presentation
december 6, 2004, bureau of economic geology

Hydrologic function of karst features in the uplands of the Edwards aquifer recharge zone—A view from the field

Adrien Lindley[1] and Susan D. Hovorka[2]
[1]The University of Texas at Austin and the [2]Bureau of Economic Geology

Abstract

Mass balance shows that most of the recharge into the Edwards aquifer occurs where major streams cross the Edwards recharge zone. However, the uplands contain abundant evidence of active karst dissolution, including sinkholes, caves, and solution-enlarged fractures. What is their hydrologic function? How much and what kind of protection do such features need as urbanization proceeds across the recharge zone?

A series of measurements of infiltration comparing karst features with paired non-karst control plots using a large-diameter single-ring infiltrometer provide direct evidence of the hydrologic function of these features under undisturbed conditions. Selected karst features are small and include soil-floored sinkholes, sinkholes having cobble-filled drains, and an excavated solution cavity. We have tested eight pairs in the Barton Springs segment of the Edwards recharge zone and plan in the next phase of the study to measure similar features in the San Antonio area.

Introduction

The vulnerability of karst aquifers to contamination is commonly known to be higher than other types of aquifers as a result of the focused flowpaths that provide rapid and direct recharge to the aquifer. These flowpaths include large-aperture karst features such as swallow holes, open-fracture zones in riverbeds, caves, and sinkholes having closed drainage basins, found across the recharge zone (Figure 1). However, the most commonly occurring karst features in the upland are subtle soil-floored depressions that commonly lack large-aperture openings. These features include sinkholes, closed depressions, solution cavities, and soil-filled fractures. Many of these features are small (less than 10 feet in diameter) and shallow (less than 8 inches in depth). Though they may have little topographic relief, they may indicate a larger, well-developed flow system located in the top few meters of soil and bedrock. The role of these features in providing a flowpath to the aquifer, in terms of either recharge or water quality, is not well known.

Currently, State law (Edwards Rules [Title 30 Texas Administrative Code (TAC) Chapter 213]) regulates activities having potential for polluting the Edwards aquifer. A key part of implementation of the Edwards Rules is the requirement for management of **“**sensitive features,” which are defined as permeable geologic or manmade features located in the recharge zone or transition zone where potential exists for hydraulic interconnectedness between the surface and the Edwards aquifer and rapid infiltration to the subsurface may occur. The initial step in managing sensitive features is to identify them through a process known as geologic assessment. Instructions to conduct the assessment are provided by the Texas Commission on Environmental Quality (TCEQ), the State regulatory agency charged with implementing the Edwards Rules. These instructions specify methods for closely inspecting a tract of land to identify geomorphic indicators of sensitive features. On the basis of the geologic assessment, the developer proposes plans for implementing “best management practices” (BMPs) to mitigate the impact of development. The hydrologic function of very common but subtle, small, soil-floored features on the upland, the correct method of classifying these features during the geologic assessment, and the determination of what, if any, BMPs are applicable are problems identified during the recent revision of the instructions for conducting geologic assessments. This study focuses on these features to determine how the Edwards Rules apply to them.

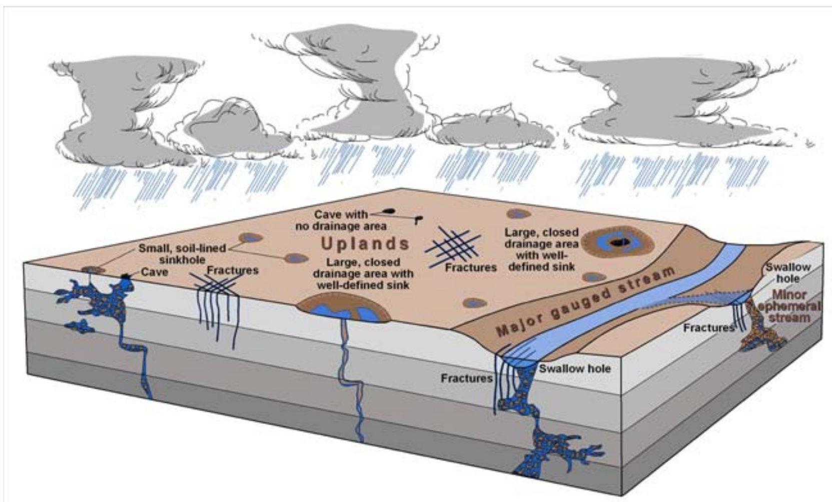


Figure 1. **Schematic diagram of the Edwards aquifer recharge zone including several types of karst features that have the potential for interconnectedness with the subsurface and where rapid infiltration to the subsurface may occur.**

This project determines hydrologic function directly by testing the infiltration rates of a population of small, subtle karst features and inducing recharge on them. This project is designed to evaluate the hydrologic function of these subtle features, specifically sinkholes in the uplands of the Edwards recharge zone, to determine what role they play in recharging the aquifer and to what extent they should be protected to mitigate water-quality degradation or reduction of recharge volume as the uplands undergo urban development.

