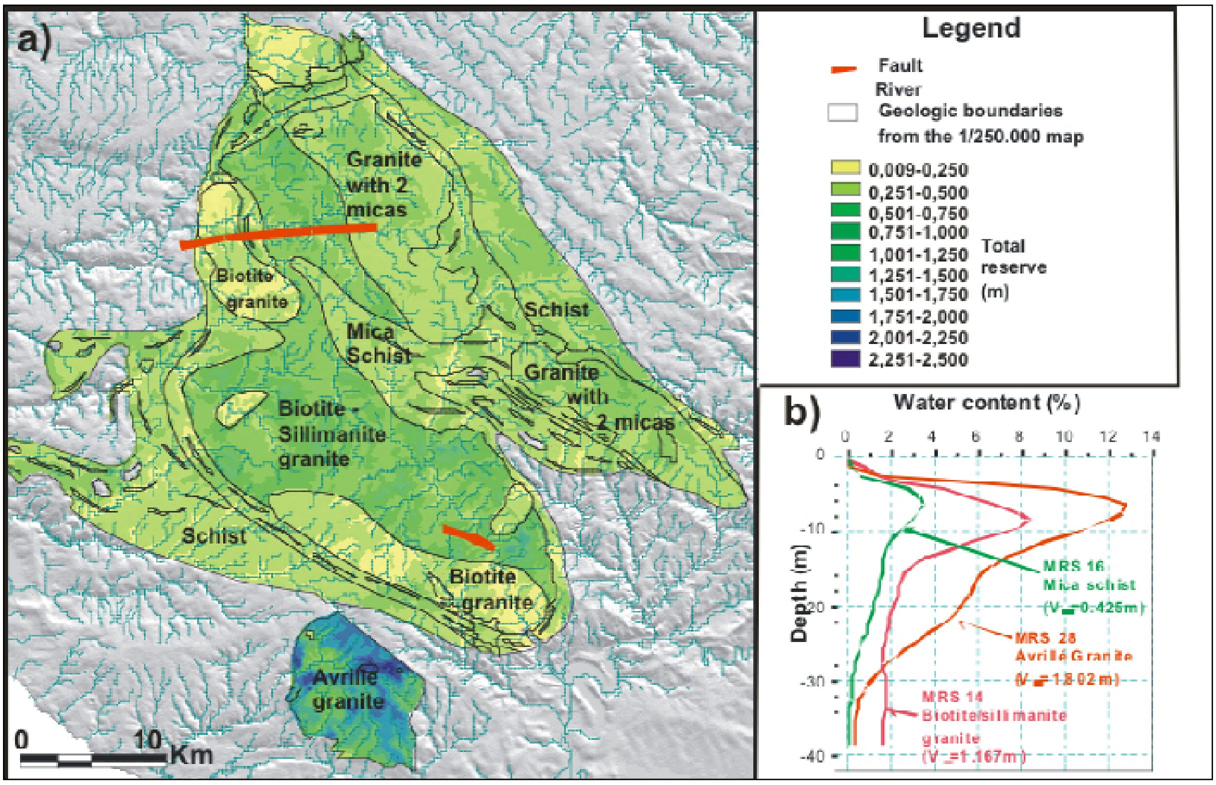

Figure 6: La Roche-sur-Yon region: a) Thickness map of total reserves in the weathered aquifers. b) Example of MRS water content profiles measured in different geological settings.

Karst gallery imaging using 2D inversion of MRS section

In most cases, interpolation of MRS 1D inversion results is sufficient to reveal the heterogeneity of aquifer along a profile of investigation. But, when studying targets of limited extension with respect to the measurement loop size like karstic conduits, the use of refined step between the soundings (down to 5 or 10m step) can provide a very precise image of the conduit. A true 2D inversion is then necessary to process the data. Such a methodology was applied over the underground Ouysse river, near Rocamadour. This karstic conduit is full of water during the whole year and its topography was controlled by speleologist divers. The 2D inversion of MRS result provided the location and size of the conduit (Figure 7) with interesting accuracy (Boucher at al. 2006). Karstic conduit detection is an important issue for water supply in many places. If today such survey cannot be widely performed, it is partly due to the number of soundings needed and the time to perform them. Mainly because MRS signal generated by a karst conduit is very low, such survey is even more vulnerable to noise conditions than MRS above continuous aquifer.

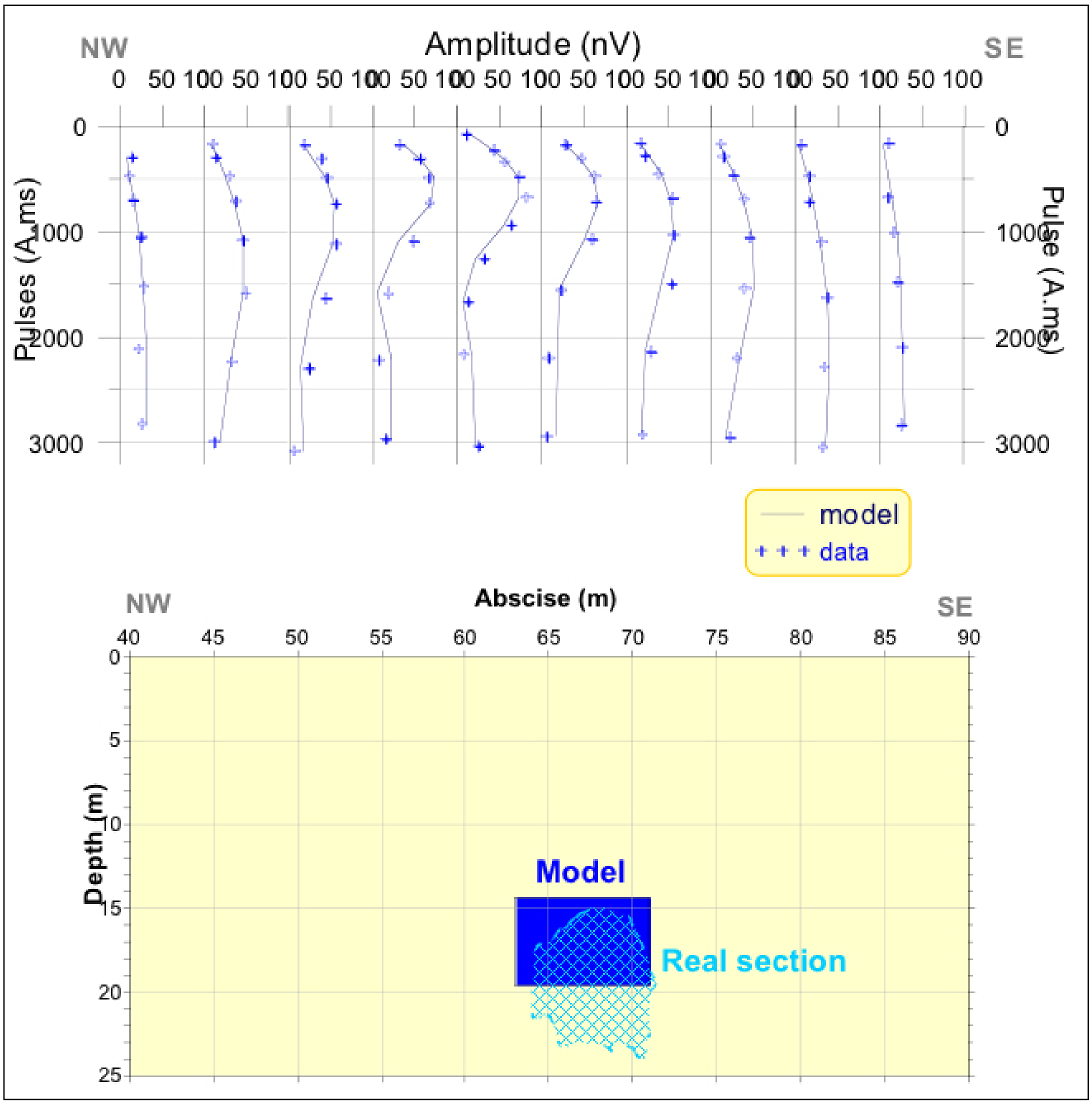

Figure 7: Karst conduit imaging near Pou Meyssen (France). 10 MRS were performed along a profile crossing the conduit. Data curves (top) were simultaneously inverted to obtain a 2D model (bottom)

Future work

Future development will be greatly impacted by reducing MRS vulnerability to electromagnetic noise. It is today the main limitation to the method application, because MRS can not be used close to urban areas or electric power-lines. At the same time, it will improve the signal to noise ratio and will result in better accuracy of measurement which then will improve reliability of results.

There also is a need to establish hydrogeophysical model for various geological contexts, and to refine the calibration of MRS water content (which part of water remains undetectable).

As it was shown in the case of karstic conduit, MRS can provide high resolution results.

Methodology for 2D-3D tomography has to be developed for improving the resolution. This issue will be a useful tool for highly heterogeneous media commonly encountered at shallow depth.

New measurement scheme will have also to be developed to measure MRS in the vadose zone for all media, not only in media with huge capillary water like chalk.

Conclusion

MRS provides useful information which may not be accessible with enough density with standard methods because of the drilling and pumping costs. Using non invasive method like MRS can reduce the cost to obtain dense information. MRS will not replace information from the borehole and pumping tests but they can detect water without ambiguity and provide geometry and hydrodynamic characterization of aquifer within the first 100m. Using calibration with borehole information accuracy of MRS results is improved. MRS do more than only interpolating the knowledge from borehole network because it will detect lateral variations. Considering hydrodynamic parameters, because the uncertainty of both methods is in the same range for transmissivity estimation (and relatively high uncertainty), MRS provide an estimation not biased by quality of water flow connection of borehole with surrounding aquifer.

Case stories prove that, used in its domain of applicability, it is nowadays a mature method and its interest for a wide range of purposes, from water resource prospecting, reserve estimation, water table mapping, to karstic conduit imagery.

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The quest for permeability evaluation in wireline logging

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Note
The author is indebted to the numerous Schlumberger geologists, petrophysicists and reservoir engineers who co-authored the articles published by Schlumberger on permeability since 1980. The present paper borrows ideas and even sentences, sometimes cited verbatim, from the 9 papers that are listed at the beginning of the bibliographical section. Nevertheless, rather than corporate views, this paper mainly reflects the author's opinion.

