# American Hydrogeology at the Millennium: An Annotated Chronology of 100 Most Influential Papers

**William Back**[1] **and Janet S. Herman**[2]

***Abstract:*** Hydrogeology developed as scientists undertook activities to describe how a groundwater system functions and to explain why it is that way, in order to solve practical problems of water supply. This paper demonstrates the evolutionary nature and growth of hydrogeology in the United States on the basis of a selection of one hundred papers that had a significant impact on subsequent activities. We have identified three revolutionary concepts that resulted directly from this evolutionary understanding and have selected papers that demonstrate important consequences. These three concepts are 1) that the mathematical expression for heat flow can be paraphrased for groundwater and used in transient flow conditions to determine aquifer characteristics; 2) that the distribution of fluid potential can be formulated in mathematical equations suitable for solution by various analytical techniques; and 3) that chemical thermodynamics can be applied to hydrogeologic systems in order to understand the processes controlling the chemical character of groundwater. One purpose of this paper is to encourage scientists to gain an additional dimension of satisfaction from their work by being aware of the contributions of those who went before them and to see how their own work fits into the current understanding of hydrogeology.

***Résumé:*** L'hydrogéologie a été développée parce que des chercheurs ont entrepris de décrire comment fonctionne un hydrosystème souterrain et d'expliquer pourquoi c'est ainsi, afin de résoudre des problèmes pratiques d'approvisionnement en eau. Cet article montre la nature évolutive et la croissance de l'hydrogéologie aux États-Unis à partir d'une sélection d'une centaine d'articles ayant eu un impact certain sur les activités ultérieures. Nous avons identifié trois concepts révolutionnaires, résultant directement de cette compréhension évolutive et nous avons sélectionné les articles qui montrent des retombées importantes. Ces trois concepts sont 1) que l'expression mathematic du transfer de caller put être transposé aux écoulements souterrains et être utilisé en conditions transitoires pour déterminer les caractéristiques de l'aquifère, 2) que la distribution de la charge hydraulique put être formulée par des équations mathématiques adaptées à une résolution par des techniques analytiques variées, et 3) que la thermodynamique chimique put être appliquée aux hydrosystèmes souterrains dans le but de comprendre les processus contrôlant la composition chimique de l'eau souterraine. Cet article a pour but, entre autres, d'encourager les chercheurs à donner un intérêt supplémentaire à leurs travaux en s'intéressant aux contributions de ceux qui sont passés avant eux, et de leur montrer comment leur propre travail prend place dans la connaissance hydrogéologique en général.

***Resumen:*** La hidrogeología tuvo su desarrollo cuando los científicos empezaron a llevar a cabo actividades para describir cómo funciona un sistema de aguas subterráneas, y a explicar el porqué es de esa manera, con el objetivo de resolver problemas prácticos de suministro de agua. Este artículo demuestra la naturaleza evolutiva y el crecimiento de la hidrogeología en los Estados Unidos de América a partir de la selección de 100 artículos que tuvieron un impacto significativo en las actividades subsiguientes. Hemos identificado tres conceptos revolucionarios que aparecieron partir de este conocimiento evolutivo, y hemos seleccionado los artículos que dan lugar a las consecuencias más importantes. Estos tres conceptos son: 1) las expresiones matemáticas para flujo de calor pueden ser aplicadas al flujo de agua subterránea y usadas en condiciones transitorias para determinar las características de los acuíferos; 2) la distribución del potencial de un fluido se puede formular mediante ecuaciones matemáticas, resolubles con varias técnicas analíticas; y 3) la termodinámica química se puede aplicar a los sistemas hidrogeológicos para entender los procesos que controlan el carácter químico del agua subterránea. Un objetivo de este artículo es animar a los científicos a obtener una dosis adicional de satisfacción en su trabajo, dándose cuenta de las contribuciones de los que vinieron antes que ellos y viendo como su propio trabajo se engloba en las tendencias actuales de la hidrogeología.

## Introduction

As we enter the final years of the second millennium, it is worth reflecting on the state of hydrogeologic knowledge and how it came into being. In order to stimulate thinking about what hydrogeologists will be doing in the first few decades of the new millennium, we provide a brief summary of what hydrogeologists have done in the past. We have selected one hundred papers (including a few books) that we believe significantly influenced activities that generated the current body of hydrogeologic knowledge. These papers are organized

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[1] U.S. Geological Survey, 431 National Center, Reston, VA 22092, USA.

[2] Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903, USA.

around three concepts, whose identification we do not claim to be original with us, but that we believe revolutionized the field of hydrogeology in the United States during the twentieth century. These concepts are 1) that the mathematical expression for heat flow can be paraphrased for groundwater, and, therefore, used in transient flow conditions to determine aquifer characteristics (hereafter referred to as the "non-equilibrium well hydraulics" concept); 2) that the distribution of fluid potential can be formulated in mathematical equations suitable for solution by various analytical techniques to develop flow-simulation models (hereafter referred to as the "groundwater flow and simulation" concept); and 3) that certain aspects of physical chemistry, such as the law of mass action, Nernst equation, Gibbs free energy, and isotopes, can be used to identify mineralogical controls and geochemical reactions that determine the chemical character of groundwater (hereafter referred to as the "hydrogeochemistry" concept). The chronology of contributions culminates in the current state of knowledge of mass-transport phenomena and points toward a future in which hydrogeologists will increasingly serve societal needs and desires, meet new scientific challenges, and conduct their professional careers in a manner advantageous to themselves, society, and the environment.

Obviously, any selection of papers is based on personal experience and bias. We think we have selected papers that either 1) first identified a phenomenon or described a concept, or 2) clearly demonstrated application of the concept to a hydrogeologic problem. Young scientists and others need to understand how their research fits into the global science and time frame in a manner that emphasizes the relevance of their own work. The importance of the list of selected papers lies not in agreement of the reader with our selections, but rather in thoughtful discussions of why a paper is on the list and whether or not other papers should be substituted. Hart (1978) found the creation of the book ranking the 100 most influential persons in history fascinating and entertaining; he extended an invitation to his readers to compose similar lists related to their interests. As readers evaluate our list, we would encourage similar intellectual activity on topics of their expertise, as Narasimhan (1997) has recently done on the history of ideas related to hydraulic characterization of aquifers.