Methods

Initially, surveys of representative karstic sites on the Edwards outcrop were conducted, with landowner cooperation, to identify subtle features and associated typical background areas to study. These surveys were conducted by walking transects 50 feet apart through the property. Potential features were photographed, and their locations were surveyed using Global Positioning System (GPS). Brief descriptions of the feature's dimensions, setting, and soil cover were collected. Microtopographic and soil thickness surveys were conducted within the feature to reveal the features of interest more clearly, as well as to quantify the volume of soil that overlies the feature. Constant head ring infiltrometer experiments were conducted in order to determine and quantify an area's connectedness with the subsurface.

There are three factors that must be quantified in order to determine the sinkhole infiltration capacity as a function of depth of ponding: the volume of water added, the time required for infiltration to occur, and the area on which the water is added. These three factors may be quantified by conducting a constant head ring infiltrometer test. Ring infiltrometers are devices used to determine the infiltration rate of an area enclosed by an impermeable boundary. A metal ring is placed around an area of interest (Figure 2), which includes a sinkhole defined by topographic depression or a background area. The ring is inserted into the ground to minimize lateral leakage by digging a trench to match the circumference of the ring and packing it with bentonite or other relatively impermeable material. Water added to the enclosed area is added quickly so that it ponds at the surface to a depth of several inches within the ring, and then water is added as needed to maintain constant head on the feature of interest.

Figure 2. Ring infiltrometer ponding water on a sinkhole with flow meter and control section.

Water supplied from a reservoir is gravity fed through a 3-inch diameter water hose to a flow-control section. Flow-control sections are required to reduce turbulence and maintain laminar flow across the paddle wheel of the flow meter. The flow-control sections are constructed from PVC pipe of varying diameters (3, 2, and 1 inch). There are three different sizes of flow-control sections to accommodate three different flow rates. Flow is regulated into the ring manually via a ball valve downstream from the flow meter.

A data logger records the volume of water that is introduced into the ring by electrical pulses sent by the paddle wheel of the flow meter. Every time the paddle wheel makes one rotation, a known volume of water passes through a specific diameter of pipe. Therefore, the volume of water that passes for one rotation in a 3-inch pipe will be different from that in a 1-inch pipe. The number of rotations is converted into a volume and logged at 5-liter intervals. Thus, by dividing the volume per time by the area, a sinkhole infiltration rate is achieved (length per time). Infiltration rate is then normalized for head by dividing the infiltration rate by maximum ponding depth.

Site description

Two main sites have been utilized for testing small karst features in the uplands of the Edwards recharge zone, J-17 Tract and Rutherford Ranch. These two sites are part of the Water Quality Protection Lands program managed by the City of Austin Water Utility. Site J-17 is located in southern Travis County, and Rutherford Ranch is located in northern Hays County west of Buda. Outcrops at both locations are principally Kainer and Person Formation limestones. Four sinkholes and their paired control plots have been tested at each site. In addition to the sinkholes, one recently excavated solution cavity was also tested. The dominant soil type for the J-17 tract is Speck stony clay loam (SsC), and the dominant soil type for the Rutherford Ranch area is the Rumple-Comfort association (RUD). These clay loams contain 30 to 40 percent clay.

J-17 features

The four sinkholes studied at the J-17 tract are subtle features having little topographic relief. Features J17SH1 and J17SH2 and their associated background control plots are developed in the Person Formation, whereas J17SH3 and J17SH4 and their associated background plots and J17SC1 are developed in the Kainer Formation as mapped in the March 2000 geologic assessment prepared by HBC Engineering, Inc. Feature J17SH1 is approximately 6 feet by 5 feet and 4 inches deep. It is one of three sinkholes that form a complex of small sinkholes that trend N38W. There was no leaf litter or evidence of rapid recharge in the sinkhole, and the soil is clay dominated with abundant organics. At the surface there were a few rocks present in the base of the bowl, but nothing to indicate an open drain. When digging the trench to install the ring infiltrometer, we encountered well-weathered, smoothed, and rounded rocks ranging in size from about 4 inches in diameter to 2.5 feet by 1.5 feet large. Feature J17SH2 is more obvious. It is 3.5 feet by 5 feet and 10 inches deep. A large cactus was growing in the bowl of the sinkhole. The loose clay loam soil had an abundance of organic detritus, and there was no direct evidence of flow into the sinkhole. Few pebbles were observed in the bowl, and few fist-sized cobbles were observed at the surface and in the immediate subsurface. J17SH3 is 5 feet by 6 feet and 6 inches deep with clay loam in the bowl and organic detritus. There were fist-sized cobbles in the near subsurface around the rim of the bowl and few larger rocks at the surface near the rim and at the base of the bowl. J17SH4 is 7 feet by 4.5 feet and 8 inches deep. It is elongated in the NNE direction. J17SC1 is a solution cavity 3 feet by 4.5 feet by 4 feet deep. It is a well-developed feature having a cylindrical shape that widens near the base and is elongated along a trend approximately N55W. This feature has recently been excavated, and the soil removed is a silty clay loam.

