Hydrogeological Concepts in the United States: A Historical Perspective

by John E. Moore and Bruce B. Hanshaw

This paper reviews the development of hydrogeological concepts in the U.S.A. from 1879 to 1987, from early qualitative reconnaissance investigations to modern quantitative and multi-disciplinary studies involving predictive analytical techniques and a consideration of management practices. The authors present a sampling of historical milestone papers in U.S. hydrology in the form of an annotated bibliography.

Introduction

Groundwater is a vital natural resource in the U.S.A. and a major source of water for drinking, agriculture, and industry. About 50% of the U.S. population and 95% of the rural population use groundwater for their drinking water supply.

From 1880 to about 1960, the major focus was on exploration and exploitation of the resource. During the past 25 years, the emphasis has changed to water-resource management and evaluation of groundwater contamination (see major reviews by Meinzer, 1934; Ferris and Sayre, 1955; Hackett, 1966; Nace, 1978; Bredehoeft, et al., 1982; Freeze and Back, 1983; Back et al., 1983, and Rosenzhein et al., 1986). The use of sub-surface water has played a significant role in the development of agricultural and industrial resources of the U.S.A. but there have also been adverse effects. These include water-level declines, land subsidence, streamflow depletion, and saltwater encroachment. During the past decade, groundwater contamination has emerged as a major environmental issue in the U.S.A.

A major milestone in the development of the science of hydrogeology in the U.S.A. was the formation of the United States Geological Survey (USGS) in 1879, just one year after

the first International Geological Congress in France. Throughout its history, the Survey has provided information for developing and managing the Nation's groundwater resources. Early on, the USGS began to focus on both the scientific and practical problems related to the occurrence, movement and development of groundwater. The organization attracted scientists and engineers who pioneered the first investigations in hydrology and hydrogeology to provide data and interpretations to guide the search for and the development of groundwater supplies.

The science of groundwater hydrology in the U.S.A. has evolved from the early qualitative reconnaissance type investigations to modern day quantitative multidiscipline predictive type investigations. In other words, the studies have shifted from "where and how much groundwater can be pumped?" to "what are the effects of development on the environment?"

The historical perspective presented here has been organized into the Early Era (1879-1910), the Meinzer Era (1911-1946), and the Modern Era (1947-1987). Emphasis in the early years was placed on qualitative appraisals of geology and availability of groundwater. The Meinzer Era was a period when qualitative exploration studies continued as a major activity, and an important period to the development of basic hydrologic principles and quantitative techniques. The Modern Era has been concerned with the development of predictive analytical techniques and interdisciplinary investigations that include economics, law, biology, organic and inorganic chemistry, and surface-water hydrology.

The Early Era (1879-1910)

The opening of the western U.S.A. in the late 1860s led to an increasing demand for information on water for agricultural, industrial and municipal needs after the Civil War. John Wesley Powell (Fig. 1), the second Director of the USGS, recognized the need for such information, and the first USGS groundwater studies were started under his leadership. The Ground-Water Branch of the USGS was founded in 1907.

Some of the basic geological controls and principles that govern the occurrence and movement of groundwater were established during this period, and the foundation was laid for studies of the theory and application of groundwater hydrology. The coopera-

tive water programs between the Geological Survey and State agencies were started during this period and had a significant effect on the character of groundwater studies and future expansion of the program.

1879- The U.S. Geological Survey is established with Clarence King as Director. The guiding principles are to develop and apply science, and prompt publication of findings. The budget for the first year is \$100,000.

1885- T. C. Chamberlin's classic treatise on artesian wells is published. This work is the first to describe regional flow and marks the beginning of the science of groundwater hydrology in the United States.

Chamberlin (Fig. 2) defines clearly the geological controls necessary for the occurrence of artesian wells and also points out that confining beds are not impervious because they contain minute pores, cracks, crevices, and fissures.

1891- Major John Wesley Powell was the leader of the "Powell Survey" and second Director of the Geological Survey. In his 1891 report to the U.S. House of Representatives, he describes artesian conditions in the arid regions. Though not a hydrologist, Powell recognizes the importance of water in the future development of the U.S.A. Under his leadership the systematic collection of hy-

drologic data is established and groundwater studies by the USGS commence.

- 1896- The first USGS Water-Supply Paper, *Pumping Water for Irrigation*, by H.M. Wilson appears. G.K. Gilbert investigates groundwater in the Arkansas River Valley in Colorado. His pioneering report describes artesian conditions, water-table conditions, and groundwater recharge to the Dakota Sandstone aquifer. At the 5th International Geological Congress hosted by the U.S.A. in 1891, Gilbert plays a leading role on the organizing committee.

