HYDROLOGY.—*The history and development of ground-water hydrology.*[1]

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UTILIZATION OF GROUND WATER

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 because they lived near springs or streams which were convenient for fishing and hunting.

When men began to raise large herds and flocks, the grazing within reach of natural watering places became inadequate; and the task of digging wells was taken up seriously, especially in arid and semi-arid regions. Thus, the patriarch Isaac was very active and successful in digging wells, as is shown by the twenty-sixth chapter of Genesis, which reads like a water-supply paper.

When men began to cultivate the soil the need for water supplies was further increased. Some of the most ancient agriculture was carried on in arid regions by means of irrigation, largely with water drawn from wells. Throughout the countries of southern Asia and northern Africa, ground water has, since ancient times, been extensively utilized for irrigation. It has been estimated that on the peninsula of India alone not less than 20,000,000 acres are under irrigation with water obtained from wells—an acreage comparable with the total irrigated area in the United States.[2]

With the growth of cities and the development of industry, the demands for new water supplies increased immensely, and these supplies were in large part obtained from wells. At present about two-thirds of the public waterworks in the United States derive their water from wells and these waterworks supply nearly 20,000,000 of our population. The ground-water developments for industrial purposes have become numerous and complex, and the requirements have become very exacting as to both quantity and quality of water.

The utilization of the ground water, of course, preceded by long

[1] Presidential address delivered before the Geological Society of Washington, Dec. 9, 1931. The term *ground water* is here used to designate the water in the zone of saturation; that is, the water which supplies springs and wells. The terms *underground water*, *subterranean water*, and *phreatic water* are also used to designate this water. The term *phreatic* is derived from the Greek word meaning *a well*. It suggests the term *phreatology* for the branch of science that is here designated by the awkward term *ground-water hydrology*. Published with the permission of the Director, U. S. Geological Survey. Received March 23, 1933.

[2] Cox, W. G. *Artesian wells as a means of water supply*. Brisbane, pp. 3–7. 1895.

ages the scientific study of the natural laws that govern the occurrence and movement of this water. However, the problems of utilization have furnished the chief urge for scientific study, and most of the men who have made contributions to ground-water hydrology have been close to the practical problems of ground-water development.

ORIGIN OF GROUND WATER[3]

From the dawn of history nearly to the present, the source of the water that flows from the springs has constituted a puzzling 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.

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

[3] The following publications give interesting and valuable accounts of the historical development of the theories on the origin of ground water:

Adams, F. D. *The origin of springs and rivers—an historical review.* Fennia **50:** No. 1, Helsingfors, Finland, 1928. See also abstract in Geol. Soc. Amer. Bull. **39:** 149–150. 1928; and note on *Rainfall and Runoff* in Science. **67:** 500–501. 1928.

Althaus, Julius. *The spas of Europe.* London, pp. 1–9. 1862.

Haas, Hippolyt. *Quellenkunde.* Leipzig, 1–10. 1895.

Imbeaux, Ed. *Essai d'hydro-géologie.* Paris, pp. 16–18. 1930.

Keilhack, Konrad. *Lehrbuch der Grundwasser und Quellenkunde.* Berlin, pp. 74–85. 1912.

Mager, Henri. *Les Moyens de découvrir les eaux souterraines et de les utiliser.* Paris, pp. 1–21. 1912.

Martel, E. A. *Nouveau traité des eaux souterraines.* Paris, pp. 77–98. 1921.

Paramelle, L'Abbé. *L'Art de découvrir les sources.* 1856. Fourth ed. 1896, pp. 64–112.

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.

The Greek philosophers.—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 great 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.) contain 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. Quoting from Adams[4]:

> Aristotle said that the air surrounding the earth is turned into water by the cold of the heavens and falls as rain. He goes on to say that it is unreasonable for any one to refuse to admit that the air which penetrates and passes into the crust of the earth also becomes transformed into water owing to the cold which it encounters there. Within the earth's crust it is condensed in the form of moisture which gathers into drops that run together into little trickling streams, so that the sources of the rivers as it were drip out of the earth and unite on its surface into brooks and rivers. The rivers thus flow from the mountains, because the mountains and high lands are suspended over the lower country like a saturated sponge. It is on the mountains also the chief rainfall occurs and the water coming out of the earth unites with the rain water to produce rivers. The rainfall alone is, he states, quite insufficient to supply the rivers of the world with water. The ocean into which the rivers run does not overflow because while some of the water is evaporated, the rest of it changes back into air or into one of the other elements.

The Roman philosophers and Vitruvius.—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.

[4] *Op. cit.*, p. 4. From Meteorologia, Book I, 13.

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. At the beginning of Book 8, as quoted from the English translation by Givilt,[5] he stated:

> As it is the opinion of physiologists, philosophers, and priests that all things proceed from water, I thought it necessary, as in the preceding seven books rules are laid down for buildings, to describe in this the method of finding water, its different properties according to the varied nature of places, how it ought to be conducted, and in what manner it should be judged of; inasmuch as it is of infinite importance for the purposes of life, for pleasure, and for our daily use.

The mountains, he explained, receive 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.

The writers of the Dark Ages.—During the Middle Ages, according to Adams,[6] 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 come 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.

The early period of modern times—Bernard Palissy.—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[7] (1509–1589), French Huguenot, inventor of enameled pottery, and pioneer paleontologist.

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

[5] GIVILT, JOSEPH. *Architecture*, by Marcus Vitruvius Pollio, Book **8**: 177–200. Translated from the Latin, 1860.

[6] *Op. cit.*, pp. 8, 9.

[7] PALISSY, BERNARD. *Discours admirable de la nature des eaux et fontaines tant naturelles qu'artificielles.* 1580.

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."

"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 replies: "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 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."

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.

