THE DEVELOPMENT OF THE SCIENCE OF HYDROLOGY

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INTRODUCTION

Since earliest times, men have been filled with curiosity about the earth on which they live. What makes the sea salty? What force causes thunder? What makes rain? What is the source of the water issuing from springs?

As his curiosity led him to seek the answers to such riddles, man often faced new riddles even more baffling. What force drives the water from flowing wells? Why does one stream have quicksand on one bank and solid rock on the other? Why does one well yield water in abundance whereas another dug to the same depth is dry?

It is interesting to review how men attempted to solve such questions. By comparison, we have today guideposts along the way, for reasoning man has built up the method of investigation and compilation of knowledge that is known as <u>hydrology</u>--the science of water.

Only a brief examination of the subject of hydrology is necessary in order to appreciate the complexity of the subject and the extent of the field. Hydrology is not a new area of endeavor. It is as old as man's efforts of survival. Throughout the ages, the well-being of the civilization has been, and will forever be, dependent on available and usable water. Land, water, and people are closely related. Without proper use of land and water, the progress and even the survival of people is questionable. The science of hydrology is intimately related to the development of human society.

In the development of man's environment, the harnessing of water for various needs has always been evident, although his scientific knowledge was scant. As cities and countries expanded with industry and growing populations, a requirement arose for water-supply development, resulting in extensive study and experimenting in hydraulics and hydrology since the turn of the 17th century. The outgrowth of the efforts of early scientists, mathematicians, engineers, and geologists is the science of hydrology. The domain of hydrology embraces the full life history of water on the earth. In practice, hydrology has been broken down into three familiar fields, atmospheric water, surface water, and ground water. The atmospheric water and surface water phases have been treated as a single unit in this report.

Although numerous investigators have been mentioned in this report, space limitations prevent the inclusion of the hundreds of individuals who have made valuable contributions to the body of knowledge encompassing hydrology. These omissions, of both individuals and specific contributions, should not be regarded as an indication that such work is not meritorious. This report provides an outline to the development of the important field of science. Individuals who may desire more detailed information on a particular phase of this subject are referred to the Selected Bibliography of this report.

This report also contains a convenient glossary of often used hydrologic terms. The definitions contained in this glossary are taken from recognized manuals, such as the American Society of Civil Engineers (ASCE) Nomenclature for Hydraulics, the ASCE Manuals and Reports on Engineering Practice, and others.

DEFINITIONS OF SCIENCE

What is a science? According to Webster's dictionary the technical definition of science is the knowledge possessed or obtained through study or practice: knowledge obtained by study, experimenting, observation and classification, or practice. It is accumulated knowledge systematized and formulated with reference to the discovery of general truths or the operation of natural and general laws that determine man's thoughts and behavior.

Also of interest is the legal dissertation of science from Corpus Juris Secundum [79 C.J.S. 455, Science (1952).]. "SCIENCE. In a sense 'science' means knowledge obtained individually by study of facts, principles, causes, etc.; knowledge of many methodically digested and arranged so as to be attainable by one; ...accumulated and accepted knowledge which has been systematized."

In all instances the implication of attained knowledge is included in the definition of science.

DEVELOPMENT OF HYDROLOGY AS A SCIENCE

Two broad types of knowledge may be gained--experimental and historical. Experimental knowledge consists of, or is based on, experiments which are made to obtain specific data. These are the bases of practically all our knowledge in the realms of physics and chemistry. They could be repeated by any competent observer who can obtain the same data and verify the results of his predecessors. By these experiments, repeated at will, the universality of the laws of nature is established, because like causes produce like effects.

Second is historical knowledge, which consists of facts that are not derived from experiments. The desired data, therefore, cannot be obtained at will. This knowledge is certain and authentic when data are competently observed, and does not contravene or negate the laws of causality. Many of the data of hydrology are natural and individual events which cannot be repeated under control of an experimenter, and therefore are historical.

Within the purview of the definitions of science, stated previously, hydrology is a science. All data, both experimental and historical, must be precisely defined and verified, and must be properly organized and correlated. The principles must be shown to be universal in the application since empirical methods alone are not adequate. The hydrologic events, such as storms, rainfall, snowfall, or floods must be analyzed. The observational data must be correlated to determine existing relationships together with their limitations and their applicability to other situations. Some of this work can be done by further experiment. Some must be accomplished by continued observation of the natural events. Some of the relationships are readily apparent while others require many tools to determine them. Fundamental physical relationships must be found before the theory of statistics and the theory of probability can be employed to advantage. It is not intended to emphasize unduly the importance of statistical principles, nor to imply that the laws of mathematics are in any way a substitute for those of hydrology. The principles of statistical procedure cannot, of course, control hydrologic activity, but statistical methods enable one to analyze and measure the variations and correlations of hydrologic data, and in the complicated domain of hydrologic activity, that function is important. The situation is such that in all hydrologic phenomena the laws of hydrology govern. That is to say, the observed causes are the effects of hydrologic principles.

Progressively extensive use of water resources of the world in recent times has necessitated far-reaching research and intensive study of water in its natural occurrence and forms. The body of knowledge developed by these scientific investigations and studies is called hydrology throughout the world. It is an interdisciplinary science, involving an integration of other earth sciences to the extent that they help to explain the life history of water and its chemical, physical, and biological constituents. A few of the other sciences concerned that are overlapping in the field of hydrology are agronomy, meteorology, climatology, geology, geomorphology, physics, hydraulics, mechanics, and mathematics.

Definitions of Hydrology

As was said by Mead in his text on hydrology (1904, p. 1), "The fundamental basis of all hydraulics engineering problems is Hydrology--the science of water."

This definition was then expanded in this early text and is very similar to an opening remark made by Dr. Robert E. Horton (1931, p. 190) in a speech before the 12th meeting of the American Geophysical Union on May 1, 1931, when he said: "As a pure science, hydrology deals with the natural occurrence, distribution, and circulation of water on, in, and over the surface of the Earth."

Hydrology is recognized by the International Association of Scientific Hydrology as one of the earth sciences.

In June 1962, The Federal Council for Science and Technology (established by the President in 1959) dealt with a modern definition of hydrology. Their widely accepted decision was: "Hydrology is the science that treats of the waters of the Earth, their occurrence, circulation, and distribution, their chemical and physical properties, and their reaction with their environment, including their relation to living things. The domain of hydrology embraces the full life history of water on the Earth" (Federal Council for Science and Technology, 1962, p. 2).

Webster's Third New International Dictionary (Merriam-Webster, 1961) defines hydrology as, "a science dealing with the properties, distribution, and circulation of water; specifically, the study of water on the surface of the land, in the soil and underlying rocks, and in the atmosphere, particularly with respect to evaporation and precipitation."

