ground water

Historical Note/ David Deming, History Editor

The Wisconsin Roots of Ground Water Hydrology

by Mary P. Anderson[1]

During the period 1920 to 1940, Professor Cyrus F. Tolman played an important role in the history of ground water hydrology in the United States by establishing and fostering a program of ground water hydrology at Stanford University (Remson 2002). During this same period, O.E. Meinzer, often called the Father of Ground Water Hydrology in the United States, was assembling and mentoring a team of scientists who would establish ground water hydrology as an important force within the U.S. Geological Survey (USGS).

However, we can trace the roots of ground water hydrology in the United States further back in time to Wisconsin. During the late 19th and early 20th centuries, there was a remarkable confluence of talent at the University of Wisconsin (now the University of Wisconsin-Madison), including Thomas Crowder Chamberlin, Franklin H. King, and Charles Sumner Slichter. Although none of these men likely would have identified himself as a hydrologist, each did seminal work in ground water hydrology.

Chamberlin was born on a farm in Illinois, just south of Beloit, Wisconsin (Figure 1). He received degrees from Beloit College in 1866 and 1869 (Bailey 1981), and completed a year of graduate work at the University of Michigan in 1868 (Deming 2002). Beloit College, founded in 1846, was then known as an excellent liberal arts college and remains so today. The first degrees were conferred in 1851. According to the college Web site (www.beloit.edu/about/ November 18, 2004), "The early curriculum was built on the classical tradition, but students were given an unusual amount of freedom to choose their own courses." (Meinzer also graduated from Beloit College in 1901.) After graduation, Chamberlin taught at Whitewater Normal School (now the University of Wisconsin-Whitewater). From 1873 to 1882, he taught at Beloit College, during which time he also worked at the Wisconsin Geological Survey (now the Wisconsin Geological and Natural History Survey), serving as chief geologist starting in 1876. He became known nationally as a result of his work on the glacial geology of the state, which led to an appointment with the USGS. In 1887, he became president of the University of Wisconsin, a position he occupied until 1892 when he left to head a new geology department at the University of Chicago. Buildings are named in his honor on the campus of Beloit College and at the University of Wisconsin-Madison. On the Madison campus, there is also Chamberlin Rock, a large, gneissic, glacially rounded boulder, perched on the side of Observatory Hill.

While in Wisconsin, Chamberlin wrote his famous essay on the method of multiple working hypotheses, which advocates that multiple lines of evidence be pursued simultaneously when investigating geological phenomena. The

Figure 1. Map of Wisconsin showing places mentioned in the article.

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first version of the paper was published in 1890, while a later, somewhat revised version was printed in 1897 (www.accessexcellence.org/RC/AB/BC/chamberlin.html). Chamberlin felt that his philosophy of working with multiple hypotheses had affected him as an administrator. Bailey (1980) quotes from a university document, "[H]e had so long trained himself to consider alternatives that it was difficult for him to give quick and positive answers to the host of petty problems which crowded in on him."

More directly relevant to ground water hydrology, in 1885, the USGS published Chamberlin's classic paper titled "The Requisite and Qualifying Conditions of Artesian Wells" as its first report on ground water. The frontispiece to this paper is a beautiful print of an artesian fountain in Prairie du Chien, Wisconsin (Figure 2). A few quotes from this elegantly written paper follow.

Regarding artesian flow:

> Artesian flow is but an expression of the common law of flowage, made a little unusual, it is true, by its special conditions. Any seeming strangeness springs from our partial observation. We see but a part of the stream. The rest lies hidden in the earth's depths, a realm which the imagination is prone to people with mysteries. Moreover, the part we do most see is a rising stream, that comes gushing up in the face of the dogma that water "never runs up hill." But water flowing up hill is one of the commonest facts of nature, an everyday, an everywhere occurrence, illustrated in every brook, rill, and river, not to say spring.

Regarding confining beds:

> It is scarcely too strong to assert that no rock is absolutely impenetrable to water. Minute pores are well nigh all pervading. To these are added microscopic seams, and to these again larger cracks and crevices. Consolidated strata are almost universally fissured. Even clay beds are not entirely free from partings.