Palissy's very sympathetic biographer, Henry Morley,[8] wrote in 1853 as follows of the reception that was given to Palissy's theory of ground water:

"By his immediate hearers Palissy's doctrine was accepted; and a few men, who read his books before they passed from obscure fame into unmerited oblivion, made practical use of his suggestion. But by the body of his countrymen, in his own day, the character of Palissy as a philosopher was not appreciated. He was one or two—now and then even three—centuries in advance of his own time, so that his own time had not ears to hear him with. Moreover, France was busy upon other matters, and had no leisure to think for half a minute about springs of water while there prevailed a more engrossing interest in pools of blood."

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

[8] Morley, Henry. *The Life of Bernard Palissy of Saintes.* 2 vols., Boston, 1853. The quotation and translation of dialogue are in **2**: 124. 125.

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.[9]

The age of Perrault, Mariotté, and Halley.—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 Burgundy 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 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 Tartaros or any other mysterious subterranean channel to conduct the water from the ocean to the springs.

The relative credit that should be given to Perrault and Mariotté has been a question of considerable disagreement. A number of writers have stated that Perrault opposed the infiltration theory. Fortunately we have in the U. S. Geological Survey library a copy of the 1678 edition of his treatise on the origin of springs,[10] first published in 1674. If I read this text correctly Perrault did not argue against the

[9] See KEILHACK, *op. cit.*, pp. 76, 77; MARTEL, *op. cit.*, p. 78; PARAMELLE, *op. cit.*, pp. 69, 70.

[10] *De L'origine des fontaines*, Paris, 1678. The name of the author does not appear in this volume but it is evidently Perrault's treatise. See also the previously cited note by Adams in Science, **67**: 500–501. 1928.

infiltration theory, but rather explained that, whereas Vitruvius and Palissy believed that ground-water recharge occurs chiefly from rain and snow on the mountains, he himself held that the rain feeds the streams directly, and that the seepage from the streams on the lower slopes supplies the ground water, which eventually returns to the surface in the lowlands.

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.[11] According to the brief digest of his works by Keilhack,[12] 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 Observatory, 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.

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.

Modern defenders of the condensation hypothesis.—A rather comical revival of the condensation hypothesis of Aristotle was presented in 1877 by the German geologist Volger[13] before a meeting of the Society

[11] MARIOTTÉ, EDMÉ. *Traites du mouvement des eaux et des autres corps fluides*, 1686. According to Keilhack, the complete works of Mariotté were published in Leyden in 1717.

[12] KEILHACK, *op. cit.*, pp. 80, 81.

[13] VOLGER, OTTO. *Die wissenschaftliche Lösung der Wasser—insbesondere der quellenfrage, mit Rücksicht auf die Versorgung der Städte.* Ver. Deutscher Ing. Zeitschr., Berlin. **21**: 482–502. 1877.

of German Engineers, in which he took the extreme attitude that no ground water is derived from rain. Some of his statements were approximately as follows:

> No ground water is derived from rain water. No scientific doctrine is more unfounded and more fallacious than the doctrine in regard to the origin of spring water from rain water. . . . Even the strongest rain wets the earth only superficially, penetrates only a little into the uppermost crust and remains suspended therein. . . . After eight days of the most severe rainy weather the ground at the depth of one-half meter will not show the slightest trace of penetration by water. . . . If the ground were permeable to water, in the manner indicated by the prevalent doctrine in regard to springs, could we see before our eyes a river flow from the heights of the mountains to the sea? Even if the river were ever so richly supplied with water, would it not in its course have to lose its water if the water percolated into the ground? Would not every sea have to sink beneath the surface? Would not the same have to happen to the ocean in spite of its great volume of water? . . . The sea of air extends into the earth to unknown depths, perhaps to the center. The atmosphere, that is, the globe of the gaseous constituent of the aggregate earth, consists therefore not alone of the sea of air that lies above the land and water surfaces. The latter is rather only a slight appendage of the real atmosphere, the vapor-globe, which exists in the ground and in the whole earth. . . . One can say, in general, that all the rocks which constitute the earth, as far as we know them, take up a larger volume of air than their own bulk, so that the ground on which we stand thereby contains so much air that it is just as though the ground were entirely absent and the whole space which it occupies were filled with air.

This paper contained so many exaggerated and erroneous statements that it is surprising that it should have received much attention. On the contrary, however, it gave rise to numerous papers—some of them supporting the condensation theory, some opposing it, and some taking an intermediate attitude. Although this revived condensation theory never gained much support, it has persisted to the present. In 1921, Ototzky,[14] the well-known Russian hydrologist, stated that the theory of infiltration has no solid scientific basis, and that infiltration of atmospheric precipitation occurs to a considerable depth only in exceptional circumstances and in restricted areas. He mentioned condensation as an important factor in ground-water recharge.

The scientific basis of the infiltration theory.—In spite of these apparent flarebacks, the infiltration theory has become firmly established. The work done in the United States alone has, it seems to me, conclusively demonstrated that the ground water is derived mainly from rain and snow. The demonstration consists of abundant care-

[14] OTOTZKY, P. *Underground water and meteorological factors.* Roy. Meteorological Soc. Quart. Jour., pp. 47–54, 1921. (Translated from the French by L. D. Sawyer.)

fully analyzed and substantiated data as to the seepage losses from streams, the downward penetration of the rain and snow water through the soil and subsoil, the rise of the water table in response to the flow of influent streams and in response to rainfall and melting snow, the slope of the water table from the demonstrated intake areas to the areas of ground-water discharge, the relation of the quantity of ground-water discharge in any area to the mean annual precipitation and to the permeability of the intake materials, and the fluctuation of discharge with fluctuations in precipitation.

The evidence that has been least conclusive is that regarding rainfall penetration, whether derived from lysimeter tests or from moisture determinations of soil borings. Negative conclusions regarding rainfall penetration have been reached, partly because inadequate methods were used and partly because it was not fully appreciated that, in spite of many negative results, there may be great recharge in certain localities of permeable material by confluence of rain water in periods of exceptionally heavy precipitation. We now have evidence that soil moisture may be moving downward to the water table, in large aggregate amounts, without any of it dripping into an ordinary lysimeter and without a large increase at any time in the moisture content of the material below the "root zone." A group of investigators in the U. S. Bureau of Agricultural Engineering, the U. S. Geological Survey, and the California Division of Water Resources are now engaged in critical studies of rainfall penetration, and are, I believe, placing this subject on a sounder scientific basis than it has hitherto had.