Rutherford Ranch features

Four sinkholes and their associated background control plots were studied at the Rutherford Ranch. RRSH1, RRSH3, and RRSH4 are developed in the Grainstone Member of the Kainer Formation, Edwards Group limestone, and RRSH2 is developed in the Leached and Collapsed Member of the Person Formation, Edwards Group limestone, as mapped in the October 1999 geologic assessment prepared by SWCA Inc., Environmental Consultants.

RRSH1 is a broad, 8-foot by 8.5-foot, shallow, 5.75-inch-deep sinkhole that was identified by a contrast in vegetation. Within the sinkhole, low grasses and knee-high lush green plants were observed. In the surrounding area, waist-high plants dominated the grasses, and those that were visible were noticeably less lush from their brown color. Desiccated algae were also observed in the base of the bowl. Few rocks were observed in the base of the bowl, though 6- to 10-inch-diameter rocks were not uncommon around the rim of the sinkhole. RRSH2 is a relatively large sinkhole that has a diameter of about 25 feet. The base of the bowl contains one drain containing fist-sized angular shaped cobbles. A 3-foot soil probe was inserted into the gaps between cobbles to a depth of about 2 feet. Leaf litter and grasses around the sinkhole indicate rapid flow to the drain. Two animal burrows were observed near the base of the bowl after a large cactus was removed. RRSH3 and RRSH4 are part of a complex of three sinkholes that trend WNW. RRSH3 is a 7.5-foot by 6-foot diameter and 7-inch deep, oval-shaped sinkhole with fist-sized weathered cobbles near its base. RRSH4 is a 7-foot by 5.5-foot and 6-inch deep, oval-shaped sinkhole with weathered rocks near the surface and in the subsurface.

Background plots for each sinkhole were located nearby on typical flat grassy upland. Soils are similarly 8 to 12 inches deep with some rocks at or near the surface.

Results

The goal was to determine the hydrologic function of the soil and bedrock system contained by the ring for both karst and non-karst features in the Edwards aquifer recharge zone. The karst features tested include soil-floored sinkholes, a cobble-drained sinkhole, and an excavated solution cavity. The results for each experiment are shown in Table 1 and include the average infiltration rate, in centimeters per minute (cm/min), as well as inches per hour (in/hr), which has been normalized for depth.

The excavated solution cavity and cobble-filled sinkhole exhibit infiltration rates that exceed 15 and 30 times background, respectively. The excavated solution cavity infiltration rate was compared with the average of all the background plots at J-17. The average infiltration rates of the soil-lined sinkholes are slightly lower than the average infiltration rates of the control plots, 0.061 and 0.097 in/hr (1.55 and 2.46 mm/hr), respectively, but the majority of the control plots lie within the range of infiltration rates for soils in the area and nearly half of the soil-lined sinkhole infiltration rates are below the range of the soil rates. The dominant, Speck stony clay loam (SsC) soil type for the J-17 tract is described in the Travis County Soil Survey as having a permeability of 0.06 to 0.20 in/hr (or 1.524 to 5.08 mm/hr), and the Rumple-Comfort association (RUD), dominant soil type for the Rutherford Ranch area, is described in the Comal and Hays County Soil Survey as having a permeability range of 0.06 to 0.20 in/hr (or 1.524 to 5.08

mm/hr). Although maintenance of a depression suggests active karst processes like soil sapping or soil piping occur, the 30 to 40 percent clay in the clay loam soil appears to retard infiltration.

Table 1. Resulting infiltration rates of features and control plots.