Abstract
For decades, a constant objective of wireline logging has been to obtain a continuous permeability log. Except for a few attempts such as the search for an acoustic log response that could directly yield a permeability indicator, most of the initial efforts have been directed towards deriving permeability from the combination of porosity with some other log-derived property related to the type of pore geometry. In sandstones, excellent results have recently been obtained with nuclear magnetic resonance (NMR) logging that, by itself, provides information on both porosity and pore size distribution. In carbonates, the NMR approach sometimes breaks down but the information about carbonate rock facies carried by continuous electrical images of the borehole walls has permitted, coupled with conventional porosity logs, to generate continuous permeability indicators in complex carbonate formations.

The challenge

Since 1856 when Henri-Philibert-Gaspard Darcy first defined fluid conductivity of a porous material in his famous technical report known as the "Mémoire sur les fontaines publiques de la ville de Dijon", permeability has become one of the most studied, yet stubbornly elusive, properties of rocks. For decades, hydrogeologists have been using pumping tests to measure permeability in aquifers, or rather to access an average permeability-thickness value, called transmissivity, masking permeability differences in different layers. Similarly, many well testing techniques were developed by the petroleum industry. Well testing rapidly became an oilfield standard because it was investigating the rock and fluid in situ, under actual reservoir flow conditions. However, none of the well testing methods, except a rather cumbersome and lengthy one called layer reservoir testing, are providing information about the variations of permeability versus depth.
To achieve this goal, cores are often taken at different depths when drilling, and core samples are analyzed under controlled laboratory conditions to measure permeability. Coring and laboratory analyses are quite expensive procedures. Wells are therefore rarely cored continuously but, even when they are, core permeability data can be of questionable value when only 6-inch spaced core plugs are analyzed in heterogeneous rocks where permeability over just a few inches can vary by five orders of magnitude. The idea thus came to try and obtain a continuous permeability profile, using the same approach that had been successful in providing

continuous profiles of porosity and fluid saturations in the formations crossed by oil and gas, and sometimes water, wells: wireline logging.

First methods for deriving permeability from conventional wireline logs

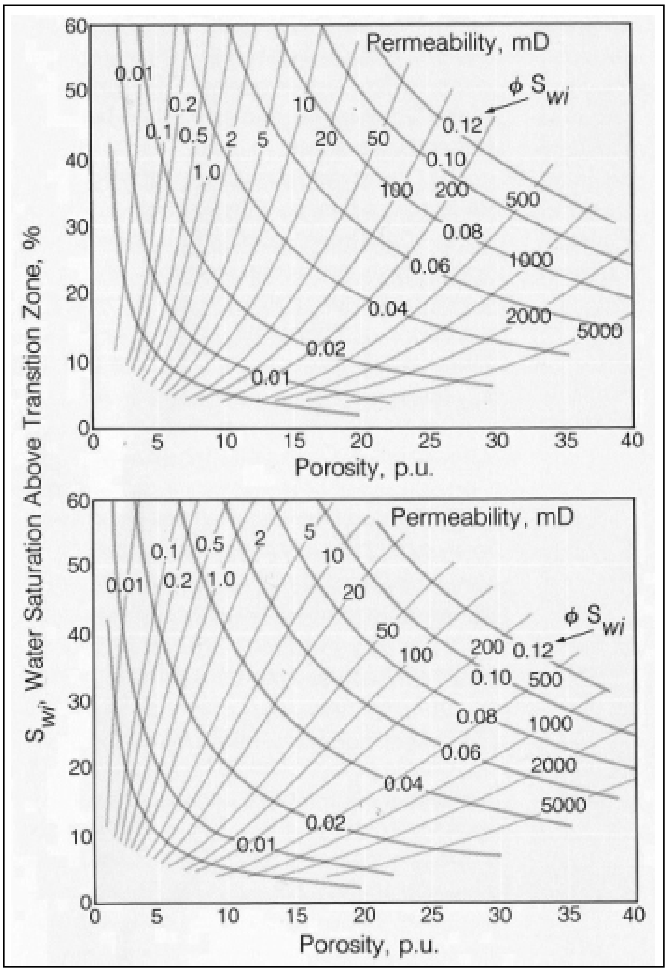

Figure 1: Charts based on permeability transforms proposed by Timur (top) and by Wyllie and Rose (bottom).

The first suggestion was to link conventional wireline log data, or log-derived rock properties such as porosity, with permeability. This idea is almost as old as wireline logging itself. Over the years, many transforms were proposed and, under certain conditions, they have been providing acceptable approximations of hydraulic conductivity, i.e. of single-phase intrinsic permeability. In the multiphase situation encountered by the oil industry, dimensionless terms called “relative permeabilities” were added to adapt Darcy’s equation in order to describe the ability of a rock to conduct one fluid in the presence of one or more other fluids, but no wireline logging solution has yet been found to estimate these relative permeability values in situ, and they have always been so far measured in laboratories on core samples.

The first formula relating intrinsic permeability with other measurable rock properties was proposed by Kozeny (1927) and later modified by Carman (1937). This formula is commonly written as: $k = \alpha.\phi^3/S^2$, in which S is the grain surface area per bulk volume, ϕ is the porosity and α an empirical constant. It well describes permeability in packs of spheres of uniform size but unfortunately breaks down in any real world formation other than unconsolidated well-sorted sands with almost spherical grains, since not only grain size but also sorting, compaction, and cementation affect permeability in sandstones (e.g., see Beard and Weyl, 1973). However, for log analysts, its greatest drawback was that the grain (or pore) surface area could only determined on core samples.

To alleviate this problem, Wyllie and Rose (1957) conjectured that grain surface area can be, in water-wet formations, approximately related to the irreducible water saturation Sw_{irr} (i.e. the amount of water in the pore space that cannot be displaced by oil), because they had noted that both grain surface area and Sw_{irr} increase when grain size decreases and when sorting becomes poorer. The advantage was that Swirr can be obtained from logs, although sometimes with difficulty. A consistent minimum of the bulk volume water over an oil- or gas-bearing sandstone interval usually provides a good Sw_{irr} estimate, but Sw_{irr} cannot be easily determined from resistivity logs when the reservoir is not at irreducible conditions i.e. when the hydrocarbon-bearing zone also produces water.

Timur (1968a) based on laboratory studies of 155 sandstone cores from different US oil fields, then proposed a slightly different relationship that was adopted by the entire oil industry:

$k^{1/2} = \phi^{2.25} / Sw_{irr}$ (Fig.1).

By the same time, in clay-rich formations, the Archie equation, used for computing water saturation in hydrocarbon-bearing formations from resistivity logs, started to be replaced by the so-called shaly sand models, and some log analysts derived Sw_{irr} and k from expressions proposed by Coates and Dumanoir (1973) for shaly sands. None of these interpretation models, however, was realistically accounting for the effects of clay type and morphology on permeability, which sometimes was leading to poor k estimates.

Neasham (1977) studied the impact of clay on the porosity-permeability relationship in sandstones. From a survey of 14 very well sorted sandstones from North Sea reservoirs, with similar textures but different types of clay morphology in the pore space, he showed that throat-bridging clay connected across the pore space was indeed causing major reduction in permeability, while porosity was much less affected. In other words, all the empirical correlations based on Sw_{irr} were likely to be working well in clean mature sandstones but marginally elsewhere.

Better permeability transforms based on more recent wireline logging tools

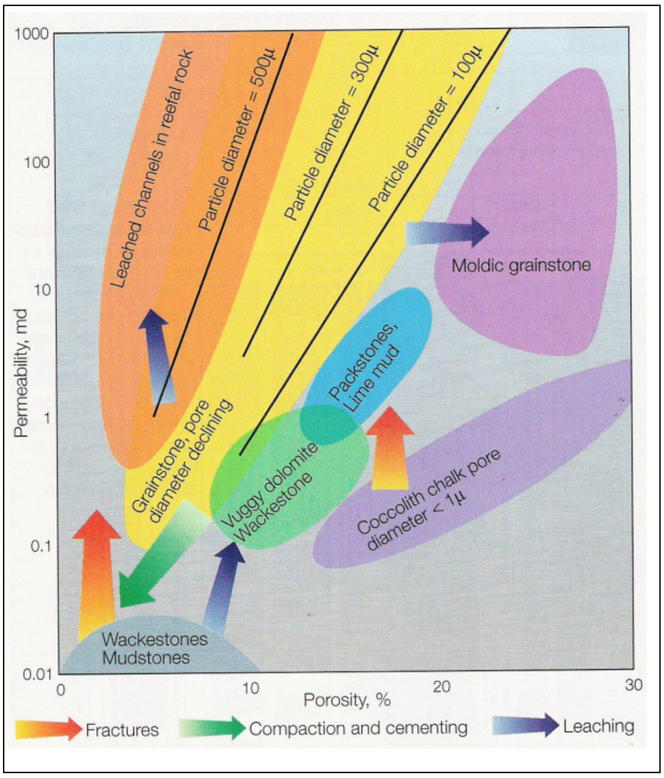

Figure 2: Porosity, pore type, and permeability in carbonates.

In the 1980s, the information brought by the conventional logs was complemented by the first geochemical logging tools that were using neutron-induced gamma-ray spectroscopy to measure the abundances of elements in a formation, then transformed into mineral abundances. The basis for obtaining permeability from those abundances was that changes in mineralogy are normally accompanied by changes in the size, shape, and morphology of rock grains; these changes affect the pore system geometry, which directly influences permeability. A function of mineral abundances was substituted for the surface area term in the Kozeny-Carman relationship by Herron (1987). This approach has been successfully used in the US Gulf Coast. More than anything else, it seems that, actually, the technique was deriving a textural maturity term from feldspar content computed from the geochemical tool readings.

In carbonates, the traditional permeability transforms, based on Sw_{irr} and ϕ, soon appeared to be of limited use. The reason is that, as shown by Nurmi (1986), porosity in carbonates is often not intergranular as in sandstones. and quite different pore types may result from the various diagenetic effects, such as dolomitization, leaching, and fracturation. For a given carbonate pore type, permeability generally increases with porosity along a fairly consistent trend, but pore connectivity is critical (Fig.2):

for instance, non-connected vugs contribute to porosity but very little to permeability. Conversely, the presence of fractures significantly increases permeability, but creates little additional porosity if fractures have not been enlarged by dissolution.