Before leaving the subject of the origin of the ground water, reference should be made to the theory of juvenile water, which was developed by Edward Suess,[15] and the theory of connate water, which in this country was developed chiefly by Alfred C. Lane. These theories supplement rather than conflict with the infiltration theory, and they can not properly be regarded as having any real relation to the old condensation and sea-water hypotheses.

THE RISE OF GEOLOGY AND ITS APPLICATION TO GROUND WATER

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 func-

[15] SUESS, EDWARD. *Über heisse Quellen.* Gesell. deutsch. Naturf. und Aertze Vortr. pp. 133–150. 1902.

tioning 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.

One of the first men to apply geology, in the modern sense, to the problems of ground water was William Smith[16] (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.

Of special interest is Smith's development of a water supply for Scarborough, described in a paper published in 1827, because of its thoroughly modern attitude in regard to the conservation of ground water. Obtaining his clues from an old flowing well, he located a water-bearing sandstone, worked out its boundaries and structure, estimated its yield per foot of drawdown, and then built a subsurface dam whereby the water was impounded in the sandstone during the wet winter season and withdrawn through a pipe by gravity in the summer. In regard to this project Smith wrote with much enthusiasm:

> This reservoir, wholly unseen, made at my suggestion in the hills at a trifling expense, to pen up in the rocks 5,000 hogsheads of water, is by far the most curious and perhaps the most useful practical hint hitherto deduced from Geology. So far, I think I was never in my life more usefully employed.

GROUND-WATER HYDROLOGY IN EUROPE IN THE 19TH CENTURY

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

[16] SHEPPARD, THOMAS. *William Smith, his maps and memoirs*, Hull, 1920.

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 Eugène 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;[17] 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[18] (1804–1866), whose work[19] on the movement of ground water was published in 1848; the Abbé Paramelle[20] (1790–1875), whose treatise on ground water was published in 1856; Jean Dumas[21] (1800–1884 ?), whose "La science des fontaines" was published in 1857; the hydraulic engineer Henri Darcy[18] (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.

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[22] were published in three large volumes in 1887. Thiem was the 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. Under his influence Germany became the leading country in supplying

[17] BELGRAND, EUGÈNE. *Étude hydrologique de la partie supérieure du Basin de la Seine*, 1846. For a list of Belgrand's principal publications, from 1846 to 1882, see MAGER, *op. cit.*, pp. 13, 14. For an estimate of his work see also POCHET, LÉON. *Études sur les sources*. **1**: 3–5. 1905.

[18] For an estimate of the work of Dupuit and Darcy see KELLER, HERMANN. *Gespannte Wässer*. Halle, p. 9. 1928.

[19] DUPUIT, JULES. *Études theoriques et pratiques sur le mouvement des eaux courantes*, Paris, 1848; also *Traité de la conduite et de la distribution des eaux*, Paris, 1854.

[20] For sketch of Paramelle's life and estimate of his work see MAGER, *op. cit.*, pp. 9–13.

[21] For estimate of Dumas' work see MARTEL, *op. cit.*, p. 79; KELLER, *op. cit.*, p. 9.

[22] DAUBRÉE, A. *Les eaux souterraines a l'époque actuelle et aux epochues anciennes*, 3 vols., Paris, 1887. For estimates of Daubrée's work see ZITTEL, K. A., *Geschichte der Geologie und Palaontologie bis Ende des 19 Jahrhunderts*, p. 304, 1899. (English translation by M. M. Ogilvie-Gordon, pp. 200–202, 1901. POCHET, *op. cit.* p. 3; MAGER, *op. cit.*, pp. 18–20.

the cities with ground water.[23] The results of his work appeared in a number of papers, the first in 1870.[24] Mention should also be made of the Italian hydrologist, D. Spataro.[25]

GROUND-WATER HYDROLOGY IN THE UNITED STATES IN THE 19TH CENTURY

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.

In 1881, C. A. White and Samuel Aughey were appointed by the Secretary of Agriculture as a geological commission to investigate the artesian prospects of a portion of the Great Plains. Their brief report, published in 1882, contains only meager data and very general conclusions.

On March 27, 1890, Major J. W. Powell,[26] Director of the United States Geological Survey, presented before the Committee on Irrigation of the House of Representatives a remarkably interesting and informative statement on the artesian conditions and prospects in the arid regions of the United States. This statements shows that considerable ground-water work had already been done and that some

[23] For estimate of Thiem's work see KELLAR, *op. cit.*, pp. 9, 10.

[24] THIEM, ADOLPH. *Über die Ergiebigkeit artesische Bohrlöcher, Schachtbrunnen, usw.*, 1870. For a list of some of Thiem's later publications see SLICHTER, C. S. *Theoretical investigations of the motion of ground water.* U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, p. 384, 1898.

[25] SPATARO, D. *Storia dell'acqua e Idrografia sotterranea d'Italia,* Milan, 1891.

[26] POWELL, Major J. W. U. S. Geol. Survey Eleventh Ann. Rept., pt. 2, pp. 260–278. 1891.

of the main features of the ground-water conditions of the country were already understood. Major Powell's summary shows a masterful grasp of the situation and his conclusions have stood the test of time.