Feature name	*Feature type*	*Average infiltration rate (cm/hr)*	*Average infiltration rate (in/hr.)*
J17BG1	Background	0.3091	0.122
J17BG2	Background	0.2410	0.095
J17BG3	Background	0.0616	0.024
J17BG4	Background	0.2133	0.084
RRBG1	Background	0.3962	0.088
RRBG2	Background	0.1796	0.071
RRBG3	Background	0.4263	0.168
RRBG4	Background	0.2475	0.097
J17SH1	Sinkhole	0.0587	0.023
J17SH2	Sinkhole	0.1460	0.057
J17SH3	Sinkhole	0.1103	0.043
J17SH4	Sinkhole	0.2039	0.080
RRSH1	Sinkhole	0.0841	0.019
RRSH2 (3in)	Sinkhole	5.6873	2.239
RRSH3	Sinkhole	0.2359	0.093
RRSH4	Sinkhole	0.2860	0.113
J17SC1	Solution Cavity	3.4382	1.354

Discussion

Most of the control plots have a somewhat higher infiltration rate than their associated sinkholes. Only the solution cavity, J17SC1, and the well-developed sinkhole RRSH2 have higher infiltration rates than their control plots. Similarly, only the J17BG3 control plot shows an infiltration rate that is significantly less than that of soil-lined sinkholes. The infiltration rate, normalized for head, has been plotted to effectively show the differences between feature types in Figure 3. The solution cavity is in the Kainer Formation and had an infiltration rate of about 1.354 in/hr, which is higher than any of the background control plots and all but one of the sinkholes tested. The one sinkhole that did indicate an infiltration rate higher than the solution cavity had an open drain in the base of its bowl with little soil to slow the flow of water to the subsurface.

Conclusions

Maintenance of numerous small depressions suggests that active karst processes such as soil sapping are focused. Experience of karst specialists in the area suggests that excavation of these subtle sinkholes will lead to discovery of more extensive karst, including potentially enterable caves. However, the results of the infiltrometer tests demonstrate that the few inches of clay loam soil dominate the infiltration of this soil/ bedrock system.

The subtle features maintain some significance in their roles as recharge features because of their maintained microtopography. Under natural conditions these features will collect and pond water during rain events. As ponding occurs, the increase in head from ponding allows for a larger volume of water to infiltrate to the subsurface.

