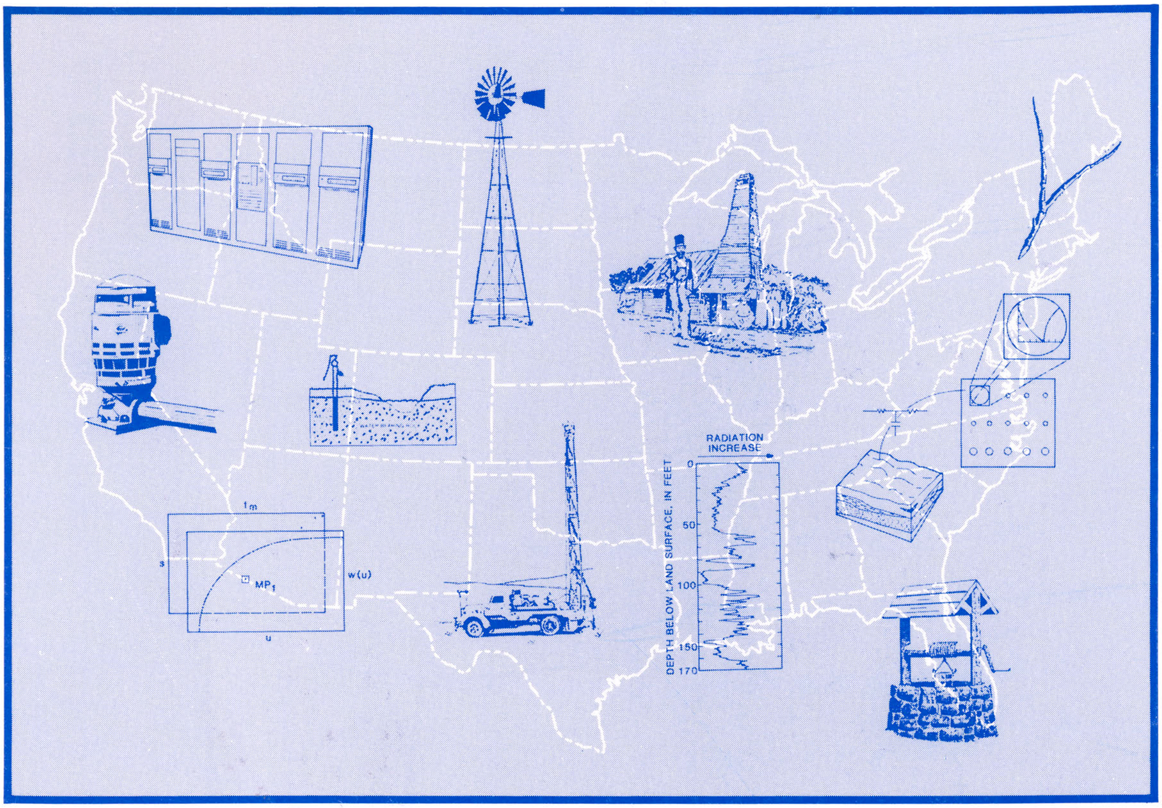
TWO-HUNDRED YEARS OF HYDROGEOLOGY IN THE UNITED STATES

U.S. GEOLOGICAL SURVEY

Open-File Report 86-480



TWO-HUNDRED YEARS OF HYDROGEOLOGY IN THE UNITED STATES

J. S. Rosenshein, J. E. Moore, S. W. Lohman, and

Edith B. Chase, Editors

U.S. GEOLOGICAL SURVEY

Open-File Report 86-480

Reston, Virginia

1986

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

U.S. Geological Survey
Water Resources Division
Branch of Scientific Publications
444 National Center
Reston, Virginia 22092

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center, Bldg. 41
Box 25425
Denver, Colorado 80225

CONTENTS

CONTENTS--Continued

CONVERSION FACTORS

For those readers interested in the International System of Units (SI), the inch-pound units used in this report may be converted using the following factors:

Multiply inch-pound unit	By	To obtain SI unit
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

PREFACE

The Hydrogeology Division of the Geological Society of America (GSA) sponsored a symposium entitled "Hydrogeology in the United States, 1776-1976" at the annual meeting of the GSA on November 9, 1976. The symposium was organized by John E. Moore to provide a forum for discussion of major eras in the history of American hydrogeology and to contribute to the bicentennial celebration of the founding of the United States. In addition, presentations were given on three historical topics--"The Hydrogeologist and Houston, Texas," "Hydrogeology, Policy, and Politics," and "A Look to the Future." C. V. Theis provided a summary of the symposium, which had an attendance of more than 150 people. John E. Moore was asked by the Hydrogeology Division to prepare the proceedings of the symposium.

The papers are published in the sequence of symposium presentation. Stan Lohman prepared two new chapters to make the historical summary complete.

We are grateful to the editors of Journal of Hydrology for permission to reprint the paper by George B. Maxey.

J. S. ROSENSHEIN,

JOHN E. MOORE,

STAN LOHMAN, and

EDITH B. CHASE, Editors

TWO-HUNDRED YEARS OF HYDROGEOLOGY IN THE UNITED STATES

J. S. Rosenshein, J. E. Moore, S. W. Lohman, and

Edith B. Chase, Editors

1. INTRODUCTION

This publication traces the development of the science of hydrogeology during the 200 years following the founding of the United States in 1776. Emphasis is on contributions of the United States scientific community. Little substantive progress took place in the development of hydrogeology as a science prior to 1879 when development took a major step forward with the establishment of the U.S. Geological Survey. Early in its history, the U.S. Geological Survey began to focus on both scientific and practical problems related to the occurrence, movement, and development of ground water. The organization attracted a group of dedicated scientists who directed their inquiry into many facets of ground-water geology, hydrology, and hydrogeology. Through both governmental and journal publications, they documented their systematic approaches to data collection, analysis, and interpretation. Much of the work prior to the 1960's was descriptive and qualitative, but it served as the underpinning for the more quantitative modern approaches in current use. Major aquifer systems were defined and their physical characteristics described during the first half of the 20th century. The result was the development of extensive and rich background literature on the ground-water geology and hydrology of the United States.

The efforts in ground-water science were strengthened further by the establishment in the early 1930's of cooperative programs between state agencies and the U.S. Geological Survey. These programs resulted in the distribution of a cadre of Survey ground-water scientists nationwide, and for many states the development of their own cadres of ground-water scientists to complement those in the U.S. Geological Survey. This program also strengthened ties at the state level and increased cooperation between university scientists and the U.S. Geological Survey. The publications yielded by cooperative efforts with state agencies and universities further enhanced the literature of ground-water science and expanded understanding of the concepts of the occurrence and movement of ground water.

The strength and growth of the science of hydrogeology in the United States is attributable also to the several scientific and technical societies concerned with earth sciences--in particular, the Geological Society of America and the American Geophysical Union. These two scientific societies served as forums for discussion and reporting of scientific achievement in their journals. Therefore, it is appropriate that this symposium was sponsored by one of these, the Geological Society of America, through its Hydrogeology Division.

This publication is divided into three sections: (1) the Early Era (1776-1910), (2) the Meinzer Era (1910-40), and (3) the Modern Era (1940-76). The degree of maturity of the science of ground water in the Modern Era is worth noting; that is, its multidisciplinary approaches and its pertinence to addressing current real-world problems. Although the contributions of only a relatively few ground-water scientists can be highlighted in this publication, many other dedicated, renown ground-water scientists obviously have played significant roles in carrying forward the science.

2. THE EARLY ERA--1776-1910

Out of necessity, some of the early settlers in America developed a rudimentary understanding and perhaps even a limited scientific interest in hydrogeology. They were dependent upon water from springs, dug wells, and streams for drinking supplies.

From 1776 to about 1865, the science of hydrogeology in the United States was characterized by slow growth in the understanding of underlying principles. Little or no fundamental systematic scientific research was undertaken, although progress was being made in Europe at the time. In the United States, the science of hydrogeology was awaiting the further development and understanding of the related aspects of geology, engineering, and other sciences that were to form the foundation of hydrogeology.

With the opening of the west in the late 1860's and the emerging demand for ground water for drinking supplies came the urgent need for systematic and scientific studies of ground-water resources. These early studies were concerned with the development of an understanding of the principles underlying the occurrence and movement of water in artesian aquifers. Some of the State Geological Surveys pioneered this development through their scientific investigations. The establishment of the U.S. Geological Survey in 1879 resulted in the formation of a national organization that was to foster a strong interest in hydrogeology through the remainder of the Early Era and, in conjunction with the State Surveys and academia, was to contribute significantly to scientific development of hydrogeology.

Birth of American Hydrogeology

By

George W. White
Research Professor Emeritus
Department of Geology
University of Illinois
Urbana, Illinois

Introduction

This paper was given at the symposium on History of Hydrogeology in the United States from notes rather than from a formal manuscript. The illustrations were a series of slides of title pages of books, illustrations, or a few lines from early reports. Only a few of the illustrations are reproduced here. When it was decided to publish the papers of the symposium, John E. Moore provided a tape-recorded transcript, which has been edited and revised. Had the author realized a recording was being made he would have been less informal and facetious at some places and striven for a more "scientific," historiographic, and scholarly presentation.

Virginia and the South

Thomas Hariot was a 25-year-old scientist with the 1585-86 Raleigh Expedition to Virginia. Hariot, who later attained fame as a mathematician and astronomer possibly second only to Newton, wrote in 1588 about the water-related culture of the Indians of tidewater Virginia (actually in present North Carolina). His artist, John White, made many beautiful watercolors, reproduced in the De Bry 1590 edition as black-and-white engravings; a few rare copies are colored. In his writing, Hariot alluded only in a vague way to ground water.

Another early settler who reported on the occurrence of water was John Clayton, a young English clergyman who had been sent with several other young ministers to America by the Bishop of London. His task was not only to minister to the spiritual needs of the colonists but also to report on the natural history of the new country. Clayton wrote several papers for the Royal Society. In his second paper (1693), Clayton reported on the springs and their quality and about wells.

Shortly thereafter, in 1705, Robert Beverley, a Virginia planter, wrote a little book, "The History and Present State of Virginia." He was the first to write a whole chapter on water--the amount, the quality of the well water, and the springs. As a prosperous planter situated near tidewater, he understood the importance of water for agriculture and for transportation. Beverley included in his book information about mineral springs, their characteristics and usefulness.

J. F. D. Smyth (1784) wrote about the relation of rainfall to the discharge of the streams in the southern colonies. He asserted that there was no question but that stream discharge depended on the rainfall and gave observations to prove the assertion.

Andrew Ellicott was the engineer who completed the plan for the city of Washington and actually did most of the work in laying out the city in 1792-93. In 1797-1800, he traveled on an official mission from Pittsburgh, Pa., down the Ohio River to New Orleans, La., and across to Florida. He made some very perceptive observations as he went along on the character of the discharge of the Ohio and Mississippi Rivers. He published a very extensive report (1803) on the hydrologic conditions and on the change of channels with streamflow. His expertise as engineer, hydrologist, and geologist shows throughout his report.

New England

Most early writers in New England included water in their descriptions. William Wood (1634) told of the ease of digging successful wells and gave details of the quality of water in Massachusetts. It is interesting to note that both the early reports and the later ones dealt with both the quality and the amount of water. Although chemical analyses were made in the late 18th century in this country, the quality of water for drinking was judged mainly by its evaporated residue, its taste, and by possible industrial use. Wood said the quality of water in the Boston region was superb; "it was almost as good as good Beere and any man would choose it before bad beere, whay or buttermilk."

In 1637, Thomas Morton, in his book "New English Canaan," told of the excellent supply of ground water in Massachusetts and of the ease in digging wells (which almost certainly were in drift--sand and gravel). He wrote about medicinal water and some of its inconvenient effects. John Josselyn (1692) was one of the first to relate snowmelt runoff on Mt. Washington, N.H., to streams and the cutting of the valleys.

Middle West

Pioneers found that water conditions across the mountains, particularly west of the Appalachian Plateau, were quite different from those they had known in the East. In the East, no problem generally existed in obtaining reasonable amounts of water from wells and in finding locations for "mill seats" along streams. A mill could be established just about any place desired in New England and on the plateau in Pennsylvania and eastern Ohio. In Pennsylvania and eastern Ohio, springs also were common, and their presence influenced house locations. However, as the pioneers moved west from the plateau onto the prairies, they found that mill seats and precious streams were uncommon. In addition, the water was not of the same composition as that they had been used to. The reports they sent back were detailed as to where settlers could find mill seats. Many reports were guides for immigrants; some were collected reports of travelers, and others were gazetteers. Almost all reports mentioned water, and many contained separate sections on water.

Many of the reports tell what geologic conditions were encountered in constructing dug wells. The reports tell about "clay" (till) overlying sand and gravel or of "clay" (till) underneath outwash. Some reports noted that, if bedrock were reached in a well, it would be either shale or sandstone and that the latter was far more favorable for a satisfactory water supply. Some reports gave details of the depths of these various strata, both surficial and bedrock.

Christian Schultz traveled in the Ohio Valley and the upper Mississippi Valley. He described (1810) layered sediment in the Mississippi flood plain, which had been exposed by bank erosion, and made estimates of the length of time to deposit these various layers. He counted 803 layers, which he said meant 803 inundations, and estimated how many years were represented. Here was early geochronology.

Water quality was mentioned frequently in the early reports on the Middle West. Salt springs and saltwater wells were very important to the settlers as a source of salt. Some reports tell about the strength of the saltwater, which they measured in various ways (would it float an egg?). Many writers described the quality of potable water. Willian Maclure (1817), the well-known geologist, discussed in detail the various kinds of rocks in which different kinds of water occurred. He said that the people who had emigrated from a region of primitive (crystalline) rocks or granites, where the water is soft, "...find our limestone water to produce a slight effect... which will prove more advantageous to health than otherwise, and which will last but a few weeks."

Many reports gave the effects of water in the prairie region as being quite "different" and that it would take a few days or a few weeks to get used to it. One of the reports described the water from a well that someone dug in an Indian mound, an ancient graveyard. At 65 feet the digger ran through a water-bearing organic layer, and the writer says the water was very noisome. Robert Sears (1848) was particularly vehement about the water quality. Sears was in an area in northern Illinois where the water was sulfurous; he said that the water was very bad and suggested that the "vile liquor," which was consumed in large amounts in that region, was popular because of the poor quality of water.

Pioneer women were particularly perceptive concerning the quality of the water because of the large amount of soap often required. Much of the water was so hard that houses had rain barrels, and later the more affluent citizens had cisterns to supply soft water for drinking and washing purposes.

John Robert Shaw, Well Digger

John Robert Shaw, in a very rare book (1807, fig. 1), told of his life and well-digging career. Shaw had been a soldier in the Revolutionary War, first with the British Army and then, following capture, with the American patriots. He fought with the infantry, the artillery, and apparently, at least part of the time, with the engineer corps.

Shaw was fascinated with the use of explosives for military and civilian purposes, and he used these in digging wells in bedrock in both Pennsylvania and Kentucky. He would set the charge, light the train of black powder (the only form of fuse at the time), and then get out. By the age of forty-five he had been blown up four times (figs. 2 and 3) because he did not get out of his wells fast enough.

In his book, Shaw (1807) listed the strata penetrated in scores of wells, the depth of the wells, the conditions under which water occurred, and the way in which he found water. He was quite clever at determining where water could be found. He was a declared "bledonist" (after a man by the name of Bledon). Bledon asserted that water had sort of an aura, and if you could detect this aura, you could locate a favorable place to find water. Shaw asserted that this was not water witching, but it seems close to it.

Water Recovery

In early days, water was obtained by windlass and bucket or by well sweep. The frontispiece (fig. 4) from a book by G. W. Atkinson (1881) shows how water was recovered in early days by well sweep--a counter-balanced pole and a bucket that went down into the well. This method was used as late as 1936 on the Coastal Plain of North Carolina (Lohman 1936, fig. 3-B). The water from the well shown in figure 4 (Atkinson, 1881) must have been of high quality because you can see from the frontispiece caption what they were using the water for.

Water was vital in early days, even as now, and some astute observers told about its presence, quality, and methods of recovery.

Acknowledgments

I am indebted to John E. Moore and Stan W. Lohman for valuable suggestions on transposing an oral recording to manuscript form.

A

NARRATIVE

OF THE

LIFE & TRAVELS

OF

JOHN ROBERT SHAW,

THE WELL-DIGGER,

NOW RESIDENT IN LEXINGTON, KENTUCKY.

WRITTEN BY HIMSELF.

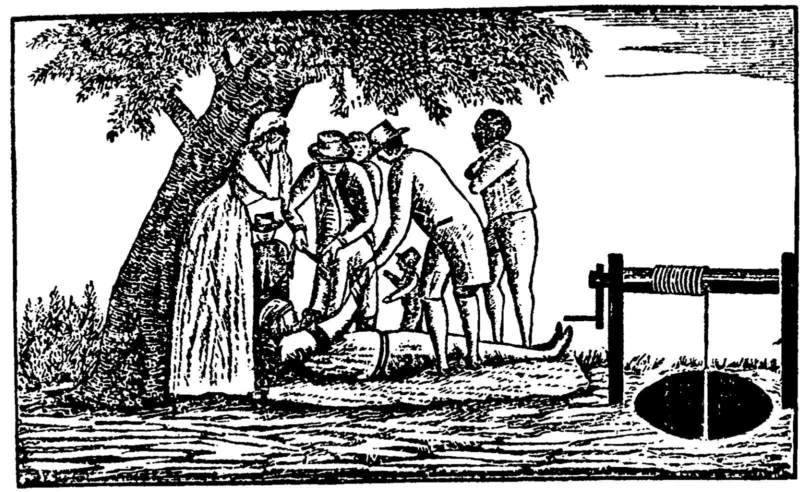
" He that once sins, like him that slides on ice,
" Goes swiftly down the slippery ways of vice ;—
" But happy he, who with a prudent care,
" Retreats betimes from the fallacious snare."

LEXINGTON:

PRINTED BY DANIEL BRADFORD.

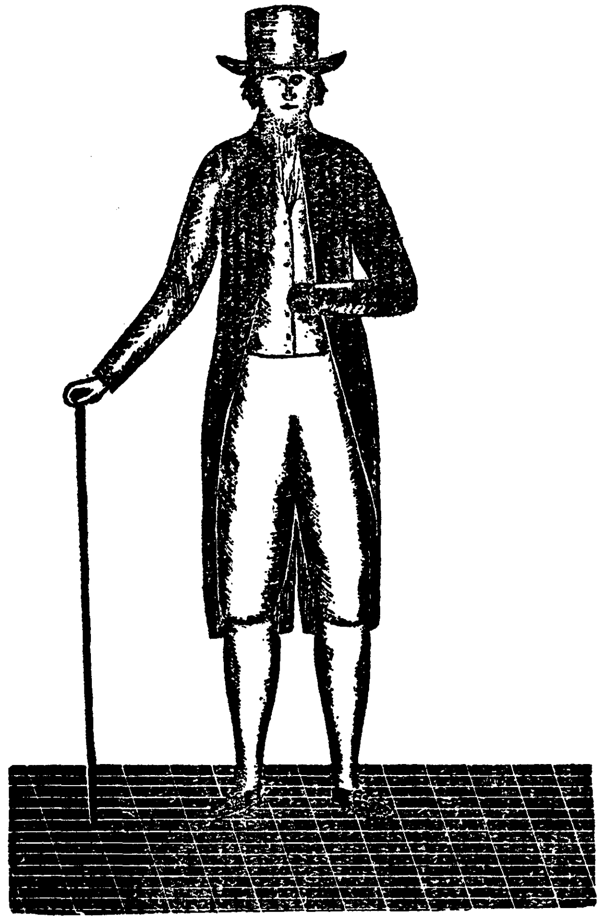
1807.

Figure 1.--Title page of book by John Robert Shaw (1807).



The Deplorable Situation of JOHN R. SHAW, late Well-Digger of Lexington, surrounded by his Friends and Distressed Famliy—23d August, 1806.

Figure 2.--Shaw's rescue from explosion in a well (note windlass).



'The Wonderful recovery of JOHN R. SHAW

I'll praiſe the LORD while I have breath,
And ſhout his holy name,
And all the wonders of his works
I loudly will proclaim.

Figure 3.--Portrait of Shaw (note false lower left arm and misshapen foot).

References

Atkinson, G.W., 1881, After the moonshiners, by one of the raiders--A book of thrilling, but truthful narratives: Wheeling, W. Va., 239 p.

Beverley, Robert, 1705, The history and present state of Virginia, in four parts: London, R. Parker, p. 40, 64, 83, 104. (Contains 14 copies of the De Bry 1590 plates. Another edition, 1722).

THE HOME OF THE MOONSHINER.

Figure 4.--Pioneer home showing well and counterbalanced pole for lowering and raising bucket. Frontispiece, Atkinson, 1881.

Clayton, John, 1693, Mr. Clayton's second letter: London, Philosophical Transactions of Royal Society, v. 17, p. 790-95; 1708, Miscellania Curiosa (Mr. Clayton's second letter, containing his further observations on Virginia: London, v. 3, p. 293-355).

Ellicott, Andrew, 1803, The journal of Andrew Ellicott: Philadelphia, Thomas Dobson, 151 p., maps and plates.

Hariot, Thomas, 1588, A briefe and true report of the newfound land of Virginia: London, 24 leaves, no illustrations.

______ 1590, A briefe and true report of the newfound land of Virginia: Frankfort, De Bry, 64 leaves, 28 plates, map.

Josselyn, John, 1692, New-Englands rarities discovered: London, G. Widdowes, 114 p.

Lohman, S.W., 1936, Geology and ground-water resources of the Elizabeth City area, North Carolina: U.S. Geological Survey Water-Supply Paper 773-A, 57 p.

Maclure, William, 1817, Observations on the geology of the United States: Philadelphia, A. Small, 127 p.

Morton, Thomas, 1637, New English Canaan: Amsterdam, J.F. Stam.

Schlutz, Christian, 1810, Travels on an inland voyage: New York, Isaac Riley, 2 vols., 224 p.

Sears, Robert, 1848, A new and popular pictoral description of the United States: New York, Sears, 608 p.

Shaw, J.R., 1807, A narrative of the life and travels of John Robert Shaw, the well digger, now resident of Lexington, Kentucky: Lexington, Daniel Bradford, 242 p. (Literal reprint, 1930).

Smyth, J.F.D., 1784, A tour in the United States of America: London, G. Robinson, 2 vols., p. 398, 455.

Wood, William, 1634, New England prospect--A true, lively, and experimental description: London, John Bellamie, also Boston, 1865.

Early Stage of Hydrogeology in the United States

By

Garald G. Parker, Sr.
Parker and Associates
Tampa, Florida

Introduction

Hydrogeology is concerned with ground water and, as ground water occurs in a geologic environment, an understanding of the geologic fabric and framework is essential to ground-water development and use. But ground-water flow, discharge, recharge, response to pumping, and other related matters, including saltwater encroachment, are described by mathematical formulas and tested by engineering techniques. Until both the sciences of geology and engineering hydrology were advanced far enough during the late 1800's to be of practical help, hydrogeologic progress was stymied.

Additionally, an economic need for hydrogeologists was required before a demand developed for such scientists. With the opening of the West in the late 1860's the demand came. Hydrogeologists were needed to find irrigation water for the arid lands. Concomitantly, in the South, ground water was needed for growing rice, corn, and cotton. The rapid growth of cities, especially in the North, required hydrogeologists to find safe supplies of clean, pure water to replace polluted surface-water sources. By the early 1900's, engineering techniques and equipment needed to drill and pump the deep wells and to evaluate the aquifer pumping tests were available, satisfactory for the times, but clumsy and awkward by modern standards. By 1910, the U.S. Geological Survey had developed into one of the foremost governmental scientific organizations in the world, and its small cadre of hydrogeologists were leaders in their science. A wealth of information concerning the history and development of the science both in the United States and abroad was summarized by Meinzer (1934).

Definition of Hydrogeology

The term "hydrogeology" apparently was first used in a publication entitled simply "Hydrogeologie" by J. B. Lamarck (the Chevalier, best known as the Father of Invertebrate Paleontology) in 1802. Lamarck intended this term to mean the study of aqueous erosion and sedimentation that have carved mountains and tablelands through the limitless vista of the past, during much of which ancient seas covered what is now dry land. He did not mean "ground-water geology." Much later, J. W. Powell (1885), pictured in figure 5, used a similar term "hydric geology" with much the same meaning as that of Lamarck.

Figure 5.--Major John Wesley Powell, founder and leader of the "Powell Surveys" (1868-79) and second Director of the U.S. Geological Survey (1881-94).

U.S.G.S. Photo Library

Probably the first use of "hydrogeology" in its modern sense was by J. Lucas (1880) in his report entitled "The Hydrogeology of the Lower Greensands of Surrey and Hampshire." But the best publication of its kind came out in 1887, a three-volume work by A. Daubree on hydrogeology entitled "Les Eaux Souterraines, Aux Epoques Anciennes et a l'epoque Actuelle."

The term "hydrogeology" came into use in the U.S. Geological Survey during the 1880's among Geologic Branch geologists assigned to ground-water studies. When a special organization for ground-water investigations was established by the U.S. Geological Survey in 1903, some indecision existed as to the proper name for this group. Fuller (1905), reporting on the ground-water program of the U.S. Geological Survey in the eastern United States before the 8th International Geographical Congress, 1904, said: "The division of hydrology, or hydrogeology, as it might be most aptly termed, is that division of the U.S. Geological Survey which deals with underground waters in the same manner as the division of hydrography of the Survey deals with surface waters."

Later in 1906 (U.S. Geological Survey Water-Supply Paper 160, p. 10), Fuller speaks of "geohydrologists" and on p. 11 says that "geohydrologists, or those devoting their entire time to the study of underground water,... ." Meinzer (1942) in his monumental work, "Hydrology," also uses the term "geohydrology," but in an earlier paper (1934) he used the term "ground-water hydrology."

Modern usage approximately equates hydrogeology with geohydrology, ground-water geology, or ground-water hydrology and intends it to mean the science of the occurrence and behavior of ground water in its geologic framework and fabric. Some scientists make a differentiation based on whether the emphasis is on the geologic environment (hydrogeology), or on the water, particularly quantitative studies (geohydrology).

1776-1865

In 1776, British colonization of the Thirteen American Colonies was more than 150-years old. About 3 million colonists had settled the eastern seaboard from Canada to Florida, and an estimated 250,000 had migrated into or across the Appalachian Mountains. Already, Boston, Philadelphia, New York, and Charleston had become large, busy cities, and their original water supplies--the shallow, dug wells or the open springs--had become unusable for public supplies. In many instances, the water from these sources was polluted by human, animal, and industrial wastes, and some sources near the ocean were contaminated with saltwater from the sea.

The usual solution to such difficulties was the development of surface-water sources from adjacent ponds, lakes, or streams. In order to take advantage of a sufficient supply of potable water for culinary purposes, to obtain water power for gristmills and other power-using industries of the times, and to utilize natural harbors for seagoing commerce, a string of colonial towns and major cities became established along that geologic and geographic feature known as the Fall Line, where estuarial tidewater meets the falls or rapids that gave this feature its name. The list of towns includes such names as New York City, Trenton, Philadelphia, Baltimore, Washington, Richmond, Raleigh, Columbia, Augusta, Macon, and Columbus.

Few "deep" wells existed in these early days of American hydrogeology. Driven wells of small diameter, commonly 1 to 2-1/2 inches, were in general use by 1865 where coarse sand or gravel offered easily obtained supplies. Larger and deeper wells were constructed chiefly by boring; that is, by rotating a rod having an auger bit attached to it at the base. It is thought that the famous flowing well at Lilliers, Artois, France, completed in 1126 A.D., was a bored well. Boring generally required a casing of some kind to prevent caving of the borehole walls, and this made the construction of such wells an expense that few private citizens or small municipalities could afford. Boring was practiced extensively in Europe beginning in the 12th century and was introduced to the United States from England in 1823 (Encyclopedia Britannica, 1972a).

Percussion methods were introduced to early America, beginning about 1808; although such methods, in a very primitive form, had been used by the ancient Chinese to produce wells as deep as 5,000 feet. The Chinese used bamboo rods and bamboo casing. Some such wells required several decades to complete, often having been started by a father, worked on for a lifetime by his son, and finally completed by the grandson.

The drilling of the first successful oil well in the United States, by Col. Edwin L. Drake, near Titusville in western Pennsylvania in 1859, and discovery of oil at only 69 feet below land surface started an "oil boom" and spurred drilling interests to develop bigger, better, and more powerful drilling and pumping equipment until, by 1910, the hydraulic-rotary method method had been well advanced over that of the first rig, built about 1890. The discovery of the Spindletop Oil Field in 1901 at Port Arthur, Texas, was the impetus for rapid advance of both cable-tool and rotary methods, and from the oil-well fields these advanced methods then became available for the drilling of deep wells that could successfully reach the deepest artesian aquifers.

Jetting is another method of well construction and involves washing a hole down into the earth by means of a stream of water issuing from a cutting bit at the end of a small diameter pipe, the jetting rod. The bit comminutes the rock, and the water washes the cuttings back up the hole inside the casing and discharges them at the land surface. Jetting was introduced in the United States about 1884 and by the end of the 19th century was the principal means of well drilling on the Atlantic and Gulf Coasts (Encyclopedia Britannica, 1972b). Few jetted wells of the time exceeded 4 inches in diameter or 500 feet in depth. Once a jetted well reached artesian water with sufficient head to cause flow, this natural pressure then was used to clean out the cuttings.

