ground water

Historical Note/ David Deming, History Editor

A Brief History of Contributions to Ground Water Hydrology by the U.S. Geological Survey

by Thomas E. Reilly[1]

Introduction

The U.S. Geological Survey (USGS) was established on March 3, 1879, as a permanent governmental agency for ". . . classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain" (Rabbitt 1989). March 2004 marked the 125th anniversary of the USGS and, in recognition of that anniversary, the editor-in-chief and the history editor of *Ground Water* invited me to summarize some of the contributions to ground water hydrology made by the USGS. Obviously, the USGS is part of a wider scientific community; however, this history comprises just the role of the USGS and is not intended to summarize contributions from the entire scientific community of ground water scientists.

Ground water hydrology involves both applied field studies that document the resource and theoretical studies on the basic physics and chemistry needed to analyze and understand the resource. Hydrology is an evolutionary science, and it is impossible to summarize and acknowledge all of the many contributions to the science that have been made by those associated with the USGS. The USGS as an organization provides a collaborative scientific environment where many individuals with different skills contribute toward a common goal, yet individual authors publish their results. This combination of significant organizational resources and intellectual freedom has enabled contributions to society and the scientific literature of hydrology.

In this brief history, I attempt to concisely summarize some key contributions to the field of ground water hydrology by the USGS on a topical basis and, along the way, provide insight into the operation of the organization as it contributes to the understanding of the nation's water resources. The scope of the technical topics discussed is limited mostly to contributions related to the assessment of the nation's resource and the development of the theory of the flow of ground water with a minor discussion on the chemistry of natural waters. The topics of contaminant hydrology, microbiology, flow in the unsaturated zone, geophysics, and other specialized topics are not discussed.

The mission of the USGS is to provide geologic, biologic, topographic, and hydrologic information that contributes to the wise management of the nation's natural resources and promotes the health, safety and well-being of the public (U.S. Geological Survey 1986). USGS studies emphasize the objective scientific analyses of physical and chemical processes, and do not directly involve any engineering design, construction, or water management. The number of USGS scientists engaged in the study of ground water has changed considerably over the years. In 1900, there were only three ground water scientists in the USGS. This changed to approximately 32 ground water hydrologists in 1932, 420 in 1960 (the number of professional staff in the Ground Water Branch, not including any ground water professionals in the Quality of Water Branch), and about 500 at present. The hydrologists of 1932 are shown in photographs taken to commemorate O.E. Meinzer's 20th anniversary as the geologist-in-charge of the Division of Ground Water (Figure 1). The present estimated number of ground water scientists is inexact because of the interdisciplinary nature of our work, but the estimates provide an indication of the level of activity undertaken by the USGS in the field of ground water hydrology during each time period.

Previous Published Histories

Much information is available on the history of hydrogeology and the USGS. There are reports on the history of the USGS (Rabbitt 1989), a seven-report series on the history of the USGS Water Resources Division including those by Follansbee (1994) and Biesecker et al. (2000), a summary on ground water at the USGS from 1879 to 2000 (Deming 2002), and reports or chapters on the history of hydrogeology in general (Meyer et al. 1988; Rosenshein et al. 1986; Fetter 2001; Deming 2002). Classic benchmark

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Figure 1. A collection of photographs of the members of the U.S. Geological Survey Division of Ground Water on July 1, 1932, which was the 20th anniversary of O.E. Meinzer serving as geologist-in-charge.

papers were selected and reprinted for both *Physical Hydrogeology* (Freeze and Back 1983) and *Chemical Hydrogeology* (Back and Freeze 1983); many of the papers selected were by USGS scientists.

National and Regional Studies

The USGS is in a unique position to describe and analyze the water resources of the nation. National and regional assessments of the resource have always been a high priority for the USGS. The early years of the USGS saw some regional studies that form the basis for understanding the nation's ground water systems to this day. Examples of some of these seminal works include Darton's (1905, 1909) works on the Central Great Plains, Mendenhall's (1905) work in the Los Angeles area of California, and the work of Veatch et al. (1906) in Long Island, New York. These and other early studies by the USGS provided the information that enabled Meinzer (1923) to produce the first assessment of the ground water resources for the entire United States.