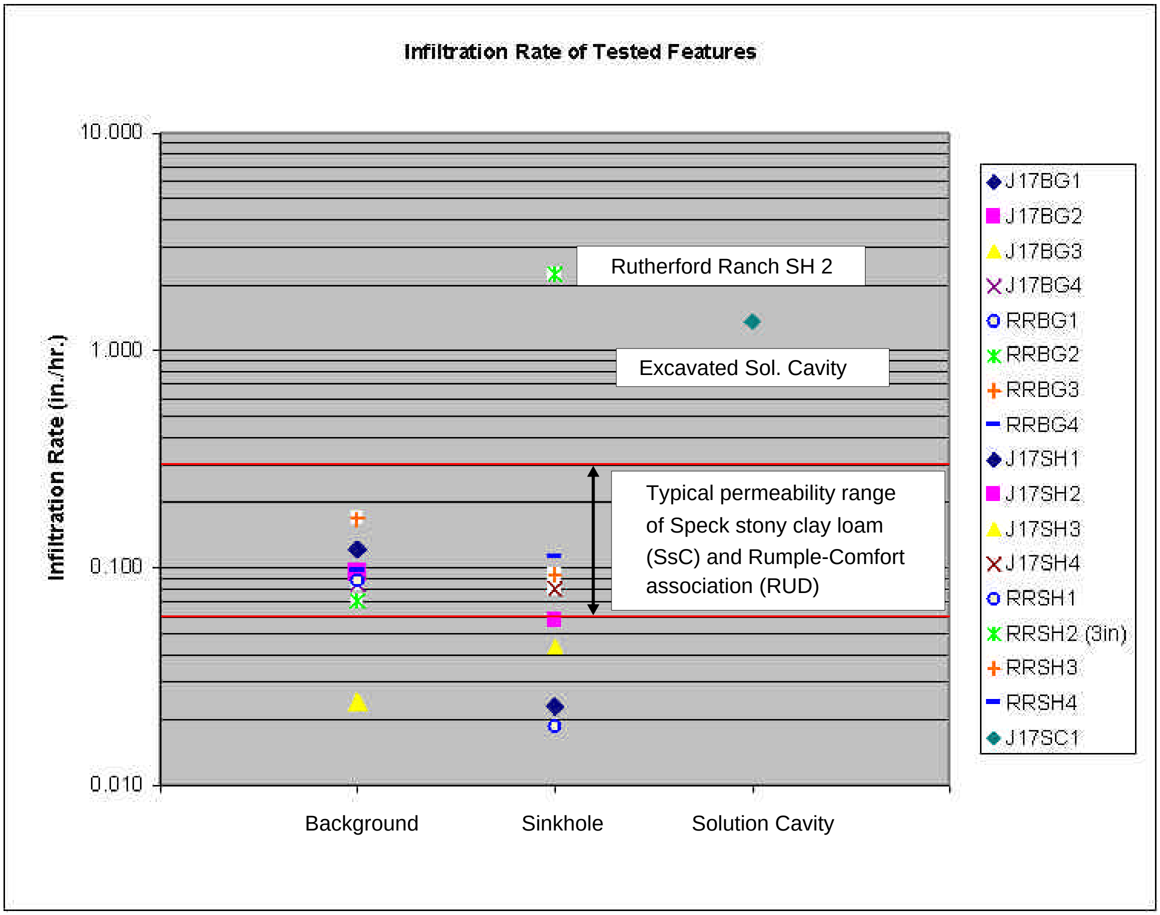


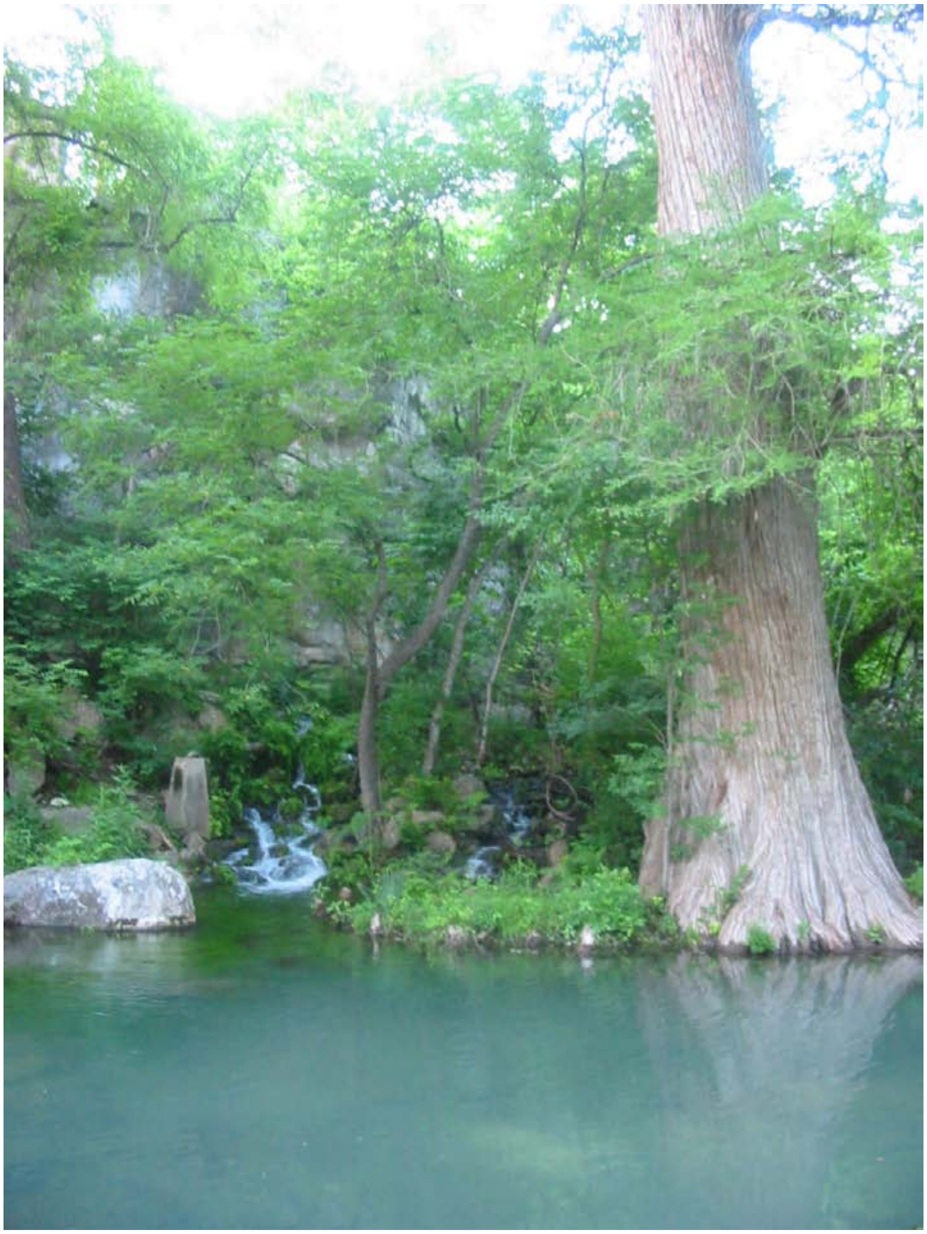
Figure 3. Infiltration rates versus feature type for J-17 tract and Rutherford Ranch.