The Hydrologic Cycle

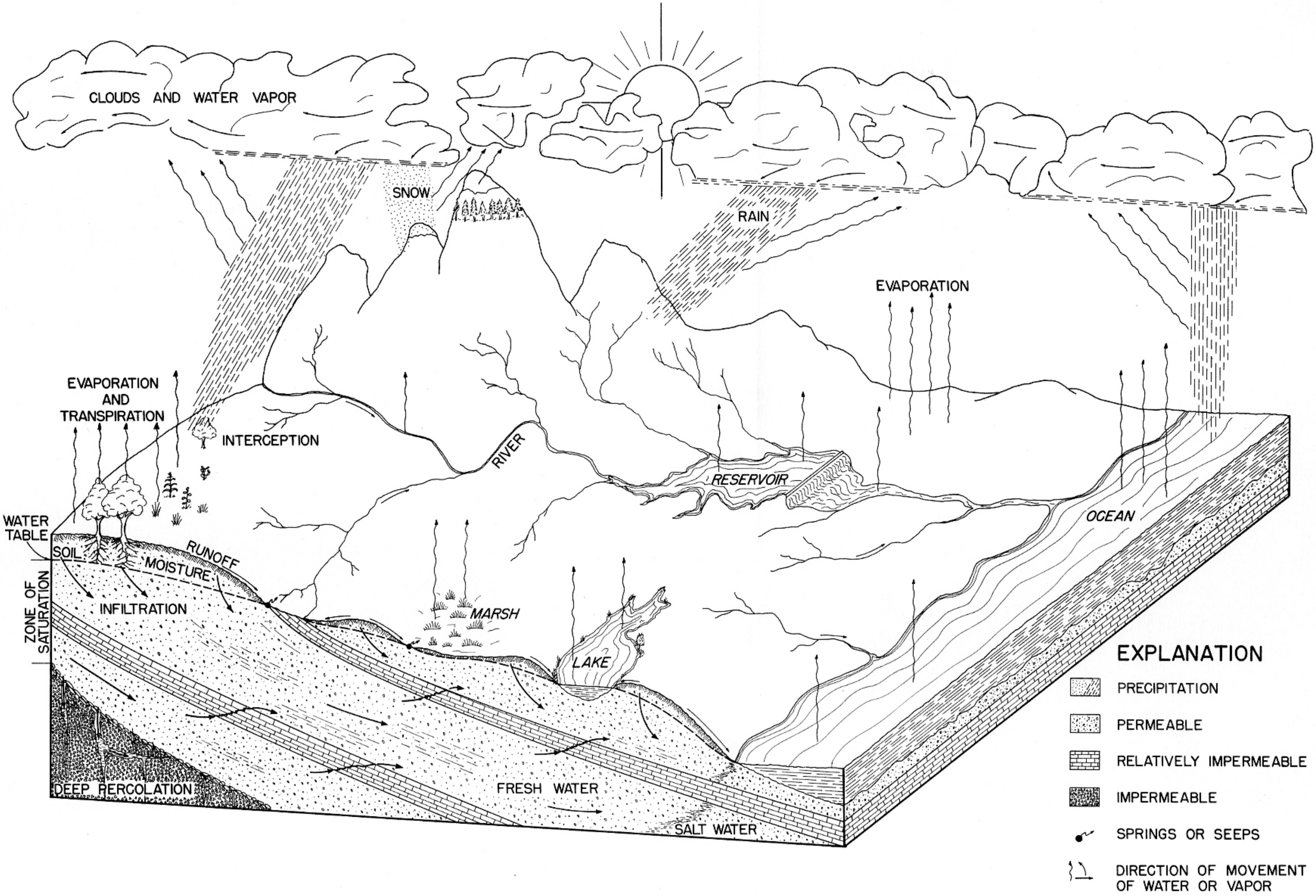
The scope of the science of hydrology is conveniently diagrammed by use of what is known as the hydrologic cycle, which is the circulation of the waters of the earth. (See Figure 1.) The cycle may be divided into three phases: evaporation and transpiration; precipitation; infiltration and runoff. (1)Evaporation and Transpiration: Water enters the atmosphere as a vapor or gas by evaporation from land and ice, snow and water surfaces and by transpiration from the living plants of the earth. (2)Precipitation: Precipitation is the deposition of atmospheric moisture on the earth as rain, snow, sleet, hail, mist, dew, frost, and rime. (3)Infiltration and Runoff: Precipitation is disposed of by evaporation back into the atmosphere, infiltration and storage in the ground, and by runoff or overland flow into streams or rivers ultimately reaching the oceans or inland marshes, lakes, and sinks.

Probably very few of the water droplets follow the complete cycle in the sequence shown in Figure 1. Numerous "short-circuits" take place within the cycle. Water may be stored as glacier ice for centuries; water evaporation from the land may not be returned immediately to the seas or other bodies of water as runoff; or atmospheric conditions may cause disturbance of the cycle through storms and droughts. However, the hydrologic cycle is a means of illustrating the natural phenomena included within the science of hydrology and provides a framework for tracing its historical development.

Surface-Water Hydrology--Historical Development

The concept of the hydrologic cycle is so generally known and understood that it is difficult to appreciate the history of early development. Man has not always known the cause of running water in rivers and springs. Some early writers believed that the water was derived from huge inexhaustible subterranean reservoirs. This postulate evidently was subscribed to by Homer in Book 21 of his Iliad as he wrote, "of the deep-flowing Oceanus, from which flow all rivers and every sea and all springs and deep wells." These thoughts were echoed in the writings of Thales about 650 B.C., and Plato, in the fourth and fifth centuries B.C., who touched lightly on the hydrologic cycle when he wrote that all waters returned by various routes to the sea. Aristotle developed the somewhat controversial theory that subterranean condensation was the source of ground water. Some of the early Roman philosophers, in the century before Christ, reckoned that the clouds imbibed waters from the ocean and rivers. Then, the force of the wind drove the clouds together and forced the rain to stream out.

The forerunner of modern concepts of the hydrologic cycle was recorded by Vitruvius in the first century B.C., in the eighth volume of his treatise De Architectura Libri Decem, as he discussed sources and distribution of water. He explained that rain and snow that fell on the mountains percolated through



THE HYDROLOGIC CYCLE

FIGURE I

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the rock strata at the foot of the mountains and there issued forth as streams and springs.

Ancient Development

Rather than condemn these leaders of antiquity, one must admire them; for, despite their probable lack of understanding, their engineering accomplishments were outstanding. The time when water was first controlled is uncertain. Dating of the irrigation projects of Egypt and Mesopotamia is also inexact. Authorities, considering this with the transition from the age of stone to copper, estimate that extensive water systems existed in both countries at least 4,000 years before the Christian era. Further anthropological evidence supports the belief that the Indus Valley civilization, of 3000 B.C., was even greater than that of Egypt. Parts of China reached an advanced state in irrigation long before Christ, but because of the intrusion of fable into written Chinese history, the time is uncertain.

Many achievements of this early age are noteworthy (Rouse and Ince, 1957). Excavations at Harappa and Mohenjodaro in the Indus Valley have revealed baths in many houses, with ceramic pipes for water supply and brick conduits under the centers of the streets for drainage. A masonry dam was built across the Nile, about fourteen miles upstream from present day Cairo, around 4000 B.C., which permitted reclamation of once useless lands as fertile productive areas. Later, perhaps 2,500 years ago, a fresh-water canal was constructed from Cairo to Suez. Evidence of several large dams remain throughout the Old World, including prehistoric Lake Moeris which was supplied by the canal of Joseph, and another dam at the mouth of the Euphrates River which was built for irrigational purposes. The first of the Roman aqueducts, built in 312 B.C., differed little from those in other parts of the world, but by the time of the Roman Empire, no less than nine of them supplied the city of Rome with as much water per capita as is now found in many parts of the civilized world. Water was supplied for three purposes throughout the city: first, to pools and fountains for free public consumption; second, to public baths with a surcharge for use; and last, to private homes, with charges made according to the size of the outlets. Waters for these aqueducts generally came from springs, but some were supplied from deep wells with the water being raised by a bucket elevator; in some instances reservoirs were used for storage and as stilling basins. With a system as great as this, there is little doubt that the Roman engineers were aware of many of the concepts of hydraulics of today such as head, slope, velocity, flow, area, and discharge rate. Frontinus, a water commissioner in Rome during the first century, rendered proper knowledge of the velocity of running water and wrote several volumes on the Roman methods of water distribution.

The Middle Ages

The fall of the Roman Empire, along with the acceptance of the philosophies of earlier educators and engineers by the Christian Church, contributed greatly to the spread of these ideas as the church became an important center of learning and men traveled to other lands. During the middle ages, water-supply systems, public baths, and water powered mills flourished in many lands. The Crusades in the 12th and 13th centuries aided in introducing and advancing the use of the water wheel for grinding and for driving bellows for furnaces throughout Europe as the military engineers served in new areas. The founding of the University of Paris and Oxford University during this period also added to the dissemination of knowledge and the advancement of philosophical science.