The improvement of pumping equipment followed rather closely the advancement of drilling equipment, although, even in 1910, the commonest form of pumps were suction types with a capability of lifting water only about 20 feet. Thus, the search was on for flowing wells, wells that would produce large quantities of water without having to be pumped.

Water-development tools and equipment aside, before hydrogeology could make its first feeble steps toward becoming a practical field of endeavor, the science of geology itself had to make some large and essential strides. One might be tempted to think that, by 1776, the science was well developed already and that the colleges and universities were founts of geologic knowledge. This was not the case. To most educated men of the times, including college professors and medical doctors, geology meant mineralogy, a branch of the science for which Georgius Agricola (1556) had laid a firm foundation in his famous book, "De Re Metallica." The Hoovers (1912) in their translation say of Agricola:

> "He was the first to found any of the natural sciences upon research and observation as opposed to fruitless speculation... the pioneer in building the foundation of science from observed phenomena."

About the time that this account begins, the most famous, respected, and revered mineralogist of these times, Abraham Gottleib Werner, was an educator at the famous Mining Academy at Frieburg, Germany. He began his teaching there in 1775 and by 1800 had attracted worldwide attention. Students from all over Europe, including Russia and the British Isles, flocked to Frieburg to learn from and to follow avidly "the great teacher."

But Werner possessed, along with other more commendable characteristics, a habit of forming judgments based on very limited data. Not having traveled outside Germany, he founded an entire, erroneous school of geologic thought on extremely restricted observations; he and his followers came to be known as the Neptunists. This name followed from Werner's teaching that all rocks were formed by successive precipitation out of a universal sea. Even the basalts were considered by Werner as a precipitate--the last to settle out.

Opposed to the teachings of Werner were those of James Hutton (1795), a Scottish medical doctor, fellow of the Royal Society of Edinburgh, and gentleman farmer. Hutton's astute geological observations of geologic form and process, which he had studied in Britain, led him to develop the "Doctrine of Uniformitarianism." He first presented his thoughts in a well-planned and documented publication entitled "Theory of the Earth, or an Investigation of the Laws Observable in the Composition, Dissolution and Restoration of the Land Upon the Globe"; publication was in the Transactions of the Royal Society of Edinburgh, 1788. But this paper came under a severe attack by Hutton's opponents, and it was not until 1795 that he published his now famous "Theory of the Earth with Proofs and Illustrations." Hutton's writing was obscure and difficult to read; therefore, it was not until Hutton's colleague at the University of Edinburgh, Dr. John Playfair (1802) published his version of Hutton's theory that his ideas became well known. Playfair's (1802) publication was entitled "Illustrations of the Huttonian Theory," and it became a best-seller of the times. To further bolster Hutton's case came the stout support of another powerful colleague at the University of Edinburgh, Sir James Hall, who later became known as "The Father of Experimental Geology." It was here, then, at the University of Edinburgh, that the "Plutonists" school developed, and it was from the opposing points of view of Werner and Hutton that geology was rended by the great controversy that lasted some 70-odd years before the Neptunists finally acquiesced.

In the United States, college faculties were staffed largely with graduates of Scottish and English universities, chiefly Edinburgh, Oxford, and Cambridge. The Neptunist-Plutonist controversy raged here, as well as in Europe, and did not die out until the 1850's.

By 1776 about 20 colleges and universities had been established in America of which the following are well-known examples: Harvard, 1639; William and Mary, 1683; St. Johns, Maryland, 1693; Yale, 1701; University of Pennsylvania, 1740; University of Delaware, 1743; Princeton, 1746; Washington and Lee, 1749; Columbia, 1754; Brown, 1764; Rutgers, 1766; and Dartmouth, 1769. For the most part, these schools prepared students for the ministry, teaching, law, and medicine. Most of the students, especially the doctors, obtained only superficial knowledge of science, and it was because of this that most of the geology of the times was done by men originally trained as medical doctors. Their chief interests in the sciences were botany and mineralogy. Botany was studied in the search for healing herbs, and mineralogy probably because of a natural interest humans have in rocks and possibly in the hope of finding precious elements, such as gold, silver, and copper.

1865-1879

The close of the Civil War saw the opening of the West, much of which was arid or semiarid and contained land that could be developed only by the use of irrigation. In those areas not adjacent to ample streamflow sources, this meant irrigation from wells. However, the early settlers soon learned that chance drilling was likely to be nonproductive, and in order to avoid risk, specialists--hydrogeologists--came into demand.

The growing population not only went West, but South, too. Wherever people sought water supplies, the magic word became artesian. Artesian water that is pure, sparkling, cool, and apparently without end; flowing water that could be obtained--if an artesian aquifer is beneath the land--only by drilling a well.

By more or less haphazard drilling of deep wells in the sedimentary rocks underlying the Atlantic and Gulf Coastal Plains, flowing wells were developed in many places from New England to Florida and west to Louisiana. Many of these deep wells were failures, however, because scientific understanding of the occurrence of artesian aquifers was not available.

With the opening of the West in the late 1860's and the great need for such artesian wells, geologists, soil scientists, and engineers of the Army, the Agricultural Department, the Interior Department, and some State Geological Surveys began searching not only for new flowing wells but to ascertain how and why such wells flow and how long they would continue to supply water. However, most uninformed people believed that the artesian water supply was infinite, so they wasted artesian flow to such an extent that some wells either ceased flowing or the flow was greatly reduced.

1880-1910

From the 1880's on, following the establishment of the U.S. Geological Survey under the first Director, Clarence R. King (fig. 6), the history of the advancement of hydrogeology in the United States is greatly influenced by accomplishments of the scientists and engineers of the U.S. Geological Survey. By the end of 1910, this governmental and scientific organization had gained worldwide recognition in hydrogeology. To detail how this came about, the names and deeds of the men and women who helped create this great institution, and the public services which they performed, is a task far beyond the scope of this paper. The evolvement of a hydrological organization in the U.S. Geological Survey is told by Robert Follansbee (1947).

Much of the work of the ground-water scientists in the early part of this period was concerned with development of artesian water supplies. The search for artesian supplies in the West included deep-well drilling, some of which was ill-advised. Haphazard drilling in the High Plains east of Denver by government agricultural agents lacking hydrogeologic understanding ended in "dusters," or dry wells. S. F. Emmons (fig. 7) in his administrative report to the Director of the Survey (June 30, 1884) says (1884, p. 45-46), "While the existence of a (Denver) synclinal basin has long been known to us from the hasty observations one makes in simply passing over the country, accurate and reliable maps and profiles are an indispensable base for the observations which shall determine the true source of the water supply [of the Denver Basin], the amount and quality that may be expected from the different horizons and the most favorable points for sinking artesian wells; it is in large degree owing to the absence of this preliminary knowledge that money already appropriated by Congress and paid for the sinking of artesian wells upon the plains of Colorado, has been so barren of practical and definite results."

The search for artesian supplies went on. The first major contribution to a better understanding of artesian wells was by T. C. Chamberlin (1883) of the Wisconsin Geological Survey (fig. 8), who published his earliest report on artesian conditions, simply entitled "Artesian Wells." Later Chamberlin, as an employee of the U.S. Geological Survey, revised and enlarged the earlier report. The revised report (Chamberlin, 1885, p. 125-173), entitled "The Requisite and Qualifying Conditions of Artesian Wells," was the first hydrogeologic report to be published by the Survey. The report became an immediate best-seller, achieving not only national but worldwide acclaim. This first hydrogeologic paper by a Survey author set an exceedingly high standard of excellence and for many years was the example by which others measured their writing capabilities.

Figure 6.--Clarence Rivers King, founder and leader of the King Survey (1867-97) and first Director of the U.S. Geological Survey (1879-81).

U.S.G.S. Photo Library

Figure 7.--Samuel F. Emmons, distinguished Survey mining geologist, recognized the artesian nature of the Denver Basin and the need for hydrogeologic studies in the High Plains (1884).

U.S.G.S. Photo Library

Figure 8.--Thomas Chrowder Chamberlin, whose greatest contribution to hydrogeology was the description of the "relevant and qualifying conditions of artesian wells" (1885).

Geological Society of America

In 1897, W. H. Norton of the Iowa Geological Survey prepared the most elaborate and complete description of an artesian system ever presented to date. Entitled "Artesian Wells of Iowa," this report makes the first known use of the term "aquifer" in United States literature.

Norton's report was followed in 1898 by another comprehensive publication, this one written by S. W. McCallie of the Georgia Geological Survey, entitled "Preliminary Report on the Artesian Well System of Georgia." In the next few years about a dozen other reports of similar nature followed in rapid succession from the State Surveys of New Jersey, Louisiana, Michigan, Washington, North Dakota, Texas, Kansas, Missouri, Illinois, and Indiana; and in Mississippi, from the Agricultural Experiment Station.

J. E. Todd (1900, p. 30) was among the first to warn that "multiplication of wells must tend to exhaustion [of supply]." He went on to say that, "If, however, the loss by [flowing] wells and leakage does not exceed the annual supply which enters [recharges] the formation [Dakota Sandstone] on the west, an equilibrium may be gained which will be as constant as a river. It may be expected to have some fluctuations. At present the pressure in the area discussed [southeastern South Dakota] is generally slightly declining."

I. C. Russell (fig. 9), discussed artesian conditions in the Snake River Plains of Idaho (1902) and warned (p. 185) that "the present [1901] waste of water is so great and the prevalent ignorance or disregard of the laws of health so general that centralization of control or general education of the people is imperative." The dawn of water-conservation thinking had arrived.

All of the reports mentioned in this section were qualitative and descriptive; none attempted to assess quantities of water available in the artesian systems reported upon, nor were any of them as definitive, as T. C. Chamberlin's classic report of 1885. However, even this famous report was not quantitative. Such reports still lay in the future, awaiting the time when hydrogeologists or hydrologists would build upon the mathematical and physical researches of such workers as Perrault (1674), Mariotte (1686), Halley (1687; 1691; 1715), Bernoulli (1738), De La Methiere (1791), Venturi (1797), Hagen (1839), Poiseuille (1846), Dupuit (1848), Darcy (1856), Dupuit (1863), Meyer (1866), Reynolds (1883), Thiem (1887), Hazen (1892), and Thiem (1906). The works of these men, though classical, will not be discussed in this short paper.

De La Methiere (1791) clearly enunciated the modern concept of the hydrologic cycle that grew out of the earlier basic works of Perrault (1674), Mariotte (1686), and particularly of Halley (1687; 1691; 1715), who apparently was the first to clearly grasp the water-budget concept; that is, P (precipitation) minus ET (evapotranspiration) equals R (return flow to the sea). It was Halley and De La Methiere who had opened the door for water-budget studies of large areas, such as river basins or entire aquifer systems, and Darcy (1856) who performed a similar service for the quantification of ground-water flow. But no one put this concept into practical use until Waldemar Lindgren (1903) made a tentative water-budget study of Molokai, Hawaiian Islands.

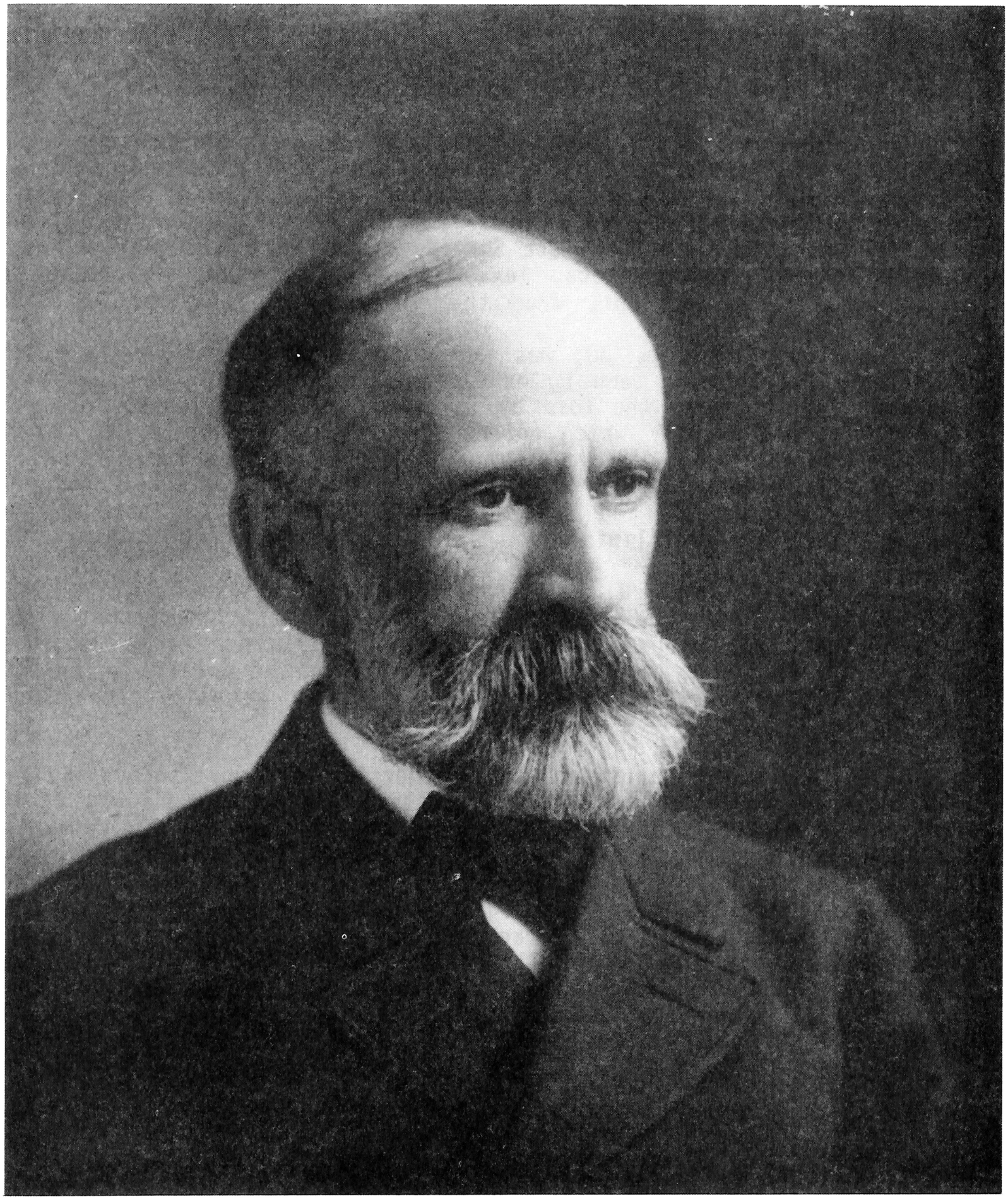


Figure 9.--Israel C. Russell, one of the U.S. Geological Survey's earliest and most highly regarded hydrogeologists.

U.S.G.S. Photo Library

The remainder of this paper pays tribute to a small group of outstanding hydrogeologists and hydrologists, including some who were mathematicians, physicists, or civil engineers by academic training--as well as to the majority who were geologists by collegiate training. These men transformed hydrogeology from a descriptive and nonquantitative, developing science into the early phases of a truly quantitative science.

1885 - Frederick Haynes Newell

In 1885, Frederick Haynes Newell (fig. 10) wrote his "Geology of the Bradford Oil Rocks--Some Experiments Pertaining to their Structure and Capacity to Furnish Petroleum." This unpublished doctoral dissertation in the Department of Geology at the Massachusetts Institute of Technology, Cambridge, reports on the first known laboratory testing of the pressurized flow of oil (kerosene) through reservoir sandstones. These experiments established a sound base for the subsequent experimental and theoretical work by King (1899), Slichter (1899; 1902; 1905), and others. Newell later became Chief of the U.S. Geological Survey's Hydraulic Survey, which was estabished in October 1888. He set up the Hydrographic and Engineering Branches to carry on the Irrigation Surveys of the West. Later, Newell became Chief of the Hydrologic Branch (May 1894) and remained with the Branch until March 1907, when the U.S. Reclamation Service (later the U.S. Bureau of Reclamation) separated from the U.S. Geological Survey. Newell was a greatly respected scientist and an administrator, one of whose most noteworthy achievements was the selection, training, and assignment of young people who later became prominent water-resources scientists and engineers in their own right.

1896 - Grove Karl Gilbert

Gilbert (fig. 11) had been a member of the U.S. Geological Survey since its founding in March 1879 and became one of the world's most renowned economic geologists. He performed one of his usual outstanding jobs in his hydrogeologic investigation of the ground water in the Arkansas River valley of eastern Colorado (Gilbert, 1896, p. 561-601). Gilbert described the topography, geology, artesian conditions, the ground-water intake areas of recharge to the Dakota Sandstone, and gave other useful information, including a description of water-table conditions in the terrace deposits and dune sands. A semiquantitative report, it was an advance over previous such reports, particularly with respect to the eloquent simplicity of his writing.

1899 - Franklin H. King

Franklin H. King, a professor of hydraulic engineering at the University of Wisconsin and an employee of the U.S. Geological Survey, published his "Principles and Conditions of the Movements of Ground Water" in 1899. This report described laboratory and field results of King's studies relating to ground-water storage; calculations of total

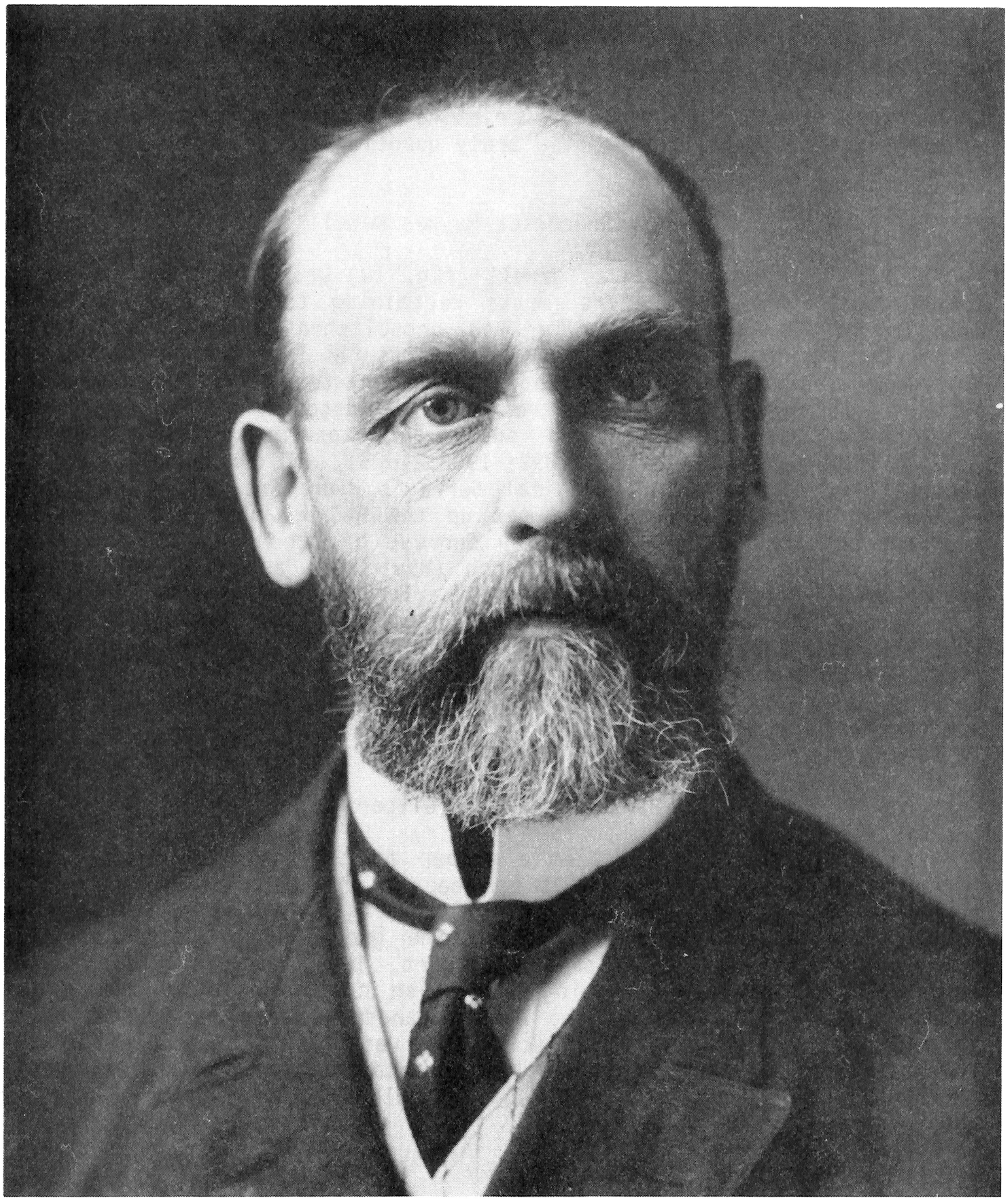


Figure 10.--Frederick Haynes Newell, first Chief of the U.S. Geological Survey's Hydrologic Branch, later guided the U.S. Bureau of Reclamation after it separated from the Survey.

U.S.G.S. Photo Library

Figure 11.--Grove Karl Gilbert, one of the world's most renowned economic geologists, accomplished outstanding hydrogeologic work of a pioneering nature in the Arkansas River valley of eastern Colorado.

U.S.G.S. Photo Library

quantity of ground water in storage in the earth's crust; depth of possible ground-water penetration (10,000 feet); ground-water movement under gravity; flow and water-level changes due to barometric effects and soil temperature; and water movement in capillary tubes. In the report, King also discussed the shape and showed the configuration of the water table by use of water-level contours (Gustave Dumont, 1856, may have been the first to publish such a map) and indicated directions of ground-water flow by using short arrows crossing the ground-water contours at right angles. His report may contain the first such use of a ground-water flow map. This type of map has proven to be a very useful in teaching students or explaining to laypersons why regional ground water flows in the directions it takes from places of recharge to places of discharge. King discussed Newell's doctoral dissertation, thus making those formerly unpublished results available in print to the public.

1899 - Charles S. Slichter

Charles S. Slichter was an outstanding mathematician and physicist whose greatest contributions to hydrogeology came from his studies of ground-water motion and the development of his "electrical" method of determining velocity of ground-water underflow in river valleys. He used an electrolyte, ammonium chloride (NH_4 Cl), placed in an upstream (upgradient) well and an arrangement of three observation wells a short distance downgradient. These observation wells were fitted with electric sensors that would show on an ammeter the time of arrival and passage of the electrolyte. He developed clock-driven, battery-actuated recorders, which were hooked to the ammeters so as to maintain continuous records.

Slichter's 1899 report, "Theoretical Investigation of the Motion of Ground Waters," was a substantial and clear advancement in the explanation of such fluid movements. He says (p. 303), "I find that the problem is capable of mathematical treatment, and I show that the question is analogous to the conduction of heat or electricity, or to any other problem involving a transfer of energy. I show that there exists in the case of ground-water movements what is known as a potential function, from which we may derive, in any determinant problem, the velocity and deviation of flow, and the pressure at every point in the saturated soil or rock. The existence of the potential function is made the basis of much of the work that follows." This formula is essentially the one developed by Dupuit (1848) and later by Forchheimer (1901), Turneaure and Russell (1901), and Gunther Thiem (1906).

Slichter was a prolific writer, and his writings are easy to read. For lack of space, attention is called to only three of his subsequent reports, all significant contributions to the advancement of hydrogeology as a quantitative science--Slichter (1902; 1905) and Slichter and Wolff (1906).

1901 - Nelson Horatio Darton

Nelson H. Darton's "Preliminary Description of the Geology and Water Resources of the Southern Half of the Black Hills and Adjoining Regions of South Dakota and Wyoming" was published in 1901. His reconnaissance report was a fairly typical one of the times but was distinguished by the comprehensiveness and thoroughness of his field work. Darton covered some 5,500 square miles by horseback and buggy and described in the report the topography, geology, ground-water horizons (aquifers, really, but he does not use the term), the kinds and numbers of wells, the irrigation, mineral resources, climate, and timber resources. Maps showing the geology and depths to the principal artesian aquifer (the Dakota Sandstone) are included among others. Another similar report is Darton's (1905) comprehensive "Preliminary Report on the Geology and Underground Water Resources of the Central Great Plains."

Darton (fig. 12) was an accomplished, prodigious, meticulous, and rapid worker. How he did, or ever found time to do, all the research and field study that he accomplished, while at the same time directing the work of the other hydrogeologists in the Western Section of the Hydrogeologic Branch, and prepared all of the top-notch reports that he wrote, is difficult to comprehend. Much of the original geology that Darton described at the beginning of the 20th century still stands unchanged by subsequent workers, although ideas concerning the Dakota Sandstone have undergone considerable revision. He set a marvelous example of accomplishment for all subsequent Survey hydrogeologists to emulate.

1904 - Myron L. Fuller

Myron L. Fuller (fig. 13) was a prodigious and competent worker. Two of his many published reports give one a feeling of the level hydrogeologic expertise at the beginning of the 20th century, of the problems to be solved, and of the people working to solve them. His report "Hydrology of the Eastern United States" was published in 1904 as U.S. Geological Survey Water-Supply Paper 102. A follow-up paper, entitled "Hydrologic Work of the U.S. Geological Survey in the Eastern United States" (1905b), was published in the Proceedings of the 8th International Geographic Congress. In these two reports Fuller described the work of the Survey under the following headings: (1) Bibliographic, (2) Statistical, (3) Technical, (4) Legal, (5) Scientific, and (6) Economic.

Fuller was not only Chief of the Eastern Section of the Hydrology (or Hydrogeologic) Branch but also was a sort of administrative superchief of all the ground-water studies in the United States. He also found time to make numerous field studies of the regional or county type, bearing such titles as "A Ground-Water Problem in Southeastern Michigan" (Fuller, 1905a). Such studies were what might be termed substantive reconnaissance investigations. They were qualitative and descriptive and generally contained quality-of-water information.

Figure 12.--Nelson Horatio Darton, Chief of the Western Section of the Hydrogeologic Branch, a trailblazer in the hydrogeology of the West.

U.S.G.S. Photo Library

Figure 13.--Myron L. Fuller, Chief of the U.S. Geological Survey's Eastern Section, Hydrologic Branch, and concomitantly responsible for the Survey's ground-water geology operations in the United States. His most notable hydrogeologic work was accomplished in the southeastern States and especially in the Atlantic Coastal Plain (1902-08).

U.S.G.S. Photo Library

Fuller was one of those Darton types who somehow found time to be a field hydrogeologist, a report writer and reviewer, a supervisor and administrator on the Washington Office level, and a scientist admired and respected by his peers. When I began my first professional hydrogeologic work in Florida, M. L. Fuller became one of my idols--a man to pattern after. He was also the first man, to my knowledge, to use the term "aquifer" in a U.S. Geological Survey report (1906).

1903 - Waldemar Lindgren

Waldemar Lindgren's "The Water Resources of Molokai, Hawaiian Islands," published as U.S. Geological Survey Water-Supply Paper 77 (1903), was a first of its kind. In this study--one of the few water studies that Lindgren (fig. 14) conducted--he made the first Survey use of the water-budget method in an attempt to determine the quantity of water available for development in a fairly large area. Molokai is a mountainous island of 259 square miles in area; it is about 37-miles long and 7- to 10-miles wide.

Lindgren recognized that P (precipitation) minus ET (evapotranspiration) equals R (return flow to the sea) as measured in stream and ground-water discharge around the periphery of the island of Molokai. His data were faulty, but he derived the following estimates of water available from the Meyers Creek basin of 54 square miles:

Average annual precipitation = 48 inches = 195 ft^3/s = 125.9 Mgal/d;
Average annual evaporation = 11.8 inches = 48 ft^3/s = 31 Mgal/d;
Average annual runoff in Meyers Creek = 9.8 inches = 40 ft^3/s = 25.8 Mgal/d; and
Average annual ground-water discharge = 25.4 inches = 107 ft^3/s = 69.1 Mgal/d.

Lindgren prepared such water-budget estimates for each of the several river basins on the island.

From this analysis he suggested that a minimum of 30 Mgal/d might be available for consumptive use, or about one-half of the minimum ground-water discharge. Although he did not use the term, Lindgren was trying to determine the water crop (Parker and others, 1964, p. 25).

This work, to my knowledge, is the first basin-wide water-budget study made by a Survey hydrogeologist and is reminiscent of the elemental work of Perrault (1674), Mariotte (1686), and Halley (1691) in their early studies of the relationship of precipitation, evaporation, and runoff in certain stream basins of France and England. If the correct data had been available instead of incorrect information supplied by local people, or that he himself estimated, Lindgren would have come up with a very useful estimate of the perennial supply safely available for consumptive use. His methodology was correct, but his data were faulty. Nonetheless, he inspired later workers in other areas to utilize the water-budget method in making evaluations of water supplies available for development.

Figure 14.--Waldemar Lindgren, first U.S. Geological Survey hydrogeologist to use the water-budget method to calculate the water crop of a large area, Molokai, Hawaiian Islands (1903).

U.S.G.S. Photo Library

1904 - Willis T. Lee

Willis T. Lee (fig. 15) prepared, among many other fine reports, two excellent quantitative reports under the following titles: "The Underground Waters of Gila Valley, Arizona," published in 1904 as U.S. Geological Survey Water-Supply Paper 104, and "Underground Waters of Salt River Valley, Arizona," published in 1905 as U.S. Geological Survey Water-Supply Paper 136.

Lee (p. 42, 1904) derived a ground-water flow equation that is equivalent to Darcy's (1856). He also developed a rational relationship between precipitation and underflow, then estimated the amount of irrigation water available by means of primitive drawdown tests in shallow wells tapping the valley underflow. Lee (1904) also described the canal system used by the Indians in prehistoric times in the Gila River valley. This is a basic and useful study and is indicative of what an imaginative and resourceful hydrogeologist can do in a very short study using minimal help and money.