Additional work is required before we define these common upland karst features as not sensitive according to the Edwards Rule definition. One question that arises is: Are these subtle features that we tested really of karst origin and not artifacts of past land management? If some or all of the small sinkholes are connected to highly transmissive karst systems beneath the soil, then a second question arises: What type of BMPs should be applied to protect the aquifer if these thin soils are modified during development?

Future research is designed to investigate these questions. Ground-penetrating radar surveys across features before and after ponding will explore the geometry of the soil and rock and distribution of water during recharge. Ponding tests with water-soluble dye will allow us to determine the area of wetting and preferential flowpaths within the sinkholes and control plots. Subsequent excavation of features will enable us to investigate the hydrologic function of the epikarst. Additional field sites in the San Antonio area are required for a more region-wide comparison of sinkhole and background control plot infiltration rates.

Adrien Lindley is a geology graduate student at The University of Texas at Austin and a graduate research assistant at the Bureau of Economic Geology. He is interested in understanding recharge via small karst features and how they may impact water quality in the Edwards aquifer. Research for his thesis includes the quantification of infiltration rates in small (12-foot diameter) sinkholes in the uplands of the Edwards aquifer Recharge Zone.

Susan Hovorka is a Research Scientist at the Bureau of Economic Geology, John A. and Katehrine G. Jackson School of Geosciences. She has been working on Edwards aquifer issues since 1992.



Rebecca Creek Springs in the Hill Country of Texas (photo by Robert Mace).

presentation

december 6, 2004, bureau of economic geology

The Public Fountains of the City of Dijon by Henry Darcy

Patricia Bobeck

Geotechnical Translations

The book *Les Fontaines publiques de la ville de Dijon* is best known to modern-day hydrogeologists as the book in which Darcy's law first appeared. The five pages of the book describing Darcy's experiment were translated into English by Allan Freeze in 1983 (Freeze and Back, 1983). An English translation of Darcy's entire book was published in 2004. The translation reveals a wealth of information about the history of water and Henry Darcy.

Henry Darcy (1803–1858) wrote the book in 1856 to describe the water-supply system he built in Dijon, France in 1839–40, and, in my opinion, to leave a record of his lifelong research into water issues. Darcy's water supply system provided abundant pure spring water to Dijon through a network of street fountains. The street fountains also made it possible to wash refuse from city streets and to fight fires. The water was free and the fountains were a maximum of 100 meters apart, so no one had to walk more than 50 meters to fetch water. In 1840, Dijon ranked second only to Rome in terms of the quantity and quality of water available to its citizens.

As a native of Dijon, Darcy spent his early years drinking the putrid water that was the only water available. At that time, Dijon collected water from roofs and from wells located in the alluvium of the stream that ran through town. The water from the shallow alluvial wells was contaminated by nearby cesspools.

After studying at the École Polytechnique and the School of Bridges and Roads in Paris, Darcy returned to his native city and worked as an engineer in the Corps of Bridges and Roads. Shortly after returning to Dijon, he began gauging springs in the area. He worked for the Corps his entire life, advancing to the position of Inspector General of Bridges and Roads at the time of his death.

Darcy states in the introduction of the book that he wrote it as a guide for other engineers in the construction of water-supply systems. The 650 pages of the original French book include a variety of historical and technical topics and numerous insights into Darcy's personality. In preparation for building the water supply system, Darcy conducted research on the history of Dijon water supply projects back to the 1400s, and he compiled an inventory of springs which makes up Appendix A.

By 1832, Darcy had selected the Rosoir Spring as Dijon's water source. Darcy gives a detailed account of the gauging of the spring, including how he gauged the spring during droughts to determine the minimum flow. Darcy also discusses the mid-nineteenth century state of the art