On April 4, 1890, an act was approved which authorized the Department of Agriculture to make investigations to determine the location for artesian wells west of the 97th meridian and east of the Rocky Mountains. Colonel Edwin S. Nettleton, irrigation engineer of the Department of Interior, was placed in charge of the field work, Robert Hay was appointed chief field geologist, and a number of other leading geologists were employed. As Congress directed that a report must be made immediately after July 1, only 60 days were allowed for making the investigation, and on August 20, 1890, the Secretary of Agriculture transmitted a voluminous report which contains much loosely-assembled information on the artesian conditions of the extensive region covered, and numerous records of head and discharge that have acquired peculiar value in showing the approximate original artesian conditions. With subsequent appropriations and extensions of time, the investigation was continued and the results were published in 1891 and 1892 in several volumes that contain a large amount of information. One of the geologists of this Survey was Robert T. Hill, who, I believe, has the distinction of being the first to recognize, in his report published in 1892, the importance of the water in the valley fill.

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[27]: Robert T. Hill, W J McGee, Israel 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

[27] For references to the first and subsequent publications on ground water by these geologists, see NICHOLS, J. M. *Geologic literature of North America 1785–1918, Pt. 1, Bibliography.* U. S. Geol. Survey Bull. **746**: 1923.

phases of the subject of ground water by three eminent American investigators: Allen Hazen,[28] Franklin H. King,[29] and Charles S. Slichter.[30]

GROUND-WATER HYDROLOGY IN THE 20TH CENTURY

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.

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[31] and Maillet[32] 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, already cited, on the general subject of ground water. Imbeaux since 1886 has published extensively on the subject of ground water, including a large recent work on "hydrogeology," already cited. Dr. Imbeaux has the distinction of being the Chairman of the Commission on Underground Waters in the Association of Scientific Hydrology of the International Union of Geodetics and Geophysics.

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

[28] Annual Reports of Mass. State Board of Health, 1892 and 1893.

[29] KING, FRANKLIN H. *Observations and experiments on the fluctuations in the level and rate of movement of ground water on the Wis. Agri. Exper. farm.* U. S. Weather Bur. Bull. **5**: 1892. *Principles and conditions of the movements of ground water.* U. S. Geol. Survey 19th Ann. Rept. Pt. 2, pp. 59–294. 1899.

[30] SLICHTER, CHARLES S. *Theoretical investigation of the motion of ground water.* U. S. Geol. Survey 19th Ann. Rept. Pt. 2, pp. 295–384. 1899.

[31] POCHET, LÉON. *Études sur les sources. Hydraulique des nappes aquifères et des sources et applications pratiques*, 2 vols., Paris, 1905.

[32] MAILLET, EDMOND. *Essais d'hydraulique souterraine et fluviale*, Paris, 1905.

literature on the subject. Among the outstanding productions are the general treatises by Prinz,[33] Keilhack,[34] and Koehne.[35]

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[36] 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.

Much valuable work has also been done in other European countries. I may mention in Russia, P. Ototzky and Alexander Lebedief; in Austria, Hans Höfer-Heimhalt,[37] P. Forchheimer, O. Smreker, U. Huber, and Charles Terzaghi; in Holland, Eugène 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 investigations of ground water.

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[38] 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.

Beginning with the 20th century and extending to the present time, a large amount of ground-water work has been in progress in this country. Most of it has been done by the staff of the United States Geological Survey, but much has also been contributed by many other workers, especially in California. Since 1900 the Geological Survey has published more than 300 papers, in about 190 volumes,

[33] Prinz, E. *Handbuch der Hydrologie.* Berlin, 1st ed. 1919, 2nd ed. 1923. Contains bibliography which lists the principal publications of the hydrologists mentioned and of other European hydrologists.

[34] Keilhack, K. *Op. cit.*, 1st ed. 1912, 2nd ed. 1917, 3rd in preparation.

[35] Koehne, W. *Grundwasserkunde.* Stuttgard, 1928.

[36] Gortani, Michele. *Saggio bibliografico dell'idrologia sotteranea d'Italia dal 1870 al 1923.* Giornale di Geologia Pratica, **19**: 1924. Contains also introduction concerning Italian ground-water work.

[37] *Grundwasser und Quellen*, Braunschweig, 1912; 2nd ed., 1920.

[38] Woodward, Horace B. *The geology of water supply.* London, 1910.

that relate primarily to ground water. These publications are largely descriptive and areal, but altogether they unquestionably make a large contribution to the science of ground-water hydrology.[39] To Walter C. Mendenhall, I believe, belongs the chief credit for beginning systematic quantitative investigation, which has become characteristic of our work in this country.

DEVELOPMENT OF DIFFERENT BRANCHES OF THE SCIENCE

Investigations of artesian principles.—Let us now make a rapid survey of the development of some of the different branches of ground-water hydrology. Artesian wells have been in existence since ancient times, and were of great interest not only because of the spectacular phenomenon of natural overflow but also because of the wholesome water which they furnished at a time when most water supplies were badly polluted. According to Keilhack, the Egyptian oases were supplied by numerous artesian wells as early as 2,000 B.C.; and Keilhack, like some of the other authorities, believes that Moses learned the art of well drilling from the Egyptians. The study of artesian water naturally came next in historical development to that of the origin of springs. Even before the emergence of geology, the basic principles of artesian pressure were understood. Pioneers in the development of the hydrostatic theory of artesian pressure were the Italian astronomer and geographer Giovanni Cassini (1625–1712), and the Italian physician Bernardini Ramazzini, whose best-known publication appeared in 1691. In the first half of the 19th century, the French were active, not only in drilling artesian wells and improving drilling methods, but also in developing the principles of artesian pressure and in making geologic applications of them in locating artesian water. During this period the hydrostatic theory became well established.

Chamberlin's paper published in 1885 is a clear, accurate, and critical statement of the general subject of artesian conditions, based largely on his own field studies. Very modestly he stated that it was not an exhaustive exposition of the subject and did not contain much that was original. He did his work so well, however, that the subsequent prevailing attitude, at least in this country, was one of complacent assumption that the principles of the subject were completely

[39] See Water-Supply Paper **427** for U. S. Geological Survey publications relating to ground water up to 1918, and the Survey's list of publications for later papers. Publications on ground water since 1928 are listed in the semi-annual volumes of Annotated bibliography of economic geology (prepared under the auspices of the National Research Council)

mastered. This attitude was challenged by M. L. Fuller in 1908 in his paper, "Summary of the controlling factors of artesian flows."[40] We now recognize that the hydrology of artesian water is a complicated subject that offers a large field for further investigation. Until recently attention has been directed mainly toward the static or structural conditions, with neglect of the hydraulics or dynamics of artesian water, although Chamberlin recognized what we may perhaps call the dynamic principle, and, indeed, considered that his original contribution lay in the recognition of this principle.