Figure 2. Artesian fountain, Prairie du Chien, Wisconsin (Chamberlin 1885).

Chamberlin's observations about confining beds foreshadowed later papers on the hydraulics of leaky artesian conditions (Hantush and Jacob 1955; Walton 1960) as well as recent papers on the hydrogeology of low permeability material (Remenda 2001). Chamberlin also recognized that openings in rock occur both as fractures and pore space.

One of Chamberlin's students at the Whitewater Normal School was Franklin H. King, who became a soil physicist (Ingraham 1972). King worked at the Wisconsin Geological Survey from 1873 to 1876, when Chamberlin also was at the survey. During 1877 to 1887, King was a professor of natural science at River Falls State Normal School (now the University of Wisconsin-River Falls), and he was a professor in the College of Agriculture at the University of Wisconsin from 1888 to 1901 (Ingraham 1972). King Hall, which currently houses the Department of Soil Science, is named in his honor. King published two important papers on ground water while at the University of Wisconsin (1892, 1899).

King (1892), as cited in Meinzer (1928), reported fluctuations in water level in an observation well at Whitewater, Wisconsin (Figure 1), in response to arrivals and departures of trains at a nearby station. Such fluctuations are now known to be caused by storage effects related to compression and expansion of the confined aquifer penetrated by the well. King's work foreshadowed later work on this topic by Jacob (1939), among others.

In his 1899 paper, King presented what may be the first ground water flow map, showing water table contours and flow lines, as well as a cross section of flow to a stream (see Figures 1 and 2 in Fetter 2004). The flow map depicts an area adjacent to Lake Mendota, Madison, Wisconsin. King identified the paradigm, later invoked by Toth (1963), among others, that the water table mimics the topography:

> The contours of the ground water level show that this surface presents the features of the hills and valleys approximately conformable with the relief forms of the surface above, the water being low where the surface of the ground is low, and high where the surface of the ground is high.

In this same paper, King alluded to his collaboration with Charles Sumner Slichter, a professor of mathematics at the university.

It appears that King began to collaborate with Slichter around 1894. He may have been motivated to contact Slichter at the suggestion of Chamberlin, who then was president of the university and knew both King and Slichter (Ingraham 1972). King describes the nature of the collaboration in the introduction to his 1899 paper, in which he also mentions Slichter's paper, published the same year (Slichter 1899):

> During our earlier investigations regarding the flow of water through soils, it appeared that if the laws of capillary flow apply to the movements of water and of air through soil, it ought to be possible to arrive at the sizes of soil grains from a knowledge of the flow of water through the samples under known conditions. Such great difficulties, however, were encountered in duplicating results with water that air was substituted as the medium whose flow was to be measured.

> The handling of the air proved so much simpler and expeditious and results could be duplicated so closely that in 1894 the plan was laid before Professor Slichter for his judgment as to the possibility of placing the method on a quantitative basis. This seemed to him possible, and he kindly consented to undertake a preliminary investigation, which resulted in the formula for computing the effective sizes of soil grains, presented in the first portion of his paper in this volume. When it was found that computed results agreed with observations more closely than had been hoped at first, a return was made to water as a means of checking the accuracy of the method and the formula. It was found that the flow of water used in the formula gave results quite comparable with those computed from air.
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> At this stage Mr. Newell [USGS] proposed, in 1896, to assist financially in an investigation of the movement of ground water, and the writer consented to undertake the work, with permission to secure Professor Slichter's services in the development of certain theoretical phases of the subject.

Slichter received a B.S. in mathematics from Northwestern University in 1885, becoming an instructor in mathematics in 1886 and then an assistant professor (1889) and professor (1892) at the University of Wisconsin. He rose up the ranks to department chairman (1902) and was dean of the graduate school from 1920 until he retired from the university in 1934. Although he worked for the USGS during some summers, he spent his entire career at the University of Wisconsin, marrying a local girl, living in a house close to campus and raising four sons (Wang 1987; Ingraham 1972). He died in Madison in 1946 and is buried there. Slichter Hall on campus is named in his honor and one of Slichter's quotes—"We are all mentioned in the wills of Homer and Shakespeare."—is emblazoned on the side of Memorial Library. His portrait hangs in the reception room of the University Club, an institution he helped found and where he was active for many years.

