Water-Supply and Irr[illegible] Paper [illegible] 160

Series O, Underground Waters, 58

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

UNDERGROUND-WATER PAPERS

1906

MYRON L. FULLER

GEOLOGIST IN CHARGE

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Geologist in Charge.

WORK OF THE EASTERN SECTION OF HYDROLOGY IN 1905, AND PUBLICATIONS RELATING TO UNDERGROUND WATERS.

By MYRON L. FULLER.

INTRODUCTION.

The present report is the fourth volume of miscellaneous short contributions, the preceding volumes of which appeared under the title of "Contributions to the Hydrology of Eastern United States." The change in name is made with the view of more clearly indicating the scope of the report.

The present volume contains eleven papers by six authors, mainly connected with the eastern section of the division of hydrology. These papers are predominantly of a theoretical or general character; papers relating to local areas, such as the quadrangle descriptions appearing in the previous reports, are omitted, as it has been shown that there is less demand for such descriptive contributions than for general or theoretical papers, which often have practical engineering and geologic applications. The fact that the report makes available a considerable number of short contributions which could not otherwise be satisfactorily placed before the public is one of the leading reasons for its publication.

As in previous reports, the present volume covers a wide range of subjects, including papers on (1) artesian nomenclature and the representation of ground-water data on maps, (2) occurrence of ground waters in igneous rocks, (3) description of the ground-water resources of special localities, (4) the use of wells in the drainage of wet lands, (5) the amount of ground water in the earth, (6) a method of tracing underground currents, (7) spring waters of peculiar composition, (8) depths reached by boring, (9) flowing wells and springs, (10) problems of water contamination, and (11) improvement of water in wells.

WORK OF THE EASTERN SECTION OF HYDROLOGY.

Personnel.—Of the permanent members of the section, M. L. Fuller has continued in charge of the work in eastern United States, and in addition to executive duties has given special attention to the water supplies of Pleistocene and Coastal Plain deposits. F. G. Clapp has been engaged mainly in the investigation of Pleistocene geology and its relation to underground waters. E. E. Ellis has devoted the greater part of the season to a study of the occurrence of ground waters in igneous rocks, especially those of Connecticut. Isaiah Bowman has been engaged in field work and in the preparation of a report on the methods of well drilling in use in different parts of the country. Samuel Sanford has had charge of the collection of deep-well records and samples. B. L. Johnson has devoted his time to a large extent to the preparation of a bibliography of the underground waters of the United States.

In addition to the permanent force the following have been engaged in work for the section during the year: W. S. Bayley, on underground waters of Maine; G. N. Knapp, in New Jersey; L. W. Stephenson, in North Carolina; S. W. McCallie, in Georgia; E. A. Smith, in Alabama; L. C. Glenn, in Tennessee and Kentucky; A. C. Veatch, A. F. Crider, and L. W. Stephenson, in Arkansas; E. M. Shepard, in Missouri; W. H. Norton and Howard E. Simpson, in Iowa; C. W. Hall, in Minnesota, and Frank Leverett, in Michigan. E. F. Lines and D. F. MacDonald have assisted in office work.

Office work.—The office work for the year has consisted, in addition to executive duties, of the preparation of a bibliography of the underground waters of the United States, and of tables relating to the discharge and other features connected with artesian wells, and of the systematic collection of well records and samples. Both the executive work and the collection of samples involve a very extended correspondence and the furnishing of information in regard to wells and underground-water conditions to a large number of applicants. Separate reports on the bibliography of underground waters, artesian tables, and collection of well samples are in preparation.

Theoretical investigations.—The principal theoretical and technical investigations undertaken in 1905 related to the fluctuations of the water level in wells, by A. C. Veatch, and the methods of well drilling by Isaiah Bowman. The report on the fluctuation of wells is in press, and that on well drilling is nearly completed.

Surveys.—Detailed surveys of underground-water problems have been conducted in Connecticut by H. E. Gregory and E. E. Ellis; in Iowa, by W. H. Norton and Howard E. Simpson; in Arkansas, by M. L. Fuller, A. F. Crider, and L. W. Stephenson; and in North Carolina by L. W. Stephenson and B. L. Johnson. In Connecticut and Arkansas the work is completed and reports are in preparation. In Iowa and North Carolina the surveys are incomplete and will require further work the coming season.

Reports.—The following reports have been published since January 1, 1905:

Bibliographic review and index of papers relating to underground waters published by the United States Geological Survey, 1879-1904, by M. L. Fuller: Water-Sup. and Irr. Paper No. 120, 128 pp.

Contributions to the hydrology of eastern United States, 1904, M. L. Fuller, geologist in charge: Water-Sup. and Irr. Paper No. 110, 211 pp.

Underground waters of eastern United States, M. L. Fuller, geologist in charge: Water-Sup. and Irr. Paper No. 114, 285 pp.

Relation of the law to underground waters, by D. W. Johnson: Water-Sup. and Irr. Paper No. 122, 55 pp.

Field measurements of the rate of movement of underground waters, by C. S. Slichter: Water-Sup. and Irr. Paper No. 140, 122 pp.

Contributions to the hydrology of eastern United States, 1905, M. L. Fuller, geologist in charge: Water-Sup. and Irr. Paper No. 145, 220 pp.

Record of deep-well drilling for 1904, by M. L. Fuller, E. F. Lines, and A. C. Veatch: Bull. No. 264, 106 pp.

Underground water resources of Long Island, New York, by A. C. Veatch: Prof. Paper No. 44, 394 pp.

In addition the following papers have been received from the authors and transmitted for publication:

Fluctuations of the water level in wells, with special reference to Long Island, New York, by A. C. Veatch: Water-Sup. and Irr. Paper No. 155.

Geology and underground waters of Mississippi, by A. F. Crider and L. C. Johnson: Water-Sup. and Irr. Paper No. 159.

Geology and water resources of northern Louisiana and southern Arkansas, by A. C. Veatch: Prof. Paper No. 46.

The following papers are nearly completed:

Flowing wells of the southern portion of the lower Peninsula of Michigan, by Frank Leverett.

Flowing wells of the northern and central portions of the lower Peninsula of Michigan, by Frank Leverett.

Artesian waters of Missouri, by E. M. Shepard.

Underground water resources of Tennessee and Kentucky west of Tennessee River, and of an adjacent area in Illinois, by L. C. Glenn.
Underground water resources of Minnesota, by C. W. Hall.

Preliminary reports on the wells and springs of Virginia and South Carolina were prepared by M. L. Fuller for the State surveys in accordance with plans of cooperation approved by the Director.

PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

The results of the work of the Survey on underground waters and springs are published as reports of various kinds. All but the folios and monographs, which are sold at cost, are for free distribution and can be obtained on application to the Director until the editions are exhausted. A number have been delivered to members of Congress for distribution.

A full subject index of the Survey publications on underground waters is contained in Water-Supply and Irrigation Paper No. 120, entitled "Bibliographic review and index of papers relating to underground waters published by the United States Geological Survey."

A list of papers published by the Survey since Water-Supply Paper No. 120 was prepared, and brief references to the most important publications of the Survey, are given below:

GENERAL DESCRIPTIVE REPORTS.

ALABAMA.

Alabama (water resources), by E. A. Smith: Water-Sup. and Irr. Paper No. 114, 1905, pp. 164-170.
For other reports see Water-Supply Paper No. 102.

ARKANSAS.

Summary of the water supply of the Ozark region in northern Arkansas, by George I. Adams: Water-Sup. and Irr. Paper No. 110, 1905, pp. 179-182.
Northern Arkansas (water resources), by A. H. Purdue: Water-Sup. and Irr. Paper No. 114, 1905, pp. 188-197.
Water resources of the Winslow quadrangle, Arkansas, by A. H. Purdue: Water-Sup. and Irr. Paper No. 145, 1905, pp. 84-87.
Water resources of the contact region between the Paleozoic and Mississippi embayment deposits in northern Arkansas, by A. H. Purdue: Water-Sup. and Irr. Paper No. 145, 1905, pp. 88-119.
For other reports see Water-Supply Paper No. 102.

CALIFORNIA.

Water problems of Santa Barbara, Cal., by J. B. Lippincott: Water-Sup. and Irr. Paper No. 116, 1905.
For other reports see Water-Supply Papers Nos. 59 and 60.

COLORADO.

Geology and underground-water resources of the central Great Plains, by N. H. Darton: Prof. Paper No. 32, 1904.
For other reports see Sixteenth, Seventeenth, and Twenty-first Annual Reports, Bulletin No. 131, and Folios 36, 68, and 71.

CONNECTICUT.

Drilled wells of the Triassic area of the Connecticut Valley, by W. H. C. Pynchon: Water-Sup. and Irr. Paper No. 110, 1905, pp. 65-94.
Triassic rocks of the Connecticut Valley as a source of water supply, by M. L. Fuller: Water-Sup. and Irr. Paper No. 110, 1905, pp. 95-112.
Connecticut (water resources), by H. E. Gregory: Water-Sup. and Irr. Paper No. 114, 1905, pp. 76-81.
For other reports see Water-Supply Paper No. 102.

CUBA.

Notes on the hydrology of Cuba, by M. L. Fuller: Water-Sup. and Irr. Paper No. 110, 1905, pp. 183-200.

DELAWARE.

Delaware (water resources), by N. H. Darton: Water-Sup. and Irr. Paper No. 114, 1905, pp. 111-113.
For other reports see Bulletin No. 138.

DISTRICT OF COLUMBIA.

District of Columbia (water resources), by N. H. Darton and M. L. Fuller: Water-Sup. and Irr. Paper No. 114, 1905, pp. 124-126.
For other reports see Bulletin No. 138 and Folio 70.

FLORIDA.

Florida (water resources), by M. L. Fuller: Water-Sup. and Irr. Paper No. 114, 1905, pp. 159-163.
For other reports see Water-Supply Paper No. 102.

GEORGIA.

Georgia (water resources), by S. W. McCallie: Water-Sup. and Irr. Paper No. 114, 1905, pp. 153-158.
For other reports see Water-Supply Paper No. 102 and Bulletin No. 138.

IDAHO.

See Water-Supply Papers Nos. 54, 55, 78, Bulletin No. 199, and Folio 104.

HAWAII.

See Water-Supply Paper No. 77.

ILLINOIS.

Illinois (water resources), by Frank Leverett: Water-Sup. and Irr. Paper No. 114, 1905, pp. 248-257.
For other reports see Seventeenth Annual Report and Folios 67, 81, and 105.

INDIANA.

Indiana (water resources), by Frank Leverett: Water-Sup. and Irr. Paper No. 114, 1905, pp. 258-264.
For other reports see Water-Supply Papers Nos. 21 and 26, Eighteenth Annual Report, and Folios 67, 81, and 105.

IOWA.

Iowa (water resources), by W. H. Norton: Water-Sup. and Irr. Paper No. 114, 1905, pp. 220-225.
Water supplies at Waterloo, Iowa, by W. H. Norton: Water-Sup. and Irr. Paper No. 145, 1905, pp. 148-155.
For other reports see Sixteenth Annual Report.

KANSAS.

Geology and underground-water resources of the central Great Plains, by N. H. Darton: Prof. Paper No. 32, 1904, pp. 433.
Water resources of the Joplin district, Missouri-Kansas, by W. S. Tangier Smith: Water-Sup. and Irr. Paper No. 145, 1905, pp. 74-83.
For other reports see Water-Supply Paper No. 6, Twenty-second Annual Report, and Bulletin No. 131.

KENTUCKY.

Water resources of the Middlesboro-Harlan region of southeastern Kentucky, by George H. Ashley: Water-Sup. and Irr. Paper No. 110, 1905, pp. 177-178.
Kentucky (water resources), by L. C. Glenn: Water-Sup. and Irr. Paper No. 114, 1905, pp. 205-208.
For other reports see Water-Supply Paper No. 102.

LOUISIANA.

Louisiana (water resources), by A. C. Veatch: Water-Sup. and Irr. Paper No. 114, 1905, pp. 179-187.
For other reports see Water-Supply Paper No. 101.

MAINE.

Maine (water resources), by W. S. Bayley: Water-Sup. and Irr. Paper No. 114, 1905, pp. 41-56.
Water resources of the Portsmouth-York region, New Hampshire and Maine, by George Otis Smith: Water-Sup. and Irr. Paper No. 145, 1905, pp. 120-128.
Water supply from glacial gravels near Augusta, Me., by George Otis Smith: Water-Sup. and Irr. Paper No. 145, 1905, pp. 156-160.
For other reports see Water-Supply Paper No. 101.

MARYLAND.

Water resources of the Accident and Grantsville quadrangles, Maryland, by G. C. Martin: Water-Sup. and Irr. Paper No. 110, 1905, pp. 168-170.
Water resources of the Frostburg and Flintstone quadrangles, Maryland and West Virginia, by G. C. Martin: Water-Sup. and Irr. Paper No. 110, 1905, pp. 171-173.
Maryland (water resources), by N. H. Darton and M. L. Fuller: Water-Sup. and Irr. Paper No. 114, 1905, pp. 114-123.
Water resources of the Pawpaw and Hancock quadrangles, West Virginia, Maryland, and Pennsylvania, by George W. Stose and George C. Martin: Water-Sup. and Irr. Paper No. 145, 1905, pp. 58-63.
For other reports see Bulletin No. 138 and Folios 13, 23, and 70.

MASSACHUSETTS.

Drilled wells of the Triassic area of the Connecticut Valley, by W. H. C. Pynchon: Water-Sup. and Irr. Paper No. 110, 1905, pp. 65-94.

Triassic rocks of the Connecticut Valley as a source of water supply. by M. L. Fuller: Water-Sup. and Irr. Paper No. 110, 1905, pp. 95-112.

Water resources of the Taconic quadrangle, New York, Massachusetts, and Vermont, by F. B. Taylor: Water-Sup. and Irr. Paper No. 110, 1905, pp. 130-133.

Massachusetts and Rhode Island (water resources), by W. O. Crosby: Water-Sup. and Irr. Paper No. 114, 1905, pp. 68-75.

Water supply from the delta type of sand plain, by W. O. Crosby: Water-Sup. and Irr. Paper No. 145, 1905, pp. 161-178.

For other reports see Water-Supply Paper No. 102.

MICHIGAN.

A ground-water problem in southeastern Michigan, by Myron L. Fuller: Water-Sup. and Irr. Paper No. 145, 1905, pp. 129-147.

For other reports see Water-Supply Papers Nos. 30, 31, and 102.

MINNESOTA.

Minnesota (water resources), by C. W. Hall: Water-Sup. and Irr. Paper No. 114, 1905, pp. 226-232.

For other reports see Water-Supply Paper No. 102.

MISSISSIPPI.

Mississippi (water resources), by L. C. Johnson: Water-Sup. and Irr. Paper No. 114, 1905, pp. 171-178.

For other reports see Water-Supply Paper No. 102.

MISSOURI.

Spring system of the Decaturville dome, Camden County, Missouri, by E. M. Shepard: Water-Sup. and Irr. Paper No. 110, 1905, pp. 113-125.

Missouri (water resources), by E. M. Shepard: Water-Sup. and Irr. Paper No. 114, 1905, pp. 209-219.

Water resources of the Joplin district, Missouri-Kansas, by W. S. Tangier Smith: Water-Sup. and Irr. Paper No. 145, 1905, pp. 74-83.

For other reports see Water-Supply Paper No. 102.

NEBRASKA.

Geology and underground-water resources of the central Great Plains, by N. H. Darton: Prof. Paper No. 32, 1904.

For other reports see Water-Supply Paper No. 12, Sixteenth, Nineteenth, and Twenty-second Annual Reports, Bulletin 131, Professional Paper No. 17, and Folios 85 and 108.

NEW HAMPSHIRE.

New Hampshire (water resources), by M. L. Fuller. Water-Sup. and Irr. Paper No. 114, 1905, pp. 57-59.

Water resources of the Portsmouth-York region, New Hampshire and Maine, by George Otis Smith: Water-Sup. and Irr. Paper No. 145, 1905, pp. 120-128.

For other reports see Water-Supply Paper No. 102.

NEW JERSEY.

Water resources of the central and southwestern highlands of New Jersey, by Laurence La Forge: Water-Sup. and Irr. Paper No. 110, 1905, pp. 141-155.

New Jersey (water resources), by G. N. Knapp: Water-Sup. and Irr. Paper No. 114, 1905, pp. 93-103.

For other reports see Water-Supply Paper No. 106 and Bulletin 138.

NEW MEXICO.

Geology and underground-water conditions of the Jornada Del Muerto, New Mexico, by C. R. Keyes: Water-Sup. and Irr. Paper No. 123, 1905.

For other reports see Twenty-second Annual Report.

NEW YORK.

The new artesian water supply at Ithaca, N. Y., by Francis L. Whitney: Water-Sup. and Irr. Paper No. 110, 1905, pp. 55-64.

Water resources of the Fort Ticonderoga quadrangle, Vermont and New York, by T. Nelson Dale: Water-Sup. and Irr. Paper No. 110, 1905, pp. 126-129.

Water resources of the Taconic quadrangle, New York, Massachusetts, and Vermont, by F. B. Taylor: Water-Sup. and Irr. Paper No. 110, 1905, pp. 130-133.

Water resources of the Watkins Glen quadrangle, New York, by Ralph S. Tarr: Water-Sup. and Irr. Paper No. 110, 1905, pp. 134-140.

New York (water resources), by F. B. Weeks: Water-Sup. and Irr. Paper No. 114, 1905, pp. 82-92.

Water resources of the Catatonk area, New York, by E. M. Kindle: Water-Sup. and Irr. Paper No. 145, 1905, pp. 53-57.

Waters of a gravel-filled valley near Tully, N. Y., by George B. Hollister: Water-Sup. and Irr. Paper No. 145, 1905, pp. 179-184.

For other reports see Water-Supply Paper No. 102 and Bulletin No. 138.

NORTH CAROLINA.

Water resources of the Cowee and Pisgah quadrangles, North Carolina, by Hoyt S. Gale: Water-Sup. and Irr. Paper No. 110, 1905, pp. 174–176.
North Carolina (water resources), by M. L. Fuller: Water-Sup. and Irr. Paper No. 114, 1905, pp. 136–139.
For other reports see Bulletin No. 138 and Folio 80.

NORTH DAKOTA.

See Seventeenth Annual Report.

OHIO.

Ohio (water resources), by Frank Leverett: Water-Sup. and Irr. Paper No. 114, 1905, pp. 265–270.
For other reports see Eighteenth and Nineteenth Annual Reports.

OKLAHOMA.

See Twenty-second Annual Report.

OREGON.

See Water-Supply Papers Nos. 7, 8, and 252.

PENNSYLVANIA.

Water resources of the Chambersburg and Mercersburg quadrangles, Pennsylvania, by George W. Stose: Water-Sup. and Irr. Paper No. 110, 1905, pp. 156–158.
Water resources of the Curwensville, Patton, Ebensburg, and Barnesboro quadrangles, Pennsylvania, by F. G. Clapp: Water-Sup. and Irr. Paper No. 110, 1905, pp. 159–163.
Water resources of the Elders Ridge quadrangle, Pennsylvania, by Ralph W. Stone: Water-Sup. and Irr. Paper No. 110, 1905, pp. 164–165.
Water resources of the Waynesburg quadrangle, Pennsylvania, by Ralph W. Stone: Water-Sup. and Irr. Paper No. 110, 1905, pp. 166–167.
Pennsylvania (water resources), by M. L. Fuller: Water-Sup. and Irr. Paper No. 114, 1905, pp. 104–110.
Water resources of the Pawpaw and Hancock quadrangles, West Virginia, Maryland, and Pennsylvania, by George W. Stose and George C. Martin: Water-Sup. and Irr. Paper No. 145, 1905, pp. 58–63.
Waynesburg folio, Pennsylvania, by Ralph W. Stone: Geologic Atlas U. S., folio 121, 1905.
For other reports see Water-Supply Paper No. 106.

RHODE ISLAND.

Massachusetts and Rhode Island (water resources), by W. O. Crosby: Water-Sup. and Irr. Paper No. 114, 1905, pp. 68–75.
For other reports see Water-Supply Paper No. 102.

SOUTH CAROLINA.

South Carolina (water resources), by L. C. Glenn: Water-Sup. and Irr. Paper No. 114, 1905, pp. 140–152.
For other reports see Bulletin No. 138.

SOUTH DAKOTA.

Geology and underground-water resources of the central Great Plains, by N. H. Darton: Prof. Paper No. 32, 1904.
Huron folio, South Dakota, by J. E. Todd: Geologic Atlas U. S., folio 113, 1904.
De Smet folio, South Dakota, by J. E. Todd and C. M. Hall: Geologic Atlas U. S., folio 114, 1904.
For other reports see Water-Supply Papers Nos. 34 and 90, Seventeenth, Eighteenth, and Twenty-first Annual Reports, and Folios 85, 96, 97, 99, 100, 107, and 108.

TENNESSEE.

Tennessee and Kentucky (water resources), by L. C. Glenn: Water-Sup. and Irr. Paper No. 114, 1905, pp. 198–208.
For other reports see Water-Supply Paper No. 102.

TEXAS.

See Eighteenth, Twenty-first, and Twenty-second Annual Reports and Folio 42.

VERMONT.

Water resources of the Fort Ticonderoga quadrangle, Vermont and New York, by T. Nelson Dale: Water-Sup. and Irr. Paper No 110, 1905, pp. 126–129.
Water resources of the Taconic quadrangle, New York, Massachusetts, and Vermont, by F. B. Taylor: Water-Sup. and Irr. Paper No. 110, 1905, pp. 130–133.
Vermont (water resources), by G. H. Perkins. Water-Sup. and Irr. Paper No. 114, 1905, pp. 60–67.
For other reports see Water-Supply Paper No. 102.

VIRGINIA.

Virginia (water resources), by N. H. Darton and M. L. Fuller: Water-Sup. and Irr. Paper No. 114, 1905, pp. 127–135.
For other reports see Bulletin No. 138 and Folios 13, 23, 70, and 80.

WASHINGTON.

See Water-Supply Papers Nos. 4 and 55, and Folio 86.

WEST VIRGINIA.

Water resources of the Frostburg and Flintstone quadrangles, Maryland and West Virginia, by G. C. Martin: Water-Sup. and Irr. Paper No. 110, 1905, pp. 171-173.

West Virginia (water resources), by M. L. Fuller: Water-Sup. and Irr. Paper No. 114, 1905, pp. 271-272.

Water resources of the Pawpaw and Hancock quadrangles, West Virginia, Maryland, and Pennsylvania, by George W. Stose and George C. Martin: Water-Sup. and Irr. Paper No. 145, 1905, pp. 58-63.

Water resources of the Nicholas quadrangle, West Virginia, by George H. Ashley: Water-Sup. and Irr. Paper No. 145, 1905, pp. 64-66.

WISCONSIN.

Wisconsin district (water resources), by A. R. Shultz: Water-Sup. and Irr. Paper No. 114, 1905, pp. 233-241.

Water resources of the Mineral Point quadrangle, Wisconsin, by U. S. Grant: Water-Sup. and Irr. Paper No. 145, 1905, pp. 67-73.

WYOMING.

Geology and underground-water resources of the central Great Plains, by N. H. Darton: Prof. Paper No. 32, 1904.

For other reports see Twenty-first Annual Report and Folio 107.

SPRINGS AND SPRING DEPOSITS.

Contributions to hydrology of eastern United States, 1904, M. L. Fuller, geologist in charge: Water-Sup. and Irr. Paper No. 110, 1905.

Spring system of the Decaturville dome, Camden County, Missouri, by E. M. Shepard: Water-Sup. and Irr. Paper No. 110, 1905, pp. 113-125.

Notes on the hydrology of Cuba, by M. L. Fuller: Water-Sup. and Irr. Paper, No. 110, 1905, pp. 183-200.

Waters of a gravel-filled valley near Tully, New York, by George B. Hollister: Water-Sup. and Irr. Paper No. 145, 1905, pp. 179-184.

Notes on certain hot springs of the southern United States, by Walter Harvey Weed: Water-Sup. and Irr. Paper No. 145, 1905, pp. 185-206.

Notes on certain large springs of the Ozark region, Missouri and Arkansas, compiled by Myron L. Fuller: Water-Sup. and Irr. Paper No. 145, 1905, pp. 207-210.

For other reports see Ninth Annual Report, Bulletins Nos. 32 and 47, and Folio 30.

MINERAL AND POTABLE WATERS.

See Fourteenth Annual Report, Bulletins Nos. 32 and 47, and the various reports on Mineral Resources from 1883 to 1904.

ARTESIAN REQUISITES, MOVEMENTS OF GROUND WATERS, ETC.

Description of underflow meter used in measuring the velocity and direction of underground water, by Charles S. Slichter: Water-Sup. and Irr. Paper No. 110, 1905, pp. 17-31.

Underflow tests in the drainage basin of Los Angeles River, by Homer Hamlin. Water-Sup. and Irr. Paper No. 112, 1905.

Underground waters of eastern United States, M. L. Fuller, geologist in charge. Water-Sup. and Irr. Paper No. 114, 1905.

Two unusual types of artesian flow, by Myron L. Fuller. Water-Sup. and Irr. Paper No. 145, 1905, pp. 40-45.

Water resources of the Portsmouth-York region, New Hampshire and Maine, by George Otis Smith: Water-Sup. and Irr. Paper No. 145, 1905, pp. 120-128.

Field measurements of the rate of movement of underground waters, by Charles S. Slichter: Water-Sup. and Irr. Paper No. 140, 1905.

Observations of the ground waters of the Rio Grande Valley, by Charles S. Slichter: Water-Sup. and Irr. Paper No. 141, 1905.

For other reports see Water-Supply Paper No. 67 and Fifth and Nineteenth Annual Reports.

LAWS RELATING TO UNDERGROUND WATERS.

Relation of the law to underground waters, by D. W. Johnson. Water-Sup. and Irr. Paper No. 122, 1905.

WELL-DRILLING METHODS.

The California or "stovepipe" method of well construction, by Charles S. Slichter: Water-Sup. and Irr. Paper No. 110, 1905, pp. 32-36.

For other reports see Water-Supply Paper No. 101 and Bulletin No. 212.

MEASUREMENTS OF FLOW AND HEAD.

Approximate methods of measuring the yield of flowing wells, by Charles S. Slichter: Water-Sup. and Irr. Paper No. 110, 1905, pp. 37–42.

Field measurements of the rate of movement of underground waters, by Charles S. Slichter: Water-Sup. and Irr. Paper No. 140, 1905.

A convenient gage for determining low artesian heads, by Myron L. Fuller: Water-Sup. and Irr. Paper No. 145, 1905, pp. 51–52.

LISTS OF WELLS AND BORINGS.

Record of deep-well drilling for 1904, by M. L. Fuller, E. F. Lines, and A. C. Veatch: Bull. No. 264, 1905.

Contributions to the hydrology of eastern United States, 1903, by M. L. Fuller: Water-Sup. and Irr. Paper No. 102, 1905.

Preliminary list of deep borings in the United States, second edition, with additions, by N. H. Darton: Water-Sup. and Irr. Paper No. 149, 1905.

DRAINAGE OF WET LANDS BY WELLS.

Drainage of ponds into drilled wells, by Robert E. Horton: Water-Sup. and Irr. Paper No. 145, 1905, pp. 30–39.

SIGNIFICANCE OF THE TERM "ARTESIAN."

By Myron L. Fuller.

INTRODUCTION.

The term artesian, derived from the town of Artois in France, where the first flowing wells of importance were secured, was originally applied only to those wells in which the water rose above the surface, but in late years has been used in a number of other senses. At the present time, in fact, one can not be assured of its meaning in a particular paper unless its use is specifically stated. In many cases, fortunately, it is so defined, but the variability of the usage in different cases is sufficient to emphasize the need of a standard definition which shall be adhered to in public discussions.

It is doubtful if any definition can be devised which will meet the approval of or be accepted by all geologists, as opinions will naturally vary greatly according to the locality and nature of the work on which the geologists are engaged. But while there is considerable diversity of practice there is nevertheless a general tendency to give the term one or the other of two meanings, and a considerable number of geologists have expressed their willingness to accept any definition agreed on by the majority of active workers on underground-water problems.

The need of uniform practice has probably been felt most severely in the United States Geological Survey, where a considerable number of men devote their entire time to underground-water investigations and to related geologic problems, and it has become desirable either to drop the use of the term entirely or to adopt some definition which will meet the needs of geologists and be in harmony with the best usage in this country. For the purpose of obtaining the views of the different authorities, circular letters were mailed to those who have at one time or another been engaged in underground-water investigations or who are at the head of organizations such as State surveys, etc. Replies were received from about fifty geologists, and although they showed a considerable range of opinion, they were of much assistance in the consideration of a definition of the term.

USE OF TERM "ARTESIAN."

ORIGINAL USE.

The question of the early use of the term has been admirably summarized by W. H. Norton.[a] The word is derived from Artesium, the Latin equivalent of Artois, the name of an ancient province of France now included in the department of Pas de Calais, where the first flowing wells to be extensively known were obtained. The term in its etymology carries no definition, but it is unquestionable that it was the overflow of the Artois wells which attracted attention to them. The water in all wells, except those sunk to the shallow unconfined ground waters, rises when encountered and in many instances stands within a few feet or even a few inches of the top. Such wells, however, never, even in the earliest times, excited any comments, while flowing waters have almost invariably been regarded by the people at large as of some mysterious and unknown but none the less wonderful origin.

[a] Artesian wells of Iowa: Iowa Geol. Survey, vol. 6, 1897, pp. 122-128.

In the early days the term bored wells (puits forés) was practically equivalent to flowing wells, since these alone at that time were bored or drilled. Later the terms bored wells, deep wells, artesian wells, artesian fountains, and even bubbling wells have all been applied to the same type. As wide a range of terms is found in French scientific literature, viz, puits forés, puits artésiens, fontaines artésiennes, fontaines artificielles, fontaines jaillissantes des puits forés, etc. The term artesian obtained a definite place in literature as early as 1805, and was applied to those wells which flowed.

USE IN RECENT SCIENTIFIC LITERATURE.

As the geologic conditions governing artesian waters became known the term artesian was gradually extended by some writers to include any well in which the water rose under hydrostatic pressure when encountered, but others, especially teachers and authors of text-books, have continued to use the term in its original sense, while a few have used it to apply to deep wells in general. In addition there is a fourth popular use of the word for any tubular well regardless of depth or other factors.

The varying meanings given to the term in this country are shown by the results of an examination of underground-water papers by 25 American authors. By "artesian" 6, or 24 per cent, of these authors mean flowing wells; 15, or 60 per cent, wells in which water is under pressure but does not necessarily flow; and 4, or 16 per cent, deep wells in general. It should be borne in mind, however, that this is not altogether an expression of present practice. The use of the term artesian has, in fact, undergone a considerable change in the last few years, and a number of writers use it in a different sense at the present time from that adopted by them in their earlier writings. T. C. Chamberlin, for instance, at the time of the publication of his report on the requisite and qualifying conditions of artesian wells,[a] in 1885, defines an artesian well as a flowing well, but in the recent text-book of Chamberlin and Salisbury the statement is made that the term is now applied to any deep bored or drilled well.

EUROPEAN USE.

As to the European use of the term artesian the following quotation may be given from the letter from C. S. Slichter, who is probably more familiar with foreign literature on artesian waters than any other from whom replies to the circular have been received. "I have found very little difference of opinion among European writers in the use of the term. Any area in which the ground water exists under an appreciable pressure is called an 'artesian' area, and wells drilled in such a water-bearing medium are called 'artesian' wells. If they flow, they are called 'flowing' wells; if not, they are called 'nonflowing' wells."

PRESENT USE.

Preferences of scientists.—The preferences as to the use of the term artesian by the geologists from whom returns were received are summarized in the accompanying table (p. 11). The figures do not in all cases express the original preferences of the geologists, several having modified their opinions since the question has been under discussion. This is especially true in regard to the administrative heads and geohydrologists who, after a full discussion of the question, were nearly unanimous in favoring the use of the term for all waters under hydrostatic pressure and for all wells in which the water rises. The table therefore represents the present views of the geohydrologists of the Geological Survey and the Survey geologists interested in underground-water investigations, and the views as expressed in replies to the circular letter of inquiry sent to geologists outside of Washington. From expressions in these replies it is believed that a considerable number of others would now accept the use of the term for all hydrostatic wells. This is especially true of those who were inclined to drop the term, there being relatively little difference in the opinions of the two classes.

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[a] Fifth Ann. Rept. U. S. Geol. Survey, 1885, pp. 125-173.

Classified opinions relating to use of word "artesian" as applied to wells.

From—	Drop term artesian.	Flowing wells.	All wells in which water rises.	Any deep wells.
Administrative heads who are also engaged in field work on underground waters	0	1	4	0
Geohydrologists devoting entire time to underground-water problems	0	1	6	0
Geologists, other than teachers, who have had experience in underground-water investigations	5	3	9	1
Teachers with extensive field experience in underground-water investigations	1	5	4	1
Teachers with limited field experience in underground-water investigations	2	2	2	0

PER CENT FAVORING THE VARIOUS PROPOSED USAGES.

		Drop term artesian.	Flowing wells.	All wells in which water rises.	Any deep wells.
Mainly field experience	Administrative heads	0	20	80	0
	Geohydrologists	0	14	86	0
	Geologists with extended field experience	28	17	49	6
Field and teaching experience	Teachers with extensive field experience	9	46	36	9
Mainly teaching or theoretical experience	Teachers with limited field experience	33	33	33	0

In the above classification the figures do not possess the full significance they would have if a larger number of individuals were represented, but as the views of practically all those who have been engaged to any extent in underground-water problems are represented the figures may be accepted as illustrating the general trend of opinion.

It will be seen that in general the proportion of those favoring the restriction of the term artesian to flowing wells varies inversely with the amount of their actual field experience, although there are some variations inside of the main divisions of the classification due to differences in the standpoint from which the question is viewed.