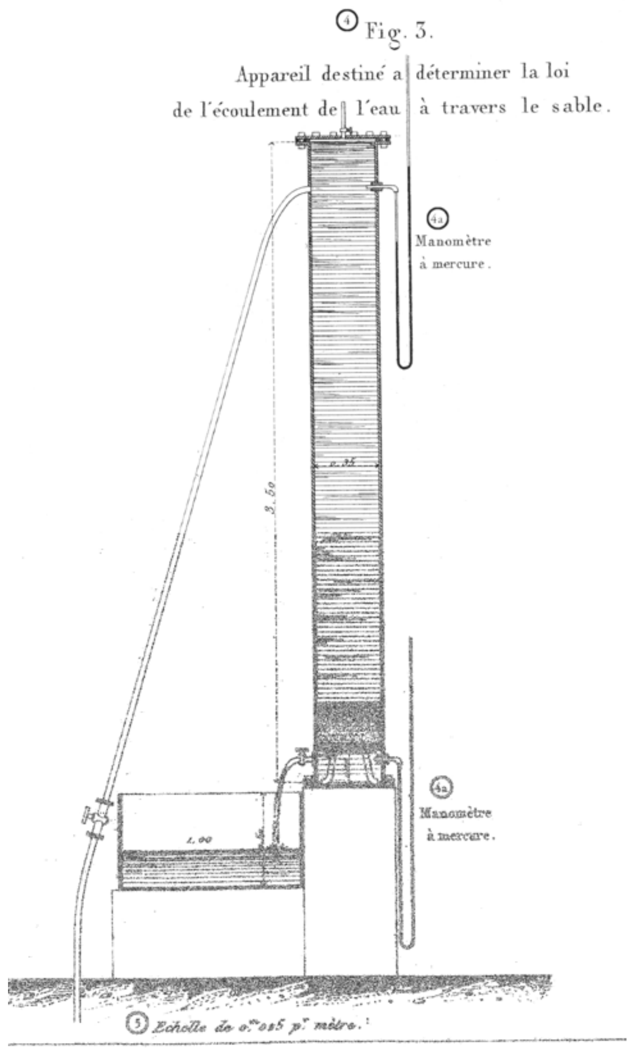


Figure 1. **Darcy's experimental apparatus. This the equipment used for Darcy's experiments on water flow through sand. The column is 3.5 meters high, and the basin is 1 meter square. Water entered through the pipe on the left. The column was packed with sand. The manometers on the right were used to gauge water levels.**

of finding springs and Roman methods of locating springs. Darcy presents contemporary ideas on the origin of artesian water and construction of artesian wells.

A third of the book is devoted to the construction of the 12-kilometer underground masonry aqueduct that brought the Rosoir water to Dijon and the internal distribution system within Dijon. The gravity-driven internal distribution system consisted of two reservoirs and a grid of interconnected conduits—a system Darcy pioneered. Darcy provides minute details on pipe sizes and valves and the cost of every component of the project. An appendix contains information on the types of pipes available at the time and pipe manufacturing.

Darcy also conducted experiments on water flow in the aqueduct and the internal distribution system to solve problems of air in the pipes, which could stop the flow of water. Darcy wrote with obvious pride about the fact that all 110 original fountains flowed with almost equal water pressure and provided cool water in summer and warm water in the winter because the aqueduct and pipes were underground.

The 200-page appendix contains eight sections on various topics: the water-supply systems of London, Paris, Brussels, and other cities and their water sources, distribution systems, and financing; water filtration and the distinction between “natural” and “artificial” filtration; a constant volume weir intake to obtain a constant volume of water from a river; spring gauging to determine the flow rate of a spring; modification of pitot tubes for stream gauging; and pipe manufacturing and testing among other topics.

The section on filtration contains a description of the experiment that led to the formulation of Darcy’s law. Darcy was aware that the large areas required for filtration beds in a city like London were a major obstacle to using surface water as a water-supply source. Filtration was inevitably necessary because of turbidity caused by flooding. His experiment was designed to establish how water flowed through sand, and he used the results to propose a filtration tank that occupied a smaller area than the filtration beds in use at the time.