Wang (1987) speculated that Slichter may have become interested in ground water soon after his arrival in Wisconsin in 1886. Ingraham (1972) placed the beginning of the collaboration with King around 1894. In any case, Slichter's first and most famous ground water paper was published in 1899. In this paper, he demonstrated that potential theory, specifically the Laplace equation, could be used to solve ground water problems. In another important paper, Slichter (1905) presented what might have been, as he claimed in the introduction to the paper, the first direct field measurements of the rate of ground water flow in the United States. In any case, he conducted a natural gradient two-well tracer test, obtained the characteristic S-shaped breakthrough curve, and correctly attributed the shape of the curve to what we now call dispersion:

> The writer formerly supposed that the gradual appearance of the electrolyte at the downstream well was largely due to the diffusion of the dissolved salt, but it is now evident that diffusion plays but a small part in the result. The principal cause of the phenomena [sic] is now known to be due to the fact that the central thread of water in each capillary pore of the soil moves faster than the water at the walls of the capillary pore, just as the water near the central line of a river channel usually flows faster than the water near the banks. . . . Owing to the repeated branching and subdivision of the capillary pores around the grains of the sand and gravel, the stream of electrolyte issuing from the well will gradually broaden as it passes downstream. The actual width of this charged water varies somewhat with the velocity of the ground water. . . .

Slichter also studied the spreading (dispersion) of solute more closely in laboratory experiments using tanks filled with sand from Picnic Point (a campus natural area) and water from nearby Lake Mendota. He confirmed his earlier conclusion based on fieldwork that the cause of the observed spreading was not diffusion, but was due to "the continued branching and subdivision of the capillary pores around the individual grains of the sand" (Slichter 1905). The spreading effect Slichter described is what we now call microscopic dispersion, but some of the spreading he observed in the field likely was due to macroscopic dispersion caused by the presence of field-scale heterogeneities (Anderson 1984). Nevertheless, he was perhaps the first person to conduct a natural gradient two-well tracer test and to document and describe field-scale dispersion.

Slichter was also one of the first, if not the first, person to point out the potential of heat as a ground water tracer. In his 1905 paper, he concluded that relatively high ground water temperatures, measured during July in Long Island, New York, reflected induced infiltration from a pond:

> These high temperatures at stations 13 and 16 show that a large portion of the moving ground water must come directly from the pond, and the rate of motion is so great that the ground water has not time to be reduced to the normal temperature of the ground.

Other of Slichter's ground water papers were published by the USGS during the period 1902 to 1906 (Wang 1987). During this time up to around 1912, Slichter was also involved in a number of engineering consulting projects including acting as an expert witness (Wang 1987; Ingraham 1972). Although his educational background and departmental affiliation at the university peg him as an applied mathematician, his career was not so different from the life of a modern-day professor of ground water hydrology.

In addition to the work on ground water hydrology produced by the nexus of Chamberlin, King, and Slichter, fundamental work in geology, largely by Charles R. Van Hise (president of the university 1903 to 1918) and C.K. Leith, was ongoing at the University of Wisconsin in the early part of the 20th century (Dott 1999). Pioneering work was also being done in limnology by Edward A. Birge (promoted to professor of zoology in 1879, dean of the College of Letters and Science 1891 to 1918, and president of the university 1901 to 1903 and 1918 to 1925). In his first limnology paper, which mainly concerns plankton in Lake Mendota, Birge (1897) introduced the term thermocline to signify the region of rapid decrease in temperature between the epilimnion and hypolimnion; in later papers, he analyzed the thermal structure of Lake Mendota in detail. In the summers of 1925 to 1942, Birge, with biologist Chancey Juday and coworkers, collected data from several hundred lakes near Boulder Junction in northern Wisconsin (Figure 1). Some of these data were published in papers with Juday, who by 1931 was a professor of zoology at the university. Other unpublished data remain in the university archives.