Rock pressure was assumed by Thales about 650 B.C., and later by Pliny, as the agency for elevating the sea water to the levels of the springs. In modern times rock pressure has been suggested by different investigators as a cause of artesian head, and there has been unprofitable argument between the champions of this theory and the defenders of the orthodox hydrostatic theory. Recent critical interpretation of the behavior of wells has led us to recognize that the artesian water supports a part of the load of the overlying rocks and that many of the water-bearing formations have measurable elasticity; however, this concept of rock pressure supplements the hydrostatic theory without displacing it.[41]

Development of the principles relating to water tables and pressure-indicating surfaces.—The concepts of the zone of saturation and of the water table, as the upper, free-water surface of that zone, developed later than the concept of the artesian basin. In a sense the early scientific thought on ground water was deficient with respect to the third dimension. It was generally considered that the water from the surface percolates downward till it reaches an impermeable bed and then percolates laterally over the upper surface of that bed to its outcrop. This concept was amplified by the recognition of artesian structures in which the water becomes confined between two impermeable beds. More recently the concept has been developed, step by step, of a zone of saturation, with large storage capacity, performing the functions both of a huge reservoir and of a very intricate system of conduits.

The simple concept of the water table has developed rather tardily, although a good contour map of the water table was published by Gustave Dumont[42] in 1856. Gradually we are coming to recognize the

[40] FULLER, M. L. U. S. Geol. Survey Bull. **319**: 1908.

[41] MEINZER, O. E. *Compressibility and elasticity of artesian aquifers.* Econ. Geol. **23**: 263–291. 1928.

[42] DUMONT, GUSTAVE. *Les eaux alimentaires de la ville de Liége*, 1856.

significance of the form of the water table, with respect to intake, movement, and discharge of the ground water, with the resulting sanitary applications; and of its fluctuations in response to devious processes of accretion and withdrawal of the ground water. We now recognize that there may be two or more separate zones of saturation above one another, each with a normal water table, and that where an impermeable body occurs between a zone of saturation and an overlying zone of aeration there can be no water table or anything that functions like a water table.

Gradually we are gaining a better concept of the zone of saturation itself, recognizing that it may include diverse geologic formations, with all of the intricate stratigraphy and structure that the geologist recognizes and much more that is beyond the reach of the present methods of geology but may nevertheless produce pronounced effects on the behavior of the water. We now recognize that as a result of the rock structure the water in the zone of saturation is everywhere under a pressure gradient, which is not a simple linear affair, as in ordinary hydraulics, but is three-dimensional, and that the ground water is everywhere moving in the direction of the gradient, chiefly along the strata, either up or down the dip, but also upward or downward across the strata.

The concept of the pressure-indicating surface, or piezometric surface, has been recognized for a considerable time, and contour maps of such surfaces have been made for several decades. Recently we have come to recognize more clearly that these surfaces are functionally different from the water table, and that for any zone of saturation, with its single water table, there may be a series of piezometric surfaces each representing a different ground-water horizon. The French have distinguished between the niveau des eaux (water table) and the niveau piezometric; while the Germans have used the term Grundwasserspiegel (ground-water mirror) to designate the water table, and have used for the other concept the French term Piezometrisches Niveau, or some German term such as Wasserdruckschicht.

As in most other fields of ground-water hydrology, the foundations in this field have been laid by the European investigators.[43] Apparently, however, the United States has now taken the lead in this line

[43] VEATCH, A. C. *Fluctuations of the water level in wells, with special reference to Long Island, N. Y.* U. S. Geol. Survey Water-Supply Paper **155**. 1906. This paper gives much information and many references relating to the developments of parts of this subject prior to 1906.

of investigation. The automatic water-stage recorder is coming to be our principal instrument of precision in ground-water work. It promises to make ground-water hydrology a more exact science and may prove to be of value in the study of geologic structure.

Investigations of the relation between fresh and salt water.—The law of equilibrium between sea water and fresh ground water under non-artesian conditions was discovered by the Dutch engineer, Badon Ghyben, and was announced by him in a paper in the Dutch language in 1887. It seems to have been independently rediscovered about 1900 by Herzberg, of Berlin. This important subject has been further developed by a number of Dutch, Belgian, and German investigators already cited. The principles produced by the European workers were introduced into American ground-water work by Walter E. Spear and John S. Brown,[44] and have been effectively applied in the Coastal Plains of the United States proper and in the Hawaiian Islands, under both artesian and non-artesian conditions.

Investigations of the movement of ground water.[45]—About 1843 J. Poiseuille, in connection with his studies of the circulation of the blood, discovered the law of flow through capillary tubes—namely, that the rate of flow is proportional to the hydraulic gradient. In 1856, Darcy verified this law and demonstrated its application to water percolating through sand. In the 75 years since Darcy's results were published, many laboratory investigations of various phases of the problem of the flow of liquids and gases through permeable materials have been made.[46] About 1899 King reinvestigated the whole subject; a little later Slichter tested Darcy's law with lower hydraulic gradients than had previously been used, in order to approximate natural conditions more closely; and in 1923, in the hydrologic laboratory of the Geological Survey, tests were made under hydraulic gradients as low as 5 feet to the mile.[47] The results of the work subsequent to that of Poiseuille and Darcy support essentially the correctness of the law known as Darcy's law.