1905 - Walter C. Mendenhall

Walter C. Mendenhall's report, "Development of Underground Waters in the Eastern Coastal-Plain Region of Southern California," was published as U.S. Geological Survey Water-Supply Paper 137. This is the first of four precedent-breaking, ground-water quantitative reports, all published in 1905, and discussed briefly below. The others are: "Development of Underground Waters in the Central Coastal-Plain Region of Southern California," Water-Supply Paper 138; "Development of Underground Waters in the Western Coastal-Plain Region of Southern California," Water-Supply Paper 139; and "The Hydrology of San Bernardino Valley, California," Water-Supply Paper 142.

These four papers represent a tremendous outpouring of work. Each report is a quantitative study of an area covering two contiguous 15-minute U.S. Geological Survey topographic quadrangles. The areas covered in these four reports were undergoing both a 10-year drought and rapid population development, coupled with greatly increasing uses of ground water, chiefly for irrigation. Mendenhall (fig. 16) studied a total of nearly 10,000 wells, well records, and water-level hydrographs. He concluded that water was being "mined"; that is, more water was being taken out of aquifer storage than nature puts in and releases. He correlated the flows of three rivers (Los Angeles, Santa Anna, and San Gabriel) with ground-water recharge and found that the flows were greatly reduced compared with that of former years, due not only to the drought but to headwaters abstraction of flow, thus, reducing flows to the coastal basins. He studied precipitation and evaporation records, plotted well locations, made maps of the water table, and areas of artesian flow and compared these with areas of preirrigation, predevelopment flow.

These four quantitative reports, alike in method and procedure, using water-budget methodology, are the most modern-looking of any Survey reports prepared hitherto. The data on precipitation, runoff, ground-water recharge,

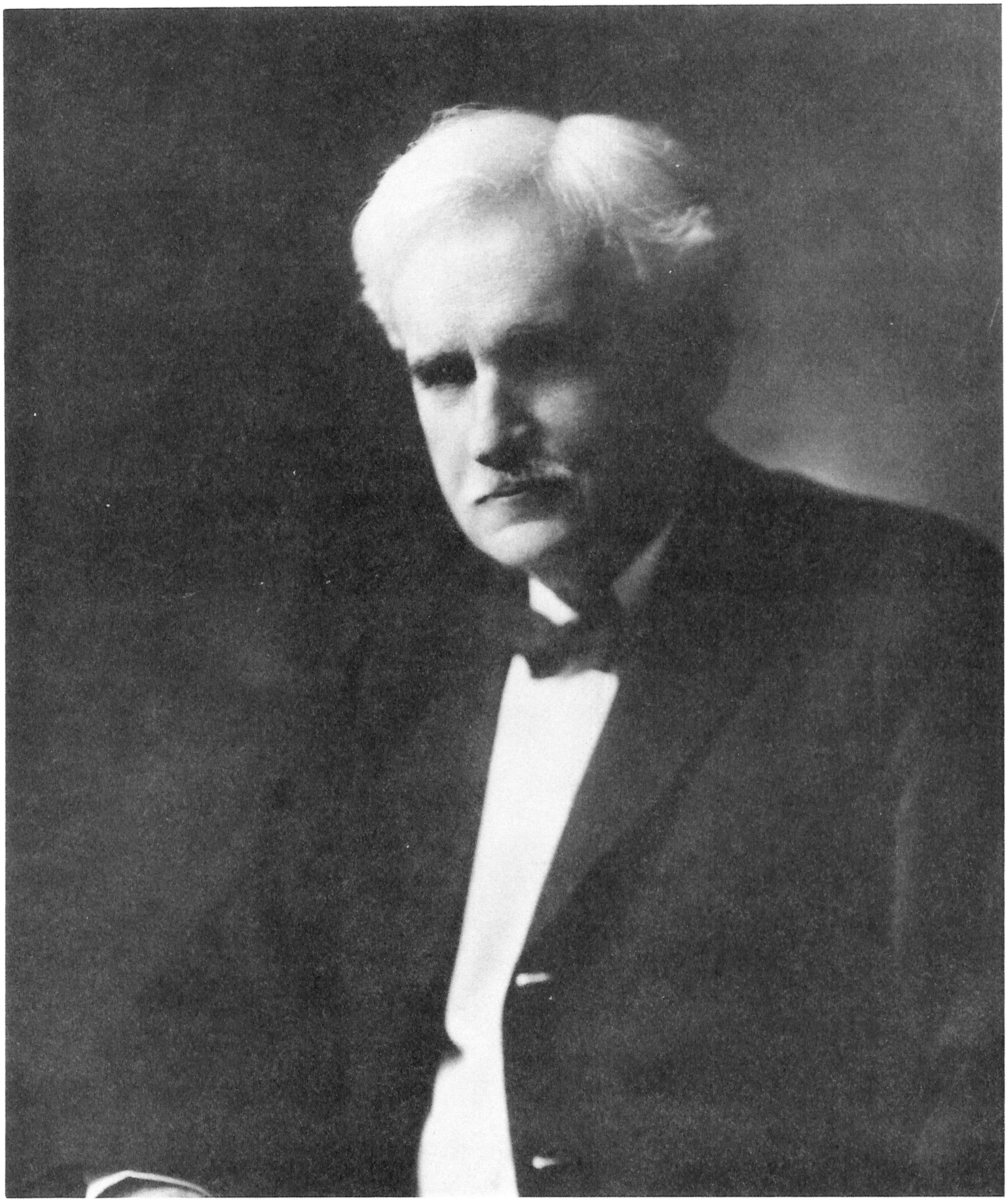


Figure 15.--Willis T. Lee, U.S. Geological Survey hydrogeologist, most most noted for his quantitative studies of western alluvial valleys.

U.S.G.S. Photo Library

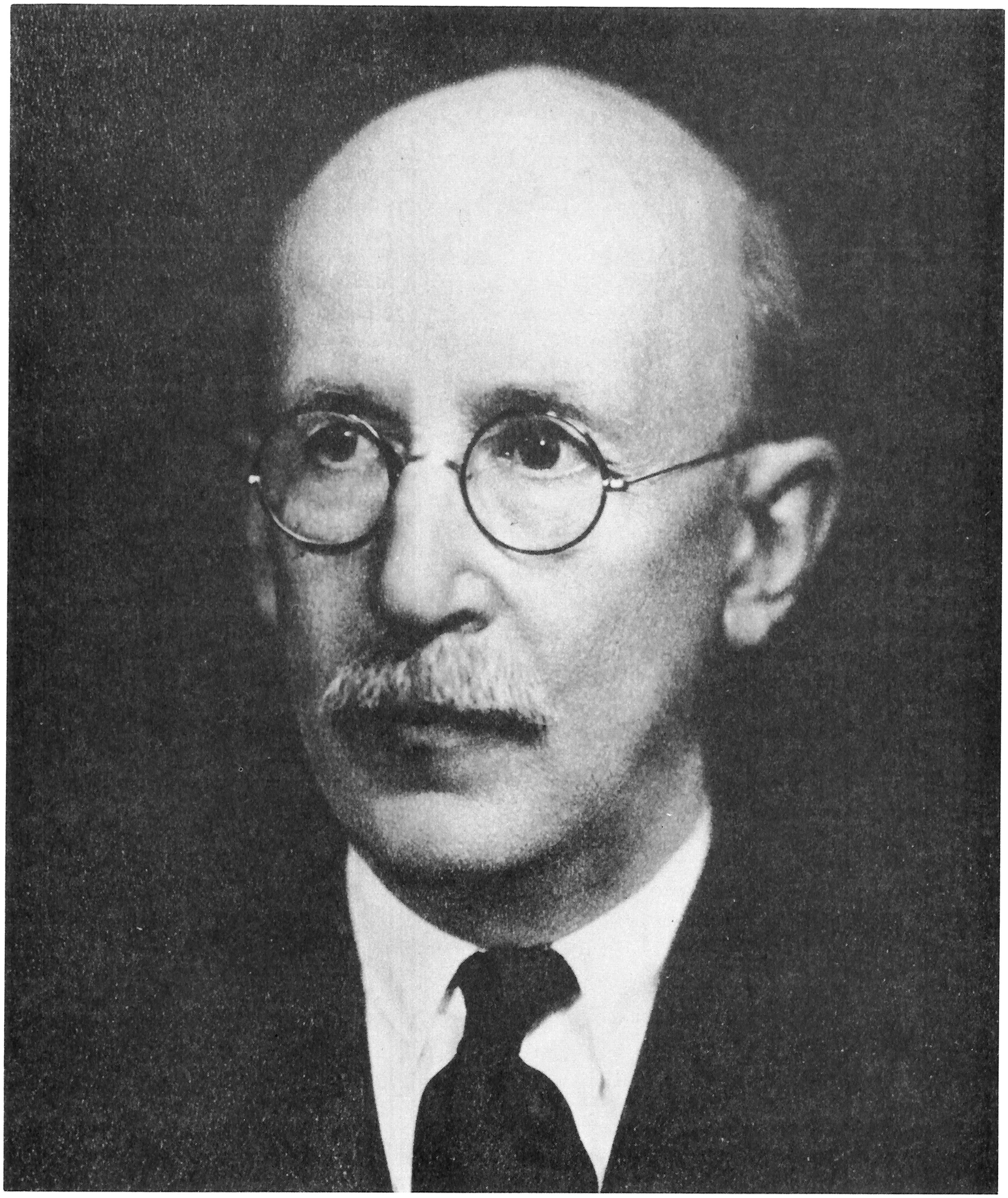


Figure 16.--Walter C. Mendenhall, outstanding U.S. Geological Survey hydrogeologist noted for his quantitative studies in southern California, second Chief of the U.S. Geological Survey's Ground Water Division (1908-11), and later Director of the U.S. Geological Survey (1930-43).

U.S.G.S. Photo Library

and evaporation plus transpiration losses were reliable. Thus, unlike Lindgren on Molokai, Mendenhall had good values to use with his equation of continuity and thus came up with remarkably fine hydrogeologic results. In any event, Mendenhall's work convinced the Los Angeles planners that, if the city were to grow to meet their expectations, another source (and a large one) would have to be sought, secured, and developed. They could not depend, as they previously had been thinking, on an undiminishable supply of ground water in the Los Angeles Basin.

These excellent examples of an application of water-budget methodology may have led O. E. Meinzer (fig. 17) and N. D. Stearns to make their excellent water-budget study of the 89-square-mile Pomperaug Basin in Connecticut, as reported in U.S. Geological Survey Water-Supply Paper 597-B (1929). These also were the basis for my selection, in 1956, of how to make the water-resources evaluation of the 12,765 square-mile Delaware River basin (Parker and others, 1964) and probably were the beacon that led Rasmussen and Andreasen (1959) to use the same methodology in their excellent intensive study of the 19.5-square mile Beaverdam Creek basin, Maryland.

Dr. Mendenhall became the second Chief of the Ground-Water Branch, U.S. Geological Survey, succeeding M. L. Fuller on January 1, 1908. He remained Chief until January 1, 1911, at which time he was elevated to the position of Chief Geologist of the U.S. Geological Survey. Later, when George Otis Smith (see his reports of 1901, 1903, 1905) retired, Dr. Mendenhall became Director and served until May 1943, when he retired. Dr. O. E. Meinzer, who entered the Survey as a Junior Geologist in 1907, succeeded Mendenhall as Chief of the Ground-Water Branch in 1911, and under his direction the modern era of hydrogeology developed.

1910 - Clarence E. Siebenthal

Clarence E. Siebenthal's report on "Geology and Water Resources of the San Luis Valley, Colorado," published as U.S. Geological Survey Water-Supply Paper 240 (1910), and the very competent, intensive field work that it represents rank high in the kind of hydrogeologic work that helped give the U.S. Geological Survey its national and international reputation for excellence. Siebenthal (fig. 18) had only one field season of work on which to base his quantitative study of the San Luis artesian basin in Colorado. During the 1904 field season, he recorded 3,234 wells in operation in the basin. Among other duties, Siebenthal had scheduled, measured, and estimated the flow of more than 1,000 of these wells, most of which were 2 to 3 inches in diameter and in which the average flow was 40 gal/min. At this rate, the 3,234 wells were producing 186.3 Mgal/d or 286 ft^3/s. Siebenthal calculated an irrigation service of 70 acres for each cubic foot per second of flow; therefore, the 286 ft^3/s would service more than 20,000 acres. He believed that actually the service area would be nearer 25,000 acres. The report not only estimated water yield on an annual basis but included an accurate topographic map and described the geology, geography, source of water supply, springs, flowing and nonflowing wells, temperature, chemical quality, and uses being made of the basin's waters.

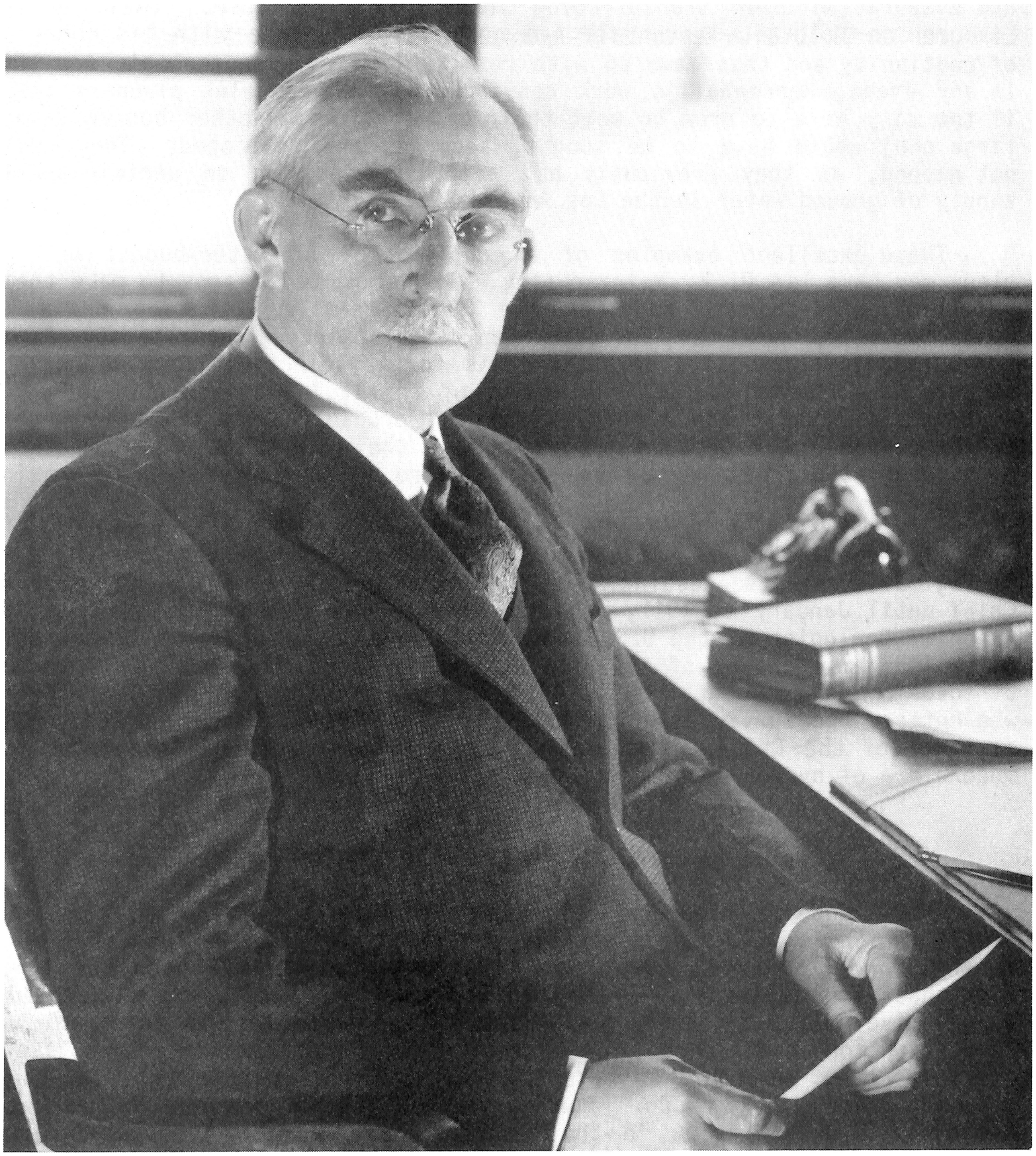


Figure 17.--Oscar E. Meinzer, third Ground-Water Division Chief (1912-46) and architect of modern hydrogeology. His professional career spanned 41 years, extending from his employment as a Junior Geologist (1907) until his death (1948), during which time he achieved international recognition as pre-eminent in ground-water science.

U.S.G.S. Photo Library

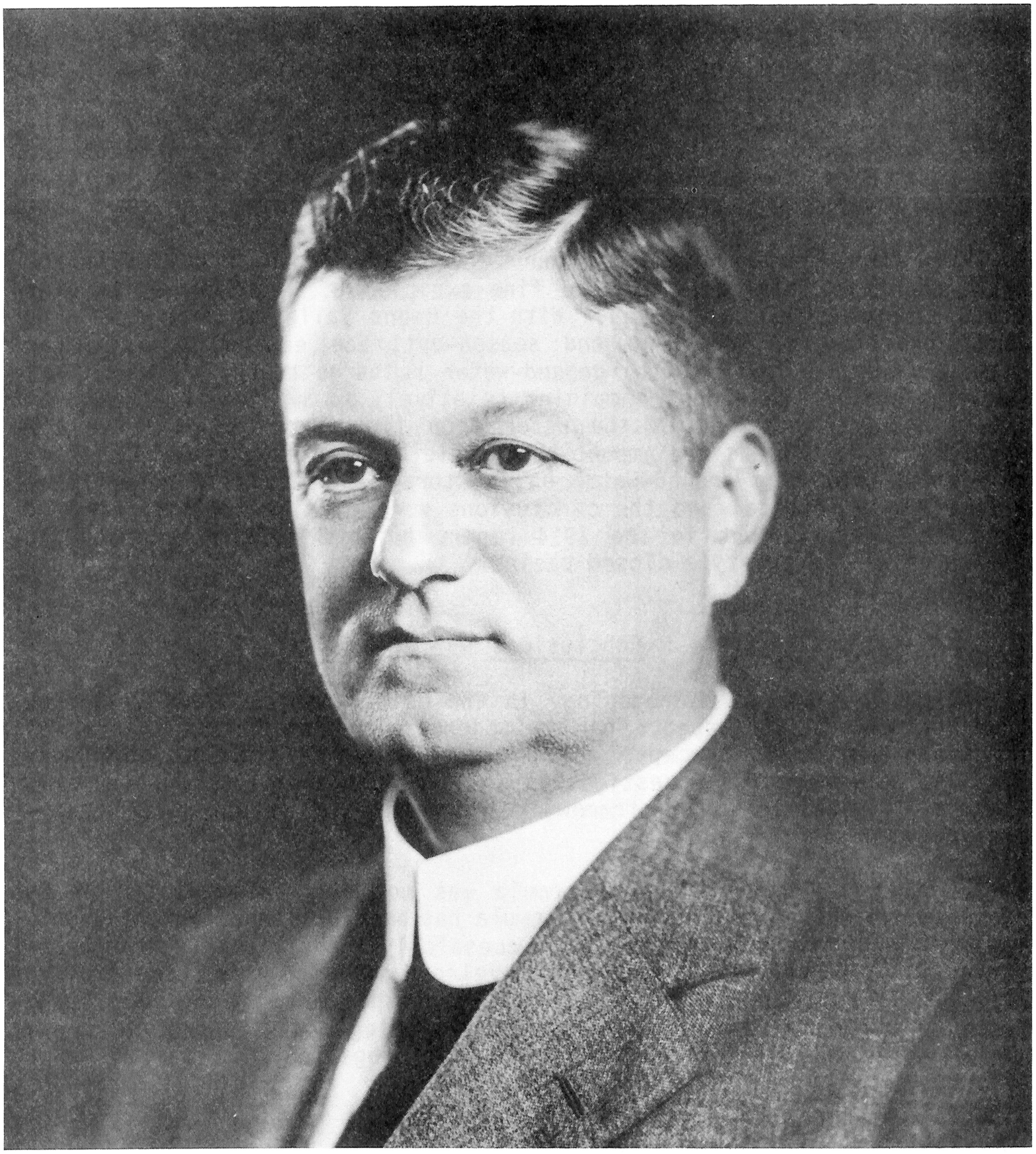


Figure 18.--Clarence E. Siebenthal, noted U.S. Geological Survey hydrogeologist, best known for his outstanding work in Colorado's San Luis Basin (1910).

U.S.G.S. Photo Library

1912 - Charles H. Lee

Charles H. Lee's report, titled "An Intensive Study of the Water Resources of a Part of Owens Valley, California," was published as Water-Supply Paper 294 (1912) and was followed in 1914 by his expanded report on "The Determination of the Safe Yield of Underground Reservoirs of the Closed-Basin Type," which was published in the Proceedings of the American Society of Civil Engineers.

These two reports, like the four Mendenhall reports previously mentioned, are quite similar. All are fine examples of water-budget studies used to determine the water crop. With the Owens Valley aquifer remaining full to overflowing, season-in and season-out, Lee equated ground-water discharge from the aquifer with ground-water recharge to the aquifer. All other elements in the budget remaining relatively equal, this approach was correct, and Lee thus derived the water crop figure of 155 ft^3/s or 180 Mgal/d. This figure was the amount that could be extracted from the valley fill without depleting ground-water basin storage. Lee's 1914 report used the same kinds of data, and the conclusions were similar to those reached in his 1912 report, but in the 1914 report he applied the water-budget approach to all desert-type closed basins.

Conclusions

The early stage of hydrogeology in the United States, 1860-1910, saw marked advances in all aspects of the science and also in its support of engineering hydrologic concepts and the mechanical development of pumps, tools, and machinery for investigating aquifers and aquicludes. Over all, the means of determining the framework and fabric of ground-water reservoirs advanced significantly.

Although the nonequilibrium formula was not published until 1935 by C. V. Theis, a workable equilibrium formula had been developed independently by several workers and was being used successfully. Additionally, the quantitative water-budget method was being developed and also used successfully, especially in some of the arid-land studies of the West. Truly, the stage had been set for the ensuing phases of hydrogeologic development that are referred to as the Meinzer and Modern Era of hydrogeology.

References

Bernoulli, Daniel, 1738, Hydrodynamica, Sive de Viribus et Motibus Fluordium Commentarii: Strassburg, France.

Chamberlin, T.C., 1883, Artesian wells: Wisconsin Geological Survey, v. 1, p. 689-701.

_____1885, The requisite and qualifying conditions of artesian wells: U.S. Geological Survey 5th Annual Report, p. 125-173.

Darcy, H.P.G., 1856, Les Fontaines Publiques de la Ville de Dijon: Paris, Victor Dalmont.

Darton, N.H., 1901, Preliminary description of the geology and water resources of the southern half of the Black Hills and adjoining regions in South Dakota and Wyoming: U.S. Geological Survey 21st Annual Report, pt. IV, p. 489-599.

_____1905, Preliminary report on the geology and underground water resources of the central Great Plains: U.S. Geological Survey Professional Paper 32, 433 p.

Daubree, A., 1887, Les Eaux Souterraines, Aux Epoques Anciennes et a l'epoque Actuelle: Paris, Dunod, 3 volumes.

De La Methiere, J.C., 1791, Theorie de la Terre: Paris, Chez Maradna.

Dumont, Gustave, 1856, Les Eaux Alimentaires de la Ville de Liege: Paris.

Dupuit, A.J.E.J., 1848, Etudes Theoriques et Practiques sur Le Mouvement des Eaux courantes: Paris, Dunod, 275 p.

_____1863, Etudes Theoriques et Pratiques sur le Mouvement des Mouvement des Eaux dans les Canaux Decouverts et a Travers les Terrains Permeables: Paris.

Emmons, S.F., 1884, Administrative report of chiefs of divisions (to the Director, U.S. Geological Survey) on progress of work by the Mining Geology Division, Rocky Mountains: U.S. Geological Survey 4th Annual Report, p. 45-46.

Encyclopedia Britannica, 1972a, Bored wells: v. 10, p. 391.

_____ 1972b, Jetted wells: v. 10, p. 391.

Follansbee, Robert, 1947, History of the Water Resources Branch, U.S. Geological Survey: Washington, D.C., 459 p.

Forchheimer, Philipp, 1886, Uber die Ergiebigkeit von Brunnen-Anlagen und Sickerschlitzen: Verein, Hannover, Zeitschrift der Architekten und Ingenieur, v. 32, no. 7, p. 539-564.

_____1901, Wasserbewegung durch Boden: Berlin, Ver Deutscher Ing. Zeitschr., v. 45, p. 1736-1741; 1781-1788.

Fuller, M.L., geologist in charge, 1904, Contributions to the hydrology of Eastern United States, 1903: U.S. Geological Survey Water-Supply Paper 102, 522 p.

_____1905a, A ground-water problem in southeastern Michigan, in Contributions to the hydrology of eastern United States, M.L. Fuller, geologist in charge: U.S. Geological Survey Water-Supply Paper 145, p. 129-147.

_____1905b, Hydrologic work of the USGS in the eastern United States, 1904: 8th International Geographic Congress Proceedings, U.S. Government Printing Office, Washington, D.C., p. 509-514.

_____1906, Underground-water papers, 1906: U.S. Geological Survey Water-Supply Paper 160, 104 p.

Gilbert, G.K., 1896, The underground water of the Arkansas Valley in eastern Colorado: U.S. Geological Survey 17th Annual Report, pt. II, p. 551-601.

Hagen, G.H.L., 1839, Uber die Bewegung des Wassers engen Cylindrischen Rohren: Leipzig, Annalen Physik und Chemie, v. 46, p. 423-442.

Halley, Edmund, 1687, An estimate of the quantity of vapor raised out of the sea by warmth of the sun: Philosophical Transactions of the Royal Society, v. 16, no. 189, p. 366-370.

_____1691, On the circulation of the vapors of the sea and the origin of springs: Philosophical Transactions of the Royal Society, v. 17, no. 192, p. 468-473.

_____1715, A short account of the cause of the saltness of the ocean and of the several lakes that emit no rivers--with a proposal by help thereof to discover the age of the world: Philosophical Transactions of the Royal Society, v. 29, no. 344, p. 296-300.

Hazen, Allen, 1892, Some physical properties of sands and gravels: Massachusetts State Board of Health 24th Annual Report, p. 541.

Hoover, H.C., and Hoover, L.H., 1912, De Re Metallica: London, England, The Mining Magazine, (Reprinted, 1950, Dover Publications, New York, 637 p.).

Hutton, James, 1788, Theory of the earth, or an investigation of the laws observable in the composition, dissolution and restoration of the land upon the globe: Transactions of the Royal Society of Edinburgh.

_____1795, Theory of the earth with proofs and illustrations: Edinburgh, 2 volumes.

King, F.H., 1899, Principles and conditions of the movements of ground water: U.S. Geological Survey 19th Annual Report, pt. 2, p. 59-294.

Lamarck, J.B., 1802, Hydrogeologie: Paris, (Translated by A.V. Carozzi, 1964, Urbana, Illinois Press, 152 p.).

Lee, C.H ., 1912, An intensive study of the water resources of a part of Owens Valley, California: U.S. Geological Survey Water-Supply Paper 294, 135 p.

_____1914, The determination of the safe yield of underground reservoirs of the closed-basin type: Proceedings of American Society of Civil Engineers, v. 40, no. 4, p. 817-887.

Lee, W.T., 1904, The underground waters of Gila Valley, Arizona: U.S. Geological Survey Water-Supply Paper 104, 71 p.

_____1905, Underground waters of Salt River valley, Arizona: U.S. Geological Survey Water-Supply Paper 136, 196 p.

Lindgren, Waldemar, 1903, The water resources of Molokai, Hawaiian Islands: U.S. Geological Survey Water-Supply Paper 77, 62 p.

Lucas, J., 1880, The hydrogeology of the Lower Greensands of Surrey and Hampshire: London, England, Proceedings of the Institute of Civil Engineers, v. 61, p. 200-227.

Mariotte, Edme, 1686, Traites du Mouvement des Eaux et des Autres Corps Fluides: Paris (English Translation, 1718).

McCallie, S.W., 1898, Preliminary report on the artesian well system of Georgia: Georgia Geological Survey Bulletin 7, 214 p.

Meinzer, O.E., 1934, Hydrology--The history and development of ground-water hydrology: Journal of the Washington Academy of Sciences, v. 24, no. 1, p. 6-32.

_____1942, Hydrology--Physics of the earth, IX: New York, McGraw-Hill Book Co., Inc., 712 p.

Meinzer, O.E., and Stearns, N.D., 1929, A study of ground water in the Pomperaug basin, Connecticut, with special reference to intake and discharge: U.S. Geological Survey Water-Supply Paper 597-B, p. 73-146.

Mendenhall, W.C., 1905a, Development of Underground Waters in the eastern coastal-plain region of southern California: U.S. Geological Survey Water-Supply Paper 137, 140 p.

_____1905b, Development of underground waters in the central coastal-plain region of southern California: U.S. Geological Survey Water-Supply Paper 138, 162 p.

_____1905c, Development of underground waters in the western coastal-plain region of southern California: U.S. Geological Water-Supply Paper 139, 105 p.

_____1905d, The hydrology of San Bernardino Valley, California: U.S. Geological Survey Water-Supply Paper 142, 124 p.

Meyer, O.E., 1866, Uber die Innere Reibung der Gase: Poggendorff's Annalen, Band 127, p. 253-281.