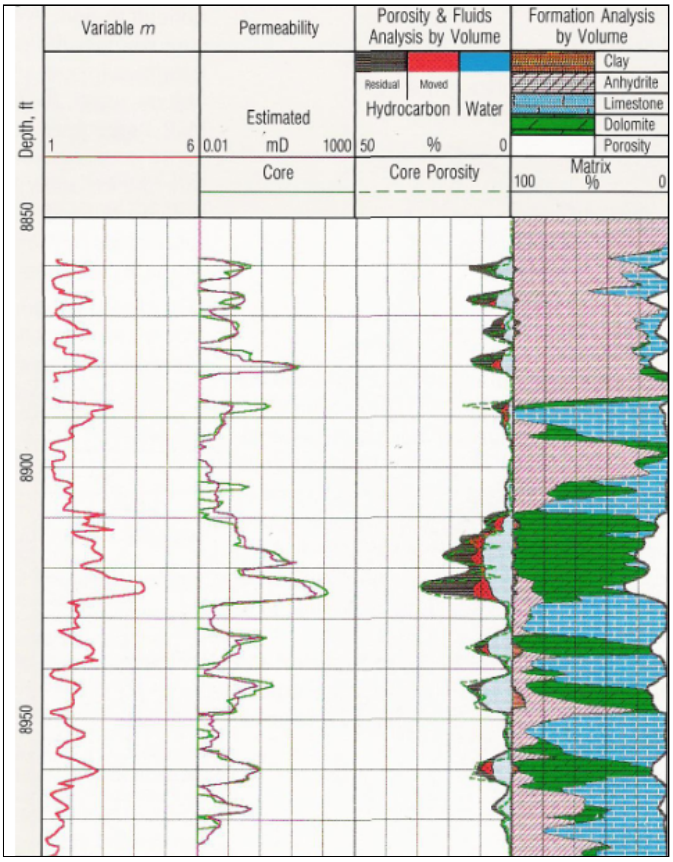

Figure 3: Comparison of "variable m" permeability and core permeability, in a Middle-East carbonate.

Guided by the intuition that the Archie exponent, m, is correlated with the pore tortuosity that also affects permeability for a given porosity value, Watfa (1987) observed that the presence of vugs that reduces permeability was typically leading to high values of m (>2), whereas the presence of fractures that increases permeability was leading to low values of m (close to 1). He thus assumed that permeability could be taken proportional to ϕ^m. This relationship at least well agrees with the observation: vugs increase m, which lowers Fm and thereby the k estimate; fractures decrease m, which increases the k estimate. The proportionality constant that Watfa said to be related to an equivalent pore radius was fitted using core permeability data, for a given carbonate formation, which then permitted a continuous derivation of k, provided that m could be continuously estimated versus depth. A method was devised that permitted estimating m continuously. It made use of a logging tool that was developed in the 1980s: the Electromagnetic Propagation Tool (EPT) records a high-frequency electromagnetic propagation travel time that responds to water-filled porosity but, contrary to resistivity measurements, does it without an exponent. As a consequence, combining this log with a resistivity log allows a continuous evaluation of m, after eliminating porosity. The method has been successfully used in the Middle-East (Fig.3).

Correlation of permeability with acoustic logging measurements

During the late 1970s, Lebreton has advocated for some years that a permeability index may be derived from a ratio of the absolute peak values of the three first half-cycles of the acoustic waveform recorded by a sonic logging tool. There was no convincing explanation why this ratio and permeability should be related. Improved acoustic coupling into fractures may have been causing the observation reported by Lebreton et al. (1978) since, right at a fracture, there is far better coupling between the borehole and the formation than elsewhere. Anyway, this triggered, in the 1980s and early 1990s, several attempts to correlate permeability with the Stoneley wave data recorded by sonic logging tools, such as the DSI (Dipole Shear Sonic Imager) tool.
The DSI tool generates low-frequency tube waves –called Stoneley waves– that propagate up and down the borehole with a special monopole transmitter operating at frequencies of 600 Hz to 5 KHz. While these waves preserve most of their energy in the borehole, some energy

is attenuated in front of permeable formations as the wave pressure pushes fluid from the borehole into the formation, similar to a quick small-scale pressure test. In so doing, this technique gains direct entry to permeability by physically moving fluid through the formation. The velocity of the wave is slowed down by an amount that can be related to the ratio of formation permeability to fluid velocity (Winkler et al., 1989). In the absence of mudcake, and knowing the acoustic velocity of the borehole fluid, the permeability can be estimated.

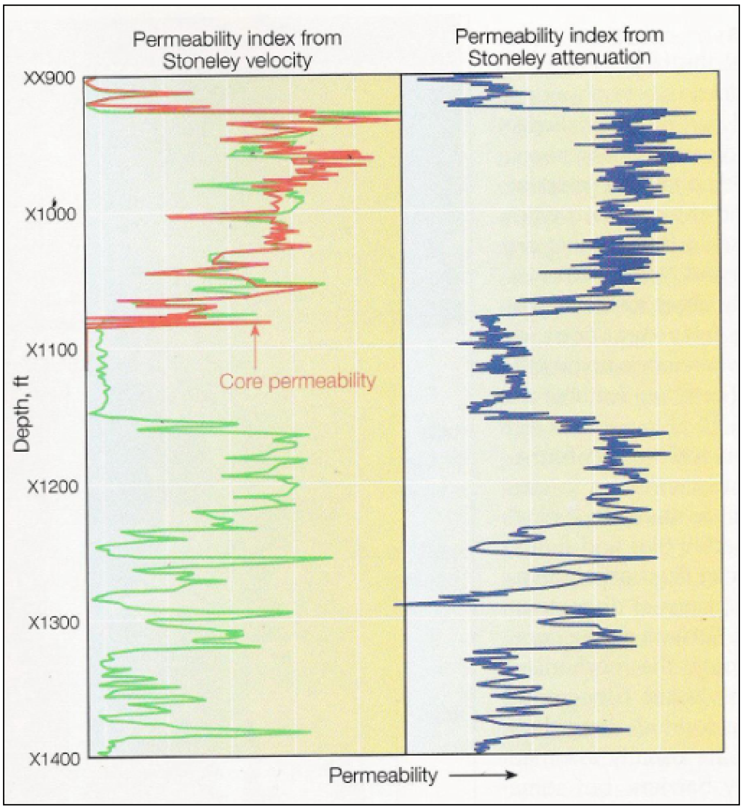

Figure 4: Comparison of core measurements and permeability indexes from Stoneley waves, in a Middle-East carbonate.

A preferred method, based on energy and not velocity attenuation, establishes permeability from Stoneley waves without needing any further information (Cassel et al., 1994). Furthermore, rather than to measure direct Stoneley energy transmission between sonic tool transmitter and receiver, it measures the attenuation seen between two adjacent receivers, thus narrowing the field of investigation to the distance between these near and far receivers i.e. about 15 cm, which provides higher resolution. Excellent agreement has been observed in Middle-East carbonates between core measurements and such permeability indicators (Fig.4). However, it may be difficult to get quantitative permeability estimates in the presence of mudcake that interferes with the wave's ability to move fluid into the formation.

It remains that Stoneley wave interpretation has been instrumental in fractured formations. The way fractures affect Stoneley waves is different than for compressional and shear waves: acoustic energy is not lost through mode conversions but as a result of moving the fluid into the fracture, and Stoneley attenuation is therefore quite independent of the fracture dipping angle and mostly a function of fracture permeability. Stoneley waves have thus proven to be an excellent fracture indicator (e.g., see Hornby et al., 1987) in tight formations where finding open fractures is equivalent to finding permeable zones.

Whereas all approaches based on Swirr were geared to oilfield conditions and hydrogeologists could not utilize them, the techniques based on geochemical, electromagnetic propagation, and sonic logging could very well be used in water wells. The same holds true for the techniques that are going to be described hereafter.

Nuclear magnetic resonance logging: a new way to estimate permeability

Magnetic resonance imaging instruments are commonly used as diagnostic tools in medicine today, but nuclear magnetic resonance (NMR) is also extensively used by the oil industry in wireline logging, as part of its quest for permeability. The physics and interpretation of NMR logs will now be thoroughly reviewed, starting from the earlier NMR tools, so as to provide the reader with explanations about a technique that, unfortunately, is still often not very well understood. In a nutshell, NMR logging gives unprecedented information about both porosity and pore size distribution that is used to successfully derive continuous permeability logs, notably in siliciclastic formations.

A brief history of early NMR logging techniques

The physical principle called nuclear magnetic resonance refers to the response of atom nuclei to externally applied magnetic fields. Many atom nuclei have a magnetic moment, i.e. behave like tiny spinning magnets. These spinning nuclei can interact with a magnetic field, producing detectable signals. For most elements, nevertheless, the measured signals are weak, but hydrogen —that is abundant in both water and hydrocarbons contained in the pore space of rocks— has a relatively large magnetic moment. As far back as 1946, NMR signals from hydrogen atom nuclei (i.e. protons) were observed by Purcell and Bloch. Oil industry interest followed right away, with several patents for NMR logging tools filed in the 1950s. The first NMR logging tool was developed by Brown and Gamson (1960) of Chevron Research and the first log was run in 1960. Schlumberger ran two versions of this tool, under license from Chevron, and later developed a tool commercialized at the end of the 1970s.
The principle of the early NMR tools was the following: the protons spinning in the formation are initially aligned to the Earth's magnetic field; the logging tool has a horizontally-mounted coil that transmits an oscillating magnetic field perpendicular, or transverse, to the direction of the Earth's magnetic field which tips the protons 90°, and then turns it off; the tipped protons immediately start to wobble or precess about the Earth's magnetic field, —just as a child's spinning top precesses in the Earth's gravitational field, its spinning axis describing a cone— at a frequency called the Larmor frequency, and they gradually relax back towards the Earth's magnetic field; the precessing protons create a small magnetic field, oscillating at the Larmor frequency, which is detected by the same tool coil. At first all the protons precess in unison but, as the protons precess about the static field, they gradually lose synchronization, mainly due to irreversible molecular interactions. This causes the magnetic field in the transverse plane, and hence the detected signal, to decay.
The quantities measured were NMR signal amplitude and decay. Because the voltage level in the tool coil was reduced by several orders of magnitude in going from transmitting to receiving mode, there was a delay before the induced signal could be measured, and amplitude had to be extrapolated back to time zero. But continuing research into the interpretation of these measurements produced some outstanding contributions. The obtained signal amplitude was found to indicate free-fluid porosity. Timur (1968b) developed the concept of free-fluid index (FFI) that he related to Sw_{irr} ($Sw_{irr} = 1 - FFI / \phi$) and he proposed a method to estimate permeability using NMR in 1968. However, the decay of the NMR signal during each measurement cycle, called the (transverse) relaxation time or T_2, generated the most excitement among the petrophysical community. Relaxation time was found to depend on pore size, larger pores that contain the most readily producible fluids allowing longer relaxation times. Seevers (1965) developed a first relationship between relaxation time and permeability of sandstones. A relationship between pore size, fluid and matrix properties was then presented by Loren and Robinson (1969).
However, with these early NMR logging tools, the volume of investigation could not be controlled and, to prevent the tool from reading borehole fluid, drilling mud had to be treated with a magnetite slurry before logging, in order to reduce the borehole signal to below measurement threshold. This time consuming treatment was not very popular with drillers and hindered the acceptance of NMR logging. The 1970s and 1980s saw continuation of this work on NMR logging by many oil companies or oilfied service companies (e.g., see Kenyon et al., 1986), in

parallel with laboratory NMR techniques developed to characterize core samples. To make the logging technique more widely acceptable meant a radical design change to use permanent magnets instead of the Earth's magnetic field for aligning protons, and to profit from advances in pulsed NMR technology commonly used in the laboratory.