Although our list includes only publications by scientists from the United States and Canada, it is clearly recognized that hydrogeologists from other countries have made significant contributions that influenced North American thinking. In addition, scientists from other disciplines have influenced the thinking of hydrogeologists, such as K. Terzaghi in soil mechanics, M. Muskat in flow of gas through porous media, L. Barnes in high-temperature geochemistry, and many others. We restricted our selection to those papers authored by scientists who referred to themselves as hydrogeologists or any of the precursor terms, or to those papers specifically on groundwater. That is, we did not include Terzaghi because he did not emphasize groundwater in his papers, even though his papers provided much of the basis of land-surface subsidence done by hydrogeologists. On the other hand, we included A. Casagrande, another outstanding expert in soil mechanics, because his 1937 paper is on groundwater flow. Similar decisions were generally made about the geochemistry section.

We have not included papers by active researchers who are continuing to contribute to the literature, because we feel that designating a rather contemporary paper as having a "significant influence" would be presumptuous. We have selected only papers by North American scientists who have died or have retired from their primary position at a university or research institution as of spring 1996, when we presented this paper at the meeting of the American Geophysical Union in Baltimore (Back and Herman, 1996). The core of our selection comes from two books of benchmark papers: Freeze and Back (1983) and Back and Freeze (1983).

## Development of Hydrogeology

### *Current Status*

Hydrogeologists in North America and other parts of the world can be most gratified at scientific contributions they have made to provide the requisite knowledge for many people to achieve a higher quality of life through availability of a safe and adequate water supply. Hydrogeology is a relatively young science based on principles of physics and chemistry as water moves through the geologic framework. The fundamental concepts and principles have originated largely within the past 100 years or so. Hydrogeologists have had significant influence on the exploration, development, inventory, and management of groundwater as a water supply. They have also provided knowledge required to resolve engineering problems, such as slope instability; dewatering of excavations, tunnels, and mines; and subsidence of land surfaces. Hydrogeologists have influenced the thinking of scientists working on geologic topics, such as ore deposition, metamorphism, diagenesis, geomorphology, and geothermal heat. This relationship of groundwater with geologic processes is neither surprising nor new. In fact, in our list of 100 influential papers in hydrogeology, our earliest (Chamberlin, 1885) and our most recent (Heath, 1984) are geologic studies of the occurrence of groundwater.

Geologic controls on the occurrence and movement of groundwater have been the integrating factor that permitted the recognition and articulation of the fundamental principles of hydrogeology. Without this geologic integration of structure, stratigraphy, lithology, mineralogy, geomorphology, and more, observation of groundwater phenomena would have been a collection of isolated facts, with little chance of recognizing universal principles. Publications that have summarized knowledge of groundwater concepts have been primarily of a geologic nature. For example, the first significant American publication was by Chamberlin (1885); although that report is restricted to artesian conditions, it clearly demonstrates that occurrence and movement of groundwater cannot be deduced without knowledge of the local geology. The second American publication that summarized the principles of groundwater as understood at the time was by Meinzer (1923b). This is essentially a geological textbook with incorporation of groundwater. More than 40 years later, Maxey (1964) and Davis and DeWeist (1966) provided the next summaries of groundwater principles in their geologic publications. A historical perspective on various regional groundwater flow studies in the United States is in Bredehoeft et al. (1982), in which the authors emphasize control of geology on hydrologic systems and the geochemistry of water. The most recent publication providing a synthesis and integration of groundwater with geologic controls and processes was published by the Geological Society of America (GSA), a co-sponsor of *Hydrogeology Journal*, in their series, Decade of North American Geology (DNAG). The volume on hydrogeology was prepared by nearly one hundred senior hydrogeologists from the United States, Canada, and Mexico (Back et al., 1988). Much of the evolution of hydrogeology has been by incorporation of the laws of physics and chemistry into the geologic framework through the language of mathematics.

We have chosen to use the term "hydrogeology" rather than options such as "groundwater science," "groundwater geology," "groundwater hydrology," and others. Hydrogeology has been used more widely in the United States during the past few decades than previously, primarily with the founding of the Hydrogeology Division of the GSA in 1959 and the publication of *Hydrogeology* by Davis and DeWeist (1966), in which Mead (1919) was credited with the first modern use of the term in his textbook. The term has long received international acceptance; for example, Lamarck's textbook *Hydrogeology* was published in 1802. We think none would argue with the elegant definition given by Domenico and Schwartz (p. 7, 1990): "Hydrogeology is the study of the laws governing the movement of subterranean water, the mechanical, chemical, and thermal interaction of the water with the porous solid, and the transport of energy and chemical constituents by flow."

Understanding of hydrogeology is based on the collection of hydrogeologic data, their interpretation, and research in the broadest sense, all of which has culminated in a body of fundamental knowledge of mass-transport phenomena. This knowledge includes at least a partial understanding of the distribution of potential and kinetic energy, chemical energy, and thermal energy within groundwater systems. This understanding permits a quantitative description, with some predictive capabilities, of topics such as quantity and rate of movement of groundwater; the source, fate, and behavior of inorganic constituents and certain organic compounds; the rate of solute transformation; and solute distribution throughout the geologic framework and over time.

Concern about environmental pollution, recognition in the 1970's of widespread occurrence of contaminant organic compounds in the subsurface, and desire for their management required use of mass-transport equations. This added a whole new dimension of thought and activity for society and for groundwater scientists. Before that time, groundwater contamination appeared to be a fairly restricted problem, associated primarily with salt-water encroachment, management of radioactive material, and drainage of acid water from coal mines. Today, groundwater investigations and research are driven largely by organic contamination. These contaminants are generating complex problems more rapidly than we are gaining understanding of the principles controlling their occurrence, movement, and chemical evolution. Currently, the occurrence of organic compounds in the subsurface presents the greatest hurdle to obtaining and managing adequate water supplies.