Norton, W.H., 1897, Artesian wells of Iowa: Iowa Geological Survey, v. 6.

Parker, G.G., Hely, A.G., Keighton, W.B., and Olmsted, F.H., and others, 1964, Water resources of the Delaware River basin: U.S. Geological Survey Professional Paper 381, 200 p.

Perrault, Pierre, 1674, De l'Origine des Fontaines (Treatise on the origin of springs): Paris, Pierre le Petit, 353 p.

Playfair, John, 1802, Illustrations of the Huttonian theory: Edinburgh, 528 p.

Poiseuille, J.L.M., 1846, Recherches experimentales sur le mouvement des liquides dans les Tubes de Tres-Petits Diametres: Academy of Sciences, Savants Estrangers, v. 9, p. 433-545 (English translation by W.H. Herschel, Rheol. Mem. v. 1, No. 1, January 1940).

Powell, J.W., 1885, Report of the Director (1883-84): U.S. Geological Survey 5th Annual Report, Washington, D. C., p. xvii-xxxvi.

Rasmussen, W.C., and Andreasen, G.E., 1959, Hydrologic budget of the Beaverdam Creek basin, Maryland: U.S. Geological Survey Water-Supply Paper 1472, 106 p.

Reynolds, Osborne, 1883, The motion of water and the law of resistance in parallel channels--An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous and the law of resistance in parallel channels: Philosophical Translations of the Royal Society, v. A-174, p. 935-982.

Russell, I.C., 1902, Geology and water resources of the Snake River Plains of Idaho: U.S. Geological Survey Bulletin 199, 192 p.

Slichter, C.S., 1899, Theoretical investigation of the motion of ground waters: U.S. Geological Survey 19th Annual Report, pt. 2, p. 295-384.

_____1902, The motions of underground waters: U.S. Geological Survey Water-Supply Paper 67, 106 p.

_____1905, Field measurements of the rate of movement of underground waters: U.S. Geological Survey Water-Supply Paper 140, 122 p.

Slichter, C.S., and Wolff, H.C., 1906, The underflow of the South Platte Valley: U.S. Geological Survey Water-Supply Paper 184, 42 p.

Siebenthal, C.E., 1910, Geology and water resources of the San Luis Valley, Colorado: U.S. Geological Survey Water-Supply Paper 240, 128 p.

Smith, G.O., 1901, Geology and water resources of a portion of Yakima County, Washington: U.S. Geological Survey Water-Supply Paper 55, 68 p.

_____1903, Ellensburg, Washington: U.S. Geological Survey Geological Folio 86, 7 p. 3 maps.

_____1905, Artesian water in crystalline rocks: Lancaster, Pa., Science, New Series, v. 21, no. 528, p. 224-225.

Thiem, Adolph, 1887, Verfahress fur Naturlicher Grundwassergeschwindegkiten [a method for measuring ground-water velocity]: Polyt. Notizblatt, v. 42, p. 229.

Thiem, Gunther, 1906, Hydrologische methoden: Leipzig, J.M. Gephardt.

Todd, J.E., 1900, Geology and water resources of a portion of southeastern South Dakota: U.S. Geological Survey Water-Supply Paper 34, 34 p.

Turneaure, F.E., and Russell, H.L., 1901, Public water supplies: New York, John Wiley & Sons, 258 p.

Venturi, G.B., 1797, Recherches experimentales sur la principe de la communication laterale du movement dans les fluides: Paris.

3. MEINZER ERA--1910-40

During the 40 years of O. E. Meinzer's employment by the U.S. Geological Survey (1906-46), hydrogeology gained recognition as being a significant branch of earth science. Under Meinzer's leadership, a systematic scientific approach was applied to the problems of hydrogeology, and the underlying principles were defined. His personal scientific efforts, insight, and leadership greatly influenced the direction and development of the science of hydrogeology both inside and outside the U.S. Geological Survey. Meinzer is often recognized as the father of ground-water hydrology.

The Meinzer Era of Hydrogeology in the United States, 1910-40

By

George B. Maxey
Water Resources Center
Desert Research Institute
University of Nevada System
Reno, Nevada

Introduction

Acceleration of agricultural, industrial, and municipal development following the Civil War resulted in unprecedented demands for knowledge in all areas of water-resources development. These demands were, in part, answered by the government in the organization and execution of the early geographical surveys sponsored by the War Department and by Congress in the late 1860's and the early 1870's. These surveys produced much substantive data but, more important, resulted in the establishment of the United States Geological Survey in 1879 which, in turn, cleared the way for systematic studies involving sources of water supply including ground-water investigations. By 1903, the U.S. Geological Survey had established a Division of Hydrology, which by 1908 had evolved into the Division of Ground Water. By this time, a Division of Surface Water and the roots of a later developed Division of Quality of Water were firmly established. O. E. Meinzer succeeded W. C. Mendenhall as Chief of the Division of Ground Water in 1912 and retained that position until his retirement in 1946, thus his period of service roughly spanned the period described in this paper. By 1910 the Geological Survey had initiated and conducted many areal ground-water studies throughout the United States, as well as many specialized studies involving investigation of the flow equations, geologic controls, artesian flow, and tracer studies.

By 1910 a substantial scientific background had been developed both independently and based upon European studies. The basic equations of flow derived from Darcy's work and extended by A. Dupuit, A. and G. Thiem, and P. Forchheimer formed a rational foundation for the permeability investigations of King, Hazen, and others. Slichter also had developed theory and methodology in applications of the flow equations and in tracer studies. Chamberlin, Ellis, Darton, Fuller, and Mendenhall developed hydrogeological aspects of far-reaching significance. Most of this work was independently developed and was not systematically put together, thus many experiments were duplicated or went unnoticed for many years. Early attempts to bring all of this work together include a textbook by Turneaure and Russell (first edition in 1901), whose second edition in 1909 might be regarded as an incomplete "state of the art" work at that time, especially when combined with Fuller's publications. However, no really complete descriptions of hydrogeological knowledge appeared until the middle 1920's when the works of Meinzer appeared.

Institutional and Organizational Developments

In 1911, a year before Meinzer became Geologist in Charge of the Division of Ground Water, the staff consisted essentially of four men: Meinzer, A. J. Ellis, Everett Carpenter, and, a year later, Kirk Bryan. Most of the older staff had transferred or resigned. However, Meinzer's earlier work (he joined the Survey as an aide in 1906) and his training under Mendenhall, his predecessor as Chief, had instilled in his mind several principles that later became guiding policies in the development of the Division of Ground Water.

1. He learned from field experience that resource evaluation studies of immediately applicable value were sorely needed throughout the country and that these studies must be as quantitative as data and knowledge would permit.

2. He recognized that knowledge of the science was incomplete and scattered, and that there was a real need to bring together existing knowledge and methodology and to develop new information in both categories.

3. He recognized ground-water geology as a multidisciplinary field and that not only geologists but physicists, chemists, and engineers were needed to develop basic principles and to apply those principles to immediate needs.

4. He recognized that a systematic approach to problem solution should be made by an organized team of experts.

5. He recognized that the public should be served by prompt and accurate release of data and information.

All these principles were employed as Meinzer slowly developed the Division of Ground Water. By 1917 nine staff members were employed. Unfortunately, World War I caused a break in the development of the Division and during and after the war the staff was much reduced. By 1929 there were only 10 geologists and engineers on the staff. The great drought and depression resulted in strong demand for ground-water studies and by 1941, there were more than 80 members on the staff.

By 1929 one of the Geological Survey staff's ambitions was fulfilled by the passage of Congressional legislation that established in principle the practice of 50:50 cooperation of the Federal agencies with State and local governmental units. This made possible training of State and other scientists as well as a significant expansion in resource evaluation and other studies and was probably a chief factor in the accelerated growth of the Water Resources Branch in the decade following. In some State or local cooperative programs, part of the staff was employed directly by the State or local agency; in others only Federal employees were involved. Also, some cooperating agencies preferred to publish all the results, thus enhancing the prestige of their publications and agencies. Other agencies saved publication costs by allowing all results to be published by the U.S. Geological Survey.

By 1940, the Division of Ground Water and Division of Quality of Water made up the largest and most able hydrogeological corps in the world. It contributed, by far, more to the literature than most of the other organizations then operating, especially in the fields of areal studies, applications of the flow equations, and quality of water problems. It was an effective force in hydrogeologic training, especially of practicing engineers and geologists in State, county, and municipal service. Most of the hydrogeologists in America today have received training from the Survey, from ex-members of the Survey, or from students of ex-members.

By the latter part of the 19th century and onward, petroleum exploration and development took place at an explosive rate. Accompanying this growth, problems regarding the flow of fluids through porous media developed, which individual scientists and engineers were invited to solve. Among these scientists, the contributions of Muskat, Hubbert, and their associates are notable.

The universities and some private consultants also made contributions. Meinzer's doctoral thesis at Chicago was concerned with the general field of hydrogeology and was published by the Survey under the title, "Occurrence of Ground Water in the United States with a Discussion of the Principles" (Meinzer, 1923a). Tolman and his associates at Stanford made many contributions in special areas of water supply, saltwater intrusion, and land subsidence. Although degrees in hydrogeology were not offered, courses were taught in many universities especially after about 1930. Tolman's textbook entitled "Ground Water" was published in 1937.

Hydrologic Advances

The trends hydrogeology set by the early surveys and the work by the Geological Survey continued until the late 1920's. The work consisted primarily of resource evaluation and areal studies. However, some research was carried on, as Meinzer said in one address given in the late 1930's, "almost surreptitiously" because of lack of funds and governmental interest, and the collection, analysis, and consolidation of the Western world's fund of knowledge of hydrogeology was in large degree accomplished in this manner. Foremost among examples of works resulting from these activities must be mentioned "The Occurrence of Ground Water in the United States, with a Discussion of Principles" (Meinzer, 1923a) and "Outline of Ground-Water Hydrology, with Definitions" (Meinzer, 1923b), which became textbooks used internationally by nearly all workers in the field. They constituted a "state of the art" review of the ground-water field and gave clean and concise definitions, many of which are still in use.

Most of the experience and understanding of the U.S. Geological Survey's ground-water staff came from the background of the areal-resource evaluation studies, which by 1930 numbered well over 100, conducted in all parts of the United States and dealing with most of the gamut of features of ground-water occurrence, availability, movement, and quality. Concurrently geologic, hydraulic, hydrologic, geochemical, and management and development disciplines also were developing, all of which formed a constantly changing scientific and engineering background from which was drawn increasingly useful knowledge and methodology to be used in hydrogeology.

Accessory to geologic and engineering developments and of great utility in hydrogeologic practice were the development of drilling technology, pumping technology, various types of equipment development, and improved mapping techniques, which peaked in the latter 1930's with the introduction and widespread use of aerial photography and photogrammetry.

Geological progress during the 1910 to 1940 period that affected hydrogeologic advances is difficult to itemize in detail. In general, more precise and quantitative practice in sedimentology, increasingly quantitative understanding of principles and processes in stratigraphy, structural geology, and geomorphology and a growing interest in areal geology all contributed significantly.

In hydraulics and analytical activities, the development and wide use of steady-state flow equations, such as the Thiem method, dominated the early part of the period and paved the way for rapid acceptance of the Theis nonsteady flow method (first introduced in 1935) and its expansion to more satisfactory solutions of many analytical problems. The Theis method and its derivatives resulted in the development of a highly quantitative technology that is still developing today, especially in reservoir and regional analysis and in modeling methodology.

Non-analytic models based on flow-net approximations (finite-difference equations) came into use during the latter part of the period. Numerical analysis and applications of iteration and relaxation methods applied to ground-water flow problems began to appear, and many reports were published on these methods following World War II. Studies of problems in drainage, engineering geology, and soil mechanics all contributed to knowledge of flow through porous media during the 1920's and 1930's.

Hubbert's "The Theory of Ground-Water Motion," published in 1940 revived the early theories of Forchheimer and emphasized the necessity to understand and apply the principles of potential distribution in the reservoir or aquifer.

Hydrologic methods for determining and balancing the water budget were introduced in several papers by Meinzer and others, most notably his and Stearns' paper on the Pomperaug basin in Connecticut (Meinzer and Stearns, 1929). Later, in 1932, Meinzer published "Outline of Methods for Estimating Ground-Water Supplies" (Meinzer, 1928), which reasonably summarized knowledge of this area of study up to the time the Theis equation was introduced. Methods described by Wenzel, Theis, and later, Jacob, Guyton, and others provided additional means for determining the perennial yield of aquifers.

Early in the establishment of the Geological Survey, it was recognized that the chemical quality of water should be determined, especially in relation to its intended use. Thus, the early work of A. C. Lane, W. Lindgren, M. L. Fuller and associates, M. O. Leighton, R. B. Dole, and others firmly established the practice of chemical analysis of waters in relation to use before 1910, and this practice continued throughout the period under discussion. Lane, Meinzer, Fisher, Jackson, and others recognized the importance of utilizing water quality as a research tool, especially in relation to mineral deposits and to saltwater encroachment; thus, early in this period a foundation was established for low-temperature aqueous geochemistry, which became important in the latter part of the period and laid the foundation for work following 1940.

In ground-water development and management, it was abundantly clear by 1910 that aquifers and ground-water reservoirs were depletable. Much of the resource-evaluation work between 1910 and 1940 was directed, not only at depletion by water withdrawal, but also at quality effects. Studies in the 1930's by Tolman and his associates pointed up the effects of saltwater encroachment and subsidence resulting from withdrawal of underground fluids. Earlier the U.S. Geological Survey had used the Ghyben-Herzberg formula in studies of encroachment along the Atlantic Coast (Brown, 1925). Later, concepts developed there were applied on the Gulf Coast and Hawaii. Thus, problems such as reservoir depletion, contamination, saltwater encroachment, and subsidence kept surfacing, and most workers in the field were convinced that management and development should be planned carefully on the basis of properly collected and analyzed data. One large step toward this objective was the development of cooperative programs in which State, local, and private officials could participate, on the one hand sharing the knowledge of the experts, and on the other, pointing out vexing and often apparently unsolvable local problems.

Thus, by 1940, the science of hydrogeology had developed a strong theoretical foundation and many methodologies that were important to the science. This background was important in the solution of the many problems generated during World War II, and laid the basis for the rapid development of the science and hydrogeologic training that took place in the decades following World War II.

Special Acknowledgments

Much of the material in this paper is from the unpublished files of the U.S. Geological Survey, and the author wishes to thank the staff for their assistance. Much general reference information also came from the 50th Anniversary Volume (Part II) of the Society of Economic Geologists (1955), especially the article entitled "The Quantitative Approach to Ground-Water Investigations" by John G. Ferris and A. Nelson Sayre.

References

Brown, J.S., 1925, A study of coastal ground water, with special reference to Connecticut: U.S. Geological Survey Water-Supply Paper 537, 101 p.

Hubbert, M.K., 1940, The theory of ground-water motion: Journal of Geology, v. 48, no. 8, pt. 1, 159 p.

Meinzer, O.E., 1923a, The occurrence of ground water in the United States, with a discussion of the principles: U.S. Geological Survey Water-Supply Paper 489, 321 p.

_____1923b, Outline of ground-water hydrology, with definitions: U.S. Geological Survey Water-Supply Paper 494, 71 p.

_____1928, Methods of estimating ground-water supplies--part I, Outline of available methods: Society of Economic Geologists, Technical Session 1928, Lancaster, Pa., 25 p.

_____1937, The history and development of ground-water hydrology: Journal of the Washington Academy of Science, v. 24, p. 6-32.

Meinzer, O.E., and Stearns, N.D., 1929, A study of the Pomperaug basin, Connecticut, with special reference to intake and discharge: U.S. Geological Survey Water-Supply Paper 597-B, p. 73-146.

Tolman, C.F., 1937, Ground water: New York, McGraw-Hill Book Co., Inc., 593 p.

Turneaure, F.E., and Russell, H.L., 1901, Public water supplies: New York, John Wiley and Sons, 808 p. (2nd edition, 1909).

_____1932-1933, Methods for ground-water supplies: Water and Water Engineering, London, v. 34, no. 411, p. 603-606, and v. 35, no. 413, p. 25-28.

Tribute to Oscar Edward Meinzer

By

S. W. Lohman
U.S. Geological Survey
Denver, Colorado

The late George Maxey was well aware of O. E. Meinzer's many accomplishments in ground-water hydrology, and these accomplishments are well-documented in the preceding paper. The purpose of this paper is to supplement the technical aspects of O. E. Meinzer with an insight into his remarkable personality gained from the recollections of those of us who worked closely with him and under his supervision during a substantial part of his 40 years of dedicated service with the U.S. Geological Survey from June 1906 until November 1946. The comments that follow clearly show that O. E. Meinzer had a genuine fatherly interest in the welfare and scientific development of his staff. These comments come from my recollections and those of my colleagues, including V. T. Stringfield, F. A. Swenson, L. K. Wenzel, and the late Walter N. White, of the old Division of Ground Water; James Gilluly, T. A. Hendricks, Ogden Tweto, and the late D. Foster Hewett, of the old Geologic Branch; and Mrs. Kirk Bryan. Additional excellent biographical material on O. E. Meinzer is contained in Sayre (1949), Hackett (1966), Fiedler (1973), and in the conclusion of this symposium (p. 103).

Although many members of the Survey, including Meinzer, possessed doctorate degrees, it was not customary to use "Doctor" in conversations within the Survey or at meetings of local scientific societies, except when addressing or referring to a medical doctor, a dentist, or a veterinarian. O. E. Meinzer adhered strongly to this tradition and in this tribute he is referred to, as was the custom of his time, as Mr. Meinzer.

Mr. Meinzer (fig. 17) is known throughout the world as "The father of ground-water hydrology." Less well known outside his "Survey family" is the fact that he was a beloved father figure to members of his staff--particularly to young unmarried ones. He was delighted one day in March 1933, when R. C. (Dick) Cady and I, without having made our plans known to each other, confided to Mr. Meinzer our intentions of getting married on April 7 and 14, respectively. Mr. Meinzer was not only religious but vitally interested in young people. So such staff marriages were celebrated by a gathering of the Survey "family" and the young couples in Mr. Meinzer's office, where he took great delight in delivering a good-natured "sermon," replete with fatherly advice and presentation of wedding gifts from the office staff. Dick's and my marriages were honored at a joint presentation, and my wife, Ruth, was embarrassed by being the only bride present because Dick's wife, Bea, had to work that day. Later, when our first child was expected any minute, Meinzer kindly offered to present a paper I was scheduled to deliver at Elizabeth City, North Carolina, and did so, much to our relief. When the baby arrived on Meinzer's birthday (November 28, 1934), we were accused by the office staff of apple polishing.

Meinzer never openly criticized a member of his staff for any real or alleged wrongdoing; but, I will never forget the kindly way he handled a minor infraction of mine. I did not have the pleasure of meeting Mr. Meinzer and most of his staff until after 4 months of field work in northeastern Pennsylvania, where I had been "broken in" during July 1930, by R. M. (Max) Leggette, in a very patient and kindly manner. I had barely gotten settled in the Washington office in November when I was detailed to evaluate 10 damsites in Virginia for the Corps of Engineers, using one of their touring cars. Before leaving for Virginia, again with Max as mentor, Mr. Meinzer reminded me that Leland (Lee) Wenzel, another newcomer, and I were invited to his house for Thanksgiving dinner. As our custom was to work 7 days a week in the field, my return to Washington was not until Thanksgiving morning. I was delayed by a steady rain, which barely left me time to change clothes and drive Lee Wenzel to Meinzer's house, where we parked in front. When Meinzer greeted us warmly at the door, I noted that he was looking at the insignia on the door of the Army car, and the enormity of my mistake hit me full force. I mumbled that I was late returning from Virginia in the rain, and we thought it was more convenient to drive out. He merely said, "Yes, it was more convenient." The matter then was promptly dropped, and we enjoyed a fine dinner with Mr. and Mrs. Meinzer and sons Robert and Roy. This was but the first of my many visits to the Meinzers, many of which included the entire staff and wives.

Mr. Meinzer devoted considerable thought and time to the scientific development of his staff and generally carried out his plans so adroitly and subtly that we were often unaware of the superior quality of the training we received until we took time to look back and take stock.

We were encouraged to join several local scientific societies, attend their meetings, and present papers whenever we had something worthwhile to report. These included the Geological Society of Washington of which Mr. Meinzer was president during the winter of 1930-31; the Section of Hydrology of the American Geophysical Union of which he was one of the chief organizers and the first chariman; and the Survey's Pick and Hammer Club, where we were free to openly criticize each other's papers.

Another local organization that helped along this line was the Geologs, which fellow member Tom Hendricks recalls was organized in 1926. The membership comprised the 27 youngest geologists in the Washington office of the Survey in terms of years of service--not age. When a new man joined the Survey, he displaced the with the most years of service. Dinner meetings at a local restaurant were supposed to be held monthly, during which a member generally described the results of his summer's field work for the approval or criticism of the others. As with the Pick and Hammer Club, criticisms were freely given, particularly inasmuch as no older Survey personnel were present. I was lucky enough to belong during the winter of 1930-31. After that no meetings were held during the rest of my stay in the Washington office, but Ogden Tweto told me it was revived during the winter of 1940-41, then stopped altogether because of World War II. The 1930-31 Geologs membership, as best Tom Hendricks and I could recall several years ago, comprised:

GEOLOGS
1930-31

D. A. Andrews	W. D. Johnston, Jr.	F. S. Parker
W. H. Bradley	P. B. King	W. G. Pierce
Josiah Bridge	M. M. Knecktel	C. B. Read
Eugene Callaghan	R. M. Leggette	J. C. Reed
G. A. Cooper	S. W. Lohman	A. N. Sayre
C. H. Dane	E. T. McKnight	Ralph Stewart
E. N. Goddard	J. C. Miller	V. T. Stringfield
T. A. Hendricks	W. H. Monroe	C. V. Theis
C. B. Hunt	B. N. Moore	J. S. Williams

The membership included 5 from the Division of Ground Water, 1 from the Conservation Branch, and 21 from the Geologic Branch. The first talk I recall was by Phil King, who discussed his interesting geologic mapping in the Marathon region, Texas (U.S. Geological Survey Professional Paper 187).

In an early effort to promote exchange of ideas, Meinzer organized the Ground Water Club so that each man would have an opportunity to discuss the results of his investigations, matters of current interest, or give reviews of important or timely publications. These meetings were held generally during the last hours of the work day in the Director's conference room. The intervals ranged from weekly to monthly during the winter, when most of the staff members were in the office preparing reports. They were held fairly continuously from 1915 to 1918, when World War I interrupted, and then were resumed during 1930-32. The minutes of these interesting meetings, kept in a faded notebook, were discovered by the late C. L. McGuinness when he became chief of the Ground Water Branch. The minutes were reproduced and distributed to members and former members of the old Division of Ground Water in August 1966, and were again reproduced in the Water Resources Division Bulletin for April-September 1977. Unfortunately neither of these releases are available to the general public. The meetings were very educational and literally covered the waterfront, including many early discussions of Mr. Meinzer's glossary of ground-water terms. This glossary was embodied later in his Water-Supply Paper 494. This report and his even more famous Water-Supply Paper 489 were published in 1923.

One day in the mid-1930's while Meinzer was cleaning out his attic, he found an armful of Water-Supply Paper 489 bearing a special cover, which he brought to the office the next day. These were distributed to the staff on a "first encountered-first served" basis, and I was lucky enough to get one. A photograph of the cover is shown in figure 19.

Of perhaps equal value to our training were the daily lunch messes (forerunners of modern brown-bag sessions), which in the early 1930's, were held in the office shared by Lee Wenzel and me. Mr. Meinzer and the other married men brought lunches from home, and we singles bought sandwiches

Compliments of
O. E. Meinzer

The University of Chicago

THE OCCURRENCE OF GROUND WATER IN THE UNITED STATES WITH A DISCUSSION OF PRINCIPLES

A DISSERTATION

SUBMITTED TO THE FACULTY
OF THE OGDEN GRADUATE SCHOOL OF SCIENCE
IN CANDIDACY FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY

BY
OSCAR EDWARD MEINZER

Private Edition, Distributed By
THE UNIVERSITY OF CHICAGO LIBRARIES
CHICAGO, ILLINOIS

Reprinted from
UNITED STATES GEOLOGICAL SURVEY WATER SUPPLY PAPER 489
1923

Figure 19.--Specially printed cover of Water-Supply Paper 489, used as dissertation for Mr. Meinzer's doctorate degree from the University of Chicago. Photograph by U.S. Geological Survey.

from a woman who set up a stand each noon at the corner of 17th and F Streets, where the Department of the Interior building stood, which now houses the General Services Administration. The lunch messes generally were attended by all members of the Division of Ground Water who were in town, plus several from the Geologic Branch, including Francis Wells and Bill Johnston, Jr. (who transferred from Ground Water), generally Arthur C. Spencer, and quite often Foster Hewett, Steve Capps, and others. Kirk Bryan, a former Ground Water Division member, and Mr. Meinzer's brother, a Presbyterian minister, attended whenever they visited Washington. The subjects discussed generally included ground water, particularly if someone needed advice on a puzzling problem, but they also covered a variety of topics. If the discussion started to lag, Meinzer adroitly suggested something else of a controversial nature. If no general agreement was reached by the end of our lunch period, Mr. Meinzer used to say with a twinkle in his eye, and in one breath "All in favor say aye, opposed no, the ayes have it."

At one of these sessions, Francis Wells told us of the footnote at the bottom of page 136 of Henry G. Ferguson's Professional Paper 172, (see Theis' concluding remarks, p. 103), which had just been published, "Merely corroborative detail added to give verisimilitude to an otherwise bald and unconvincing narrative. -- W. S. Gilbert, Mikado, Act 2." Mr. Meinzer convulsed with laughter but could not believe that such a gem could pass all the reviewers and editors, and the Director. Francis went next door to get a copy of the report and showed the footnote to Mr. Meinzer. With tears of laughter in his eyes, he said, "I don't care if it _is_ in print -- I _still_ don't believe it!"

During the early 1930's, each of us took turns answering letters from the public concerning ground water by drafting replies for the Director's signature. Mr. Meinzer laid down helpful guidelines regarding the preparation of such replies, which he rightfully considered very important, and he generally went over the first effort or two with the writer at his side. He strove for plain, constructive letters and would not tolerate one with a negative tone. We were taught to first check the location in an atlas, then determine if it was in or near an area covered by a ground-water report, a geologic folio, or any other geologic report. In those days, it was rare to encounter such help. In the absence of a nearby report, we would rely on a state or United States geologic map, on Meinzer's Water-Supply Paper 489, or other general sources and try to be as helpful and constructive as possible, yet keeping our replies in general terms. I'll never forget a sentence in one of Nelson Sayre's replies to a woman inquirer, "The reason your well went dry _probably_ was because the water level declined below the bottom of the well." Although answering inquiries seemed like a chore at first, particularly when we were busy preparing our own reports, we soon learned how broadening and instructive our efforts had been for we became more and more familiar with the geology and ground-water resources of large parts of the country.

During the 1930's, Mr. Meinzer personally reviewed every report prepared in the Division, and generally an author's first report was revised with the author by his side. Such personal attention to proper writing probably was the most valuable training we received, for as

Jim Gilluly of the Geologic Branch remarked, Meinzer was one of the Survey's very best writers. In such personal reviews, Mr. Meinzer was known to criticize some of his own earlier writings not clearly identified as such. Thus in reviewing one of Lee Wenzel's reports all went smoothly until Meinzer began to tear apart one sentence and rewrite it. When he had finished, Lee informed him he had taken it verbatim from one of Meinzer's Water-Supply Papers. Mr. Meinzer laughed and said, "Well, I guess I must have changed my mind since then."

I was so impressed with how beautifully and clearly Mr. Meinzer could express a concept with minimal use of commas or other pauses, which tend to distract the reader's attention, that I formulated "Meinzer's law of the conservation of commas." Later, when I was put in charge of my first district office, I dictated both the words and the punctuation of letters until each new secretary learned not to use unnecessary commas as taught in most secretarial schools.

In a talk given at Lincoln, Nebraska, a year after he retired, Mr. Meinzer commented upon his having succeeded W. C. Mendenhall as head of the Division of Ground Water in 1911, an appointment made permanent on July 1, 1913, and stated (Meinzer, 1947):

> "Mr. Mendenhall always used the title 'Geologist in charge' and I have used the same title. I have preferred it to 'Chief of the Ground Water Division' because the latter has a more bureaucratic connotation and contains no suggestion that our work is of scientific character. 'Geologist in charge' is, I think, not entirely satisfactory now that we have so many engineers in the Division. However, the designation 'Chief Hydraulic Engineer' is, I think, still more unsatisfactory in view of the facts that there are so many geologists and chemists in the Branch, and, moreover, the work that is done by the surface-water and ground-water engineers is hydrologic work rather than hydraulic engineering. Perhaps 'Chief Hydrologist' and 'Hydrologist in charge' (for the division chiefs) would be better."

Here again Meinzer was ahead of his time for now we have a Chief Hydrologist, but in 1947 the old divisions became branches and the branches became divisions.

In the same talk at Lincoln, Nebraska, Mr. Meinzer (1947, p. 10) mentioned that in the past ground-water geologists and ground-water engineers generally worked independently without fully understanding each other, but that later they began working harmoniously together, gradually learned much of each other's work, and many finally became well-rounded ground-water hydrologists. In the early 1940's, when I was District Geologist for Kansas, I used Meinzer's own thoughts on this matter to best him in an argument--the only time I ever came out ahead or even tried to. On a visit to the Washington office I mentioned to Lee Wenzel that I needed an engineer for an investigation that would involve several pumping tests.