During the period known as the Renaissance, a gradual change was perceptible from the purely philosophical science of Scholastics toward the observational science of the present day. One of the events of the last half of the 15th century considered quite important was the development of the printing press which allowed wider publication of man's growing knowledge. Also, a genius, Leonardo da Vinci (1452-1519) appeared on the scene. So extensive were his accomplishments that he dwarfed his contemporaries. His fields of endeavor were many, extending to geology, mechanics, engineering, and architecture. In 1502 he was appointed Chief Engineer to Cesare Borgia, planning and supervising canal and harbor works over most of middle Italy. He also served in France under Louis XII and Francis I. His notes are at once the joy and the despair of modern times. In his writings he was very careless, roamed without system, at times he wrote left handed in mirror image, and often from back to front of a sheaf of pages. His practice of keeping private records instead of sharing knowledge with associates precluded the formation of an influential school of thought.

Scientific Developments

Perhaps the beginning of the modern science of hydrology began in the 17th century with the measurements of Perault, Mariotte, and Halley. Perault made measurements of rainfall during a 3-year period along the Seine River and made an estimate of drainage area and runoff. Thus, he computed the quantity of water which fell on the basin was about six times the quantity discharged by the river. He also made several experiments on loss of water by evaporation.

Mariotte, using a float method, computed the discharge of the Seine River after measuring its width, depth, and velocity. He too advocated the infiltration theory and created some of the modern thoughts on the subject.

Halley also made observations on the rate of evaporation and demonstrated that evaporation from the Mediterranean Sea was sufficient to supply the quantity of water returned by inflowing rivers. His evaporation tests were made with great care but his estimates of stream discharge were very crude.

Vitruvius, da Vinci, and Pilissy were discoverers and pioneer advocates of correct hydrologic principles, but their contributions were not effectively followed up. Perault, Mariotte, and Halley, however, undertook hydrologic research of the modern scientific type and may well be regarded as the founders of hydrology.

Many other scholars contributed to the development of this science during the 17th and 18th centuries. New discoveries and experiments were contributed by several--Daniel and John Bernouilli, father and son mathematicians; Castelli, a pupil of Galileo; Torricelli, who invented the barometer; Huygens, inventor of pendulum clocks; Pitot, who developed a measuring device still used today with little refinement; Chezy, who in 1775 developed a formula for the velocity of flowing water that is still known today as the Chezy formula; and Venturi, who contributed the theory on contracted flow. Benjamin Franklin made the first American contribution to hydrology with his experiments in towing tanks in which he studied design of boat hulls.

This period was truly the era of experimental hydrology. Five primary tools of laboratory and field were introduced: the piezometer, the Pitot tube, Woltman's current meter, Smeaton's scale models, and towing tanks.

With the impetus acquired by the end of the 18th century, the science of hydraulics and hydrology began to advance. The contributors were many and from almost every country in the world. French engineers maintained their leadership in the field but several scientists of other lands are also immortal to history.

During the early part of the century, French engineers and hydrologists especially active were Coulomb, Girard, Prony, Poncelet, Loval, and Deschamps. The first three made mathematical and mechanical contributions while the others made hydrometric recordings throughout France as they investigated artesian flow, worked on river velocity formulas, and drilled the first deep water well.

To the south two Italian hydrologists were Venturi, who analyzed and gaged the flow of the Tiber River over a period of years (1825-36), and Lombardini, who wrote many papers discussing the effects of lakes in equalizing flow. Lombardini also analyzed by statistical methods the discharge of several Italian rivers.

Several German investigators who contributed to the hydraulic theories were Weisbach, Eytelwein, Meyer and Bischof.

Nineteenth Century Advancements

In the United States during the first half of the 19th century, hydrology was stimulated by the needs for water supply and the requirement for river and canal transportation. DeWitt Clinton in 1817 commenced an extensive study of the hydrology of lakes and rivers, including evaporation and percolation, though he is better known as Governor of New York and builder of the Erie Canal. In 1822 General Simon Bernard and Colonel Joseph Totter made a report on the Ohio and Mississippi Rivers to the Commandant of the United States Engineers that was the forerunner of the elaborate hydrologic studies made on these rivers during the last 100 years.

The art of systematically measuring the discharge of streams progressed slowly during the 19th century. Several early records of note are those made by Escher de la Linth on the upper Rhine during the years 1809-21. Baumgarten made a series of measurements and observations of the Garonne River during the period 1837-46.

In the United States the earliest records of river flow were made on the Ohio River at Wheeling, West Virginia, during 1838-48 and at Memphis, Tennessee, on the Mississippi from March 1, 1850, to February 28, 1851 (Jarvis, 1943). These records are identified with C. G. Forsbery, Lieutenant Robert A. Marr, George G. Meade (later Major General, United States Army), and Charles Ellet, Jr.

In 1850 appeared the Manual of Hydrology by the English civil engineer Nathaniel Beardmore which remained a source book for hydrologists and hydraulic engineers for almost 50 years. His manual had an important effect in making hydrology a field of open scientific research and discussion.

During 1848-50 several notable publications appeared in the United States as a result of the detailed study on the Mississippi River by Bernard and Totter. In 1850 the Congress of the United States authorized the study of hydrology on a large scale when it directed that a "topographical and hydrographical survey of the delta of the Mississippi River" be made to determine "the most practical plan to secure it from inundation" (Meinzer, 1942, p. 21). The trailblazers in this study were Captain A. A. Humphreys and Lieutenant H. L. Abbot who made numerous painstaking observations. Their conclusions were carefully drawn and well supported. This report, published in 1861, has stood the test of time and remains even today instructive reading.

Except for Benjamin Franklin, the first distinguished American experimenter in the field of hydraulics was James B. Francis (1815-92). He is noted for his improvement of the water turbine. Three other American engineers who typified the growth of their relatively new country were Lester Pleton, Clemens Herschel, and John Freeman. These men were prominent in projects constructed to harness the waters of rivers on the eastern seaboard through their contributions in research and publications.

The late 19th century witnessed world-wide indulgence in study, experiments, and publications on hydrology. Although European countries, particularly France and Germany, remained leaders in the field, the United States, being dependent on water to such a large extent for transportation, irrigation, milling, and power, through necessity, intensified its interest in hydrology. With our natural waters so important, it was desirable to inventory the flow of the rivers. Some records had been made during the earlier part of the century by various individuals and the U. S. Army, but now more records were necessary for development of the West. The United States Geological Survey was established in 1879 and Major John W. Powell, who was intensely interested in water resources, became its director in 1881. The first fiscal appropriation for water-resource study was made in 1888 and systematic stream gaging began the next year. In January 1889 the first regular gaging station of the Geological Survey went into operation at Embudo, New Mexico, on the Rio Grande. Development of the systematic stream-gaging program of today is credited to Frederic H. Newell (often called "The Father of Systematic Stream Gaging") who was Chief Hydrographer with the Geological Survey from 1888 to 1906, and to Nathan C. Grover who was Chief Hydraulic Engineer of the Water Resources Branch of the Geological Survey from 1913 to 1939.

Closely connected with water supply, of course, is rainfall. A few observations of rainfall were made during colonial days. Organized meteorological observations have been made by governmental agencies since 1817. Early records were collected by the United States General Land Office. In 1870 a National Weather Service was established in the Signal Corps of the U. S. Army. In 1891 the United States Weather Bureau was organized in the Department of Agriculture, and transferred to the Department of Commerce in 1941. The meteorological data-collection program has developed into a vast network of observing and recording stations which provide data from many thousands of locations throughout the United States.

The 19th century was in many ways the grand age of experimental hydrology, for the advancement during that period exceeded in quantity those of all the past centuries combined. But above all the science had reached the point at which the design of projects for the utilization of water, whether for power, navigation, or municipal purposes, could proceed on a reasonable and sound basis.

The Twentieth Century

The vast study of the 1800's of necessity continued into the present century. The requirement for study and development in our country in the field of hydrology has attracted several of the leading engineers of the 20th century.