[44] SPEAR, WALTER E. *Report on water supply from Long Island sources.* Bd. of New York City Water Supply. **1**: 149–157. 1912.
BROWN, JOHN S. *A study of coastal ground water, with special reference to Connecticut.* U. S. Geol. Survey Water-Supply Paper **537**: 1925. Contains bibliography and digest of American and foreign literature on coastal ground water.

[45] For more detailed statement of the development of this subject, with numerous references to publications, see MEINZER, O. E. *Methods of estimating ground-water supplies.* U. S. Geol. Survey Water-Supply Paper **638**: 126–140. 1931.

[46] For review of this subject to close of 19th century by King and bibliography by Slichter see U. S. Geol. Survey, Nineteenth Ann. Rept. Pt. 2.

[47] STEARNS, NORAH D. *Laboratory tests on physical properties of water-bearing materials.* U. S. Geol. Survey Water-Supply Paper **596**: 152–159. 1927.

The pioneer in developing field methods for measuring the flow of ground water was Adolph Thiem, whose first paper on the subject was published in 1879. His method was to dig two test wells approximately in line with the direction of the movement of the ground water as determined from the slope of the water table, then dose the upper well with salt and at suitable intervals take samples from the lower well which he tested for their chloride content. A notable advance was made by Slichter in 1901 when he devised the electrolytic method.

In 1906 Günther Thiem,[48] son of Adolph Thiem, published his paper describing the field method for determining permeability and rate of flow from a pumping test and the resultant drawdown in observation wells. This method is now used in the United States and is being further investigated and developed by the Geological Survey.[49] More recently we have developed in this country, chiefly through the work of David G. Thompson,[50] a rating-curve method, by which an empirical relation is established between head and inflow, in areas in which ground water is extensively used.

Dye tests were made by Doctor Dionis, in France, in 1882, during an epidemic of typhoid fever, and since that time frequent use has been made of dyes, chiefly in sanitary investigations, to trace underground streams, such as occur in limestone.[51] In 1921 dye was used by Charles W. Stiles[52] and his associates in connection with an investigation at Fort Caswell, N. C., which involved a minute 3-dimensional survey of the direction and rate of movement of the ground water in a sand formation.

Molecular physics in relation to ground-water hydrology.[53]—The two principal forces that control the water in the rocks are gravity and molecular attraction. Many rocks have only very small interstices, and in these the molecular forces become effective. Indeed, the influ-

[48] THIEM, GÜNTHER. *Hydrologische Methoden*, Leipzig, 1906.

[49] WENZEL, L. K. *Recent investigations of Thiem's method for determining permeability of water-bearing materials.* Amer. Geophysical Union Trans., pp. 313–317. 1932.

[50] THOMPSON, DAVID G. *Ground-water supplies of the Atlantic City region.* N. J. Dept. of Conservation and Development Bull. **30**: 35–88. 1928.

[51] For historical development and bibliography of this subject see DOLE, R. B. *Use of fluorescein in the study of underground waters.* U. S. Geol. Survey Water-Supply Paper **160**: 73–85. 1906.

[52] STILES, C. W., CROHURST, H. R., THOMPSON, G. E., and STEARNS, N. D. *Experimental bacterial and chemical pollution of wells via ground water, with a report on the geology and ground-water hydrology of the experimental area at Fort Caswell, N. C.* U. S. Pub. Health Service Hygenic Lab. Bull. **147**: 1927.

[53] For more detailed statement of the development of this subject, with numerous references, see MEINZER, O. E. *The occurrence of ground water in the United States, with a discussion of principles.* U. S. Geol. Survey Water-Supply Paper **489**: 2–101. 1923.

ence of molecular attraction makes the hydraulics of ground water a quite distinctive subject.

Investigations of capillarity in water-bearing materials were made about 250 years ago by Perrault, who established the limits of capillarity in sand and showed that water absorbed by capillarity can never form accumulations of free water at higher levels. Since Perrault's time the occurrence and movement of water under molecular forces in soils and other fine-grained materials have been studied by many investigators in different countries and for a variety of purposes. Among the distinguished early investigators in this field in the United States, in the order in which their first important publications appeared, are Eugene W. Hilgard, 1860; Franklin H. King, 1892; Allen Hazen, 1893; and Lyman J. Briggs, 1897. Many other investigators in this field in both the United States and Europe might be mentioned, most of them belonging to the present century. Thus the results of much critical investigation have become available for the uses of hydrology. In the hydrologic laboratory of the United States Geological Survey we are now proceeding with the comprehensive project of determining the mechanical composition, porosity, moisture equivalent, and permeability of a group of samples from every water-bearing formation in the United States that is amenable to laboratory methods.

In our quantitative studies of intake, discharge, and safe yield of ground water, we are vitally concerned with the mechanical composition and porosity of water-bearing materials, the capillary fringe, the capillary potential and the laws of capillary movement of water, the specific retention, the specific yield and other varieties of effective porosity, and the moisture equivalent, wilting coefficient, and hygroscopic coefficient; we are eager to cooperate with the soil physicists and agricultural engineers in all investigations that involve the moisture properties of fine-textured materials. It appears that the European literature on ground water is somewhat defective in respect to molecular physics and that the American hydrologists are making a definite contribution in cultivating this field.

Investigations of discharge of ground water.—Ground water is discharged by two processes: the hydraulic process, or discharge through springs; and the less conspicuous but equally important process of evaporation—both evaporation directly from the soil and transpiration of plants in areas having a shallow water table.[54]

[54] For more detailed historical statement and references to the literature regarding discharge of ground water by transpiration see MEINZER, O. E. *Plants as indicators of ground water.* U. S. Geol. Survey Water-Supply Paper 577. 1927.

The complex subject of the geologic and hydraulic conditions that produce springs was one of the first fields of ground-water hydrology to receive attention and has been given much study. Fluctuations in the flow of springs and of streams at low stages was given critical study about the beginning of this century by Maillet, with the purpose of developing methods of forecasting their flow. He mentions a number of investigators of this subject, dating back to 1863. The subject has also received some attention in this country, by Arthur C. Veatch and others. On account of the drought of 1930, new interest has recently been developed in this subject, and considerable investigation has been started, especially as to the relation of the water table to the discharge of springs and to the ground-water run-off.