He said, "How about Fishel? He feels that he is in a rut running the one-man hydrologic laboratory with little or no work coming in and would like very much to do field work." V. (Vint) C. Fishel was indeed eager to make the change. So the matter was put to Mr. Meinzer, who offered many reasons why Fishel should not be transferred--particularly, as it would mean closing the laboratory for lack of a suitable replacement. Finally Meinzer delivered what he expected to be the clincher, "You say you need an engineer, but Fishel is a physicist!" I caught him off guard by saying, "Oh come now, Mr. Meinzer, you know very well that Fishel is no more a physicist than I am a geologist!" His jaw dropped, and before he could muster a reply I followed up my advantage by stressing that by now I hoped that both Fishel and I had become ground-water hydrologists. Meinzer acquiesced, Vint was transferred, and the hydrologic laboratory remained closed until its successor was opened in Lincoln, Nebraska, in about 1948, by the late George H. Taylor, with A. Ivan Johnson in charge.

As A. G. (Al) Fiedler (Meinzer's assistant "chief" and later Assistant Chief of the Water Resources Division) once aptly remarked, "His [Meinzer's] conservative views with respect to the demon rum were the subject of much comment, particularly among his wetter colleagues," which included most of the staff. Among the "wetter colleagues" was Walter N. White who, with Gerald A. Waring, had assisted Mendenhall on quantitative ground-water studies in southern California beginning in 1905. Walter told me that while he was driving Mr. Meinzer through part of western Texas one hot summer day during "Prohibition," he longed for a drink but was loathe to bring it up knowing Meinzer's feelings on the subject. Finally, when they drove through a small town where Walter had stayed many times, he had a sudden inspiration and said, "Mr. Meinzer, why don't we stop for a cool, refreshing drink?" Meinzer readily agreed, so they entered the town's only restaurant, and Walter said to his old friend the waiter, with a knowing wink, "I'd like a tall glass of cold ginger ale." Much to Walter's consternation Meinzer said, "That sounds good, I'll have the same." When the drinks arrived Walter found his own drink liberally laced with alcohol, but neither said much as they consumed their "ginger ale." When they resumed the drive, Meinzer said, "Walter, you had an excellent idea, that ginger ale surely hit the spot." I do not know whether or not Walter ever learned if Meinzer's drink also had been spiked.

This calls to mind an incident in September 1938, at Wichita, Kansas, when Mr. Meinzer visited our temporary field home, and we had all the staff over after dinner to meet the "boss." It was a hot evening, so I announced that I had cold beer and coke and asked for choices. Absolute silence! To break the ice, I said, "Mr. Meinzer, I know you will have a coke, I'll have beer, what will the rest of you guys have?" Immediately all but one asked for beer, but Ray Delameter, instrument man on our level crew, asked for a coke. The next day while I was driving Mr. Meinzer through the area, he said, "That Mr. Delameter certainly is a fine young man."

Strict as he was about drinking, Mr. Meinzer not only was lenient about smoking but actually indulged in the habit in an amateurish sort of way. At our daily lunch messes, he generally would accept an offered cigar or cigarette but never quite mastered the art of smoking or of flicking ashes into an ash tray, with the result that most of the ashes ended up on his vest and pants. He finally realized that he should make an effort to repay the donors, so he bought a package of cigarettes, opened it, and kept it on top of his desk for reimbursement. We quickly learned to light-up before entering his office, for the thoroughly desiccated cigarettes were not only highly flammable but practically explosive!

Mr. Meinzer generally was very polite and mild mannered, seldom raised his voice, and almost never used any words even bordering on profanity. It came as quite a shock to me, therefore, to be with him in his office on two occasions when he "blew his top" and used words befitting a longshoreman. One such outburst arose over his continued dissatisfaction with the air-conditioning system installed long after the old Interior building was built; the other resulted from an action by a much disliked chief clerk of the Geological Survey.

The only real fault members of his staff ascribed to Mr. Meinzer, if indeed it could be so regarded, was his unwillingness to accept long overdue raises in his own salary simply because he always had the taxpayers best interests at heart. This caused him to lose the services of at least one eminent geologist, Kirk Bryan, and nearly resulted in the loss of others. As told by the late D. Foster Hewett and verified by Jim Gilluly and Mrs. Bryan, Kirk said in effect, "Foster, much as I hate leaving Mr. Meinzer, for as you know I love him dearly, I've had a better offer from Harvard which I'm going to accept. Meinzer won't accept a raise himself, so what chance for advancement do the rest of us have?" Becoming a distinguished professor at Harvard in no way diminished Bryan's high esteem for Meinzer, and as noted above, he always visited Meinzer and attended our lunch messes when he came to Washington. He even rejoined the Ground Water Division during the summer of 1936 to participate in the Rio Grande Joint Investigation under the supervision of C. V. Theis. Finally, Meinzer's supervisor forced him to accept a raise in order to relieve the bottleneck.

I have touched upon Meinzer's sense of humor; in closing, I shall give a more concrete example, with a few comments on ground-water work during the great depression. In 1932 my regular work in Pennsylvania was interrupted because the State Geological Survey was unable to provide any matching funds, so I was assigned to field work in Michigan and North Carolina. The small beginning of a cooperative program in Michigan, which later grew into a substantial one, involved the technique of jetting shallow wells into very permeable glacial outwash in time to extinguish nearby forest fires. Mr. Meinzer wanted to witness a demonstration of the technique, so he and I traveled by train to Columbus, Ohio, where Lasley Lee, then District Engineer, Surface-Water Division, made a "present" of an antique but still serviceable panel truck for my use in the field (the meager allotment was barely adequate to cover a few weeks salary and expenses for me--a junior geologist drawing $2,000 "per annum," later cut to $1,700). We drove our windfall to the Michigan Forest Fire Experiment Station near Roscommon, where we met the cooperating official, R. A. Smith, State Geologist, and other State and local personnel.

The next day the men who had perfected the technique put on a demonstration that left us amazed. In just 5 minutes, two men jetted down a shallow 4-inch casing, inserted a 3 1/2-inch screen and pipe, jacked up the 4-inch casing, attached the pipe to a piston pump, and had 50 gallons a minute shooting a stream 125 feet long from a 3/8-inch nozzle. Mr. Meinzer took over the hose and nozzle and was like a kid with a new toy as he directed the stream over the tops of the Jack pine, which constituted the fire hazard in the area. Seconds after I took the photograph in figure 20, the antique hose burst at his feet, and a stream of water from a small hole hit Meinzer squarely in the face. This brought a chorus of guffaws from the assembled crowd, in which Meinzer good naturedly joined. But he spied R. A. Smith standing a little apart from the group, and let him have it squarely in the face, knocking off his cap. I thought to myself, "Oh me, there goes the cooperative program down the drain before it even got started." But Smith laughed it off, and the day was saved for Mr. Meinzer was as highly esteemed by colleagues of his generation, including cooperating state officials, as he was by members of his own staff (fig. 21).

Mr. Meinzer and my father were the two greatest men I ever knew, and Meinzer was the finest supervisor I ever had the pleasure of serving under, and most of my colleagues agree.

References

Fiedler, A.G., 1973, Oscar E. Meinzer--Father of ground-water hydrology: Washington, D.C., Cosmos Club Bulletin, v. 26, no. 1, p. 3-5.

Hackett, O.M., 1966, Ground-water research in the United States: U.S. Geological Survey Circular 527, 8 p.

Meinzer, O.E., 1947, Forty years of progress in ground-water investigations: U.S. Geological Survey Proceedings of West-Central Branch Conference, Water Resources Branch, Lincoln, Nebr., April 9-12, 1947, p. 5-14 (mimeographed).

Sayre, A.N., 1949, Memorial to Oscar Edward Meinzer: Proceedings of Geological Society of America, volume for 1948, p. 197-206.

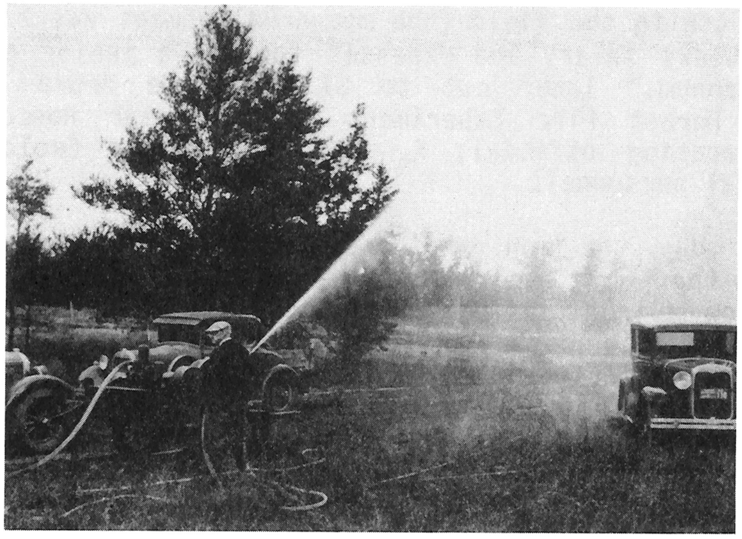


Figure 20.--O. E. Meinzer demonstrating fire-fighting ability near Roscommon, Michigan, October 1932. Photograph by S. W. Lohman.

Figure 21.--O. E. Meinzer and G. E. ("Doc") Condra, Nebraska State Geologist, standing on intake point of the Dakota Sandstone in bed of small stream draining part of the Black Hills, Fall River County, South Dakota, September 1940. Photograph by S. W. Lohman.

4. MODERN ERA--1940-76

With the foundations laid during the Meinzer Era (1910-40), hydrogeology reached maturity as a science in the Modern Era. As a science it has become truly multidisciplinary. It has remained a dynamic science in that the content of hydrogeology continues to broaden through the expansion of basic research and in the sophistication of methodology and applications. The science draws upon advances in related sciences and integrates the appropriate technology into its own body of knowledge. As a result, ground-water geology and hydrology have become recognized as distinct branches of earth science not only in the United States but internationally. Hydrogeology is called upon to address many of the most complex problems of advanced and developing societies. The careful and systematic application of hydrogeology continues to play, as it has in the past and will continue to do in the future, a significant role in the economic development of much of the United States. The application of the science has both direct and indirect impact upon a broad segment of economic, legal, and, therefore, political and sociological aspects of our modern society.

Scientific Advances

By

Gerald Meyer
U.S. Geological Survey
Reston, Virginia

Introduction

Responding to the increasing complexity of ground-water problems and the growing requirements for quantified answers to water-resources questions, hydrogeology evolved into a multi-element, quantitative discipline between 1940 and the present (1976), a chapter in history characterized in this group of papers as the "Modern Era" of United States hydrogeology.

The Modern Era witnessed advances in application of geology to ground-water investigation and analysis, increased perception of geochemical behavior and its role in aquifer functioning, and an enlarged suite of geophysical methods and instrumentation. Most prominently, however, the Modern Era is characterized by rapid improvements in quantitative problem analysis and predictive methodologies. These several changes have taken the form of a broadened scope of discipline activities, increased interdisciplinary affiliations, the introduction of realistic simulation and systems analysis methods, and, concomitantly, pronounced increases in the number of people engaged in hydrogeologic practice, research, and education, and in the cash flow supporting these expanded activities.

Thus, the multi-element scope of the disciplines now embraced by the term "hydrogeology" in the United States necessitates a broad and liberal conception of the term. No longer purely geological and no longer the domain of the geologist alone, principles of geology are now intertwined with principles from physics, hydraulics, chemistry, and mathematics to form the interdisciplinary science of hydrogeology. For example, the numerical and quantitative simulation methods now a prominent part of ground-water practice are accepted companions to geologic, geophysical, test-drilling, and aquifer-test methods of interpretation of an aquifer system's internal makeup, geometry, and boundaries.

Continued increases in scope and rigor of hydrogeologic activity can be anticipated as field and laboratory problems become more complex as a result of increasing stresses on the ground-water systems, as better definition of the cause-effect relations in ground-water systems are sought, and as data collection is modified to meet requirements of the advancing dicipline.

Quantitative Methods

J. D. Bredehoeft (1976) has categorized the ground-water history of the past four decades into an early quantitative period (1935-50), a middle period that saw the rise of formal systems-analysis approaches (1950-65), and, most recently, the period of development of numerical-analysis methodologies (1965-present). The orderly evolvement of new ideas, new principles, new understanding, and new techniques in the field of ground water has been a symbiotic community process, each investigator building on the work of colleagues. Except for a very few notable exceptions, attempts to ascribe advances solely to single individuals is fraught with difficulty. The following historical summary, adapted partly from Bredehoeft's excellent review paper, covers only selected milestone advances in quantitative methods and necessarily omits reference to many important contributions and notable contributors.

Early Quantitative Period

The quantitative concepts and methodologies now universally employed in ground-water analysis are traceable largely to the original and perceptive work of C. V. Theis (1935; 1938; 1940; 1941), who recognized that ground-water flow in permeable rocks is analogous to the flow of heat in solids and that ground-water storage is an important element of the flow system that must be taken into account in aquifer analysis. Introduction of the "Theis equation" for nonsteady-state flow to a well was a major milestone and the cornerstone for subsequent developments and modifications that would enable treatment of complex boundary conditions.

During that time, M. K. Hubbert (1940) prepared a very significant and comprehensive treatise that examined the Darcy flow-gradient relationship starting from basic principles and analyzed the concept of fluid potential in ground-water hydrodynamics and potential theory. C. E. Jacob (1940; 1946) developed a physical foundation for the Theis equation, starting from basic principles and physically defined the coefficient of storage. Jacob's derivation of the Theis equation from hydraulic considerations alone and his mathematical definition of the coefficient of storage led to development of the equations for transient ground-water flow. H. S. Carslaw and J. C. Jaeger's classical text (1947) on conduction of heat in solids became a standard reference for ground-water researchers, with significant influence on evolving quantitative methods. Dealing primarily with petroleum reservoirs, but very relevant to ground-water reservoirs as well, Morris Muskat's two comprehensive books on flow in porous media (1937; 1949) contain many reservoir-behavior and fluid-flow concepts applicable to ground water, and these volumes are also standard reference books for ground-water investigation.

In addition to the aquifers themselves, other aspects of ground-water systems attracted interest during the latter part of this period, most particularly the role of confining layers and the movement and storage of water in and through them. Jacob's 1946 theory of steady drawdown in leaky artesian aquifers was followed by the nonsteady theory of M. S. Hantush and Jacob in 1955. An important modification by Hantush (1960) was made to consider storage in the confining layers. Fine-grained materials associated with aquifers are now fully recognized as important considerations in ground-water analysis, as potential indirect water sources, as influential controls on flow patterns, and as terrane materials favoring land subsidence.

Systems Analysis

During the early quantitative period, investigators recognized that real aquifer systems are more complex than the idealized ones necessitated by the level of expertise in the analytical art. Methods of problem solution developed during that period were limited largely to assumptions of homogeneous internal properties and simple geometry and boundary conditions. During the following years, termed the "systems-analysis" period (1950-65), investigators were able to come closer to realistic conceptions of flow systems, including nonhomogeneous aquifers having complex geometry, irregular boundaries, anisotropic permeability, and subjected to complicated pumping patterns.

Rapid advances were made during this period in models of ground-water systems, including both physical and analog methods. Within the U.S. Geological Survey, R. R. Bennett experimented in the 1940's with continuous-field resistance-type analogs for solution of steady-flow problems. H. E. Skibitzke, also of the U.S. Geological Survey, subsequently developed an analog resistor-capacitor (R-C) network for solving the general equations of ground-water flow (unpublished report in files of U.S. Geological Survey, 1954). Others had used R-C networks to solve the flow equations--for example, the so-called "Carter Analyzer" devised by W. A. Bruce (1943) of Carter Oil Company Research Laboratory. In 1960, the U.S. Geological Survey formally established an analog laboratory in Phoenix, Ariz., for design and construction of large analog models and analysis of large-scale problems. During this same period, several other organizations developed similar analog capabilities. Formal U.S. Geological Survey analog-laboratory services to its field personnel were terminated for the most part by 1977. A complete description of the evolution of analog methods is given in a summary paper on modeling advances prepared by T. A. Prickett (1975).

In addition, dispersion and interface problems were addressed utilizing scaled physical models (Ogata, 1964; Skibitzke, 1964).

Numerical Analysis

Though constituting a versatile and competent tool for solving complex problems of ground-water flow, analog methods required expensive electronic hardware, construction effort, and specialized personnel, which limited the number of analog centers. Only the largest organizations could afford to install fully equipped facilities. By the early 1960's, digital computers of comparatively high speed were available at reasonable cost, and the period of numerical analysis arose (1965-present). Numerical methods having an impact on hydrogeologic practice were rapidly adopted, begommomg first with simple, "single-layer" ground-water problems.

Capitalizing on earlier advances in numerical solutions to multiphase fluid flow in petroleum reservoirs, hydrologists proceeded to develop numerical models of various kinds to solve the equations of ground-water flow. The size and speed of computers available in the late 1960's limited applications to problems involving one stressed layer, but numerical analysis gradually expanded to more complicated problems as computer capability and numerical techniques increased. In the early 1970's, capability extended to more complex problems dealing with the transport of chemical constituents and heat energy in ground water, and numerical solutions are now available for many of them (Appel and Bredehoeft, 1976; Prickett, 1975).

Today, numerical methods of problem analysis are a common and effective methodology utilized extensively by hydrogeologists and other groundwater investigators, aiding deeper insight into the geochemical and flow behavior of aquifers, the nature of geologic and boundary controls, and the predictive problem solution.

References

Appel, C.A., and Bredehoeft, J.D., 1976, Status of ground-water modeling in the U.S. Geological Survey: U.S. Geological Survey Circular 737, 9 p.

Bredehoeft, J.D., 1976, Status of quantitative groundwater hydrology, in Advances in Groundwater Hydrology, Zubair Saleem, ed.: American Water Resources Association, 1976 Symposium Proceedings, p. 8-14.

Bruce, W.A., 1943, An electrical device for analyzing oil reservoir behavior: American Institute of Mining Engineers Transactions, v. 151, p. 112-114.

Carslaw, H.S., and Jaeger, J.C., 1947, Conduction of heat in solids: London, Oxford University Press, 386 p.

Hantush, M.S., 1960, Modification of the theory of leaky aquifers: Journal Geophysical Research, v. 65, no. 11, p. 3713-3725.

Hantush, M.S., and Jacob, C.E., 1955, Nonsteady radial flow in an infinite leaky aquifer: American Geophysical Union Transaction, v. 36, no. 1, p. 95-100.

Hubbert, M.K., 1940, The theory of ground-water motion: Journal of Geology, v. 48, no. 8, pt. 1, p. 785-944.

Jacob, C.E., 1940, On the flow of water in an elastic artesian aquifer: American Geophysical Union Transaction, pt. 2, p. 574-586.

_____ 1946, Radial flow in a leaky artesian aquifer: American Geophysical Union Transaction, v. 27, no. 2, p. 198-205.

Muskat, Morris, 1937, The flow of homogeneous fluids through porous media: New York, McGraw-Hill Book Co., Inc., 763 p.

_____ 1949, Physical principles of oil production: New York, McGraw-Hill Book Co., Inc., 922 p.

Ogata, Akio, 1964, The spread of a dye stream in an isotropic granular medium: U.S. Geological Survey Professional Paper 411-G, 11 p.

Prickett, T.A., 1975, Modeling techniques for groundwater evaluation, in Advances in Hydroscience, Ven Te Chow, ed.: New York, McGraw-Hill Book Co., Inc., v. 10, p. 1-143.

Skibitzke, H.E., 1964, Extending Darcy's concept of ground-water motion: U.S. Geological Survey Professional Paper 411-F, 6 p.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transaction, v. 16, p. 519-524.

______1938, The significance and nature of the cone of depression in ground-water bodies: Economic Geology, v. 33, no. 8, p. 889-902.

______1940, The source of water derived from wells--Essential factors controlling the response of an aquifer to development: Civil Engineering, v. 10, no. 5, p. 277-280.

______1941, The effect of a well on the flow of a nearby stream: American Geophysical Union Transaction, 22nd Annual Meeting, pt. 3, p. 734-738.

The Quantification of Hydrogeology

By

S. W. Lohman
U.S. Geological Survey

Until the latter part of the Meinzer Era (1910-40), most ground-water investigations were qualitative in nature, but a good start had been made on quantitative studies. These investigations have been discussed thoroughly by G. G. Parker's paper in this proceedings volume and need not be repeated here.

The development of the nonsteady flow equation by Theis (1935) during the latter part of the Meinzer Era and the many other flow equations that followed allowed for the first time the determination, under a wide variety of boundary conditions, the two essential quantitative properties of aquifers--transmissivity (*T*) and storage coefficient or specific yield (*S*)--generally by means of discharging-well tests. But the need for determining or estimating many *T* and *S* values for aquifers of large areal extent, sometimes termed "putting numbers on the rocks," did not become acute until the development of crude electric analog models in the 1940's, sophisticated ones in the 1950's, and digital models in the late 1960's. In the absence of sufficient discharging-well tests, additional *T* and *S* values commonly are estimated using methods summarized by Lohman (1972, p. 52-53).

In the early 1940's, several members of the Ground Water Branch (Ground Water Division at that time) of the U.S. Geological Survey used simple electric analog models for the solution of steady-flow problems, including R. C. Bennett, C. V. Theis, R. W. Stallman, and several others in and out of the Geological Survey. Bennett (U.S. Geological Survey, oral commun., February 1978) used thin sheets of aluminum foil and later Teledeltos Paper[1] to simulate either the cross section or areal extent of an aquifer having a relatively constant electrical (and hydraulic) conductivity in all directions. Negative boundaries were simulated by suitable cutouts using scissors; positive ones were painted on using highly conductive silver paint. Later, pegboard models using connected resistors were used to permit directional variations in electrical (and hydraulic) conductivity, but the methods were unsatisfactory for the solution of the more needed nonsteady-flow problems because the models did not include the storage coefficient or specific yield.

---

[1] A carbon-coated paper obtained from the Western Union Telegraph Company. The use of brand names in this paper is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

The pressing need for an electrical analog-model computer capable of solving nonsteady-flow problems became known to H. E. Skibitzke. According to E. S. Patten (U.S. Geological Survey, oral commun., February 1978), Skibitzke took the challenge and, with the encouragement of Theis and Bennett, came up with the solution in an unpublished 1954 U.S. Geological Survey report entitled "The use of numerical and electrical methods in the solution of ground-water flow problems." Briefly, to large pegboard arrays of connected resistors, grounded capacitors were soldered to the common junction points of every four resistors, and the release of stored electricity in a given time was analogous to the release of stored water. Using a complex array of electronic components, electrical pulses were fed to appropriate points, potentials were measured where desired, and the resulting drawdown after known periods of time was observed and measured on a calibrated oscilloscope. Once proven workable, further development of the method was undertaken by M. J. Bermes, who established the Survey's electric analog model unit at Phoenix, Ariz., in 1960. Patten was placed in charge of the growing unit in 1962, and from 1962 to 1973, when the unit was moved to Reston, Va., many dozens of models were made and used for the solutions of complex problems in many parts of the country. A typical model of a 150-mile reach of the Arkansas Valley in southeastern Colorado was 4-feet high and 48-feet long, and contained about 60,000 resistors and 15,000 capacitors. The Survey's electric analog model unit was discontinued in 1976 owing to the increasing use of cheaper digital models using sophisticated computers.

According to L. F. Konikow (U.S. Geological Survey, oral commun., February 6, 1978), development of a formal digital model for the solution of ground-water problems, at least within the Survey, probably was first made by G. F. Pinder and J. D. Bredehoeft (1968), who later (Bredehoeft and Pinder, 1973) developed the solute-transport model for the solution of ground-water-quality problems. Digital models were used as a supplement to some of the later electric analog models, and the dual use had many advantages.

Since the early 1940's, C. E. Jacob and a few others tried to promote the use of consistent units in ground-water flow equations in Geological Survey reports, so that these reports would be more comprehensible to foreign and many domestic colleagues. The use of thousands of $\underline{T}$ and $\underline{S}$ values in electrical and digital models helped spark the abandonment of inconsistent units in Survey reports and the adoption at long last of consistent units for $\underline{T}$, $\underline{K}$ (hydraulic conductivity), and $\underline{k}$ (intrinsic permeability), and for the redefinition or clarification of $\underline{S}$ and many other terms (Lohman and others, 1972).

References

Bredehoeft, J.D., and Pinder, G.F., 1973, Mass transport in flowing groundwater: Water Resources Research, v. 9, no. 1, p. 194-210.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Lohman, S.W., and others, 1972, Definitions of selected ground-water terms--Revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Pinder, G.F., and Bredehoeft, J.D., 1968, Application of digital computer for aquifer evaluation: Water Resources Research, v. 4, no. 5, p. 1069-1093.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transaction, v. 16, p. 519-524.

Geochemistry

By

William Back
U.S. Geological Survey
Reston, Virginia

During latter years of the "Modern Era," quality-of-water studies underwent a dramatic change that added a new dimension to hydrogeology. This change was the application of chemical thermodynamics to ground-water systems, which permitted identification of controlling chemical reactions within the hydrogeologic framework. This application advanced studies from largely descriptive investigations to interpretative and predictive analysis. An excellent description of this transition period is provided by two papers, one by J. D. Hem (1959), which summarizes the earliest geochemical work and demonstrates the most advanced understanding at that time. The second paper (Back and Hanshaw, 1965) reviews the first attempts to demonstrate the hydrogeologic significance of the law of mass action, chemical-free energies, the Nernst equation, oxidation-reduction potential, concept of hydrochemical facies, effects of clay-membrane phenomena, and isotopes of hydrogen, oxygen, sulfur, and carbon (both stable ^{13}C and radioactive ^{14}C, which are used for determination of age of water, velocity of flow, and permeability of the aquifer). These topics, some of which had become more or less operational, provided the general theme for geochemical studies, and in 1970, Hem once again provided an excellent updated summary of geochemical concepts and understanding.

During the last few years of the Modern Era, studies were refined, and a certain degree of sophistication was added, such as determining the distribution of ionic speciation in equilibrium studies and a greater understanding of the mechanisms of isotopic fractionation. In addition, a general awareness developed of the need for a broader conceptual base for geochemistry of ground water that would include the kinetics of reactions, gases in both the soil and water, and the role of organic compounds and bacteria. This later period is summarized by William Back and J. A. Cherry (1976), who emphasize that much of the current activity in the study of the geochemistry of ground water is designed to provide the data required to develop predictive models based on mass transfer, transport of solutes, and attenuation of contaminants.

References

Back, William, and Hanshaw, B.B., 1965, Chemical geohydrology, in Advances in hydroscience, Van Te, Chow, ed.: New York, McGraw-Hill Book Co., Inc., v. 2, p. 50-109.

Back, William, and Cherry, J.A, 1976, Chemical aspects of present and future hydrogeologic problems, in Advances in Groundwater Hydrology, Zubair Saleem, ed.: American Water Resources Association, 1976 Symposium Proceedings, p. 153-172.

Hem, J.D., 1959 (1st ed.), 1970 (2nd ed.), Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473, 269 p. (1st ed.), 364 p. (2nd ed.).

Surface and Borehole Geophysics--Application to the Solution of Ground-Water Problems

By

W. Scott Keys
U.S. Geological Survey
Denver, Colorado

The application of geophysics to hydrogeology may be separated into two approaches, surface and borehole geophysics. Of the two types of techniques, borehole geophysics has been applied more extensively in ground-water investigations. P. H. Jones of the U.S. Geological Survey not only conducted original research in the field of borehole geophysics as applied to ground water (Jones and Buford, 1951) but was responsible for establishing a major borehole-geophysics program within the U.S. Geological Survey, both applied and research.

Although borehole geophysics ("well logging") is thought to have started with the Schlumberger brothers in France in 1927, earlier work in using temperature logs to analyze ground-water flow in wells was reported by W. B. Hallock (1897) and C. E. Van Orstrand of the U.S. Geological Survey (1918). Hallock plotted "depth temperature curves," and Van Orstrand speculated that such curves might "afford a means of determining the relative water content of rocks in situ." In the "Modern Era" the earliest extensive application of borehole geophysics to the development of the understanding of ground-water systems was for estimating water quality from multi-electrode resistivity logs and identifying lithology from various types of electric logs and natural gamma logs. The first loggers utilized by the U.S. Geological Survey were "Widco," and the president and founder of the Widco Company, Hubert Guyod, was also an early researcher and teacher in ground-water applications of borehole geophysics. Early equipment utilized a single-conductor cable to make single-point resistance, self-potential (S.P.), and gamma logs. The most common use of these logs was for aquifer identification, which permitted lateral correlation, measurement of thickness, and selection of depths to set well screens. The first comprehensive description of subsurface geophysical methods in ground-water hydrology was published by P. H. Jones and H. E. Skibitske in 1956.

A second phase in the application of borehole geophysics to ground water began with the organization of a research effort in the U.S. Geological Survey and a training program and manual on techniques by Keys and MacCary (1971). The second phase tended to be more quantitative, with emphasis on the measurement of porosity, moisture content, water quality, and the location and identification of fractures and zones of flow. Recent applications of well logging include aid to artificial-recharge and waste-disposal problems, geothermal exploration, and state-of-stress measurements related to earthquake prediction.