By the turn of the century several American engineering schools had established hydraulics laboratories; the first was founded in 1887 at Lehigh University by Mansfield Merriman. Closely following Lehigh were Worcester Polytechnic Institute and Cornell University. According to Meinzer (1942) in his text, Hydrology, in 1939 there were 238 hydraulic and hydrologic laboratories in the world, of which 109 were in the United States. Although laboratory study was predominant in early 20th century advancements, considerable knowledge was gained in extensive field tests sponsored by the Department of Agriculture. By the early thirties the sedimentation problems of the United States began to receive quantitative attention primarily under the U. S. Army Corps of Engineers, the U. S. Bureau of Reclamation, and the U. S. Soil Conservation Service.

The volumes of publications on hydraulics and hydrology are many. By the end of the 19th century, scientists had learned the value of, and practiced, free exchange of experimental knowledge for future reference. For instance, Michele Gortani in his bibliography on hydrology listed about 1,000 publications on the hydrology of Italy written between 1870 and 1923. In 1940, the American Geophysical Union had 741 members who that year contributed 600 technical papers and reports covering about 3,000 pages of printed matter.

In 1904, Daniel W. Mead, of the University of Wisconsin, published his Notes on Hydrology as the first American text. His later texts (Mead, 1919, 1950), are widely used today. Some other leaders in this field are Oscar E. Meinzer (1942), Adolph J. Meyers, Edgar E. Foster (1948), and C. O. Wisler (Wisler and Brater, 1959). These comprehensive and systematic presentations have contributed greatly toward the development of hydrology as a distinct science.

In nearly every European country there were scientists during this period who made contributions to hydrology, among whom the following may be mentioned: In England, William Whittaker and Horace B. Woodward; in Holland, W. Badon Ghyben who is generally regarded as the first discoverer of the law of salt-water balance, Eugene Dubois, J. Pennink, and J. Versluys; in Belgium, Rene D'Andrimont who also made studies of the relations of salt and fresh waters; in Sweden, Johan S. Richert who developed successful methods of artificial recharge; in Russia, P. Ototsky and Alexander Lebedeff who studied chiefly the distribution and movement of soil moisture; in Switzerland, Albert Heim and Arnold Engler who studied the relation of forests to water supply; in Italy, D. Spataro, G. Cuppari, and M. Canavari; in Spain, G. Garcia. Much work has also been done in Australia, India, and Japan; some limited studies have been made in other parts of Asia, Africa, and the Latin American countries.

In the United States there has been a great increase in the quantity and intensiveness of hydrologic investigations along a wide front, largely through governmental agencies. The investigations have many points of common interest but may be classified roughly according to the following dominant aspects: surface water and ground water by the U. S. Geological Survey; precipitation and related weather features by the U. S. Weather Bureau; snow surveying by several agencies coordinated through the Western Interstate Snow-Survey Conferences; stream dynamics and river-system hydrology by the U. S. Army Corps of Engineers; infiltration, erosion, and transpiration by the U. S. Forest Service and the U. S. Soil Conservation Service; and various other phases of hydrology by these and other bureaus of the Department of Agriculture, the National Hydraulic Laboratory of the U. S. Bureau of Standards, the U. S. Bureau of Reclamation, the Tennessee Valley Authority, the International Boundary and Water Commissions, and others. Much work has also been done by hydrologists in State organizations, in universities and technical schools, and in private practice. This work has been coordinated to some extent by the Water Resources Committee of the National Resources Planning Board and its predecessors, beginning with the Mississippi Valley Committee in 1933. More recently, the Federal Council for Science and Technology was established in 1959. The Ad Hoc Panel on Hydrology within that council has been established with membership including leading engineers and hydrologists of various Federal agencies. The concern is for the future adequacy of our water supply to meet ever increasing demands. The efforts of many are necessary to cope with this paramount problem.

The readiness with which today's problems are mastered will indicate the extent to which hydrologists of today will merit recognition in the continued history of their science.

Ground-Water Hydrology--Historical Development

Ancient Times to 1900

The first roots of hydrologic knowledge date back to antiquity. This is particularly true of man's quest for ground water, and knowledge concerning it. Quoting from Meinzer's historical review of the development of ground-water hydrology:

> "Digging for water is doubtless a very ancient art. Indeed, even some of the lower animals, such as the coyote, are known to dig down to water where it occurs not far below the surface. However, in the early stage of human development, men progressed very little beyond the coyote in well digging....[1]
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> "From the dawn of history nearly to the present, the source of the water that flows from the springs has constituted a puzzling

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[1] Meinzer, O. E., 1934, History and development of ground-water hydrology: Washington Acad. Sci. Jour., v. 24, no. 1, p. 6, Jan.

problem that has been the subject of much speculation and controversy. Prior to the latter part of the 17th century it was generally assumed that the water discharged by the springs could not be derived from the rain, first because the rainfall was believed to be inadequate in quantity, and secondly, because the earth was believed to be too impervious to permit penetration of the rain water far below the surface. With these two erroneous postulates lightly assumed, the philosophers devoted their thought to devising ingenuous hypotheses to account in some other way for the spring and stream water. Two main hypotheses were developed: one to the effect that sea water is conducted through subterranean channels below the mountains and is then purified and raised to the springs; the other to the effect that in the cold dark caverns under the mountains the subterranean atmosphere and perhaps the earth itself are condensed into the moisture which feeds the springs.[2]

"The sea-water hypothesis gave rise to subsidiary hypotheses to explain how the sea water is freed from its salt and how it is elevated to the altitude of the springs. The removal of the salt was ascribed to processes of either distillation or filtration. The elevation of the water was by different writers ascribed to processes of vaporization and subsequent condensation, to rock pressure, to suction of the wind, to pressure exerted on the sea by the wind and waves, or later to capillary action. One curious explanation was that, owing to the curvature of the earth, the water in the middle of the ocean is actually at a much higher altitude than the springs and hence furnishes the necessary head.[3]

"We can well be sympathetic with the misconceptions of the old Greek philosophers, who were pioneering in the vast untrodden fields of thought. It appears to me that in some respects they were not very far from the truth. The Greeks were familiar with cavernous limestone terranes, and hence they conceived the subterranean regions to have open spaces with natural processes comparable with those on the surface. The writings of Homer (about 1000 B.C.), Thales (about 650 B.C.), and Plato (427-347 B.C.) contained passages which indicate that these ancient philosophers correctly believed that the spring water is derived from the ocean, but erroneously postulated that this return flow occurs through subterranean channels. Aristotle (384-322 B.C.) on the other hand, developed the hypothesis of subterranean condensation which was suggested by the condensation of atmospheric water vapor.[4]

"The Roman philosophers in general followed the Greek ideas, and did not contribute much to the Greek hypotheses except erroneous details. Seneca (3 B.C.-65 A.D.?) accepted Aristotle's condensation hypothesis, while Pliny (23-79 A.D.) adopted the sea-water concept and attempted to explain how the water is elevated.[5]

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[2] Meinzer, op. cit., p. 7.
[3] Ibid, p. 7-8.
[4] Ibid, p. 8.
[5] Ibid.