Figure 1: J.W. Powell, second Director of the USGS (1881-1884). USGS photo.

- 1896- Noah Horatio Darton (Fig. 3) reports on the Dakota Sandstone. One of the giants of American geology and one of the USGS's most accomplished, meticulous and productive scientists, his schooling was meager, and he was largely self taught. He started with the Survey in 1886, and became interested in groundwater while doing geological mapping in the Atlantic Coastal Plain. He became a leading expert on artesian water and regional groundwater flow systems.
- 1899- Franklin H. King, a professor of hydraulic engineering and part-time employee with the USGS, publishes detailed principles of groundwater movement. His classic report described laboratory and field evaluations of groundwater storage, groundwater flow, and directional permeability. He was probably the first investigator to prepare groundwater maps for flow-system analysis.

- 1905- Walter C. Mendenhall authors four quantitative reports on southern California. In his study of the hydrology of San Bernardino Valley, California, he defined the importance of regional and local geological structure in controlling the movement of groundwater. The second Chief of the Ground-Water Branch and the fifth Director of the Geological Survey (1930-43), Mendenhall was an outstanding scientist who stressed the importance of quantitative methods in groundwater hydrology. When the 16th Session of the International Geological Congress was hosted by the U.S.A. in 1933, W.C. Mendenhall was the Secretary General.

Figure 2: T.C. Chamberlin, a leading glacial geologist, whose greatest contribution to hydrogeology was his 1885 description of artesian wells. GSA photo.

- 1906- A.C. Veatch and C.S. Slichter and their colleagues complete one of the early quantitative groundwater investigations. Veatch shows that groundwater levels in artesian aquifers in Long Island, New York, respond to the influence of the elastic deformation of the aquifer by superimposed loads, such as passing railroad trains, the rise and fall of ocean tides, changes in barometric pressure, and changes in nearby stream and reservoirs.
- 1909- A.J. Ellis reviews the occurrence of water in crystalline rock in Connecticut. This is

one of the first studies to describe aquifer storage and transmission characteristics. Ellis points out the importance of geological structure in controlling groundwater movement. In this year N.H. Darton also publishes his classic report on the geology and groundwater in South Dakota.

- 1910- *Geology and Water Resources of the San Luis Valley, Colorado*, by C.E. Siebenthal (Fig. 4) is released. The report contains information on water use, geology, and occurrence of groundwater. He accomplished an outstanding amount of field work in a short time with only a horse and buggy for transportation.

Meinzer Era (1911-1946)

During the next 35 years major advances in groundwater hydrology were made in the definition of fundamental concepts and principles, and the development of quantitative method. Oscar E. Meinzer (Fig. 5) is recognized as the father of modern groundwater hydrology. He joined the Geological Survey in 1906, and in a span of 40 years his contributions and leadership transformed groundwater investigations in the U.S.A. to a full-fledged science. Meinzer (1876-1948) can be credited with much of the scientific progress in groundwater hydrology through his scientific contributions and leadership as Chief of the USGS Ground-Water Branch. The reports containing his groundwater definitions and principles have become standard textbooks used throughout the world. During his leadership the Branch made investigations of the relations between saltwater and fresh-

Figure 3: N.H. Darton, A trail blazer in the hydrogeology of the western U.S.A.

water, groundwater mining, recharge, evapotranspiration, water quality and aquifer-stream relations.

The most significant work during this period was the development of quantitative field and laboratory methods to describe the storage and transmission characteristics of aquifers. C.V. Theis (Fig. 6) revolutionized the science of groundwater hydrology by opening the door for modern analytical methods that were quantitative and predictive when he developed the equation for nonsteady-state flow. The Theis equation enabled hydrologists for the first time to predict the yield of wells and to evaluate their effects in both time and space.

1912- Charles H. Lee publishes the results of a study of Owens Valley, California, in which he made tank experiments of the rates of water use by salt grass, grown with different depths to the water table.

1916- W.C. Mendenhall and others report on the San Joaquin Valley, California, probably the first geologists to use stream-flow records for a groundwater evaluation. They use records from paired gaging stations to determine channel loss.

1923- O.E. Meinzer's reports on the Occurrence of Ground-Water in the United States, with a discussion of principles. This and his "Outline of Ground-Water Hydrology" are still standard references for the hydrogeologist.

1925- In one of the early applications of the Ghyben-Herzberg principle in the U.S.A., J.S. Brown uses the formula in studies of saltwater encroachment along

the Atlantic Coast. The basic concepts developed in his report are also applied to the Gulf Coast and Hawaii.