Surface techniques, which can be divided into electrical, seismic, gravity, and magnetic methods, have not been applied to ground-water studies on a routine basis but are very successful under certain conditions. Resistivity surveys have been used by many investigators for several decades to delineate buried stream channels (Zohdy 1964; 1965) and to map freshwater-saltwater interfaces (Breusse, 1950). Seismic techniques have been used to map buried channels, measure depth to the water table, and determine gross stratigraphy and lateral facies changes in an aquifer (Eaton and Watkins, 1970). Gravity methods have seen limited use for determining the gross configuration of an aquifer and estimating average total porosity. The application of magnetic surveys has been limited to studies of basalt aquifers and sedimentary basins underlain by magnetic basement rock (Mabey and Oriel, 1970).

Within the U.S. Geological Survey the application of surface geophysics to ground-water investigations within the last decade has received most of its impetus from Zohdy, Eaton, and Mabey, who wrote a manual on the subject (1974) and who have carried out most of the research and training. The most recent application of surface geophysics has been to the delineation of geothermal reservoirs.

References

Breusse, J.J., 1950, La prospection electrique applique aux recherches hydrologique dans la presequile de Dakar: International Geological Congress, pt. V, p. 16-25.

Eaton, G.P., and Watkins, J.S., 1970, The use of seismic refraction and gravity methods in hydrogeological investigations: Proceedings of the Canadian Centennial Conference on Mining and Ground-Water Geophysics, Ottawa.

Hallock, W.B., 1897, Subterranean temperatures at Wheeling, W. Va., and Pittsburgh, Pa.: Columbia School Mines Quarterly, v. 18, January, p. 148-154.

Jones, P.H., and Buford, T.B., 1951, Electric logging applied to ground-water exploration: Geophysics, v. 16, no. 1, p. 115-139.

Jones, P.H., and Skibitzke, H.E., 1956, Subsurface geophysical methods in ground-water hydrology, in Advances in Geophysics, v. 3: New York, Academic Press, Inc., p. 241-300.

Keys, W.S., and MacCary, L.M., 1971, Application of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chapter E1, 124 p.

Mabey, D.R., and Oriel, S.S., 1970, Gravity and magnetic anomalies from the Soda Springs region, southeastern Idaho: U.S. Geological Professional Paper 646-E, 15 p.

Van Orstrand, C.E., 1918, Apparatus for the measurement of temperature in deep wells, and temperature determinations in some deep wells in Pennsylvania and West Virginia in West Virginia Geological Survey County Reports of Barbour and Upshur Counties by D.B. Reger and D.D. Teets, Jr.: Wheeling, W. Va., West Virginia Geological Survey, p. LXVI-CIII.

Zohdy, A.A.R., 1964, Earth resistivity and seismic refraction investigations in Santa Clara County, California: Stanford, Calif., unpublished doctorial dissertation, Stanford University, 132 p.

_____1965, Geoelectrical and seismic refraction investigations near San Jose, California: Ground Water, v. 3, no. 3, p. 41-48.

Zohdy, A.A.R., Eaton, G.P., and Mabey, D.R., 1974, Application of surface geophysics to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chapter D1, 116 p.

The Hydrogeologist and Houston, Texas

By

William F. Guyton and Ralph A. Scalapino
William F. Guyton & Associates
Austin, Texas

Houston, Texas, is now the fifth largest city in the United States. Its metropolitan area has a population of about 2,500,000 (1976). At least a part of the growth of the area must be attributed to its ground-water supply. This abundant and comparatively inexpensive water supply has made it possible for large water-using industries to locate almost anywhere in the area without much concern as to the availability or cost of water. The most intensive developments have been along the Houston Ship Channel, where large petrochemical and other types of industries have access to ocean transportation.

Although the abundance of the ground water has not lessened in recent years, land subsidence caused by pumping of the ground water has become a major problem. Strict limitations now are being imposed on pumping in the eastern part of the area where the land surface is low and the subsidence is causing increasingly larger acreages to be inundated by the sea.

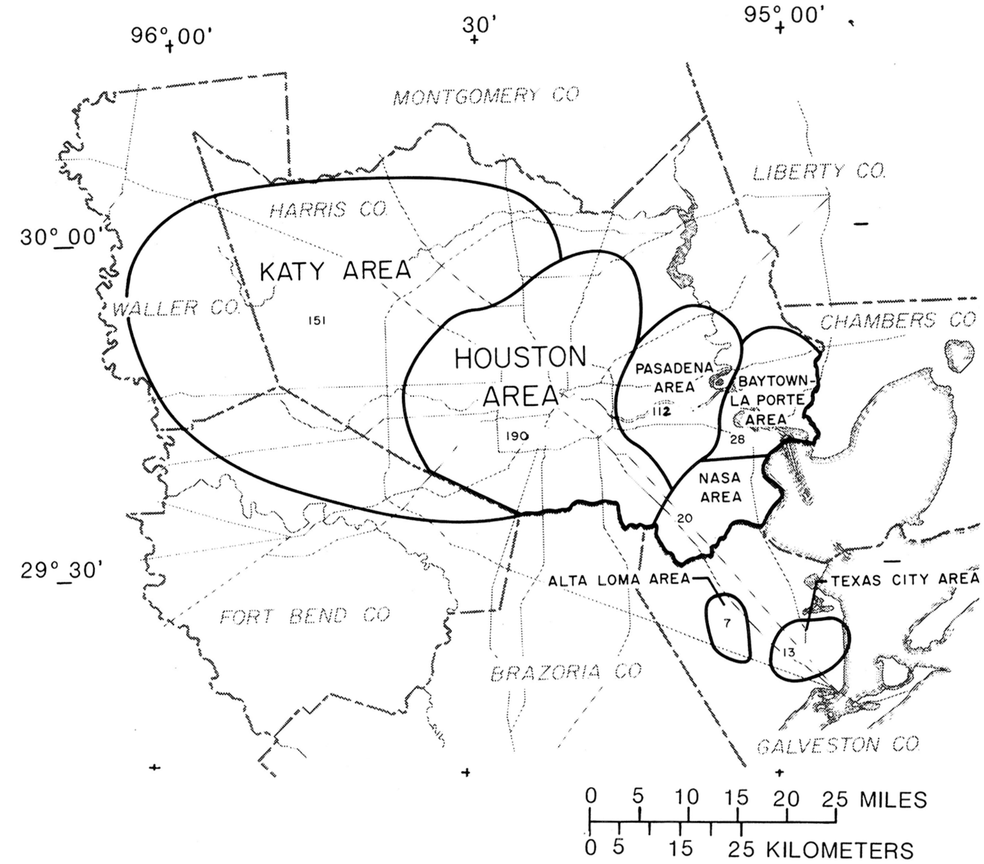
Until 1954, the area depended almost entirely on ground water. In that year an additional water supply was developed from the San Jacinto River, which flows along the eastern side of Houston, and since then, water also has been developed from the Trinity River farther east.

Present pumpage from wells in the Houston area averages about 500 Mgal/d. The location of subareas for which the pumpage has been inventoried and the 1974 pumpage in each are shown in figure 22[1]. A graph of the pumpage since the beginning of record is shown in figure 23.

Ground water is obtained principally from large-diameter gravel-walled wells ranging in depth from about 300 to 2,500 feet. The wells yield as much as 3,500 gal/min. They draw on artesian sand of Pleistocene and Pliocene age, interbedded and interfingered with clay. Individual sand and clay beds generally cannot be correlated over long distances, but it is possible to correlate zones in which the beds are predominantly sand or predominantly clay. A generalized cross section from northwest to southeast along the general dip of the sand and clay beds shows the sandy and clayey zones that have been identified (fig. 24). The general position of fresh and brackish water, and the positions and levels where most of the pumping occurs also are shown in addition to the approximate position of the 1974 potentiometric surface in the central part of the area.

---

[1] The data presented in the illustrations of this paper have been taken primarily from reports and unpublished records of the U.S. Geological Survey.



EXPLANATION

(13) **AREA OF GROUND-WATER DEVELOPMENT--Number is 1974 pumpage in million of gallons per day**

Figure 22.--Principal areas of ground-water development and 1974 pumpage, Houston area, Texas.

The first hydrogeologic studies of the aquifers in the Houston area were conducted for the U.S. Geological Survey by T. U. Taylor (1907) and Alexander Deussen (1914). In 1930, the Geological Survey established a district office for ground-water investigations in Texas, and the following year opened a suboffice in Houston. Since then ground-water observations and investigations have been made continuously by the Geological Survey in this area. This work has been done in cooperation with the Texas Water Development Board and its predecessors and with the cities of Houston and Galveston. Industries and other water users generally have cooperated wholeheartedly in the work. The area also has benefited greatly by the notable cooperation of the local well-drilling contractors.

When the U.S. Geological Survey's district office was opened in 1930, it was under the direction of Walter N. White, one of the pioneers in ground-water investigations in the United States. Mr. White took a

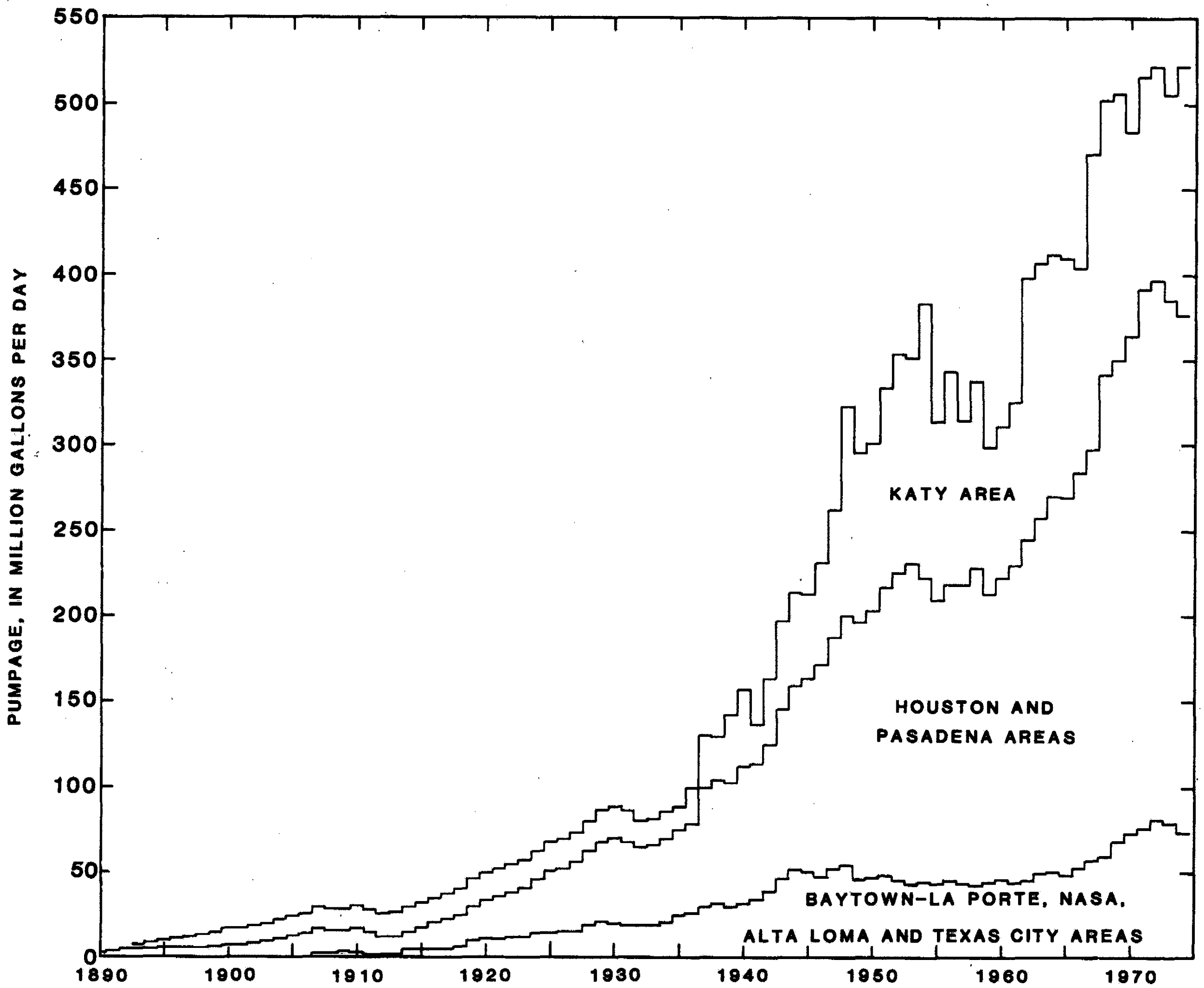


Figure 23.--Pumpage, Houston area, 1890-1974.

personal interest in the Houston studies and spent a great deal of effort on them. He continued in charge of the Texas district until 1946, when at age 71 he retired from Federal service. He subsequently continued to work on ground water in Texas, however, as an engineer with the Texas Board of Water Engineers until the end of 1950, at which time he became an independent consultant. While he was with the Geological Survey, Mr. White worked under the general supervision of Oscar E. Meinzer. Dr. Meinzer kept in close touch with the work in Texas and participated personally in the interpretation of the results and the preparation of reports. Mr. White and the Houston staff also were assisted from time to time by advice from C. V. Theis and David G. Thompson, and other persons of such stature.

The first ground-water investigations in the Houston area were primarily concerned with inventorying wells and pumpage, studying drillers' logs, measuring water levels in wells, and making chemical analyses of water samples. Because of the proximity to the Gulf Coast, a monitoring program of chemical quality of the ground water was established to detect

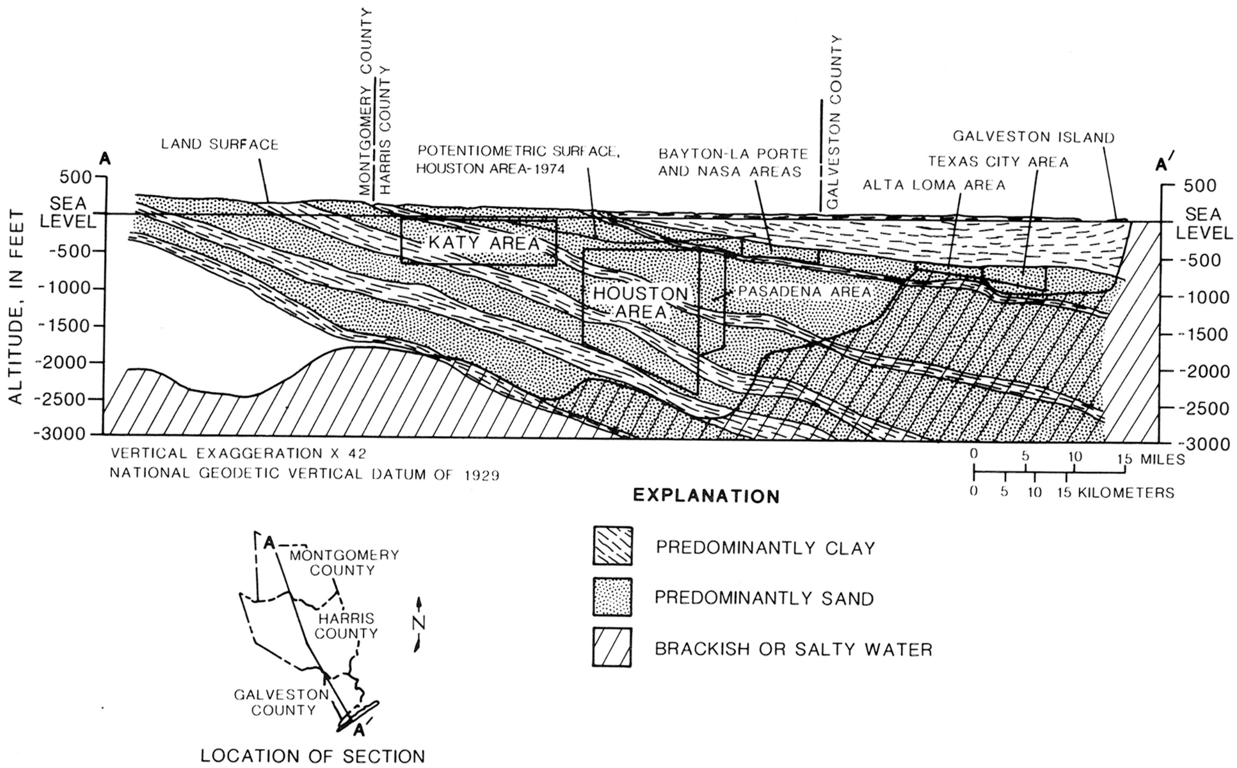


Figure 24.--Generalized cross section, Houston area, Texas.

any increase in salinity as a result of saltwater encroachment. The relationship between pumpage and water levels was studied, and an observation program was established for studying recharge. The availability of recharge, increasing pumping lift, and the possibility of saltwater encroachment initially were considered to be the major questions, or problems.

Beginning in the mid-1930's, the advent of electrical logging had a major impact on investigations. The Houston area is dotted with oil and gas fields, and many wildcat wells have been drilled. As electrical logging became commonplace, hundreds of oil tests were electrically logged through the fresh water-bearing sand, and these logs have become available for ground-water studies. The logs are mostly of the multiple-resistivity curve type, and estimates of water quality, as well as detailed identification of the sand and clay layers, have been possible. The city of Houston and nearly all other large ground-water users have made electrical logs a standard part of the construction of wells. Through interpretation of electrical logs, the city of Houston determined that water wells in the central and eastern part of the city could be drilled nearly twice as deep and obtain much greater pumping capacity, where previously the drillers' logs had indicated less than favorable conditions at the deeper levels. Electrical logs also have made it possible to select efficient settings for well screens to obtain optimum well yields at the lowest cost.

In 1938 and 1939, and again in 1949, the city of Houston, in cooperation with the Geological Survey, conducted an extensive test-drilling program, involving the use of coring, drill-stem tests, and electrical logging. The results of these investigations, together with similar information developed from other studies, made it possible to develop a general correlation between the resistivity shown by electrical logs and the chemical quality of the water in the sand. With this information and that determined from many electrical logs of oil tests, the base of the fresh ground water in the area was delineated so that wells could be drilled as deep as practicable without danger of producing saltwater from the lowermost sand. Using electrical logs, test holes also were planned and drilled, and monitoring wells constructed in the proper localities and at the proper depths to study saltwater encroachment in the southeastern part of the area.

As early as the 1930's, various water planners attempted to set limits on the amount of ground water that could be pumped in the Houston area, or to fix what they have called a "safe yield." In at least one instance in the early 1940's, a nationally prominent engineering firm made a strong recommendation to the City that the "safe yield" of the Houston and Pasadena areas be set at 75 Mgal/d. Apparently the decline of water levels in wells was thought to represent a depletion of the aquifer and that pumpage would have to be limited to this number to keep the water levels from declining to unreasonable depths. Mr. White and others of the U.S. Geological Survey questioned this concept and pointed out that recharge appeared to be ample, the drawdown, or decline, of water levels would be in proportion to the overall pumping rate, and additional drawdown was available to support increased ground-water development. The pumpage in these two areas is now (1976) more than 300 Mgal/d, and the pumpage in the entire region more than 500 Mgal/d. Various estimates have been made that as much as 700 Mgal/d to 1,000 Mgal/d could be withdrawn in the region without causing undue amounts of ground-water depletion. Also, as the years have passed, saltwater encroachment has been found to be occurring much slower than was first contemplated.

Originally, wells flowed in much of the Houston area, but the flows soon stopped as artesian pressures declined in response to withdrawals. The decline of the potentiometric surface has remained generally in proportion to the rate of pumping, as little of the aquifers actually have been dewatered. The total decline of the potentiometric surface for the principal aquifer from 1906 to 1973 is shown in figure 25.

In 1939, with the help and leadership of C. E. Jacob, the Houston office of the Geological Survey undertook a long series of pumping tests of City wells and analyzed these tests by means of the Theis equation. Efforts then were made to use the transmissivity and storage coefficient determined from the pumping tests to compute long-term drawdown effects from known and predicted increases in pumping. The discrepancies between computed and actual declines indicated that either a larger storage coefficient was required for the long-term computations than had been determined in the short-term tests or other processes are involved. C. V. Theis pointed out one possible process that might be involved; that is, although leakage through the clay was very slow, it did occur and over a large area and the amount of water involved could be significant. This insight by Theis was part of the beginning of development of the concept that compressible clay and leaky aquifer conditions occurred in this area.

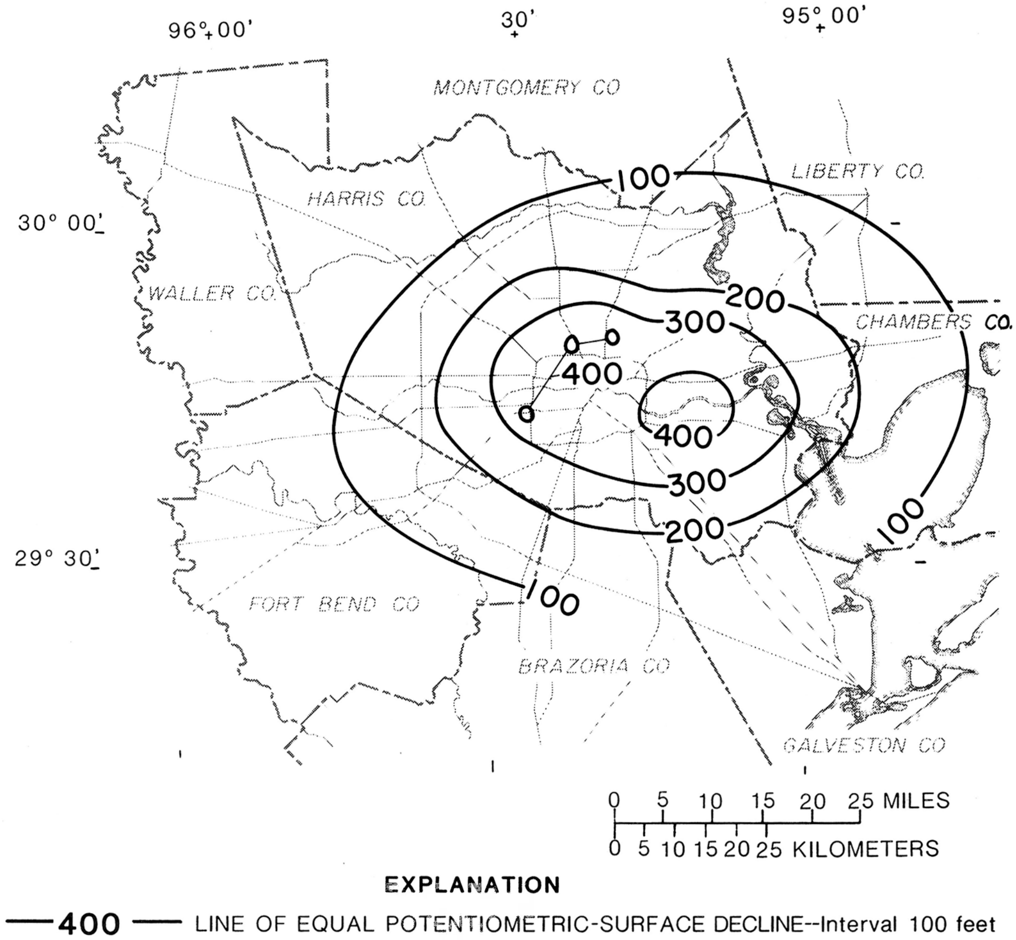


Figure 25.--Potentiometric-surface decline, principal aquifer, Houston area, Texas, 1906-73.

Based on the results of pumping tests and the continuing pumpage and water-level observation program, reasonable estimates could be made of future potentiometric-surface decline from pumping new wells. These estimates, in turn, made possible the selection of well spacings on the basis of well interference and the setting of pumps to provide for future decline in pumping levels. Also, based on detailed studies of well construction and the character of the sand, wells could be designed in advance for given yields and ranges of specific capacity. In addition, with the large amount of water-quality data available from the well-inventory and monitoring program, some degree of selectivity could be exercised with respect to chemical quality of the water to be produced from a well, particularly the hardness of the water. Altogether, the work of hydrogeologists made it possible to design wells and well fields to be as efficient and economical as practical and to help assure their dependability for long-term operation.

By 1954, land-surface subsidence was recognized as a major problem in the Houston area. Additional leveling by the U.S. Coast and Geodetic Survey aided better definition of this problem. At first, the amount of subsidence was correlated with the decline in the potentiometric surface, and the relation was thought to be about 1 foot of subsidence for each 100 feet of decline of the potentiometric surface of the principal aquifer. Later investigators realized that this ratio was not constant, that a substantial lag occurred in subsidence, and that the ultimate amount would be substantially greater than 1 foot for each 100 feet of decline of the potentiometric surface. Studies also indicated that the amount of subsidence would depend on the percentage and thickness of the clay layers and their character in each locality.

For more than 20 years, the subsidence was monitored and studied as it continued to increase. The amount of subsidence from 1906 to 1973 is shown in figure 26. In 1975, the State Legislature formed the Harris-Galveston Coastal Subsidence District and empowered it to regulate the withdrawal of ground water for the purpose of ending subsidence. At present (1976), the subsidence district is actively studying the situation and developing a plan for immediate reductions in pumpage in critical areas and placing limitations on future increases in adjoining areas, so that potentiometric surfaces will be raised in the coastal areas and then held at elevations that would minimize or prevent subsidence in the future. The U.S. Geological Survey is cooperating with the subsidence district and is furnishing technical assistance necessary for the district's directors to reach conclusions. A number of monitoring wells have been installed to measure the compaction of the earth between land surface and various depths below the surface.

Although future subsidence projections obviously are still crude because of lack of data, enough money and effort apparently are being spent on the problem so that in time the conclusions and projections should become progressively more accurate.

Pumpage (1976) in the Pasadena area along the Houston Ship Channel was expected to be reduced by about 80 Mgal/d by mid-1977 as surface water from the Trinity River is made available to industries and municipalities in this area from the Coastal Industrial Water Authority. This reduction would be the first big decrease in the pumpage in the Houston area. The subsidence district has rushed the completion of its monitoring wells in order to be prepared to monitor the rising water levels following this reduction in pumpage.

The Geological Survey has made two electrical analog models of the ground-water system underlying the Houston area for the purpose of computing pumpage and water-level relations and now is in the process of making a

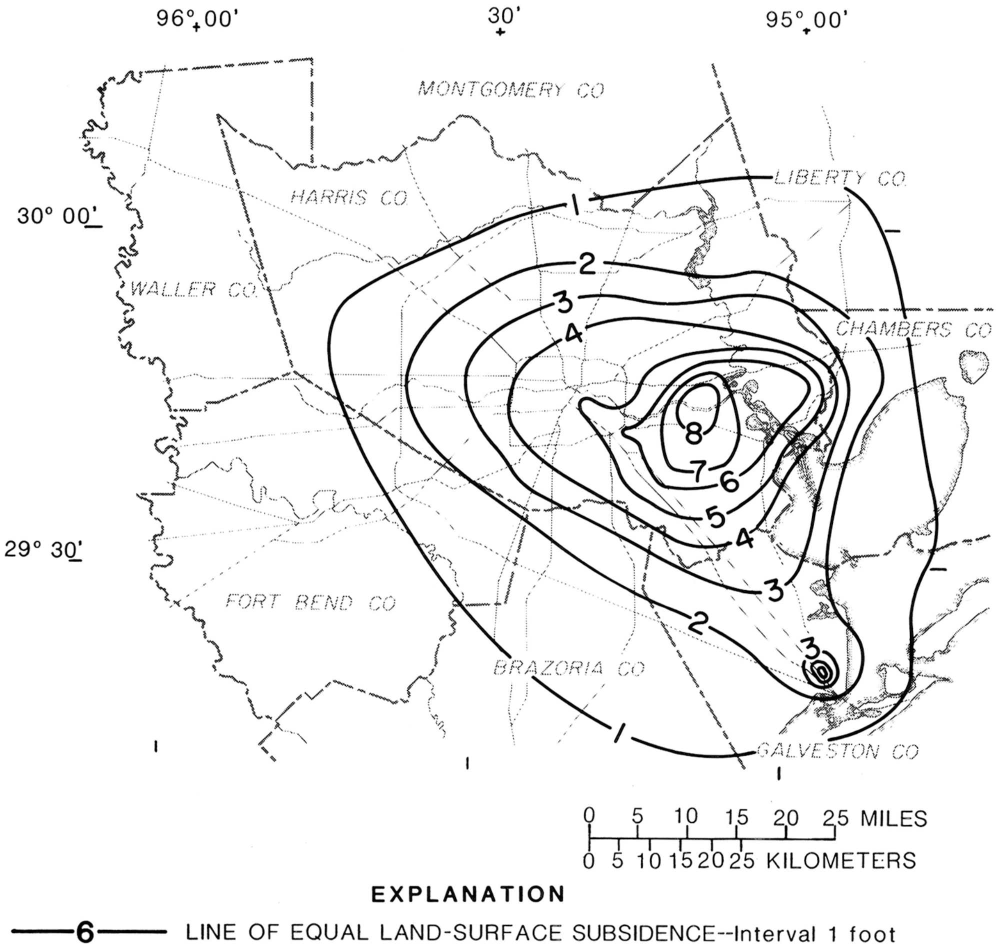


Figure 26.--Land-surface subsidence, Houston area, Texas, 1906-73.

digital model. All of these models take into consideration leakage between the land surface and the various water-bearing zones, and the later models will take into consideration the water obtained from the compaction of the clay layers. Because of the amount number of sand involved, the variety of conditions associated with leakage between beds, compaction of the clay layers, and the large number of unknowns that must be balanced against one another in the development and calibration of the models, it has not been possible yet to accurately represent all the ground-water conditions. However, as with the subsidence studies, refinements are continuing, and the models should become more representative of the ground-water conditions as the models are modified to include the refinements.