"The theory now generally accepted that the ground water is for the most part derived from rain and snow by infiltration from the surface, was briefly but clearly stated by Marcus Vitruvius, who lived about the time of Christ. Vitruvius was not a philosopher but an architect. He produced a work on architecture in ten books, and in conformity with the importance given by the Romans to water supplies, he devoted one of the 10 books to that subject.6/

"The mountains, he explained, received a large amount of rain, which they allow to percolate through the rock strata to their base, where, issuing forth, it gives rise to streams.7/

"During the Middle Ages, according to Adams, all the philosophers and interpreters of Holy Scripture, from St. Jerome (340-420 A.D.) down, taught that the springs have their origin in the ocean. They generally based this assumption on passages in the Bible such as Ecclesiastes 1,7: 'All the rivers run into the sea, yet the sea is not full; unto the place from whence the rivers came thither they return again.' These writers stated that the sea water escapes through holes in the bottom of the ocean, flows into the bowels of the earth, and thence is elevated to the springs.8/

"Beginning with the middle of the 16th century numerous publications appeared which contained discussions of ground water, some of them relating primarily to this subject. Until near the close of the 17th century the two old Greek hypotheses chiefly occupied the field, with many fantastic adornments, although the infiltration theory was explained by a few writers, especially in 1580 by Bernard Palissy (1509-1589), French Huguenot, inventor of enameled pottery, and pioneer paleontologist.9/

"Palissy was reared in poverty and was not educated in Greek or Latin. He began early to observe nature and he based his theories on his own observations. 'I have had no other books,' he wrote, 'than Heaven and Earth, which are open to all.' His discourse on water and springs was written in French, whereas the philosophic treatises of that period were generally in Latin. This discourse is in the form of a fascinating dialogue between 'Theory' and 'Practice.'10/

"'When for a long time,' says Practice, 'I had closely considered the cause of the sources of natural fountains and the place whence they might proceed, at length I became plainly assured that they could proceed from or be engendered by nothing but the rains.' Theory replied: 'After having heard your opinion I am compelled to say that you are a great fool. Do you think me so ignorant that I should put

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6/ Meinzer, op. cit., p. 9.
7/ Ibid.
8/ Ibid.
9/ Ibid.
10/ Ibid, p. 9-10.

more faith in what you say, than in so large a number of philosophers who tell us that all waters come from the sea and return thither? There are none, even to the old men, who do not hold this theory, and from all time we have believed it. It is a great presumption in you to wish to make us believe a doctrine altogether new, as if you were the cleverest philosopher.' To which Practice replies: 'If I were not well assured in my opinion, you would put me to great shame; but I am not alarmed at your abuse or your fine language; for I am quite certain that I shall win against you and against all those who are of your opinion, though they be Aristotle and the best philosophers that ever lived; for I am quite assured that my opinion is trustworthy.'11/

"Thus the argument is developed. Theory defends first the sea water and then the condensation hypothesis, while Practice, with clear and valid arguments, shows the absurdities of these hypotheses, and then presents simple but convincing evidence that the ground water is derived from rain.12/

"Two great men of the 17th century who rejected or ignored the teachings of Palissy were the German astronomer Johann Kepler (1571-1630) and the French philosopher René Descartes (1596-1650). The hypothesis that the earth functions somewhat like an animal, or indeed that it is a living being, became current early in the 17th century and had adherents as late as the 19th century. Kepler adopted this hypothesis and expressed the opinion that the earth, like a huge animal, takes in the water of the ocean, digests and assimilates it, and discharges the products of these physiological processes through springs. Descartes taught that the sea water finds its way into the depths of the earth through underground channels and is there vaporized by the heat of the earth's interior; furthermore that the vapor rises through caverns, is condensed at higher levels, and thus supplies the springs.13/

"A new epoch in the history of hydrology began in the latter part of the 17th century through the work of Pierre Perrault (1608-1680) and Edmé Mariotté (1620-1684) and other French physicists, and of the English astronomer Edmund Halley (1656-1742). These men put hydrology for the first time on a quantitative basis. Perrault made measurements of the rainfall during three years; and he roughly estimated the area of the drainage basin of the Seine River above a point in Bergundy and of the run-off from this same basin. Thus he computed that the quantity of water that fell on the basin as rain or snow was about six times the quantity discharged by the river. Crude as was his work, he nevertheless demonstrated the fallacy of the age-old assumption of the inadequacy of the rainfall to account for the discharge of springs and streams. Mariotté computed the discharge of the Seine at Paris by measuring its width, depth, and velocity at

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11/ Meinzer, op. cit., p. 10.
12/ Ibid.
13/ Ibid, p. 10-11.

approximately its mean stage, making the velocity measurements by the float method. He essentially verified Perrault's results. About the same time Halley made crude tests of evaporation, and demonstrated that the evaporation from the sea is sufficient to account for all the water supplied to the springs and streams, thus removing the need for Plato's Tarraros or any other mysterious subterranean channel to conduct the water from the ocean to the springs.14/

"Mariotté, who discovered Mariotté's law of gases, also known as Boyle's law, probably deserves more than any other man the distinction of being regarded as the founder of ground-water hydrology, perhaps I should say of the entire science of hydrology. In his publications, which appeared after his death in 1684, he defended vigorously the infiltration theory and created much of the modern thought on the subject. According to the brief digest of his works by Keilhack, he maintained that the water derived from rain and snow penetrates into the pores of the earth and accumulates in wells; that this water percolates downward till it reaches impermeable rock and thence percolates laterally; and that it is sufficient in quantity to supply the springs. He demonstrated that the rain water penetrates into the earth, and used for this purpose the cellar of the Paris Observàtory, the percolation through the cover of which compared with the amount of rainfall. He also showed that the flow of springs increases in rainy weather and diminishes in times of drought, and explained that the more constant springs are supplied from larger underground reservoirs.15/

"The ground-water literature near the close of the 17th century, throughout the 18th century, and in the early part of the 19th century, was largely devoted to the defense of the old hypotheses as against the infiltration theory. Nevertheless, the infiltration theory gradually but irresistibly gained ground and eventually became almost universally accepted among scientists, while the old hypotheses became more and more shadowy until they lurked only in obscure haunts like emaciated ghosts.16/

"Geology affords the framework on which ground-water hydrology is built; more accurately, it describes the rock formations that make up the great and intricate systems of natural waterworks, the functioning of which forms the essential part of the subject of ground-water hydrology. Therefore, although earnest attempts were made by Vitruvius and others to give useful information as to the water-bearing properties of different rocks, the subject of ground-water hydrology could not be far developed until the fundamental principles of geology were established near the close of the 18th century.17/

14/ Meinzer, *op. cit.*, p. 11.
15/ *Ibid*, p. 12.
16/ *Ibid*.
17/ *Ibid*, p. 14-15.

"One of the first men to apply geology, in the modern sense, to the problems of ground water was William Smith (1769-1839), who has been called the Father of English Geology. Although Smith was deeply interested in geology for its own sake, he was even more interested in the fact that as a civil engineer he was able to apply his knowledge of the new science to engineering problems and to the development of mineral and water resources. Although he never wrote a treatise on any phase of the subject of ground water, he was greatly interested in the application of geology to ground-water problems. His notes show that he was interested in wells and springs, not only because they furnished clues as to the stratigraphy and structure, but also because of their value in determining the ground-water conditions.18/

"In the first half of the 19th century, the French engineers, geologists, and drillers took the lead in the study of ground water, largely because there was intense interest in the artesian conditions and the great activity in drilling artesian wells during that period in France. About the middle of the century there appeared a number of publications, chiefly in France, based on extensive research in different phases of the subject of ground water, and it should perhaps be considered that ground-water hydrology, as a branch of science, had its beginning at this time. I refer especially to the work of the following men: The engineer Eugené Belgrand (1810-1878), who in the first of his many works, published in 1846, made the fundamental distinction between permeable and impermeable formations as applied to ground water; the German chemist Karl Gustav Bischof (1792-1870), the results of whose work on ground water are given in his text-book of chemical and physical geology published about 1847; Jules Dupuit (1804-1866), whose work on the movement of ground water was published in 1848; the Abbé Paramelle (1790-1875), whose treatise on ground water was published in 1856; Jean Dumas (1800-1884?), whose 'La science des fontaines' was published in 1857; the hydraulic engineer Henri Darcy (1803-1858), often called the founder of the science of hydrology, the first results of whose experiments on the laws of flow of ground water were published in 1856 in a work with the modest title 'Les fontaines publiques de la ville de Dijon' and Henri Bazin, who was associated with Darcy but active into the present century.19/

"Two notable workers in ground water in a little later period were the French geologist Gabriel Auguste Daubrée (1814-1896), and the German hydrologist Adolph Thiem (1836-1908). Daubrée made a large and valuable contribution to the subject of the relation of geologic structure to the occurrence and movement of ground water. His principal results were published in three large volumes in 1887 Thiem was a pioneer of intensive ground-water work in Germany. He introduced field methods for making tests of the flow of ground water and applied the laws of flow in developing water supplies.