The administrative heads, including State geologists and the geologists in charge of the eastern and western sections of hydrology of the United States Geological Survey, who meet the problem both in the field and in the office, or, in other words, who are familiar with both the field problems and the problems of logical treatment in reports, favor in the proportion of 4 to 1 the more extended use of the word.

Of the geohydrologists, or those devoting their entire time to the study of underground waters, only 1 out of 7 favors returning to the original definition of the term, while of geologists not devoting their entire time to underground-water work, but who have had extended experience with water problems, only 3 out of 18 favor returning to the original definition.

In the class of teachers the effect of their characteristic methods of thought is at once apparent, the percentage of those favoring the original use of the term artesian jumping to 46 per cent among those with extensive field experience and to 33 per cent among those with limited field experience in underground-water investigations.

Popular use.—The popular use of the term artesian is even more variable than the use by scientists. As pointed out in the letter of T. C. Chamberlin, there were not many flowing wells in the eastern portion of the country twenty-five years ago, and there was at that time no dominant practice, but "with the multiplication of wells and the growth of speech and common literature relative to them usage has drifted strongly toward the application of the term artesian to deep wells quite irrespective of the rise or flow of water, and it seems useless to try to stem the tide of this growing practice. It is easy to see how this arises and how inevitable it is. An individual or a community in considering the question of sinking a deep well in hope of a flow naturally uses the term artesian in reference to the proposed well. The drillers do the same, and the name thus becomes fixed before the result is determined. Many wells are now designated artesian solely for the hygienic implications of the term."

The uses mentioned by Professor Chamberlin are widely prevalent throughout the eastern United States and often in those areas in the West in which flowing wells are absent. In general the term artesian is used for flows in those areas where flowing wells are common, but elsewhere the other usage predominates. The use of the term in various parts of the country, as brought to light by the work of the division of hydrology, may be summarized as follows:

Summary of popular use of term "artesian."

Locality.	Use of term.	Authority.
New England	Any deep well entering rock beneath the drift	M. L. Fuller.
Atlantic and Gulf Coastal Plain.	Any deep wells and those shallow wells which flow. Occasionally also for a shallow tubular well.	Do.
Piedmont Plateau	Any deep well	Do.
Paleozoic areas	Variable, but generally for any deep drilled well obtaining water (not oil or gas).	Do.
Great Lakes region	Any deep rock well drilled for water. Term not always applied to drift wells even when flowing.	Do.
Great Plains	Generally flowing wells	N. H. Darton.
Great Basin	Generally flowing wells, always in flowing-well districts.	G. B. Richardson.
Pacific coast	Generally for flowing wells	W. C. Mendenhall.

Summary of present use.—From the preceding discussion it is clear that no definite meaning can be assigned to the word artesian in a publication unless a definition is given in the same paper, a fact which is emphasized by the various ways in which the term is used, even the same writer sometimes employing it differently in different publications.

The predominant scientific usage, as brought out by the table on page 11, is for all wells in which the water rises; in other words, for those exhibiting the hydrostatic or artesian principle. In popular practice it is applied, in addition to the uses previously mentioned, to deep wells in general, especially those in rock, and to a certain extent to any drilled wells yielding water of good sanitary quality.

ARGUMENTS FOR VARIOUS USES.

DEFICIENCY OF TERMS.

In artesian-water reports several types of wells and waters occurring under a variety of conditions must, in many cases, be constantly referred to. Of these, the most common are: (1) Unconfined waters, (2) confined waters, (3) hydrostatic principle, (4) hydrostatic basin, (5) nonhydrostatic wells, (6) nonflowing hydrostatic wells, and (7) flowing wells.

The term ground water is commonly used for the unconfined portion of the underground-water body, the top of which is represented by the water table, while the term flowing wells can be satisfactorily applied to those wells in which the water rises above the surface. On the other hand, the term nonflowing is not sufficient to express the character of a well in which the water rises but does not flow, as it does not distinguish between such wells and wells drawing from the water table.

The original use of the term artesian, as has been seen, was for flowing wells, but if restricted to such wells it can not be logically applied to basins in which the water is under pressure, but which do not yield flowing wells, nor can it be used to distinguish confined waters from the ordinary unconfined ground waters, the top of which is represented by the water table, or for the general result of the action of the hydrostatic principle.

SUMMARY OF ARGUMENTS.

Most of the arguments urged for the different uses of the term have been outlined or suggested in the preceding pages, but a brief statement summarizing them may not be out of place.

Use of term for flowing wells.—The arguments brought forward by those favoring the use of the term for flowing wells are—

(1) The term artesian was first used for flowing wells, and hence such use has priority over all others.

(2) The advocates of this usage believe that it is the predominating scientific use.

(3) They believe it likewise predominates in popular usage.

(4) The term is capable of precise definition and is based on conditions apparent to the layman as well as to the scientist.

(5) It is argued that the term is applicable and necessary for the practical discrimination of flowing and nonflowing waters, a distinction regarded as of great economic importance.

Use for well waters under pressure.—The advocates of the use of the term artesian for wells in which the water is under hydrostatic pressure present the following arguments:

(1) The definition given to the term should agree with the most common usage.

(2) The common European use of the term is for wells in which the water is under pressure, but which do not necessarily flow.

(3) The proposed usage is followed by the majority of field investigators in America.

(4) It is impossible at the present time to return to the original meaning.

(5) The term artesian, if used at all, should be applied to the hydrostatic principle and not to flows which are an accidental result.

(6) The term flowing describes the well exactly and in terms which can not be mistaken, making it unnecessary to restrict the term artesian to such wells.

Use for deep wells.—Those favoring the application of artesian to deep wells in general advance the following considerations:

(1) Depth and not flow was the significant feature of the original wells at Artois.

(2) Such definition of the term is according to popular usage.

DISCUSSION OF ARGUMENTS.

Original use of term.—All geologists, with one possible exception, are agreed that the original significance of the wells at Artois was their flow and not their depth, the fact that they were sunk in rock, nor the fact that they were drilled instead of dug. It can therefore probably be accepted as a fact that the term was originally applied to flowing wells (see pp. 9–10).

Predominant usage.—It has been shown (pp. 10–11) that although scientific practice varies considerably, the majority of geologists, including the European ones, use the term in the modified sense as applying to the hydrostatic principle and basin, and to wells in which the water rises. The popular usage is so variable that it would seem as if little would be gained by conforming to it, even if some one use largely predominated, which, however, is not the case.

Precise definition.—The term artesian, whether applied to all wells in which the water rises or only to flowing wells, is equally capable of precise definition, since a rise of the water is as positive a fact as is the flow, hence no argument can be based upon such preciseness of definition.

Necessity of term artesian for flowing wells.—That some term is necessary for designating flowing wells will be admitted by all, but that this must necessarily be the word "artesian" is very doubtful. Any word which will express the meaning will answer and the term flowing has an advantage over artesian in that it is self-explanatory.

Impossibility of returning to original meaning.—That it is probably impossible to return to the original meaning of the word artesian, except perhaps by scientists, will be recognized by everyone. It will, however, doubtless be equally impossible to secure the uniform adoption of any other definition, so this argument can not be advanced in favor of any of the proposed uses.

Basis of nomenclature.—A definition of the term artesian, if it is to be redefined, should, it is believed, be based on a fundamental principle rather than on accident. The rise of the water in wells is the result of the action of the hydrostatic principle, which results from well-defined properties of liquids and definite physical laws, the rise taking place in all wells regardless of kind, size, depth, material, or location, provided only that confined waters are encountered. Flows, on the other hand, depend on the location. One well may flow and another on land a few inches higher may not flow. Again, a well may not rise to the level of the surface, but may yield flows when piped laterally to a slightly lower level.

TERMS TO BE SELECTED.

NATURE.

To secure the best results it is believed that certain principles should be assumed as a guide in the selection of terms. These are briefly outlined as follows:

(1) The question of depth should not enter into the probable nomenclature.

(2) Definitions should, if possible, be based on principle and not on accident.

(3) The terms should be scientific and should be capable of accurate definition.

(4) Provision should be made for terms for the hydrostatic basin and principle.

(5) The terms should meet the needs of the greatest possible number of workers

PROPOSED DEFINITIONS.

Along the line sketched in the preceding pages, the replies received from other geologists being considered, the terms to be used were thoroughly discussed by the members of the division of hydrology at the Survey, as a result of which the following definitions were agreed on with practical unanimity as the most expedient at the present time:

Artesian principle.—The artesian principle, which may be considered as identical with what is often known as the hydrostatic principle, is defined as the principle in virtue of which water confined in the materials of the earth's crust tends to rise to the level of the water surface at the highest point from which pressure is transmitted. Gas as an agent in causing the water to rise is expressly excluded from the definition.

Artesian pressure.—Artesian pressure is defined as the pressure exhibited by water confined in the earth's crust at a level lower than its static head.

Artesian water.—Artesian water is defined as that portion of the underground water which is under artesian pressure and will rise if encountered by a well or other passage affording an outlet.

Artesian system.—An artesian system is any combination of geologic structures, such as basins, planes, joints, faults, etc., in which waters are confined under artesian pressure.

Artesian basin.—An artesian basin is defined as a basin of porous bedded rock in which, as a result of the synclinal structure, the water is confined under artesian pressure.

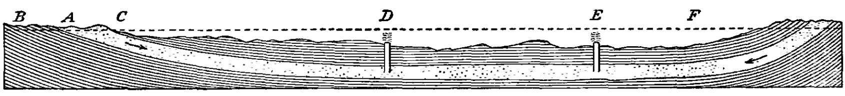


FIG. 1.—Conditions in an artesian basin.

Artesian slope.—An artesian slope is defined as a monoclinal slope of bedded rocks in which water is confined beneath relatively impervious covers owing to the obstruction to its downward passage by the pinching out of the porous beds, by their change from a pervious to an impervious character, by internal friction, or by dikes or other obstructions.

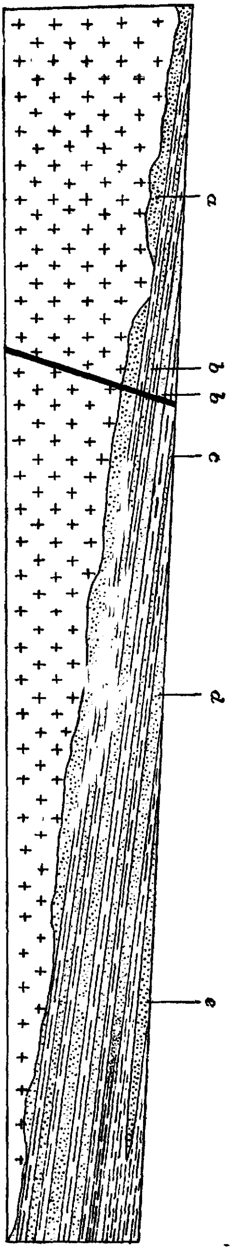


FIG. 2.—Possible conditions in an artesian basin slope. *a*, Water bed cut off by unconformity; *b*, beds cut off by dike; *c*, bed in which friction is the only obstruction to downward motion; *d*, porous bed changing to impervious; *e*, bed pinching out.

Artesian area.—An artesian area is an area underlain by water under artesian pressure.

Artesian well.—An artesian well is any well in which the water rises under artesian pressure when encountered.

REPRESENTATION OF WELLS AND SPRINGS ON MAPS.

By Myron L. Fuller.

INTRODUCTION.

In general there has been no attempt at uniformity of practice in the delineation on maps of underground-water features or of wells or springs, but the increase in the number of men engaged in underground-water investigations both on local and national surveys and the increasing number of reports issued has been so rapid within the past two or three years that it now appears desirable that a concerted movement be made to develop a uniform system of symbols for use on maps. As by far the greater portion of the underground-water literature, other than that in engineering magazines, is published by the United States Geological Survey, it is thought that the adoption of some such system by its members will go far toward securing uniformity in the country as a whole.

GENERAL CONSIDERATIONS.

It is believed that the various types of wells and springs can be best shown by symbols of different colors, but unfortunately colored maps can not always be had, and it becomes necessary to represent a considerable number of features in black and white. Symbols which can be readily and quickly made are also a great convenience in note keeping in the field and result in much saving of time.

The number of symbols devised should be sufficient for the representation of all features which it is desirable to show. If wholly arbitrary devices are used, confusion will result whenever a considerable number are used simultaneously, but this difficulty will be largely avoided if the system adopted is based on a few suggestive forms grouped according to easily remembered principles. Unnecessary duplication should of course be avoided, although even a multiplicity of symbols leads to less confusion than the attempt to use a single device to represent several different things.

The older generalized maps, such as the early topographic sheets of this country, have given place to maps in which the features are shown in great detail, yet not only are the maps not crowded and confusing, but their usefulness has been increased many fold. It is believed that the use of any necessary number of symbols will likewise add to the usefulness of underground-water maps. The system should in fact be as nearly complete as is practicable, for although the use of many symbols on a single map might be objectionable, in reality only a few would, in most cases, be used at one time.

The principles to be considered in devising a system of well and spring symbols for underground-water maps are (1) simplicity, (2) clearness, (3) ease of making, and (4) suggestiveness. Failure to answer these various requirements ruled out many of the arbitrary systems used in the past, although several of the old symbols have been utilized in the new system proposed.

SYMBOLS.

It is believed that a system of symbols can be most logically developed if a single arbitrary device is taken as a base. In common practice a circle is most often used for a well, while more or less closely allied devices are used for springs. Inasmuch as both wells and springs are ordinarily approximately circular, this device, which seems to have both the required simplicity and suggestiveness, is proposed.

WELL SYMBOLS.

Base symbol.—The cross section of all but a few shallow open wells being circular, the unmodified circle is proposed as a base symbol to indicate all wells.

Successful and unsuccessful wells.—The most significant feature of a well from the economic and practical standpoints is its success or failure, and provision for its representation has to be made at the very start. It is thought that a successful well—a "full" well in many instances—can be best shown by a filled circle, or rather a circular dot, while an empty or unsuccessful well can be best shown by a simple circle.

Nonmineral and mineral wells.—Next to obtaining water its quality is most important and it becomes necessary to devise a symbol for indicating the mineral property. If an ordinary nonmineral well is represented by a circle, a mineral well, or one in which the water includes mineral matter in solution, may well be represented by a circle inclosing a dot.

Hydrostatic pressure in wells.—Next to quantity and quality the problem of whether or not the waters will rise is of the greatest importance, and a further symbol for distinguishing the wells simply sunk to the water table and in which the water does not rise from those sunk to confined or artesian waters becomes necessary. It is thought that a vertical line can be best used to designate the vertical rise of the water. Such a line, to be superimposed on any of the other well symbols, is therefore recommended.

Flowing wells.—The wells in which the waters rise are still further subdivided into those which fail to reach the surface and those which flow. For the latter the plus sign has often been used and is proposed in the present instance. It is to be superimposed on other well symbols as in the case of the vertical line.

Wells from different horizons.—In many areas all of the successful wells do not draw from the same horizon, in some instances as many as four or five different water-bearing beds being utilized. As no limit can be put to the number of horizons which it may be necessary to indicate, and as the horizons do not necessarily have any relation to the character of the well it has not seemed desirable to devise symbols for their representation. Instead it is recommended that the horizon of the supply be indicated by letters placed to the left of the well symbol, the space to the right being left for the insertion of figures giving the depth, height of water, elevation, etc.

SPRING SYMBOLS.

Base symbol.—As a base symbol for springs a circle with a short irregular line, indicative of a stream, leading away from the circumference, is considered as most in harmony with common usage, especially in topographic maps. All springs yield water, so there is no demand for distinguishing springs as in the case of successful and unsuccessful wells.

Mineral and nonmineral springs.—The presence of mineral matter in the water may be indicated by a dot placed in the center of the circle as in the case of the wells.

Superficial and artesian springs.—In some springs the water is unconfined, the flows taking place where the surface of the water table is cut by a depression. The movement of the water in such instances is almost entirely downward, and the springs are frequently spoken of as superficial or gravity springs, since the water has not been to any distance below the water table and emerges under the direct action of gravity. The water of such springs will not rise if confined. In artesian springs, on the other hand, the water comes from below and rises under the influence of hydrostatic pressure, and when confined will sometimes rise to considerable heights above the spring mouth. In such instances it is recommended that, as in the case of the wells, the hydrostatic principle be represented by a vertical line superimposed on the base symbol, but not extending beyond the circumference of the circle. Flows do not need to be represented, since all springs possess this property.

Thermal property.—Springs may be further divided into cold or warm, but only one symbol, that for the thermal property, is required. For this a horizontal bar is proposed as the simplest device which can be superimposed on all others. It is intended that this bar shall not extend beyond the circumference of the circle so that there may be no confusion with the device indicating flowing wells.

SUMMARY.

Base or primary symbols.—As primary symbols the following devices are proposed:

○ = well.

♀ = spring.

Secondary symbols.—The secondary symbols to be superimposed on the primary symbols are six in number:

● = water (for wells only).

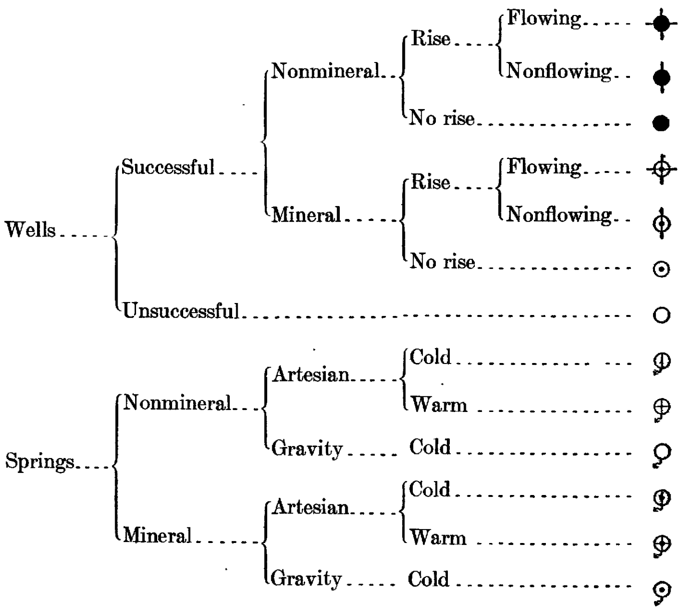
• = mineral property.

| = waters which rise.

┼ = waters which flow (for wells only).

– = thermal waters (for springs only).

Application.—The use of the various devices is illustrated below. The arrangement is not intended as a classification of wells and springs, but is simply for convenience in showing the use of the symbols.



OCCURRENCE OF WATER IN CRYSTALLINE ROCKS.

By E. E. Ellis.

INTRODUCTION.

While the laws governing the occurrence of ground water in unconsolidated materials and in porous sedimentary formations are now generally understood, little has been written concerning the sources of supply for wells in the so-called crystalline rocks. For this reason, when an opportunity was presented in connection with an investigation of the underground waters of Connecticut, special attention was given to the occurrence of water in such rocks.

The term "crystalline" is applied to rocks whose component grains have crystallized into their present relative positions; contrasted with them are the sedimentary types, which are laid down under water and which generally consist of fragments of older rocks mechanically arranged. Under the head of crystalline rocks two main types may be distinguished—igneous rocks, such as granite, diabase, gabbro, granodiorite, etc., which were once in a molten condition, and crystallized and consolidated on cooling; and metamorphic rocks, such as schists and gneisses, which were originally either sedimentary or igneous, but have been altered by metamorphic processes to their present form. The Connecticut limestones, or marbles, are classed with the crystalline rocks.

It is the purpose of the present paper to call attention to some of the features of special economic interest, with the hope that they may be of value to those seeking for information as to the probabilities of success in drilling in similar regions elsewhere in New England or along the Piedmont Plateau to the south. All discussion of the literature of the subject and, so far as practicable, all local references are omitted, being reserved for the special detailed report on the occurrence of water in the crystalline rocks of Connecticut.

ROCK TYPES.

CRYSTALLINE ROCKS.

The principal types of crystalline rocks dealt with are granite, gneiss, and schist, although some diabase and limestone areas were studied. The granites, although of many varieties, are mainly of the ordinary somewhat coarsely crystalline types, consisting mainly of quartz, feldspar, and mica. The gneiss is more variable, but may be distinguished by the driller from the granite by its banded appearance. The granodiorite resembles ordinary granite, but is darker, frequently being known as black granite.

In the schists the banding is more highly developed, mica is present in large amounts, and there is a decided tendency to cleave into more or less flat fragments. Some of the schists, in which little mica is present, much resemble slate. Pegmatite, usually called "feldspar" by the quarrymen and drillers, occurs as dikes or more irregular masses cutting the older rocks, and is usually recognized by its large crystals and white or light color. Diabase, or trap rock, may be distinguished by the driller from its crystalline character

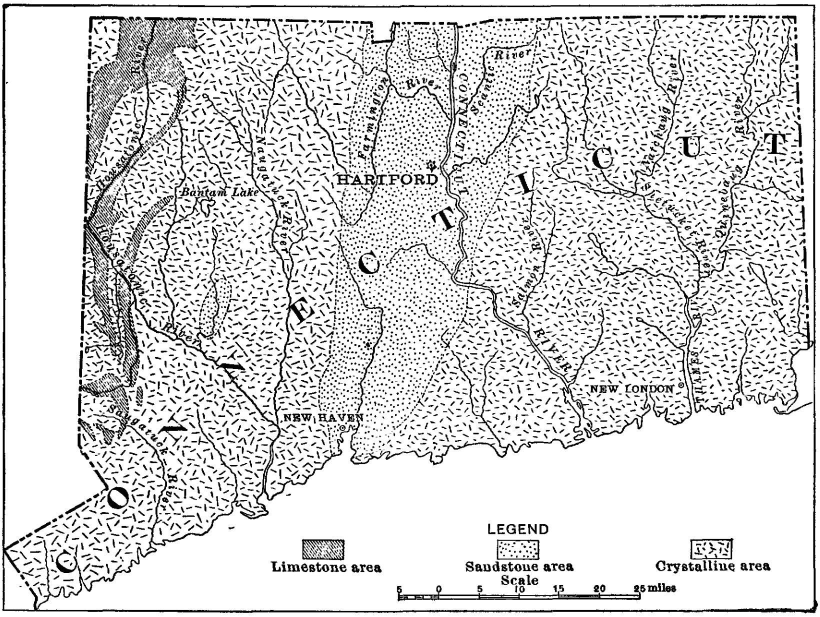


FIG. 3.—Geologic sketch map of Connecticut. The present paper deals with the crystalline and limestone areas.

and dark greenish-black color. The distribution of the crystalline rocks and limestones are shown in fig. 3.

DRIFT.

In the region under investigation the rocks are in large measure covered with deposits left by the ice sheet which once occupied the region, part consisting of a heterogeneous mixture of bowlders, sand, and clay known as hardpan or till, and part of stratified sand, gravel, and clay. The till is seen largely on the hills, averaging about 15 feet in thickness, while the stratified drift occurs mainly in the valleys, where it has an average thickness of about 36 feet. In general, therefore, the hills have a configuration corresponding rather closely to the underlying rock surface, the minor irregularities of which are masked by the overlying drift. On the other hand, the valley bottoms are flat and would show a decidedly different topography if the sand and gravel deposits were removed.

DRILLING PRODUCTS.

The marked characteristics of these rocks give equally characteristic products in drilling. In many cases fragments will be yielded by the drill which are large enough to show the general texture; in others the drillings will all be in the form of finely broken fragments. In general the granite drillings yield an even-grained product, with a large proportion of the white or pink minerals, quartz and feldspar, and maintain the same character and color of material for a number of feet. Gneiss gives a somewhat similar product, but will usually have a larger proportion of biotite, or black mica, and the character of the drillings will change rapidly, usually every few inches. Schist is generally softer and more readily drilled than either of the preceding types and the drillings contain a conspicuous amount of mica, which occurs in larger particles than the other minerals.

The drillings maintain a fairly uniform appearance, as in granite. Phyllite is usually a hard rock to drill, owing to its fineness of grain and the frequent nearly vertical position of its cleavage. Trap rock is considered the most difficult rock to drill, because of its hardness, and is readily distinguished. Limestone drillings are ordinarily white, and may be tested by adding acid or strong vinegar, which will produce an effervescence, owing to the escape of carbon-dioxide gas.

WATER IN CRYSTALLINE ROCKS.

OCCURRENCE IN PORES.

The occurrence of water in crystalline rocks is very different from that in sedimentary rocks, largely owing to the great difference in porosity. The sedimentary deposits, which are made up of fragments of older materials generally cemented into new rock, are commonly very porous and often absorb several per cent of their volume in water. (See table by M. L. Fuller, p. 61) Porosities of sandstone average about 15 per cent, shales about 4 per cent, and limestone 5 per cent. In granites and other crystalline rocks, however, the absorption is usually less than half of 1 per cent of the volume. The limestones here discussed have about the same porosity. In such rocks the water moves through the pores so slowly that it can never escape fast enough to be of value in wells. Fortunately there are in the crystalline rocks many large passages, some of which are described below.

OCCURRENCE IN JOINTS.

Joints are the more or less extensive and generally smooth and straight planes cutting the rock in various directions, and are the result of fracturing forces which have split it into blocks of different shapes and sizes, although usually without any appreciable separation or movement of the rocks.

TYPES OF JOINTS.

Vertical joints.—The most common type of joint is that having an approximately vertical position (70°–90°), but joints with many other inclinations occur. In the region investigated the character of the joints is as follows:

Inclination of joints in Connecticut rocks.

Inclination.	Number of localities observed.
80°–90°	40
70°–80°	17
74° (mean)	75
40°–70°	14
Below 40°	4

The joints are mostly straight, but a few that were curved or showed other irregularities were observed.

Horizontal joints.—In many of the rocks there is another class of joints which are very different from the vertical type, both in their degree of inclination and in their general nature. These occupy an approximately level position, rarely more than 20° from the horizontal, and usually much less than this. In general this joint structure follows the surface configuration of the rock, but occasionally is found to pitch at a low angle in a direction opposite to the slope of the hillside.

Fissility and schistosity openings.—The porosity of schist, while probably greater than that of slate, is too small to admit artesian circulation through the pores. In the crumpled schists there appear to be openings between the laminæ, but they probably do not permit sufficient rapid circulation for well supplies. It is upon the more or less pronounced fracture planes parallel to the schistosity, especially those near the surface, that the wells depend.

Faults.—Faults may be considered as extreme types of joints in which there has been movement of one wall of the joint plane past the other. The work of Hobbs, Davis, and others has shown that there has been a considerable amount of faulting in Connecticut, while it is not uncommon to find strongly marked shear zones, indicating slipping in the crystalline rocks. They are comparatively rare phenomena, however, and are seldom encountered in well drilling, and accordingly will be treated simply as special cases of jointing. They are possibly important as sources for springs, although it is extremely difficult and generally impossible to ascribe any particular spring to a fault plane.

SPACING AND CONTINUITY OF JOINTS.

Vertical joints.—The vertical joints, which are the important water carriers, have no regularity of spacing even for the same rock. From a large number of observations it appears that at the places where jointing is well developed the spacing of all joints is commonly between 3 feet and 7 feet to a depth of 50 feet, the average spacing, however, between vertical joints of the same series for the crystalline rocks, excluding trap and limestone, is more than 10 feet for this depth, while the study of well records indicates that this is not far from the average spacing for all joints to a depth of 100 feet.

Although there are many exceptions, joints of this type are generally continuous for considerable distances both along the line of outcrop and that of dip. Faults, however, have the greatest continuity and frequently extend for several miles across the country, occasionally for tens of miles. The sheeted zones of close jointing are probably nearly as continuous as faults, and their dimensions should be measured in hundreds of feet. Where there is a well-defined parallel joint series the prominent joints may extend several hundred feet, while the minor intersecting joints will be much shorter.

Horizontal joints.—There is much greater regularity of spacing in the horizontal joints than in the vertical joints. They are apparently surface phenomena and diminish in number rapidly with depth, and it is probable that they do not exist as fractures at 200 feet below the surface. In the first 20 feet below the surface these horizontal joints average 1 foot apart, in the next 30 feet they average between 4 and 7 feet, and in the next 50 feet they are much more widely spaced, running from 6 to 30 feet or more apart.

The continuity of individual horizontal joints rarely exceeds 150 feet, but owing to their intersection of each other a continuous opening might be formed of several hundred feet which would be in the form of a curved sheet approximately parallel to the hill slope, each lower sheet having less curvature than the other. They are probably better developed on the hills than in the valleys, as the pitch of the joints is usually less than the slope of the surface, which consequently cuts across the joints; and as they are wider spaced with depth the horizontal joints which cross the valleys will be widely spaced.

DEPTH.

Not only do joints become tighter with depth, but they are farther apart. The application of this principle in the drilling of wells is of the utmost importance, as it is frequently asserted that water can always be obtained by going deep enough, whereas, in fact, the deeper the well the less the chance of striking fractures, which are the only passages permitting water transmission in crystalline rocks. It is further evident that, owing to the closing of joints with depth, there will be a much greater circulation in the upper half than in the lower half of any individual joint.

The number of fractures supplying water varies greatly in different wells. In some cases the greater part of the water appears to come from a single opening, while in others the water comes in slowly from a large number of openings. In the average well there are from one to four horizons from which the principal supplies of water come, although the yield from one of them is usually greater than from all the others together. This is particularly true of the deeper wells (from 200 to 300 feet), in which the principal source is usually very close to the bottom of the well.

If an average inclination of 70° from the horizontal and an average spacing of 10 feet be assumed for the vertical joints for the upper 200 feet of rock, each well 200 feet in depth will intersect seven joints. This is probably not far from the average for all the wells, the small and discontinouus fractures near the surface being neglected. Below 200 feet the average number of joints intersected would be somewhat decreased for the next 100 feet, and greatly decreased at depths greater than 300 feet.

INTERSECTION OF JOINTS.

The intersection of joints with one another is very important in determining the nature of the underground circulation. While all joints intersect, the circulation is greatest where the joints of the principal systems meet and where, in addition to the vertical joints, horizontal fractures occur.

WIDTH OF OPENINGS.

At the immediate surface, joints often have an opening of one-half inch to 2 inches and occasionally much greater. This wide opening is due to various weathering and mechanical agencies, which act only near the surface, and consequently is not found at depths below which these agents act. In an artificial cut, such as a quarry wall, joints which may be open one-half inch at the surface are often found to be too tight to admit a knife blade at 25 feet below the surface.

While the joints at 30 feet below the surface may have only one-twentieth the opening that they have at the surface, the same proportionate tightening will not continue at lower depths, although it is certain that the greater the depths the greater must be the tendency of joints to close, owing to increased pressure and the smaller opportunity for lateral expansion below the level of minor topographic relief.

QUALITY OF THE WATER.

The waters of the crystalline rocks are variable in mineral composition, but in most instances are relatively soft, the carbonates or sulphates of calcium or magnesium being present only in small amounts. They are practically always safe for domestic purposes and give little trouble in boilers. Some wells on islands or very near the coast on the mainland yield brackish water.

WELLS.

VARIABILITY OF CONDITIONS.

In crystalline rocks it is impossible to foretell the conditions that will be encountered in a well, since these often depend on the occurrence of joints of which there may be no indication at the surface. One well may be entirely different in both the quantity and quality of its waters from another only a few feet away. It is not therefore advisable for a driller to guarantee water unless an additional charge is made to insure him against risk of failure.

Among 237 wells of which information was secured only 3, or 1¼ per cent, failed to get water, and although there is a general reluctance to give information in regard to such wells, the probabilities of failure are probably not more than one in twenty. It should be remembered, however, that this applies only to domestic wells, and that the chance of failure when large supplies for manufacturing or similar purposes are demanded is considerably greater. It is probable, however, that 90 per cent of the wells sunk have obtained supplies sufficient for the use required.

FLOWING WELLS.

Although wells in which the water rises above the rock surface are common, very few instances where it reaches the surface of the overlying drift are known. Only six yielding permanent flows have been reported, although a number of others flowed for a few minutes when first drilled. All of the flowing wells are located on slopes with considerably higher elevations near by, and are generally found only where there is a considerable thickness of drift resting on the rock surface and serving to confine the water in the rock.

The flows are ordinarily of no especial value if the water is to be utilized at the well, as the rise above the surface is very slight. In some instances, however, when the wells are on hillsides, the water can be piped to a point lower down, giving a continuous flow without pumping. Flows can occasionally be obtained by the use of siphons when the water is within 30 feet of the surface and the point where the water is used is more than 30 feet below the mouth of the well.

WATER SUPPLY.

GENERAL STATEMENT.

The yield of a well depends on its depth, its topographic location, and the nature of the rock in which it is made.

As previously stated, only 3 out of the 237 wells reported were completely dry. Only 17, or 12½ per cent, furnished less than 2 gallons a minute. About 15 gallons a minute is the average yield, although some yield over 30 gallons a minute on continuous pumping. They are remarkably constant, showing little variation in yield, either annually or through a period of years. Some have shown increased and others decreased yields, but generally the change is inappreciable. The level to which the water rises is nearly as unchangeable as the yield, usually being little if at all affected by dry seasons. Generally the water regains its original level very quickly after pumping has ceased, although in some wells it returns very gradually.

Some details are given in the following table:

Yield in gallons per minute at various depths (beneath surface covering) in various types of rock.

Depth below surface covering (feet).	Schist.		Granite.		Gneiss.		Granodiorite.		Quartzite schist.		Total.	
	No. of wells.	Yield.	No. of wells.	Yield.	No. of wells.	Yield.	No. of wells.	Yield.	No. of wells.	Yield.	No. of wells.	Yield.
0- 30	2	3.2	1	7	1	1.0					4	3.6
30- 50			9	6.7	13	11.9					22	9.75
50- 70	4	9.5	5	9.8	14	12.4					23	11.3
70- 90	3	21.6	2	20.5	7	7.6	1	8.0	1	6.0	14	12.4
90-110	6	22.1	8	14.4	2	5.5	1	0			17	15.2
110-200	2	8.5	5	13	8	8.3	6	46			21	20.2
200-300			3	16	2	33.0	3	12.7	1	0	9	16.7
300-400			1	0	2	22.0	1	2			4	11.5
400-500			1	0	1	50					2	26
500-650					2	14			1	2	3	5.2

There is, in general, a slight increase in the yield of water with increased depth from 15 feet down to 200 feet, beyond which the chances decrease, wells over 400 feet being in many cases failures. The results of observations on the latter class are summarized in the following tables:

Yield of wells over 400 feet deep.