The complexity of hydrogeologic problems is greater now than in the past because of increased population and expectations of the people for higher standards of living. During the next few decades, hydrogeologists will be involved in satisfying the needs of society for 1) a safe and adequate water supply; 2) containment of radioactive and other toxic wastes; 3) geotechnical activities in urban areas; 4) risk evaluation of natural hazards; and 5) environmental assessment of sites, areas, and regions. Some of these issues are relatively new and others are as old as hydrogeology itself. In past times, an adequate water supply was obtained from a dug well near a farm house. "Is it safe to drink?" was a yet-unasked question. We have seen the increased need of water supply for domestic use, irrigation, and industry. In many areas, we have seen the nature of management change from a fair and equitable distribution of supply to a fair and equitable distribution of demand. Nature is demanding its fair share for wetlands, fish in the streams and lakes, and shoreline habitats in order to maintain a viable ecology. For some people, their potable supply will be from the desalinization of brackish groundwater, with its attendant problems of energy demands and disposal of brines and salts.

Management of radioactive wastes has been a hydrogeologic problem since nuclear waste was first generated. An adequate strategy has not yet been identified, and this topic will remain an area of investigation for decades to come. Hydrologic geotechnical problems will increase as urbanization expands into less desirable sites; these include problems of water-supply distribution, sewage disposal, foundation dewatering and stabilization, soil erosion from construction activities and devegetation, effects of acid rain, slope instability, decrease in recharge, and others. The public demands more protection from natural hazards and the hydrogeologist has a role to play in providing information for zoning plans and building codes to decrease damage from hurricanes, earthquakes, and floods. Although hydrogeologists have made significant contributions to the understanding of many geologic processes, their talents have not yet been brought to bear on risk, timing, and consequences of earthquakes, volcanoes, landslides, and hurricanes. In addition, the public will increasingly demand a more rigorous and specific assessment of the degree of contamination of sites and areas and the potential of contamination of areas and regions in the future.

### Historical Perspective

Principles of hydrogeology were developed in America, as well as in other parts of the world, by a mix of problem-solving and puzzle-solving efforts of scientists. Hydrogeologic problems were commonly generated by the need for water for some particular use, in some particular area, and hydrogeologic knowledge was gained through attempts to solve the problems. Hydrogeologic puzzles, generated by the curiosity of individuals, led to basic research and fundamental breakthroughs. For example, Henry Darcy developed his equation by solving the problem of determining the size of sand tanks required to filter the water supply for the city of Dijon, France; C.V. Theis developed his transient flow equation to evaluate the availability of groundwater that was urgently needed in specific areas affected by the Great Drought of the 1930's in the U.S.A.; O.E. Meinzer and others developed the concept of compressibility as they attempted to solve the puzzle of how water could be produced from the downgradient portion of the artesian aquifer in an amount that was greater than that which entered the upgradient recharge area.

Evolution of the American hydrogeology is intimately entwined with the cultural and demographic history of the United States. Although Native Americans had made extensive use of natural rainfall, lakes, and rivers, they had no need to develop groundwater through wells and used it only at springs. Their various techniques for use and management of water had a profound influence on their own cultural diversification (Back, 1981). Because the eastern United States is humid, early European settlers in that region were able to obtain adequate water supplies from lakes, rivers, springs, and shallow wells.

Springs were used not only as a water supply by Native Americans, but they also had used springs for thousands of years for medicinal purposes. Later, when European settlers recognized similar benefits, therapeutic use of springs generated the early need for chemical analysis of water. Groundwater geochemistry had its beginnings in the formulation of analytical techniques in response to development of spas centered around mineral springs used for physical and psychological rejuvenation during the 1800's (Back et al., 1995). When water was to be ingested, quantitative chemical analyses were deemed important. Analyses of mineral waters occupied a large part of the chemical literature of the 18th century and provided valuable scientific data on the ranges of substances dissolved in natural waters.

The primary impetus for development of hydrogeology in America was the western expansion of "civilization" into the "uninhabited" lands of the more arid western parts of the continent. This expansion began in earnest with discovery of gold in California in 1849. Many potential gold seekers found the unplowed virgin land more appealing than gold and, therefore, aborted their trip or later retraced their steps to establish a homestead. This migration accelerated after passage of the Homestead Act in 1862, and again after completion of the Transcontinental Railroad in 1869. During the next 30 years, thousands of miles of railroad were constructed, as land developers and railroad owners recruited millions of immigrants from Europe, primarily Germany, Ireland, Scandinavia, and Russia, to settle the land. The goal was to generate profits from freight as natural resources and agricultural products moved eastward and agricultural supplies and equipment moved westward.

Another direct influence of railroads on hydrogeology was the need for water of a suitable chemical composition for use in boilers of steam locomotives. The limited capacities of boilers required that the water supply for refilling them be available at relatively short intervals along the tracks. Water with low total dissolved solids was greatly desired because chemical deposits from hard water were extremely expensive to remove from boilers and piping on trains. This need stimulated exploration for well sites and development of techniques for chemical analysis of water.

Crop-growing farms in the U.S.A. were restricted to more humid eastern areas, whereas farther west grazing areas were developed in more arid zones. In the Great Plains area, for a period of about 20 years following the end of the Civil War (1865), rainfall was abundant and the more humid agricultural lands experienced an optimistic westward expansion. Public debate erupted when John Wesley Powell, the second Director of the U.S. Geological Survey, was opposed to subdividing land into parcels he knew to be too small to support a family engaged in dry-land farming. The most desirable land was along river courses. Because a cow can walk only about five miles for a drink of water, grazing was restricted to a narrow band along each side of rivers. Introduction of windmills in the 1880's to pump groundwater opened up more land, because they allowed the area for grazing to be expanded far beyond rivers, and they also provided domestic and stock water for farms and ranches.