18/ Meinzer, *op. cit.*, p. 15.
19/ *Ibid*, p. 15-16.

Under his influence Germany became the leading country in supplying the cities with ground water. The results of his work appeared in a number of papers, the first in 1870. Mention should also be made of the Italian hydrologist, D. Spataro.[20]

"In the United States not much systematic ground-water work was done before 1873. In 1856, George G. Shumard made a brief report on artesian prospects on the Llano Estacado for the Pacific Railway survey, which was not published until 1892. In 1857, the New Jersey Geological Survey published the 'Geology of the county of Cape May,' by George H. Cook, which included a brief discussion of the artesian conditions. Later reports of the New Jersey Geological Survey contain considerable information on the artesian waters of the State by Lewis Woolman and others. In 1859, W. W. Mather published a report on certain artesian wells in Ohio. Some early work on artesian conditions was also done at New Orleans, Charleston, S.C., and in other parts of the country. From 1873 to 1879, in connection with the Geological Survey of Wisconsin, Thomas C. Chamberlin made a thorough study of artesian conditions in Wisconsin. His principal report on the artesian wells was published by the State survey in 1877; his well-known paper, 'The requisite and qualifying conditions of artesian flow,' was published by the U. S. Geological Survey in 1885.[21]

"About this time great interest developed in ground water, not only in the arid regions but also in the more humid sections of the country, and many ground-water investigations were undertaken, chiefly by the United States Geological Survey. Thus in the last decade of the 19th century a group of eminent American geologists directed their attention to ground water and published comprehensive and thoroughly sound areal reports on the subject. Let us call the roll of these geologists in the order in which their first publications on ground water appeared: Robert T. Hill, W. J. McGee, Isreal C. Russell, Nelson H. Darton, Robert Hay, Grove K. Gilbert, Frank Leverett, Warren Upham, George H. Eldridge, William H. Norton, T. Wayland Vaughn, Edward Orton, S. W. McCallie, and Willard D. Johnson. The largest part in this early work was taken by Darton. Near the close of the century notable work was also done on the hydrologic phases of the subject of ground water by three eminent American investigators: Allen Hazen, Franklin H. King, and Charles S. Slichter."[22]

The Twentieth Century

Developments and new findings related to ground water during the last quarter of the 19th century continued and accelerated during the 20th century. Quoting again from Meinzer's historical review of the development of ground-water hydrology:

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[20] Meinzer, op. cit., p. 16-17.
[21] Ibid, p. 17.
[22] Ibid, p. 18-19.

"From the beginning of the 20th century to the present time there has been increased activity in the study of ground water, with more workers than in any earlier period, and consequently a rapidly increasing literature and a differentiation of the subject along a number of specialized lines. This activity may to some extent be judged by the considerable number of comprehensive treatises that have appeared on the subject, most of them the products of many years of ground-water investigation by the authors. I do not feel qualified to select the leaders in this recent period, but I will mention a few representative workers, all of whom made substantial contributions.23/

"Among the French my attention has been called especially to the work of the following men: Léon Pochet, Edmond Maillet, F. Diénert, Louis Dollé, Edouard Martel, and Edouard Imbeaux. Both Pochet and Maillet published treatises in 1905 on the hydraulics of ground water. Martel has studied especially the occurrence and movement of water in cavernous limestone, and has also published a treatise...on the general subject of ground water. Imbeaux since 1886 has published extensively on the subject of ground water, including a large...work on 'hydrogeology,'....24/

"Among the ground-water hydrologists of Germany I may mention, in alphabetical order E. Ebermayer, A. Grund, A. Hertzberg, K. Keilhack, H. Keller, W. Koehne, O. Luegar, E. Prinz, L. Reuter, M. Rother, W. Salmon, A. Steuer, G. Thiem, and R. Weyrauch. These and other German hydrologists have produced a large and valuable literature on the subject. Among the outstanding productions are the general treatises by Prinz, Keilhack, and Koehne.25/

"I am not familiar with the literature of Italy, but the high rank of that country in ground-water work can in some degree be judged by the fact that a bibliography prepared by Michele Gortani lists about one thousand publications on the ground-water hydrology of Italy between 1870 and 1923. Outstanding names are perhaps those of G. Cuppari and M. Canavari.26/

"Much valuable work has also been done in other European countries. I may mention in Russia, P. Ototzky and Alexander Lebedief; in Austria, Hans Hofer-Heimhalt, P. Forchheimer, O. Smreker, U. Huber, and Charles Terzaghi; in Holland, Eugéne Dubois, J. Pennink, and J. Versluys; in Belgium, René D'Andrimont; in Switzerland, Albert Heim, T. Hug, and Arnold Engler; in Sweden, J. Richert; in Denmark, Hilmar Odum; and in Spain, Bartotomü Darder Pericás, who recently published a treatise on investigation of ground water.27/

23/ Meinzer, op. cit., p. 19.
24/ Ibid.
25/ Ibid, p. 19-20.
26/ Ibid, p. 20.
27/ Ibid.

"The British hydrologists have been active in making areal ground-water surveys and in developing ground-water supplies but have perhaps contributed less notably to the science of ground-water hydrology. Outstanding names in this field are those of Horace B. Woodward and William Whittaker, author of numerous areal ground-water reports for the Geological Survey of Great Britain. Much ground-water work has been done in Australia, India, and other parts of the British Empire; also in other parts of Asia and Africa, in the Latin American countries, and in the uttermost parts of the earth. Most of this work has, of course, been descriptive, but some critical investigations have been made, especially in India."28/

Regarding American contributions to ground-water hydrology, tremendous advances have been made in the short interval from the end of the 19th century to present. As already mentioned important theoretical contributions were made by A. Hazen, C. King, and C. S. Slichter. Detailed field investigations were made by men such as T. C. Chamberlin, N. H. Darton, W. T. Lee, and W. C. Mendenhall. Dr. O. F. Meinzer, through his keen interest and dynamic leadership, has stimulated much of the progress in ground-water hydrology this century.

A major contribution in ground-water hydraulics was made by Theis in 1935 with his development of a solution for the nonsteady flow of ground water derived by the analogous flow of ground water and of flow of heat by conduction. This solution allowed hydrologists for the first time to predict future changes in ground-water levels resulting from pumping.

Since 1935 a large number of important papers have been published on quantitative hydrology, in fact the field has enlarged so rapidly as to discourage comprehensive text books.

The accompanying bibliography gives only a sampling of this quantitative work. Much of the work has been directed toward the development and solution of formulas by means of the calculus to simulate the type and location of hydrologic boundaries and changing hydrologic characteristics. In cases where the field conditions are compatible with the theoretical mathematical relations, quick answers can be given by hydrologists regarding the prediction of future water levels, the design of well fields, and the determination of optimum well yields and pump types. However, situations are frequently encountered where complicated hydraulic conditions cannot be expressed by easily solvable mathematical relations. In such instances tremendous advances have been made through use of modern computer methods, including analog models.

It is evident from the foregoing that ground-water hydrology is relatively a new science. It is founded upon other and better established sciences such as meteorology, geology, physics, chemistry, and botany, besides upon a rapidly growing body of physical data peculiar to itself.

It is difficult to analyze why progress in the science was slow during certain times; however, when one considers that most of the phenomena of ground-water hydrology are exceedingly complex, it may not be so hard to understand.

28/ Meinzer, op. cit., p. 20.