The subject of the discharge of ground water by transpiration of plants and evaporation from the soil has until recently not received much attention either in Europe or in the United States, for the reason that these processes are not readily discerned in humid regions. One of the most curious defects of the early ground-water literature in this country is its silence on this subject. Even the geologists who worked in the arid West took with them the inadequate ideas acquired in the humid regions and failed at first to appreciate the magnitude of the ground-water resources of the arid regions because they did not understand the significance of ground-water discharge by transpiration and soil evaporation.

These processes are, however, conspicuous when once discerned in arid regions. When we consider the vast development of ground-water supplies in southern Asia and northern Africa in very ancient times, we must believe that knowledge of this subject, especially as to the significance of native plants as indicators of ground water, is also very ancient. Moses spent a large part of his life in stock-raising in a desert country, where he doubtless had numerous problems of water supply and abundant opportunity to observe the relation of the native vegetation to the occurrence of ground water. Later he was successful in the tremendous undertaking of furnishing water supplies in this desert country to a great host of people, doubtless because of his first-hand knowledge of ground-water conditions, including the significance of desert plants as indicators of ground water. Vitruvius had a knowledge of plant indicators and evaporation phenomena which he may have acquired by observations in arid regions. In his work on architecture he gave a list of plants that indicate ground water and endeavored to specify the conditions under which they may be regarded as reliable indicators. He also explained the process of alkali accumulation by evaporation of ground water. Similar statements in regard to plant indicators are found in the writings of Pliny, who apparently quoted Vitruvius, and in those of Cassiodorus, in the sixth century, who obtained his ideas largely from an "aquilege," or professional water finder, who came to Rome from the arid regions of Africa. "Because of the great aridity of the terranes of his country," wrote Cassiodorus, "the art of discovering springs is there cultivated with the greatest care."

Vitruvius and the other Roman writers who have been mentioned discussed also less tangible methods of locating ground water, such as color and dampness of the soil, mists rising from the ground early in the morning, and sponges becoming moist when placed in shallow holes in the ground. Obviously these methods border closely on divining, or water-witching, and it is greatly to the credit of Vitruvius, Pliny, and Cassiodorus that none of them recognized divining or any other magical method for locating ground water. Although the means suggested by Vitruvius as aids in finding water may not have had much value, yet they were serious efforts to discover practicable methods at a time when the science of geology was still a complete blank.

That plants in general, and especially forest trees, draw upon the ground-water supply has been recognized by numerous authorities in recent times. Most of these have, however, not been much concerned as to whether the plants withdraw water from the zone of saturation or merely absorb the soil moisture before it reaches the water table, and they have not distinguished between different species in this respect. The relation of specific plant species to the water table was recognized by F. Amy in 1861, Frederick V. Coville in 1893, and the Danish ecologist Eugen Warming in 1895. The subject of plant indicators was treated at length by Henri Mager[55] in 1912, and references to plants that depend on ground water are found in many publications relating to arid regions.

In the last 25 years the geologists and hydraulic engineers who have worked on ground-water problems in the western part of the United States have given considerable study to evaporation of ground water and to the native plants that habitually feed on ground water, the depths to which the plants of each species will send their roots to reach ground water, and the quality of the water that they indicate. Tank experiments of the rate of discharge of ground water by capil-

[55] MAGER, HENRI, *Op. cit.*, pp. 310–319.

lary rise and subsequent evaporation were made by Slichter in 1905, Charles H. Lee in 1910, R. B. Sleight, in 1916, and other investigators more recently. In 1912 Lee[56] published the results of his investigations in Owens Valley, Calif., in which he made tank experiments of the rates of discharge of salt grass with different depths to the water table, and applied these rates to a map which he made of the salt-grass area showing depths to the water table. Since that time a number of investigations have been made in which areas of ground-water discharge have been mapped and rates of discharge have been applied thereto.

Daily fluctuations of the water table were observed by King in his experiments at Madison, Wis., in 1888, and he recognized their significance in recording the discharge of ground water through vegetation. The method was successfully applied by G. E. P. Smith, in Arizona, by the use of water-stage recorders on wells in 1917, in tracts of cottonwood and mesquite, and later also in tracts of salt grass and alkali sacaton. Smith also developed the theory of upward percolation and showed that the daily vegetal discharge could be computed from the rate of rise of the water table at the nocturnal mid-stage if the specific yield were known. More recently Walter N. White,[57] in his work in Escalante Valley, Utah, devised methods of evaluating the daily fluctuations in terms of quantity of water discharged, and developed the method of computing ground-water discharge from the dry weight of the principal phreatophytes.

INVESTIGATIONS OF THE CHEMISTRY OF GROUND WATER

I will not attempt to sketch the development of our knowledge of the mineral composition and chemical reactions of the ground water and of their relation to the occurrence, movement, head, and temperature of this water. Much good work has been done in this field, which involves chemistry, physics, and geology; but much remains to be done. Fortunately, we now have a chemical laboratory in the United States Geological Survey, devoted entirely to the investigation of the natural waters, in which, under the direction of W. D. Collins, are analyzed samples of water from practically all water-bearing formations in the United States, collected by the geologists who are investigating these formations.

[56] Lee, C. H. *An intensive study of the water resources of a part of Owens Valley, Calif.* U. S. Geol. Survey Water-Supply Paper **294**: 53–60. 1912.

[57] White, Walter N. *A method of estimating ground-water supplies based on discharge by plants and evaporation from soil; results of investigations in Escalante Valley, Utah.* U. S. Geol. Survey Water-Supply Paper **659**: 1–105. 1932. This paper contains a statement of the work of King and Smith.