The assessment by Meinzer (1923) was followed several decades later with state-by-state summaries on ground water resources (McGuinness 1952, 1963); summary appraisals for 21 regions of the nation in the 1970s in the USGS Professional Paper series 813; the National Water Summary 1984 (U.S. Geological Survey 1985); and the USGS Professional Paper series 1400 through 1425 dealing with the Regional Aquifer-System Analysis (RASA) Program that evaluated 25 of the nation's most important regional ground water systems (Sun and Johnston 1994). The RASA Program focused on a quantitative evaluation that used numerical systems analysis as its foundation. The RASA studies led to many innovations in modeling ground water systems, as well as documenting the state of the nation's ground water resources.

National and regional evaluations by the USGS provide a framework of the nation's ground water resources, and this understanding has increased over time as demands on the resource and the issues of concern change. The Ground Water Atlas of the United States (Miller 2000) provides the most recent consistent hydrogeologic framework of the nation's ground water resources.

Advances in Quantitative Analysis of Flow

The development of quantitative methods is another area of strong contributions by the USGS. I focus on USGS contributions related to understanding and developing the governing equations, well hydraulics, systems analysis, and other technical topics.

Developing and Understanding the Governing Equations of Flow

One of the early quantitative scientists was C.S. Slichter, who was a professor of mathematics and later the dean of the Graduate School at the University of Wisconsin (Wang 1987). Slichter worked intermittently for the USGS during the early years and in his work for the USGS he used potential theory to quantitatively describe the steady-state flow field in response to a discharging well (Slichter 1899). He was one of the first to recognize that "the solution of any problem in the motion of groundwaters depends upon the solution of [Laplace's] equation . . ." (Wang 1987).

The examination and documentation of ground water systems was limited to steady-state or equilibrium conditions until the work of C.V. Theis in the 1930s. Theis (1935) developed the nonequilibrium equation based on an analogy to heat flow, which for the first time enabled hydrologists to analyze the time-dependent response of a ground water system to a pumping well. The development of the equation by Theis allowed the source of water stored in ground water systems to be included in any quantitative calculations for the understanding and management of the resource.

Jacob (1940) derived the Theis equation from basic hydrologic concepts, which included a rigorous definition of specific storage. In the early 1960s, some debate occurred as to the validity of Jacob's equation because of concern over the importance of the deformation of the porous media when water from storage is removed. In response to this criticism, Cooper (1966) derived the equation of ground water flow in both fixed and deforming coordinates and determined that Jacob's equation (the standard three-dimensional transient flow equation that is commonly used) is correct when negligible terms are omitted. This effectively put an end to the debate and confirmed the appropriateness of the governing equations and the analytical solutions for transient well hydraulics that had been developed to date.

Well Hydraulics

The USGS has made significant contributions to the analysis of flow to wells over the years. Perhaps the best known contribution to the analysis of ground water flow to a well is the Theis equation that describes the transient response of a homogeneous aquifer to a fully penetrating pumping well (Theis 1935). Contributions, however, have taken place on a continuing basis in the development of closed form analytical solutions to various well hydraulic problems for homogeneous aquifers (Jacob 1940; Hantush and Jacob 1955; Cooper et al. 1967; Papadopulos and Cooper 1967; Weeks 1969; Moench 1997). In addition, the analysis of flow to wells through the use of both analog (Stallman 1963; Bennett et al. 1967) and digital (Reilly 1984; Rutledge 1991; Reilly and Harbaugh 1993) models that enable more complex aquifers to be evaluated have evolved over the years. The publications by Ferris et al. (1962) and Lohman (1972) were important publications in the USGS that served as both summaries of the state-of-the-science of well hydraulics at their times of publication and as educational texts to enable hydrologists to effectively use aquifer tests.

Systems Analysis

Theis (1940) provided an early statement of the importance of understanding the sources of water to an aquifer and discharging wells on a system-wide basis. At that time, however, few tools were available to perform a system-wide analysis. In the 1950s and 1960s, Robert R. Bennett and his colleagues in the (then) Research Section of the Ground Water Branch fostered the application of system-wide approaches to ground water investigations, first through flownet analysis, then through electric-analog simulation, and ultimately through digital simulation. Each of these methods had been used in related fields, notably engineering seepage studies and petroleum reservoir analyses, but their adaptation to regional ground water investigations represented a major shift in the study of ground water, in which the USGS played a central role. An excellent example of flownet analysis in regional studies was provided in Bennett and Myer (1952); electric analog simulation (Figure 2) was adapted to hydrology by H.E. Skibitzke and his colleagues (Skibitzke 1960); and Pinder and Bredehoeft (1968) provided an early application of computer models to simulate ground water flow problems.