The first American experience with serious widespread drought started in about 1885, when the average annual rainfall in the United States began to diminish. For three consecutive years in the 1890's, rainfall was much below normal and the deficit culminated in the great drought of 1894 and 1895, which brought complete crop failure and disaster. In some areas, as many as 90 percent of the settlers abandoned their land (Tannehill, 1947). As lake levels dropped and streamflow decreased during this drought, the use of wind mills expanded. Wind mills, however, can produce only a small amount of water. The only large source of groundwater was from flowing wells, until deep-well turbine pumps were perfected between 1910 and 1930 (Davis and DeWeist, 1966). Large supplies of water were required for municipalities and irrigation projects, and this need prompted hydrogeologists to study artesian conditions. The study of artesian conditions was so important that Chamberlin's 1885 report is generally recognized as the beginning of hydrogeology in the United States.

As the population continued to grow, particularly in the eastern coastal areas, the next major hydrologic problem to attract the attention of scientists was salt-water intrusion. As early as 1824 the problem was recognized in New Jersey (Carlston, 1963), and salt-water contamination became a threat elsewhere when additional wells were drilled in coastal areas. Coastal saline groundwater was the subject of a major scientific study by S. Sanford in 1910 and has continued to be a topic of active research. Investigation of the problem of salt-water encroachment into coastal aquifers stimulated the development of both physical and chemical aspects of hydrogeology and afforded early training for many leading scientists. In the early years, the chemists and engineers had responsibility for studying chemistry of natural water, but the salt-water problem brought the talents of geologists to work on chemistry of water.

In the years following the 1890's drought, average annual rainfall increased and the period from 1905 to 1915 was generally wet. The high prices for food during World War I caused great expansion of agriculture, and brought about the introduction of tractors and other labor-saving machines. In those years of plentiful rainfall throughout the country, it was difficult for O. E. Meinzer, Chief of the Ground-Water Branch of the U.S. Geological Survey during 1911-46, to offer convincing arguments to gain public support and funding to study groundwater (Rosenshein et al., 1986). Unfortunately, for the farmers, ranchers, and others, dryer times started in about 1917 and culminated with the Great Drought of the 1930's. Drought seemed to be chronic. Wells were dug deeper and deeper until in some areas it took a gallon of gasoline to pump a gallon of water. The sub-soil moisture was depleted to a great depth (Tannehill, 1947). During these dry years, deep-well turbine pumps were introduced, resulting in the expanded use of groundwater in other areas of the Great Plains and in the alluvial valleys of the west, such as the San Joaquin Valley of California.

Extensive use of deep-well turbine pumps for irrigation, which allowed large withdrawals of groundwater and resulted in substantial declines in water levels, was a major factor contributing to the problem of land-surface subsidence. The seriousness of the problem was recognized in the early 1940's. Building upon contributions in soil physics by K. Terzaghi (Terzaghi, 1943; and Terzaghi and Peck, 1948), the first rigorous scientific studies of subsidence were undertaken by hydrogeologists in California under the leadership of Poland and Davis (1969). Their work established the direct correlation between the amount of water withdrawn and the amount of subsidence of the land surface. Subsidence caused by groundwater pumpage has also occurred in Houston, Texas; Las Vegas, Nevada; southern Arizona; Shanghai, China; Venice, Italy; Mexico City, and elsewhere. Understanding of the phenomena leading to this serious engineering problem has been gained primarily through the efforts of hydrogeologists.

The American drought years of the 1930's were defined in people's minds by the huge dust storms that took place. The first great dust storm of the drought years in the Great Plains occurred in November, 1933. The dust from these storms, which continued intermittently for the next several years, was carried to the Atlantic coast. In addition to the loss of top soil and crops, the drought brought other troubles, with grasshoppers being the worst. Dry, warm weather is favorable for the hatching of grasshoppers, and they destroyed millions of dollars worth of crops and other vegetation. With the vegetation gone, the soil became even more susceptible to erosion, and the bare soil further contributed to dust storms. The drought generated additional interest in groundwater. C. V. Theis was assigned to evaluate the aquifer potential of the Great Plains, work that led to the development of the Theis equation for nonsteady-state flow to a well, which we, like others (e.g., Davis and DeWeist, 1966), identify as the first revolutionary concept in American hydrogeology. The drought ended in about 1940, and the Great Plains returned nearly to normal in time to meet America's agricultural demands for World War II. The dry years demonstrated, however, the desirability of understanding the basic principles of hydrogeology in order to evaluate the potential of this resource.

In anticipation of the need for developing groundwater, O. E. Meinzer of the U.S. Geological Survey had by 1932 gathered into his Division of Ground Water 29 geologists, chemists, and engineers who were virtually the total cadre of groundwater scientists in the United States; these gentlemen are pictured in *Figure 1*; the Division was renamed the Ground-Water Branch in 1949. The Great Depression had begun in 1929, and it ended as America prepared to participate in World War II. Because many industrial plants had been non-operational during the depression, hydrogeologists were greatly needed for advice on obtaining water supplies for new war-products plants and the many military installations. They gained a great deal of experience in the United States and foreign countries, particularly the Pacific islands. For example, Theis himself worked on water supplies for more than 50 military installations and air fields along the Alaskan highway, which was constructed in 1943-44 (Clebsch, 1994).

After World War II and through the 1950's and 1960's, the need for hydrogeologists expanded greatly, reflected in the increased staffing of the U.S. Geological Survey's program, in cooperation with the States, to evaluate the geology and groundwater resources of virtually every county in the Nation. The initiation of this program was prompted by industrial expansion, growth of municipalities, and development of new suburban subdivisions and towns. The need for safe water supplies motivated additional study of the physical and chemical properties of aquifers. Dramatic advances in understanding of the occurrence, movement, and storage of groundwater came about from application of flow-simulation models, initially by electric analog models, to complex hydrogeologic systems; this is the second revolutionary concept of American hydrogeology. Also in the early 1960's, with increasing interest in the chemistry of groundwater, the application of chemical thermodynamics to groundwater systems moved this field of study significantly forward; this is the third revolutionary concept in hydrogeology.