1928- O.E. Meinzer's paper on the compressibility of artesian aquifers is published, a major contribution to the understanding of groundwater flow.

1929- In discussing the Pomperaug Basin, Connecticut, Meinzer and N.D. Stearns present methods for determining the characteristics of groundwater recharge and discharge on a basin wide or regional scale. Included is a hydrography method for estimating groundwater discharge.

1932- Meinzer develops a method for estimating groundwater recharge and out flow.

1933- A.G. Fiedler and S.S. Nye describe the effects of large-scale groundwater development on the Roswell artesian basin.

Figure 5: O.E. Meinzer, architect of modern hydrogeology and third Chief of USGS Ground-Water Division (1912-46). USGS photo.

1935- C.V. Theis publishes an equation to describe non-steady flow. This is considered the greatest single contribution to the science of groundwater hydraulics in this century. Theis recognized that groundwater flow is analogous to heat flow in solids and pointed out the importance of aquifer storage. His equation is a major breakthrough and opens the door for modern quantitative investigations.

1935- Victor T. Stringfield contributes significantly to the understanding of regional groundwater flow with a potentiometric map of the Florida Aquifer.

1939- O.E. Meinzer publishes his major report, Ground-Water in the United States, which contains a summary of conditions and scientific methods.

1940- In a second classic paper, C.V. Theis explains the source of water derived from wells, the nature and the significance of the cone of depression, and the key factors that control the response of an aquifer to development.

1940- M.K. Hubbert, one of the pioneers of groundwater flow concepts, discusses the influence of groundwater flow on the accumulation of hydrocarbons.

1940- C.E. Jacob, a major contributor to the understanding of groundwater hydraulics, defines the transient-flow equations using flow hydraulic rates from the heat-flow analogy.

1941- C.V. Theis presents a method to estimate the effects of water withdrawal from a well on a nearby stream.

1942- A.N. Sayre and R.R. Bennett show that the Edwards Limestone aquifer is part of a major regional aquifer system that extends across much of central Texas.

1945- In a study of groundwater levels and precipitation on Long Island, New York, C.E. Jacob develops an analytic solution for recession of the potentiometric surface when recharge ceases. He demonstrates that the geohydrologic characteristics of aquifers determine their response to changing conditions of recharge or discharge.

1946- Jacob presents a method for analyzing data on interference resulting from the pumping of several wells. He develops a physical basis for the Theis equation, defines the storage coefficient, and analyzes radial flow in a leaky artesian aquifer. He also identifies the influence of leakage from confining beds.

The Modern Era (1947-1987)

The last forty years have seen the development of predictive groundwater models and an emphasis on interdisciplinary problems. The new electric analog and digital models have provided the hydrologist and water planner with a powerful tool to analyze water-resource problems. The USGS established an analog-model laboratory in Phoenix, Arizona in 1960, and more than 100 analog models were then constructed to 1975. Digital computer models replaced the analog approach in the 1970s and now play a major role in the analysis of

Figure 4: C.E. Siebenthal, best known for his work in the San Luis Basin of Colorado. USGS photo.

groundwater problems. These models are widely used to calculate changes in water quality, quantity, and to determine the effects of economic and legal constraints. Much interest exists in developing digital methods to evaluate transport and attenuation of contaminants, and plans for cleaning up hazardous-waste sites.

Emphasis was also given to interdisciplinary approaches to water-resource problems. In addition to groundwater hydrology and hydrogeology, these include studies of surface water, water quality, geochemistry, geophysics, economics, and biology.

- 1947- H.S. Carslaw and J.C. Jaeger publish a classical book on conduction of heat in solids, which becomes a standard reference for groundwater hydrologists.
- 1948- John G. Ferris applies the Theis formula and the method of images for locating hydrologic boundaries. In 1949, he prepares a groundwater chapter to be included in a hydrology textbook (Wisler and Brater, 1949), which also becomes a standard reference for hydrologists.
- 1949- Morris Muskat's book Physical Principles of Oil Production is published, to become a standard reference for groundwater investigations.
- 1950- M.D. Foster demonstrates by laboratory experiment that the occurrences of high bicarbonate groundwater in the Atlantic Coastal Plains are caused by ion-exchange between water and clay minerals. This is one of the first papers linking laboratory experiments and field situation. It is an outstanding example of the scientific method in practice.
- 1951- In The Conservation of Ground-Water H.E. Thomas describes the occurrence of groundwater and the effects of its use. It contains the first detailed map of the U.S.A. showing productive aquifers and potential yield to wells.
- 1952- R.R. Bennett and R.R. Meyer complete a classic hydrogeology report on the Baltimore area, presenting one of the first uses of a flow-net analysis.
- 1954- H.E. Skibitzke and G.M. Robinson develop an analog model to solve a groundwater flow problem. This involves the use of resistor-capacitor model analogs for solutions of non-steady flow in groundwater systems.
- 1955- M.S. Hantush and C.E. Jacob are largely responsible for the formulation of leaky aquifer theory and the development of mathematical models that

predict responses to pumping such aquifers. Previous mathematical groundwater flow models assumed that formations overlying and underlying an aquifer are impermeable.