Location.	Depth.	Yield per minute.
	Feet.	*Galls.*
Valleys	583	25
	690	10
	503	26
	425	50
Hills	850	40
	548	Small.
	420	2
	485	Dry.
Slopes	610	12
	645	4
Island	1,465	[a] 3

[a] Salty.

The average depth in rock of 163 wells is 88.8 feet and the average total depth, including the surface material overlying the rock, is 108.4 feet. Ninety per cent of the wells are less than 300 feet in depth and 82 per cent less than 200 feet in depth. In many of the wells which have gone below 250 feet the main and in several cases the entire supply has come from seams at less than 250 feet in depth. From a study of the recorded wells it would appear, therefore, that if a well has penetrated 250 feet of rock without success the best policy is to abandon the place and sink in another location. In the case of wells in granodiorite which have been successful at an average greater depth than in other rocks this depth might be somewhat too small, while in other rocks it is very possible that a maximum depth of 200 feet should be adopted.

The following table summarizes the depths of the wells under 400 feet and the proportions of each in rock and drift:

Average depths of surface material and of the entire well, exclusive of wells over 400 feet in depth and of wells known to be dry.

Position.	Average thickness of drift.	Average depth in rock.	Average total depth.	Number of records.
	Feet.	*Feet.*	*Feet.*	
Valleys	36	104.5	140.5	26
Hills	17	94.0	111.0	67
Slopes	21	79.4	100.4	54
Plains	10	74.0	84.0	16

The average total depth of the 163 wells is 108.4 feet.

TOPOGRAPHIC LOCATION.

It has been found that on an average water is encountered in the crystalline rocks at a less depth on the hills than in the valleys, but this is due largely to the heavier deposits of drift that must be penetrated before rock is reached in the valleys.

Average depth from surface to water level.

Position.	Depth to water.	Number of records.
	Feet.	
Hills	19	76
Valleys	11	30
Slopes	15	44
Plains	8	30

The average yield of the wells in the valleys is, however, somewhat greater. Wells on the slopes for some reason have an average yield of less than one-half that of those in either of the other locations.

Average yield of wells in various locations.

Location.	Yield per minute.	Number of records.
	Galls.	
Valleys	24.4	18
Hills	20.5	27
Slopes	8.7	25
Plains	18.8	9

Some rather puzzling features are brought out by the following table, showing the relation of the water level to the level of the rock surface (bottom of overlying drift) in wells in various topographic locations:

Relation of water level to surface of rock (bottom of overlying drift).

POSITION OF WATER LEVEL.

Material.	Topographic location.	Wells observed.	Below rock surface.	Above rock surface.	At rock surface.
			Per cent.	*Per cent.*	*Per cent.*
Hills	Granite		37	50	13
Valleys	Granite		11	89	0
Slopes	Granite		41	50	8
Plains	Granite		50	50	0
Hills	Schist		62.5	37.5	0
Valleys	Schist		0	100	0
Slopes	Schist		50.0	33	17
Plains	Schist				
Hills	Gneiss		69	21	10
Valleys	Gneiss		22	78	0
Slopes	Gneiss		44	36	20
Plains	Gneiss		0	50	50
Hills	Granodiorite		71	0	29
Valleys	Granodiorite		0	100	0
Slopes	Granodiorite		60	40	0
Plains	Granodiorite		33	67	0

SUMMARY OF ALL WELLS.

Hills		42	61.9	26.2	11.9
Valleys		24	12.5	87.5	0.0
Slopes		35	48.5	40.0	11.5

It is seen that in nearly all valley wells, no matter in what kind of rock they may occur, the water is under artesian pressure and rises above the rock surface. In schists, gneisses, and granodiorites the percentage of wells on hills and slopes in which the water is below the rock surface is invariably and rather uniformly greater than those in which the water level is above the rock surface, the percentage ranging from 62 to 70. In the granites, on the contrary, exactly the opposite is true, the water failing to reach the rock surface only in 37 per cent of the wells. In other words, in hill wells the granite waters rise to the rock surface nearly twice as frequently as in the case of other rocks.

The situation of the wells with reference to the sea is very important, most of the wells which fail to get pure water being in fact located along the coast or tidal rivers. Wells within 100 feet of the sea are always liable to be spoiled by the entrance of salt water, while there are cases where the latter has penetrated to wells 500 feet distant. There are, however, exceptions to this rule, some good wells being obtained even close to the water. Much may depend on the amount pumped, as a well which yields fresh water when only a little water is used may become salty if heavily pumped. When a choice of location can be had a point as high and as far removed from the sea as possible should be selected.

NATURE OF ROCK.

The amount of water in a well depends to a considerable extent on the nature of the rock in which it is made, largely because of the greater frequency of joints in some rocks than in others. In general the yield from wells in granite, gneiss, and common schist does not vary greatly from 13 gallons a minute. In those in granodiorite, however, two and one-half times as much is obtained, in quartzite schist only about one-half as much, while in the slaty rocks the supplies are very small. The details are well brought out by the following table.

Yield of wells in various types of rock.

Material.	Depth of surface covering.		Depth in rock.		Total depth.		Yield.	
	No. of records.	Feet.	No. of records.	Feet.	No. of records.	Feet.	No. of records.	Gallons per minute.
Granite	45	20.6	45	102.5	54	122.5	35	13
Gneiss	69	16.3	70	112.6	73	131.4	50	12.3
Quartzite schist	3	32.5	3	411.0	3	443.5	3	7.25
Schist other than quartzite	23	13.7	23	96	23	109.7	16	13.9
Granodiorite	15	24.1	16	138.5	19	156.6	13	33
Phyllite (slate)	4	14.4	5	80.2	5	93.8	....	Very poor.

The drift plays a very important part in the occurrence of water in the crystalline rocks. When drift is absent over the catchment area the rain runs rapidly off the surface of the smooth, bare rock and little is absorbed, but when there is a considerable thickness of drift large amounts of water are absorbed by its porous materials and are regularly and continuously supplied to the underlying crystalline rocks through their joints. The importance of a drift mantle in affording conditions favorable to flows at the well sites has already been mentioned. It is apparent, then, that in general water will both be more abundant and rise to a higher level when the crystalline rocks in the catchment areas and at the wells are covered with drift than when they are bare. This is especially true when the drift occupies basinlike depressions in the rock surface.

COST OF WELLS.[a]

The cost of wells is very variable, depending on the diameter of the hole, whether the well is sunk by the day or by the foot, and whether or not a supply is guaranteed. Two-inch wells are the most common, and cost about $2 a foot for the wells under 100 feet in depth, $2.50 for wells between 100 and 200 feet, $3 for wells between 200 and 300 feet, and $3 to $4 for wells over 300 feet. The cost of a well drilled by the day will vary greatly according to the depth at which water is struck, but seems to average a little higher than by the foot. The cost when water is guaranteed is probably slightly higher than under either of the other methods. For wells of larger diameter the price is much higher. The average cost of 123 wells, averaging 108 feet in depth and yielding a mean of 12.7 gallons a minute, is $4.25 per foot.

SUMMARY.

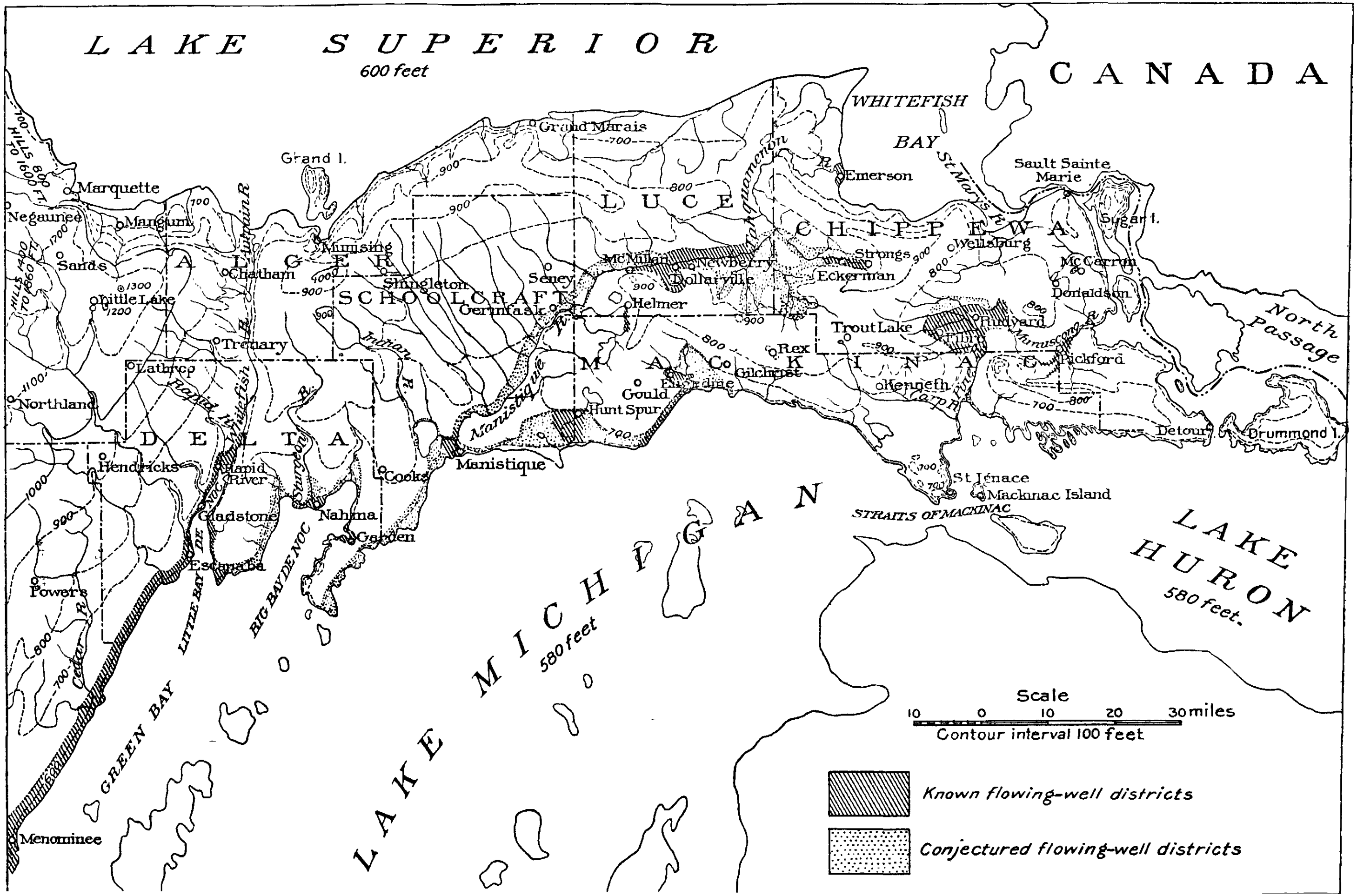
The water of the crystalline rocks occurs, so far as it can be secured by wells, wholly in joints, faults, or other fracture openings, the pores and schistosity planes being too close to permit active circulation. The water seems to occur largely in the vertical joints or faults, especially in the sheeted zones consisting of numerous crowded fracture planes. In Connecticut a common spacing between the surface joints is 3 to 7 feet, but in some cases they are much farther apart. At depths of more than 50 feet the space becomes greater owing to the dying out of subordinate joints.

The spacing of the horizontal joints is rather regular. In the first 20 feet below the surface they average 1 foot apart, for the next 30 feet from 4 to 7 feet, and in the following 50 feet they are from 6 to 30 feet or more apart.

The most favorable points for water are at the intersection of two or more of the joint systems, the circulation often being concentrated at these points.

It is impossible to foretell the success or yield of a well in crystalline rocks, but the chances of a moderate supply are at least as good as 9 in 10. The character of the water obtained is in general excellent, both for domestic and manufacturing purposes, and is usually soft. Hills and places where the soil is thick are the most desirable locations for drilled wells. In general, it is better to abandon a well and seek a new location if not successful when a depth of 250 feet has been reached, as the possibilities of a supply below this depth are much less than at shallower depths.

[a] Data mainly by M. L. Fuller.


LAKE SUPERIOR
600 feet
CANADA
WHITEFISH BAY
St Marys R.
Sault Sainte Marie
Sugar I.
North Passage
Drummond I.
Detour
LAKE HURON
580 feet.
LAKE MICHIGAN
580 feet
STRAITS OF MACKINAC
St Ignace
Mackinac Island
GREEN BAY
LITTLE BAY DE NOC
BIG BAY DE NOC
Grand I.
Grand Marais
Marquette
Negaunee
Mangum
Sands
Little Lake
Munising
Chatham
Trenary
Lathrop
Northland
Hendricks
Rapid River
Gladstone
Escanaba
Powers
Menominee
Nahma
Garden
Cooks
Manistique
Shingleton
Germfask
Seney
Helmer
McMillan
Newberry
Dollarville
Hunt Spur
Gould
Engadine
Gilchrist
Rex
Trout Lake
Kenneth
Rudyard
Pickford
Donaldson
McCarron
Wellsburg
Strongs
Eckerman
Emerson
ALGER
SCHOOLCRAFT
LUCE
CHIPPEWA
DELTA
MACKINAC
Tahquamenon R.
Manistique R.
Indian R.
Whitefish R.
Rapid R.
Sturgeon R.
Cedar R.
Munuscong R.
Carp R.
Au Train R.
HILLS 800 TO 1600 FT.
HILLS 1400 TO 1660 FT.
Scale
10 0 10 20 30 miles
Contour interval 100 feet
Known flowing-well districts
Conjectured flowing-well districts

FLOWING-WELL DISTRICTS IN THE EASTERN PART OF THE NORTHERN PENINSULA OF MICHIGAN.

By Frank Leverett.

GENERAL STATEMENT.

The flowing wells of the northern peninsula of Michigan are obtained in part from the Pleistocene deposits and in part from Silurian and Cambrian formations. The rocks dip southward toward the basins of Lakes Huron and Michigan and southeastward toward the Green Bay basin and the adjacent portion of the Lake Michigan basin. In consequence of this arrangement of the strata, water absorbed in the part of the peninsula bordering Lake Superior, which is as a rule an elevated tract, passes toward the basins of Lakes Huron and Michigan and Green Bay under sufficient hydrostatic pressure to yield flows at moderate elevations above the surfaces of these water bodies. Already flows have been obtained along the western side of Green Bay throughout its entire length, in wells ranging from 200 feet or less up to about 800 feet in depth. They have been obtained on Garden Peninsula, lying between Big Bay de Noc (at the northern end of Green Bay) and Lake Michigan. They have also been obtained along the northern shore of Lake Michigan at several points from Manistique eastward. On the borders of Keweenaw Peninsula there are also flowing wells from the Cambrian sandstones, but these are outside the district covered by the writer.

Wells from the drift have already been extensively developed in a low district lying north of the "Niagara" escarpment in Chippewa and Luce counties and on the western shore of Whitefish Bay at Emerson, and there are small areas in other parts of the peninsula where they are either already obtained or may be expected to be obtained.

Very little information could be secured from drillers or well owners concerning the character of the rock formations which yield flows. In most cases they report that the flows are obtained under a bed of rock, which was hard to penetrate with the drill, and which seems to have served as a cover to prevent the natural escape of the water. In some cases, as at Gladstone and other points along the western side of Green Bay, water is obtained at more than one horizon, but because of the meagerness of the data the writer did not attempt to work out the stratigraphy of these water-bearing beds. Some identifications made by Lane and by Alden appear in the Annual Report of the State Geologist for 1903.

The flowing wells obtained in the drift deposits usually penetrate a bed of clay and obtain water in sand or gravel. In Chippewa County the clay is a laminated, nearly pebbleless deposit, apparently laid down in the bed of a great glacial lake, Lake Algonquin, which covered this region after the retreat of the ice. But in Luce County the clay deposits are in some cases found to be stony, and are probably of glacial rather than lake deposition. Beneath the clay deposits of Chippewa County a bed of sandy material full of water generally occurs, but is not a good source for flowing wells, since it is too fine grained to furnish water rapidly. It is termed slush by the drillers, and it is their custom to continue through it to a bed of gravel.

In the division of the wells into districts (Pl. I) there is usually the probability that over part of the intervening territory the altitude is too high to permit flows. But in some cases further exploration may develop wells between districts now placed in separate groups. An attempt is made to indicate possible extensions of the flowing-well areas as well as their present limits. The districts are taken in order from east to west, those in the drift deposits being first considered and then those in rock.

FLOWING-WELL AREAS.

FLOWS FROM DRIFT.

McCARRON.

Two shallow flowing wells have been obtained in a ravine near McCarron post-office, Chippewa County, at an altitude of about 650 feet above tide. One at the residence of David McCarron in sec. 4, T. 45 N., R. 1 E., is 30 feet in depth and has a head of about 3 feet. The water is sulphurous and has a temperature of 45° F. About one-eighth mile northeast of the McCarron well, at the residence of Samuel Boyle, in sec. 34, T. 46 N., R. 1 E., is a well 37 feet deep, with similar head and quality of water, and a temperature of 44.9°. The temperatures were taken August 10, 1905, when the air temperature was 85° F. Both wells penetrate a laminated, pebbleless, red clay and enter a bed of gravel.

DONALDSON.

A flowing well was obtained in the autumn of 1905 at Donaldson, by Robert McKee, which was reported by the driller, Judson Daley, of Pickford, to be 78 feet in depth and to flow one-third gallon a minute. It is located in a ravine about 15 feet above a tributary of Charlotte River, at an altitude of about 650 feet, and penetrated clay to the gravel bed at its bottom. It lies in sec. 31, T. 46 N., R. 1 E., and is used as a public well.

McEVOY.

This is probably the oldest flowing well in Chippewa County, having been running for at least twenty-five years. It is located in sec. 14, T. 46 N., R. 1 W., on the Mackinaw road running from Sault Ste. Marie to St. Ignace. It stands in a slough tributary to Charlotte River, about 15 feet below the bordering plain at an altitude of 700 feet above tide. It has a depth of 45 feet and a head of about 5 feet or less above the surface. The well, which is said to have maintained its strength, yields over a gallon a minute.

PICKFORD DISTRICT.

The Pickford flowing-well district is a narrow strip along Munuscong River and its tributaries, in the vicinity of the village of Pickford, most of the wells being in Chippewa County, but a few in Mackinac County. Of the 32 wells already developed 26 are within the village limits. The outlying wells, however, seem to indicate that flows may be obtained from the junction of the two forks of Munuscong River northeast of Pickford for a distance of 5 or 6 miles up the west fork and 2 or 3 miles up the east fork. The water obtained is suitable for boiler use, there being only a moderate amount of lime present. It has a little iron and in some cases a slight sulphurous odor. The temperature of the water where not surface heated is 43.5° to 45° F., but in most cases the flow is so weak that it can not overcome the effect of the air on the portion of the pipe above the surface, nor of the warm soil around the upper portion of the pipe. The data contributed by Mr. Daley are from careful records in his notebook. They show an interesting variation in the thickness of the laminated red clay and the underlying sandy slush, the cause of which is not clearly understood. It is possible, however, that a change to more sandy texture may set in at 50 feet or less in wells where the driller has classified material as red clay to a depth of over 100 feet. In the table given below several wells are included which would not flow at the level of the ground, but are made to flow by being piped into cellars or basins below the surface.

Flowing wells at Pickford (T. 43 N., R. 1 W.).

Owner.	Location.	Driller. (a)	When made.	Altitude [b]	Depth.	Diameter.	Flow per minute.	Head.	Temperature.	Section. Red clay.	Section. Slush.	Section. Gravel.	Remarks.
				Feet.	*Feet.*	*Inches.*	*Galls.*	*Feet.*	*°F.*	*Feet.*	*Feet.*	*Feet.*	
A. Roe	Pickford	J. D.	1905	630	128	2	1.0	+3.5	46.2	80	34	14	
Central Hotel	do	J. S.	1895	630	128	4	Strong.			80	34	14	Distribution system.[c]
J. Crawford	do	J. D.	1904	630	128	2			43.5	80	32	14	
J. Cameron	do	J. D,	1902	630	128	2	.25		46	80	40	8	
J. Robinson	do	J. D.	1905	631	129	2	.10	+2	45	109	0	20	Sandy gravel.[d]
Geo. Wilson	do	J. D.	1903	631	131	2		+3	50	107	0	24	Temperature in tank.
H. Miller	do	J. D.	1901	635	127	2		−3		124	0	3	Roily water.
Creamery	do	J. S.	1900	628	67	3	Strong.						Newly driven in 1900.[e]
D. Bacon	do	J. D.	1903	632	127	2				119	0	8	
I. Watson	do	J. D.	1901	625	88	2	.5	+6	46	45	40	3	
F. Green	do	(?)	(?)	630									Flows in cellar.
J. O'Niel	do	J. D.	1901	630	98	2							Flows in basement of store.
J. McDonald	do	(?)	(?)	630	87	2							Flows in cellar.
F. Taylor	do	(?)	(?)	630	89	2							Do.
J. Barton	do	J. D.	1902	630	119	2		−1					Flows in tank.
D. Aldridge	do	J. D.	1905	635	127	2		−3					Do.
S. Crawford	do	J. D.	1902	620	87	2		+3		74	0	13	Strong flow.
D. Stevens	do	(?)	(?)	625	95	2		+5					Weak flow.
H. Blair	do	J. D.	1901	632	122	2		0					Gravel at bottom.
F. Johnson	do	J. D.	1901	635	140	2		−1.5		120	13	7	Flows in tank; strong well.
Schoolhouse	do	J. D.	1902	635	122	2		−4		102	0	20	Flows in basin.
F. H. Taylor	do	(?)	(?)	614	87	2	.1		54				Well in ravine.
Chippewa Hotel	do	I. M.	1895	630	126	4		+3					Flows in basin.

[a] J. D. = Judson Daley, professional driller, Pickford. J. S. = James Somerville, professional driller, Newberry.
[b] Altitudes are barometric.
[c] Drawn off 3.5 feet below surface and piped to gristmill on lower ground to cool a gasoline engine. It is 22 feet from the Crawford well, and greatly weakened that well when piped to lower ground.
[d] Can be easily lowered only to 8 feet below surface by heavy pumping.
[e] Flows into open well 12 feet below surface. New pipes were driven in 1900, as the old ones had begun to leak.

Flowing wells of Pickford (T. 43 N., R. 1 W.)—Continued.

Owner.	Location.	Driller.	When made.	Altitude.	Depth.	Diameter.	Flow per minute.	Head.	Temperature.	Section. Red clay.	Section. Slush.	Section. Gravel.	Remarks.
				Feet.	*Feet.*	*Inches.*	*Galls.*	*Feet.*	*°F.*	*Feet.*	*Feet.*	*Feet.*	
Dr. Webster	Pickford	J. S.	1899	630	128	3	....	0	....	....	....	....	Barely flowed; pump attached.
O. S. Roe	do	(?)	1899	622	68	2	....	+6	45.8	....	....	....	Piped to barrel.[a]
A. Taylor	do	(?)	(?)	630	78	....	....	0	....	....	....	....	Barely flows.
W. P. McDonald	Sec. 7	J. D.	1903	635	151	2	....	0	....	100	49	2	Do.
W. Bacon	Sec. 6	J. D.	1903	615	86	2	Weak.	+2	....	74	0	12	
J. Clagg	Sec. 6	J. D.	1904	620	120	2	....	0	....	110	8	2	Piped to lower ground.
T. Morrison	Sec. 12	J. D.	1902	635	98	2	.25	+4	....	52	46	....	
J. Taylor	Sec. 13	J. D.	1905	635	114	2	6.0	+8	45.4	110	0	4	(b)
Wm. Wise	Sec. 14	J. D.	1905	650	112	2	.2	....	....	110	0	2	(c)

[a] Piped to barrel 7 feet below the well mouth; flows three-fourths-inch stream. Water is from sand.

[b] Flows over top of pipe 8 feet above surface. Present discharge is through a three-fourths-inch hole in side of pipe 4 feet above surface. Well is 8 feet above Taylor Creek and stands on the creek bank.

[c] Twenty feet above Munuscong River. An older well near it, 65 feet in depth, has a head 15 feet below the surface.

In a district so flat as that near Pickford it is somewhat difficult to determine by barometer the slight differences in altitude of the wells. If we may trust the barometric readings, there is a slight decrease in the height to which water will rise along a line running southwest and northeast through this district, or in the direction of drainage of the west fork of Munuscong River. As indicated in the table, the flow from the westernmost well (that of W. Wise) appears to rise to an elevation 15 feet greater than is reached by flows from the wells in Pickford, while the wells a mile east of Pickford, in the valley of East Fork, on the farms of William Bacon and J. Clagg, have a head several feet less than that of wells in the village. The high land lying a few miles southwest of Pickford seems likely, therefore, to be the main catchment area for this district. The drift is loose textured in that region, the compact laminated clay penetrated by the flowing wells not being present.

A number of wells with strong hydrostatic pressure have been obtained in the vicinity of Pickford on ground a little higher than that within the flowing-well district, as indicated in the table below. They are probably supplied from the same catchment area.

Wells near Pickford having head nearly at surface.

Owner.	Location. T.	Location. R.	Location. Sec.	Driller.[a]	When made.	Altitude.[b]	Depth.	Diameter.	Head.	Section and remarks.
						Ft.	*Ft.*	*In.*	*Ft.*	
R. Smith	43 N.	1 W.	6	J. D.	1905	670	160	2	−30	Clay to gravel at bottom.
E. Cottle	43 N.	1 W.	5	J. D.	......	665	104	3	−30	Largely sand, gravel at bottom 18 feet.
Bronson estate	43 N.	1 W.	5	O.	1905	660	120	....	−27	Mr. Bronson dug a well 27 feet, which caved in and killed him. The well was then driven to 127 feet. Said to be mainly sand.
C. Harrison	43 N.	1 W.	4	J. D.	1905	650	92	2	−14	Clay to gravel at bottom. Cost $23.
F. Bye	43 N.	1 W.	2	J. D.	1905	650	88	2	−10	Clay to gravel at bottom.
J. Dunbar	44 N.	1 W.	30	J. D.	1905	670	82	2	− 7	Do.
W. Best	44 N.	1 E.	31	J. D.	1904	645	91	2	−11	Red clay 73 feet; sand and gravel 18 feet.
Kirkbride	44 N.	1 E.	31	J. D.	1903	640	105	2	− 8	Red clay 95 feet; gravel 10 feet.
J. Henderson	43 N.	1 E.	6	J. D.	1905	630	92	2	− 3	Near east Munuscong River, 8 feet higher than Bacon flowing well and 150 yards distant. Clay to gravel at bottom.
C. Pennington	44 N.	1 E.	33	J. D.	1897	635	92	2	−10	Well entered gravel 8 feet.
I. McDonald	Pickford		......	J. D.	1901	635	130	2	− 4	Red clay 115 feet; gravel 15 feet. Supplies engine in planing mill.
J. Hill's store	Sterlingville		......	......	......	635	125	3	−10	Mainly bluish gray "putty sand." Dug 27 feet; driven 3-inch pipe below.

[a] J. D. = Judson Daley, driller, Pickford. O. = owner.
[b] Altitudes are barometric.

RUDYARD-FIBER DISTRICT.

This flowing-well district is located in the drainage basin of Pine River and the extreme headwaters of the west branch of Munuscong River. It occupies about 60 square miles in Tps. 43, 44, and 45 N., Rs. 2, 3, and 4 W. The Soo Line Railroad traverses it from a point 2 miles northeast of Rudyard westward to a point 2 miles west of Fiber. At the time of the investigation, in the autumn of 1905, there were 66 flowing wells. They are obtained on the general level of the plain, and not, as in the Pickford district, confined to the stream borders. The general elevation of the plain is about 690 feet, or higher than the head of any of the wells in the Pickford district.

The wells show greater head in the northern and western parts of the district than in the southern and eastern parts, thus indicating that the catchment area is on the north and west. There is a range of high limestone hills south of the eastern portion of the area which apparently serves as the catchment area for the Pickford district but not for the Rudyard-Fiber district, there being a decided falling off in head in passing southward toward this limestone ridge in the latter district. There are sandy tracts on the northern and western borders of this district, while an elevated limestone tract lies southwest of it. Both the sand and the limestone are readily absorbent, and likely to be sources of supply for the flowing-well district.

In the flowing-well district there is a heavy coating of red laminated clay nearly free from pebbles, which, like that in the Pickford district, appears to have been deposited in the Glacial Lake Algonquin. This clay is underlain by a sandy slush, which in turn rests upon gravel. Wells are usually driven through the slush, but if screens are used flows of considerable strength may be obtained in it. Without the use of screens the wells soon become clogged.

The water contains a small amount of iron and is moderately hard, though in most cases suitable for boiler use. In a few cases it is sulphurous.

It will be observed by reference to the table that the wells differ greatly in rate of flow. This difference is in part attributable to the texture of the water-bearing bed, the slower flow being obtained in sand and the more rapid flow in gravel.

The temperature is about 45° F. in wells that are not greatly affected by surface influences. In one case a well flows so slowly that the stream freezes in the coldest weather, and rises about 10° above its normal temperature in the hottest; but in wells of rapid flow there appears to be only a fraction of a degree variation in temperature in the course of the year.

Flowing wells in Rudyard-Fiber district.

Owner.	Location.			Driller. (a)	When made.	Altitude.[b]	Depth.	Diameter.	Flow per minute.	Head.	Temperature.	Remarks.
	T. N.	R. W.	Sec.									
						Ft.	Ft.	In.	Galls.	Ft.	° F.	
Fountain House	Rudyard			J. D.	1903	682	278	2	0.2	+22	47.5	Red clay 204 feet, black clay 20 feet, gray quicksand 53 feet, gravel 1 foot.
J Anderson	do			J S.	1904	682	285	3	.2	+22	52	Red clay 240 feet, dark sandy slush 40 feet, gravel 5 feet. Distance from Fountain House well about 200 feet.
H Bonner	do			G. L	1904	685	268	2	.08	....	50.7	Head not determined.
H Cottle	44	2	5	H C	1901	697	125	45	40	+12	45.8	Soft water with no iron stain. Well estimated to flow more than a barrel a minute. Red clay with some pebbles 90 feet, blue sand 30 feet, gravel 5 feet.
Do	44	2	5	H. C	....	695	233	....	....	+12	....	The deeper borings were failures, as no gravel bed was found, and rate of flow from sand was very slow. Distance from 125-foot well 500 to 600 feet.
Do	44	2	5	H. C.	....	695	233	....	....	+12	....	
Do	44	2	5	H. C.	1895	700	84	....	....	....	....	Well was one-fourth mile east of the others and flowed a strong stream. Pipe was pulled when the 125-foot well was obtained, that being nearer the residence.
B Weiring	44	2	6	G. L.	1904	695	190	2	.25	(?)	55	Red clay 140 feet. Sand to cemented crust at bottom. Flows from pipe 5 feet above ground.
J. Kamper	45	2	32	J K.	....	700	100	1	....	+ 1	55 32	Flows about 1 gallon an hour. Penetrated hard clay 45 feet, soft clay 35 feet, gray quicksand 20 feet. Freezes in coldest weather.
Do	45	2	32	J K.	....	700	90	....	....	+ 1	55 32	Freezes in coldest weather. Section and rate of flow similar to preceding.
G Kamper	45	2	32	G. K.	1905	700	90	2	....	+ 1	50	Red clay pebbly in lower part, gravel at bottom. Weak well.
L. A. Halbert	45	2	31	J. K.	1905	700	118	2	.25	+ 8	50	Red clay 85 feet, sand 25 feet, gravel 8 feet. Slight iron stain.

a Drillers' initials:
G. L.=George Lawler, professional driller, Rudyard.
J. D.=Judson Daley, professional driller, Pickford.
J. S.=James Somerville, professional driller, Newberry.
G. H.=George Huntley, farmer, Rudyard.
J. K.=John Kamper, farmer, Rudyard.
G. K.=George Kamper, farmer, Rudyard.
G. D.=Garrett Dolman, farmer, Rudyard.
H. C.=Henry Cottle, farmer, Rudyard.
D. B.=D. Boucher, farmer, Rudyard.

b Altitudes of wells near Soo Line Railroad determined from railroad survey; remainder, barometric.

Flowing wells in Rudyard-Fiber district—Continued.