Concerns about environmental contamination resulting from human activities, such as the widespread use of pesticides and petroleum products and incautious waste-disposal practices, were being voiced as early as 1962 in Rachel

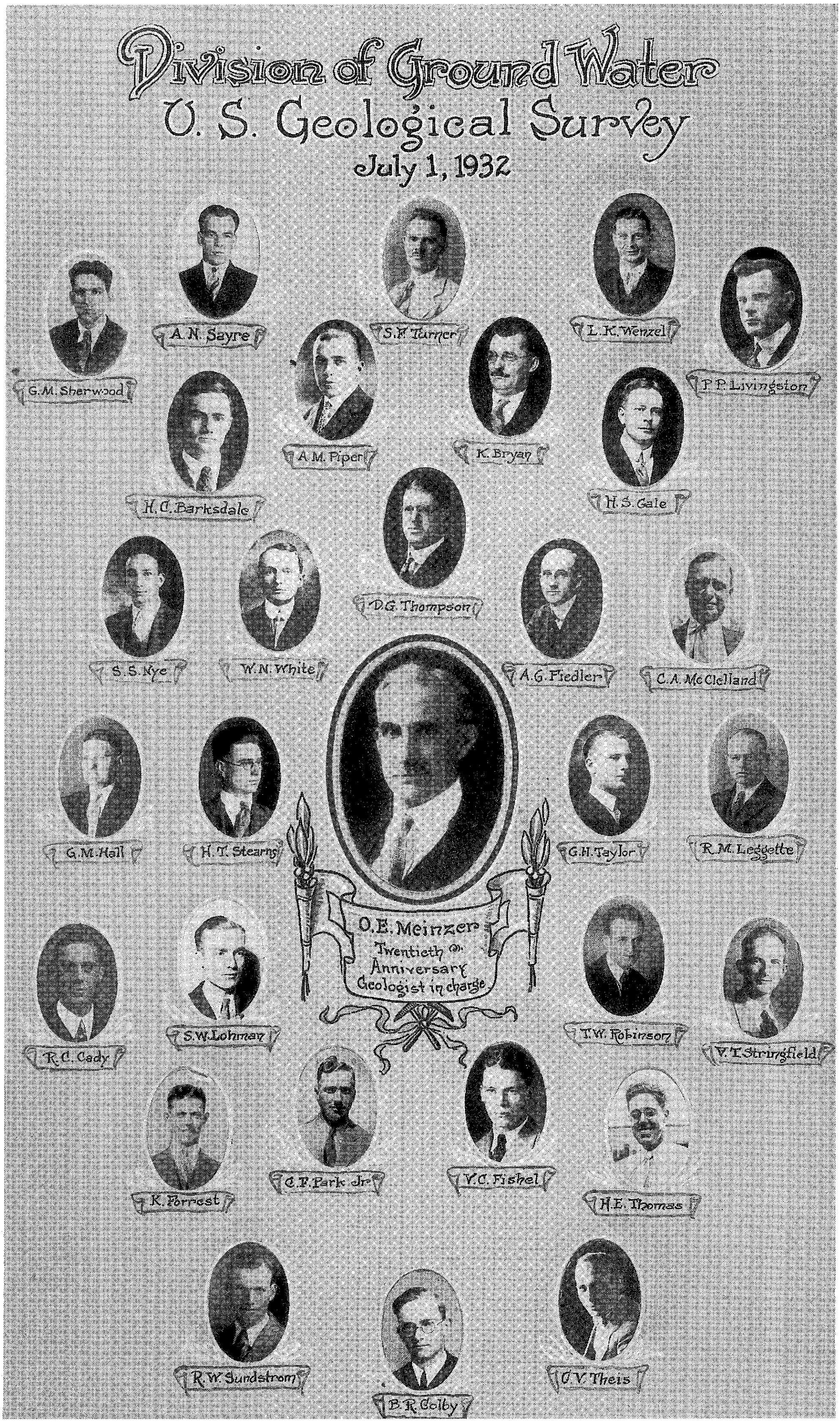

**Figure 1. Virtually the entire cadre of American groundwater scientists in 1932. Photograph provided by David W. Pollock, U.S. Geological Survey.**

Carson's *Silent Spring*. The most obviously contaminated portion of the Earth's surface in the 1960's was the atmosphere, and the Clean Air Act of 1963 addressed the need for emission standards, thus reducing the incineration of wastes and other direct emissions into the atmosphere. With the consequent increased diversion of wastes to water bodies, the increasing contamination became obvious, and major efforts to clean up surface waters was reflected in legislation such as the Federal Water Pollution Control Act (the "Clean Water Act") in 1972. This Act, which restricted the freedom to dispose wastes into bodies of surface water, resulted in more disposal on land. Subsequently, industrial-effluent lagoons, sewage-treatment discharges, landfills, and deep-well injection all contributed to increased contamination of soil and groundwater.

Various types of chemicals are recognized as contaminants in groundwater, including synthetic organic chemicals; hydrocarbons; inorganic cations, including metals; anions; radionuclides; and biological materials, such as pathogenic bacteria or virus. Although natural sources exist for many of the chemical and biological species in groundwater, the most problematic contaminants derive from anthropogenic sources. The Safe Drinking Water Act of 1974 requires that public supplies of water for human consumption meet some minimum standards of chemical quality. Laws such as the Resources Conservation and Recovery Act (RCRA) of 1976 and the Comprehensive Environmental Response Compensation and Liability Act (CERCLA, or "Superfund") of 1980 were meant to regulate toxic wastes and other substances that are major sources of groundwater contamination. These Acts give the Federal government a role in the clean-up and restoration of badly contaminated sites. The most significant sources of groundwater contamination are agricultural chemicals, landfills, surface impoundments, septic tanks and cesspools, underground storage tanks, and injection wells.

Beginning in earnest about 1980, a new effort of hydrogeologists was directed toward the problem of groundwater contamination. Much hydrogeological research in the 1980's and 1990's turned to questions of assessment and remediation of aquifer contamination. In this effort, knowledge of the occurrence and movement of groundwater had to be coupled to an understanding of chemical properties of the water and the aquifer. Recently, recognition of active biological processes in the subsurface has resulted in consideration of microbiologically mediated chemical reactions in most modern studies of contaminated aquifers. The underpinnings of current hydrogeologic research and applications are three revolutionary concepts that brought about dramatic advances in hydrogeology.