The more recent generations of NMR logging tools

The use of powerful permanent magnets, applied to the formation as the logging tool moves up the borehole, permits that the position of the measurement volume can be controlled by tool design, thus eliminating the need for borehole mud doping. The use of a pulse sequence helps compensate for some reversible dephasing effects caused by the inhomogeneity of the static magnetic field. When this field is not perfectly homogeneous, the protons precess at slightly different Larmor frequencies, causing a decay that is not a property of the formation. The protons can be rephased when pulses that tip them 180° are transmitted. Pulses are applied repeatedly in an evenly spaced train. Each time the protons rephase, they generate a signal, called a spin echo.

This configuration was proposed by Jackson (1980 & 1984) who filed his patent in 1978 and the first experimental pulsed logging tools were eventually developed in the late 1980s. The MRIL (Magnetic Resonance Imager) tool built in 1990 by NUMAR —now a subsidiary of Halliburton— was the first commercial pulsed NMR tool. It incorporates a long permanent magnet to create a static lateral field in the formation. The tool is run centralized in the borehole, and the measurement volume consists of a thin concentric cylindrical shell with a length of 61 cm along hole and a depth of investigation varying with the borehole diameter (about 7.5 cm for a 10 in. or 25 cm hole).

A side-looking configuration invented by Schlumberger (Kleinberg et al., 1992) was the basis for the CMR (Combinable Magnetic Resonance) tool commercialized in 1995. It is run pressed against the borehole wall by a bowspring. A short directional antenna sandwiched between a pair of permanent magnets focuses the measurement on a zone located 2.8 cm inside the formation, with a length along hole of only 15 cm providing high vertical resolution.

By design, the area between the CMR tool skid and the measurement volume does not contribute to the NMR signal. This provides immunity to the effects of mudcake and hole rugosity. The two permanent magnets generate a focused static magnetic field which is about 1000 times stronger than the Earth's magnetic field, i.e. of about 550 gauss in the measurement region. The measurement sequence starts with a wait time of about 1.3 sec to allow for complete polarization of the hydrogen protons in the formation along the length of the skid. Then the antenna typically transmits a train of several hundred magnetic pulses into the formation. The entire pulse sequence, a 90° pulse of 4 gauss switched on for 16 µsec oscillating at the Larmor frequency followed by a long series of 180° pulses, is called a CPMG sequence after its inventors: Carr, and Purcell (1954) and Melboom and Gill (1958). The antenna also acts as a receiver and records each spin echo amplitude. The Larmor frequency for hydrogen nuclei in a field of 550 gauss is about 2.3 MHz. The echo spacing is 320 µsec for the CMR tool. T_2 distribution is derived from the decaying spin echo curve.

In the latest Schlumberger tool, the MRX (Magnetic Resonance eXpert) tool, the number of echoes and their spacing are programmable, among other novel features, so as to adapt to conditions where it is needed to measure long T_2 values (e.g., see Freedman, 2006).

A deeper insight into the interpretation of NMR logs

Molecules in fluids are in constant Brownian motion. Besides the relaxation by molecular diffusion in magnetic field gradients that the CPMG pulse sequence is compensating for, there exist two main NMR relaxation mechanisms, i.e. bulk fluid relaxation and grain surface relaxation. Both mechanisms result from molecular interactions and create the irreversible dephasing that can be observed by means of the decaying amplitude of spin echoes. The bulk relaxation is caused by the magnetic interactions between neighboring precessing protons in the fluid itself, while the grain surface relaxation is caused by the probability for a precessing proton moving about pore space of colliding with a grain surface.

Bulk fluid relaxation can often be neglected but can be important when water is in very large pores, which may be the case in vuggy carbonates, and when, therefore, hydrogen protons rarely contact a surface. Water in a test tube has a long T_2 relaxation time of 3700 msec at 40°C, a value that may be approached in a rock with very large vugs. Bulk relaxation also matters when non-movable hydrocarbon is present in the measurement region: the nonwetting phase does not contact the pore surface, and so it cannot be relaxed by the surface relaxation mechanism; in addition, increasing fluid viscosity shortens bulk relaxation times.

Grain surface relaxation is, by far, the most important process affecting relaxation times. Because of complex atomic-level electromagnetic field interactions at the grain surface, there is a high probability -characterized by a parameter called the surface relaxivity, ρ_2- that the proton in the fluid will relax when it encounters a grain surface. For a given grain type, e.g. in sandstones, the speed of relaxation depends on how frequently protons can collide with the surface, and this depends on the surface-to-volume ratio (s/v) and thereby on pore size. For example, relaxation times for a sandstone typically range from 10 msec for small pores to 500 msec for large pores. Collisions are less frequent in large pores that have a small s/v and relaxation times are, therefore, relatively long. Conversely, small pores have a large s/v and short relaxation times.

For a single pore, nuclear spin magnetization decays exponentially, and the signal amplitude decays with time constant $T_2 = (\rho_2.(s/v))^{-1}$. Rocks have a distribution of pore sizes, each with its own value of s/v. The NMR signal is the sum of the signals coming from all the pores located in the measurement volume. The initial NMR signal amplitude is thus proportional to porosity; its overall decay is the sum of the individual decays, which reflects pore size distribution. Separating out ranges of T_2 values by a mathematical inversion process produces the T_2 distribution curve. The area under the curve represents the porosity and the curve shape the distribution of pore sizes. This inversion process normally requires stacking, in order to improve the signal-to-noise ratio, which slightly degrades the vertical resolution.

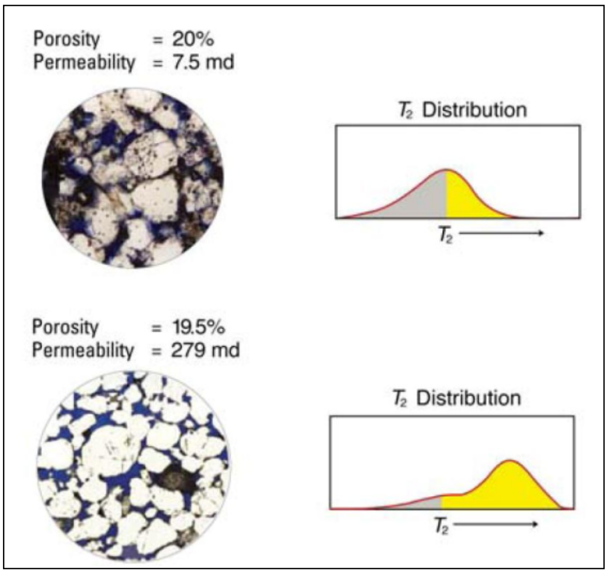

Figure 5: T_2 distributions for two sandstones with same porosity but different permeabilities and pore sizes (the yellow area corresponds to free-fluid porosity).

From NMR-derived porosity and pore size distribution to permeability

Traditionally, the total porosity seen in formations is subdivided into three components: free-fluid porosity, capillary-bound water, and clay-bound water. NMR free-fluid porosity is determined by applying a cutoff, of generally 33 msec for sandstones, to the T_2 distribution curve. The area underneath the curve above the cutoff gives free-fluid porosity (Fig.5). As NMR tool technology has improved over the last decade with shorter echo spacing (today, for example, the CMR-200 and CMR-Plus tools can measure T_2 down to the 0.3-msec

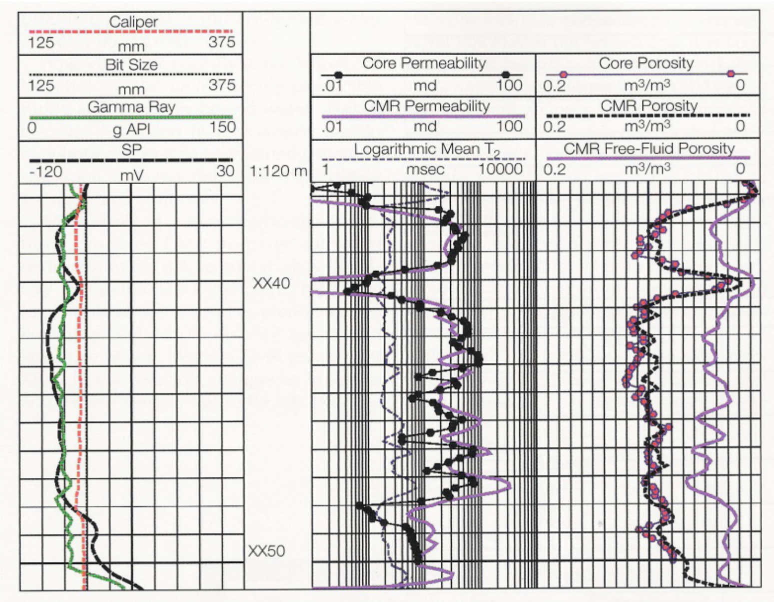

Figure 6: Comparison of CMR porosity and CMR permeability with core measurements.

range), the fast decaying clay-bound water signal with T_2 values below 3 msec can also now be measured and distinguished from capillary-bound water.

NMR permeability is derived from empirical relationships that were developed from brine permeability measurements and NMR measurements concurrently made in the laboratory on hundreds of different core samples. The two widely applied permeability transforms are the Timur-Coates and the Schlumberger-Doll Research (SDR) equations. While the Timur-Coates transform contains the total porosity and the ratio of the free-fluid volume to the bound-fluid volume, the SDR transform is based on the NMR porosity and the logarithmic mean of T_2 :

$$k_{NMR} = C\,(\phi_{NMR})^4\,(T_{2,\log})^2$$

where k_{NMR} is the estimated permeability, ϕ_{NMR} is CMR total porosity, T_2,log is the logarithmic mean of the T_2 distribution, and *C* is a constant depending upon the formation, e.g. 4 for sandstones and 0.1 for carbonates.