Thus, it is hydrogeologists who, in the early stages of Houston's growth, helped to develop the large ground-water resources of the area and now are helping to devise means of managing them so as to minimize the adverse effects of development of these resources. As the years pass, the role of the hydrogeologist should become increasingly important in the management process. Ground water is too important to the well-being and the growth of the Houston area to be abandoned. Its development and use can be managed so as to obtain the benefits of development as well as to restrain adverse effects.

References

Deussen, Alexander, 1914, Geology and underground waters of the southeastern part of the Texas Coastal Plain: U.S. Geological Survey Water-Supply Paper 335, 365 p.

Taylor, T.U., 1907, Underground waters of the Coastal Plain of Texas: U.S. Geological Survey Water-Supply Paper 190, 73 p.

Hydrogeology, Policy, and Politics

By

Harold E. Thomas
Hydrogeologist,
U.S. Geological Survey, Retired
Woodside, California

Two-hundred years ago the science of hydrogeology had not been invented, and ground-water development and use were exclusively by laymanology and serendipity. In eastern North America, with rainfall well distributed throughout the growing season and with an abundance of perennial springs and streams, problems of water supply were probably among the least of the colonist's worries. As to water rights, there is a commentary by Blackstone (1765) that, "because water is a movable, wandering thing and must of necessity continue common by law of nature, one can only have a temporary, transient, usufructuary right therein."

American colonists had considerable discussion and dissatisfaction about rights in general. For more than a century they had been emigrating from the old world and found that in the new world landownership was claimed by the Crown by right of discovery, and control was maintained by force of arms. Opposition to the system was whispered and then spoken louder, as by Samuel Adams (1772), "Among the natural rights of the colonists are these: first a right to life, secondly to liberty and thirdly to property." With the Declaration of Independence (1776) citing "certain inalienable rights," the Revolution was underway.

I don't know whether to mention it as policy or politics, but our land has always been fertile ground for discussion and controversy over "rights." Certainly the Constitution, by specifying and limiting the powers of the Federal government and by including amendments to protect property rights and other rights of the people, became the basis for significant changes in social policy. Many people hoped and expected the Revolution to lead to a more democratic form of land tenure, with ownership under fee-simple titles and each individual to have broad freedom in the exercise of his rights. Thomas Jefferson called small landowners "the most precious portion of the State" and favored wide distribution of the public lands as a basis of personal independence and democracy.[1/]

---

1 According to Huxley (1958, p. 112), "It is a political axiom that power follows property. But it is now a historical fact that the means of production are fast becoming the monopolistic property of Big Business and Big Government. Therefore, if you believe in democracy make arrangements to distribute property as widely as possible."

Following the Revolutionary War, about 80 percent of the total land area of the United States had been in the Federal public domain, acquired by cession from the original colonies (formerly "Crown" lands), by purchase, or by treaty. Today (1976), only about 30 percent is Federal property, and another 15 percent is represented in grants to the states (for schools, railroads, canals, rivers, reservoirs, reclamation of swamplands). Thus, in two centuries the Federal government has disposed of more than 400 million hectares, or 1,000 million acres, including especially the lands most desirable for habitation, agriculture, and economic resources. More than a million families received title to about a quarter of this land--250 million acres--under the Homestead Act of 1862 and its several amendments, which placed a 160-acre limitation on individual homesteads. Federal policy continued to favor the "precious small landowners" in the Reclamation Act of 1902, but with the aid of politics the government extended helping hands also to other minority groups, including those subsequently described as robber barons.

Evolution of Ground-Water Rights

As of 1776, I find nothing pertaining to ground-water rights except the old Roman maxim, "Cujus est solum, ejus est usque ad caelum et ad inferos," meaning the owner of the soil owns also all above it and beneath it--and that includes ground water and other minerals as stock resources. This maxim is followed in the Code Napoleon of 1804 and the French Civil Code that was subsequently established in Louisiana. It also appears in the English common law, based on a court decision (Acton vs. Blundell, 1843) that a landowner owns ground water as an ingredient of his soil. Several states have followed the "English rule" that the landowner's right is absolute and independent of the right of all others. But in New Hampshire (Bassett vs. Salisbury, 1862) it was decided that a landowner had no right to waste ground water unnecessarily or to export it from the area; this decision became the basis for the "American rule" of reasonable use, which was accepted in many other states.

The common-law doctrine is for gentlemen and good neighbors to use the water that is within your property lines, all you need, so long as you do not diminish the quantity or the quality of it for your neighbors. The doctrine is best suited to regions where water is so plentiful that nobody misses the amount you consume, and plenty exists for dilution of pollution. The first 30 states admitted to the Union are in such a humid region that annual precipitation exceeds evapotranspiration, creating a surplus of water, which is evident in the perennial streams, springs, and wetlands. But what to do when or where water is insufficient for all wants? As summarized by Trelease (1959):

> "The uncertainties that are inherent in these court-made rules of ground-water law, coupled with the uncertainties of the court-devised classification of ground waters into percolating waters, underground streams, and underflow of streams (which have no basis in science or in fact) leave the water titles of many well owners dependent on physical supplies, the action or non-action of his neighbors, and his ability to grab what he can while he can."

The 31st state admitted to the Union was California, and it brought in some environmental contrasts and cultural conflicts--snowy mountains and rainy coastal lands, deserts and semiarid valleys, and practically no rain anywhere all summer. The cultural conflict was between the Spanish heritage and the Yankees' Manifest Destiny and was partly resolved when the State Legislature in 1850 adopted the English common law. This action had a significant effect upon water development in the State. Common-law restrictions upon the right to store water contributed to the slow development of large dams on California streams, while much spring runoff was wasting to the oceans. Landowners could develop wells without restriction, and many of them did so, with resulting overdraft in several ground-water basins. Chief Justice Lucien Shaw of the California Supreme Court has stated (1922):

> "The opponents of the doctrine of riparian rights had pointed out these results with much emphasis and repetition in the political campaign prior to the decision in Lux v. Haggin (1886) and they are still referred to as evidence that the doctrine is contrary to a sound public policy in States having the arid climate of California. The obvious answer on the question of policy is that the objection comes too late, that it should have been made to the legislature in 1850 prior to the enactment of the statute adopting the common law. When that is done the riparian rights became vested, and thereupon the much more important policy of protecting the right of private property became paramount and controlling. This policy is declared in our constitutions, has been adhered to throughout our national history and it is through it that the remarkable progress and development of the country has been possible."

Because of the arid climate and water deficiency in its valleys, California has faced problems of apportioning scarce ground-water supplies. Under the "California" doctrine (Katz vs. Walkinshaw, 1903) the owners of land overlying a ground-water reservoir have correlative rights in a common supply, and each is limited to reasonable and beneficial use of the water. The landowner has a right only to the water necessary for use on his own land, and any surplus may be appropriated and exported from the area. In a basin where appropriators continued to pump long after the surplus vanished (Pasadena vs. Alhambra, 1949), the California Supreme Court decided that the appropriators who caused the overdraft acquired prescriptive rights by infringing on landowner rights for more than 5 years, but the landowners who continued to pump to meet their needs had infringed on the infringers and also gained rights. The losers were the landowners who had not pumped any water; they were like the man who had a talent but kept it buried (Matthew 25: 14-28) and lost his right.

Several Western States have repudiated the common-law doctrine of water rights and declared waters of the state to be public property subject to appropriation as specified by statute (sometimes called the "Colorado" doctrine, from its appearance in that State's Constitution in 1876). By this doctrine, beneficial use is the basis, the measure, and the limit of a water right, and the first in time is the first in right. In contrast to the landowner right, the appropriative right is to a specific quantity or rate of flow and is lost by nonuse; nevertheless it is a property right, demanding Constitutional protection. As defined by the U.S. Supreme Court (Arizona vs. California, 1931): "To appropriate water means to take and divert use in accordance with the laws of the State where such water is found, and by so doing to acquire a right under such laws, a vested right to take and divert from the same source and to use and consume the same quantity of water annually and forever."

Thus the settlement of the West brought new rules and new policies. Most of the West is semiarid or arid; the average annual precipitation is less than the potential evapotranspiration, so that a perennial deficiency of water exists. Although mountains have surplus water that accumulates as snow and runs off in annual freshets, rainfall is insufficient for agriculture in the valleys and lowlands that would otherwise be most suitable for habitation. Early settlers, therefore, chose the most suitable land available and appropriated water that had originated in mountainous areas in quantities sufficient for their needs. This practice was sustained in an early decision of the California Supreme Court (Tartar vs. Spring Creek, 1855), "... a prior appropriation of either (wood or water) to steady individual purpose establishes a quasi-private proprietorship, which entitles the holder to be protected in its quiet enjoyment against all the world but the true owner [that is, the United States]."

The idea of appropriation--taking water from the proprietor of the land whence it originates--had never occurred to many peoples. Especially in deserts, a landowner's right very generally is subordinated to the human right to survival, especially if the landlord is "absentee." This right is a basic in the right of thirst and the right of nomads to water their flocks in the great desert regions of the Sahara and Arabia. Generally, the right is to a specific quantity of water for a designated use, or to a rate of flow, a flow resource that continues so long as the use continues. In these arid regions, as stated by Caponera (1973, p. 29), "The land itself is of secondary importance, its only value being derived from its productivity which, in turn, depends on irrigation rights attached thereto. As water becomes scarcer, it becomes more essential to soil fertility and gradually develops into an object of ownership independent of the land."

Although Eastern States have a natural overall surplus of water, the withdrawals for use in some areas have become large enough to approach the limits of available supplies. For example, New Jersey uses more freshwater per unit of area than any other state. Competition and conflict among communities became serious enough that in 1907 the State Water Supply Commission was established to regulate the division of surface water for public supply, and in 1910 its authority was extended to ground water. As summarized by McGuinness (1963, p. 550):

> "Regulatory efforts have always followed the principle of equitable allocation among inhabitants, rather than among agencies, in accordance with prevailing riparian [common-law] doctrine which holds that the water belongs to the people who

own the land and not to the state. Thus in effect the state acts under the police power to protect the rights of individuals to use their water. Municipalities as such have no right to divert water, and control of municipal usage is exercised in the interest of equitable apportionment of water among people. Thus pursued, the state's policies have gained public acceptance, and accordingly the state encountered no serious difficulty when, in 1947, it assumed control over private uses of ground water exceeding 100,000 U.S. gallons per day in designated areas. The basis for the control is the argument that by the time a property owner has diverted 100,000 gpd from wells he has exhausted the 'riparian' right he possesses under the common law."

In the Southwest some water rights originated with grants of land and the rights appurtenant thereto made by Spain, Mexico, and the Republic of Texas before the United States had achieved its present boundaries. In determining the rights of holders of titles from prior sovereigns, the controlling laws generally are those in effect when the grants were made, and subsequent changes in law commonly recognize rights already vested (Hutchins, 1961, p. 3-6). Because of these rights traceable to former sovereigns, the solution of property rights can be quite complicated.

To a burgeoning metropolis in the Southwest, one of the most desirable, but rare and uncertain, water rights is the "pueblo" right, which constitutes a paramount right to all the water needed by a community for its continued growth. This right is limited to the towns that received pueblo grants prior to the Treaty of Guadalupe Hidalgo in 1848. This right has been described (Hutchins, 1960) as attaching to all the waters naturally in the watershed in which the pueblo is located--surface water and ground water, including tributaries from source to mouth and flood flows that may be stored. The right is perpetual and cannot be lost by nonuse or forfeiture. Thus, it hangs like a sword of Damocles over any other inhabitants of the watershed who may be using water or want to use it. This creates an excellent environment for legal controversy.

Two cities in California -- Los Angeles and San Diego - have pueblo water rights, adjudicated by the California Supreme Court (Feliz vs. Los Angeles, 1881; San Diego vs. Cuyamaca Water Co., 1930), but the Los Angeles pueblo right has been back in court repeatedly in subsequent years, most recently when the City sought a declaration of its rights to the ground water in the upper Los Angeles River area.

Santa Fe, New Mexico, was established in 1610 and is "the oldest seat of government in the United States" but without any pueblo grant by the King of Spain. The New Mexico Supreme Court could not see how "a mere colony of squatters could acquire under the Spanish law this extraordinary power over the waters of an entire non-navigable stream known as 'pueblo right'." (New Mexico Products Co. vs. New Mexico Power Co., 1937). The Pueblo Water Rights doctrine has touched down in New Mexico at the town of Las Vegas, which was established in 1835 as The Pueblo de Nuestra Senora de Las Dolores de Las Vegas. In the case of Cartwright vs. Public Service Co. of New Mexico (1958), the New Mexico Supreme Court adopted the doctrine of pueblo water rights as declared in California decisions and adjudicated to the town of Las Vegas a pueblo right to the waters of the Gallinas River and tributaries.

The city of Albuquerque has claimed that, as successor to the pueblo San Filipe de Albuquerque founded in 1706, the city has an absolute and unconditional right to divert and use so much of the surface and underground waters of the Rio Grande as is necessary for its use and that of its inhabitants. The pueblo rights questions were rejected by the New Mexico Supreme Court (Cartwright vs. Reynolds, 1963).

In states that have declared some or all waters within their boundaries to belong to the public, the historic role of the state has been to prescribe conditions under which rights may be acquired to use water, to record the rights and adjudicate conflicting claims, and to allocate water in accordance with rights thus established. Many states also have exercised their authority to reject proposed developments inimical to the public interest and to reserve water for uses having public significance. However, although nonconsumptive use and pollution are closely related, they commonly are kept separate in the public mind and in public agencies. Thus, a water right for nonconsumptive use can be granted without specifying any responsiblity for the resulting pollution.

Federal Authority Over Water

Under the U.S. Constitution (Amendment 10) the Federal government is limited to those powers expressly delegated or reasonably implied; all other powers are reserved to the states, respectively, or to the people. The Constitution does not mention ground water, but by the Property Clause (Art. IV, sec. 3) the Congress has unlimited power over the public domain. The four-fifths of the country that has been in the public domain includes all the Nation's major aquifers except those of the Atlantic Coastal Plain.

By legislation of 1866 and 1870, Congress recognized as valid the appropriation system that had grown up among the occupants of public lands in the West. Subsequently, the Supreme Court (California Oregon Power Co. vs. Beaver Portland Cement Co., 1935) held that, "following the [Desert Land] Act of 1877, if not before, all non-navigable waters then a part of the public domain became publici juris, subject to the plenary control of the designated states, including those since created out of the territories named, with the right in each to determine for itself to what extent the rule of appropriation or the common-law rule in respect of riparian rights should obtain. For since 'Congress cannot enforce either rule on any state,' [Kansas vs. Colorado, 206 U.S. 46, 94, (1907)], the full power of choice must remain with the state."

There are, of course, numerous wells on the public lands of today, notably several hundred irrigation wells on the U.S. Bureau of Reclamation's Minidoka Project in southern Idaho. Otherwise, the Federal government has a very low profile in the development, use, and control of ground water. But its authority is supreme over most of the surface waters of the Nation.

From ancient times, many peoples have regarded large bodies of water as belonging to no one (or belonging to everybody) and not subject to monopoly or exclusive possession. In ancient Rome, Justinian in his "Classification of Things" (534 A.D.) stated, "By natural law these things are common to all: air, running water, the sea, and as a consequence the shores of the sea."

The public rights and Federal authority as to surface water are not specifically mentioned in the Constitution, and they have developed over the years by increasingly broad interpretation. One of the early problems arose soon after the invention of the steamboat, when private interests sought to monopolize navigation throughout the State of New York. The U.S. Supreme Court (Gibbons vs. Ogden, 1824) held that under the Commerce Clause of the Constitution (Art. 1, sec. 8, cl. 2), the power of Congress comprehends navigation within the limits of every State in the Union. Congress began exercising this power in the River and Harbor Act of 1826, and the power has been extended to embrace all navigable waters (Gilman vs. Philadelphia, 1865), including those suitable for use by small boats (United States vs. Appalachian Electric Power Co., 1940); it also includes the non-navigable reaches of a navigable waterway, and its non-navigable tributaries (Oklahoma vs. Atkinson, 1941). The commerce power also extends to flood control (Jackson vs. United States, 1913) and to development of power (Green Bay & Mississippi Canal Co. vs. Patton Paper Co., 1898; Ashwander vs. Tennessee Valley Authority, 1936).

Several other clauses of the Constitution have served to enlarge the scope and enhance the authority of the Federal government. Thus, the General-Welfare Clause (Art. I, sec. 8) is interpreted broadly by the Supreme Court (United States vs. Gerlach Livestock Co., 1950), "the power of Congress to promote the general welfare through large-scale projects for reclamation, irrigation, or other internal improvement is now as clear and ample as its power to accomplish the same results through resort to strained interpretation of the power over navigation." Also under the Constitution, the President has power, by and with the consent of the Senate, to make treaties, and international treaties (Witmer, 1968, p. 381-487) have existing and potential importance relative to the basins of international streams, of which the largest are the St. Lawrence, Yukon, Columbia, Colorado, and Rio Grande Rivers. The Compact Clause of the Constitution (Art. I, sec. 10, cl. 3) prohibits any state from entering into any agreement or compact with another state, without the consent of the Congress. In 1911, Congress gave blanket consent for compacts for conserving the forests and water supply of the United States.

Now, after two centuries, the Federal government has authority over all waters that are navigable or floatable or have been so in historic time, the streams that contribute to the navigability of these waters, flood waters and waters that produce hydroelectric power, and waters that stand or flow along or across interstate or international boundaries. These are most of the flow resources that are involved in the hydrologic cycle, but Federal authority has not been certified as extending to subterranean water--soil moisture and ground water--except in the public lands.

Ground water has been separate and unequal throughout most of history--segregated scientifically and administratively and also legally, as indicated in an early court decision (Chatfield vs. Wilson, 1855): "The secret, changeable and uncontrollable character of underground water and its operations is so diverse and uncertain that we cannot well subject it to the regulations of law, nor build upon it a system of rules, as is done in the case of surface streams."

In the expansive years after World War II, we tried to put it all together with comprehensive planning. The case for integration was presented in papers on utilization of ground-water storage in stream-system development (Conkling, 1946) and coordinated use of surface- and ground-water storage (Thomas, 1955). Conjunctive use became a popular objective especially in California, the leader in ground-water withdrawals. In its plans for the Central Valley Project, the U.S. Bureau of Reclamation (1949) said, "In planning and constructing the necessary works [Friant-Kern and Madera Canals] special attention must be given to the problem of using ground-water reservoirs to best advantage. Only by the full use of these underground basins can the irrigable areas of east side upper San Joaquin Valley be developed completely." Unfortunately the Bureau, supplying its water under contract to several local agencies, must line its canals with concrete where they traverse natural areas of ground-water recharge, to prevent "loss" by seepage.

Conjunctive use of ground water and surface water has long been recognized as essential in the California Water Plan. As stated by Berry (1962), p. 3):

> "The answer for the future thus lies in the full development and use of our ground-water basins, both for conservation of local supplies and for seasonal and long-term cyclic regulation of imported water supplies. This will involve the planned use of ground-water storage in conjunction with surface storage facilities."

If ground-water reservoirs were public resources, Federal and State agencies could include them in overall stream-system development and management involving replenishment and storage for the common good. In California, however, private property rights have been asserted and protected particularly as to ground water. Federal or State agencies thus lose control of and title to the water they put into ground-water reservoirs. This has necessitated some change in policy, as described by Thomas and Phoenix (1976, p. E46):

> "At a panel discussion of practical considerations in implementing public policy (McGauhey, 1967, p. 78), moderator Harvey Banks asked John Teerink, Deputy Director of the California Department of Water Resources: 'How can we bring about the necessity of coordinated operation of long aqueducts and ground

water basins to even out aqueduct flows without undue interference with local control of ground water basins?' Mr. Teerink replied: 'In determining the need for regulatory storage along the California aqueduct, we looked for surface storage reservoir sites. We did consider that ground storage was a real possibility. But there did not exist, and there does not exist today, any means by which the State can involve itself in ground water basin management, so we had to go to surface storage.'

"Kreiger and Banks (1962) noted that Californians have made relatively few attempts to stretch the available water supplies and have tended to squander them; they pointed out that one means of checking this waste would be a basin management program of ample scope to maximize the use of the State's ground-water basins. This 'demands the immediate attention of our courts, lawmakers, local governing bodies, and water distributing entities, the skill and resources of lawyers, engineers, geologists, economists, financiers, and political scientists... .' Eight years later the California Water Plan still faced the same impediment (California Department of Water Resources, 1970, p. 72): 'Full realization of such integrated surface water-ground water system operations in areas where the ground water resource is available will require legal and legislative action and social and political acceptance.'

"This action may be delayed yet awhile. Fortunately, the California legislature has generally supported local initiative in ground-water basin management and also the conjunctive use of surface and ground water. It has passed special legislation when required for the effective operations of public agencies in populous areas, notably the Orange County Water District, as well as in rural areas such as the small mountain-rimmed basins included in the Tehachapi-Cummings County Water District (Porter, 1967). Conjunctive use of surface and ground water currently depends heavily upon the conjunctive operations of local agencies, whose dominant concern is ground water, and Federal and State agencies, whose dominant concern is surface water."

Thus, we have resegregation into surface-water and ground-water camps. The development of surface water is chiefly a public enterprise--by Federal and State agencies and large municipalities or utility districts--particularly for construction of large dams and operation of large surface reservoirs. In arid regions, such reservoirs have large losses by evaporation, as foretold for California by Conkling (1946, p. 279), "...no matter how large the reservoir capacity, streams of erratic annual and cyclic flow will yield for useful purposes no more than 50 or 60 percent of the average annual discharge because the remainder will be lost, over the years, by evaporation from the excessive water surface of the reservoir necessary to impound the water of the infrequent years of large discharge."

The development and use of ground water have been predominantly by private and local enterprise. In many areas where surface-water supplies also are available, the ground-water users are included in local agencies (county water districts, irrigation districts, conservation districts, etc.) who generally act as user-cooperatives in the purchase, distribution, and retailing of surface water obtained from the agencies that are managers and wholesalers of reservoir supplies. The cost of the surface water can be manipulated to encourage its use for preseason irrigation or for underground replenishment. Thus conjunctive use may be achieved by "self-governing, voluntarily cooperating groups, capable of functioning outside the bureaucratic systems of Big Business and Big Government" (Huxley, 1958, p. 114).

Rights and Responsibilities

We have considered the property rights of landowners and the human right to water needed for existence, prosperity, and enjoyment. We have also a birthright, as pointed out by the Committee on Water of the National Academy of Science (1966, p. 38), "Water is regarded as a birthright of Americans--a common holding in which there are some common stakes. Other commodities are not so regarded; water is singled out for special consideration." But "Liberty does not consist in mere declaration of the rights of man" (Woodrow Wilson). "Liberty means responsibility; that is why most men dread it" (G. B. Shaw). Until recently there has been far more emphasis on water users' rights than on their responsibilities for any deleterious effects of their use of water.

Most water is used nonconsumptively--for drinking, processing, cooking, cleaning, flushing, transporting, heating or cooling--and is polluted by suspended or dissolved solids or fluids, floating debris, organic materials, or heat. It then becomes the wastewater of individual homes, towns, farms, cities, or industry. If waste is discharged into a "common supply" the polluter may be charged with committing a nuisance or sued for damages, but this may be difficult to prove if many have shared in the pollution or if there has been significant dilution of the polluting waters. Like the water that carries them, pollutants may cross property boundaries, city and county lines, State and National boundaries, so that the problem goes beyond the limits of control and jurisdiction of local and State authorities. As pollution increases, the Federal government has become increasingly involved.

Early Federal legislation concerning water pollution included the "Refuse Act" comprising Sections 9 through 20 of the River and Harbor Act of 1899, which is still in effect. The statute was originally intended merely to prevent obstructions to navigation, based on the Commerce Power of Congress, and it took half a century to find that the statute also was effective against polluters of running water, the sea, and the shores of the sea. Since 1971, the act has become the basis for a permit system administered by the U.S. Department of the Army in coordination with the U.S. Environmental Protection Agency.

Conscious effort and legislation toward comprehensive water-pollution control began with the Water Pollution Control Act of 1948. Cautious in the face of constitutional limitations on Federal power, this act declared, "The policy of Congress to recognize, preserve, and protect the primary responsibilities and rights of the states in controlling water pollution*** and to provide Federal technical services to state and interstate agencies and to industries, and financial aid to state and interstate agencies and to municipalities, in the formulation and execution of their stream pollution abatement programs." The Act was concerned primarily with abatement of stream pollution, and it directed the Surgeon General to "prepare or adopt comprehensive programs for eliminating or reducing the pollution of interstate waters and tributaries thereof and improving the sanitary condition of surface and underground waters."

The objective of the Federal Water Pollution Control Act (1972), as amended (Public Law 92-500), is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters. This act also depends upon the Commerce Power for its prime authority (Title I, Sec. 101), "...it is the national goal that the discharge of pollutants into the navigable waters be eliminated by 1985," and the National policy is to "develop technology necessary to eliminate the discharge of pollutants into the navigable waters, waters of the contiguous zone, and the oceans." The Federal standards and enforcement of effluent limitations (Sec. 301-316) and the National Pollutant Discharge Elimination System (Sec. 402) are concerned exclusively with surface waters where Federal authority is supreme.

As to ground-water pollution, Public Law 92-500 may be counterproductive. By minimizing discharges of pollutants to surface water, the act can be responsible for increasing use of land-surface and subsurface disposal of waters, thus increasing danger of ground-water pollution. The act calls for development of "comprehensive programs for preventing, reducing, or eliminating the pollution of navigable waters and ground waters and improving the sanitary condition of surface and underground waters" (Sec. 102); it calls also for research, investigation, training, and information in categories ranging from aquatic ecosystems to waste from toilets and includes monitoring "the quality of the navigable waters and ground waters and the contiguous zones and oceans" (Sec. 104). But a fundamental weakness of Public Law 92-500 is its failure to integrate ground water into the total water resource that it proposes to protect from pollution.

The Federal government has clear and ample power to eliminate discharge of pollutants into the "navigable" waters of the United States, and during more than a century this term has been broadened until practically all surface waters can be claimed and confirmed as navigable waters. In recognition of the principles of continuity of the hydrologic cycle and interrelations of the waters in the various phases of that cycle, could the Federal power be further extended to include ground water? I believe it could, but not all ground water indiscriminately and certainly not all subterranean water.

Federal authority might be asserted and confirmed, for example, where large springs discharge into and, in some instances form, navigable streams where a river continues flowing during an extended drought because of base flow derived from ground-water discharge and perhaps also where the flow of a river is stabilized and regulated by ground-water reservoirs within its drainage basin.

On the other hand, the assertion of Federal authority over the inflow to a ground-water reservoir would be more controversial and unacceptable particularly to private landowners. So long as the water remains within the unsaturated rock materials, it moves up or down or reposes within the landowner's domain and is appurtenant to his property. The right of a landowner to the water derived from rain upon his own land rarely has been questioned and, in several instances, has been confirmed by the courts. In Utah, where the Legislature has declared all waters whether above or under the ground to be public property, the Utah Supreme Court (Riordan vs. Westwood, 1949) stated that those waters diffused and percolating through the soil near the surface, sustaining beneficial plant life on the property owner's land without artificial diversion and having no course traceable onto the lands of others, are considered part of the soil and not public property subject to appropriation.

So the general picture emerges; Federal authority is minimal over the recharge areas except in the Federal lands and is potentially greatest over ground-water discharge to surface water. And what about the aquifers, which contain the bulk of recoverable and usable ground water?

Discrimination and Nondiscrimination in Aquifers

Hydrogeologists have done much to describe and emphasize the individuality of aquifers--their boundaries, distribution of permeability in three or four dimensions, dynamics of flow and stress, and quality of water. Although we have little or no information about many aquifers, especially the deeper ones, it is evident that they do not submit well to standardization. Some are of value and interest solely to a single landowner, others are clearly of community interest, and still others are of regional and even National interest and concern.

Ground water in watercourses comes closer than any other ground water to navigable streams and their non-navigable reaches and tributaries--the public waters where Federal responsibility and authority have been recognized as paramount. So closely interrelated are the waters in a watercourse that the ground water therein has a legal classification separate from that of other ground waters, and water rights apply equally to the surface water and the underflow. Thus, the ground water and surface water (including navigable water) in watercourses could together be construed as public waters. If the Standards and Enforcement (Title III) and Permits and Licenses (Title IV) of Public Law 92-500 were applied to all the waters in watercourses, the ground water interrelated and adjacent to the navigable water could be denied as an alternative receptor for discharge of pollutants under the National Pollutant Discharge Elimination System (NPDES). This denial also would reduce the danger of future stream pollution by devious underground routes, as discharge of pollutants directly to the stream is prohibited.

In law, a watercourse, as defined by Hutchins (1971, p. 22), is "a definite stream of water in a definite natural channel, originating from a definite source or sources of supply... . The stream may flow intermittently or at irregular intervals, if that is a characteristic result of the sources of supply in the area." A natural channel is an indispensable element, including bed and banks or sides. The flood plain of the stream is a part of the watercourse. Underflow is also a part of the watercourse, "To constitute underflow, it is essential that the surface and subsurface flows be in contact and that the subsurface flow shall have a definite direction corresponding to the surface flow (Hutchins, 1971, p. 60)."

To the earth scientist, a watercourse is a hydrologic unit in which the surface water and ground water are interrelated and moving in the same general direction; it is also a mappable geologic unit composed of materials of varying textures and permeability, all deposited by the stream (Thomas, 1951, p. 136). The less permeable beds of silt and clay provide no more than local isolation of surface water from ground water, or of the water in individual gravel-and-sand aquifers from one another. Maps prepared by the U.S. Geological Survey and the Corps of Engineers for flood-plain zoning aid in delineation of the surface area of watercourses. Aerial photography, remote sensing, seismic and other geophysical surveys, test drilling, and aquifer tests also are used for three-dimensional mapping of watercourses.