## Evolution of Three Revolutionary Concepts

Although we have identified three separate revolutionary concepts, a certain commonality exists in the motivation and the knowledge available to the groups who formulated these concepts. For example, geochemical studies explaining the regional distribution of constituents derived from chemical reactions could not have been done without the understanding of flow characteristics and knowledge of the spatial distribution of hydraulic conductivity and transmissivity gained from aquifer tests and regional aquifer studies. All three concepts depend on having an understanding of regional and local flow systems, which began with the study of the geologic controls on artesian aquifers. Analog and digital models could not have been applied meaningfully without values of transmissivity or hydraulic conductivity and of storativity that were determined by application of the Theis equation. Hydrogeology is still based on the consequences of these three concepts. For example, flow-simulation models are used extensively in research studies and are applied in practical investigations of environmental problems, particularly those related to groundwater contamination. The use of these increasingly sophisticated models permits evaluation of the hydraulic stresses applied to the aquifer, quantification of fluxes of various constituents, and the degree of interconnection of layers of differing permeability.

The relative importance of the three concepts has changed over time. The non-equilibrium well hydraulics approach was tremendously important for a long time in evaluating aquifer characteristics and designing water-supply systems. Then, as drillers and engineers gained expertise in this approach and scientists became less involved in water-supply development, the use of flow-simulation models became much more prominent. In the 1970's, the results of simulation modeling of groundwater systems occupied the bulk of contributions to hydrogeology. Then, in the 1980's, the geochemistry of water supplies rose in importance, and much of hydrogeologic research is now being driven by the need to understand aquifer geochemistry in the context of restoring chemically contaminated sites. In this endeavor, the need to apply non-equilibrium well hydraulics has emerged again. For example, a common practice in aquifer remediation is to pump groundwater to the surface and there apply some treatment scheme; aquifer response to transient conditions must be understood to remediate the site effectively. For assessment and remediation of contaminated sites, interdisciplinary work that embraces physical, chemical, and biological understanding, which is rooted in the three revolutionary concepts, is now the standard. Consequently, the focus of current research is largely directed toward the comprehensive integration of principles from various disciplines to hydrogeologic regimes.

### *Non-Equilibrium Well Hydraulics*

We consider that since 1856, when Henry Darcy described groundwater flow through porous media, the first revolutionary concept in hydrogeology was the heat-flow analogy that led to Theis's equation, published in 1935. Between those dates, American hydrogeologists were becoming aware that a steady-state description of groundwater flow systems was inadequate to evaluate aquifer properties. Theis studied the transient cone of depression around a discharging well and developed a mathematical method to determine the transmissivity and storativity from the rate of drawdown (Clebsch, 1994). This methodology allowed the determination of *in situ* hydraulic properties of aquifers and the prediction of the response, such as drawdown with time and distance, of groundwater systems to pumping. Using this method, hydrogeologists could address quantitatively the transient flow conditions that form the basis for modern hydrogeology. The results of aquifer tests interpreted with the Theis equation are used to guide groundwater development and management, from siting wells to the installation and operation of pumps. Development of water supplies, demanded by an increased population and industrialization, was such an important activity of hydrogeologists that Bredehoeft (1984, p. 436) stated "the period 1935 to about 1962 was a golden era in transient groundwater hydrology, and Theis's original work was the basis of almost all of the scientific information accumulated over that period."

C.V. Theis is responsible for much of our current understanding of aquifer characteristics for two specific reasons. The first is that Theis demonstrated that the study of hydrogeology could be facilitated by the use of analytical models that describe physical phenomena. The second reason is that later contributions in well hydraulics, mainly by C.E. Jacob, M.S. Hantush, H.H. Cooper, Jr., and others, built on Theis's original work. Further, the concept of storativity, demonstrated by Theis, has found widespread application; it implies that rock bodies are not rigid but rather are compressible. Before development of the Theis equation, the occurrence and movement of groundwater could not be treated quantitatively, because aquifers are not under static equilibrium conditions, as had been the treatment in the Thiem equation (Wenzel, 1936). As exemplified in the papers listed in *Table 1* and in other papers, the use of Theis's contribution generated knowledge about many topics, including the relation of groundwater levels to precipitation and flooding, the flow behavior in leaky aquifers, compression of elastic artesian aquifers, water supply from leaky artesian aquifers, and land-surface subsidence.

### Groundwater Flow and Simulation

The second revolutionary concept was the recognition that the distribution of fluid potential can be formulated in mathematical equations and solved by various techniques to generate flow-simulation models. Knowledge of the distribution of fluid potential was achieved by the numerous regional field studies that produced maps depicting the fluid potential, commonly referred to as head, on contour maps showing water levels or piezometric surfaces. Hubbert (1940) pointed out that "piezometric" is a misnomer because it comes from the Greek word for "pressure," and pressure is obviously not the driving force; therefore, "potentiometric" is now used to refer to head, or fluid potential. Flow-simulation models are used extensively to calculate the head distribution.

As shown in *Table 2*, regional flow of groundwater was initially studied in the U.S. by Chamberlin (1885), who described the pervasive occurrence of water in the subsurface and the role of geologic media of contrasting permeabilities; and by Darton (1897), who mapped recharge and discharge areas of the artesian Dakota aquifer. The mechanics of artesian flow were understood generally from these early studies. Continuing studies on geologic controls included investigation of aquifer stratigraphy, hydraulic properties of aquifers, and the geology of groundwater resources in a variety of locations. By the late 1950's, the stage was set for a bifurcation of activities in this field, in which one branch of investigations continued in the mode of field-based regional studies of groundwater flow, and the second branch emphasized the use of simulation models. This bifurcation is reflected in the papers listed under the two branches in *Table 3*.