The earliest developed USGS computer model simulated flow in two dimensions (Pinder 1970, which was superseded by Trescott et al. 1976). The earliest USGS three-dimensional model (Trescott 1975) was modified by many investigators to meet specific needs. The experiences of a cadre of investigators using the code and the large number of code modifications made by various investigators to address different hydrologic processes led the USGS to develop MODFLOW (McDonald and Harbaugh 1988). MODFLOW was originally called the modular model because its modular structure enabled changes and improvements to be made in a more systematic manner. The application of nonlinear regression techniques to aid in the calibration of models was evolving in the USGS (Cooley 1977) and this technique also was added to MODFLOW. MODFLOW has been referred to as the most used tool worldwide for quantifying ground water flow systems. The computer model MODFLOW has continued to evolve (Harbaugh et al. 2000; Hill et al. 2000) and be an important contribution for the study of ground water. In fact, the March–April 2003 issue of *Ground Water* was a special theme issue featuring MODFLOW

Models for the evaluation of solute transport also arrived in the early 1970s (Bredehoeft and Pinder 1973; Rubin and James 1973). The model developed by Konikow and Bredehoeft (1978) was the first publicly available USGS solute-transport code; this code has continued to evolve to be three-dimensional and compatible with the MODFLOW family of computer programs. A two-dimensional code for the flow and transport of variable-density fluids (Voss 1984) was an important tool for the analysis of salt water intrusion and has recently been updated for three-dimensional analysis. Pollock (1989) developed a method and computer code for the computation of pathlines for three-dimensional systems, also for use with the MODFLOW family of codes. (All current public domain computer models developed by the USGS are available for no cost over the Internet at *http://water.usgs.gov/software/index.html*.)

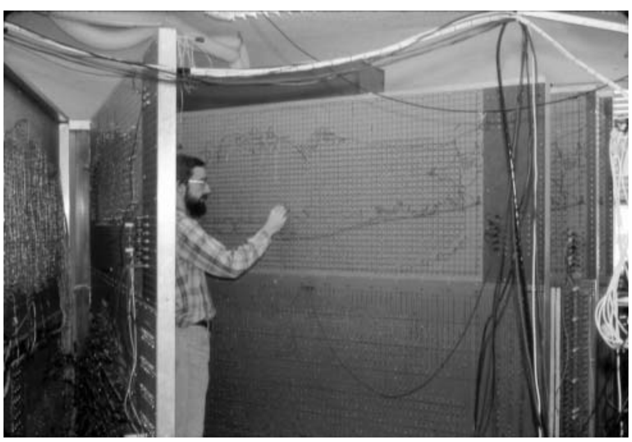

Figure 2. Arlen Harbaugh, in about 1975, making a voltage measurement on the three-dimensional electric-analog model of Long Island, New York.

Other Technical Topics

Although I attempted to group the contributions of the USGS to quantitative analysis of flow under a limited number of categories, a few selected other topics need mentioning. The understanding of ground water systems in variable-density coastal environments was advanced substantially by Cooper, Henry, Glover, Kohout, Lusczynski, and Swarzenski (Cooper et al. 1964; Lusczynski and Swarzenski 1966) in the early 1960s. The documentation, analysis, and understanding of subsidence was led by Poland (Tolman and Poland 1940) and continued by Poland and other investigators in the USGS for many years including Poland and Davis (1956) and Ireland et al. (1984). The estimation of ground water recharge from streamflow recessions was advanced by Rorabaugh (1964) and its application to the field enhanced by Rutledge (1993). The USGS made early contributions in the area of artificial recharge through the combination of applying both field and theoretical analyses in order to test feasibility of the concept and to develop appropriate procedures for implementation by water management authorities; the studies of Sniegocki et al. (1965), Brown et al. (1978), and Vecchioli and Ku (1972) are representative of these contributions. The use of chlorofluorocarbons to age date modern ground water led by Busenberg and Plummer (1992) and applied by USGS investigators throughout the nation has proven immensely useful in understanding shallow ground water flow systems.

Advances in the Analysis of the Chemistry and Quality of Natural Waters

Contributions by the USGS in the field of water chemistry, solute transport, and contaminant hydrology would fill volumes unto themselves. Although the topic of contaminant hydrology is beyond the scope of this paper, as a physical hydrologist, I wanted to acknowledge a few of the USGS contributions in the study of the chemistry and quality of natural waters. The Piper diagram, still used to illustrate the chemical nature of a water, is an early important development (Piper 1944). A standard reference that has retained its relevance for more than 40 years is the “Study and interpretation of the chemical characteristics of natural water” (Hem 1985). The computer models WATEQ (Truesdell and Jones 1973) and PHREEQE (Parkhurst et al. 1980) improved our ability to analyze natural waters and were applied to many different ground water systems throughout the nation. PHREEQE has continued to be improved over time and is an important tool for understanding the chemistry of natural waters (Parkhurst and

Appelo 1999). NETPATH (Plummer et al. 1991) is an interactive computer program that was developed to provide new capabilities in the examination of possible geochemical reactions along a flowpath.