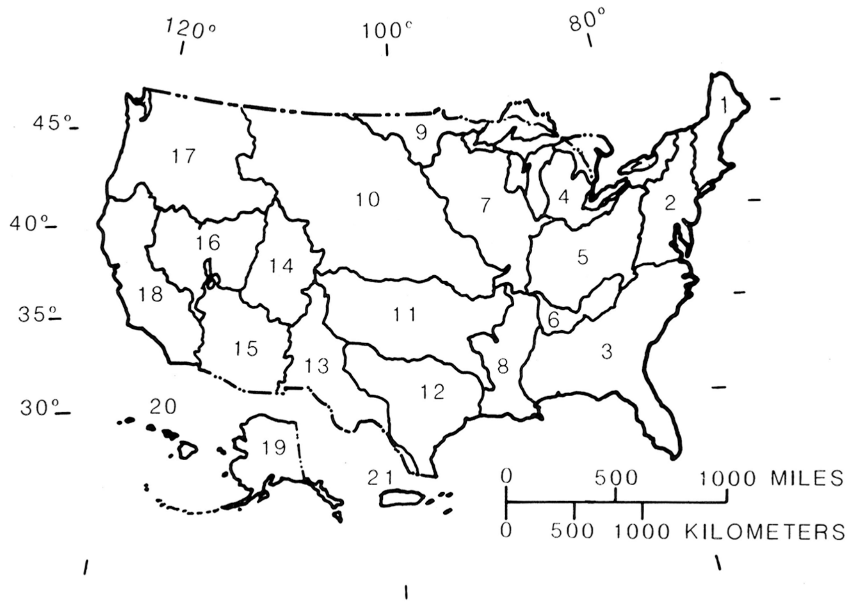
The interrelation of surface and ground water in watercourses is recognized in water law; rights in the watercourse include rights to the underflow, and the rules governing rights to water quality of watercourses and lakes are equally applicable to their underflows (Gindler, 1967, p. 114). This interrelation is apparent also in the legal classification of ground waters into: (1) definite underground streams, including underflow, the counterpart of surface watercourses; and (2) percolating waters, comprising all ground waters other than those in definite underground streams.

In addition to the watercourses, where ground water is intimately related to our modern streams, there are sand-and-gravel aquifers that have been deposited by rivers or by lake or shore currents or by wind during the past several million years of geologic history in the intermontane valleys of the West, the Great Plains east of the Rocky Mountains, the Coastal Plains along the Atlantic and Gulf Coasts, and the glacial drift and associated outwash plains of the northern States. Many of these aquifers contain huge quantities of water. They are recharged chiefly in areas where they are accessible to downward percolation of water from precipitation and in some places from streams; some are high above and others far below present-day streams, and some receive very little recharge from anywhere. The water in some of these unconsolidated aquifers has been declared public water, in others claimed as private property, as indicated in table 1. (See figure 27 for U.S. Water Resource Council Regions referred to in tables 1 and 2.)

Among the consolidated rocks (table 2), limestone and dolomite permit large volumes of water to flow underground, replacing surface drainage in some areas. Large springs discharge from limestone aquifers, notably in Florida, Georgia, Alabama, Missouri, Arkansas, Oklahoma, Kansas, Texas, New Mexico, Tennessee, and Kentucky. Another very permeable aquifer is volcanic

Table 1.--*Qualifications of unconsolidated aquifers as "public-water" bearers*

Type of aquifer	U.S. Water Resources Council Region (see fig. 27)	Favorable factors	Unfavorable factors
Sand and gravel in:			
Watercourses.............	All	Water classified as a "definite underground stream," closely related to navigable waters.	Juristic predilection for "percolating-water" classification.
Intermontane valleys....	10-18	Large storage developed and maintained by streams. Recognized as public water subject to appropriation in several Western States.	Closed basins may be entirely in one parcel of private property, therefore entitled to water rights apprutenant to landownership.
High plains	10-13	Replenishable resources serve to regulate streamflow.	Nonreplenishable resources acknowledged as private property.
Coastal plains...........	1-3, 8, 11-13	Freshwater adjacent to and under oceans and estuaries, vulnerable to encroachment of salinewater.	General acceptance of private ownership of ground water in coastal plains.
Glacial drift...........	1, 2, 4, 5, 7, 9, 10, 17	May be recharge source, or barrier roof, to limestone and sandstone aquifers.	Generally, small aquifers may be entirely within a single parcel of land.



EXPLANATION

NUMBER INDICATES WATER-RESOURCES REGION

Figure 27.--U.S. Water Resources Council regions.

rock basalt, which is the source of large springs and spring-fed rivers in Idaho, California, Oregon, Washington, and Hawaii. As suggested in table 2, these aquifers have several factors that may qualify them as bearers of public waters. Sandstone commonly has rigidity that maintains pore space occupied by fluids, but the permeability may be so small as to restrict the movement of those fluids. Thus, sandstone can be a reservoir--for storage of water (or oil and gas)--rather than a conduit for transmittal of water from one place to another; other types of sandstone transmit water great distances but at small rates of flow.

I am aware that in suggesting that the water in some aquifers can qualify as "public" water I also offer a means of expansion of governmental authority and dominance into areas where private property rights now are generally recognized. In this campaign year [1976], everyone is opposed to bureaucracy and particularly to any expansion of it. However, the great majority of people are opposed to pollution--of water, air, or land--and would strike it down wherever it rears its ugly head if someone else will pay the cost.

Increasing Federal authority over water would involve no significant change in policy but merely a continuation of the growth by attrition that has characterized Federal power over the resources during the last 150 years. This has been accomplished by the U.S. Supreme Court elucidating the rights expressed or implied by the Constitution. Each of us has individual rights--property rights, landowner or tenant rights, minority rights, rights of privacy--that may be in conflict with the collective rights asserted and maintained by the "government of the people" and "for the people." Hydrogeology--knowledge of the characteristics of individual aquifers and their flow patterns--would be essential to a court in its deliberations as to private versus public rights in ground water.

Table 2.--*Qualifications of bedrock aquifers as "public-water" bearers*

Type of aquifer	U.S. Water Resources Council Region (see fig. 27)	Favorable factors	Unfavorable factors
Basalt- - - - - - - - - -	17, 18, 20	Large springs contribute to navigable waters. Recharged from infiltration on public lands.	
Limestone and dolomite- -	3-8, 10-16	Large springs contribute to navigable waters. Underground drainage equivalent to a stream system. Rapid transmission of water-borne diseases; need for control.	
Sandstone - - - - - - - -	4, 7, 9-15	Public desire to maintain reservoir characteristics, particularly in deep zones.	Spotty knowledge of natural water quality and recharge.
Crystalline rocks - - - -	1-6	- - -	Small lateral movement; soil moisture and ground water may remain in single ownership.

An alternative approach would be by statute or executive order that would prohibit, monitor, or regulate pollution underground without discrimination. This would doubtless result in increased data-collection programs, computer programs, and bureaucratic authority. But I am dubious about scientific achievement. Here I quote Huxley again (1958, p. 21-23), "Science may be defined as the reduction of multiplicity to unity. It seeks to explain the endlessly diverse phenomena of nature by ignoring the uniqueness of particular events, concentrating on what they have in common and finally abstracting some kind of 'law', in terms of which they make sense and can be effectively dealt with.... . The Will to Order can make tyrants out of those who merely aspire to clean up a mess."

References Cited

Adams, Samuel, 1772, Statement of rights of colonists.

Berry, W.L., 1962, Ground water in California's future: Proceedings of Third Conference on Ground Water Recharge, Berkeley, Calif., 1961, p. 1-14.

Blackstone, Sir William, 1765, Commentaries.

California Department of Water Resources, 1970, The California Water Plan--outlook in 1970: Department of Water Resources Bulletin 160-70, 170 p.

Caponera, D.A., 1973, Water laws in Moslem countries: Rome, FAO Irrigation and Drainage Paper 20/1, 223 p.

Committee on Water, 1966, Alternatives of water management: National Academy of Science National Resource Council Publication 1408, 51 p.

Conkling, Harold, 1946, Utilization of ground-water storage in stream-system development: Transactions of American Society of Civil Engineers, v. 111, p. 275-354.

Gindler, B.J., 1967, Water pollution and quality control _in_ Waters and Water Rights, R.E. Clark, ed.: Indianapolis, Allen Smith, v. 3.

Hutchins, W.A., 1960, Pueblo water rights in the West: Texas Law Review, v. 38, p. 748-50.

_____ 1961, The Texas law of water rights: Texas Board of Water Engineers, Austin, p. 3-6.

_____ 1971-74, Water rights laws in the nineteen western states: U.S. Department of Agriculture Miscellaneous Publication 1206, v. I (1971), 650 p.; v. II (1974), 756 p.

Huxley, Aldous, 1958, Brave New World Revisited: New York, Harper & Row, 118 p.

Krieger, J.A., and Banks, H.O., 1962, Ground water basin management: California Law Review, v. 50, p. 56-77.

McGauhey, P.H., coordinator, 1967, Practical considerations in implementing public policy, panel discussion: Proceedings of Sixth Conference on Ground Water Recharge, Berkeley, Calif., 1967, p. 34-83.

McGuinness, C.L., 1963, Role of ground water in the national water situation: U.S. Geological Survey Water-Supply Paper 1800, 1121 p.

Porter, C.V., 1967, Implementing policies through legislation: Proceedings of Sixth Conference on Ground Water Recharge, Berkeley, Calif., 1967, p. 26-33.

Shaw, Lucien, 1922, Development of the law of waters of the West: California Law Review, v. 10, 435 p.

Thomas, H.E., 1951, Conservation of ground water: New York, McGraw-Hill, 290 p.

Thomas, H.E., and Phoenix, D.A., 1976, Summary appraisals of the Nation's ground-water resources--California region: U.S. Geological Survey Professional Paper 813-E, 51 p.

Thomas, R.O., 1955, General aspects of ground-water utilization: American Society of Civil Engineers, v. 81, Separate no. 706, p. 706.

Trelease, F.J., 1959, Desirable revisions of western water law: Boulder, University of Colorado, Western Resources Conference Papers 1, Boulder, p. 203-212.

U.S. Bureau of Reclamation, 1949, Central Valley Basin: U.S. 81st Congress, Senate Document 113, 430 p.

Witmer, T.R., 1968, Documents on the use and control of interstate and international streams--Compacts, treaties, and adjudications: U.S. 90th Congress, House Document 319, 784 p.

Court Decisions

Acton vs. Blundell, 12 Mees. & W. 324, 152 Eng. Rep. 1223 (1843).

Albuquerque vs. Reynolds, 71 N. Mex. 428, 379 Pac (2d) 73, 76-77 (1963).

Arizona vs. California, 283 U.S. 423 (1931).

Ashwander vs. Tennessee Valley Authority, 297 U.S. 288, 328 (1936).

Bassett vs. Salisbury Mfg. Co., 43 N.H. 569, 82 Am. Dec. 179 (1962).

California Oregon Power Co. vs. Beaver Portland Cement Co., 295 U.S. at 163-164 (1935).

Cartwright vs. Public Serv. Co. of N. Mex., 66 N. Mex. 64, 343 Pac. (2d) 654 (1958).

Cartwright vs. Reynolds, (1963).

Chatfield vs. Wilson, 28 Vt. 49 (1855).

Feliz vs. Los Angeles, 58 Cal. 73, 78-80 (1881).

Gibbons vs. Ogden, 22 U.S. (9 Wheat) 1, 1927 (1824).

Gilman vs. Philadelphia, 3 Wall. 713 (1865).

Green Bay & Mississippi Canal Co. vs. Patton Paper Co., 172 U.S. 58 (1898).

Jackson vs. United States, 230 U.S. 1, 23 (1913).

Katz vs. Walkinshaw, 141 Cal. 116, 74 Pac. 766 (1903).

Lux vs. Haggin, 69 Cal. 255, 4 Pac. 919 (1884), 10 Pac. 74 (1886).

New Mexico Products Co. vs. New Mexico Power Co., 42 N. Mex. at 318, 77 Pac (2d) 634 (1937).

Oklahoma vs. Guy F. Atkinson Co., 313 U.S. 508 (1941).

Pasadena vs. Alhambra, 33 Cal. 2d 908, 207 Pac. 2d 17 (1949).

Riordan vs. Westwood, 115 Utah 215, 229; 203 Pac. (2d) 922 (1949).

San Diego vs. Cuyamaca Water Co., 209 Cal. 105, 137, 142-143, 227 Pac. 475 (1930).

Tartar vs. Spring Creek Water & Mining Co., 5 Cal. 395 (1855).

United States vs. Appalachian Electric Power Co., 311 U.S. 377, 416, 426 (1940).

United States vs. Butler, 297 U.S. at 63 (1938).

United States vs. Gerlach Livestock Co., 339 U.S. 735, 738 (1950).

5. CONCLUDING REMARKS

By

Charles V. Theis
U.S. Geological Survey
Albuquerque, New Mexico

This has been a most interesting symposium covering a great period of time from the American standpoint and looking into the future. My remarks will be in the nature of more or less personal footnotes to the preceding papers.

With regard to the early development of ground-water thought, it has occurred to me that, just as when treating the development of the physical and natural sciences we must always consider the work of Leonardo da Vinci, so in the history of American science, we must consider the contributions of Benjamin Franklin. Franklin, of course, contributed to meteorology and oceanography, but as to ground water I can find only that Poor Richard said in 1746: "When the the well is dry, we know the worth of water." I suspect that even Franklin could not have guessed that 200 and more years later the descendants of his compatriots would try to prove that in nearly all the country his statement was correct.

As a footnote to Garry Parker's paper on the early stages of U.S. hydrology, I recall my more or less casual and short contacts with a couple of giants in geology and hydrology of my early days. One was Nelson Horatio Darton, who was probably the greatest reconnaissance geologist the Geological Survey has had and who did a great deal of ground-water work, and the other was Thomas Chrowder Chamberlin, who was outstanding among several great geologists of his generation in his capacity for creative thought.

Chamberlin wrote a report on the artesian wells of Wisconsin for Wisconsin publication. In 1885, he wrote his "Requisite and qualifying conditions of artesian wells" for the 5th Annual Report of the U.S. Geological Survey. This is a paper of much historical interest, for considering Chamberlin's ability, it indicates pretty well the state of hydrogeological science nearly a century ago.

In this paper, Chamberlin made probably the first mention of leaky artesian aquifers, although he did not use that term. One of his qualifying conditions was that there should be high ground and consequently a high water table between the outcrop of an aquifer and the wells into it so that water could not leak upward from the artesian aquifer. Chamberlin even recognized that water might be added to the artesian aquifer in this way.

Chamberlin also described what must be the original packer, which seems to have been primarily used when the production of a flowing well decreased owing to leakage from defective casing. A leather sleeve was constructed to fit around a smaller pipe and still go inside the casing. The sleeve was filled with flax seed, and its ends constricted around the smaller pipe. The pipe and sleeve were lowered into a tight part of the casing; the flax seed got wet and swelled, sealing the small pipe inside the casing, and the flow of the well was restored.

Chamberlin recognized that one well could interfere with another but apparently had no concept of the cone of depression. Dupuit and Adolf Thiem had already published on that subject in the European literature. Chamberlin must have been familiar with some of the European geological literature for he had given a paper, apparently in French, to the International Geological Congress in Paris in 1878. It would seem that he was not interested in the hydraulics of wells and aquifers or was perhaps deferring to the work of F. H. King (1899) and C. S. Slichter (1899) who already may have been studying the hydraulics of ground-water flow at the University of Wisconsin. Slichter's paper in the 19th Annual Report of the Survey (1899) definitely established the concept of the cone of depression in American literature.

It is appropriate that we should consider the Meinzer Era today, for in just 3 weeks we reach the centennial of Meinzer's birth. That era should not be passed without recalling the distinct effects that the personality of O. E. Meinzer had not only on his associates but also on the scientific community as a whole.

The sincere dedication of Meinzer to the science of ground water was widely recognized among his colleagues. It was this dedication that dignified a profession that had too little recognition when he began his career. Two primarily surface-water hydrologists, Walter Langbein and William G. Hoyt (1959, p. 20) have written:

> "The position of ground-water hydrology as a science in this country may be credited largely to the late O. E. Meinzer.
>
> He was not the first--others preceded him--but he was foremost in his dedication to ground-water hydrology as a science.
>
> By himself and through studies made under his stimulation and direction, he made a greater contribution to that science than has any other, and the public is to that extent greatly in his debt."

Meinzer's interest in "the public" is made clear in the concluding paragraph of his historical "Introduction" to the volume on "Hydrology," which he edited. Citing several instances of engineering projects in this paragraph he wrote:

> "The science of hydrology is thus intimately connected with the development of human society. In each project, advance in hydrology has come in response to the needs of the people, and each advance in the science has made possible more effective service."

Meinzer's own research was done under difficult circumstances. The climate in the Water Resources Division was not at all conducive to research. When Meinzer gave his address as retiring president of the Washington Geological Society, he said, "We have had to do our research almost surreptitiously." It was only Meinzer's capacity for continuous prolonged work that enabled him to make his own contributions. Kirk Bryan, who was one of four or five close associates of Meinzer, once said to me, "When Meinzer is at his desk he is working every minute of the time. You know that couldn't be said of you or me."

Meinzer's prestige in the scientific community enabled him to get done a considerable amount of "surreptitious" research. All of our work was done under cooperation with the States. We had no Federal money for research, but Meinzer's stature enabled him to persuade some willing cooperators to undertake problems of general interest. Outstanding among these was L. K. Wenzel's study (1936) of Thiem's method in Nebraska in cooperation with Dr. Condra of the Nebraska Geological Survey. I did much of the work on transient flow after working hours, but I received only encouragement from my own cooperators--the successive State Engineers of New Mexico--for general work done on their time. But nevertheless, there were always the chores of running an office, starting new investigations, and dealing with personnel, which Meinzer had to do largely by himself until A. G. Fiedler came into the office as Assistant Chief, not many years before Meinzer's retirement.

I recall one instance of the meticulous care that characterized Meinzer's work. In the early years of World War II, I made a short investigation for the U.S. Corps of Engineers in the Tularosa Basin in the vicinity of the village of Orogrande. Meinzer, in his Water-Supply Paper 343, published in 1915, had given the depth of a certain well on the property of R. L. Raley as 250 feet. We visited Mrs. Raley, a remarkably intelligent woman, who had driven the horse to haul up all the dirt her husband dug from the well. She reported the well to be 356 feet deep. When I wrote my report, I gave both depths and sent the report to Meinzer for review with a comment on the discrepancy in my cover letter. Meinzer replied that he had got out the Tularosa notebooks from his attic, which notebooks he hadn't looked at for 25 years, and on page so and so, in notebook number so and so, he found his notes about the well. He hadn't measured the well but had acquired his information in Orogrande, but he had considered the information authentic because he hadn't put a question mark after the data as he ordinarily did after reported information. I don't know how many men could go back over their notes of a quarter of a century before and in a short time find the details of their forgotten observations.

As to Harold Thomas' paper in this proceedings, I can add one or two historical notes about the ground-water law in New Mexico and indicate that there was some human drama and that some courage was required in leading the public to an appreciation of the ground-water facts of life.

To go back to the early years of this century, when ground water was legally a mystery not to be linked to surface water, which could be seen, the spring pool at North Spring near Roswell was big enough that a steam yacht was operated on it for picnics and other recreation. According to a Mr. Robinson, who had been the editor of the local paper at Roswell at the time, the spring level began to lower. He wrote in his paper about the lowering and pointed out that it was caused by the flowing wells, which were first being drilled in the Roswell Basin at that time. We think that this concept is elementary, but at the beginning of the century the populace knew heresy when they saw it. They hung Robinson in effigy. Nevertheless, in 20 years, when the springs had dried up and there were many more wells in the valley, most of which were now pumped, Al Fiedler and Bill Nye were welcomed to make an investigation. After the investigation, the people in the valley spearheaded the introduction of New Mexico's ground-water law in the legislature, and ground water was put under the same appropriation doctrine that had been written into the State Constitution for surface water.

One of the reasons for the success of the New Mexico ground-water law has been the high type of men who have been State Engineers in New Mexico. They must administer the law, and at every hearing someone is disappointed. Although the State Engineer is appointed by the governor and governors change every 2 or sometimes 4 years, only four men have served as State Engineer over the past 40 years, and none has ever been changed by a governor. Two resigned for reasons of health, one died, and the fourth is still there.

The growth of ground-water precedent has not been without incident. Tom McClure, who was the first of these long-time New Mexico State Engineers and whose integrity gave character to the job (he told one of our most political governors that, "politics and water don't mix"), said to me some 40 years ago, "In New Mexico there is no connection between ground water and surface water." This was a handy legal precedent in discussing the rights of the Texas users of Pecos River water below the Roswell Basin. Tom's successors came to see that natural laws must supersede New Mexico's laws and that state law must be brought into conformity with those of nature's.

When Steve Reynolds, shortly after he was appointed State Engineer just over 20 years ago, declared that practically the whole Rio Grande Valley was one hydrologic system and that equivalent surface-water rights must be retired before drilling new wells, he opened a hive of bees. Hanging in effigy was out of fashion by this time, but the notion of heresy apparently was not. I heard one man in a small meeting describe him as a Hitler and follow that up with other invectives, and the Albuquerque papers gave Steve a very hard time for a while. Reynolds said that at one public meeting he could smell the tar heating in the alley. But good hydrologic theory prevailed, and in a couple of months the storm subsided. Steve is still in office and by this time has established a record for length of service as State Engineer.

Discussing the Modern Era of hydrogeology, Gerald Meyer has told us that flow-system modeling (that is, mathematical capability) has outrun the hydrogeologic data base. I do not question this idea, but I am reminded again of Kirk Bryan. Kirk would often make a statement worthy of George Bernard Shaw and then literally stick his tongue in his cheek. One of these statements was, "I was greatly interested in hydraulics until I found out that all the constants were variables." He would have found in the last decades the constants getting more in number, and getting variable-er, and variable-er. It seems that as we get more and more sophisticated in our mathematical approaches, the real world is likely to get farther and farther away. It may be worthwhile to unite the historical and the prophetic to some degree and to quote two turn-of-the-century warnings.

The first of these is in T. C. Chamberlin's reply to Lord Kelvin's last paper on the age of the earth, titled "On the age of the earth as an abode for life," both paper and reply published in Science in 1899. Chamberlin, in introducing his prophetic questioning of Kelvin's 19th century physics said:

> "The fascinating impressiveness of rigorous mathematical analysis, with its atmosphere of precision and elegance, should not blind us to the defects of the premises that condition the whole process. There is, perhaps, no beguilement more insidious and dangerous than an elaborate and elegant mathematical process built on unfortified premises."

I am indebted for this quotation to King Hubbert's paper (1974), "Is being quantitative sufficient?", and to Ike Winograd for bringing this paper to my attention.

The other reference which I have tried to keep in mind throughout my career is the introductory statement "On the nature of mathematical reasoning" in Mellor's "Higher Mathematics for Students of Chemistry and Physics," published originally in 1902. These few pages are all good reading, for this section expounds the principle that assumptions enter into all applied mathematical expositions. But a couple of abbreviated paragraphs must suffice here:

> "By no process of sound reasoning can a conclusion drawn from limited data have more than a limited application. Even when the comparison between the observed and the calculated results is considered satisfactory, the errors of observation may quite obscure the imperfections of formulae based on incomplete or simplified premises... . The only safeguard is to compare the deductions of mathematics with observation and experiment... . We must remember that we cannot get more out of the mathematical mill than we put into it, though we may get it in a form infinitely more useful for our purpose... ."

And, as a concluding paragraph:

> "There is a prevailing impression that once a mathematical formula has been theoretically deduced, the law embodied in the formula has been sufficiently demonstrated, provided

that the differences between the 'calculated' and the 'observed' results fall within the limit of experimental error. The important point ... is overlooked ... that any discrepancy between theory and fact is masked by errors of observation. With improved instruments and better methods of measurement, more accurate data are from time to time available ... (and) the approximate nature of the formulae becomes more and more apparent . .... ultimately it is necessary to 'go over the fundamentals.' .... Thus, from the first bold guess of an original mind, succeeding generations progress step by step toward a comprehensive and a complete formulation of the several laws of nature."

It seems to me that in ground-water studies we may have our own principle of indeterminancy. We are dependent either on surface measurement of geophysical properties, which may not be correlative with the hydrologic features and can hardly hope to show the essential heterogeneities, or upon test wells and observation wells that disturb the hydraulic features in the neighborhood and probably, in most cases, short-circuit the effects of heterogeneity. To this must be added the economic and time constraints on extensive drilling and refined procedures in drilling. It may be that we can only hope by our preliminary testing to roughly estimate the pattern of flow and the quantity and velocity of flow, in order to set up a proper system of monitoring the effects of continuous operation of the system, whether it involves merely production of water or the more difficult phenomena of transport.

Finally, in somewhat lighter vein, let us consider the function of the Pick and Hammer Show[1] in the past and future perspectives of our work. Last night many of you saw the current version of the Denver Pick and Hammer Show. The function of the show has always been to prick the bubbles of excessive self-esteem, to show the other side of the coin, and be the specter at the feast of lore expounded at scientific meetings. Going back 40 years to 1937, the Pick and Hammer Show of that year had a song that has since much delighted me:

"If you're anxious for to shine in the speculative line
    as a man of thought profound,
You must vent exotic gabble that will flabbergast the rabble
    by its awe-inspiring sound.
The meaning doesn't matter, so you simulate the patter
    of a Plato or a Kant;
If your cheek is monumental and your language transcendental,
    that is all the groundlings want.
And everyone will say, as you talk your mystic way,
If this young man expresses himself in words too deep for me,
What deeply thoughtful thoughts the thoughts this thinker thinks
    must be!"

---

1 The Pick and Hammer Show is presented annually by the Pick and Hammer Club. The show is presented in jest and is performed by members of the U.S. Geological Survey. The show may be viewed as light comical satire in which the members of the Geological Survey make good-natured jest of each other and the idiosyncrasies of the organization.

Some of you may recognize this as being a direct steal from Gilbert and Sullivan's "Patience." The second verse is by Henry Ferguson of the old Metals Section of the U.S. Geological Survey, who was well known for an irreverent attitude toward some Survey institutions:

"You must bring in hydrostatics and the higher mathematics
As you deftly wield your chalk,
Writing out a long equation with quick prestidigitation
To illuminate your talk.
Though by none it will be followed, it will avidly be swallowed
By those who would seem wise;
And you'll make a deep impression and attain in your profession
Some grandly glittering prize.
And everyone will say as you talk your mystic way;
If his thoughts transcending language must be clothed in formulae,
What deeply thoughtful thoughts the thoughts this thinker thinks must be!"

I suppose in order to bring this up to date we should amend these last lines:

"And everyone will say as you talk your mystic way,
If his thoughts still more astuter must be fed to a computer,
What deeply thoughtful thoughts the thoughts this thinker thinks must be!"

References

Chamberlin, T.C., 1885, The requisite and qualifying conditions of artesian wells: U.S. Geological Survey Annual Report 5, pt. C, p. 125-173.

_____1899, Lord Kelvin's address on the age of the earth as an abode fitted for life: Science, New Series, v. 9, p. 889-901, v. 10, p. 11-18.

Fiedler, A.G., and Nye, S.S., 1933, Geology and ground-water resources of the Roswell artesian basin: U.S. Geological Survey Water-Supply Paper 639, 372 p.

Hubbert, M.K., 1974, Is being quantitative sufficient?, in The impact of quantification on geology, D.F. Merriam, ed.: Syracuse University Geological Contribution 2, Proceedings of the 1st Geochautauqua held on occasion of the dedication of the Heroy Geology Laboratory at Syracuse University, October 6, 1972, p. 27-50.

Kelvin, Lord (William Thomson), 1899, The age of the earth as an abode fitted for life: Science, New Series, v. 9, p. 665-674, 704-711.

King, F.H., 1899, Principles and conditions of the movements of ground water: U.S. Geological Survey Annual Report 19, pt. II, p. 59-294.

Langbein, W.B., and Hoyt, W.G., 1959, Water facts for the Nation's future--Uses and benefits of hydrologic data program: New York, Ronald Press Co.

Meinzer, O.E., 1942, Hydrology--pt. 9, Physics of the earth: New York, McGraw Hill Book Co. (Also Dover Publications, Inc., 1949).

Meinzer, O.E., and Hare, R.F., 1915, Geology and water resources of Tularosa Basin, New Mexico: U.S. Geological Survey Water-Supply Paper 343, 317 p.

Mellor, J.W., 1902, Higher mathematics for students of chemistry and physics: London, Longmans Greene and Co. (First American edition; New York, Dover Publications, 1946).

Reynolds, S.E., 1976, A State Cooperator's view of the Geological Survey, p. 21-24, in National conference of district chiefs, Albuquerque, New Mexico, 1975: U.S. Geological Survey Open-File Report 76-467.

Slichter, C.S., 1899, Theoretical investigation of the movement of ground waters: U.S. Geological Survey Annual Report 19, pt. II, p. 295-384.

Wenzel, L.K., 1936, The Thiem method for determining permeability of water-bearing materials and its application to the determination of specific yield, results of investigations in the Platte River Valley, Nebraska: U.S. Geological Survey Water-Supply Paper 679-A, p. 1-57.

☆ U.S.G.P.O.: 1987 - 756-180/40161