**Table 1. The most influential papers on non-equilibrium well hydraulics. Organized by decade; full citations appear at the end of the paper.**

| Decade | References |
|---|---|
| 1930's | Theis (1936)<br>Wenzel (1936) |
| 1940's | Cooper and Jacob (1946) |
| 1950's | Ferris and Sayre (1955)<br>Hantush and Jacob (1955)<br>Rouse and Ince (1957) |
| 1960's | Walton (1960)<br>Lohman (1961)<br>Ferris et al. (1962)<br>Bentall (1963)<br>Cooper (1966)<br>Poland and Davis (1969) |
| 1970's | Lohman (1972) |

These two lines of investigation continue to be closely linked. Fundamental hydrogeologic processes are understood through field study of the physical system; those phenomena are simulated in numerical models, and the success of the model is evaluated by comparison to hydrogeologic observations in the field, leading to refinement of the model. In truth, models are useful tools for generalization of a complex system, the properties of which we can never fully measure. Yet, neither can models fully reflect the complexity of a natural system. Each avenue of investigation supports the other as hydrogeologists seek to quantify groundwater flow in aquifers.

Field-based investigations of aquifers have provided the basis for our understanding of physical properties of aquifers. The geologic controls on groundwater occurrence and migration are summarized for a variety of aquifers in the GSA DNAG volume mentioned earlier. The second branch followed more directly from the innovative application of

**Table 2. The most influential papers on groundwater flow and simulation. Part 1, Regional flow, descriptive, tied to geologic framework (1880's-1930's). Organized by decade; full citations appear at the end of the paper.**

| Decade | References (Regional flow, descriptive, tied to geologic framework) |
|---|---|
| 1880's | Chamberlin (1885) |
| 1890's | Darton (1897)<br>King (1898)<br>Slichter (1899) |
| 1900's | Mendenhall (1905)<br>Darton (1905)<br>Fuller (1908)<br>Darton (1909) |
| 1920's | Meinzer (1923a)<br>Meinzer (1923b)<br>Meinzer and Hard (1925)<br>Meinzer (1928)<br>Russell (1928) |
| 1930's | Fiedler and Nye (1933)<br>Stringfield (1936)<br>Tolman (1937)<br>Casagrande (1937) |

flow-simulation models, specifically electric analog models, to the regional flow of groundwater. These models employed the flow of heat and electricity as an analogy for the flow groundwater. The simplest model was composed of conductive graphite paper cut into the shape of the mapped area or cross section, with permeable boundaries simulated with strips of solder, and impermeable boundaries represented by the edge of the graphite paper. A voltmeter was used to determine voltage intervals, and the lines of equal voltage simulated equipotential lines, which were traced with a stylus attached to the voltmeter. Flow lines were then added, based on the principles of flow-net analysis, as previously described by Casagrande (1937) and others.

More advanced analog models used electronic components of voltage regulators, resistors, and capacitors to simulate flow, transmissivity, and storativity, respectively. These electronic components were overlaid on maps that were mounted on large poster boards as much as 1-2 m high and 5-8 m long. A fixed transmissivity was built into the model and the head was measured at nodes under various conditions of recharge and discharge. The experience gained with analog models led directly to formulation of digital models of groundwater flow when the computer became available. Although electric analog models were exceedingly useful as expressions of a physical model for aquifers, they were eclipsed very rapidly by digital computer models in the 1960's and 1970's. Developments by H.E. Skibitzke, W.C. Walton, T.A. Prickett, C.G. Lonnquist, R.A. Freeze, and P.A. Witherspoon established the new field of digital groundwater flow modeling. Digital computers provided the means for assessment of groundwater resources on a regional scale within the context of the full hydrologic cycle.

The application of these developments in digital flow modeling culminated in the use of such models to quantify solute migration in aquifer systems (Bredehoeft and Pinder, 1973). These numerical flow models are still widely used in the management of aquifers to solve not only problems of groundwater supply but also to predict the fate of chemical constituents in groundwater. Much current work with numerical simulation models is conceptually similar to this effort at quantifying mass transport in groundwater. New advances in numerical methods and computing power led to increased complexity of the models in terms of dimensions, fluid density, aquifer heterogeneity, and geochemistry. Probably the greatest strength of numerical groundwater flow models is the possibility to evaluate the effects of physical and chemical heterogeneity and their impacts on actions aimed at remediating groundwater contamination. Current activities seek to consider adequately flow in fractures and karst and to couple the models to robust geochemical models.

### *Hydrogeochemistry*

The third revolutionary concept was the recognition, in the early 1960's, that certain principles of physical chemistry could be used to identify the reactions and processes that determine the chemical character of water. Prior to that time, knowledge of groundwater chemistry followed an evolutionary development from the earliest analyses in the nineteenth century. The most influential papers on hydrogeochemistry are listed in *Table 4*.

Early in the twentieth century, studies of groundwater that considered geochemistry did so from the perspective of reporting the results of the chemical analyses of water samples. The chemical composition of natural waters placed limits on utilization of the resource for various intended purposes. Observations of groundwater composition in different geological settings were useful in developing early ideas about the geochemical evolution of groundwater. Important techniques in graphical representation of chemical data, developed in the 1920's through the 1950's, helped illustrate chemical relationships and reactions influencing groundwater composition. The literature on groundwater chemistry moved from descriptions of the outcomes of a process to the understanding of the process itself (e.g., Foster, 1950; Back and Hanshaw, 1965; and Back, 1966). Beginning in the 1960's, mineral equilibria studies based on the law of mass action, Gibbs free energy, and the Nernst equation provided the basis for understanding chemical processes. At that point,