In Fig.6, CMR porosity shows a good match with core porosity measurements and, after fine-tuning of constant *C*, CMR permeability overlays core permeability points over the whole interval. Notably, over the zone with little porosity variation and where permeability varies from 0.07 md to 10 md, CMR permeability values compares well to that of core measurements. The value of *C* used for this well was applied to subsequent CMR logs in the same formation, enabling the oil company to reduce coring costs.

It has also been observed that the sum of all spin-echo amplitudes is proportional to the product of porosity and average T_2, and correlates well with permeability. This alternative yields better results in high noise environments and can be interpreted without stacking, which leads to a new NMR permeability indicator (Sezginer, 1999) with higher vertical resolution (typically 20 cm).

Some specific interpretation issues related to NMR logs in carbonates

The interpretation model assuming that, in water-saturated reservoir rocks, the T_2 and pore-size distributions are directly related well explains why NMR T_2 curves are successfully used to characterize sandstones containing mixed pore-size distributions. However, there is some concern within the oil industry that NMR does not work as well in carbonate reservoirs. First, NMR responses in carbonates differ from those in sandstones: all pore surfaces are not equally effective in relaxing hydrogen nuclei and carbonates are about three times less efficient in relaxing the nuclear magnetism than sandstones. For carbonates, relaxation times therefore tend to be three times longer and a 100 msec cutoff was proposed for free-fluid porosity. This cutoff value has often to be locally adapted. For instance, in the Thamama formations of Abu Dhabi, permeable grainstones could be distinguished from lower permeability packstones and mudstones with a 225 msec cutoff. But, while carbonate formations contain mixed pore-size distributions, e.g., intergranular porosity and vugs, NMR logging data in these formations nevertheless frequently yield unimodal T_2 distributions, which often results in inconsistent T_2 cutoff values to distinguish bound and free fluids, and leads to unreliable permeability predictions.

Developments in NMR research (Ramakhrisna, 1999) have now explained why the conventional approach breaks down in grain-supported carbonates which have dual pore systems. The breakdown is due to diffusion of spinning protons between the micro- and macropores. If the surface relaxivity is small enough, protons originally in the micropores can diffuse into the macropores before their nuclear spins relax; the decay of these spins then proceeds much more slowly. Conversely, spinning protons originally in the macropores can penetrate into the micropores where they encounter more surface interactions, speeding up their decay. Diffusion therefore causes the area under the short T_2 peak -the porosity fraction associated with micropores- to decrease; at the same time, the position of the higher T_2 peak shifts towards shorter times. Acting together, these two effects tend to merge the two peaks and produce a unimodal T_2 distribution that bears little resemblance to the bimodal distribution one would expect from a dual-porosity system.

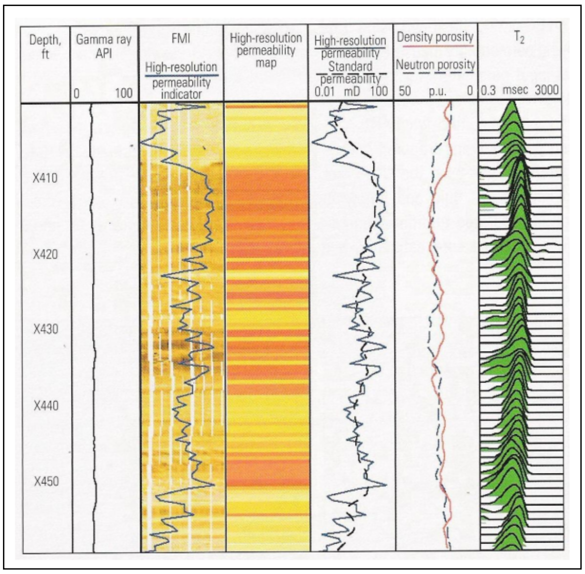

Figure 7: Comparison of CMRPlus high-resolution permeability with FMI borehole electrical images

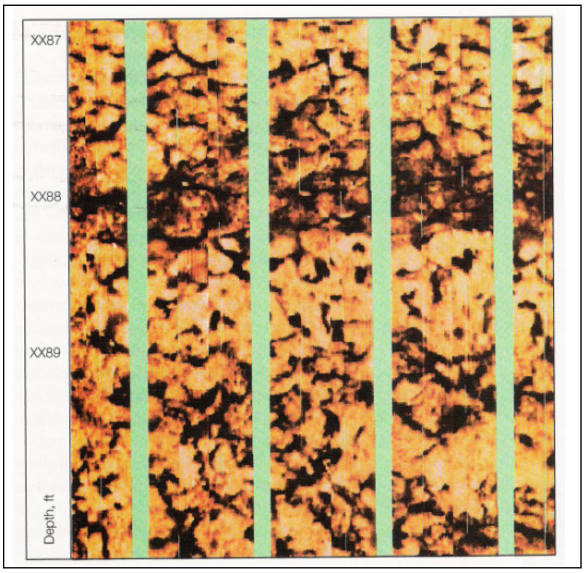

Figure 8: Mottled fabric of a Middle-East carbonate rock shown by a FMI image (dark = pores, light = grains and matrix).

In chalk formations with a single pore system, NMR logging performs very well, as demonstrated by an example from the Ekofisk formation in the North Sea (Fig.7). While it is widely believed that chalk formations are homogeneous, borehole electrical images have revealed thin laminations. In the image, light yellow indicates electrically resistive low-porosity chalk and dark brown more conductive higher porosity chalk. While the standard CMR permeability transform show little evidence of these laminations, the high-resolution permeability indicator log shows permeability variations that are consistent with the laminations seen in the images.

Borehole image analysis: a way to access permeability through rock facies typing

In carbonates with complex pore structure and sometimes difficult NMR interpretation, a saving grace for permeability logging (Akbar et al., 1995 & 2000) has been the development, in the late 1980s, of high-resolution borehole imaging tools, such as the FMI (Fullbore formation Micro Imager) tool which provides a picture of most of the borehole wall with 192 small current-emitting electrodes mounted on four pads and four flaps pressed against the formation. As the tool is pulled up the hole, a measurement is made every 2.5 mm and the small electrodes also have an effective horizontal spacing of 2.5 mm. Borehole orientation, tool azimuthal orientation, and borehole diameter are all recorded, allowing the 3-dimensional positioning of every measurement. Small scale conductivity variations in the elec-

trical images (Fig.8) permit to identify the presence of macro or vuggy porosity in carbonates and to recognize the facies …and permeability in carbonates is predominantly a function of the facies (or rock type).
While pores in clastic rocks are located between grains and uniformly distributed throughout the rock, in carbonates the diagenesis can significantly modify pore space and permeability because those rocks are highly susceptible to dissolution: grains can be dissolved to form new pore space, shells can be dissolved creating moldic porosity, dissolution along fractures or cracks can create large vugs or even caves; depositional bedding is rarely preserved; also, whereas clastic diagenesis normally does not involve a change in mineralogy, in carbonates a diagenetic process i.e. the replacement of calcium carbonate by magnesium carbonate, called dolomitization, can significantly improve the permeability.

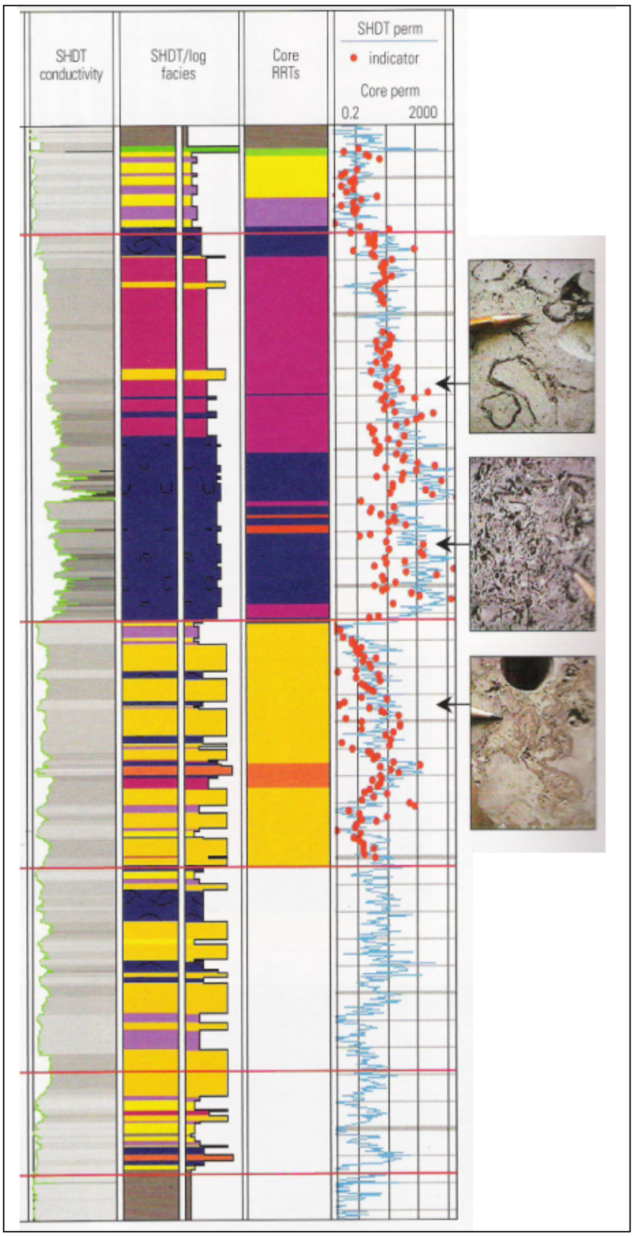

Figure 9: Rock type zonation and continuous permeability indicator derives from high-resolution dipmeter data combined with conventional porosity and lithology logs.

A trend in FMI interpretation in the early 1990s has been towards automated quantitative image analysis (Delhomme, 1992), and an innovative method for characterizing rock type and permeability was later developed. First the textural variations in the borehole electrical images are captured: the types, sizes, and densities of both conductive and resistive features are determined, conductive paths between large conductive features (usually cracks or fractures connecting large vugs) are identified.
This information about the internal organization of the rock is summarized as "textural" logs that are then combined with conventional logs such as gamma ray, neutron, and density providing information about porosity and lithology. This is achieved by means of an artificial neural network (ANN) software that produces a continuous identification of the rock types (carbonate facies).
Once the rock type is identified, a porosity-permeability transform could be specified, at each depth, to estimate permeability, as suggested in Fig.2. However, it has been found simpler, and more efficient, to use the ANN software for producing directly a continuous quantitative permeability estimate.
The ANNs for both rock type and permeability determination are trained on cored intervals, from the same well or from a nearby well.
This approach has proved to be so powerful that it has been successfully retrofitted to be applied to old wells where only high-resolution dipmeter (e.g. SHDT) data, and not images, had been acquired. Fig. 9 dis-

plays results obtained in that way from an Abu Dhabi well. Photographs in the composite plot show blown-up pictures of 3 distinct rock types. Note the more precise log-derived rock type zonation, and the good agreement of log-derived permeability estimates with core permeability data.