For indeed, to a casual observer the irregularities and apparent inconsistencies are often so great as to make the existence of fundamental laws and cause-and-effect relationships seem hopelessly obscure and even nonexistent. Notwithstanding this seeming confusion, however, the occurrence of all natural phenomena will be found based upon law and order, if one can only analyze the conditions surrounding these phenomena and evaluate the varying influences and effects of these conditions in each instance. In this connection Tolman summarizes well:

"Centuries have been required to free scientists from superstition and wild theories handed down from the dawn of history regarding the unseen subsurface water, and one should learn to control his impatience at the constant reminders that this is still an age of popular superstition with respect to the occurrence of ground water. The elementary principle that gravity controls motions of water underground as well as at the surface is not appreciated by all engaged in the development of ground-water supplies.29/

"The popular belief exists that 'rivers of underground water' pass through solid rock devoid of interconnected interstices and flow under intervening mountain ranges. For example, it has been stated that the ground water of the coastal valleys of California originates in the Sierra Nevada, passes under the Great Valley of California and the intervening mountains of the Coast Range, regardless, of course, of geologic structure. It has been repeatedly stated that large springs flow from fissures at the top of the highest peaks of a mountain range. Many people still believe that the magical forked witch stick is able to point to underground water streams and will actually twist in the hands of the operator in its endeavor to do so.30/

"These popular superstitions are examples of the ability to believe without the foundation of facts, and this peculiar ability exists in the minds of both 'educated' and 'uneducated' men. Inasmuch as the movements of underground water cannot be observed at the surface, they have been subject to wild speculation. Even a judge in our courts has ruled that 'percolating water moves in a mysterious manner, in courses unknown and unknowable.'31/

"Present day knowledge in regard to the occurrence of ground water and especially the control of geologic structure over its motions should be of wide interest. People should be freed from superstitions regarding the mysterious and 'unlawful' wandering of water underground. Every user of well water should know something about the source and underground motions of his water supply. In this way he may guard against contamination and be able to decide whether or not advice is sound, which is usually given by well

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29/ Tolman, C. F., 1937, Ground water: New York, McGraw-Hill Book Company, p. 22.

30/ Tolman, *op. cit.*, p. 22.

31/ *Ibid.*

drillers, as to the advisability of deepening a well or sinking others. Owners of estates in the rolling foothills or in the pleasant valleys of the Coast Range in the vicinity of San Francisco have put down deep wells to encounter the currents of water that, according to popular belief, must exist at depth. Yet in much of this area ground water occurs in fractures in impervious rocks, and most of these fractures die out with depth."[32]

The 20th century has seen numerous advances made in describing the natural laws which govern the movement of water under the earth's surface, and the successful application of this knowledge.

Professional Status in the United States

A survey of the development of the science of hydrology would not be complete without mention of its status in the United States through a sketch of three characteristics which are implicit in a science--education of the individuals who use the principles of hydrology, technical societies by which they participate to exchange technical information, and their employment.

Education

As has been illustrated, hydrology cuts across several sciences. In practice, the principles of hydrology have been applied for many years as part of associated sciences such as engineering, geology, and agriculture. The development of hydrology has proceeded with the rapid growth of technology in general in the past few years, and has emerged as a distinctive scientific field. As would be expected, the development of education in hydrology has followed a similar pattern.

In 1904, Daniel W. Mead, a civil engineer, published the first American book on hydrology for use in what is believed to be the first separate technical study course in the United States on hydrology. Mead was followed in 1918 with a text by Adolf Meyer. Mead published Hydrology the Fundamental Basis of Hydraulic Engineering in 1919. During the next 30 years hydrology developed into the science as we know it today. The technical progress during this interim was reflected in numerous articles in periodicals and other scientific literature culminating in the publication of several important texts on hydrology in 1949.

The development of hydrology has markedly been associated with the development of water supplies. Consequently, even though there is the opposing tendency for a growing body of science like hydrology to separate into a specialty of its own, yet because of the engineering background, in particular civil engineering, hydrology has for the most part remained a part of engineering. This is important when considered with the following discussion of undergraduate and graduate curricula in hydrology to show that many universities and colleges in

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[32] Tolman, *op. cit.*, p. 23.

the United States offer courses in hydrology as part of their engineering and/or geology programs, either as part of other courses or as separate courses.

As reported in Scientific Hydrology (Federal Council for Science and Technology, 1962, p. 16): "In a sample of about 120 engineering schools, all had either an elementary course in hydrology or gave some instruction in hydrology in connection with other courses such as waterpower, irrigation, or water supply and sewerage. Elementary or basic courses in hydrology were provided by about two-thirds of the engineering institutions. About half as many institutions offered such a course at the graduate level."

Many schools offer undergraduate degree plans in civil engineering with hydraulic option which includes work in hydrology. The University of Arizona offers a program leading to the degree of "Bachelor of Science in Hydrology." This academic program includes study in the several fields of hydraulics, mathematics, geology, chemistry, physics, and meteorology.

A number of universities offer graduate study in programs encompassing hydrology which generally lead to the master's or doctoral degree in civil engineering, geophysics, agricultural engineering, or engineering mechanics (Office of the Federal Register, 1962). For example, the University of Texas offers the degree of Master of Science in Civil Engineering and Doctor of Philosophy. Both degree programs are flexible enough to allow the student to elect his course of study under the guidance of graduate advisors. This would include graduate work in hydrology. The University of Arizona offers the degrees of Master of Science and Doctor of Philosophy in Hydrology.

Increased interest in the education of hydrologists is evidenced by the participation of 19 universities in the Inter-University Conference on Hydrology held at Lake Arrowhead, California on August 7-9, 1962 (Todd, 1962). One of the accomplishments of the Conference was the agreement to establish a Universities Council on Hydrology (UCOH) which is intended to be a unifying body representing all universities interested in hydrology for encouraging graduate education and research.

Technical Societies

One of the characteristics of a growing science such as hydrology is technical societies for dissemination of scientific knowledge. Three technical societies that perform this function in the United States are the American Society of Civil Engineers (established in 1852), the American Geophysical Union (established in 1919) in the National Research Council of the National Academy of Sciences, and the Geological Society of America (established in 1888).

The Hydraulics Division of the American Society of Civil Engineers was organized in 1938. The purpose is (Am. Soc. Civil Engineers, 1963, p. 30): "the advancement and the dissemination of scientific and engineering knowledge in all branches of hydraulics, hydrology, hydraulic engineering and water resources. In particular this shall embrace meteorology and hydrology as the sciences dealing with the occurrence of water in the atmosphere, on the earth's surface and in the ground, fluid mechanics for the understanding of all flow phenomena, applied hydraulics for the design and planning of hydraulic structures and of comprehensive systems, and those social, economic and administrative aspects basic to the conservation and utilization of water as an essential natural resource." Within the Hydraulics Division there is the Committee on Surface-Water Hydrology with the purpose (Am. Soc. Civil Engineers, 1963, p. 33): "to study all aspects of precipitation and runoff from the time rainwater or other precipitation touches the ground; to study the natural occurrence of floods and droughts, snowmelt runoff, the establishment of design floods, water losses through evaporation, transpiration, and infiltration, and detention of water in snow deposits."

The American Geophysical Union is similarly organized with a technical section on hydrology which began in 1931 (Meinzer, 1931).

A Hydrogeology Group was established in 1959 within the Geological Society of America. The By-Laws of this Hydrogeology Group show its purpose to be: "To bring together scientists interested in hydrogeology, to facilitate the presentation and discussions of their problems and ideas, to promote research and the publication of results on hydrogeologic studies, and to advise and assist the officers and committees of the Society in matters pertaining to hydrogeology."

Employment of Hydrologists

The Texas Water Commission employs technical personnel under the distinct job classification of "Hydrologist." Hydrologists are employed in the Surface Water, Ground Water, and Planning Divisions of the Commission.