Owner.	Location.			Driller.	When made.	Altitude.	Depth.	Diameter.	Flow per minute.	Head.	Temperature.	Remarks.
	T. N.	R. W.	Sec.									
						Ft.	*Ft.*	*In.*	*Galls.*	*Ft.*	° F.	
W. Johnson	45	2	33	G. D.	....	695	68	3	5	+ 8	46	Red clay 50 feet, sandy slush to gravel at bottom. Sulphurous water.
G. Dolman	44	2	4	G. D.	1905	700	72	2	.5	+ 2	46	Flow affected by Johnson well. No sulphur taste.[a]
H. H. Wyatt	44	2	5	J. S.	....	700	104	3	.3	+ 4	....	Not visited.
D. Boucher	44	2	17	D. B.	1898	685	220	2	....	+ 4	....	Flows into basin. Red clay 175 feet, blue sandy slush 20 feet, fine sand at bottom. Weak well.
J. Desrocher	44	2	17	G. L.	1905	685	216	2	1	+25	46	Red clay 208 feet, sandy slush 4 feet, blue gravel 4 feet.
P. Royer	44	2	7	G. L.	1905	685	270	....	....	....	....	Head barely at surface.
G. Kelly	44	2	8	J. D.	....	680	113	3	....	+ 4	....	Flow greatly decreased in summer of 1905.
S. Kendrick	44	2	5	J. S.	1896	680	100	3	8	....	45	Discharges 2 feet above surface from 1½-inch pipe.
H. Johnson	44	2	8	G. H.	1896	680	98	3	3	+(?)	45	Discharges 3½ feet above surface from ¾-inch pipe.
G. Huntley	44	2	5	G. H.	1897	680	96	3	3	(?)	45	Discharges 3 feet above surface through ½-inch hole.[b]
A. Pitsen	44	2	9	G. H.	1898	680	92	5	4	(?)	45	Flows from ¾-inch hole in side of pipe.
T. Micheau	44	2	4	G. H.	1900	680	92	3	5	(?)	44.5	Do.
—— Naeme	44	2	8	J. S.	1898	680	98	3	.5	(?)	....	Hard crust at bottom.
—— Nesse	44	2	9	G. L.	1904	680	104	2	....	0	....	Head barely at surface.
—— Bolman	44	2	4	G. L.	1904	680	82	2	....	+ 2	....	Flows mere trickle. Enters gravel 2 feet.
—— Glastader	44	2	3	(?)	(?)	685	100	3	.1	+ 3	....	Flows scarcely a pint a minute.
Michigan Land Co.	44	2	10	(?)	(?)	680	(?)	(?)	....	+ 5	48	Flows a mere trickle 5 feet above surface.
—— Habella	44	2	9	J. D.	1903	680	108	2	{ 32 { 10	+ 5	....	Flow of a barrel a minute was reduced to 10 gallons by driving pipe to a crust of hardpan under the gravel. Red clay 100 feet, gravel 8 feet.
—— Housin	44	2	3	G. L.	1904	680	151	2	3	+ 5	45	Discharges from ½-inch faucet 4 feet above ground.
Rev. G. A. Smith	44	2	10	J. D.	1903	680	171	2	1.25	(?)	45	Largely through soft sandy slush. Was driven 115 feet in 1½ hours.
—— Gervin	44	2	10	....	....	680	100	3	....	0	....	Barely rises to surface.
A. Wice	44	2	16	....	1899	680	88	3	....	0	44.5	Do.
—— Jacobson	44	2	9	G. H.	1901	680	113	2	....	0	43.5	Do.

—— Germain	44	3	12	G. L.	1905	680	403	....	....	00	....	Fine sand below red clay. Very weak flow.
H. Loughheed	44	3	10	J. S.	1896	685	165	2	....	+1 / 0	46	Flowed for 2 years.
Mrs. J. Poirier	44	3	11	J. S.	1897	686	167	3	....	1 / 0	46	Flowed a ½-inch stream at first.
—— Turcot	44	3	11	(?)	1902	678	160	3	.25	+7	45.7	Discharges through ½-inch hole 3 feet above ground.[c]
G. Vigneu	44	3	11	(?)	(?)	688	±160	....	....	0	....	Head barely at surface.
A. Le Gault	44	3	11	....	....	688	±160	....	....	0	....	Do.
C. Gowan	44	3	9	J. S.	1901	695	145	3	2 / 1	2.5	45.75	Red clay 16 feet, gravel and clay 10 feet, red clay to gravel at bottom. Flow is decreasing.
J. T. Joyal	Dryburg			J. S.	1904	680	158	3	2.5	+10	46	Red and blue clay 110 feet, gravel 1 foot, clay and sand alternating 47 feet. Gravel at bottom.
E. Baril	....do			J. S.	1899	685	153	3	2.5 / 1.25	+5 / +3	46	Lowered 2 feet by Joyal well, 300 yards distant.[d]
J. Elferdink	....do			J. S.	....	690	147	3	.6	+2	45	Not affected by Joyal well, ¼ mile distant.
C. Everett	44	3	17	J. D.	1901	685	104	2	.2	+15	47	Red clay 102 feet, gravel 2 feet.
R. G. Trimble	44	3	17	J. S.	1900	690	130	3	1.5	+13	46	Discharges from pipe 6 feet above ground.
T. Askwith	44	3	17	G. L.	1904	690	138	3	5	+13	45.5	Head tested when well was first made.
J. B. Wilson	44	3	17	....	1900	690	135	2	2.5	+13	45	Discharge pipe 7 feet above ground.
H. Ferstneau	44	3	16	J. D.	1901	690	116	2	.25	+3	....	On bank of Bear Creek 25 feet above stream.
T. Holland	44	3	16	J. S.	1901	680	115	3	1	+12	45	Red clay to gravel at bottom.[e]
Armstrong Mill	Fiber			J. S.	1903	697	110?	3	10	+17	45	Discharges 7½ feet above surface. Water suitable for boiler use; very little scale. Red clay 85 feet from sand under cemented crust.
T. Anderson	....do			J. S.	1900	697	110	1½	1	+18	44.3	Red clay 100 feet, sand 10 feet. Discharges 8 feet above surface and is piped to dwelling.
Ross & Bros. mill (2 wells).	2 miles west of Fiber.			....	1898	735	115	1½	10	(?)	....	Mainly red clay. Pipes now pulled.[f]
—— Savoie	44	3	21	....	1903	685	113	2	.5	+5	46	Gravel 1 foot at bottom.

[a] If the Johnson well is allowed to flow freely it will lower the head of the Dolman well 7 inches within an hour, but not so rapidly after the first hour. Distance between the wells about one-eighth mile.

[b] A well near this was dug 50 feet and bored 24 feet. It obtained a flow, but the water had a rank odor, coming from a black sand struck at about 40 feet. Odor apparently sulphurous. The well was filled and the present well, which apparently missed the black sand, was drilled. Its section is: Red clay, 74 feet; blue sandy slush, 6 feet; gravel, 20 feet.

[c] This well is in a ravine 100 to 150 yards distant from the Loughheed and Poirier wells and is thought by the owners to have caused the loss of head in those wells. It appears, however, that the Loughheed well began losing head before the Turcot well was sunk.

[d] The Baril well is about 300 yards northeast of the Joyal well and appears to be influenced by the flow in that well. When the Joyal well was opened the Baril well ceased flowing for two days, and then came back to a head 2 feet lower than when first made and to half its original rate of flow.

[e] An old boring about 20 feet distant and on ground 6 feet higher still flows, though the pipe has been pulled.

[f] Two wells only 10 yards apart each flowed a full pipe, 1½-inch stream. Holes 3 inches in diameter were drilled and 1½-inch pipes inserted in them, but since the mill has ceased operation the pipes have been pulled and the water escapes around the holes.

Flowing wells in Rudyard-Fiber district—Continued.

Owner.	Location.			Driller.	When made.	Altitude.	Depth.	Diameter.	Flow per minute.	Head.	Temperature.	Remarks.
	T. N.	R. W.	Sec.									
						Ft.	*Ft.*	*In.*	*Galls.*	*Ft.*	° F.	
R. Cartright	44	3	22	J. S.	1902	685	132	2	....	....	....	Flows a mere trickle.
H. McCraig	44	3	22	(?)	1900	685	(?)	2	.25	+ 5	47	
E. Davidson	44	3	22	J. S.	1898	680	147	3	.75	+1.5	46.5	Red clay 75 feet, sand below.
Do	44	3	27	J .S	1903	680	150	2	1	+ 3	....	Similar to preceding.
—— Dersher	44	3	28?	J. D.	1901	....	114	2	....	+ 2	....	Not visited.
—— Ackridge	43	3	4	....	1904	....	117	2	.25	....	....	Do.
A. Douglass	44	3	35	G. L.	1904	670	188	2	{ 36 12.5	....	45	Flow decreasing.[a]
S. N. Peffer	44	3	36	G. L.	1904	670	186	2	2.4	....	46	Red clay 180 feet, sandy slush 6 feet. On bluff 40 feet high. Slight iron stain.
P. Stevenson	44	2	31	G. L.	1904	670	173	2	3	....	46	Red clay to sand at bottom.
S. McDonald	44	2	31	G. L.	1904	670	208	2	.5	+ 2	46.5	

[a] This well when first drilled, in August, 1904, was one of the strongest flows in this district, the discharge being about 36 gallons a minute from a 2-inch pipe. It began to decrease perceptibly in May, 1905, and on August 22, 1905, discharged only 12½ gallons a minute.

About 2 miles northeast of Rudyard there is a tract of land whose altitude is 715 to 730 feet, or about 30 to 45 feet above Rudyard station. The red clay is comparatively thin on this prominent tract, and wells are obtained in gravelly sand at depths of 28 to 42 feet. In three of the wells on ground about 715 feet above tide the water stands only 6 feet below the surface. One of these, at the residence of J. C. Sass, will stand pumping 2 barrels in seven minutes without lowering, though it has only a 3-inch pipe. The source of supply for these wells is probably to the north in the higher land, which is loose textured and free from the capping of red clay.

STRONGVILLE.

Several deep wells near Strongville, 2 to 3 miles south of the eastern part of the Rudyard-Fiber flowing-well district, on ground 10 to 20 feet lower than the flowing wells, have a water level several feet below the surface, as indicated in the table below. As already stated, the passage of underground water appears to be from north to south, and this naturally results in the decrease of head here displayed.

Wells near Strongville (T. 44 N., R. 2 W.) with strong hydrostatic pressure.

Owner.	Location.	Altitude.[a]	Depth.	Head.	Remarks.
		Feet.	*Feet.*	*Feet.*	
L. R. Adamson	Sec. 21	670	147	−12	Red clay 130 feet, black sandy slush 15 feet, gravel 2 feet. Strong well with 3-inch pipe in lower part, but dug 4 feet square to depth of 37 feet.
George Potts	Sec. 26	670	120	−20	
M. Knauf	Sec. 28	670	144	−16	Similar to Adamson well, but not so strong.
D. Perry	Sec. 22	670	67	−20	Weak well.

[a] Altitudes are barometric.

EMERSON.

There are nine flowing wells at Emerson, on the shore of Whitefish Bay, all on the property of the Cheesbrough Lumber Company. They range in depth from 116 to 123 feet. In each well a 5-inch hole was made and cleaned out, then a 1¼-inch pipe inserted. The wells passed through 17 feet of sand and then 90 to 95 feet of blue clay to sand at bottom. The clay is said to be laminated and pebbleless and is apparently a lacustral rather than a glacial deposit. The rate of flow ranges from less than a pint a minute in the weakest to 1½ gallons a minute in the strongest wells. The escape pipes are from five-sixteenths to three-eighths inch in diameter, and the water will rise to a height of 5 or 6 feet above the level of Lake Superior. It carries a small amount of iron, but appears to have very little lime, as is natural, in view of the fact that this well district is north of the limestone formations. The temperature ranges from 44° to 49° F in the different wells. These wells are distributed over a space of about half a section and the area of flows might perhaps be extended 2 or 3 miles along the shore of the bay.

TAHQUAMENON DISTRICT.

Occurrence.—The Tahquamenon district embraces several groups of flowing wells distributed along the southern border of a large swamp traversed by the east and west branches of Tahquamenon River in western Chippewa and southern Luce counties. Flows have been obtained at Strong and Eckerman, and near Soo Junction, Newberry, and Dollarville, and can probably be obtained along the swamp between these stations. This district, like the Pickford and Rudyard-Fiber districts, lies in the lowland underlain by the "Lorraine" (Hudson) and "Utica" formations, in a belt of thick drift. There is no heavy and continuous deposit of laminated clay here as in the other two districts mentioned. Instead the wells often penetrate a large amount of fine sand and, in some cases, scarcely any clay. Located, as this district is, in a trough-like lowland, it seems to afford favorable conditions for receiving water both from the south and north. On the south is a morainic belt with pervious drift, largely of sandy gravel, which will readily absorb water to supply the low tract where the wells are found. On the north also is a moraine of loose-textured drift, under which the rocks dip southward beneath this swamp. The altitude of the wells ranges from about 725 feet at Dollarville and points farther east, near Tahquamenon River, to nearly 850 feet at Strong. The wells of high altitude are along the east branch of Tahquamenon River, a stream that descends rapidly westward, but the wells of low altitude are along the west branch, a sluggish stream flowing eastward. It is probable that the underground drainage of the east fork leads westward, conforming to the slope of the surface, and this may be a leading cause for the westward decline in head. The head declines northward toward the west fork, from the southern moraine a distance of from 1 to 3 miles, but it can scarcely be expected to continue farther north, in view of the northward rise of both the drift surface and the underlying rock formations. The water is of fair quality for boiler use, though moderately hard. It contains a small amount of iron.

Strong.—At Strong, in western Chippewa County, are two flowing wells, one at Turner's mill and one at the boarding house, both driven in 1899 by James Somerville. The altitude of the mill well is about 840 feet and that of the boarding-house well 845 feet. The mill well was driven to rock at 220 feet, but the pipe was pulled back to 185 feet because of a flow of water from the sand bed at that depth. The well passed through clay to this water-bearing sand. The flow is only a quart a minute from a 2-inch pipe and the temperature is 45.8° F.

The boarding-house well is 203 feet in depth and discharges about 2 gallons a minute from a 2-inch pipe. Part of the water is piped to the mill. It has a temperature of 46° F. After passing through 7 feet of surface sand, the well penetrated 168 feet of clay that changed in color from red to gray toward the bottom. Beneath this clay was 10 feet of gravelly hardpan, then 16 feet of quicksand, followed by a hard crust 2 feet thick, under which a flow of water was struck.

Eckerman.—At Eckerman three shallow flowing wells have been obtained at about the level of the railroad station, or 800 feet above tide. They are at the base of the moraine that passes Eckerman on the south and are probably supplied from it. The well at George Johnson's hotel, made in 1896, is 47 feet in depth, 3 inches in diameter, and discharges 6 quarts a minute through a half-inch pipe about 5 feet above the surface, or 808 feet above tide. The flow at first was 2 gallons a minute. The temperature of the water is 44.2° F. The well penetrated reddish till for 40 feet and sand for 7 feet.

A flowing well at Lake's livery stable is 35 feet deep and flows 2 quarts a minute, the water having a temperature of 44.8° F.

At the dwelling now used as the post-office, just east of the railroad depot, is a 35-foot well, which penetrated 15 feet of sand before entering clay, and terminated at the bottom of the clay bed. Although the water overflowed, a pump is now used, and the temperature by pumping is 44.8° F.

Soo Junction.—A flowing well 172 feet deep and 3 inches in diameter was made in 1893 by James Somerville on the White and France property north of Soo Junction, on the north side of Tahquamenon River at an altitude of about 720 feet above tide. It was largely through a "putty clay," but there was a thin bed of gravel resting on the rock. The head was 8 feet above the surface when drilled. This well was not visited by the writer and its present condition was not ascertained.

Newberry.—There have been several shallow flowing wells at Newberry, on the low ground in the northwestern part of the village. These are now drained by deeper wells at the furnace and chemical works. The shallow wells pass through a thin bed of clay 6 to 18 feet, beneath which is a fine sand that changes to coarser at a depth of about 30 feet. The flows are of moderate strength, one being as high as 3 gallons a minute. The altitudes are 755 to 760 feet.

The well at the furnace, at an altitude of 760 feet, is 80 feet deep, and flows if pumping is discontinued for a few hours.

At the chemical works, 100 yards north of the furnace, are ten wells with depths ranging from 80 to 108 feet, all 6 inches in diameter. The first well was put down 128 feet and entered a hard material, possibly bed rock, for a few inches. The pipe was then pulled back to about 100 feet. All these wells will flow after a brief intermission from pumping. The water is sufficiently hard to form a coating of lime on the stills. It is struck at about 20 feet from the surface in fine sand under a clay bed. The sand increases in coarseness below, and for this reason the wells are extended to the depths named. The amount of water obtained seems unlimited. No temperature observations were taken, since the water is carried some distance through surface pipes before discharging.

At Harris's celery farm, in the northeastern part of Newberry, is a driven well 60 feet in depth, which formerly flowed, but now has a pump attached, the water scarcely rising to the surface. Near this well, at a railroad section house, is a well 765 feet above tide, which has flowed, but is now pumped. It was sunk in 1889 to a depth of 54 feet. The temperature of the water is 45° F.

On the Ryberg farm, about half a mile east of the wells just mentioned and at the same altitude, is a well 142 feet deep which is still flowing 3½ feet above the surface, discharging 3 pints a minute. The temperature is 45° F.

The public supply of the village of Newberry is from three 6-inch wells 110 feet in depth, which have a head of about 10 feet, the ground being about 15 feet above the level of the railroad station, or 780 feet above tide. The wells are through sand to a depth of 90 feet, where a bed of gravel is struck which furnishes an unlimited supply of water. It is of moderate hardness and carries but little iron.

Dollarville.—The Danaher Lumber Company has three flowing wells at the village of Dollarville, 2 miles west of Newberry, one of which has a flow of 10 gallons a minute; the other two are much weaker. There is a fourth well with water near the surface, but it has a pump attached. The strong well is located about 200 yards east of the railroad station at an altitude of about 725 feet above tide. It is thought to be 95 feet in depth and is 3 inches in diameter with a 1-inch discharge pipe. The water supplies several families and is piped to a livery barn. It has a slight iron taste and is moderately hard. The temperature is 45° F. A well about 300 yards farther east flows 3 quarts a minute and has a temperature of 46° F. The water carries considerable iron and stains boards and other objects over which it flows. The well is thought to be about 130 feet deep and appears to have struck rock at the bottom. Another well, now plugged, also appears to have reached rock at 120 feet; its water tastes of sulphur, which seems to indicate that it may be supplied in part from the rock. All the wells penetrate a bed of clay above the water bed.

South of Dollarville.—In a recess of the moraine 2 or 3 miles south of Dollarville are flowing wells at an altitude 15 to 20 feet higher than those in the village, or about 740 feet above tide. A prominent ridge stands between these wells and the village of Dollarville. The first well of this group was dug in 1889 on the John Carlson estate in the west part of sec. 9, T. 45 N., R. 10 W. It was through red clay nearly to the bottom, ending in sandy slush at a depth of 102 feet. The water barely rises to the top of the well, so a pump is now attached. About one-fourth mile east of this well and on slightly lower ground John Hunter has a strong flowing well 103 feet deep, which penetrated only 40 feet of red clay and was then in sandy slush to a gravel bed at the bottom. The water in this well rises at least 11 feet above the surface, or to fully 750 feet above tide. It once discharged a full stream from an inch pipe at an estimated rate of 20 gallons a minute, but now burst up around the pipe, thus lessening the discharge through the latter. The water is hard and carries a little iron. The temperature is 45 F°. There are several strong boiling springs near this well. About one-half mile southeast of the Hunter well, in the southwestern part of section 10, is a flowing well 103 feet deep on the farm of A. Pentland. It discharges 2 quarts a minute, with a temperature of 45.5° F. It was largely through red clay to sand at 90 feet. In the northwestern part of section 11, on the farm of John Peterson, is a flowing well 53 feet deep which yields a gallon a minute, the temperature being 45° F. This well was mainly through red clay to sandy slush at bottom, in which the pipe is suspended. If unsupported the pipe would sink several feet into the slush. About 300 yards east of the Peterson well, in the southwestern part of section 2, on the farm of John Swanson, is a flowing well 84 feet in depth. The altitude appears to be about 10 feet higher than that of the other flowing wells of this group, or 750 feet, and the head is only 2 feet above the surface, so a siphon is used to carry the water into a tub. This well passed through sand for its entire depth. A 3-inch hole was made, but the pipe is only 1¼ inches. The flow is 3 quarts a minute and the temperature 45° F. Near this well, along a small stream, are boiling springs covering an area several yards square, which probably have a similar source with the wells. Other strong boiling springs occur one-half mile south on the borders of a lake.

The flowing wells near Dollarville are the westernmost yet developed, but it is probable that flows can be obtained along the swamp westward across the divide between the Tahquamenon and Manistique drainage basins, and possibly throughout the southern part of the great swamp drained by Manistique River. The latter swamp is uninhabited and is so flooded with surface water that there is no occasion to test for flowing wells. The village of Germfask, which stands near the southeastern edge of the swamp, may, however, find it worth while to test for such wells.

ISOLATED WELLS IN BASINS.

It is probable that flowing wells may be obtained in small basins on the borders of lakes or in swamps.

Shelldrake.—One such well is reported to have been obtained in a swamp west of Shelldrake, in Chippewa County, at a lumber camp in sec. 28, T. 49 N., R. 7 W. It is only 16 feet deep and apparently passed through nothing but swamp muck to the sand bed that yields the flow. The swamp is surrounded by sand ridges rising 20 to 30 feet above it, and they probably serve as a catchment area and furnish the head.

Helmer.—Another isolated flowing well is at Helmer post-office at the east end of Manistique Lake, in the southwestern part of Luce County. The depth is 70 feet, and water is from gravel below clay. The head is at least 8 feet, or about 15 feet above Manistique Lake and 715 feet above tide. The water is piped into the hotel owned by Mr. Helmer. The natural rate of flow could not be determined, because a stone had become lodged at the bottom of the pipe, greatly obstructing the discharge. The temperature is 46° F. This lake is in a basin in a morainic belt, and it is probable that flowing wells can be obtained at other points on the shore.

ONTONAGON COUNTY.[a]

A flowing well 355 feet in depth was made by Mr. Geismar in 1893 near Ewen, Ontonagon County, in sec. 21, T. 48 N., R. 39 W. It is at about the same altitude as Ewen station—1,134 feet. It penetrated a pebbleless, gritless red clay for 125 feet, under which was found a gravel bed 13 feet thick, yielding a weak flow. A sandy clay slush was then struck, which extended to 354 feet, where gravel with a strong flow of water was found. The well discharged a full 1-inch stream 16 feet above the surface. The well is remarkable because of great variations in the temperature of the water. In the winter months this is about 44° F., but in the spring, about the time of the snow melting, a lowering of temperature is noted, which continues till about June 1, when it reaches 38° F. This low temperature continues well into the summer before a rise begins. Mr. Geismar refers the low temperature to the access of snow water to the bed of gravel from which the well flows.

There are three flowing wells at Ewen, belonging to the village, with depths of 208 to 224 feet. They penetrated red clay to the water-bearing gravel at the bottom. Beneath the gravel is a reddish rock, thought by the drillers to be granite. The wells flow with considerable strength.

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[a] Data furnished by Superintendent Leo Geismar, of the State experimental farm at Chatham, Mich.

FLOWS FROM ROCK.

NORTHERN BORDER OF LAKE MICHIGAN.

Occurrence.—Flowing wells have been obtained at several points near the Lake Michigan shore from St. Ignace westward to Manistique, and at various depths. So far as ascertained they are all from the rock, and there appear to be two or more horizons from which flows are obtainable. Part of the data concerning these flows are from the annual reports of the State geologist for 1901 and 1903, and the only interpretations as to geologic horizons are those presented by him. As already stated, the present writer had no opportunity to examine samples of well drillings nor to get accurate data on the formations penetrated. The flowing wells now obtained range in altitude from near lake level up to about 100 feet above, or from 600 feet or less up to about 680 feet above tide. It is not certain, however, that wells may generally be expected to flow to levels 100 feet above the lake. More likely the upper limit will be found to be generally within 50 feet above lake level. This opinion is based on the fact that some of the wells near lake level, such as those at Manistique, have not sufficient pressure to rise 50 feet above the lake.

St. Ignace.—Two deep flowing wells have been made in the vicinity of St. Ignace at an altitude of 20 feet above the lake, or 600 feet above tide, the first in 1887 and the second in 1901. In the first the Monroe beds extend down to about 500 feet and yield a small amout of bitter salt water. The Niagara and "Clinton" limestones extend 400 feet farther down, the Medina (?) sandstone being struck at 900 feet and penetrated 19 feet. In the second well, located about 2 miles north of the old one, in sec. 31, T. 41 N., R. 3 W., the Niagara is reached at 400 feet and supplies a flow of water from a depth of 575 to 681 feet and more at 1,040 feet. This well was stopped at 1,155 feet. The temperature of the flow was found to be 51° F., or about 6° above the temperature of shallow flowing wells, though 2° less than in wells of similar depth at Cheboygan and Alpena.

Engadine.—A strong flowing well was made in 1905 on the farm of Peter Praten north of Engadine, in sec. 4, T. 43 N., R. 10 W., at the altitude of Engadine station (674 feet). It is only 60 feet deep, but enters limestone for some distance. At the village of Engadine are two deeper wells, one of which, 206 feet deep, had a weak flow, and the other, 146 feet deep, had water nearly level with the surface. The deeper of these two was made by the lumber company in July, 1905, and flowed for a month or more, but became clogged with sand. The other, located at the mill, has never flowed. The sand is thought to work down into crevices in the limestone outside the pipe in the deeper well, thus choking it.

Deuels Lake.—The Simmons Lumber Company has an intermittent flowing well on the shore of Deuels Lake, about 10 miles southwest of Engadine, in sec. 23, T. 42 N., R. 11 W. The well is 108 feet in depth and is in limestone from a depth near the surface. The water rises 3 feet above the surface in the spring and early summer, but in the fall it drops below the surface, apparently on account of drought. The altitude is estimated to be scarcely 50 feet above Lake Michigan, and the well is less than 2 miles from that lake. It is probable that similar flows can be obtained along the shore of Deuels Lake at other points. Possibly a deeper well might obtain water with sufficient head to flow through the dry season.

Hunt Spur.—A well was made about 1890 by the Michigan Cedar Company at Hunt Spur, on the Soo Line Railroad, near the western border of Mackinac County, which discharged a stream with sufficient force to throw a jet 20 feet in the air. A hose was attached, and the flow was used in cleaning off logs. No data were obtained concerning the depth, but it is thought not to exceed 200 feet. The altitude of the well mouth is 684 feet, and the well is in limestone from a depth near the surface. Another well at a barn of the same company has a weaker flow.

Manistique.—There are several flowing wells in Manistique with depths between 200 and 300 feet and one (at the Hiawatha Hotel) with a depth of 800 feet. The shallower wells have a head in some cases about 16 feet above the surface, or 630 feet above tide, while the deep well at the Hiawatha Hotel is said to have a head 30 or 40 feet above the surface, or about 650 feet above tide. The State geologist in the report for 1903 interprets the horizon of the deep flow to be Trenton, and of all the others to be Niagara. The temperature of the shallower wells is 45° to 46° F., as noted by both the State geologist and the writer.

Several of the flowing wells are furnished with fire hydrants and are drawn on in case of fire, the yield by pumping being sufficient to supply all the water needed.[a]

SHORE OF BIG BAY DE NOC.

Garden Peninsula.—On the western side of Garden Peninsula, at Vans Harbor and Garden village, strong flowing wells have been obtained, concerning which the following data were furnished by the driller, George W. Gray, of Cooks Mill, Mich.:

Flowing wells on Garden Peninsula.

Owner.	When made.	Altitude.	Depth.	Diameter.	Flow per minute.	Head.	Remarks.
		Feet.	*Feet.*	*Inches.*	*Galls.*	*Feet.*	
L. Van Winkle	1905	590	233	5	60	+18	The only flow at Vans Harbor. Cased 40 feet; limestone at 18 feet under bowldery clay.
W. Stillwagen	1902	592	175	....	40	+16	Deepened an old well 82 feet. First flow at 107 feet; stronger flow at 173 feet. Used for fish pond and house.
Bondreau & Disco	1903	588	199	5	30	+18	Two water beds, as in preceding well. Limestone under bowldery clay at 20 feet. Cased 38 feet and at a leakage at 60 feet.
Garden village:							
No. 1	1902	593	195	....	25	+ 6	Limestone under red clay and sand at 14 feet. Cased 52 feet. Flow weaker than 25 gallons July to October and January to April.
No. 2	1903	595	220	....	....	....	Now plugged because it drained well No. 1, but water comes up around pipe. Main flow at 193 feet.
No. 3	1905	588	104	5	8	....	Drift, very bowldery at 12 feet.

The decrease in the flow of the village well No. 1 seems referable to drought in the late summer and the frozen condition of the ground in the winter. The second village well, although on slightly higher ground, apparently has an advantage over the first by drawing water from a lower depth.

Conditions seem very favorable for obtaining flowing wells along the Lake Michigan slope of the Garden Peninsula, but no instances of the occurrence of such wells came to the writer's notice. The shore rises gradually back from the lake and the flowing-well belt should extend a mile or more inland.

Nahma.—At Nahma, on the western side of Big Bay de Noc, opposite Garden, are two flowing wells made by the Big Bay de Noc Lumber Company. One sunk in 1883 is 133 feet deep, 2 inches in diameter, and flows scarcely a gallon a minute. It ends in limestone. Another sunk in 1895 is 80 feet deep, 4 inches in diameter, and will fill a barrel in about five minutes. It does not enter rock.

Probably flowing wells are obtainable at moderate depths both along the shore of the bay and up the Sturgeon River Valley, but no others have come to the writer's notice.

[a] The city is now (1905) building a waterworks plant which will obtain water from Indian Lake, which lies about 3 miles to the northwest.

BORDER OF LITTLE BAY DE NOC.

Rapid River.—In the village of Rapid River, at the head of Little Bay de Noc, several flowing wells are in operation and two flows have been obtained in test wells for oil several miles north of the village, which show a possible extension of the district in that direction. It is probable that flowing wells may be obtained along the entire western side of the bay on ground below the 600-foot contour, and in places at higher altitudes, as in the Hendricks boring noted below.

Flowing wells at Rapid River.

Owner.	Location.	When made.	Altitude.	Depth.	Flow per minute.	Temperature.
			Feet.	*Feet.*	*Galls.*	*° F.*
A. Conner	East of Main street	1895	588	270	0.75	46.8
H. W. Coles	.....do	1897	586	258	2.00	45.0
Village No. 1	Main street	1897	588	273	4.00	45.5
Village No. 2	West of Main street	1898	590	275	1.5	45.5
Dr. A. Laing	.....do	1903	590	273	2.0	45.5
A. Schaible	.....do	1904	588	273	6.0	45.2
A. Bodah	North part of town	1899	590	275	....	....
Mrs. J. Fish	Half mile west	1897	593	273	....	....
School well	Masonville	1905	590	....	....	....

The wells at Masonville, which are located a mile southwest of Rapid River, and the Fish and Bodah wells in Rapid River, were not visited. The head was not determined in any of the wells, though it is known to exceed 8 feet, some of the wells having been carried to that height without reaching the full limit.

The two oil-well borings, 7 miles north of Rapid River, in sec. 34, T. 42 N., R. 21 W., were each drilled to a depth of 800 feet or more. Samples inspected by the State geologist form the basis for the following interpretation of the strata penetrated:

Hypothetical log of Rapid River oil well.

	Thickness.	Total.
	Feet.	*Feet.*
Swamp, peat, and muck	6	6
Marl	10	16
Trenton limestone with geodes	264	280
St. Peter (?); Undifferentiated "Calciferous" } with strong flow of water, temperature 47.3° F	350	630
Potsdam sandstone (white)	80	710
Potsdam sandstone (red)	50	760
Feldspathic sandstone (Potsdam)	10	770
Micaceous red sandstone (Potsdam)	30	800
Decomposed chloritic schist, like Archean rocks, at bottom.		

Gladstone.—At the furnace in the northern part of Gladstone there are several flowing wells which range in depth from 230 to 700 feet and have diameters of 4 and 6 inches. They are about 5 feet above lake level, and one has a head 27 feet above the lake, or 607 feet above tide. There are two horizons from which flows are obtained, one being at about 230 feet and the other about 700 feet, with small quantities of water at intervening levels. The lowest water horizon is reported to be the strongest and the water is thought to be softer than in wells of shallower depth. This, however, was not verified by chemical analyses. The earliest well was made about 1899 and others have been sunk from time to time as needed.

Temperatures reported by Lane are found to range from 44.9° to 49.3° in the different wells, the highest being in a well 500 feet deep.

At a boarding house kept by Mrs. Martin adjacent to the furnace is a well 230 feet deep and 4 inches in diameter, made in 1902, which yields a moderate flow.

At the roundhouse in the western part of Gladstone a well made by the Minneapolis, St. Paul and Sault Ste. Marie Railway in 1903 reached a depth of about 700 feet and obtained a strong supply of water at 690 feet, which stands a test by pumping of 150 gallons a minute and has a hardness of 5.86° on Clark's scale. The water rises to 12 feet below the surface or about 600 feet above tide, the railroad station near by being 612 feet. The following record appears in the report of the State geologist for 1903:

Log of railroad well at Gladstone.

	Thickness.	Total.
	Feet.	*Feet.*
Sand	51	51
Clay and hardpan	10.5	61.5
Sand and gravel	15	76.5
Clay and limestone bowlders	14.5	91
Trenton limestone	234	325
Sandstone and limestone (St. Peter?)	89	414
Undifferentiated "Calciferous" limestone	228	642
Potsdam sandstone	100	742

Hendricks.—A boring in sec. 8, T. 41 N., R. 24 W., obtained a weak flow from a reddish sandstone which was struck at 350 feet and penetrated for 146 feet. It is a 4-inch well and was made in the winter of 1901–2, at a cost of about $1,000.[a]

WEST SHORE OF GREEN BAY.

Several flowing wells have been sunk in the cities of Escanaba and Menominee, Mich., as well as at cities and villages on the borders of Green Bay in Wisconsin. The flows are partly from the St. Peter sandstone and partly from the Potsdam. Possibly the sandy beds of the "Calciferous" also yield flows, and they may be obtainable from the Trenton limestone at certain points. The few data here presented are from the annual report of the State geologist for 1903:

Log of Wagner well near Escanaba.

	Thickness.	Total.
	Feet.	*Feet.*
Drift, gravel, and clay	9	9
Lorraine (Hudson) shale	192	201
Utica bituminous shale	50	251
Trenton limestone, with geodes or quartz inclusions, at 406 and 457 feet and shale at 485–489 and 518–522 feet	271	522
St. Peter sandstone (in part)	38	560
St. Peter shale	2	562
Undifferentiated "Calciferous" limestone, etc	78	640

[a] Reported by J. M. White, Wells, Mich.

In a recent well near by, a broken formation, perhaps the conglomerate of the Archean quartzite, was struck at 860 to 900 feet; above it was a good body of sandstone.

A flowing well at Flatrock near Escanaba is reported to be 800 to 900 feet deep.