What about permeability anisotropy ?

In the past years, reservoir engineers have increasingly paid attention to permeability anisotropy. With more and more highly deviated and horizontal wells in the oil and gas fields, vertical permeability may be the most important reservoir parameter because it affects production -the larger the vertical anisotropy, the higher the productivity index-, injection performance, or gas and water coning. Vertical permeability is routinely determined from cores, but the problem with anisotropy is that it varies with scale: permeability barriers anticipated from core plug data may have, or lack, lateral extension and influence, or not, the flow patterns at a larger scale. Vertical interference testing with the Modular formation Dynamics Tester (MDT) tool (Pop, 1993) is more a wireline-conveyed technique than a true logging one, but it provides this type of information.
Horizontal anisotropy is also a major concern in oil and gas fields. A horizontal well drilled normal to the direction of larger horizontal permeability will be a much better producer, or injector, than one drilled parallel to it. Wireline logging measurements in a pilot vertical well provides valuable information for horizontal well design. Shear sonic logging may, for instance, be used to identify the maximum and minimum stress directions that usually coincide with the maximum and minimum horizontal permeability directions: natural (micro)fractures aligned with the maximum stress direction open up in the direction normal to it, but stress anisotropy may also cause minor permeability anisotropies in the absence of fractures, by distorting the pore space.
Hydrogeologists may soon be facing the same situation than reservoir engineers if horizontal wells start to be drilled for aquifer storage and recovery or to mitigate saltwater intrusion in coastal aquifers.

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DARCY 126

What grains can tell on Darcy velocity ?

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Abstract
In the pursuit of methods to estimate hydraulic conductivity - the key parameter in the description and prediction of flow in porous media - grain-size based methods have the appeal of simplicity, but their reliability is not without question. A number of these empirical methods have been surveyed and summarized. Their validity was assessed by comparing the predictions to actual measurements performed on several representative samples (taken from previous studies). Although the reduced number of samples precludes sweeping statistical conclusions and does not necessarily apply to all modeling situations, the results nevertheless show that grain-size based methods, particularly those that take into account grain size dispersion and properly account for the controlling influence of the smaller fractions, can be an acceptable substitute for more expensive laboratory measurements and field tests when accuracy is not of the essence and small-volume support is desired. Among the described methods Beyer's and the US soil classification formula are favoured.

Introduction

In the hydrogeological description of flow systems, the hydraulic conductivity as introduced by Darcy 1856 is the key parameter (1).

$$K = \frac{Q \cdot \partial l}{A \cdot \partial h}$$

where K Hydraulic conductivity [L/T]
Q/A Darcy velocity [L/T]
$\partial l/\partial h$ hydraulic gradient [-].

Most techniques which have been developed in order to measure K are modifications of Darcy's original experiment. All these experimental methods – field tests as well as laboratory measurements - derive hydraulic conductivity by performing a flow experiment under controlled boundary conditions. Either flow through columns of aquifer material is performed, or radial flow towards a pumping well is induced. The discharge is measured and subsequently related to the geometry of the experiment and additional information on the aquifer's conditions.
Whereas the physical process of flow is independent from the spatial scale of the experiment, the results for K are not. Field pump tests always result in effective K-values, which might be understood as an integral value over the aquifer volume which is affected by the experiment. The inherent heterogeneous structure of the considered aquifer cannot be ascertained at a scale smaller than the affected aquifer volume. The problem of up- and downscaling has been addressed by many authors, e.g. Gomez-Hernandez 1998, Renard and de Marsily 1997, Bierkens et al. 2000). However, for most applications dealing with groundwater resources and their accessibility the small-scale spatial heterogeneity of aquifers doesn't play an important role. On the contrary, considering solute transport the small-scale variability of K becomes important, since the hydrodynamic dispersion is understood as a function of aquifer heteroge-

neity and transport distance (Beims 1983, Kinzelbach 1992, Schafmeister 1990).
K-values derived from laboratory experiments (e.g. permeameter tests) are based on aquifer material from small sample volumes (~ 1000 cm^3) and thus comprise a much smaller scale of heterogeneity than field experiments. In addition the anisotropic characteristics of *K* can be approached by varying the direction of flow with respect to the orientation of the sample and thus its inherent texture.
Lab-experimental results from many samples distributed in space may thus give better information on the spatial structure of an aquifer by means of appropriate regionalization techniques e.g. geostatistical simulation (de Marsily et al 1998) rather than one or two expensive pump tests. However permeameter experiments are very time consuming especially when low-permeability sediments are considered. For many practical purposes these permeameter tests are not very adequate.
Hydraulic conductivity *K* is related to the intrinsic permeability *k* by including the specific conditions of the fluid 'water' e.g. dynamic viscosity μ density ρ_w and gravitational acceleration *g* (2):

$$K = k \cdot \frac{\rho_w g}{\mu_w}$$

where
K Hydraulic conductivity [m/s]
k intrinsic permeability [m^2]
$\rho_w g$ weight density of water [N/m^3]
μ_w dynamic viscosity [$N/(s\ m^2)$].

Given the fact that the intrinsic permeability is strongly related to the pore space, i.e. its volume and shape, it was concluded that the ability of materials to conduct fluids can be derived from the grain-size spectrum, which can easily and cheaply be assessed from small samples (< 1 kg) of unconsolidated material.
Empirical formulas have been developed relating hydraulic conductivity K to specific parameters which can be read from cumulative curves of grain-size distribution, some of which are discussed later in this paper. The resulting values are quasi-point supported given the small sample size compared to results from field pump tests.
Since the appearance of these empirical formulas, many studies have investigated how the K-values derived from grain-size analysis compare with values from other laboratory or field methods, e.g. Pekdeger and Schulz (1975). Results from these studies are discussed below. The question however, which of all methods provides the "true K value", can never be answered. The "true", or better "effective" hydraulic conductivity depends on the considered volume since K varies in space. In addition hydraulic conductivity is a tensor, of which the tensorial properties can theoretically be assumed but practically hardly be proven (De Marsily 1986, Mathéron 1967). However, as mentioned before K-values derived from grain-size distribution from small sized samples can be understood as point supported. Also these methods don't allow the consideration of the tensorial aspect of K.
It should be noted that the empirical grain-size methods apply only to hydraulic conductivity of unconsolidated aquifers. However, since most of the socio-economically relevant aquifers in Germany are situated in young unconsolidated Quaternary and Tertiary deposits, these methods have gained high acceptance.

Methods

The methods discussed below are all based on grain-size curves. Grain-size curves are derived from sieve-analyses of loose sediments with grain-diameters bigger than 0.063 mm which marks the limit between coarse silt and fine sand. Below this, laser particle-size detectors (Leschonski 1987, Wachernigg 1987) or settling tests (hydrometer analyses) are used. Results are depicted as cumulative curves of weight percent of material vs. the logarithmic axis of grain-diameter in mm (Fig. 1). The number and opening-sizes which are used in practice differ from country to country. According to the German Industrial Norm (DIN 18123 1996) six sieves with diameters of 2000, 1000, 500, 250, 125 and 63 μm are used for grain diameters above 0.063 mm.

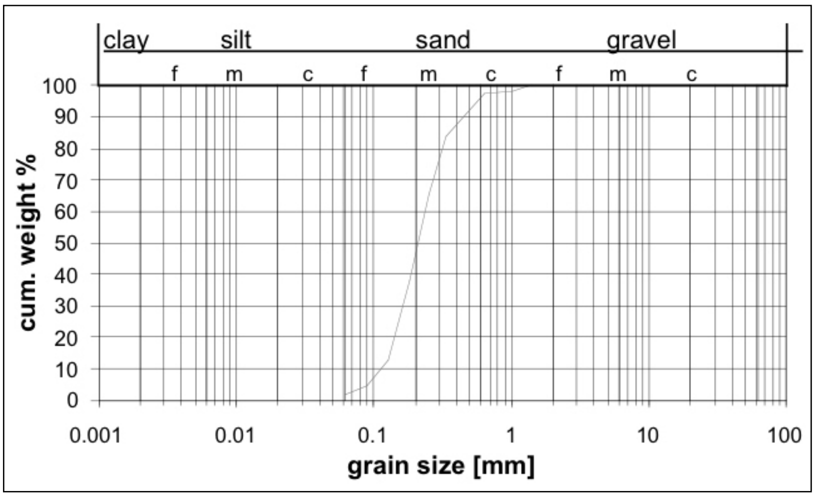

Figure 1: Example of a cumulative grain size distribution curve for a fine to medium sand

Most empirical formulas for hydraulic conductivity have in common that a specific grain size, the effective grain size d_e, is squared and then multiplied by a coefficient *C*. The latter is either a constant or varies with the grain sorting or other grain shape parameters.

The following parameters can directly be read from the grain size distribution curve: coefficient of uniformity *U*, and effective grain size d_e. Additional information on the shape of the grains is required for the method of Kozeny-Köhler (Kozeny 1927, Köhler 1960). Coefficient of uniformity U is a dispersion measure of the grain size distribution and is defined as the relation of d_{60} to d_{10}, i.e. the 60 percentile over the 10 percentile grain fraction. *U* approaches 1 the better the sediment is sorted. However values of $U > 20$ are reported for soils which are dominated by the silt and clay fraction. The effective grain size d_e is defined as the equivalent grain diameter of a strictly uniform sand which has the same intrinsic permeability as the actual sediment. It can be related to the specific surface *O* of the material (3):

$$O = \frac{\sum O_i}{V_{tot}}$$

$$d_e = m \cdot \frac{6}{O}$$

where
O_i surface of grain *i* [L^2]
O specific surface [L^2/L^3]
V_{tot} total Volume of solids
$m = 1$ for spheres and cubes

The value 1 for m can be assumed for most fluvial and washed sediments (Beyer 1964). Usually d_e is represented by a smaller grain fraction which can easily be understood since the smaller grains determine the pore space. Many empirical formulas use d_{10}, but d_{20} or d_{50} are common as well.

A simple and worldwide well acknowledged empirical formula was developed by Hazen (Hazen 1893, Zieschang 1961) for medium sands. It relates K to d_{10} as follows (4):

$$K = 0.0116 \cdot d_{10}^2 \cdot (0.70 + 0.03 \cdot T)$$

where
K Hydraulic conductivity [m/s]
d_{10} 10 percent grain fraction [mm]
T temperature of weakly mineralized water.