While Slichter and Birge knew each other socially and interacted through their administrative posts at the university (Ingraham 1972), apparently they never collaborated scientifically. Birge and Juday (1934) recognized that there was the possibility for exchange of water between lakes and the ground water system. Nevertheless, the paradigm at the time was that lakes were essentially sealed off from ground water by fine-grained lakebed sediments so that seepage to and from ground water was small and insignificant, if it occurred at all (Hutchinson 1957). Not until Meyboom's (1966) work was it recognized that exchange with ground water is potentially important in many seepage lakes. What might have happened had the nexus of ground water hydrology at the University of Wisconsin enveloped Birge and Juday?

References

Anderson, M.P. 1984. Movement of contaminants in groundwater—Groundwater contamination. In *Studies in Geophysics*, 37–45. Washington, D.C.: National Academy Press.

Bailey, S.W. (ed.). 1981. *The History of Geology and Geophysics at the University of Wisconsin-Madison 1848-1980*. Department of Geology and Geophysics, University of Wisconsin-Madison, Madison, Wisconsin.

Birge, E.A. 1897. Plankton studies on Lake Mendota, 2. The crustacea from the plankton from July, 1894, to December, 1896. *Transactions of the Wisconsin Academy of Science, Arts and Letters* 11, 274–448.

Birge, E.A., and C. Juday. 1934. Particulate and dissolved organic matter in inland lakes. *Ecological Monographs* 4, 440–474.

Chamberlin, T.C. 1885. Requisite and qualifying conditions of artesian wells. U.S. Geological Survey Annual Report 5, 131–175.

Chamberlin, T.C. 1890. The method of multiple working hypotheses. *Science* 15, no. 366: 92–96. www.accessexcellence.org/RC/AB/BC/chamberlin.html. November 18, 2004.

Deming, D. 2002. *Introduction to Hydrogeology*. New York: McGraw-Hill.

Dott, R.H. 1999. The Wisconsin School of Geology: Early intellectual exports. *Wisconsin Academy Review* 45, no. 3: 29–36.

Fetter, C.W. 2004. Hydrogeology: A short history, part 2. *Ground Water* 42, no. 6: 949–953.

Hantush, M.S., and C.E. Jacob. 1955. Non-steady radial flow in an infinite leaky aquifer. *Transactions of the American Geophysical Union* 36, 95–100.

Hutchinson, G.E. 1957. *A Treatise on Limnology, Volume 1, Geography, Physics, and Chemistry*. New York: John Wiley & Sons.

Ingraham, M.H. 1972. *Charles Sumner Slichter: The Golden Vector*. Madison, Wisconsin: The University of Wisconsin Press.

Jacob, C.E. 1939. Fluctuations in artesian pressure produced by passing railroad trains as shown in a well on Long Island, New York. *Transactions of the American Geophysical Union* 20, 666–674.

King, F.H. 1892. Observations and experiments on the fluctuations in the level and rate of movement of ground water on the Wisconsin Agricultural Experiment Station Farm, and at Whitewater, Wisconsin. U.S. Weather Bureau Bulletin 5.

King, F.H. 1899. Principles and conditions of the movements of ground water. U.S .Geological Survey 19th Annual Report, Part 2.

Meinzer, O.E. 1928. Compressibility and elasticity of artesian aquifers. *Economic Geology* 23, 263–291.

Meyboom, P. 1966. Unsteady groundwater flow near a willow ring in hummocky moraine. *Journal of Hydrology* 4, 38–62.

Remenda, V. (ed.). 2001. Theme issue on confining units. *Hydrogeology Journal* 9, no. 1.

Remson, I. 2002. The history of hydrology at Stanford University. *Ground Water* 40, no. 2: 205–206.

Slichter, C.S. 1899. Theoretical investigations of the motion of ground waters. U.S. Geological Survey 19th Annual Report, Part 2.

Slichter, C.S. 1905. Field measurements of the rate of movement of underground waters. U.S. Geological Survey Water-Supply and Irrigation Paper No. 140.

Toth, J. 1963. A theoretical analysis of groundwater flow in small drainage basins. *Journal of Geophysical Research* 68, 4795–4812.

Walton, W.C. 1960. Leaky artesian aquifer conditions in Illinois. Illinois Water Survey Report of Investigations 39.

Wang, H.F. 1987. Charles Sumner Slichter—An engineer in mathematician's clothing. In *The History of Hydrology*. Washington, D.C.: American Geophysical Union.