Local Studies

Much of the USGS work is conducted under what is called the Cooperative Program. This program, which began in 1929, enables state and local governments to share in both the selection and the cost of studies undertaken by the USGS. The studies undertaken must have a federal interest in understanding the water resources of the nation. The USGS performs the work; however, program costs are shared by the USGS and local agencies. Much of the day-to-day work conducted by the USGS is in the Cooperative Program. These studies are important to the advancement of science because they focus the attention of a large federal agency (the USGS) on relevant problems that need a solution. Over the history of the USGS, these local studies have kept the agency relevant by solving real problems, developing new methods to solve these problems, and providing in aggregate an ability to summarize the state of the nation's ground water resources. These local studies (frequently referred to as county studies in the 1950s and 1960s) provide much detail on the hydrogeologic system that in aggregate enables comprehensive regional descriptions. These USGS local studies also serve as a valuable source of basic site-specific hydrogeologic information for a locale. There are too many studies to reference or cite as examples, but all of these studies are documented in USGS publications, reports by cooperating agencies, or in technical journals.

Collection and Archives of Ground Water Related Data

The collection and storage of field observations has always been a priority of the USGS. Water level measurements have been and continue to be filed and published routinely. With the advent of digital computers, an attempt was made in the 1960s to establish a standard approach to the storage of water level data; however, it was not until 1974 that a standardized computer database named the Ground Water Site-Inventory (GWSI) file was implemented (Mercer and Morgan 1982). Currently, almost all ground water level data collected by the USGS are entered and maintained in GWSI, which is part of the USGS National Water Information System—or NWIS—database. Currently, data for approximately 850,000 wells and test holes are available in the USGS GWSI database. (These data are available online at *http://waterdata.usgs.gov/nwis/gw*. Some measurements of wells monitored by the USGS also are available online at near real-time at *http://waterdata.usgs.gov/nwis/rt*.)

Training

Training and education have always been important to the USGS. The USGS training programs contribute to a collaborative state-of-the-science work environment and enable new techniques and theories to be tried, critiqued, and tested by many experienced individuals. The USGS conducts short courses in ground water and related topics primarily for its employees, but these courses are also open to the staff of cooperating agencies. The first set of courses began in 1951 and continued through the 1960s. At one point in the 1960s, new employees were put through a six-month training period before beginning their work. After the 1960s, the courses became more specialized in content. In the 1970s, training in numerical approaches to systems analysis became especially important because it brought new technology to many individuals and also served as a testing ground for the new methods being developed.

Throughout the years, members of the USGS have served as adjunct faculty at many universities. One unique contribution to higher education was the assignment of John Ferris to the University of Arizona from 1959 to 1965 to help establish a curriculum in hydrology. The USGS also publishes reports that serve as educational and training documents. Some notable pedagogical publications include Bennett (1976), Heath (1983), Hem (1985), Franke et al. (1990), and Franke et al. (1991). Earlier reports like those of Ferris et al. (1962) and Lohman (1972) still serve as key educational resources.

Closure

Some of the USGS publications referenced in this article are available online at *http://water.usgs.gov/pubs/* and *http://infotrek.er.usgs.gov/pubs/*. Most of the newer publications prepared by the USGS, such as the publications on topics of current interest in the USGS circular series, are also available online at *http://water.usgs.gov/pubs/circ/*. Older USGS publications are being scanned and added to the available online publications routinely, so the collection of USGS reports available at no cost on the Internet is continually growing.

I have not mentioned a multitude of important contributions by scientists of the USGS both because of publication space constraints and because of my selection of topics. Even as it is, I have packed too much information in too short an article and, as a result, many of the advances presented here are not put in their proper broader historical context. The USGS provides an excellent stimulating collaborative environment, and many of the scientific advances have evolved through extensive communication and collaboration among individuals with wide ranges of expertise. The USGS ground water community continues to foster collaborative interdisciplinary work, training, and mentoring, and I look forward to many more future contributions by the USGS.

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Editor's Note: We invited Dr. Reilly to contribute an article to commemorate the 125th anniversary of the founding of the U.S. Geological Survey.