At temperatures of 10°C the factor in the parentheses becomes 1. The formula applies for sands which are well sorted only, i.e. d_{10} greater than 0.063 mm and U less than 5.

Beyer (1964) extended Hazen's formula for less well sorted sands. He found out that the correlation between d_e and d_{10} depends on the coefficient of uniformity *U* (Fig. 2a) and therefore introduced factor *C* which incorporates the grain sorting (5). Factor *C* increases with decreasing *U*, i.e. with increasing grade of sorting (Fig. 2b). The formula applies for U less than 30 and d_{10} ranging from 0.063 to 0.63 mm. It can easily be seen from (5) that the method of Beyer always results in smaller K-values compared to the method after Hazen.

$$K = C \cdot d_{10}^2$$

where
K Hydraulic conductivity [m/s]
d_{10} 10 percent grain fraction [mm]
C factor ($120 \cdot 10^{-4} > C > 60 \cdot 10^{-4}$).

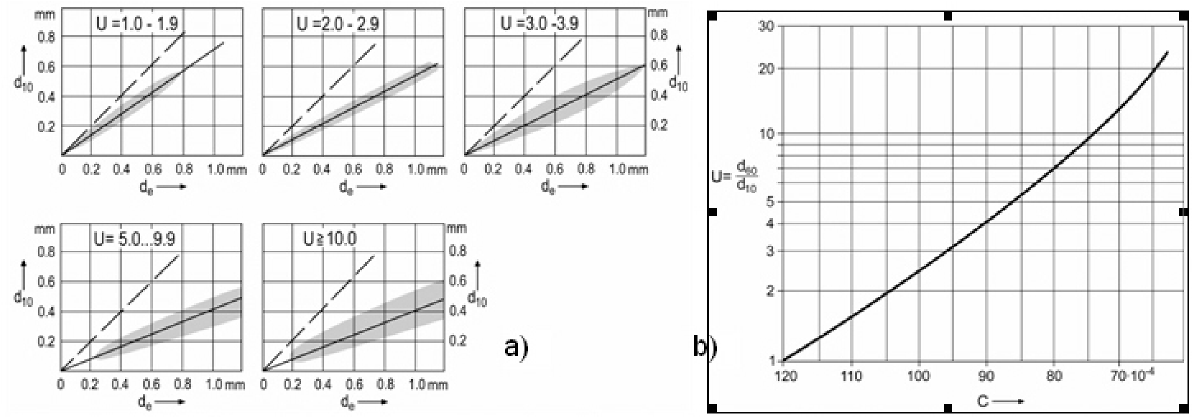

Figure 2: a) Relation between de and d10 for different ranges of U; b) Factor C as function of U (modified after Beyer 1964)

It should be mentioned here that already in 1880 Seelheim developed an empirical formula which relates K to the median grain size d_{50} as follows (6):

$$K = 0.00357 \cdot d_{50}^2$$

where
K Hydraulic conductivity [m/s]
d_{50} 50 percent grain fraction [mm].

The US Bureau of Soil Classification recommends (after Mallet and Pacquant 1954):

$$K = 0.0036 \cdot d_{20}^{2.3}$$

where
K Hydraulic conductivity [m/s]
d_{20} 20 percent grain fraction [mm].

The Kozeny method (Köhler 1960) relates K to porosity, grain shape, kinematic viscosity of water and de, the latter being estimated as the harmonic mean of the grain size distribution. Today the method is known as the simpler Kozeny-Carman equation (modified from Bear 1972):

$$K = \left(\frac{\rho_w g}{\mu_w}\right) \cdot \left(\frac{n^3}{(1-n)^2}\right) \cdot \left(\frac{d_{50}^2}{180}\right)$$

where
K Hydraulic conductivity [m/s]
n porosity
d_{50} 50 percent grain fraction [m]
$\rho_w g$ weight density of water [N/m³]
μ_w dynamic viscosity [N/(s m²)].

Mash and Denny (1966) developed an empirical formula relating K directly to d_{50} and reciprocally to the dispersion measure σI, both given in phi-grades. The dispersion measure σI, is calculated from the marginal reaches of the cumulative grain size curve (d_5, d_{16}, d_{84} and d_{95}).

ID	classification of sand	1 Permea-meter	2 Infiltration	3 Borehole dilution	4 Hazen	5 Beyer	6 US Soil Class.	7 Seelheim	8 Kozeny-Carman	9 Mash-Denny
a	very fine	3.8	0.1	n.d.	2.5	1.9	1.1	9.6	3.9	5.5
b	very fine	7.7	0.2	n.d.	2.8	2.0	1.4	10.8	4.4	5.2
c	fine	n.d.	n.d.	6.8	5.7	4.9	n.d.	6.4	2.6	6.1
d	medium	12.0	n.d.	n.d.	33.5	29.0	13.5	45.9	18.5	16.7
e	medium	n.d.	n.d.	24.0	37.6	33.7	n.d.	35.1	14.2	15.0
f	medium	20.0	n.d.	n.d.	61.4	52.9	22.6	75.9	30.7	17.5
g	medium	13.0	n.d.	n.d.	61.4	53.9	19.3	75.9	30.7	25.0
h	coarse	29.0	n.d.	n.d.	78.4	62.5	36.6	205.4	82.9	33.3
i	medium/coarse	34.0	n.d.	n.d.	78.4	66.9	32.2	113.4	45.8	15.8
j	medium	34.0	n.d.	n.d.	84.6	74.0	30.1	93.8	37.8	18.3
k	medium	n.d.	n.d.	n.d.	84.6	75.1	32.2	93.8	37.8	25.5

n.d. not determined

Table 1: K-values in 10^{-5} m/s derived from flow tests (1 to 3) and grain size distribution curves (4 to9)

Results

From several hydrogeological research projects 11 selected grain-size distribution curves were analyzed and K-values were determined using the empirical formulas given above. Where available K-values derived from flow tests, i.e. borehole dilution, permeameter and infiltration test, for the same samples are compared with the results from the empirical methods

(table 1).
Samples a and b are very fine grained poorly sorted sands from top soils on Pleistocene glacial tills (Darsow 2003). The d_{10} values are 0.05 mm and thus slightly below the lower validity limit for the methods of Hazen and Beyer. Samples c and e originate from Pleistocene well sorted fluvial, partly eolian sands deposited on Precambrian rocks at Chalk River, Ontario (Hoffmann 1997). Samples d, f, g, h, i, j are medium and medium-coarse Pleistocene glaciofluvial sands from a sand pit in North Germany (Auer 1990, Karnani 1990). Sample k is a Tertiary fluvial medium-coarse sand whose grain-size distribution was published by Langguth and Voigt (2004).

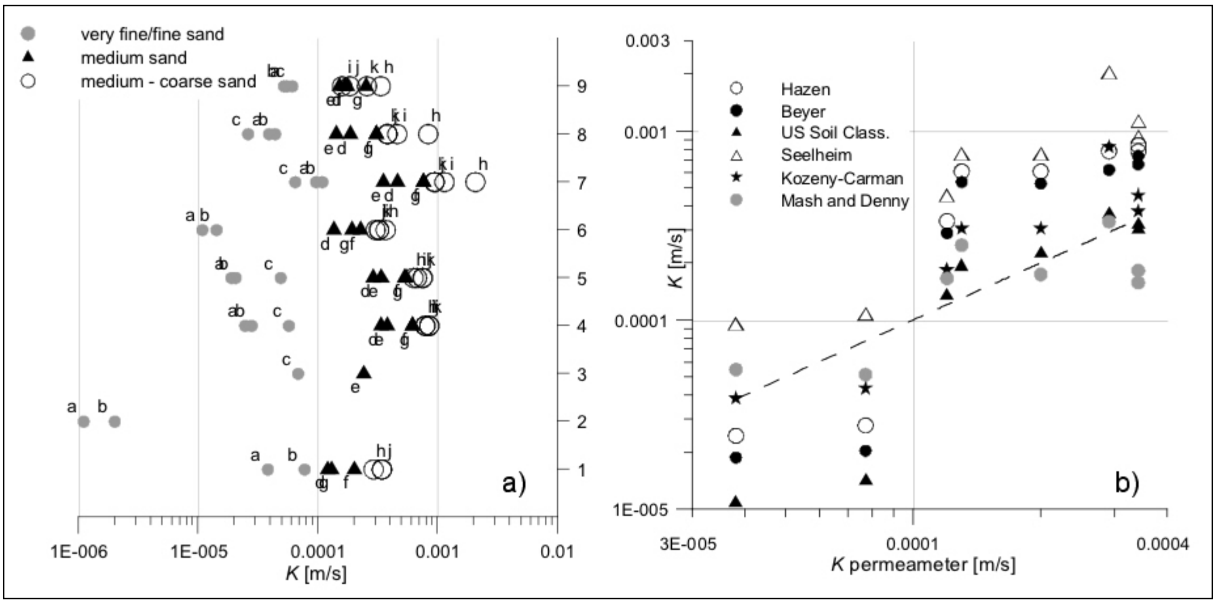

Figure 3: a) K-values for 11 samples from permeameter (1), infiltration (2), borehole dilution (3) tests and after empirical methods Hazen(4), Beyer(5), US Soil Classification (6), Seelheim (7), Kozeny-Carman (8) and Mash-Denny(9); b) All methods compared to permeameter results (1 : 1 line)

In fig. 3a the data are sorted by lithology (symbols), and by method (vertical axis). It can be seen that the infiltration method (2) results in the smallest K-values. Comparing the permeameter (1) and borehole dilution (3) results to those from grain size empirical relations it can be concluded that the latter are more sensitive to the lithology, i.e. the fine, medium, and medium-coarse sands are better separated from one another, except for the method of Mash and Denny (9). For the analyzed samples the methods of Hazen (4) and Beyer (5) provide almost the same results, K-values after Hazen being slightly bigger. This is explained by the fact that the grain size distribution curves are rather steep, i.e. the U values are ranging between 2 and 3.5. Similar to Hazen and Beyer the US soil classification method (6) uses a small effective grain diameter and thus provides 2 to 3 times lower values than Hazen and Beyer for the given samples.
The methods of Seelheim (7), Kozeny-Carman (8) and Mash and Denny (9) use the median grain diameter as $d_{e,}$. However the latter two methods include other parameters which relate to grain shape and packing. Kozeny-Carman uses the porosity. By this the K-spectrum is reduced by a factor of 2.5 compared to the Seelheim results. Both Seelheim and Kozeny-Carman lead to more clearly separated results for the coarser sand samples The method of Mash and Denny includes the spreading measure sI which lowers the K-values according to the degree of sorting. The method of Seelheim (7) tends to overestimate K compared with all other methods.