At Menominee S. M. Stephenson has a flowing well in town and another on his farm 3 miles west. The latter is 720 feet deep on ground 30 feet above Lake Michigan and has a head of only 1 foot. Water was found at various levels, but the main supply is at 620 feet. The water of the town well has a temperature of 55.5° F., but no data as to depth of the water bed are reported. A well near the Stephenson Hotel in Menominee is thought to be in Potsdam sandstone, but no definite data are given as to depth, the statement being 500 to 1,000 feet.

There are a number of other flowing wells in Menominee, Marinette, and Escanaba, but the writer is not in possession of data concerning them.

LAKE SUPERIOR SHORE.

Grand Marais.—A deep boring was made at Grand Marais a few years ago, with the expectation of obtaining a flowing well. It is on ground about 30 feet above Lake Superior. It penetrated 100 feet of drift before entering Potsdam sandstone, and was carried 1,100 feet into that rock. The water, though abundant and of good quality, will not overflow, and in consequence no use is made of it. The dip of the rock formations being southward from the shore of Lake Superior, the underground flowage is probably in that direction, or away from the lake shore. This being the case, the further testing of this shore for flowing wells can not be encouraged.

NONFLOWING WELLS.

In the districts where flowing wells can not be obtained a number of records were collected which throw light on the distance to water, and in some cases on the head. In general it may be stated that an exceptionally good water is obtainable, at moderate depths, throughout the part of the northern peninsula underlain by Cambrian and Silurian rock formations. It need scarcely be stated that it is decidedly softer in the sandstone districts bordering Lake Superior than in the limestone districts bordering Lakes Michigan and Huron, a feature which also characterizes the lakes. The water table, except in prominent glacial and limestone ridges and elevated gravel and sand plains, is near enough to the surface to be easily reached by dug wells, a common depth being 20 to 30 feet. Probably 80 per cent of the farm wells are less than 30 feet in depth. The records collected are mainly of wells of exceptional depth, no attempt having been made to compile a complete list. In the statements which follow, the well districts are taken up in order from east to west.

CHIPPEWA COUNTY.

Sugar Island.—On Sugar Island wells are 15 to 25 feet deep. On clay plains they penetrate to underlying sand and gravel, while on gravelly ridges they go down about to the level of the bordering plains.

St. Marys River.—Along St. Marys River from Sault Ste. Marie to the mouth of the Munuscong the wells are generally only 15 to 30 feet in depth, corresponding to their altitude above the river. There are, however, places where a solid bed of clay extends some depth below the river level, as indicated in the following table:

Wells along St. Marys River.

Owner.	Location.			Altitude.	Depth.	Head.	Remarks.
	T. N.	R. E.	Sec.				
				Feet.	*Feet.*	*Feet.*	
B. Gilroy	47	1	22	620	60	−18	Sand 12 feet, red clay 45 feet, gravel and sand 3 feet.
Do	47	1	22	615	77	−10	Section same as preceding.
Sam Preslon	47	1	22	615	70	−10	Clay to water bed in gravel at bottom.
D. F. Grier	46	1	22	610	70	{ − 2 −25	Head at first near surface, but now 25 feet below.
J. W. Hinds	46	1	13	590	100	....	No water obtained. Clay to bottom.
John Baylus	46	1	25	600	80	− 4	Sand 9 feet, clay to gravel at bottom.
J. Wright	46	1	26	600	78	− 4	Sand 7 feet, clay 68 feet, gravel 3 feet.

Wells on the high plain above the Nipissing beach, south of Sault Ste. Marie, at altitudes between 670 and 700 feet above tide, are from 35 to 100 feet in depth, and obtain water from gravel or sand under a laminated, nearly pebbleless, clay. The head is generally 30 feet or more below the surface. Temperatures wherever tested were 45° F. or slightly less.

Pickford.—Wells on the gravelly table-land northwest of Pickford are 55 to 75 feet or more in depth when at an altitude of about 775 feet, and the water rises but little in the wells.

Wellsburg.—On the high sandy plain at Wellsburg, at an altitude of 225 feet above Lake Superior, a well was sunk by the railroad company in 1885 to a depth of 280 feet, entirely through sand. The water rises to —45 feet, or about 180 feet above the lake. A well in the ravine south of the station, about 15 feet lower, obtains water at only 25 feet depth. North of Wellsburg on the same plain are wells 100 to 160 feet in depth. A well on the Van Leuven homestead in sec. 25, T. 47 N., R. 4 W., on a morainic ridge overlooking Lake Superior, and at an altitude about 225 feet above lake level, is 140 feet in depth.

Rexford.—At Rexford, on a high sand plain about 325 feet above Lake Superior, a well was obtained at only 45 feet, and a similar well was obtained at the target range, about a mile west of Rexford. South of these high sand plains, in the vicinity of Trout Lake and Alexander, wells are obtained at slight depth, much of the region being swampy.

Shelldrake.—At Shelldrake, on the shore of Lake Superior, a boring was sunk by Colonel Culhane to a depth of 250 feet without reaching rock, although at an altitude of only 5 feet above Lake Superior. It passed through clay with associated thin beds of sand and obtained a weak supply of water with a head of 60 feet. Several wells in Shelldrake are from 75 to 85 feet, there being but little water obtainable at less than 75 feet.

LUCE COUNTY.

Newberry and vicinity.—In the vicinity of Newberry several deep wells have been made on elevated ground, at the State Insane Asylum, and on surrounding farms. One well at the asylum, 457 feet deep, struck rock (limestone) at 320 feet, and entered shale in the lower 70 feet. Water is from near the top of the limestone, and the well will yield by pumping 200 gallons a minute. It has a diameter of 7½ inches. The head is —104 feet, and the altitude of the well mouth about 865 feet. Another asylum well is 245 feet, and there are four wells 186 feet in depth. All these wells struck the first water bed at a depth of about 100 feet, and there is little if any rise of water, that depth being apparently the level of the ground-water table. Other wells have been made at wood camps on the asylum property, 1 to 2 miles south and east of the buildings, one well being 100 feet and another 170 feet deep. The deeper well penetrated sand 100 feet and below this a blue hardpan 65 feet, obtaining water in sand under the hardpan. The altitude of these wells is about the same as that of those at the institution. At a schoolhouse near the asylum the well has a depth of 138 feet. A partial analysis of water from a well adjacent to the asylum grounds, made in 1893 by Doctor Nicholson of Newberry, showed the presence of only 65 parts per million of calcium and magnesium carbonates, and but a trace of iron, while chlorides seemed to be entirely absent. The depth of this well is 128 feet and the head —110 feet.

About 2 miles west of the asylum, on a prominent knoll of similar altitude, are three deep wells. One at a schoolhouse, in the western part of section 9, is 192 feet deep and has a head of —135 feet. It was largely through sand. Across the road, in section 10, at the residence of John Templeton, is a well 196 feet deep, with a similar head. About a mile northeast of these wells A. Carlson made a well 150 feet in depth, with a head of —130 feet. The altitude of these three wells is about 850 feet. Another well on lower ground (760 feet above tide), in the southeastern part of section 4, has a depth of 106 feet and a head of —26 feet. There were nearly 20 feet of clay near the top, but the remainder was through sand.

At a limestone quarry 12 miles southeast of Newberry (sec. 6, T. 44 N., R. 8 W.) are two wells 100 feet in depth, with a head 80 feet below the surface. The altitude of the wells is about 900 feet. An analysis of the boiler scale, made by the Dearborn Drug and Chemical Company, Chicago, gave the following proportion of mineral constituents:

Analysis of boiler scale from quarry well water.

	Per cent.
Silica	3.20
Oxides of iron and alumina	1.16
Calcium carbonate	80.08
Magnesium carbonate	14.01
Calcium sulphate	1.40
Loss, etc	.15
	100.00

McMillan.—At McMillan the schoolhouse well has a depth of 80 feet and an altitude of 785 feet. The water is from sand under clay. The well at the cooperage company's mill, on ground 35 feet lower, is 60 feet in depth and has a head of —16 feet.

Manistique Lake.—North of Manistique Lake are several wells nearly 100 feet in depth. One at the schoolhouse in sec. 29, T. 45 N., R. 12 W., is 96 feet and has a head of —60 feet. It entered limestone at 40 feet. Jerry Holland has a well on the eastern side of section 30, which is 85 feet deep and enters limestone at 18 feet. The head is —20 feet. Across the road, in section 29, at the residence of Charles McKenna, is a well 86 feet deep, on ground about 35 feet higher than the Holland well. It has a head of —56 feet and entered limestone at 40 feet. John Richards has a well in the southern part of section 21 with a depth of 76 feet and a head of —68 feet. It penetrated clay for 12 feet and sand for 64 feet, striking rock at the bottom.

A well east of Little Manistique Lake on the farm of J. Fyne, in sec. 17, T. 45 N., R. 11 W., with a depth of 58 feet, has a head of only —7 feet. It penetrated clay 40 feet, below which was a sandy gravel.

MACKINAC COUNTY.

Wells on the Niagara limestone, in southeastern Mackinac County, are often sunk to depths of 60 to 75 feet, and in most cases there is little rise of the water.

Palms.—At Palms (Kenneth post-office) are two wells 108 and 117 feet in depth, made by W. J. Ross, which have an altitude of 795 feet and a head of —35 feet. Another well at Leonard's mill, at an altitude of 770 feet, is 75 feet deep and has a head of —8 feet.

Ozark.—On a limestone hill east of Ozark, a well having an altitude of about 875 feet, reached a depth of 100 feet. Farther south, near Allenville, wells are difficult to obtain, because of the large amount of shale in the Monroe beds, and borings 100 to 150 feet are not rare.

Lewis and Rex.—In wells in the vicinity of Lewis and Rex, water is obtained at very shallow depths, although the altitude is about 860 feet. Those at Lewis are from sand at about 16 feet. Some near Rex enter rock at 10 feet, but others are entirely from sand.

Gilchrist.—At Gilchrist, at an altitude of 780 feet above tide, the railroad company made a well 1,180 feet in depth, which entered rock at 80 feet and has a head of —70 feet.

West end of county.—From Millecoquins Lake southwestward past Engadine and Gould to Corinne nearly all the wells enter rock at slight depths. The shallowest are about 40 feet and the deepest over 200 feet, the common depth being about 80 feet. The water seldom rises to more than 40 feet below the surface. A test boring made at Corinne in 1888, for the purpose of obtaining a flowing well, reached a depth of 180 feet and had a head of —25 feet, or 748 feet above tide. A well at Ferguson's store, in Gould, is 116 feet deep and has a head of —12 feet, or 724 feet above tide. The majority of wells around Corinne and Gould are 65 to 80 feet in depth. Deep flowing wells at Engadine have already been discussed (p. 43), and also the flowing well at Deuels Lake (p. 43).

SCHOOLCRAFT COUNTY.

Seney.—At Seney wells were made some years ago, with a depth of 110 to 115 feet, which obtained a strong supply but not a flow.

Germfask.—East of Germfask are wells about 80 feet deep, on the Stafford farm, in sec. 12, T. 44 N., R. 13 W., with a head of —45 feet. A well on Thomas Kennedy's farm, on section 14 has a depth of 70 feet and very little rise of water. A neighboring well at S. Burns's residence, on a high ridge in section 15 has a depth of only 14 feet.

Blaney.—The William Mueller Lumber Company, of Blaney, sunk a well 214 feet for the purpose of procuring a supply for waterworks, but an insufficient and unsuitable supply was obtained. The water tastes "like bog ore." The supply is partly from a depth of 42 feet and partly from near the bottom of the well. The head is about 40 feet below the surface. There were 113 feet of drift and 101 feet of shale. The following drift beds were penetrated: Clay loam and sand, 15 feet; quicksand, 26 feet; gravel, 4 feet; blue bowlder clay with sand streaks, 68 feet.[a]

Manistique.—On a table-land east of Manistique wells are 30 to 60 feet in depth without reaching rock. The deeper wells are near the edge of the table-land, and are reported to be entirely through sand.

Hiawatha.—In the Hiawatha settlement, about 12 miles north of Manistique, wells are 40 to 65 feet in depth, through gravel and sand, and there is very little rise of water, the ground-water table being about 40 feet below the surface, or near the level of the small lakes which occur in that region in basins in the gravel plain.

Indian Lake.—On each side of Indian Lake, from a point near Manistique to Cooks Mill, is a limestone district in which wells are often 50 to 75 feet in depth, and have very little rise of water, the ground-water table being near the level of Indian Lake.

DELTA COUNTY.

Garden Peninsula.—On Burnt Bluff, on Garden Peninsula, are two wells 228 feet in depth, which have a head of —203 feet, which is about at the Lake Michigan level. Rock was entered at 3 feet. Several wells in that vicinity are 100 to 140 feet in depth. Rock is usually entered at a depth of 30 feet or less on Garden Peninsula, and in some cases wells are carried to 25 to 30 feet below Lake Michigan level before a strong supply is obtained[b].

St. Jacques.—At St. Jacques the hotel well is 35 feet in depth and obtains a supply from gravel under a bed of sandy loam. Two dug wells near the hotel are only 26 feet in depth,

[a] Data furnished by George W. Gray, driller, Cooks, Mich.
[b] Data on Garden Peninsula furnished by George W. Gray, driller.

but a well one-fourth mile east on slightly higher ground is 65 feet deep. The altitude is 15 to 25 feet higher than at the railroad station, or 630 to 640 feet above tide.

Ensign.—At Ensign rock is struck at about 10 feet, but wells are usually obtained at the base of the drift, the rock being a shale with very little water.

ALGER COUNTY.

From the head of Little Bay de Noc northward to Lake Superior is a district in which rock is found at shallow depth, usually less than 20 feet, and wells are obtained either at the base of the drift or at a moderate depth in the rock, a well more than 40 feet in depth being rare. The altitude near the head of Little Bay de Noc is only about 600 feet above tide, but on the brow of the calciferous escarpment in the vicinity of Rumely, Lawson, and Carlshend it is 1,050 to 1,150 feet, yet the water table is sufficiently near the surface to furnish wells at very slight depth.

MENOMINEE COUNTY.

The drift is also of moderate depth west of Little Bay de Noc and Green Bay, in Delta and Menominee counties, and wells are usually obtained at the base of the drift or in the upper portion of the rock at depths of 40 feet or less. The drift is a sandy or clayey loam with thin beds of clear gravel or sand associated with or underlying it.

MARQUETTE COUNTY.

In eastern Marquette County, from Little Lake northward to Harvey and Mangum, is a belt of very heavy drift in which wells 90 to 200 feet in depth have not reached rock, while a boring to test for iron ore near Little Lake found rock at a depth of about 250 feet. A well at S. C. Miller's, in the southwestern part of sec. 35, T. 47 N., R. 25 W., at an altitude of about 1,150 feet above tide, is 205 feet in depth, and strikes water at 191 feet. It was mainly through sand, though there is a little clayey material near the surface. The water does not rise above the level at which it was struck. Mr. Miller has a shallow well only 18 feet in depth, which gives out in dry seasons. A neighboring well on the farm of James Kindlen is 184 feet in depth; in it the water stands at 164 feet below the surface. The altitude is slightly lower than at Miller's, being probably 1,130 feet above tide. This well is thought to have struck bed rock at the bottom, though it may perhaps have been merely a cemented crust in the drift, for the Miller well penetrated a crust at 186 feet. Both these deep wells are on a prominent moraine, about 2 miles northeast of Sands station, on the Chicago and Northwestern Railway. A few miles farther north, on the same moraine, a well was made some years ago at Frazier's lumber camp, in sec. 21, T. 47 N., R. 25 W., 190 feet in depth, which penetrated only gravel and sand. It is at an altitude of over 1,200 feet. Near this well in the southwestern part of section 16, at an altitude only a few feet lower, is a shallow dug well having water standing within 10 feet of the surface, thus repeating the conditions noted at the Miller wells.

On a moranic ridge west of Mangum are several wells 80 to 90 feet deep on the farms of James Barry, Carl Whitler, William Preab, and Mr. Huebner. They penetrate a large amount of white sand, but in some cases pass through a thin bed of bowlder clay at the surface and another near the bottom of the well.

In the vicinity of Skandia wells are 30 to 50 feet in depth and in some cases enter rock near the bottom.

PUBLIC WATER SUPPLIES.

About half the population of the Northern Peninsula is found in cities and villages provided with public water supply. The sources of supply set forth in the table below are chiefly from surface water, only a few villages drawing a public supply from wells. This is a natural condition, in view of the contiguity of large bodies of fresh water, and, in most cases, the supply is fully as good as can be obtained from underground sources. The principal danger appears to be that of sewage contamination around the intake pipes, and this may be guarded against by placing these pipes out of reach of the sewage.

Municipal and institutional water supplies.

Town.	Population, 1900.	Ownership.[a]	Source.	System.[b]	Remarks.
Atlantic mine	±3,000	P.	Creek and well		Partial domestic supply from well.
Baraga	1,185	P.	Keweenaw Bay		
Bay Mills	1,000	P.?	Whitefish Bay	T.	
Beacon	±1,500	M.?	(?)		Hydrants for fire.
Bessemer	3,911	M.	Springs and impounded water.		Springs for domestic use.
Blaney	± 300	P.	Creek		Operated by lumber company.
Crystal Falls	3,231	M.	Impounded water		Also supplies Vulcan.
Dollar Bay	±1,500	P.			Partial distribution for employees of Lake Superior Mining Co.
Escanaba	9,549	P.	Little Bay de Noc	D.	Filtration works planned.
Ewen	500	M.	Flowing wells		
Garden	465	M.	Rock wells, 104-220 feet		Partial system.
Gladstone	3,380	M.	Little Bay de Noc	D.	
Grand Marais	2,000	M.	Lake Superior	D.	
Hancock	4,050	M.	Filter gallery	R.	Manual American Waterworks.
Houghton	3,359	M.	Springs	R.	Reservoirs, high pressure and low pressure.
Iron Mountain	9,242	P.	Infiltration wells	R.	The wells are developed springs.
Iron River	1,482	M.?	Iron River		
Ironwood	9,705	P.	Montreal River	T.	Manual American Waterworks.
Ishpeming	13,255	M.	Small lake	G. and D.	Do.
Lake Linden	2,597	M.	Well and creek	D.	Do.
L'Anse	620	M.	Spring-fed creek	G.	Do.
Laurium and Red Jacket.	10,311	P.	Lake Superior	D.	Do.
Mackinac Island	665	P.	Lake Huron	R.	
Manistique	4,126	M.	Indian Lake	G. and D.	Runs to reservoir in city.
Marquette	10,058	M.	Lake Superior	D.	High parts of city have private tanks.
State prison	[c] 300	St.	Small stream		
Menominee	12,818	P.	Green Bay	D.	Manual American Waterworks.
Munising	2,014	M.	Springs, and Lake Superior.	T.	Lake Superior for emergency.
Negaunee	6,935	M.	Teal Lake	D.	Manual American Waterworks.
Newberry	1,421	M.	Tubular wells	D.	Data given above.
State asylum	[c] 600	St.	do	T.	Do.
Norway	4,170	M.	Impounded water	R. and D.	Manual American Waterworks.
Ontonagon	1,267	M.	Lake Superior	T.	Do.
Palmer	799	P.	Springs and wells	WM.	Partial system.
Quinnesec	600	M.	Mine water		Chiefly fire protection.
Rapid River and Masonville.	±1,200	M.	Rock wells, 275 feet	D.	Fire hydrants on flowing wells.
Republic	±2,500	M.?	Springs and lake		Installed in 1906.
Rockland	±1,000	P.	Springs	WM.	Partial system.
St. Ignace	2,271	M.	Lake Huron	T.	
Sault Ste. Marie	10,538	M.	Whitefish Bay	T.	Base of tank 114 feet above Lake Superior.
Stambaugh	695	M.	Iron River	D.	Manual American Waterworks.
Vulcan	2,000		Impounded water		Supplied from Norway.
Wakefield	1,191	M.	Sandy Lake		Fire protection.

[a] Abbreviations under ownership as follows: P=Private; M=Municipal; St.=State.
[b] Abbreviations under system as follows: T=Tank or standpipe; R=Open reservoir; G=Gravity; D=Direct pressure; WM=Windmill.
[c] Population in 1906.

QUALITY OF WATER.

Analyses of Lake Superior water have been published by the State geologist in the annual report for 1903, pages 113 to 118, and analyses of water from Green Bay on pages 119 to 120, while several analyses of Lake Michigan water appear in Water-Supply Paper No. 31 of the United States Geological Survey. The sanitary analysis of a flowing well at Menominee also appears in the annual report of the State geologist for 1903, pages 121 to 122. It appears from these analyses that the hardness of the waters in Lake Michigan and Green Bay is about twice that of Lake Superior, being 7° to 9° or more on Clark's scale, while on Lake Superior it is only about 3° in several of the analyses.

DRAINAGE OF WET LANDS IN ARKANSAS BY WELLS.

By A. F. Crider.

INTRODUCTION.

The disposal of surface waters and sewage in level countries where there is insufficient natural drainage, has long been a serious problem, and one that is becoming more pressing as the country becomes more thickly settled.

The method of drainage into the underlying subsoil by means of wells is not new, although little practiced in the United States. It has long been successfully used in the low provinces of France, and it was tried in Michigan as long as twenty-five years ago. Here, however, it was found to be impracticable, at least so far as the subsoil and shallow wells were concerned. Later, success was attained by the use of deep wells. Such wells will often penetrate sandy strata into which the water from overlying strata can be drained, thus lowering the ground-water level. In the Coastal Plain, where there are numerous porous strata of sand alternating with beds of clay, the possibility of reclaiming swampy districts by such well drainage is promising and at least deserves a thorough test.

WELL DRAINAGE IN OTHER STATES THAN ARKANSAS.

DRAINAGE BY WELLS IN MICHIGAN.

On the retreat of the glaciers a large part of Canada and the northern United States was left covered with glacial accumulations. In places large areas were left with a very irregular surface, marked by numerous sink holes, ponds, and lakes. The glaciated area, in places, had little relief, so that many of these ponds and lakes are still undrained.

In the spring the heavy rains and melting snows fill these undrained depressions to a depth depending on the area drained and the amount of precipitation. Many of the larger ponds contain more or less water throughout the year. The soil in these depressions is very fertile, and when drained becomes of great value for farming. An attempt was made about twenty-five years ago, in Parma Township, Jackson County, Mich., to drain one of these depressions into the subsoil underlying the surface hardpan. The attempt failed, but within the last few years a large number of ponds in Jackson County have been drained into the underlying porous strata by means of deep wells. The methods used and results obtained have been described by Robert E. Horton in Water-Supply Paper No. 145, pages 30 to 39. Mr. Horton describes a deep-drain well on Fred Watkins's place in Parma Township. The well is located in the center of a pond, which drains about 35 acres of sloping tilled land of permeable gravelly loam. The water covered an area of about 2½ acres, and rarely dried up. When first drilled, the well was stopped in the first water bed at a depth of about 90 feet, and the unprotected open pipe was allowed to project upward in the water near the surface. The water was drawn down very rapidly at first, but was soon greatly checked by organic material which clogged the pipe and perhaps the water bed at the bottom of the well. Two months of flow failed to drain the pond. This result being unsatisfactory, the well was drilled to a depth of 170 feet and the top of the pipe protected with a screen. In a short time the pond was completely drained.

DRAINAGE BY WELLS IN GEORGIA.

During the summer of 1903 Mr. S. W. McCallie, in cooperation with the United States Geological Survey, made some valuable experiments in Quitman, Ga., on the drainage of sewage into deep wells.

A well was bored to improve the city's water supply. At a depth of 123 feet the drill entered an apparent opening in the limestone 6¾ feet deep and the water immediately rose to within 77 feet of the surface. Efforts were made to lower it by continuous pumping, but without success. It was likewise found that large volumes of water could be forced into the well without raising the static head above 77 feet below the surface. The well was then bored deeper and a second water-bearing horizon encountered at a depth of 321 feet.

To test the carrying capacity of the upper water-bearing stratum, a second well, 6 inches in diameter, was bored near Russell's pond, a stagnant pool, the water from which was drained into the well. About one-half million gallons of water were drawn down in a few hours without raising or lowering the static head of the water, which stood at 77 feet below the surface.

The town authorities concluded that the underground water course could be used for carrying away the city's sewage. The results of an elaborate experiment carried on by Mr. McCallie, however, proved conclusively that a pollution of the other wells would result from such a procedure, and the proposed disposition of the sewage was therefore abandoned.

DRAINAGE BY WELLS IN ARKANSAS.

In the Coastal Plain of northeastern Arkansas are millions of acres of flat lands, occupied by swamps, old sloughs, and shallow lakes. Thousands of acres of this area are covered with water in the spring and early summer, and thereby made worthless for agricultural purposes. Attempts have been made in a few instances to drain small portions of this area by means of deep wells, but the difficulties encountered have not been overcome, and the success of the work is still much in doubt.

TOPOGRAPHY OF THE AREA.

The area of northeastern Arkansas, extending from the Paleozoic hills to Mississippi River, is a level plain, with a minimum elevation of about 100 feet at the mouth of Arkansas River on the south and of 296 feet near the Missouri line. The monotony of the surface is broken by Crowleys Ridge, a low swell, from 1 to 12 miles wide, extending from Commerce, Mo., to Helena, Ark. The highest points of the ridge are about 120 to 140 feet above the flat lands on either side.

West of the ridge the country is diversified with wooded lands, prairies, and broad swells 15 to 20 feet above the general level. These low ridges have a general north-south direction roughly parallel to Crowleys Ridge. The region is drained by White River and its tributaries, Black, Cache, and L'Anguille rivers. East of the ridge the country is much flatter. St. Francis and Mississippi rivers are the only streams of any importance. The St. Francis and its tributaries are very crooked and have very little grade. In many places near the Missouri line St. Francis River is little more than a series of broad lakes. The country is known as the "sunken lands" of St. Francis River. The numerous lakes were caused by the earthquakes of 1811 and 1812.

After a long rainy season the country east of Crowleys Ridge is completely inundated. There is not enough drainage to carry off the water in rainy seasons, so it collects in the lower lands and often remains for months. The great amount of water is a hindrance in the spring to putting in the crops, and occasionally destroys them after they have become more or less mature.

CHARACTER OF SURFACE STRATUM.

A large area adjacent to Crowleys Ridge on the west and a narrow fringe on the east have a thin surface stratum of light-gray sandy clay nearly impervious to water and containing numerous nodules of limonite. Along the present streams and old water courses of the entire region, the limonitic hardpan has been removed or covered with stream alluvium, consisting of fine silt and sand. The clay, therefore, where not present as a surface stratum, spreads over the region as a subsoil. The nodules of limonite and the impervious clay soils have given rise to the terms "buckshot" and "slash lands." On the higher ridges, the clay loam is very similar to the Columbia formation, and is doubtless the reworked product of the loess and Columbia, which are present on the top and sides of Crowleys Ridge.

CHARACTER OF THE UNDERLYING STRATA.

The material underlying the surface hardpan consists of interstratified beds of sands and clays. The following are typical well sections, which show the relations of the strata underlying the surface clay:

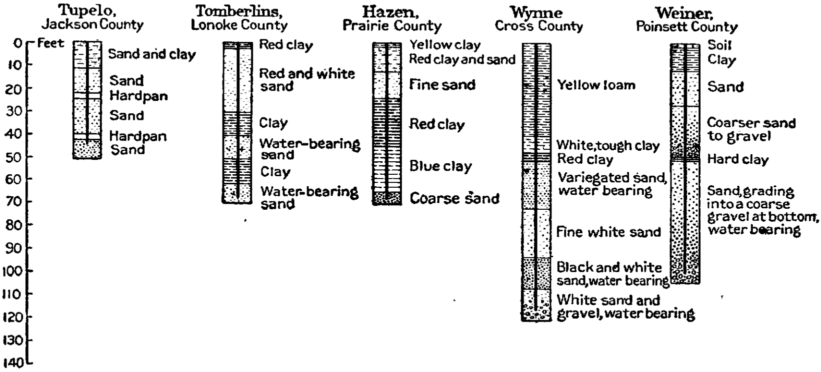

FIG. 4.—Well sections west of Crowleys Ridge in Arkansas, showing the variation of the strata and the source of the well waters in different localities. The Tupelo section is after Purdue.

DEPTH OF STANDING SURFACE WATER.

The depth of the water on the lowlands depends on the amount of rain and the elevation of the area compared to the surrounding country.

The average amount of rainfall of northeastern Arkansas is usually between 40 and 50 inches a year. After weeks of continuous rain, especially in the spring, the streams become swollen and the water often covers the lowlands to a depth of 1 to 10 feet.

In May and June, 1905, much of the country between Blytheville and Jonesboro was covered with water to a depth of from 6 inches to 2 feet. West of Crowleys Ridge, between Jonesboro and Wynne, is a flat swampy area which is usually covered with a thin sheet of water that rarely dries up early enough in the spring to permit cultivation. In this region deep-well drainage has been tried.

HEIGHT OF THE WATER TABLE.

The height of the water table varies in different parts of the area and in different seasons of the year. There are in most places three water horizons, the first at a depth of 18 to 20 feet, the second at from 30 to 40 feet, and the third at from 50 to 60 feet. Water in most places is obtained at the base of the surface clay loam.

During the dry season of the year the water rises in the wells to within 12 to 15 feet of the surface; in the wet season it stands within 3 to 5 feet of the surface, and occasionally rises to the top.

NUMBER OF WELLS NECESSARY TO DRAIN AN ACRE.

The well owned by Fred Watkins, in Parma Township, Jackson County, Mich. (see p. —), drains about 35 acres; but this is in the center of a depression, and the water has a tendency to collect about the mouth of the well. In Arkansas the conditions are somewhat different. The entire country on which the water stands is practically level. It is hardly possible that one well will drain so large a territory where the area is level. It is estimated by an experienced well digger at Harrisburg, Ark., that it will require about four 12- to 16-inch wells to drain an acre, or one well to each quarter of an acre. This estimate, however, is doubtless too large. A fairer estimate would be one 12- to 16-inch well to the acre, and this would bring drainage within reach of all.

After a period of four to six months the wells are apt to become clogged and cease to carry off the water, but the silt and débris can often be removed from a 12- or 16-inch well with a sand bucket and the well be restored to its former carrying capacity.

COST PER ACRE.

The cost of putting down the wells depends, of course, on their depth. A 12- to 16-inch well can be bored and curbed with wood for 50 cents per foot. This is the cheapest well, and is doubtless as good as any other for drainage purposes. Wells of this class usually can easily be cleaned out with a sand bucket when they become clogged with silt and vegetable matter.

The first sands encountered, immediately underlying the surface hardpan or clay, are sufficiently porous to carry off the surface waters. The hardpan varies in depth from 10 to 40 feet over the larger part of the wet areas. The minimum cost, therefore, of a 12- to 16-inch well, curbed with wood, is $5 and the maximum cost $20. There must be added to this the cost of tile, ditching, and laying of tile. The cost of tile varies greatly, according to its size and the distance from the factory. An average price for all sizes is about $12 per thousand. But the smallest tile would be large enough to carry off the water, and the price per thousand would therefore be much less than $12. So far as known no tile has been used in carrying water to the drain wells, and the amount of tile necessary to drain an acre is not known.

VALUE OF DRAINAGE.

When the land is drained it is very desirable for corn, cotton, and alfalfa. Similar land is found in southeastern Missouri east of St. Francis River, where a large area has been drained by means of canals. Dredge boats were used to open up the main canals, at State and national expense, and the landowners then cut small canals to drain into the larger ones. The land, which could have been bought for from $1.50 to $3 an acre before it was drained is now selling at from $50 to $100 an acre. Similar results could be expected in Arkansas if deep-well or surface drainage could be perfected. Before the land is drained it is practically worthless, except in very dry seasons. After it is thoroughly drained it will produce to the acre from 75 to 100 bushels of corn or four to five cuttings of about 1 ton of alfalfa which readily sells for $10 a ton.

RESULTS OF EXPERIMENTS.

Well drainage in Arkansas has been considered impracticable, owing to the large amount of clay in the surface soil, which, when taken into solution and permitted to enter the well, silts up the water-bearing sands and prevents further escape of the water. The experiments made have not on the whole been successful. No effort has been made to overcome the difficulty, but it could be obviated by digging a series of settling pools into which the water from the surrounding land could be drained and permitted to settle before it entered the well. The number of pools would depend on the amount of clay in the soil. The greater the amount of clay the greater the amount of material which would be taken into solution and the more settling it would require to clear the water. Doubtless two or three pools would be a sufficient number to clear the water. The water from the surrounding land should be permitted to enter only one of the pools and then should be conveyed to the second and third by means of pipes or open troughs near the tops of the pools, the water flowing out of a pool on the opposite side from which it entered. In this way it would have a chance to settle. The well should be located in the third or last pool, with the open pipe projecting upward near the surface of the water. The well should be curbed to prevent the water which enters it from becoming impregnated with clay.

SANITARY EFFECTS OF WELL DRAINAGE.

In the United States few experiments have been made in regard to the sanitary effects of draining surface waters into underground water beds, the only authentic experiment being that made by Mr. S. W. McCallie at Quitman, Ga., in which he found that there was an intimate relation between wells in the same vicinity deriving their waters from the same geologic horizon, and that the pollution of the first water-bearing bed at a depth of 123 feet of the surface likewise contaminated the water in the second bed at a depth of 321 feet.

Large bodies of stagnant water highly impregnated with organic matter should not be drained into underground water horizons which supply the wells of a community with drinking water. It is quite probable that in northeastern Arkansas the surface water could be drained into the first or second sands from the surface, and the drinking water be obtained from a much lower horizon without any injurious effects.

TOTAL AMOUNT OF FREE WATER IN THE EARTH'S CRUST.

By Myron L. Fuller.

INTRODUCTION.

The problem of the amount of water in the earth's crust is of paramount interest to drillers and others seeking deep underground supplies, as well as to those interested in the problems of underground circulation as affecting mining. Probably no other question is so frequently asked in the field as that in regard to the water zone which most people suppose to exist somewhere below the surface and which they invariably believe will always be found if a well only "goes deep enough." The present paper considers the subject of the total free water in rocks of various types, incidentally showing the absence of the immense "underground lakes" of popular imagination.