**Table 3. The most influential papers on groundwater flow and simulation. Part II, Bifurcation (1940's-1980's). Organized by decade; full citations appear at the end of the paper.**

| Decade | References | |
|---|---|---|
| | **Branch 1: Regional flow, quantitative, tied to geologic framework** | **Branch 2: Flow-simulation models and mathematical analysis** |
| 1940's | Sayre and Bennett (1942) | Hubbert (1940)<br>Jacob (1940) |
| 1950's | Bennett and Meyer (1952)<br>Todd (1959) | Stallman (1956) |
| 1960's | Vernon (1961)<br>Simpson (1962)<br>Farvolden (1963)<br>Maxey (1964)<br>Chow (1964)<br>Lohman (1965)<br>Davis and De Wiest (1966)<br>Legrand and Stringfield (1966)<br>Stringfield and Legrand (1966)<br>Maxey (1968) | Skibitzke (1961)<br>Skibitzke and Robertson (1963)<br>Walton and Prickett (1963)<br>Toth (1963)<br>Tyson and Weber (1964)<br>Remson et al. (1965)<br>Patten (1965)<br>Freeze and Witherspoon (1966)<br>Freeze and Witherspoon (1967) |
| 1970's | -- | Walton (1970)<br>Prickett and Lonquist (1971)<br>Bredehoeft and Pinder (1973) |
| 1980's | Heath (1984) | -- |

groundwater geochemistry became quantitative, and it became possible to predict the outcome of water-rock interactions.

Focused questions in hydrogeochemistry evolved out of development of coastal water supplies. With most of the population of the U.S. settled in coastal regions, extensive pumping of groundwater readily induced salt-water intrusion into the water-supply aquifers. Investigations of salt-water encroachment have been done since the early years of American hydrogeology (Sanford, 1910). Grappling with this problem motivated advancements in flow modeling of fluids of varying densities, increased availability and quality of thermodynamic and analytical data, and the quantification of water-rock interactions for a common hydrogeologic setting.

The 1960's and 1970's brought the application of isotopes to hydrogeologic investigations, specifically as useful tools in the study of geochemical and hydrogeologic processes. Stable isotopes yielded insights to climatic conditions of groundwater recharge, thermal conditions of water-rock interactions, and the impact of biological processes on water chemistry. Radioactive isotopes were used to interpret groundwater flow velocities and mineral-water reaction rates.

The thermodynamics-based approach to groundwater geochemistry is supported today by computer-based geochemical models (Truesdell and Jones, 1974). The computational advances afforded by the computer allow complex systems of many elements, aqueous species, and minerals to be considered in the prediction of water chemistry. These models have proven useful in the analysis of aquifer characteristics, site characterization, and performance assessment for underground waste repositories. Current research is focused on evaluation and simulation of rates of reactions, the behavior of organic compounds in aquifers, and the mediation by microorganisms of chemical reactions. Coupling of geochemical models to groundwater flow and transport models is currently under development and should lead to an improved understanding of the fate of chemicals in the subsurface environment.

## Conclusions

Many of the above needs and desires can be addressed by a responsible application of basic principles and current understanding of hydrogeology. However, for some topics the knowledge is insufficient for the precision demanded for adequate resolution of particular problems.

We believe that the broad topics of hydrogeologic research over the next few decades can be grouped as 1) development

**Table 4. The most influential papers on hydrogeochemistry (1910's-1970's). Organized by decade; full citations appear at the end of the paper.**

| Decade | Reference |
|---|---|
| 1910's | Sanford (1910)<br>Palmer (1911)<br>Emmons and Harrington (1913)<br>Mendenhall et al. (1916)<br>Rogers (1917) |
| 1920's | Collins (1923)<br>Renick (1924)<br>Brown (1925)<br>Thompson (1928) |
| 1930's | Langelier (1936) |
| 1940's | Tolman and Poland (1940)<br>Hill (1940)<br>Stearns and MacDonald (1942)<br>Piper (1944)<br>Brown and Parker (1945) |
| 1950's | Foster (1950)<br>Stiff (1951)<br>Piper et al. (1953)<br>Winslow et al. (1957)<br>White (1957a)<br>White (1957b)<br>Perlmutter et al. (1959)<br>Hem (1959) |
| 1960's | Kohout (1960)<br>Berry and Hanshaw (1960)<br>Garrels (1960)<br>Craig (1961)<br>Cooper et al. (1964)<br>White (1965)<br>Seaber (1965)<br>Graf et al. (1965)<br>Hanshaw et al. (1965)<br>Garrels and Mackenzie (1967)<br>Krauskopf (1967)<br>Dincer and Davis (1968)<br>Hitchon and Friedman (1969)<br>Runnells (1969)<br>Barnes and Clarke (1969) |
| 1970's | Davis et al. (1970)<br>Langmuir (1971)<br>Truesdell and Jones (1974) |

of effective models for flow and transport in fractured and soluble rocks, 2) determination of rates of chemical reactions and flow, and 3) development of more refined transport models that couple the rates of flow and reactions. These challenges reflect the control of physical and chemical heterogeneity on groundwater systems. The controls of heterogeneity will be elucidated to a large extent by the study of isotopes, tracers, organic compounds, and microorganisms in groundwater and the application of geophysical techniques to aquifer systems.

Hydrogeologists have had compelling professional responsibilities since the science was identified and achieved formal recognition. These have included the development of scientific principles and the application of these principles to satisfy the needs of society. These activities have been performed, and will continue to be performed, with a code of professional ethics and integrity. However, because of expansion of complex societies, these activities are no longer adequate, and we have identified three other increased responsibilities that should be fulfilled by hydrogeologists. These are to 1) enhance public awareness and knowledge of groundwater, 2) demonstrate the justification for funding of investigations and research, and 3) contribute to amelioration of international environmental disasters.

Because of time constraints on planners, legislators, and water managers, we can no longer assume that publication of articles in scientific journals, or even popular literature, will necessarily reach the appropriate decision-makers. We must devote some amount of time each year to the efforts of governmental institutions, universities, professional societies, and other non-governmental organizations that have programs to improve scientific literacy of the public. It is particularly important for young children to become conscious of, and sensitive to, nature and the environment. These children are the future decision-makers. Such outreach programs will eventually demonstrate the desirability of funding for hydrogeology and other sciences. Many areas of the world have undergone environmental devastation, and because of expanding population and urbanization, increased stress has been placed on water resources. Inhabitants of those areas will need the advice of hydrogeologists as they plan for a sustainable future.

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**(See *Tables 1-4* for chronological listing by decade)**

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