- 1956- Numerical methods for analysis of regional water-level networks are developed by R.W. Stallman to define aquifer parameters and recharge-discharge characteristics.
- 1959- A report by H.H. Cooper, Jr., on the dynamic balance of freshwater and saltwater in a coastal aquifer, is followed by a study of the Biscayne aquifer in the Miami, Florida area.
- 1959- J.D. Hem completes his classic Water-Supply Paper, Study and interpretation of the chemical characteristics of natural water. The report provides an introduction to water chemistry, with emphasis on inorganic chemistry. His discussions of the significance of properties and constituents in natural waters are frequently quoted as a standard reference. The report is updated in 1970 and again in 1985.
- 1960- A classic text on mineral equilibria by R.M. Garrels appears. This provides the tools of chemical thermo-dynamics to hydrogeologists. Most of the geochemical work applied to hydrogeology since then has been based on his work and that of his students.
- 1960- The theory of leaky aquifers is published by M.S. Hantush, who modifies the artesian aquifer

equation to include storage in the confining layer.

- 1960- While studying land subsidence in the San Joaquin Valley, California, J.F. Poland, discovers that subsidence is not the result of dewatering the artesian aquifers, but rather of dewatering and compaction of the confining beds. The study also shows that once dewatered and compacted, the confining beds have little capacity to take water back into storage and allow land surface to rebound in the subsiding areas.
- 1962- In a series of laboratory experiments, B.B. Hanshaw demonstrates that compacted clays behave as semi-permeable membranes and can cause anomalously high or low potentiometric heads. The membrane behavior of clay is also shown to account for unexpectedly high or low salinity of water. These laboratory studies corroborate field evidence, presented earlier by F.A.F. Berry and Hanshaw, that suggests the membrane effects of shale.
- 1963- I.S. Papadopoulos develops a method for preparing type curves for computing hydraulic diffusivity for a wedge-shaped aquifer.
- 1963- A comprehensive review of the groundwater conditions in each state is published by C.L. McGuiness.
- 1963- Robert W. Stallman points out that the groundwater flow is an efficient mechanism for transporting heat.
- 1963- H.H. Cooper, Jr. and M.I. Rorabaugh develop an analytical methodology for estimating changes in bank storage and groundwater contribution to streamflow.
- 1963- W.C. Walton and T.A. Prickett prepare one of the first papers demonstrating the use of analog models in hydrogeology, based on Skibitzke's earlier pioneering work. Earlier work by H.F. Skibitzke pioneered electric analog simulation of transient flow in aquifers.
- 1965- A classic paper on patterns of contaminated zones in groundwater is published by Harry E. LeGrand, who points out the difficulty in locating the contamination zone because of numerous physical and chemical factors.
- 1965- L.A. Wood and R.K. Gabrysch describe one of the first applications of an analog model, which they use to evaluate the effect of large groundwater withdrawals in the Houston, Texas area.

Figure 6: C.V. Theis, who developed the equation for non-steady-state flow of groundwater.