By free water is meant the water which occupies the joints, solution passages, pores, or other openings of the rock. It should be carefully distinguished from the chemically combined water in the minerals of the rocks. The free water is present in the form of a liquid which possesses a more or less definite circulation even in the densest rocks, while the water in combination is not in liquid form, but is a part of the mineral compound itself. The free water should also be distinguished from the available water, since some materials, like clay, hold great quantities of water and yet often give up only insignificant amounts. It is in fact possible for a rock to hold 35 or 40 per cent of water and yet yield almost none to a pump; that is, almost none of its water is available.

From the nature of the case the discussion necessarily deals with average conditions, as local conditions vary so greatly and so rapidly that generalizations of value can not be made from isolated regions. While it is believed that the present estimate of the amount of underground water is fairly close for the earth as a whole, it is to be expected that the amount in certain materials and at certain localities will depart considerably from the figures given.

PREVIOUS ESTIMATES.

ESTIMATE OF DELESSE.

Of the many estimates of the total ground water that of Delesse [a] is among the most widely quoted, possibly because of the striking results reached. The estimate is based on the assumption that the water in rocks diminishes from 5 per cent of their weight or 12½ per cent of their volume at the surface to nothing at a depth of 6 miles, and that water may exist in liquid form at a temperature of 600° C., which was considered as equivalent to a depth of 18,500 meters. Under these conditions the amount of ground water is calculated as 1,175,089 million million cubic meters or 1,530,000 million million cubic yards, which is equivalent to $\frac{1}{921}$ of the earth's volume or to a sheet water over 7,500 feet thick surrounding the earth.

ESTIMATE OF SLICHTER.

Of the attempts made in America to estimate the total ground water since a definite knowledge of the porosities of rocks has been available that of C. S. Slichter [b] is among the most notable. The amount postulated, though less than half that of Delesse, is still immense, being equivalent to a uniform sheet from 3,000 to 3,500 feet in thickness.

[a] Delesse, Achille, Bull. Soc. géol. France, 2d ser., vol. 19, 1861, p. 64.
[b] Motions of underground waters: Water-Sup. and Irr. Paper No. 67, U. S. Geol. Survey, 1902, p. 14.

As a basis for his estimates Slichter has taken the results of L. M. Hoskins,[a] accidentally crediting them, however, to C. R. Van Hise,[b] whose statements were in reality based on the calculations of Hoskins. These calculations, to summarize them briefly, tended to show that cavities can not exist at depths of more than 6,520 meters when water free, or, where occupied by waters under hydrostatic pressure, at depths of more than 10,350 meters.

Slichter says:

The writer estimates the entire amount to be about 565,000 million million cubic yards, or about 430,000 million million cubic meters. He has arrived at this result by considering that the geologic limit of the existence of ground water is at an average depth of 6 miles below the surface of the land and 5 miles below the floor of the ocean. The land surface and water surface he has assumed to be 52,000,000 square miles and 144,700,000 square miles, respectively. The average pore space of the surface rocks which is occupied by water or moisture he has taken as 10 per cent of their total volume. He believes that the estimate of 10 per cent is too large rather than too small. It forms, however, a convenient basis for the estimates.

According to these estimates, the total amount of underground water is sufficient to cover the entire surface of the earth to a uniform depth of from 3,000 to 3,500 feet. Assuming a mean depth of the ocean of 12,000 feet leads to the conclusion that the total amount of oceanic water is about 1,800,000 million million cubic yards, so that the total quantity of ground water is nearly one-third the amount of the oceanic water.

ESTIMATE OF VAN HISE.[c]

Van Hise's estimate is the most moderate yet made. Taking one-fifth of Dana's estimate[d] (2.67 per cent of the weight of the rock) of the amount of water in the rocks at the surface and assuming the pore space to diminish to zero at the lower limit of the zone of fracture at 10,000 meters, he obtained an average porosity of 0.69 per cent, which would be equivalent to a sheet 69 meters, or 226 feet, thick over the continental areas. No computations were made regarding the oceanic areas.

ESTIMATE OF CHAMBERLIN AND SALISBURY.

The estimate of T. C. Chamberlin and R. D. Salisbury,[e] while not based on anything like a complete analysis of the problem and not claimed to be of the nature of a measurement, is of interest in connection with the discussion.

The estimate is based on the assumption that the average porosity of rocks is between 5 and 10 per cent of their volume at the surface and decreases to 0 at a depth of 6 miles. With the lower value, giving an average porosity of 2½ per cent, the water in the earth would be equivalent to a layer 800 feet deep over its entire surface, while with an assumed porosity of 5 per cent it would form a layer 1,600 feet in depth.

FACTORS IN ESTIMATES OF UNDERGROUND WATERS.

GENERAL STATEMENT.

As a more intimate knowledge of the occurrence of subterranean waters of the United States has been obtained through the work of the division of the Geological Survey dealing with underground waters, it has become clear that the problem is not as simple as has been postulated by previous writers. Not only are there certain factors affecting the problem which are not taken into account in earlier computations, but a more careful analysis of the data appears to show that a closer approximation can be made in the values of the factors used. It is believed that the pore space of the rocks has been overestimated and that the assumptions as regards complete saturation are incorrect. This has resulted, it is thought, in estimates considerably in excess of the true amount.

The more important factors affecting the estimates are considered in detail below. Nothing need be said in regard to temperature, which was once thought to be a limiting factor to the penetration of water, as it has been shown and is now well known that the increase

[a] Flow and fracture of rocks as related to structure: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 845–875.
[b] Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 593.
[c] Van Hise, C. R., a treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 128–129, 570–571.
[d] Dana, J. D., Manual of Geology, 4th ed., 1895, pp. 205, 311.
[e] Geology, vol. 1, pp. 206–207.

of pressure is sufficient to prevent the conversion of the water into steam at temperatures under the critical temperature, beyond which point, although a gas, the behavior of the water, so far as its relations to the rocks are concerned, differs but little from its behavior below the critical temperature, since it is far below the depth of critical pressure.

POROSITY OF ROCKS.

The absorptive capacities of rocks are commonly expressed in terms either of porosity or of the ratio of absorption. The first may be defined as the percentage of pore space, while the second is the ratio between the weight of water absorbed and the weight of the rock tested. The relationship between porosity and ratio of absorption is not constant, but varies with the specific gravity of the rock. The tendency of the most advanced workers is to state porosity rather than the ratio of absorption, but in the table given below, with the exception of the determinations credited to Buckley, all figures represent recalculations from the ratios of absorption. The determinations of Buckley are the most recent and are probably the most accurate of those quoted, but being limited to the rocks of a single State are in some ways not so representative as those taken from the book of Professor Merrill, in which the results, which appear to have been the work of several different laboratories, cover a wider range of rock types. Unfortunately part of the ratios of absorption are expressed as decimals and part as common fractions, but no explanations are given. The common fractions only have been used in the present computations, as the decimals taken as they are expressed in the book give results manifestly incorrect.

In connection with the figures credited to Delesse and Geikie it should be stated that, in the absence of statements of the specific gravity of the specimens tested, this has been assumed throughout to be 2.65.

Porosity of rocks.

Rock.	Authority.	Number of tests.	Minimum.	Maximum.	Average or mean.	Remarks.
Granite, schist, and gniess.	Buckley [a]	14	0.019	0.56	0.16	Wisconsin rocks only.
Do	Merrill [b]	22	.37	1.85	1.2	
Gabbro	do	1			.84	
Diabase	do	2	.90	1.13	1.01	
Obsidian	Delesse [c]	1			.52	Specific gravity not given.
Sandstone	Buckley [a]	16	4.81	28.28	15.89	Mainly brownstones.
Do	Merrill [b]		3.46	22.8	10.22	
Quartzite	do	1			.8	
Do	Giekie [d]				.21	Specific gravity not given.
Slate and shale	Delesse [c]	2	.49	7.55	3.95	
Limestone, marble, and dolomite.	Buckley [a]	11	.53	13.36	4.85	Wisconsin rocks only.
Chalk	Geikie [d]				53	Specific gravity not given.
Oolite	Merrill [b]	8	3.28	12.44	7.18	Indiana stone only.
Gypsum	Geikie [d]		1.32	3.96	2.64	Specific gravity not given.
Sand (uniform)	King [e]	Many	26	47	35	Theoretical porosity; actual results similar.
Sand (mixture)	do	do	35	40	38	
Clay	do	do	44	47	45	
Do	Geikie [d]				53	Specific gravity not given
Soils	U. S. Dept. Agr	Many	45	65	55	Common range.

[a] Buckley, E. R., Building and ornamental stones (of Wisconsin): Bull. Wisconsin Geol. Survey No. 4, 1898, pp. 400-403.
[b] Merrill, G. P., Stones for Building and Decoration, Appendix.
[c] Delesse, A., Bull. Soc. géol. France, 2d ser., vol. 19, 1862, p. 64.
[d] Geikie, A., Text-book of Geology, vol. 1, p. 410.
[e] King, F. H., Principles and conditions of the movements of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1898, pp. 209-215.

THICKNESS OF SEDIMENTS.

Evidence of sections.—From the nature of their occurrence it is usually very difficult to obtain any accurate idea of the thickness of the sedimentary rocks, especially in the flatter portions of the surface where the outcrops are often covered by drift or by mantles of residual soil. In mountainous regions, especially where the rocks are strongly folded or upturned in great monoclines, immense thicknesses are sometimes exposed. A single section recently measured by C. D. Walcott in Montana shows about 40,000 feet of pre-Cambrian shales and limestones. The sediments in eastern Pennsylvania have also been estimated by some to attain a similar thickness, but in the western portion of the State they are probably not much over a mile thick. In Europe the sediments in the Alps are estimated by Judd to have a thickness of nearly 8 miles, and it is not impossible that as great or greater thicknesses are exposed in other mountain masses.

Evidence of faults.—The evidence of faults is of interest in this connection, for by them sediments previously deeply buried have frequently been brought to the surface. The thickness exposed is generally much less than that shown in folded regions, for the greatest faults, such as those of the Appalachians of this country—one of which is estimated to have a displacement of 5 miles—are often inclined at a low angle to the horizon and the thickness of sediments elevated is relatively slight. Even if the greatest faults yet recognized were vertical the strata brought up would be thinner than in sections such as those measured by Walcott in Montana.

Evidence of borings.—While even in the case of the deepest borings only a little over a mile of sediments has been penetrated, they are of interest as furnishing accurate data concerning the underlying beds at the points at which they are drilled. The deepest wells are those sunk in Germany, South Africa, and the United States, the maximum depths reached being 6,572, 5,582, and 5,575 feet, respectively. There are, however, many deep wells in other localities.

Estimates of total thickness.—Of the various estimates of the thickness of the sedimentary beds, one of the earliest to be widely quoted was that made by J. D. Dana [a] in 1875. He estimated the thickness of the sediments over the land area as not exceeding 5 miles, which would be equivalent to 1.3 miles over the whole surface. A few years later T. Millard Reade stated [b] that a moderate estimate of the sedimentary crust of the earth is 10 miles, but on a later page [c] says it may safely be provisionally assumed that the actual average thickness of the sedimentary crust of the globe is not less than a mile, an estimate very similar to Dana's.

In 1894 G. K. Gilbert,[d] from a study of the chemical analyses summarized by F. W. Clarke [e] and of the composition of sea water, calculated the amount of crystalline rocks necessary to furnish the sodium of the ocean. His conclusions were "that somewhat more than a mile in thickness of crystalline rocks upon areas equal to all the present land of the globe must have been worked over to give our sedimentary rocks." Allowing for an increase of one-third in volume, this would be equivalent to 1⅓ miles of sediments over the land or about one-third of a mile over the whole surface. Nothing is said of the sodium locked up in undecomposed crystalline fragments in the sediments, as in the Carboniferous conglomerates and in the arkose sands of the Potomac (Cretaceous), as well as in smaller quantities in nearly all sedimentary rocks. If this was not considered in the estimate something should be added to the figures given by Gilbert, but in any case it is clear that the result would be something less than half a mile of sediments over the whole surface of the earth.

Recently F. W. Clarke has made a similar calculation on the basis of the sodium chloride in sea water, reaching the conclusion that the total thickness of the sediments, if distributed

[a] Manual of Geology, 2d ed., 1875, p. 657.
[b] Chemical Denudation in Relation to Geologic Time, 1879, p. 29.
[c] Op. cit., p. 53.
[d] The chemical equivalence of crystalline and sedimentary rocks: Am. Geologist, vol. 13, 1894, pp. 213–214.
[e] Bull. U. S. Geol. Survey, No. 78, 1891, pp. 34–42.

over the earth's surface as a whole, would be only about half a mile. The details of the calculation and the results will be published soon.

C. R. Van Hise, in his Treatise on Metamorphism,[a] after quoting previous writers, estimates the thickness of the metamorphosed sediments at 2 kilometers (1⅓ miles) over the land surface, which is equivalent to three-tenths of a mile over the entire surface of the earth.

In view of the fact that later refined investigations have shown that the thickness of sedimentary series encountered in the field has been almost invariably overestimated when first studied, it seems probable that the figures given by the earlier writers must be considered in general as representing maximum estimates, especially as considerable thicknesses of sediments have sometimes been postulated beneath the ocean deeps. The best evidence seems to show, however, that except in the continental platforms and their extensions, the deposits of the ocean may be neglected in rough computations of the thickness of sediments.

It is believed that, in view of the general tendency to overestimate the thickness of exposed rock series and the great areas in which crystalline rocks constitute the surface, the estimates postulating a thickness of sediments of from three-tenths to one-half mile over the whole earth's surface are most probable. In the present paper the writer has taken approximately one-half mile, or 2,600 feet, as a conservative estimate of the thickness of the unaltered sediments.

PROPORTIONS OF THE VARIOUS SEDIMENTS.

Summary of estimates.—A number of interesting estimates of the proportions of the various sediments have been made. Reade,[b] in his study of the chemistry of sea and river waters, estimated a thickness of 528 feet of limestone. Dana,[c] apparently from general stratigraphic data, estimated the thickness of limestone as 1,000 feet. Gilbert,[d] as a result of his chemical studies, estimated the limestones to comprise 19 per cent, the shales 42 per cent, and the sandstones 39 per cent of the sedimentary beds.

Van Hise,[e] after pointing out several sources of error in the calculations of Reade, computes the proportion of limestones on the basis of the depletion of calcium oxide in the sandstones and shales as compared with the original rocks,[f] and reaches the conclusion that an estimate of 5 per cent of the mass of sediments for limestones is as near the truth as can be made at the present time. The shales are estimated to comprise 65 per cent and the sandstones 30 per cent of the total thickness of metamorphosed sediments.

The writer's estimate.—It is believed by the writer that Van Hise's estimate of the limestone will prove to be somewhat too low, while that of Gilbert may be slightly high. In the deposits of this country, which may be taken as fairly typical, shales almost everywhere predominate over sandstones. Even in the Carboniferous rocks of the Appalachian region, where the sandstones reach a great development, they probably do not comprise more than 40 per cent of the whole. For the purposes of the present discussion the following values are assumed: Sandstone 40 per cent, shales 50 per cent, and limestone 10 per cent.

DEPTH OF ZONE OF FRACTURE.

As already pointed out (p. 60), the studies of L. M. Hoskins have shown that in rocks of ordinary specific gravities cavities free from water can not exist at depths of more than 6,520 meters, or where occupied by waters under hydrostatic pressure at depths of more than 10,350 meters. Rock-inclosed, liquid-filled cavities can, however, exist to an indefinite depth at which water and rocks are miscible in all proportions. As this is in no sense free ground water it need not be considered in the present discussion.

[a] Mon. U. S. Geol. Survey, vol. 47, 1904, p. 939.
[b] Chemical Denudation in Relation to Geologic Time, p. 53.
[c] Manual of Geology, 2d ed., p.—.
[d] Am. Geologist, vol. 13, 1894, pp. 213-214.
[e] Mon. U. S. Geol. Survey, vol. 47, 1904, p. 941.
[f] Op. cit., pp. 990-991.

The results of drilling in sedimentary and crystalline rocks, as well as studies of deep mines, show that in all probability water does not commonly exist in the rocks under great hydrostatic pressure, although such may be exerted in an occasional crevice. It is not believed that hydrostatic waters exist, except possibly in rare instances, at depths of over 10,000 feet, and it is almost certain that water plays no part in preventing the closing of cavities and that in reality the estimate of a depth of 6,520 meters, or 20,000 feet, as the limit of the zone of open cavities is closely approximate to the truth.

Beneath the land, then, it seems safe to assume that all physical pores are closed at a depth of about 20,000 feet, but under the sea the conditions are different. The average depth of the ocean is estimated at 14,000 feet, and since the ratio of its specific gravity to that of the rocks is approximately 1 to 2.65, it follows that the pressure at a depth of 20,000 feet will be considerably less than at a similar depth on the land. In reality it is only where a depth of 28,700 feet from sea level is reached that all cavities will become closed. Of this depth, as has been seen, 14,000 feet are of water, hence the rock within the zone of fracture has a thickness of only 14,700 feet.

Assuming 17,400 feet (20,000 minus 2,600 feet, the thickness of the sediments) as the thickness of the crystalline rocks in the zone of cavities over the land (one-fourth of the earth's surface) and 14,700 feet as the thickness beneath the sea (three-fourths of the surface) we obtain an average thickness of 15,375 feet.

DEPTH OF ACTIVE CIRCULATION.

Evidence of thermal springs.—The evidence of thermal springs as to the depth of penetration of waters is of considerable interest. Notwithstanding the numerous and profound faults and the even more numerous joints, we have in this country, outside of what may be considered as igneous regions, or regions of very recent disturbance, only a few scattered examples of hot springs, the Georgia, Virginia, North Carolina, and Arkansas springs being about the only examples of note. These conditions are similar to those prevailing on other continents. If waters were freely circulating at great depths within the zone of fracture, hot springs would certainly be more common along the numerous faults or joints of the Piedmont, Appalachian, and similar regions.

Again, the temperature of the springs appears to indicate an essentially superficial origin. Tests made on wells by the writer show that with a steady and moderately rapid flow of water through a pipe with a diameter of one-half inch the change in temperature, due to a difference of 15° in that of the surrounding material, amounted to only about 1° for 1,000 feet. It is therefore clear that the temperature of the larger warm springs, if undiluted by the ingress of surface water, would be essentially that which they possessed at the point of heating. In most instances, however, there will probably be some dilution, but in no case could any copious circulation from great depths take place without its being felt in the temperature of the springs.

Springs with a temperature of over 150° F. are rare, if they occur at all outside of igneous regions. As this temperature represents only a depth of 5,000 feet on the basis of an increment of 1° to each 50 feet of depth, it is readily seen that we have ordinarily no truly deep-seated springs whatever. Springs at the boiling point would represent a depth of only about 8,000 feet. The rarity, even in igneous regions, of solfataras and fumaroles, which in some cases may be considered to represent waters approaching the surface at a temperature of more than 212°, is of significance.

Evidence of deep mines.—There are two quite diverse views held in regard to the significance of the evidence afforded by mines as to underground-water conditions, one being that they show the waters to increase in amount with depth, and the other that the circulating waters are largely of meteoric origin and are essentially superficial. This diversity of opinion is the natural result of a familiarity with a certain class of mines to the exclusion of others. In many instances the conditions as regards the ground waters are controlled by accidents of topography, especially in the case of the shallow mines, the evidence presented by which is, in fact, of slight value. In order to bring out the general underground-water conditions, the following summary of the conditions in the deeper mining districts has been prepared, together with statements of the character of the rock and topography:

Summary of ground-water conditions in deep mines in the United States.

Mining district.	Maximum depth of mines (feet).	Character of rocks.	Topographic conditions.	Underground-water conditions.	Authority (oral statements to writer, except where otherwise indicated).
Ely, Vt.	[a] 1,700	Crystalline schists	On slope, 200 feet above drainage.	No water below 600 feet	W. H. Weed.
Calumet, Mich.	5,000	Interbedded traps and felsitic conglomerates.	Not elevated	Water mainly in upper 500 to 600 feet. Little water in lower levels; is salty. Separated from fresh by sharp line.	A. C. Lane. [b]
Boundary Creek, Canada	800	Volcanic tuffs and some limestone; intrusives near.	Local drainage level with springs 200 to 400 feet below mines.	All dry	W. H. Weed.
Marysville, Mont.	1,600	Argillite and diorite	Sidehill, 600 feet above drainage.	Most of water is above 900-foot level, although vein is open.	Do.
Elkhorn, Mont.	1,800	Limestone	In valley, at drainage level.	Open solution channels to bottom, but present water mostly above 1,400 feet.	Do.
Butte, Mont.	2,400	Granitic rocks	Sidehill, 400 feet above drainage.	Water is descending, reaching to bottom in cases, but with large bodies of dry rock. One at 1,600 feet, 1,200 feet in width, is absolutely dry.	Do.
Lincoln County, N. Mex. (Old Abe mine).	1,370	Calcareous shales and porphyry.	Sidehill, 500 feet above drainage.	Damp, but only a few bucketfuls raised per week.	L. C. Graton.
Leadville, Colo.	1,500	Limestones, sandstones, and shales. Faulted and folded into local basins.	Deepest mines are on mountains 1,000 feet or thereabouts above drainage. Others in valleys.	Water occurs under artesian pressure in each fault basin. Mainly along faults, especially in limestone. Not much diminution with depth.	S. F. Emmons.
Cripple Creek, Colo.	1,500	Closed "basin" of porous breccia in granite.	Plateau a few hundred feet above drainage.	Joints everywhere saturated with water. No diminution with depth.	W. Lindgren.
Cœur d'Alene, Idaho	1,950	Quartzite	Deepest mine starts at drainage level.	Much surface water, but no strong flows in lower levels.	F. L. Ransome.
Nevada City and Grass Valley, Cal.	2,200	Granodiorite and diabase	Undulating foothills, slightly above drainage.	Water in fissures in first 1,000 feet. Little water in lower level. Some stopes entirely dry.	W. Lindgren.
Mother Lode, Cal.	2,800	Black slate and diabase, some granite.	do	Considerable water in fissures in upper 1,000 feet. Little water in lower levels, but some to bottom.	Do.

[a] 3,600 feet on incline of about 25°.

[b] Am. Geologist, vol. 34, p. 303.

Summary of ground-water conditions in deep mines in the United States—Continued.

Mining district.	Maximum depth of mines (feet).	Character of rocks.	Topographic conditions.	Underground-water conditions.	Authority (oral statements to writer, except where otherwise indicated).
Mother Lode, Cal				Water mainly in upper 800 feet. If this is collected balance of mine is dry. Water is hoisted with ore, pumping not being necessary.	Ross E. Browne.[a]
Bisbee	1,200	Limestone	In valley, within 200 feet of drainage level.	Much water to bottom levels. Possibly connected with faulting.	F. L. Ransome.
Globe	1,200	Fault in diabase limestone and quartzite.	Hillside, 50 to 200 feet above drainage.	Not much water until mines strike faults connecting laterally with adjacent gravel-filled basin.	Do.

[a] California Mines and Minerals, California Miners Association, 1899, p. 66.

An examination of the foregoing table will show a considerable range of conditions as regards the occurrence of underground waters in mines. Certain generalizations, however, can be made. For instance, it appears that in the deep mines in the crystalline rocks of the eastern portion of the country, in which there has been no igneous activity since early geologic times, water is rarely found below the 600-foot level, the mines in some instances being practically dry from surface to bottom.

In the West, where igneous activity is more recent, the underground waters are more abundant, especially where the rocks are severely shattered, as in the Colorado mines, where much water occurs, even at the lowest levels. In the Arizona mines there is considerable water locally along faults, although the amount in other portions of the rock is not usually excessive. In the Mother Lode, California, water occurs in such slight amounts that it can be hoisted with the ore without pumping, although the workings reach a depth of 2,700 feet. In Nevada City and Grass Valley, Cal., and in some of the Montana mines the water is generally confined to the upper 1,000 feet. In other of the Montana mines, however, local water-bearing fissures or solution channels occur to depths of at least 1,600 feet. The mass of the rock, however, is relatively free from water. In three of the fifteen districts included in the table water occurs in abundance without much diminution to the bottom of the workings. In four it occurs in abundance, at least locally, up to a depth of 1,500 feet. In the remaining eight, or more than half of the deep mines, there is a general absence of water below the 1,000-foot level.

Evidence of deep borings.—The nonsaturation of the rocks at many localities is clearly brought out by deep borings. For instance, a well recently reported to the writer was sunk to a depth of over 1,000 feet in limestones near Lexington, Ky., without finding any water whatever. Another conspicuous example is the widely quoted well sunk by the Wheeling Development Company 4 miles southeast of Wheeling, in which the lower 1,500 feet were drilled in absolutely dry rock. Still other examples are the deep wells sunk at Northampton, Mass., to a depth of 4,022 feet, and the 4,000-foot well reported to have been sunk in red sandstone, etc., at New Haven, by the Winchester Repeating Arms Company, both of which failed to obtain water.

This absence of water is, moreover, not due to lack of porous rock, as shown by the two wells last mentioned and by the W. J. Bryan well No. 11, Aleppo Township, Greene County, Pa. This well is 3,397 feet deep and is cased to 3,110 feet, which represents the last water. Below the casing, however, were found the Thirty Foot, Fifty Foot, and Gordon sands, 20, 60, and 18 feet in thickness, respectively, making a hundred feet of porous, but perfectly dry sandstones. The depth at which water was found in this well is greater than the normal, no fresh water being found in many wells beyond a depth of 500 feet.

Examples of wells failing to encounter water at great depths might be multiplied indefinitely, for wells in which water has to be poured for the purposes of drilling are of everyday occurrence. The above specific citations, however, are sufficient to show the nature of the evidence. Considerable light is also thrown by wells on the nature of the crevices, including both solution passages and actual or potential openings along joint and fault planes, which are frequently encountered in rocks of all types. Frequently the joints are open or are bordered by sufficiently disintegrated material to cause the drill to "jam." Notwithstanding all this, many carry no water whatever, although others may carry considerable. The theory of the cementing of the portion of the joint planes near the surface, as advanced by G. O. Smith [a] to explain the artesian conditions in crystalline rocks near York, Me., may also offer an explanation of the absence of water in certain joints.

It is well recognized by those who have investigated the occurrence of underground waters in crystalline rocks that joints sufficiently open to constitute water passages are almost uniformly a surface feature. While it is true that a water-bearing joint was encountered at 1,160 feet in the deep Atlanta well,[b] no more were found, although the well was

[a] Water resources of the Portsmouth-York region, New Hampshire and Maine: Water-Sup. and Irr. Paper No. 145, U. S. Geol. Survey, 1905, pp. 120-128.
[b] McCallie, S. W., Artesian-well system of Georgia: Bull. Geol. Survey of Georgia No. 7, 1898, p. 205.

continued to 2,175 feet, and in general investigators are agreed that it is not advisable to drill more than a few hundred feet into crystalline rocks in search of water. J. A. Holmes[a] concluded, from investigations in the Piedmont area of crystalline rocks in North and South Carolina, that the chance for obtaining water in deep wells was about one in ten.

The present writer has stated[b] in an earlier publication, as a result of his experience with wells in granites, gneisses, and schists, that water supplies, if obtained in these at all, are usually found within 200 or 300 feet of the surface and that it is generally useless to go deeper than 500 feet. These views have received substantial corroboration through the detailed work of E. E. Ellis on the occurrence of water in the crystalline rocks of Connecticut. His investigations, which are summarized on pages 19–28 of this report, show that practically all supplies are obtained at depths not greater than 250 feet.

Evidence of drift waters.—Not only do the consolidated rocks, as outlined in the preceding section, in many cases fail to carry water even where porous, but many very porous unconsolidated sediments are free from water, even where below the water table. Many examples were encountered in the 300 artesian localities in Michigan examined by Frank Leverett and others for the United States Geological Survey in 1904. One of the most conspicuous examples is that found in the extensive sand plain at Clinton, Mass., in which many hundreds of borings were made in connection with the construction of dikes for the big metropolitan reservoir. These borings developed a normal, gently sloping water table in sand. Below the sand an impervious clay was encountered, while below the clay was found a "hard-packed" sand destitute of water. The same feature was brought out repeatedly in boring after boring. In fact, the finding of porous deposits capable of holding immense quantities of water, but in which none whatever is actually found, is a common experience of almost every driller working in deposits of stratified drift in this country. Often they are found several hundred feet below the surface, far below the true water table or that lying above the first impervious stratum and, in many instances, much below the level of the lowest surface drainage.

Evidence of oil, gas, and associated brines.—The evidence afforded by these closely related substances is very convincing to one who has investigated their occurrence in the field. Commonly they occur in large amounts only in relatively flat rocks, their tendency being to accumulate beneath the highest point of the confining impervious roof. When this roof is broken by a prominent joint or by a fault, or when the beds are highly upturned, the hydrocarbons are no longer found in any but the smallest amounts. In other words, as soon as a passage is opened in the impervious cover, either by jointing, faulting, folding, or erosion, meteoric waters penetrate, a circulation is set up, and the oil, gas, and salt water are soon removed to the surface, appearing as the oil, gas, and salt springs so common in certain parts of the country. The oil and gas of the productive pools, so far as known to the writer, are, however, never associated with fresh waters, and although oil-bearing rocks near the surface may be invaded by fresh waters, as indicated by the oil and gas springs, the mere presence of either in pools as ordinarily known indicates an absence of circulation of meteoric waters.

Evidence of gypsum and anhydrite deposits.—Anhydrite, or anhydrous calcium sulphate, is deposited from solutions saturated with sodium chloride and calcium sulphate at 26° F., a temperature often reached in the summer seasons even in high latitudes, and, although doubtless formed under a variety of other conditions, it has probably been most commonly deposited from supersaturated sea water through evaporation.

When fresh waters are brought into contact with the anhydrite, however, water is taken on and the rocks are converted into gypsum, or hydrous sulphate of calcium. The occurrence of anhydrite in the rocks, therefore, is of special interest in connection with the problem of underground waters, pointing to the absence of circulation at the points at which the anhydrite occurs.

[a] Trans. Am. Inst. Min. Eng., vol. 25, p. 936.

[b] Underground waters of eastern United States: Water-Sup. and Irr. Paper No. 114, U. S. Geol. Survey, 1905, p. 29.

When the beds are exposed at the surface the calcium sulphate is usually in the hydrous form, owing to the circulation of fresh ground waters. In the large quarries near Windsor, New Brunswick, however, only the upper few feet have been converted into gypsum, the great mass of the deposit still being in the anhydrous state.

Deposits have been frequently penetrated by deep borings in both this country and in Europe, but in most cases, unfortunately, no distinction is made between the anhydrous and hydrous types. At Stassfurt, however, the salt beds, which have an aggregate thickness of 1,197 feet, include thousands of anhydrite layers averaging about one-fourth of an inch in thickness and occurring at intervals of from 1 to 8 inches. At Hartlepool, in Yorkshire, borings show the limestone to be "interleaved with anhydrite and to be overlain by more than 250 feet of that deposit."[a] Again, in the Mont Cenis tunnel in the Alps over 1,500 feet of alternating anhydrite, talcose schist, and limestone are reported.[b]

From these and numerous other instances that might be cited it is clear that not only are circulating waters practically absent in many regions, even near the surface, but interstitial water is also absent. If any fresh water whatever was present in the pores of the anhydrite, hydration to gypsum would take place.

Evidence of salt deposits.—While less conclusive than that of anhydrite and of oil and gas deposits, the occurrence of salt, including sodium chloride and the more soluble potassium salts, affords considerable evidence as to the absence of circulating ground waters. The evidence of such circulating waters would be apparent at once on the thin laminæ of salt interstratified with other materials, and even the thick beds would present evidences of circulating waters if the latter occurred in any considerable amounts. So great is the rapidity of solution that even the larger masses in any but the most recent geologic formations would have long since been removed if active circulation existed. Nothing but analyses would show the presence of small amounts of interstitial water in the salt itself, but the evidence of the interlaminated anhydrite conclusively proves the absence of water in many instances.

Evidence of brines in Coastal Plain deposits of eastern United States.—Near the outcrop of most of the Coastal Plain deposits, at least of those of the coarser types, the waters are fresh, the salts in solution being practically all obtained from the containing materials. As the distance from their landward boundary increases, however, and the dip carries the beds farther below the surface, the waters often become more mineralized and in some instances are distinctly saline. At Fort Monroe and at Norfolk, Va., about 60 miles from their border, only salt waters were encountered for about 700 feet down to the granite at about 2,250 feet. Again, at Wilmington, N. C. about 115 miles from the border, the waters are salt, while at Charleston, S. C., and Savannah, Ga., wells at similar distances yield fresh waters. The depth to which circulation extends downward is not, therefore, dependent on distance from the outcrop. In reality it seems to be related, to some extent at least, to the character of the materials, being greater in prevailingly sandy beds than in more clayey beds, as at Wilmington. It is probable that leakage through vertical joints, which are common even in unconsolidated materials, has much to do with determining the distance of penetration of surface waters. The age of the strata also appears to be a factor of importance, since the more recently deposited beds, as in the vicinity of Wilmington, often show higher salinity than older beds occurring under similar conditions.

It is clear, therefore, that while active circulation may extend to considerable depths and distances in the Coastal Plain deposits, such circulation is often absent, in which case the originally inclosed sea water probably constitutes most of the water present.

Evidence of joint studies.—Recent investigations in Connecticut, made by E. E. Ellis for the United States Geological Survey, have shown that in the ordinary granites and gneisses of the region the water occurs largely in the vertical joints, which have an average spacing of between 3 and 7 feet at the surface. At depths of more than 50 feet the spacing is greater,

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[a] Geikie, Text-Book of Geology, vol. 2, 1903, p. 1071.
[b] Hunt, T. Sterry, Chemical and Geological Essays, 1875, p. 335.

owing to the dying out of subordinate joints. At still greater depths there appear to be very few water-bearing joints, 250 feet being the depth fixed as a limit beyond which it is not advisable to go for water. Of the horizontal joints, almost all are confined to the upper few feet of the rock, being generally above the water table. Mr. Ellis finds that while the joints may be half an inch or more in width at the surface, they rapidly narrow with depth, and that the common width in the upper 200 or 300 feet is 0.01 inch. With a double system of joints, each with the fractures at an average distance of 5 feet from one another, there would be, even if they were completely filled with water, only 1 cubic inch of water to 125 cubic feet of rock, equivalent to $\frac{1}{215000}$ or less than 0.000046 of the mass.