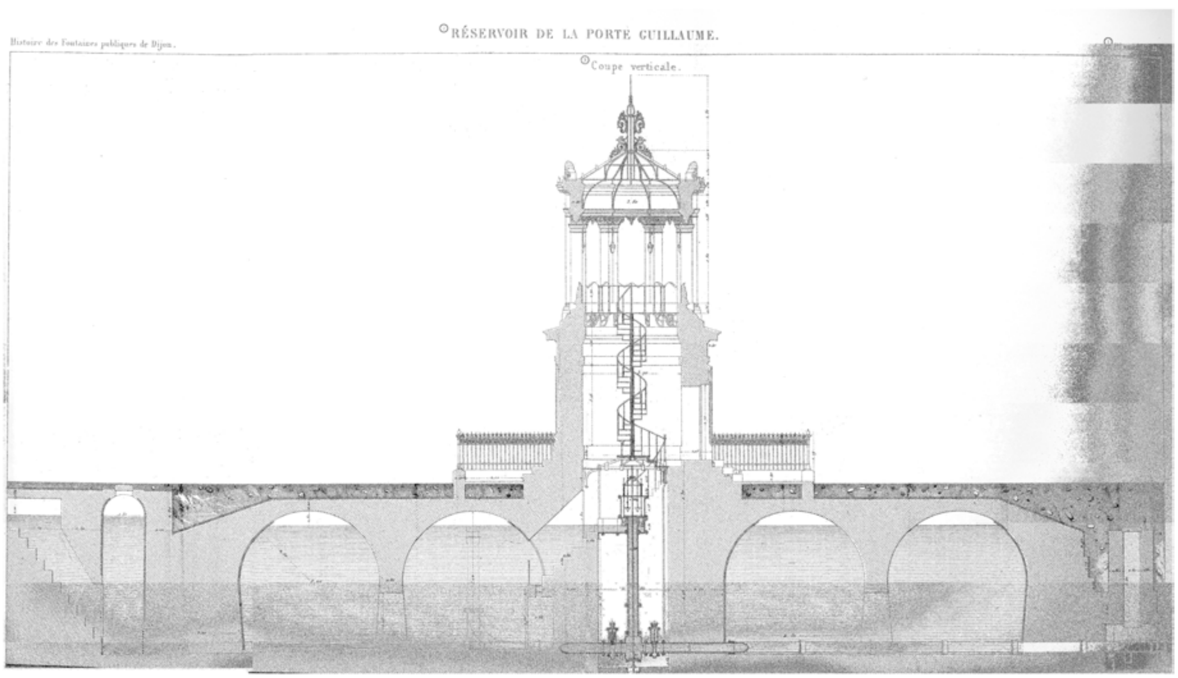


Figure 2. **Cross section of the Porte Guillaume Reservoir. The Porte Guillaume reservoir is located at the end of the aqueduct in Dijon. It is circular in shape with two concentric chambers. There is a central well at the center. The water enters on the left by cascading down the stairs. The water goes to the central well via a pipe on the floor. At the central well, the water goes up a pipe and then cascades down another stairway. The water can freely move from chamber to chamber through openings made for this purpose. The height of each chamber is about 5 meters. The structure on top of the reservoir provides access. Water leaves the reservoir on the right through the main artery. The main artery connects this reservoir with a second reservoir. Distribution lines off the main artery supply the street fountains.**

Dijon's water supply system was evidently expensive, because there is a discussion in the book in which city officials are trying to get more revenue from the water system. Darcy suggests a marketing plan to city officials to increase revenue by encouraging more subscribers to have water piped into their homes and voices his support for the continued availability of free water for the poor.

Darcy's 28-plate atlas of engineering drawings, originally published as a separate volume, is included in the English translation. The atlas contains a map of the city showing the locations of all the street fountains, drawings of the aqueduct, reservoirs and the branches of the internal distribution system, a drawing of the apparatus Darcy used in the experiments that led to Darcy's Law, a drawing of the filtration tank described above, and illustrations of other topics Darcy discusses.

The book provides insight into Darcy's personality and sense of humor. Darcy discusses dowsing and analyzes the success of a priest who was well known for his ability to find water. Darcy criticizes London's water corporations for poor water quality, high cost and exorbitant profits, and the lack of free street fountains. Darcy devised a system for negotiating with landowners to purchase 556 parcels of land for the construction of the aqueduct, and all the landowners were satisfied with the settlements. He shared water generously with towns located along the aqueduct. Above all, he was concerned that the less fortunate classes have access to abundant pure water.

The French original has been a rare book for decades, and, in any event, most American hydrogeologists would not be able to struggle through the antiquated French. The English translation makes Darcy and his ideas accessible to today's scientists and engineers.

The Public Fountains of the City of Dijon by Henry Darcy—English Translation by Patricia Bobeck is available from Kendall Hunt Publishing Co. of Dubuque, Iowa. 1-800-338-8290. www.kendallhunt.com.

References

Freeze, R. A. and Back, W., 1983, Physical hydrogeology: Benchmark Papers in Geology, Hutchinson-Ross, v. 72, 431 p.

Patricia is past president, president-elect, and vice-president of the Austin Geological Society (1995–1998). She received master's degrees in geology and linguistics from The University of Texas and the University of Michigan, respectively, and a bachelor's degree in French from Rosary College (now Dominican University). For her master's thesis—Igneous Petrology and Structural Geology of Nine Point Mesa, Brewster Country, Texas—*she mapped 40 square miles of the Chihuahuan desert. She has worked for the State of Texas as a geologist for 13 years. She translates French and Spanish into English, specializing in the earth sciences. Other books include the French to English translation of* 1000 Photos of Minerals and Fossils *for Barrons in 1999.*