The title of the Chief Hydraulic Engineer of the Water Resources Division of the U. S. Geological Survey was changed to Chief Hydrologist by memorandum of March 21, 1963. The memorandum stated, "The broadening scope of Division activities has placed greater emphasis on hydrology as an interdisciplinary science combining many skills, including engineering, geology, chemistry, and others. The change...has been made as a natural consequence of this emphasis on hydrology." Other scientists employed by the Federal government, although not classified or called "hydrologists," are doing hydrologic work in such United States agencies as the Weather Bureau, the Corps of Engineers, the Bureau of Reclamation, and the Soil Conservation Service, all of which have hydrologic missions as part of their services (Office of the Federal Register, 1962). In some instances these agencies have technical personnel specifically grouped in organized sections or divisions of hydrology.

In private industry and in the professional consulting field, there are scientists who practice as hydrologists. Additionally, there are engineers, meteorologists, geophysicists, geologists, agronomists, and others who apply hydrology either principally or secondarily but do not refer to themselves as "hydrologists" (Cosens, 1957).

SUMMARY

Technology has developed means to use water for the survival and convenience of civilizations from the beginning of recorded history. Technology has responded to the problems of where the water comes from and how it may be controlled to meet the indeterminable needs of burgeoning populations and industries through the development of hydrology--a science of ancient origin but of continuing development and increasing significance.

GLOSSARY OF SELECTED HYDROLOGIC TERMS

Aquiclude. A formation which, although porous and capable of absorbing water slowly, will not transmit it fast enough to furnish an appreciable supply for a well or spring.

Aquifer. A strata, formation, or group of formations, which are porous, permeable, and water-bearing and have hydraulic continuity.

Artesian aquifer. An aquifer that is confined both above and below by an impermeable layer, the water is under hydrostatic pressure, and the water will rise above the point at which it is first encountered.

Cloud. A mass of fine particles of water vapor in the atmosphere, which are not of sufficient size to fall to the earth, and so remain suspended in the air usually at a considerable distance above the surface of the earth. When the mass is in contact with or close to the earth's surface, it is called fog.

Cone of depression. The depression, roughly conical in shape, produced in a water table or piezometric surface by pumping (or artesian flow).

Confining bed. One which, because of its position and its impermeability or low permeability relative to that of the aquifer, gives the water in the aquifer artesian head.

Evaporation. The process by which water or other liquid passes from a liquid state to vapor--the gaseous state.

Evapotranspiration. Water withdrawn from soil by evaporation and plant transpiration.

Ground water. Subsurface water occupying the saturation zone, from which wells and springs are fed. In a strict sense the term applies only to water below the water table.

Ground-water divide. A line on a water table on each side of which the water table slopes downward in a direction away from the line.

Head. The height of the free surface of fluid above any point in a hydraulic system; a measure of the pressure or force exerted by the fluid.

Hydrometry. The instrumentation and measurement of elements of the hydrologic cycle on the earth's surface and in the ground.

Impermeable. A term applied to a material through which water cannot pass or through which water passes with great difficulty.

Infiltration. The absorption of water by the soil, either as it falls as precipitation, or from a stream flowing over the surface.

Interception. The process by which precipitation is caught and held by foliage, twigs, and branches of trees, shrubs, and other vegetation, and lost through evaporation, never reaching the surface of the ground.

Interstice. A pore or small open space in rock or granular material, not occupied by solid mineral matter.

Lithology. The composition and texture of rocks. The study of rocks.

Perched ground water. Ground water separated from an underlying body of ground water by unsaturated rock. Its water table is a perched water table.

Percolation, deep. The moisture which penetrates the ground below the depths from which it may be used by plants; it represents that part of the water absorbed which exceeds the field capacity of the soil within the depth of root development. Also, the amount of water lost from a basin through the geologic formation.

Permeability, coefficient of. The volume of a fluid of unit viscosity passing through a unit cross section of the medium in unit time under the action of a unit pressure gradient.

Permeable. Having a texture permitting water to move through it perceptibly under the head differences ordinarily found in subsurface water.

Piezometric. An imaginary surface that coincides with the static water level in an artesian aquifer. The surface to which the water in a given aquifer will rise under its own head.

Porosity. The ratio, stated as a percentage, of the volume of all pore space to the total bulk volume of a given rock.

Precipitation. The total measurable supply of water of all forms of falling moisture, including dew, rain, mist, snow, hail, and sleet; usually expressed as depth of liquid water on a horizontal surface in a day, month, or year, and designated as daily, monthly, or annual precipitation.

Recharge. The process by which water is added to an aquifer, either by natural or artificial means.

Runoff. That portion of the earth's available water supply that is transmitted through natural surface channels. In the general sense it is defined as that portion of the precipitation which is not absorbed by the deep strata but finds its way into the streams after meeting the persistent demands of evapotranspiration including interception and other losses.

Safe yield, ground water. The rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible.

Sediment. Any material carried in suspension by water, which would settle to the bottom if the water lost velocity.

Seepage. The slow movement of water through small cracks, pores, interstices, etc., in the surface of unsaturated material into or out of a body of surface or subsurface water.

Soil moisture. Available and unavailable moisture in the ground generally within the range of plant roots.

Specific yield, ground water. The quantity of water that a formation will yield under the pull of gravity if it is first saturated and then allowed to drain; the ratio expressed in percentage, of the volume of this water to the total volume of the formation that is drained.

Storage, coefficient of. The amount of water in cubic feet that will be released from or taken into storage by a vertical column of the aquifer having a base one foot square when the water level or piezometric surface is lowered or raised one foot.

Streamflow. A term used to designate water which is flowing in a stream channel.

Subsurface water. Water beneath the surface of the earth (in the lithosphere). It may be in liquid, solid, or gaseous state.

Surface water. Water that flows or rests upon the surface of the earth. It may occur in either liquid or solid state.

Transmissibility, coefficient of. The amount of water in gallons per day which will pass through a vertical strip of the aquifer one foot wide under a hydraulic gradient of one foot per foot.

Transpiration. The process by which plants dissipate water into the atmosphere from leaves and other surfaces.

Vaporization. The process by which water changes from the liquid state or solid state to the gaseous state.

Water supply. A general term for the sources of water for public or private uses.

Water table. The upper surface of a zone of saturation, where the body of ground water is not confined by an overlying impermeable formation. Where an overlying confining formation exists, the aquifer in question has no water table.

Water-table aquifer. An aquifer that is unconfined and the water is under atmospheric pressure and will not rise above the point at which it is first encountered.

Water vapor. The gaseous form of water; molecules of water present as a gas in an atmosphere of other gases.

Zone of saturation. That portion of the lithosphere in which the functional interstices of permeable rock or earth are completely filled with water under positive hydrostatic pressure, that is, pressure in excess of atmospheric pressure. It is the portion of the lithosphere that supplies water to springs and wells and which contains the ground water.

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APPENDIX

DEFINITION OF "HYDROLOGIST"
as Applicable to Employment in the Surface Water Division of the Texas Water Commission

A hydrologist is one who is concerned with the task of making rigorous studies of all base data to determine the principles and laws involved in the occurrence, movement, and work of the waters in the hydrologic cycle.

A hydrologist in the Surface Water Division of the Texas Water Commission is concerned with the development of accurate and feasible methods and the use of such methods in making hydrologic measurements of diverse kinds, and with the accumulation, compilation, analyzation and interpretation of the mass of resulting quantitative data involved with tracing and accounting the natural occurrence, distribution, and circulation of water of atmospheric origin on, in and over the surface of the Earth as directly affecting the availability of water as a natural resource for development and conservation in the State of Texas.

Work of a hydrologist in the Surface Water Division of the Texas Water Commission involves the determination of the quantities and rates of movement of water at all times including the quantities and rates of rainfall; streamflow; storage in reservoirs and natural lakes and ponds; infiltration into the soil and movement of soil moisture; discharge of springs and of total effluent seepage; interchange of surface and underground waters; losses by evaporation from land and water surfaces, and from the soil and objects on the surface; transpiration from growing plants, including agricultural crops, native and cultivated trees and vegetation; the loads of dissolved and suspended matter contained in, and transported and deposited by, the waters of the State; and the evaluation of the changes in the above determined quantities and rates as might be caused by the conservation and use of soils and water.