The subject of the physiological effects of the natural waters is closely related to, rather than a part of ground-water hydrology. The subject is inherently so obscure that it lends itself to further befogging by pseudo-scientists. However, there is here probably a field for genuine research; at least, this is suggested by the discovery of the function of iodine in preventing goiter and the recent discovery by Margaret Smith[58] and her associates of the relation of fluorine to the puzzling affliction of mottled teeth.

INVESTIGATIONS OF THE BIOLOGY AND BACTERIOLOGY OF GROUND WATER

Considerable study has been given to the subject of living organisms in ground water, but less to the hydrologic conditions under which these organisms exist. Work on the occurrence, viability, and movement of bacteria in ground water has both sanitary and scientific significance, but is difficult because it must be done under aseptic conditions. Bacteria are introduced into wells by the drilling processes, and therefore great caution must be exercised in drawing conclusions as to the origin of bacteria delivered by wells, even when the samples are taken by the most approved methods. The Fort Caswell investigation, by Stiles and his colaborers, was exceptionally valuable because of the clear evidence that it produced of the viability and movement of *Bacterium coli* in a bed of water-bearing sand, under rigid bacteriological control and under definitely determined hydrologic conditions. However, the results have only limited application, and further work must be done before broad generalizations can safely be made.

STATUS AND PROSPECTS OF GROUND-WATER HYDROLOGY

It is evident, from the foregoing sketch of the history and development of ground-water hydrology, that although much effective work has in the aggregate been done in this branch of science, it is still in a formative condition, with relatively few workers, and with an impressive front of problems that are fairly begging for investigation. The main stimulus and support of ground-water hydrology has always been the human need for water supplies, and the glory of ground-water work has been that human betterment, through the development of more abundant, convenient, and wholesome water supplies, has followed close in the wake of our work. However, this

[58] SMITH, M. C., LANTZ, E. M., and SMITH, H. V. *The cause of mottled enamel, a defect of human teeth.* Univ. of Arizona Exp. Sta. Tech. Bull. **32.** 1931.

utilitarian urge has become so extreme that at present in this country practically all funds available for ground-water work must be used in applying our knowledge to specific ground-water surveys or water-supply problems, with virtually no opportunity for research work except as it is carried on inadequately and almost surreptitiously in connection with these utilitarian projects. We are constantly compelled to follow the wasteful course of applying the little that we now know instead of being able to devote a reasonable part of our efforts to the fundamental task of developing the basic principles of the science so that in the future we will have something more worth while to apply. What is primarily needed at present is not more money for ground-water work but a more rational use of the money that is spent.

The term hydrology has never come into such general use as might be expected in view of the magnitude and importance of the subject that it covers. This fact is in itself not of much consequence, but it is, I suspect, indicative of a real weakness that has pervaded the science, particularly in so far as it applies to the ground water. Certainly ground-water hydrology has suffered from the fact that the workers in the subject have largely been in two groups, inadequately correlated; namely, geologists, who have devoted their attention to the structure of the water-bearing formations without sufficient understanding of the laws of physics that govern the behavior of the water in them; and hydraulic engineers and physicists, who have studied the laws of fluid mechanics without sufficient knowledge of geology to apply their results effectively. It is doubtless desirable that we should continue to draw our recruits partly from the university departments of geology and partly from the schools of engineering, with smaller numbers from the departments of physics and chemistry. Moreover, it is evident that as the subject of ground-water hydrology develops, specialization within the subject will become increasingly necessary. However, to obtain the best results it is imperative that we recognize more largely that although hydrology is built on geology, physics and chemistry, it has a distinctive technique and subject matter, much as we recognize that the science of geology, although it is built on physics, chemistry, and biology, has its distinctive technique and subject matter.

While we recognize that ground-water hydrology is largely built on geology, we should also recognize that, conversely, a properly developed science of ground-water hydrology will be a substantial aid to geology, because the materials of geology are to a considerable extent the product of ground water. Geologists encounter many problems that involve ground-water hydrology, but frequently, because of the lack of a background in the subject, they are incompetent to deal effectively with these problems. The proximate reasons for this lack are obviously to be found in the textbooks of geology, most of which treat ground water only in a rudimentary if not amateurish manner, and in the university departments of geology, most of which have paid almost no attention to the subject. The more fundamental reason is doubtless to be found in the lack of organized subject matter that ground-water hydrology has had to offer. Courses devoted largely to ground-water hydrology are at present given at Harvard and in a few of the other universities. With the progress that is being made in the development of the subject, I believe it is safe to predict that before long no department of geology that undertakes to train graduate students will be considered complete unless it offers a course in ground-water hydrology, not merely as a branch of economic geology but as a part of the foundation upon which the training of a geologist must be built.

BOTANY.—*Hawaiian algae collected by Dr. Paul C. Galtsoff.*[1] MARSHALL A. HOWE, New York Botanical Garden. (Communicated by WILLIAM R. MAXON.)

Under date of March 28, 1932, William R. Maxon, Associate Curator, Division of Plants, United States National Museum, sent to the writer for study 23 jars of marine algae, collected in the summer of 1930 by Paul C. Galtsoff of the Bureau of Fisheries. Part of the specimens came from Kaneohe Bay, Oahu, and part of them were from the Pearl and Hermes Reef, which lies in the mid-Pacific Ocean approximately in North Latitude 27° 45′ to 28° and in West Longitude 175° 45′ to 176°. Most of the latter material was apparently obtained from a sand or "coral" bottom at depths of 2–67 ft. in water of temperatures ranging from 22.7°C. to 27.3°C. The Pearl and Hermes Reef lies more than 1200 miles northwest of Oahu, and it has been considered desirable to keep the two localities separated in the following list. So far as is known to the writer, no algae have hitherto been reported from the Pearl and Hermes Reef. However, a considerable number of algae, largely of plankton habitat, were collected in 1896 by H. Schauinsland on Laysan, which lies about 300 miles southeast of the Pearl and Hermes Reef. These were recorded in 1905 by E.

[1] Received August 31, 1933.