- 1965- In a paper on the use of isotopes in hydrology, B.B. Hanshaw and others use measurement of the radio-carbon content of dissolved carbonate species to estimate groundwater flow velocities in an aquifer. They obtain close agreement between flow velocities calculated by means of Darcy's Law and those determined by radio-carbon.
- 1965- D.A. Domenico and M.D. Mifflin give an analytical method to evaluate land subsidence by combining the Terzaghi theory of consolidation with Jacob's theory of groundwater flow.
- 1966- William Back develops geochemical interpretations of groundwater flow patterns from hydrochemical facies.
- 1966- M.I. Rorabaugh and others release the first intensive study of the relation between groundwater storage and streamflow in the Columbia River basin. This is a full-scale field test of theories developed by Rorabaugh and H.H. Cooper, Jr., by using water levels in a well as an index for the calculation of groundwater outflow, groundwater recession curves as an index of low flow, and river stage for calculating bank storage.
- 1967- A numerical solution of groundwater flow in complex hydrogeological environments is published by Alan Freeze and P. Witherspoon.
- 1968- G.F. Pinder and J.D. Bredehoeft publish a paper describing the use of digital computer models for aquifer evaluation. This is a landmark in the application of digital models in groundwater hydrology.
- 1969- S.N. Davis makes a careful and thorough review of the porosity and permeability of earth materials, pointing out their importance to hydrogeologists.
- 1969- In a thorough review of the history of ideas concerning the hydraulics of leaky aquifers, S.P. Neuman and P.A. Witherspoon summarize various methods and formulate solutions for leaky aquifers that takes into account water released from storage in the aquitard and leakage from the unpumped aquifer.
- 1969- D.D. Runnells is among the first to recognize the hydrologic significance of the dispersive mixing zone between saltwater and freshwater in an aquifer. He demonstrates the chemical reactivity of the mixing zone, leading others to work on geochemical and hydrologic models of the mixing zone.
- 1970- A hydrologic model that demonstrates the interrelation between aquifer, stream, and water use, is published by J.D. Bredehoeft and R.A. Young.
- 1972- S.W. Lohman publishes his classic paper on groundwater hydraulics, which is destined to become a standard reference. In a separate publication with others, he also redefines many groundwater terms, setting forth the use of consistent units for transmissivity, hydraulic conductivity, and permeability.
- 1972- S.P. Neuman and P.A. Witherspoon describe an aquifer test method for determining hydraulic properties of leaky aquifer systems.
- 1973- J.D. Bredehoeft and George F. Pinder develop a solute-transport model for the evaluation of groundwater quality problems.
- 1973- An interactive groundwater flow model to simulate two- and three-dimensional groundwater flow is published by Peter C. Trescott.
- 1973- Leonard F. Konikow and Bredehoeft present a method to model chemical-quality variations in a groundwater system by applying mass transport equations.
- 1973- The effects of dispersion and transport of solutes in groundwater are analyzed by Jacob Rubin and R.V. James.
- 1974- A. Zohdy, C. Eaton and D. Mabey publish a comprehensive technical manual on the applications of surface geophysics to groundwater.
- 1974- Because of the complexity of geochemical calculations associated with regional groundwater studies, computer programs have by now become essential for these calculations. One of the first geochemical models is published by A.H. Truesdell and B.F. Jones.
- 1976- C.A. Appel and Bredehoeft describe the status of groundwater modelling in the USGS. About 100 electrical analog models were constructed from 1960 to 1975, and between 1970 and 1976 digital models were developed for more than 90 flow problems.
- 1978- R. William Nelson prepares a classic report evaluating the environmental consequences of groundwater contamination.
- 1979- Attention has now been turning increasingly to applications of geochemistry and geochemical models to environmental problems, especially groundwater contamination. M.P. Anderson reviews the state of development of chemical transport models, a major effort of geochemists and hydrogeologists in the U.S.A. at the present time.
- 1979- W. Back, Hanshaw, and others publish the first series of papers on the hydrologic and geochemical mixing zone. They point out that in this zone, the processes of mineral dissolution and precipitation, dolomitization, chertification and ore formation can occur.
- 1984- Ralph C. Heath describes in detail the major groundwater regions in the U.S.A.

A View to the Future

The concern with cleaning up groundwater contamination has stimulated research in the movement of contaminants in aquifers and has enhanced our understanding of geochemical and biological processes. The emphasis has been on field investigations from a two-dimensional to a three-dimensional evaluation of flow systems and transport processes. The tracing of contaminant movement will require the hydrologist to make quantitative descriptions of heterogeneities in aquifers. The effective use of computer models in the future will be, as it is today, limited by the costs of collecting the chemical, biological, geological and hydrological data that are needed to construct and calibrate the model.

Effective groundwater protection and reduction of contamination will receive increased attention by federal, state, and local governments in the future. The next ten years will see increased funding for research and field investigations to improve our ability to identify and trace accurately the movement of contaminants, and to propose ways to reduce contamination. A major need exists for more accurate field data to describe the extent, character, and flow of contaminants in three dimensions, and there will have to be efforts made to provide field verification of computer models.

Interest in interdisciplinary cooperation in the study of the fate and transport of contaminants will increase. Scientists today do not know enough about groundwater transport and

chemical interactions to make accurate quantitative predictions of contaminant movement. No ready answers exist to common questions such as: how contaminated is groundwater? Is its quality deteriorating or improving? How best can the contaminated site be cleaned up? Where should monitoring wells be placed and how frequently should they be measured? In short, much remains to be done and it will require the best available multi-disciplinary technology.

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