If we assume an average width of the joints of 0.1 inch, which may be regarded as a maximum, the amount of water in them would still be only 0.00046 of the volume of the rock.

The joints do not always carry water to their full capacity. In fact, water in amounts sufficient to supply even domestic wells is seldom obtained at depths greater than 300 or 400 feet. The writer estimates the relative amounts of water in joints as follows:

Relation of actual water in joints in crystalline rocks to their full capacity.

Depth in feet.	Proportion of full surface capacity.
0–100	Full.
100–200	One-half.
200–300	One-third.
300–500	One-fifth.
500–2,000	One-tenth.
2,000–34,000	Practically no water.

The water present in joints in the upper 2,000 feet of the crystalline rocks is estimated, therefore, to be only 16 per cent of their capacity, or 0.000007 of the rock volume.

In the case of sedimentary rocks the joints are still farther apart than in crystalline rocks, and while they carry much water, the proportion so held to that held in the pores is very small. Caverns may be considered in the same class with joints. Being larger, they carry large amounts of water, as evidenced by the large springs, etc., coming from such passages, but even in completely honeycombed rocks the actual volume is very slight indeed as compared with the whole mass of the rock while, moreover, the circulation is essentially superficial.

The amount of water in both joints and caverns is so small compared with that in the pores of the rock itself that they have no material effect on the computations and may be disregarded.

What the amount occupying the pores may be we have no way of determining, but it is believed that not over 25 per cent of the pore space is occupied. To be on the safe side, however, 50 per cent is here assumed.

MAGMATIC WATERS.

In recent years much has been said, in connection with the discussion of ore deposits, in regard to magmatic waters as a source of vein solutions. All molten rocks reaching the surface carry water, usually in considerable amounts, and from contact phenomena it is equally evident that the same is true of many intrusive magmas, especially those of pegmatites and other acidic rocks. It is not impossible, therefore, that considerable additions to the underground-water body may take place from magmatic intrusions which fail to reach the surface, but the number of such intrusions giving off water at any one time will be exceedingly small and confined to limited areas. In a consideration of the crust of the earth as a whole their amount can be practically disregarded.

DEGREE OF SATURATION.

The theoretical absorptive capacities of rocks are essentially the same as their porosities, since, as has been shown, the amount in joints, etc., can be disregarded. In the preceding section evidences tending to show that the actual amounts are considerably less than the theoretical amounts have been adduced along a considerable number of lines. From the nature of the information available, however, it is impossible to make definite quantitative statements, but it is believed that a reasonable estimate may be made. The following is an estimate by the writer, based on his underground-water investigations for the Geological Survey:

Relation of actual water in sedimentary rocks to their full capacity.

Depth in feet.	Proportion of full surface capacity.
0-250	Full.
250-500	One-half.
500-1,000	One-third.
1,000-2,000	One-fifth.

Average per cent of full capacity, 37.

The relation of the actual water in joints to their full capacity has been discussed, it being estimated that only 16 per cent of the joint spaces are occupied. What the amount occupying the pores may be we have no way of determining, but it is believed to be much less than the capacity as indicated by their porosity.

SUMMARY.

FACTORS IN PROBLEM.

Porosity factors.—The various factors assigned in the computation of the underground waters occurring in the pores of the rocks are summarized below. In the summary the unconsolidated surface deposits are disregarded, partly for the reason that they are of inconsiderable thickness as compared with the total thickness of sediments and partly because of the fact that, while they are more porous than most of the consolidated beds, only a part of their mass lies below the water table and is saturated, the remainder being relatively water free. It is believed, therefore, that on the average the amount of water held is not greatly different from that in the consolidated sediments.

For the sandstones, shales, and limestones full porosity values are given, as in most cases the pressure has done little toward closing the pores. In the crystalline rocks, on the contrary, it is assumed that the porosity decreases from the normal at the surface to nothing at the level of no openings, hence one-half of the surface value is used in the computations. Summarizing the porosity, we have: Sandstones, 15 per cent; shales, 4 per cent; limestones, 5 per cent, and crystalline rocks, 0.2 per cent.

Saturation factors.—These have already been discussed in a preceding paragraph, but the results may be repeated as follows:

Average percentage of the theoretical capacity of stratified rocks actually taken up by water	37
Average percentage of the theoretical capacity of igneous rocks actually taken up by water	50

Thickness factor.—The average thickness of the sedimentary rocks, as outlined on page 63, is taken as 2,600 feet, while that of the portion of the crystalline rocks in which water can occur is estimated to be 15,375 feet (p. 64).

Recapitulation.—The various factors affecting the computation of the volume of underground water may be tabulated as follows:

Factors in computation of volume of underground waters.

Rocks.	Thickness.	Porosity.	Saturation factor.	Volume occupied by water.
	Feet.	*Per cent.*	*Per cent.*	*Per cent.*
Sandstone	1,040	15.0	37	5.25
Shale	1,300	4.0		1.48
Limestone	260	5.0		1.75
Crystalline rocks [a]	15,375	.2	50	1
	17,975			

[a] See p. 64.

Average per cent of rock occupied by water, 0.52.

CONCLUSION.

On the basis of these factors the total free water held in the earth's crust would be equivalent to a uniform sheet over the entire surface with a depth of little less than 100 feet (96 feet), which is only about one seventy-fifth of the amount postulated by Delesse, one thirty-fifth of that of Slichter, one-sixteenth to one-eighth of that of Chamberlin and Salisbury, and three-sevenths of that of Van Hise.

If the average depth of the ocean is 14,000 feet, its volume is equivalent to a layer 10,500 feet deep over the whole earth's surface. The underground water would, therefore, be roughly only one one-hundredth of the volume of the ocean, instead of one-half, as indicated by the figures of Delesse; one-fourth, as indicated by Slichter's estimates,[a] and one-ninth to one-eighteenth on the basis of the estimate of Chamberlin and Salisbury.

It is recognized that locally, where the sediments are very porous and of considerable thickness, several times the amount of water estimated may exist in unconsolidated deposits, or in the stratified rocks alone. There is a general tendency, however, to overestimate the amount of water in the ground owing to the impression of great volume which a large well often conveys, the fact that a large area is drained being frequently overlooked. The writer's studies of the conditions in deep wells in the United States lead him to the belief that the average amount of water present in the earth is probably under, rather than over, the amount estimated.

[a] Slichter takes 12,000 feet as the mean depth of the ocean, which would raise the underground water factor to one-third of its volume.

USE OF FLUORESCEÏN IN THE STUDY OF UNDERGROUND WATERS.[a]

By R. B. DOLE.

NTRODUCTION.

This paper is an account of the use of fluoresceïn for tracing the course of subterranean waters. The methods for its application and detection are described, a brief discussion is given regarding its fitness for use under various conditions, and the results of practical experiments are cited. Nearly all of the material is taken from reports and papers on work of this character undertaken by the city of Paris. At the end is given a partial bibliography of articles relating to the subject. For copies of the original reports and discussions acknowledgment is made to the courtesy of M. Max le Couppey de la Forest, ingénieur agronome de la commission scientifique de perfectionnement de l'observatoire municipal de Montsouris.

GENERAL CONSIDERATIONS.

It frequently happens that the chemical and bacteriological examinations of a water do not show whether it is polluted. This failure results from several causes. Sometimes the polluting matter has been so diluted that the tests employed are not sufficiently delicate to find it. Frequently it is intermittent in character, so that the samples examined may have been taken at a time when no afflux occurred, though at other times the water may be in a dangerous condition. If a decision is based on chemical results alone, the presence of harmless organic material may be used to condemn a water, because the data do not distinguish between the organic matter which is vegetable and that which is animal in its origin. These troubles are experienced to a greater extent in the study of underground than in that of surface waters, first because the sources of pollution are obscure in their relation to the subterranean beds, and, second, because variations in the chemical constituents of a given spring or well under study are usually neither so large nor so diverse in character as the changes in the same figures for rivers or lakes. Chloride-bearing rocks or drift deposits sometimes give so high a chlorine content to waters in them that slight changes caused by the introduction of fecal matter are either inappreciable or can be attributed as well to natural sources as to dangerous contamination. Other constituents besides chlorine may change from similar causes without affording the analyst an opportunity to distinguish harmless from dangerous affluents.

Consequently every means for determining the flow and pollution foci of underground waters should be used. In studying the potability of a well or spring water it is important to know not only its chemical composition, but also its source, its rate of flow, the area tributary to it, the nature of the material through which it passes, and the contaminations to which it may be subjected before or during its underground journey. It is often a matter of much importance to know whether the flow is from a cesspool toward a neighboring well or in the opposite direction; it may be necessary to determine whether or not water

[a] Prepared in connection with the work of the division of hydroeconomics; M. O. Leighton, hydrographer in charge.

seeps from a contaminated brook into wells of a neighboring region; whether collecting galleries for public water supplies receive seepage from well-established sources of contamination; whether, in general, known foci of pollution are in immediate, though obscured, connection with sources of drinking water. Knowledge of this nature is especially important in the study of waters passing through formations full of seams or crevices, where there is opportunity for rapid circulation without much purification. The determination of the area draining to the underground supply affords data in regard to the quantity of available water as well as its quality. These and many other considerations make the study of conditions in the subterranean basin more important than laboratory examinations into the nature of the water itself.

FLOW INDICATORS.

MATERIALS.

For such hydrologic studies as have been indicated above much knowledge has been gained by introducing some foreign material into the aquifer under study and tracing its journey by samples from wells, springs, or temporary borings along its possible course.

A large number of substances have been proposed for this purpose. A few of those which have been more or less extensively employed are given in the following lists:

A. Materials dissolved in the water and recognized by chemical or physical tests: Sodium chloride, calcium chloride, ammonium chloride, potassium nitrate, lithium salts, and iron salts.

B. Materials dissolved in the water and recognized by their color: Potassium permanganate, fuchsine, Kongo red, methylene blue, and fluoresceïn.

C. Materials suspended in the water and recognized by microscopic examinations: Starch, flour, etc.

D. Cultures of bacteria suspended in the water and recognized in samples taken by their cultural characteristics: *Bacillus prodigiosus*, *B. subtilis*, *Saccharomyces cerevisiæ*, and *Mycoderma aceti*.

The principal requisites in the choice of a proper so-called flow indicator are—

1. It should descend to and traverse the aquifer in a manner and rate similar to the water itself.

2. It should be easily and quickly detectable in the samples of water taken.

3. It should not be decomposed nor its intensity greatly affected by the materials with which it comes in contact.

For different purposes and in different materials the selection of an indicator is varied. For determining the percentage of water entering one level from another the chlorides are especially fitted, because the amounts present can be accurately and rapidly determined. When, however, the volumes of water are extremely large and the subterranean journey is long the amount of salt or other chloride necessary to cause an estimable change in chlorine content is so great that the experiment is often impracticable. For the study of underground flows in alluvial deposits the use of ammonium chloride and sodium chloride as electrolytes appears to be especially good.[a] For investigating the purification power of strata through which water passes, cultures of beer yeast have proved very satisfactory.[b] For tracing the flow, however, of large or small underground streams through well-defined channels of size in rocks, especially calcareous formations, fluoresceïn has proved superior to anything else which has been tried. Its diffusion is rapid, it is applicable under many conditions, and it can be easily detected in enormous dilutions by means of the fluoroscope when it is not present in quantities large enough to be visible to the naked eye. On account of its many admirable qualifications, fluoresceïn has been extensively used by the city of Paris in the study of springs from which the major part

[a] Slichter, C. S., Rate of movement of underground waters: Water-Sup. and Irr. Paper U. S. Geol. Survey No. 140, 1905.

[b] Le Couppey de la Forest, M., L'étude des eaux de sources: Bull. Soc. sci. hist. et nat. de l'Yonne, pt. 2, 1902.

of the drinking water is taken. The records given on page 81 of experiments with fluoresceïn are taken from published reports of the Commission scientifique de perfectionnement de l'Observatoire municipal de Montsouris and from various articles published elsewhere by members of the laboratory staff.

HISTORY

Probably the first coloration experiments to establish the water origin of typhoid fever were made by Dr. Dionis des Carrières[a] in 1882, during a severe epidemic at Auxerre, a city about 85 miles southeast of Paris. Since that time the use of various dyes has been frequent for studying the underground movements of water. In 1887 fluoresceïn was used in the valley of the Avre.[b] M. Trillat in 1899 conducted elaborate investigations into the delicacy of certain dyes for flow indicators and the effect on them of passage through common soils.[c] The fluoroscope invented by him and perfected by M. Marboutin[d] is capable of detecting minute traces of fluoresceïn, and has made possible the extensive studies of ground flow now being conducted with that material. The work has assumed such proportions that the so-called sanitary analysis of water plays a rather subordinate rôle in the consideration of the springs. Under the direction of the Montsouris commission geologists, hydrologists, chemists, physicians, and other skilled professional men make a detailed study of the region in order to ascertain the purity of the water and the means for preventing avoidable pollution. Their work embraces a study of the water flow and of the geology of the formations, determination of the supply basin, inquiry into epidemics and hygienic conditions on the watershed, as well as the study of the water itself as regards chemical and bacteriological condition, discharge, temperature, etc. From the results of all these researches a definite decision concerning the availability of the supply and its chances of pollution can be made.

FLUORESCEÏN.

CHARACTER AND APPEARANCE.

Fluoresceïn (resorcin-phthalein, diresorcin phthalein, tetraoxyphthalophenone, uranin, Kruger's indicator) is a coal-tar product. It can be prepared by heating two molecular weights of resorcin with one molecular weight of phthalic anhydride, on an oil bath, between 190° and 200° C., until aqueous vapors are no longer evolved. The mass is then extracted with hot water and the residue powdered, dissolved in a solution of potassium hydrate, and reprecipitated with an acid. It is important to use pure materials in order to obtain a pure product, otherwise the final purification of the fluoresceïn is rendered extremely difficult. It occurs as crystalline powder or amorphous masses, varying in color from reddish yellow to dark brown. It is insoluble in water,[e] slightly soluble in cold, and more readily in hot alcohol, and easily soluble in ether, dilute acids, or alkaline solutions. The sodium or potassium salts of fluoresceïn are soluble in alkalies and in water. In the presence of alkalies its solution is red by transmitted light and bright green by reflected light—a phenomenon known as green fluorescence. Though fluoresceïn is not affected by free carbonic acid, its solution is rendered colorless by acetic and the mineral acids.[f]

The red color shown by transmitted light is not apparent in very dilute solution, but by the use of a long tube filled with the alkaline liquid the green appearance shown by

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[a] Dionis des Carrières, Étiologie de l'épidémie typhoïde qui a éclaté à Auxerre en septembre 1882: Bull. et mém. Soc. méd. des hôpitaux de Paris, vol. 9, 2d ser., 1882, p. 277.

[b] Brard, Étude des pertes de l'Avre et de ses affluents: Comptes rendus Soc. ingénieurs civils de France, octobre 1899.

[c] Trillat, Sur l'emploi des matières colorantes pour la recherche de l'origine des sources et des eaux d'infiltration: Comptes rendus Acad. sci., vol. 128, 1899, p. 698.

[d] Marboutin, Nouvelle méthode d'étude des eaux de sources: Mém. Soc. ingénieurs civils de France, février 1901, vol. 131, p. 365; Sur la propagation des eaux souterraines: Bull. Soc. belge géol., etc., vol. 15, 1901, mém., p. 214.

[e] This statement of insolubility applies especially to chemically pure fluoresceïn sold ordinarily in the form of a yellow powder. The fluoresceïn commonly used in the coloration experiments has a reddish brown or slightly orange color and is completely and rapidly soluble in water.

[f] Cohn, Indicators and Test Papers, 2d ed., p. 75.

reflected light is apparent when extremely small quantities of fluoresceïn are used. For a flow indicator it is important to use fluoresceïn of good quality, as otherwise the coloration will not be visible in a solution sufficiently dilute. The commercial article varies greatly in intensity of fluorescence according to the purity of the materials from which it is manufactured and the care used in its preparation and storage. Nine different samples from the market examined by M. Marboutin[a] had greatly different fluorescent powers. With the fluoroscope their limits of visibility ranged from 1 part in 500,000,000 to 1 part in 10,000,000,000. The most practical test of the applicability of a given sample of fluoresceïn seems to be that when suspended in water it should show with the fluoroscope a perceptible fluorescence in a dilution of 1 part in 10,000,000,000. If weaker materials are used it is of course necessary to use larger quantities of them. Fluoresceïn costs from $2.25 to $12 a pound

THE FLUOROSCOPE.

The instrument known as the fluoroscope is used for detecting the presence of minute quantities of fluoresceïn in solution by observing the green fluorescence in a great depth of liquid against a dark background. As perfected by M. Marboutin,[a] chemist of the Montsouris laboratory, it consists of 12 tubes of pure-white glass of even bore, each 95 cm. long and about 15 mm. in diameter. The white tubing used for manufacturing certain kinds of burettes would answer the purpose very well. Each tube is closed at its lower extremity by a rubber stopper blackened with powdered plumbago. The box for carrying the apparatus is provided with a rack in which the tubes may be held side by side in a vertical position. When they are filled with the samples to be examined the presence of fluoresceïn is recognized by the appearance, projected on the black stopper, of a greenish reflection which is entirely different from the natural tint of the water itself, though sometimes confused with it by inexperienced observers. It is often convenient to use for comparison standard tubes containing quantities of fluoresceïn varying from 0 to 0.002 part per million. The use of a little ammonia to excite the fluoresceïn is suggested when the dye is present in small amount. This is of course impossible in magnesium-bearing waters on account of the white turbidity produced. The limit of visibility depends a great deal on the nature of the fluoresceïn used. It has been placed at 0.0001 part per million or 1 part in 10,000,000,000 of clear water. For practical demonstrations of its presence 0.0005 part per million is better. The limit of ordinary visibility with the unaided eye seems to be 0.025 part per million. Therefore a quantity of fluoresceïn may be used which is detectable with the fluorescope and still not visible to the naked eye.

By comparison with tubes of known content the amount of fluoresceïn in the samples may be estimated by the intensity of the green coloration. With this and other data the amount of seepage from one water-bearing stratum to another may be determined.[b]

APPLICATION OF FLUORESCEÏN.

Fluoresceïn can be poured down where there is expected to be a connection with the underground flow—in general at any point of higher elevation than the water level in the bed under study. Sink holes, cesspools, privy vaults, temporary borings, or the beds of degravelling streams are all desirable places to introduce the dye. A solution containing about 300 grams per liter is a convenient one for use. If it is poured down where there is no considerable flow of water toward the lower strata, such as in a dry boring or in a vault, enough water should be poured on it to wash it down. The quantity of fluoresceïn to be used varies with the distance traveled, the time of the journey, the size of the water sheet, and the nature of the material traversed. The amount generally employed is between one-half pound and 2 pounds, though experiments have been made with much larger weights. From tables given later (pp. 79–81), an idea may be formed of the amounts desirable to use. In general

[a] Marboutin, Contribution à l'étude des eaux souterraines: Comptes rendus Acad. sci., vo . 132, 1901, p. 365.
[b] See experiment at Auxerre, p. 82.

the quantity is 2 pounds of fluoresceïn per hour for a flow of about 31,700 gallons per minute from the bed. It is of course necessary to add enough to produce a detectable coloration in the water of the well or spring under examination. Having determined the flow of the latter, an approximation may be made of the amount of fluoresceïn necessary to insure the presence of between 0.02 and 0.0005 part per million in the effluent. Since, however, all of the water of the underground bed will probably not be delivered at the points of examination, it will be seen that with the distance traveled the amount of fluoresceïn should be increased.

METHOD OF TAKING SAMPLES.

A preliminary determination of the water level in the wells and springs in the region will eliminate those points round the spot at which the fluoresceïn is put down that are manifestly outside of the circulation zone. All other wells or springs should be marked for examination, whatever their apparent disconnection with the water sheet under study. The most economical manner of taking the samples is hourly by concentric circles successively removed from the point of putting in the color. An agent supplied with 12 bottles is stationed at each well or spring to be examined in the nearest circle. In general, samples taken hourly for twelve hours will mark the arrival and departure of the fluoresceïn. Sampling, however, should not cease at any point until the passage of the dye or its nonarrival is established. The first sample should be a blank taken at the instant when the fluoresceïn is put down, and each should be plainly marked with the name of the well or spring and the date and hour of sampling. After the color has passed one zone of wells, the agents can be moved to another circle. Their advance will, of course, depend on the rapidity with which the coloring matter progresses. The 12 samples representing the water for twelve hours are then examined in series as rapidly as possible.

EXAMINATION OF SAMPLES.

The 12 tubes of the fluoroscope are filled from the 12 bottles representing one well water. Care is taken to arrange them in chronological order. Then, by looking at the tubes along their axes, those showing fluorescence can be readily selected. It is often convenient for a beginner to use for comparison tubes containing dilute fluoresceïn solutions. With practice, however, the natural tint of the water will not be confused with traces of fluoresceïn. The examination should be made in broad daylight before a white wall. Special care must be taken to avoid a green background. By these tests the hours of arrival and of departure of the color at each point of examination are determined, and if desired the intensity of the fluoresceïn can be estimated.

ACTION OF FLUORESCEÏN.

Method of movement.—Generally fluoresceïn progresses more slowly than the water in which it is suspended; on account of the greater density of its solution it tends to accumulate in low places along the route traversed. M. le Couppey de la Forest[a] has noted that, when fluoresceïn is poured into a small stream which later widens out into a basin of still water, coloration is visible for a certain length of time in the stream below the basin; the coloration grows weaker, till finally not a trace can be found, though relatively large amounts of fluoresceïn-tinted water remain at the bottom of the basin; if finally the basin be agitated by the sudden influx of larger amounts of water, the more densely colored water will be washed out and the fluoresceïn will once more appear in the effluent. It may be conjectured that large subterranean caverns could effect a retention of fluoresceïn in a similar manner. The first appearance of the dye at the outlet might be unnoticed on account of its small amount, so that a later one caused by heavy inflows of water to the caverns would lead to a wrong conclusion regarding the rate of flow in the bed. Several instances of this character have been noted where one introduction of fluoresceïn has caused two or more distinct colored flows at springs in relation. (See p. 81.)

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[a] Le Couppey de la Forest, M., Mode de propagation de la fluorescéine sous terre: Bull. Soc. belge géol., etc., vol. 17, 1903, proc.-verb., p. 249; mém., p. 515.

The usual method of expressing the rate of flow of the fluoresceïn underground is in meters per hour or feet per minute, found by dividing the horizontal distance in a straight line from the point of entry to the point of appearance by the time which elapses between the hour of putting down the solution and its first appearance at the spring under consideration.

It has been mathematically demonstrated by M. de la Foresta[a] that the rate thus expressed is always less than the real rate of progress in the subterranean stream, from the fact that a certain length of time, generally indeterminate, is consumed by the solution in soaking into the lower stratum. If V = rate in feet per second, D = distance in feet, and T = time in seconds, then the rate is calculated thus:

$$V=\frac{D}{T}$$

Now T is evidently made up of two parts, or $T = t_1+t_2$, where t_1 =time consumed in infiltrating through the material separating the surface where the dye was put down from the bed in which the water circulates, and t_2 = real time during which the fluoresceïn is traversing the water stratum. Therefore the true rate V_1 is found thus:

$$V_1=\frac{D}{t_2}=\frac{D}{T-t_1}$$

And the difference between the true and the calculated rate is:

$$V_1-V=\frac{D}{T-t_1}-\frac{D}{T}=\frac{Dt_1}{Tt_2}$$

Whence it will be seen that the greater the time consumed by the preliminary infiltration the larger will be the error of the calculated rate; and the error will vary inversely with the permeability of the soil where the coloring matter is put down. If, furthermore, several wells are sampled at various distances from the entrance of the dye, it is usually found that the greater the distance traveled the greater is the calculated velocity for this reason:

$$V=\frac{D}{T}=\frac{D}{t_1+t_2}.$$

But in the same experiment t_1 is constant, while t_2 varies in proportion with D. It is clear, therefore, that t_2 = KD where K is a constant indeterminate for the same experiment. So, substituting this value for t_2 in the above equation,

$$V=\frac{D}{t_1+KD}=\frac{1}{\frac{t_1}{D}+K}$$

In other words, the calculated rate varies directly with the distance traveled. In many cases this has been found to be true. (See p. 81.)

Decomposition of fluoresceïn.—In its underground passage certain substances exert a decomposing influence on fluoresceïn. Since its color is destroyed by acid solutions, it is evident that it can not be used in waters containing any free acids, except carbonic acid. A large amount of calcareous matter in solution, especially the carbonates, will decolorize the dye to some extent. M. Trillat[b] has reported the effect on fluoresceïn of contact with soils of widely different character. Fluoresceïn solution containing 1 part per million was passed through 30 cm. of soils containing large amounts of selected materials. The effluent was

[a] Op. cit., p. 251.

[b] Sur l'emploi des matières colorantes pour la recherche de l'origine des sources et des eaux d'infiltration: Bull. Soc. belge géol., etc., vol. 17, 1903, proc.-verb., p. 301.

then examined for change in the intensity of the color. The result may be summarized thus:

Effect of certain soils on fluoresceïn.

Soil containing—	Percentage of organic matter.	Percentage of clay.	Change in fluoresceïn.
Lime	0	6.09	None.
Sand	4.56	0	Practically none.
Clay	7.96	79.20	Do.
Peat	49.07	35	Entirely decolorized.
Farm manure	....	....	None.

From this table it is seen that peaty soil will destroy the color, but that ammoniacal organic matter has practically no effect on it. Sandy soils and clay have almost no effect. By contact with water containing a large quantity of carbonate of calcium for twenty-four hours M. Trillat found that the intensity of the color was decreased about one-third.

EXPERIMENTS WITH FLUORESCEÏN.

Experiments in the Dhuis region.—The springs of Dhuis, an important part of the city water supply, are situated about 80 miles from Paris. The geologic strata in the region are a succession of permeable and impermeable beds—loam, limestone and millstone, (meulières de Brie), green clay, Champigny travertine, and *Pholodomya ludensis* marl, of which the travertine is the principal aquifer. This formation, 60 to 80 feet thick, is permeable and cut by fissures. Water circulates in it with great ease, often excavating large caverns by its action. It forms the bottom of all the valleys and ravines and a great part of their slopes. Since it is extremely permeable, it absorbes rain water and frequently engulfs the waters of brooks through sink holes (bétoires). From this bed the springs of Dhuis flow at a mean rate of about 3,670 gallons a minute. In 1901 experiments were made to determine the connection of these springs with possible sources of surface pollution. Fluoresceïn in varying amounts was poured into sink holes at different parts of the watershed and its progress noted by samples taken along its possible course. The results are as follows:

Experiments with fluoresceïn in Champigny travertine.[a]

No. of experiment.	Fluoresceïn used.	Distance traveled.	Difference in elevation.	Mean rate of slope.	Time elapsed.	Rate of flow.	Hardness.[b]
	Pounds.	*Feet.*	*Feet.*	*Per cent.*	*Hours.*	*Feet per minute.*	*Parts per million $CaCO_3$.*
1	1.1	0	....	....	....	....	....
1a	....	10,004	169	1.6	13	12.8	236
1b	....	10,332	166	1.6	14	12.3	218
1c	....	9,512	156	1.6	13	12.2	....
1d	....	9,676	159	1.6	13	12.4	....
2	.66	0	....	....	....	....	....
2a	....	4,756	162	3.4	7	11.3	762
2b	....	4,920	207	4.2	9	9.1	238
2c	....	6,396	226	3.5	12	8.9	234
2d	....	8,856	164	1.8	18	8.2	242
3	2.64	0	....	....	....	....	....
3a	....	17,384	126	.72	33	8.8	365

[a] Commission de Montsouris, Travaux des années 1900 et 1901, p. 208.
[b] The hardness of these waters was expressed in "degrés hydrotimétriques," 1° is equivalent to 10 mg. of calcium carbonate per liter. Post, Analyse chimique appliquée aux essais industriels, p. 9.

Experiments with fluoresceïn in Champigny travertine—Continued.

No. of experiment.	Fluoresceïn used.	Distance traveled.	Difference in elevation.	Mean rate of slope.	Time elapsed.	Rate of flow.	Hardness.
	Pounds.	*Feet.*	*Feet.*	*Per cent.*	*Hours.*	*Feet per minute.*	*Parts per million $CaCO_3$.*
3b		18,040	189	1.04	30	10	226
3c		18,532	188	1.01	30	10.3	218
3d		18,532	188	1.01	30	10.3	232
3e		18,532	188	1.01	32	9.6	218
4	1.76	0					
4a		10,824	117	1.08	12	15	249
4b		10,824	114	1.05	12	15	710
5	.22	0					
5a		1,312	42	3.2	4	5.5	214
5b		1,640	40	2.4	5	5.5	220
5c		1,640	40	2.4	5	5.5	210
5d		1,640	40	2.4	5	5.5	220
6	1.98	0					
6a		8,856			18	8.2	
6b		8,856			14	10.5	

In column 1 the number of the experiment is given; the lettered numbers indicate points at which samples were taken; in experiment No. 1, for instance, samples were taken at four different places, numbered, respectively, 1a, 1b, 1c, 1d. Column 2 shows the amount of fluoresceïn used in each experiment. In column 3 is given the distance in a straight line between the point at which the fluoresceïn was put down and the point at which the sample was taken. In column 4 is shown the difference in elevation between the entering point of the fluoresceïn and the sampling point. Column 5 gives the average rate of slope of the water bed; it is found by dividing the difference in elevation by the distance between the points. In column 6 the time elapsed between the hour of putting down the fluoresceïn and its first appearance at each sampling point is given, while column 7 expresses the rate of flow of the fluoresceïn underground in each case. The total hardness of the water in column 8 is given to show that experiments with fluoresceïn may be conducted even when the amount of lime in the water is rather high.

One of the most striking features of these experiments is the distances that the fluoresceïn traveled. In experiment 3c, 3d, and 3e it went considerably over 3 miles and the time taken for the journey was over a day. Even for this great distance, however, the amount of fluoresceïn necessary was not excessive, being a little over 2.5 pounds. The rate of flow varied in different parts of the formation from 5.5 feet to 15 feet per minute, a figure which is influenced both by the slope of the water bed and the size of the apertures through which the water passes. In experiment 3 to 3e particular attention is called to the concordance of the results. In 3a, with a distance traveled of 17,384 feet and a total fall of 126 feet, the fluoresceïn progressed at the rate of 8.8 feet per minute. With an increase of the slope and some increase of distance traveled as shown in 3b to 3d there was, as would be expected, a corresponding increase in the rate of flow. In 3e, through some underground influence, there was a slight decrease in the rate of flow. Though these waters contained amounts of calcium, corresponding to a total hardness of 218 to 762 parts per million, yet no difficulty was experienced in making the experiments, even when the fluoresceïn was in contact with the calcareous rock from five to thirty hours.

These have been chosen as typical results in formations where there is free circulation of water through well-defined veins or seams, and not a slow seepage through beds of rock having small interstices. The principal points to be noted are:

1. Fuoresceïn is capable of traveling long distances.

2. Large amounts of calcium may be present without preventing the experiment.

3. Fluoresceïn is not destroyed by comparatively long contact with underground waters.

Experiments in the region of Yonne and Cure.—The results of only five experiments in the valleys of Yonne and Cure are noted in the following table, but they are noteworthy on account of the various conditions under which they were performed:

Experiments with fluoresceïn in the valleys of Yonne and Cure.[a]

No. of experiment.	Fluoresceïn used.	Distance traveled.	Difference in elevation.	Mean rate of slope.	Time elapsed.	Rate of flow.
	Pounds.	*Feet.*	*Feet.*	*Per cent.*	*Hours.*	*Feet per minute.*
1[a]	0.6	492	....	....	24	0.34
2[b]	6.6	0	....	....	....	....
2a	....	15,580	228	1.4	100	2.5
2b	....	15,744	226	1.4	100	2.6
2c	....	15,744	226	1.4	101	2.6
2d	....	16,794	224	1.3	74	3.8
2e	....	19,680	230	1.1	72	4.6
3[c]	2.2	0	....	....	....	....
3a	....	4,100	....	1.6	1.25	55
4[d]	4.4	0	....	....	....	....
4a	....	19,680	....	1.5	34	9.6
4b	....	27,552	....	1.1	32	14
4c	....	38,048	....	1.1	42	15
		38,048	....	1.1	60	10
4d	....	37,884	....	1.1	40	16
		37,884	....	1.1	66	9.6
4e	....	38,212	....	1.1	43	14.8
		38,212	....	1.1	59	10.8
5[e]	4.4	0	....	....	....	....
5a	....	42,984	322	.76	168	4.3
		42,984	322	.76	220	3.2
5b	....	43,558	328	.75	172	4.2
		43,558	328	.75	222	3.3

[a] Le Couppey de la Forest, M., Commission de Montsouris, Travaux de l'année 1902, pp. 38, 284.
[b] Idem, p. 259.
[c] Idem, p. 272.
[d] Idem, p. 286.
[e] Idem, p. 262.

In experiment 1 a small amount of fluoresceïn was put into a well about 160 feet deep bored in the compact limestones of the Rauracian. It required twenty-four hours for the coloring matter to progress a distance of about 500 feet. This experiment shows how slow the rate of flow is in limestone when that rock is compact and not cut up by large fissures. It also shows that fluoresceïn can permeate fairly solid rock even when it is not full of fissures.