n = 8	Hazen	Beyer	US Soil Cl.	Seelheim	Kozeny-Carman	Mash-Denny
Correlation coefficient	0.91	0.90	0.93	0.77	0.77	0.55

Table 2: Correlation coefficient between permeameter results and empirical grain size analyses

On the whole it can be seen that for the medium grained samples all methods provide comparable results
Assuming that the permeameter test reproduces Darcy's original experiment best it can serve as a calibration measure for the empirical grain size methods. The above listed results were obtained after coring the samples with a minimum grade of disturbance. The grain size distribution was assessed from the disturbed sample after the permeameter test. Fig. 3b demonstrates that all grain size methods tend to underestimate *K* for the fine sands and overestimate K for medium and medium-coarse sand fractions with respect to the permeameter results. The Seelheim method always overestimates *K* by a factor of 1.4 for fine sands up to 7 for coarse sands. Again d_{50} as effective grain diameter appears to be a bad representative of the effective grain diameter since it puts too much weight on the coarser grain fractions and suppresses the influence of the finer grains on the pore space. However if d_{50} is supplemented by other factors, e.g. porosity, grain shape and spread, as in the formulas of Kozeny-Carman and Mash and Denny, the resulting *K* values approach the range of the permeameter results. Still the correlation between these methods and the permeameter test (table 2) is less than the correlation with method of Hazen, Beyer and the US soil classification, which indicates that for the given samples these methods provide results which reliably reflect the process of flow through porous media.

Discussion

The results presented above are based on a very limited number of samples from arbitrarily selected sites and thus cannot stand a proper statistical proof. However they compare well with results from other studies which are discussed below.
Musolff et al. (2004) analyzed 42 samples of very fine grained and silty soils on glacial tills, for which samples a and b are representatives. Since d_{10} was always smaller than 0.06 mm the methods of Hazen and Beyer are not valid. It was shown however that the infiltration method provides reliable results for these soils. This field test is designed to determine the hydraulic conductivity of unsaturated soils in the field as a function of tension head of the undisturbed soil (Bohne 1998, Wooding 1968). K-values derived by the US soil classification method for the same samples correlate weakly with the infiltration but not with the permeameter results (Darsow 2003).
Hoffmann (1997) calculated K values form 145 grain size curves from core samples of 11 wells in fluvial, partly eolian sands deposited on Precambrian bedrocks in Chalk River/Ontario. Borehole dilution tests were performed at 15 selected segments within the wells and correlated with the respective samples. The d_{50} values vary between 0.07 and 0.3 mm, representing very fine, fine and medium sands. K-values derived after Hazen and Beyer correlate with the borehole dilution results at 0.66 and 0.68, respectively and cover the same range of hydraulic conductivity between 0.5 and 4.10^{-4} m/s. The method of Mash and Denny even shows a higher correlation of 0.72. However only the smaller values compare well with the borehole dilution results; K-values from samples in higher permeable segments are significantly reduced by a factor of 3 by Mash and Danny.
Schafmeister and Pekdeger (1993) investigated spatial heterogeneity of K and its effect on

hydrodynamic dispersion. 219 undisturbed samples were taken from a 2 m by 2 m cross section in a sand pit in North Germany (Auer 1990, Karnani 1990). With a mean d_{50} of 0.5 mm the samples were classified as medium to coarse sands. Permeameter test were performed for 48 undisturbed samples in the lab and the results were compared to *K*-values derived after Beyer. The average *K* for Beyer and the permeameter test are 6.10^{-4} and $2.3.10^{-4}$ m/s, respectively. Here the method after Beyer provides 2.5 times higher values than the permeameter test, which is due to the fact that the dense packing of the undisturbed samples, which is not considered within the simple formula of Beyer. It can be expected that here the Kozeny-Carman method might give better results.
Pekdeger and Schulz (1975) compared K-values derived from permeameter tests, grain size analyses (Beyer, Hazen) and from pump tests which were evaluated by different methods. The test sites are situated in glacio-fluvial sands in North Germany. The d_{50} grain diameter was 0.2 mm thus indicating medium sands. Again the permeameter tests yielded the lowest results (fig. 4). For all test sites the method after Beyer revealed the smallest variation within the samples and slightly lower values than the method of Hazen, which both results from the fact that the Beyer formula includes the coefficient of uniformity *U*. The high range of variation of the pump test results must be lead back to the variety of different interpretation methods which have been applied based on the same pump test data. This example illustrates nicely that even if pump test might reflect the groundwater flow conditions more reliably than any laboratory test it still depends on level of information on the hydrodynamic boundary conditions whether realistic results are obtained.

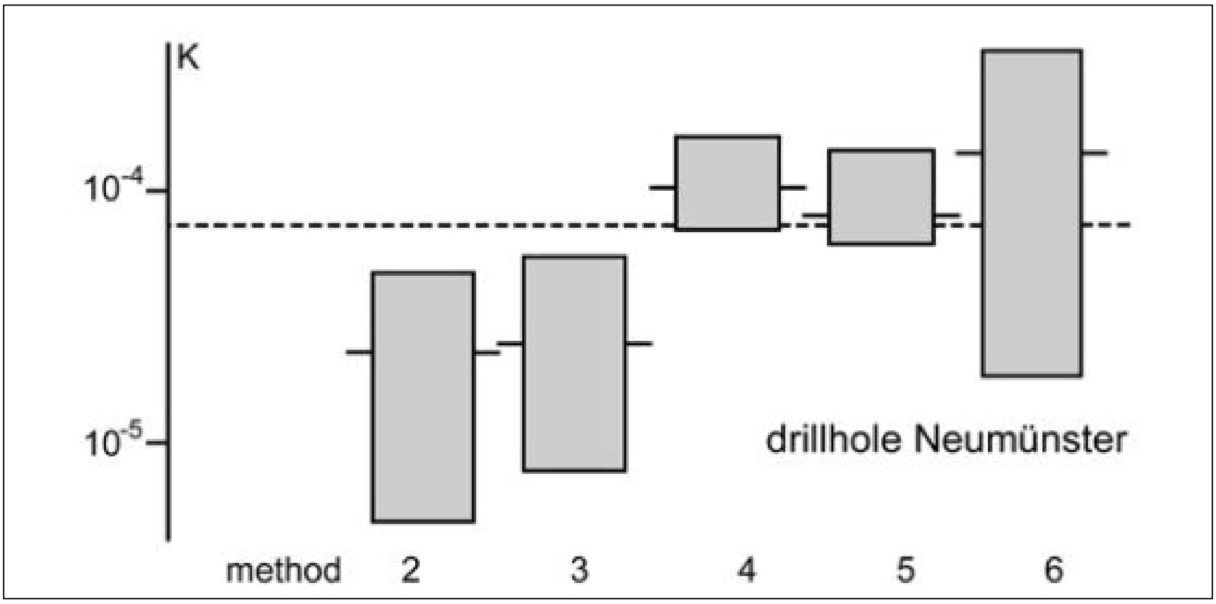

Figure 4: Comparison of permeameter tests, flow downwards (2) and flow upwards (3), Hazen (4) and Beyer (5) and pump test results (6) (modified after Pekdeger and Schulz 1975)

As the governing parameter in groundwater hydrology hydraulic conductivity is one of the first measured parameters in any investigation, be it for practical or research interests. Before deciding which method should be applied the purpose of the investigation must be very clear. Questions involving groundwater resources and groundwater production require information on the hydrodynamic flow system on a much broader scale than most applications which deal with the question of solute transport and hydrodynamic dispersion, the latter being influenced by small scale contrasts in hydraulic conductivity. Methods which involve a bigger aquifer volume, e.g. pump tests will fail to reveal the aquifer's small scale heterogeneity. Here any

method based on a large quantity of small samples taken uniformly within the area of interest will better serve to assess and reproduce aquifer heterogeneity (Schafmeister and de Marsily 1994).
There is not much doubt that laboratory permeameter tests come closest to the physical process of fluid flow through porous medium as it was originally described by Darcy. Thus these tests are well suited when flow at a small scale is investigated. Even the tensorial aspect of K can be approached. However these tests are quite time consuming and much care must be put to the experimental design: e.g. samples should be undisturbed and air inclusions during the test must be avoided.

Conclusions

Within the framework of geological and hydrogeological studies in unconsolidated aquifers grain size analysis is one of the standard investigation methods in order to classify the sediment. Thus the empirical determination of hydraulic conductivity from grain size distribution curves is certainly the cheapest method and fastest approach with the least effort. The use of a computer is barely necessary. However special care should be put on the validity of the chosen method.
Among the above discussed methods the one of Hazen is the easiest one since it requires one parameter (d_{10}) only, however the validity range is very restricted to uniform sands, i.e. U > 5. The method of Mash and Denny is well known in the US, but barely used in Europe. It uses the older phi-grades rather than the metric mm. The spread measure is calculated from the extreme reaches of the cumulative grain size curve and may thus be subject to measurement errors.
Although the formula of Seelheim hasn't been used much recently it was included in this study for reasons of completeness. Based on d_{50} it tends to overestimate *K* and thus turns out be the weakest of all described methods. The methods of Kozeny-Carman and Mash and Denny which use d_{50} as well provide more reasonable results by including porosity and grain shape or a spread measure. However because porosity is often not measured and the grain shape is only qualitatively assessed the Kozeny-Carman formula bears many sources of misinterpretation too.
The disadvantage of Hazen's formula of not being valid for poorly sorted sands has been repaired by Beyer's formula which includes the coefficient of uniformity *U* as a spread measure. This easy to use and cheap method has proved to be very effective especially for glacial and fluvial aquifers in Germany (Pekdeger and Schulz 1975) and is widely used there but hasn't become well known elsewhere.
The US soil classification method which uses d_{20} as effective grain diameter is similarly easy to use. For the selected samples it yielded good results compared to the permeameter tests. However it seems to work best for very fine grained soils, i.e. with a higher percentage of silt and clay. It may thus serve as an appropriate alternative for sediments which are beyond the range of validity for Hazen and Beyer, i.e. $d_{10} < 0.06$ mm.
In conclusion empirical formulas for the determination of K from grain size distribution curves of small samples of unconsolidated aquifer material provide reasonable results with a minimal technical effort and are thus a cheap and fast alternative to any sort of flow tests, i.e. pump, permeameter, or infiltration test, in explorative hydrogeological investigations.

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