Experiment 2 to 2e indicates the progress of the seepage from an irrigated tract of land about one-fourth mile from the hamlet of Souille. A brook flowing a little over 10 gallons a minute was diverted on a field of about 5 acres, where its waters were slowly but entirely absorbed into the soil. In the belief that this water reached springs of the region 6.6 pounds of fluoresceïn were poured into the brook; it appeared in these springs after intervals varying from seventy-two to one hundred and one hours. The rates of flow were low. Moreover, the springs farthest removed from the point where the fluoresceïn was put down had the highest rates of flow, though the mean slope toward them was less than in the nearer springs. This fact shows, as discussed on page 78, that the time consumed for the infiltration of the fluoresceïn from the surface to the underground aquifer was considerable and concealed the true rate of flow in the subterranean channels of the lithographic limestones of the Sequanian and the Rauracian. Another interesting fact is that springs 2a, 2b, and 2c, namely, those nearest the irrigated field, were but slightly colored for twelve hours; on the other hand, springs 2d and 2e were colored for thirty-six hours with an intensity visible to the naked eye. The connection of springs 2d and 2e with the infiltration from the irrigated field would probably never have been suspected from a topographic survey of the region, because three dry valleys and considerable distances intervened.

On the left bank of Cure River a cavern called La Grotte des Goulettes is in direct communication with the river and engulfs a considerable portion of its water at all seasons of the year. At the time when experiment 3 to 3a was performed the cavern absorbed about 100 gallons a minute. After 2.2 pounds of fluoresceïn had been put into the water at the entrance to this cave it appeared in the water of a spring (3a) 4,100 feet distant, in one hour and fifteen minutes, after traveling at the high rate of 55 feet a minute. In this instance there was undoubtedly a well-defined subterranean channel of good size connecting La Grotte des Goulettes with the spring in question.

At Petit-Banny (experiment 4 to 4e), located in the valley of Druyes, 4.4 pounds of fluoresceïn were put on the porous bed. It traveled for the extraordinarily long distances of 19,680, 27,552, 38,048, 37,884, and 38,212 feet, through fissured limestone formations. It will be noted that in this experiment and in others where the distance traveled was less, with an increase of distance there is a corresponding increase in the rate of flow, showing that some time is taken for absorption into the underground channel. For springs 4c, 4d, and 4e two rates of flow are given, corresponding to two successive influxes of colored water, separated from each other by eighteen, fourteen, and fourteen hours, respectively. Probble reasons for two influxes, as previously discussed (p. 77), are either that the colored water arrived at the outlets by two different routes or that it became sedimented in some cavity and was then washed out by a later influx of water.

Experiment 5 to 5b gives the greatest distance for the underground journey of fluoresceïn noted in the reports at hand, namely, 43,558 feet in the experiment at Courson. Courson Brook is absorbed by progressive infiltration in the permeable beds of the Sequanian in a distance of about 650 feet along its bed. Four and four-tenths pounds of fluoresceïn were put into the stream. It was found at Crisenon (5a) and Grosse-Pierre (5b), over 8 miles away, after having traversed the fissured limestones of the Sequanian and the Rauracian at the rate of 4.3 and 4.2 feet a minute, respectively. At both of these springs a second flow occurred as noted. Even after such long journeys as these there is an apparent influence of the time taken for infiltration through the absorption bed.

Experiment at Auxerre.—An especially noteworthy experiment[a] was conducted at Auxerre to demonstrate the passage of polluted water from a ditch through alluvial deposits of sand and gravel into a collecting gallery from which the city supply was taken.

A collecting gallery about 300 feet long in the alluvium of the Yonne is situated 130 to 230 feet from the river. Its top is 2.8 feet and its water plane 4.3 feet below the surface. A polluted brook ran directly toward the collecting gallery until within 28 feet, then turned nearly at a right angle and paralleled it at about the same distance. Its water surface was from 1.2 to 3.5 feet above that of the gallery, from which 1,130,000 gallons of water were pumped daily. Two and two-tenths pounds of fluoresceïn were put into the brook 254 feet in a straight line from the collecting galleries, and samples were then taken of the water pumped from the galleries. Fluoresceïn was shown two and one-fourth hours after the dye was put into the brook, and an intense coloration was clearly visible to the naked eye in about ten hours, lasting thirteen hours. By examining samples from many sources throughout the city and estimating the amount of fluoresceïn present, it was found that the city water was colored for thirteen hours at an average of 1 part of fluoresceïn in 30,000,000. During that period about 600,000 gallons were pumped

[a] Le Couppey de la Forest, M., La fièvre typhoïde à Auxerre en 1902: Revue d'hygiène et de police sanitaire, vol. 24, pt. 6, 1902.

from the galleries, containing, therefore, 0.17 pound of fluoresceïn. Since 2.2 pounds were put into the brook and 0.17 pound reached the city water, it may be estimated that the ditch water reaches the galleries in the proportion of 2.2 to 0.17, or, to allow for some small error, about one-fifteenth of the brook water infiltrates to the town supply. Since the stream flowed at that time 950 gallons a minute, or about 1,370,000 gallons a day, while the gallery consumption was 1,130,000 gallons a day, it will be seen that about 8 per cent of the city supply was water from the polluted brook.

As previously stated, it took two and one-fourth hours for the fluoresceïn to reach the filter galleries. Assuming that the infiltration extended from the point at which the fluoresceïn was put down, the coloring matter would have progressed with a rate of 113 feet an hour through the alluvial deposits. If, on the contrary, the infiltration took place between the ditch and the gallery at the nearest point, it occurred at the rate of 12.4 feet per hour. Assuming a maximum filtration rate of 3,000,000 gallons per acre per day for an efficient sand filter, it may be inferred that this brook water reached the collecting galleries with practically no purification.

SUMMARY.

1. In determining the sanitary value of a well or spring it is more important to study the underground flow than to analyze the water itself.
2. Foreign substances put into the aquifer and traced from point to point are of great use in this study.
3. With the fluoroscope one part of fluoresceïn can be detected in 10 billion parts of water.
4. Fluoresceïn is a particularly valuable flow indicator for fissured or cavernized rocks.
5. It is also available in gravels, where it has been used with success.
6. It progresses at a slightly lower rate than the water in which it is suspended.
7. It is not decolorized by passage through sand, gravel, or manure; it is slightly decomposed by calcareous soils.
8. It is entirely decolorized by peaty formations and by free acids, except carbonic acid.
9. It has been used with much success for several years by the city of Paris.

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PECULIAR MINERAL WATERS FROM CRYSTALLINE ROCKS OF GEORGIA.

By Myron L. Fuller.

INTRODUCTION.

In this paper are described a number of wells and springs in the Piedmont area of Georgia which, in view of the character of the rock in which they are sunk, afford mineral waters of remarkable character. The attention of the writer was called to the springs by Mr. S. W. McCallie, assistant State geologist of Georgia, who accompanied him on a visit to the locality and courteously furnished a number of analyses made by Dr. Edgar Everhart, of the local survey.

The waters, which, for supplies coming from crystalline rocks, are enormously high in chlorine and sulphates, are obtained from a number of wells and springs situated near the town of Austell, on the Southern Railway, in Cobb County, near the Douglas County line, 20 miles northwest of Atlanta and a little west of Sweetwater Creek, a tributary of Chattahoochee River. They are included in the Marietta quadrangle of the United States Geological Survey. One spring and three wells have been developed within a short distance of the town, their waters being placed on the market for medicinal purposes.

DESCRIPTION OF WELLS AND SPRINGS.

BORDEN LITHIA SPRING.

This spring, which is situated about a mile south of Austell and a similar distance northeast of Lithia Springs station, is stated to be the most important spring in Georgia from the standpoint of value of shipments. The water issues from a crevice in the bottom of a basin blasted out to a depth of several feet in the gneissoid granite, which here outcrops in strong ledges of almost unweathered rock. The basin is protected by a glass covering, and all surface seepage is carefully excluded. The yield, which is about 3 gallons a minute, is very constant, and the water has shown no noticeable change in composition since first discovered many years ago. In fact, the locality, because of the visits of deer to it for salt, has been known to the Cherokee Indians as the "deer-lick" from the time of their earliest traditions.

The composition of the water is shown in the table of analyses on page 88. The temperature is normal.

The principal spring at Austell was originally a few hundred feet west and across the strike from the Borden spring, but was ruined some years ago by an ingress of fresh water brought about by blasting in an effort to increase the flow.

Another salt spring, known as the Medlock spring, is located a short distance from the Medlock well (see p. 87), but is no longer used, and no analysis of its water was made. In composition, however, the water appears to be similar to those of neighboring wells and of the Borden Lithia Spring.

ARTESIAN LITHIA WELL.

This well, which is located near Sweetwater Creek, a little north of Austell, is 2 inches in diameter and is reported by some to be 900 feet deep, though others state that it is not over 750 feet. It appears to have been put down in search of anthracite coal, which someone imagined could be found in the granite of the region. The well penetrated for most of the way a gneissic rock, with which, it is said, some thin hornblendic layers were interbedded. The water, which is encountered in fissures at a number of different depths, rises nearly to the surface. It has a distinct saline taste, similar to that of the Borden Lithia Spring. An analysis is given in the table on page 88. This water, which is supplied at the rate of several gallons a minute without reference to season, is sold somewhat extensively as a mineral water.

An interesting point in connection with the occurrence of this saline water is that the Sulpho-Magnesia well, which was drilled to a depth of 750 feet only a short distance from the Artesian Lithia well, obtained only fresh water, although, so far as could be determined, the same succession of rocks was penetrated.

MEDLOCK WELL.

This well is located near the left bank of Sweetwater Creek, five-eighths of a mile northwest of Austell station and a few hundred yards southwest of the Sulpho-Magnesia well. It is 6 inches in diameter, 65 feet deep, and yields a supply of several gallons a minute from a fissure near the bottom of the well, the water rising to within a few feet of the surface. Except 5 feet of surface alluvium, the well is in a fine-grained gneiss. The composition of this water, which is highly saline, is shown in detail in the table on page 88.

J. H. LOUCH WELL.

This well, which was drilled in 1903, is located a few hundred feet from the Medlock well. It is 6 inches in diameter, 80 feet deep, and furnishes 1,500 gallons of water per day of twenty-four hours, the water rising to within 5 feet of the surface. The rock, as in the Medlock well, is a fine-grained gneiss. The water, which is very similar to the preceding, is put on the market in considerable amounts. The analysis is given in the table on page 88.

OTHER WELLS.

In addition to the saline wells already described and the Sulpho-Magnesia nonsaline well, there are four deep wells within the corporate limits of Austell. Two of these, near the railroad station, are 133 and 150 feet deep, respectively. Of the two others one is located at the Lithia Springs Hotel, and is 5½ inches in diameter and 150 feet deep. The other is the Brunk well, near Spring street, one-half mile south of the station. It is 6 inches in diameter and 110 feet deep.

The water in all four wells is low in mineral matter, soft, and free from salt, and is well suited for domestic or boiler purposes. So far as can be determined it comes from crevices similar to those from which the saline waters are obtained and from the same kind of rock. The locations are not such as to suggest any difference in geologic conditions.

COMPOSITION OF THE WATERS.

ANALYSES.

The composition of the waters is best shown by chemical analyses, a number of which made by Doctor Everhart, are given in the table below. The analyses in the first four columns are of the saline mineral waters, while that in the fifth column is of the nearly normal water from the Sulpho-Magnesia well, which is given for purposes of comparison.

Analyses of well and spring waters, Austell, Ga.

[Parts per million.]

	Saline waters.				Nonsaline waters.
	Bowden Lithia Spring.	Artesian Lithia well.	Medlock well.	Louch well.	Sulpho-Magnesia well.
Ionic statement.					
Iron (Fe)	1.05	0.21	....	0.45	0.61
Aluminum (Al)	1.33	.48	....	.40	.66
Manganese (Mn)	.20	....	Trace.	Trace.	Trace.
Calcium (Ca)	116 8	120 8	473.8	194.5	25.0
Magnesium (Mg)	9.2	12 9	53.8	26.9	3.6
Barium (Ba)	.18	.14	....	.22	Trace.
Lithium (Li)	5 6	17 0	14.5	8.8	2.5
Sodium (Na)	702 3	650.9	2,790.6	1,995.1	11.1
Potassium (K)	20 3	5.3	64.3	63.9	4.2
Silica (SiO_2)	32 6	24.3	26.2	11.6	18.0
Carbonate ion (CO_3)	80 3	113.6	....	35.0	51.5
Free carbon dioxide (CO_2)	70.9	80.0	....	70.1	82.7
Sulphate ion (SO_4)	181.4	178.1	769.8	581.2	3.6
Phosphate ion (PO_4)	27	.54	.15	Trace.	.47
Chlorine (Cl)	1,101 6	1,032.0	4,769.3	3,134.2	7.7
Bromine (Br)	20.7	....	....	2.8	....
Arsenic (AS)	.10	Trace.	....	....	Trace.
Iron oxide and alumina ($Fe_2O_3+Al_2O_3$)	....	....	18.4	....	....
Analyst's combinations.					
Manganese oxide (MnO)	....	....	....	....	Trace.
Iron carbonate ($FeCO_3$)	4 4	.90	....	1.22	2.6
Aluminum sulphate ($Al_2(SO_4)_3$)	10 9	3.9	....	1.36	5.5
Manganese carbonate ($MnCO_3$)	50	....	Trace.	....	....
Calcium carbonate ($CaCO_3$)	156 6	189.3	40.7	....	62.5
Calcium sulphate ($CaSO_4$)	183.9	153.2	787.4	670.8	....
Magnesium carbonate ($MgCO_3$)	....	....	267.6	....	12.6
Magnesium sulphate ($MgSO_4$)	45 9	64.2	....	133.3	....
Barium sulphate ($BaSO_4$)	30	....	....	.38	....
Lithium chloride ($LiCl_2$)	34.0	47.0	41 9	24.6	7.2
Sodium carbonate (Na_2CO_3)	....	....	....	....	24.8
Sodium sulphate (Na_2SO_4)	.30	21.1	....	....	1.2
Sodium phosphate (Na_2HPO_4)	.80	.80	.20	Trace.	.66
Sodium arsenite ($NaAsO_2$)	.40	....	....	....	Trace.
Sodium chloride (NaCl)	1785.0	1634.3	7093.8	5070.9	....
Sodium bromide (NaBr)	....	4.0	....	....	....
Potassium sulphate (K_2SO_4)	....	....	....	....	5.1
Potassium chloride (KCl)	.30	....	122.8	119.5	3.7
Potassium bromide (KBr)	30.8	16.2	....	4.2	Trace.
Total solids	2,286.6	2,159.2	9,058.0	6,096.0	131.4

Edgar Everhart, Geological Survey of Georgia, analyst.

COMPARISON WITH NORMAL WATERS.

A comparison of the analyses of the mineral waters near Austell with the normal waters of the region brings out some interesting features. Although the total solids in the mineral waters are from 16 to 70 times as great as in the normal water, the iron constituent is practically the same and in one case even less than in the ordinary water. The calcium, on the other hand, varies from 4 to 20 times, the magnesia from 3 to 15 times, the sodium from

60 to 250 times, and the potassium from about the same to 15 times as much as in the normal water. The silica, though varying from less than the amount in the unmineralized water to twice this amount, is essentially normal.

Not only does the absolute amount of the mineral ingredients vary greatly, but the proportion of the principal mineral substances also varies considerably, as shown in the following summary of the relative percentages of chlorine, sodium, magnesium, calcium, and potassium—five of the more important constituents of the waters.

Summary of percentage composition

	Average of four Austell mineral waters.	Sea water.	Normal Austell water.
Calcium (Ca)	5.2	1.2	48.6
Magnesium (Mg)	.6	3.5	6.9
Sodium (Na)	35.4	28.2	21.4
Potassium (K)	.9	1.0	8.2
Chlorine (Cl)	57.9	66.1	14.9
	100.0	100.0	100.0

In no instance does the amount of an ingredient in the Austell mineral waters occur in anything like the same proportion as in the normal water. The disagreement in the principal constituents—chlorine, sodium, and calcium—is especially marked, being as 57.9: 14.9, 35.4:21.4, and 5.2:48.6, respectively.

GEOLOGIC CONDITIONS.

LOCATION.

The Austell springs and wells are situated about 20 miles northwest of Atlanta, and are therefore located within the limits of the Piedmont Plateau. The distance from Austell to the borders of the Coastal Plain area to the southwest is about 90 miles, while the metamorphosed sedimentary Ocoee beds lie at a distance of about 10 miles to the northwest. The nearest point at which the later Paleozoic rocks occur is over 20 miles to the northwest.

The rocks in the vicinity of the spring and in the adjacent region in general are prevailingly of the gneissic type so common in the Piedmont area of this part of Georgia, although some more basic rocks occur as interbedded bands in the near vicinity. No unaltered sedimentary rocks occur nearer than the later Paleozoic border, 20 miles to the northwest.

CHARACTER OF ROCKS.

The rock from which the water issues is a light-gray granite with a well-marked gneissoid structure, which strikes with considerable uniformity in a north-south direction and is inclined at an angle of about 45° to the east. The granite appears to be interrupted by bands of a dark hornblende schist, a belt of which outcrops a short distance east of the wells and springs. The same or a similar rock was also encountered in the deeper wells.

A microscopic examination of the granite by Albert Johannsen showed it to consist essentially of quartz, microcline feldspar with a little albite and biotite-mica. The accessary minerals are titanite, apatite, and a little zircon. The composition was normal, no minerals being recognized which could have furnished the chlorine that is so abundant in the waters of the wells and springs.

The dark schist when examined under the microscope was found to consist mainly of hornblende, with quartz, augite, and a little plagioclase feldspar. As in the case of the granite, nothing was recognized which could have afforded the chlorine of the mineral waters.

JOINTING.

Owing to the mantle of decomposed rock constituting the surface throughout the Piedmont belt, joints are not so noticeable as in many regions. They are, however, to be seen in greater or less abundance in practically all the quarries throughout the belt. There are several different series which in a given district are generally fairly constant in direction. The best developed joints, according to T. L. Watson, have nearly due east-west or north-south directions, although in many instances the major series trend northwest and southeast.

SOURCES OF MINERALIZATION.

SURFACE ROCKS.

With the exception of the apatite in the gneissoid granite no mineral capable of yielding chlorine is present in the surface rocks of the region, and even the apatite is present only in exceedingly small amounts—no more than in all of the granites of the region—and is not sufficient to account for the wide variation of the Austell waters from the normal. The same is true of the hornblende schist, making it clear that the source of mineralization lies outside the rocks from which the springs issue and from which the wells draw their supplies.

DEEP-SEATED ROCKS.

The derivation of the mineral matter from the surface rock by meteoric waters being apparently ruled out because of the absence of minerals capable of furnishing to the water the dissolved substances, especially the chlorine, a deeper-seated origin suggests itself. To furnish chlorine in the amounts observed contact of the meteoric waters with some rock rich in sodalite or apatite must be postulated. This might be a sodalite-syenite or other syenite rich in sodalite, or a granite or similar rock high in apatite, and might be assumed to occur as a granitic or pegmatite intrusion reaching within the limit of circulating waters, but failing to reach the surface. An analysis made by N. Sahlborn of a pyroxene-apatite-syenite from Finland showed 14 per cent of apatite,[a] which if it was a chloro-apatite would be equivalent to 0.9 per cent of chlorine. In the sodalite-syenites the chlorine may run even higher, one sample of such rock from Greenland analyzed by N. V. Ussing showing 2.25 per cent chlorine.[b] Bearing in mind that the chloride minerals are in general much more soluble than the silicate minerals, one easily sees that rocks of the character indicated might well be the source of saline waters. No such rocks, however, have been reported in the part of Georgia under consideration, and if they occur they must be deep below the surface.

MAGMATIC WATERS.

It may be conceived that instead of forming a part of the circulating system of meteoric waters and deriving its mineral matter from some deep-seated rock with which it came into contact, the mineral water may represent what is known as magmatic water, or that excluded on cooling from some molten rock such as may have been intruded at some point below the surface near Austell. What has been said in regard to the absence of evidence as to the existence of chlorine-bearing rocks applies with equal force to intrusions capable of furnishing the magmatic waters. There is little evidence of disturbance of any kind in this region, either dynamic or igneous, in late geologic time, and if the water is of magmatic origin it probably represents an intrusion of considerable age.

IMPRISONED SEA WATERS.

As the general character of the Austell mineral water was suggestive of a sea water, figures showing the relative composition of the latter have been inserted in the summary. The resemblance of the two is very marked in the case of nearly every constituent.

[a] Washington, H. S., Chemical analyses of igneous rocks: Prof. Paper U. S. Geol. Survey No. 14, 1903, p. 313.
[b] Op. cit., p. 303.

In the case of silica, however (not included in the summary), a difference is noted. The lowest amount in the Austell waters is 11.6 and the highest 32.6 parts per million. In sea water, however, ordinarily only from 2 to 5 parts per million are present. The difference, however, is probably not so great as would appear, as in the process of analyses the sea water was filtered before determination of the silica, while the spring waters were probably not filtered. Unfiltered sea water often gives results quite as high as that of the Austell springs.

SUMMARY.

Four possible explanations of the source of mineralization of the abnormal waters of the Austell springs have been suggested. These are: (1) That the mineral matter has been derived from the superficial country rock; (2) that it has come from deep-seated sodalite or apatite-bearing rocks; (3) that it represents water excluded from an igneous magma, and (4) that the water is in the main an imprisoned sea water conducted by joints and faults, etc., from the area of sedimentary rocks to the northwest.

The difficulty to be met by the first supposition is that the granite and schist in the vicinity of the springs and wells are normal and incapable of furnishing the observed chlorine. Except near the north-south line, along which the wells and springs described are located, none of the waters from the granite are saline.

The second and third views seem more probable, but the rarity of rocks high in sodalite or apatite, and the improbability that buried masses of such rocks or recent intrusions occur at the particular point under discussion, since they are not known elsewhere in the region, throw doubt on these explanations.

The origin from imprisoned sea water is favored by the percentage composition of the mineral waters, which is almost identical with that of sea water. The few minor points of difference are readily explained by the admixture of the normal fresh waters of the rock. The presence of such waters in close proximity to the fissures bearing the salt water is shown by the breaking in of fresh waters when blasting out the basin of the original spring, and by the fresh waters encountered by the four nonsaline wells described. The slightly high calcium in the mineral waters as compared with sea water could be produced by a very slight admixture of the normal waters of the locality.

The difficulty under the last hypothesis of origin lies in the absence of any source for the water. The crystalline rocks have not, as far as known, been covered by the sea since Archean time. The distance of the springs from sedimentary rocks, the metamorphism of the latter at the points nearest the springs, the rarity of saline waters even within the area of the sedimentary rocks, and our present lack of knowledge of any connection by faulting or jointing with these rocks are further difficulties in the way of the acceptance of such an origin. At the same time the lateral transition of water through joints or similar passages for long distances is not unknown. The writer has called attention to such a case on Fishers Island, New York,[a] the distance in that instance being at least 6 or 7 miles.

While the waters of the sedimentary area are in general not saline, such waters have been noted in the region. A well in Chickamauga Park, the waters of which were analyzed by Dr. Edgar Everhart, of the Geological Survey of Georgia, showed a total of nearly 60,000 parts of sodium chloride, or several times the amount in the Austell waters.

CONCLUSION.

It is the opinion of the writer that of the four sources of mineralization enumerated the first may be omitted from consideration. Of the remainder the probabilities of the second and third are primarily about equal and either may well be the true explanation. Owing, however, to the close agreement in percentage composition between the Austell mineral and ordinary sea water, the hypothesis of imprisoned sea water conducted from the sedimentary area by joints or faults to the point of emergence is not considered entirely impossible, notwithstanding the serious difficulties in the way of such transmission.

[a] Geology of Fishers Island: Bull. Geol. Soc. America, vol. 16, 1905, p. 372.

PROBLEMS OF WATER CONTAMINATION.

By Isaiah Bowman.

INTRODUCTION.

There exists at the present time a considerable body of legal decisions relating to the disposition or the pollution of underground waters. These decisions are the outgrowth of controversies between well owners, and are based on real or supposed facts concerning the nature and movement of subterranean waters. In recent years our knowledge of the relation of water movement to rock structure and other factors has been greatly extended, and it is not surprising, therefore, that the decisions which would be affected by new acquisitions of knowledge should be inadequate when applied to cases at present under consideration. To secure justice in an action in tort decisions should be rendered not in accordance with precedent, but in accordance with the principles of justice sought to be established in preceding cases, the present better knowledge of the facts being taken into account.

This condition is illustrated in several sections of the country to-day, and it is desired here to present such cases in the hope that they may lead to worthy results both in the construction and care of wells of every variety and in the revision or promulgation of statutes intended to cover adequately the principles involved.

OIL AND GAS WELLS.

In the oil and gas regions of Pennsylvania, Indiana, Kansas, Texas, and other States considerable damage has been done by improperly allowing water to enter oil and gas sands to the exclusion of the oil and gas. The results have been so grievous that laws have been enacted in nearly every State where these substances are prospected looking toward their protection. By properly plugging abandoned holes wherever such water is known to enter, the driller has discharged his duties according to law by preventing contamination.

WATER WELLS.

DECAY OF CASINGS.

In the case of water wells, which, as a class, are of much wider distribution than either oil or gas wells, the same care is not exercised, though the results are sometimes as pernicious as in the preceding cases, if not of as great economic importance. In many States, as, for example, in Michigan, Wisconsin, and Washington, it has been made unlawful for a well owner to allow water from an artesian well to escape in needless amounts through the opening in the pipe at the surface. Often, however, it can be shown that even where such precautions are taken large amounts of water are being lost continually through defective casing.

When iron piping is put into the ground in the form of a sewer, it is not expected to last more than ten or fifteen years at the longest, but if it is put into the earth in the form of well casing there is usually no consideration of its longevity. It is tacitly assumed to last forever, while observations on casing withdrawn after having been in the earth both short and long periods show conclusively that it suffers deterioration and decay, and should be examined at short intervals for resulting defects.

No rule can be laid down as to the rate of decay, which will depend entirely on the conditions in individual cases. Casing withdrawn from wells fifteen to twenty years old has been found to be in reasonably good condition except at the joints, though the usual experience is that casing of this age is too badly decomposed to be withdrawn at all, except in sections, and even this is not always possible. On the other hand, if the waters which come into contact with the casing are heavily charged with minerals, their reaction on the pipe usually results in more rapid decay. At Dallas, Tex., the writer observed holes the size of a cent in casing withdrawn after having been in the earth but one year. The strong mineral waters in one of the formations of that State, the Glen Rose, had so damaged the casing that it was little better than a sieve.

CONDITIONS OF CONTAMINATION.

Some general considerations at this time will make clearer the cases discussed in a later paragraph and may also throw light on future difficulties in problems of water supply or contamination.

Let us assume a condition which is so frequent throughout the country as to need no specific illustration—that of deep waters under much greater head than those lying nearer the surface, and further assume the no less common condition of defective casing—and we arrive at the result that large quantities of water must be lost before reaching the surface. Again, let us assume that the deeper water has been found to be unsatisfactory for domestic purposes because of dissolved minerals and that, while it rises in the well hole with artesian effect, it does not flow at the surface. If the well is now abandoned, the decay of the casing will in time allow this water access to higher water-bearing strata, and its entrance will mark the beginning of pollution of the upper waters. Before the condition is remedied, at the average speed with which municipal authorities move in matters of this sort, enough of the mineral substances will have entered and been deposited in the upper strata to make their redemption by natural filtration long and difficult.

PREVENTION OF CONTAMINATION.

Plugging.—The primary cause of the trouble must be dealt with, the polluting waters being shut out by plugging the bore hole above the point where such waters enter. This is done by driving down a wooden plug, which expands under the action of water and fits the well wall snugly. Earth is then thrown over the plug, which compacts, and by the time the plug has decayed is itself a preventive of further trouble. Various modifications may be introduced into specific cases which will complicate the problem, but a remedy can undoubtedly be found in each case.

Use of packers.—Where a hole is drilled in firm rock, throughout its entire length water may and often is derived from several strata—let us suppose three. If one of the sources proves unpalatable, it is necessary to separate the different waters and determine the source of the undesirable water. This may be done by temporarily shutting off two of the sources, thereby testing each one separately. If it is desired to test the lowest source, an expanding hollow rubber plug or packer is inserted above it, with a pipe connecting the top of the packer and the well head. Clutches, working automatically, keep the lower part of the packer in position, while the weight of the attached pipe presses down the upper part of the packer. By this means the middle part of the packer is forced to expand and to fit the walls of the well tightly. The lowest water is then drawn from the well through the attached pipe, being by the above means entirely separated from the waters above. By the proper adjustment of pipes, packers, and plugs each of the waters can be separated and examined in turn.

The remedy applied to a particular case will, of course, depend on the nature of the above determinations. If the lowest water is found to be the source of trouble, it may be plugged off, as already explained. Should the uppermost water be unpalatable, it may be shut off by applying a rubber packer below the undesirable water-bearing stratum and drawing water for use from the pipe connecting with the lower waters. In some cases it may be possible to keep a water of inferior quality in the rock by natural means. For instance, in drilling for an additional supply the driller may come to a sand in which the water is of lower head than the upper waters through which he has passed. In this event he may allow natural infiltration from the upper waters into the undesirable bed to take place. Unless the well is pumped too vigorously this will serve as a remedy, but the total yield of sweet water could in this case be utilized only by plugging the lowermost water.

NEED OF CAREFUL INVESTIGATIONS.

The only way by which municipal interests could be protected under any of the above conditions would be by making a thorough examination of the well hole and an exploration of the amount and quality of each water contributing to the yield of the well. This would be very greatly facilitated by having at hand a log of the well—that is, a record of the character and extent of each of the formations through which the bore hole had been drilled. This has been recognized by one State at least. South Dakota requires this in the following statute:

It is hereby made the duty of the township board to embody in the contract for the sinking of said public artesian wells a proviso that the person sinking said wells shall make a record of the depth of each well and the formations entered or passed through in the construction of the same, and such provision is hereby made an essence of the contract, and a violation thereof shall be construed to be a violation of the contract. (Laws, 1891, chap. 80, sec. 35.)

It is interesting to note that this same State also requires that every person sinking an artesian well shall provide for such well a proper casing, in order to prevent the well from caving in, and to prevent the escape of the water when it is desirable that such water be confined. It is not clear, however, under the terms of the law, precisely what is meant by a proper casing, inasmuch as through the decay of the casing it may fulfill its function of confining strata or water for several months only, while again it may last for years.

It is not possible at this time to take up in greater detail the means by which the bore hole in various conditions may be explored. It is sufficient here to state that such exploration can in every case be accomplished along scientific lines, and that more and more this is actually being done.

To further suggest a way in which these ideas may be applied in a practical way to specific cases, let us take the instance of the partial failure of a given water supply as expressed by a loss of head. Heretofore this has generally been assumed to indicate that the limit of available waters had been passed and that in some way means should be adopted looking toward the maintenance of head. May it not be that in such cases the loss of head is partly or even entirely due to defective casing, which allows the water from lower sources to escape through the pipe and enter porous nonwater-bearing strata at a higher level, or to enter water-bearing strata the water of which is standing at a lower head? Several cases have come to the writer's notice in which the conditions were almost identical with the assumed case above, and it can not be too strongly emphasized here that some such result as the one above outlined must follow.

SPECIAL PROBLEMS OF CONTAMINATION.

Two specific illustrations of some of the above-mentioned conditions have been supplied to the writer by Mr. J. E. Bacon and are a result of experiments conducted by him looking toward the improvement of the water supply in the cities of Saginaw, Mich., and Dallas, Tex. Mr. Bacon's kind assistance in gathering these data and putting them at the disposal of the writer is hereby gratefully acknowledged.

Conditions at Saginaw, Mich.—At Saginaw, Mich., there are a large number of salt wells, many of which have been abandoned for one cause or another. In the abandoned wells the bore hole allows salt or brackish water to reach the surface under the influence of the natural head of the water, together with convection currents and diffusion. A part of the city supply had, previous to 1902, been drawn from a deep-well system consisting of about 20 bored wells having an internal diameter of 4 inches and a depth ranging from 89 to 230 feet. Most of these wells are in the bed rock and draw their supply from sources which have been contaminated by the infiltration of brine from the salt wells. Up to the time that Mr. Bacon began his investigations almost no attention had been paid at Saginaw to the protection of surface water from contamination of this kind. The seriousness of the situation may be appreciated from the fact that possible sources of ground-water supply at Saginaw are limited to the loose sands and gravels which overlie the rock and the top of the rock itself. Manifestly the only way in which this water can be conserved in its original purity is by plugging abandoned salt wells at a suitable distance below the surface and exercising great care in maintaining the casing in others intact. The condition has been partly remedied by the above means and water obtained for municipal purposes from the glacial sands and gravels overlying the sandstone.

Conditions at Dallas, Tex.—The second case is the one illustrated by conditions at Dallas, Tex., where Mr. Bacon is at the present time (January, 1906) investigating the source and yield of potable water for city use. Water is yielded by four formations—the Woodbine, the Paluxy, the Glen Rose, and the Trinity—named in the order of their occurrence downward. While these are locally separated, the Glen Rose is really a part of the Trinity division. The lower Trinity sands have never been explored in the Dallas region, and their value as water producers is therefore unknown, but both the Paluxy and Woodbine formations contain sweet water. Most of the city wells derive water at the present time from the Woodbine, and it is the inadequacy of the supply from these sands which has led to the present investigations.

The peculiar conditions which are to be recognized here are those arising from the fact that one of the city wells penetrates the Glen Rose formation, and the water supplied from these sands is under a greater head than that from the overlying Paluxy. Moreover, the Glen Rose water is strongly mineral. Its exact composition has not been determined for this locality, but west of Austin the upper Glen Rose beds yield water containing strontium, magnesium, and sodium. Many residents of Dallas use the water for its real or supposed medicinal value.

This mineral water attacks the well casing so strongly that casing which had been in the well but one year exhibited breaks and checks in great number, and several of these were observed the size of a cent. The threads at the joints were completely decayed and unserviceable, so that when an attempt was made to pull the casing each length was lifted out as if it had no connection with the next lower length. Its value, therefore, as a tight casing was practically zero. Add to the conditions outlined the fact that the Glen Rose water is under greater head than the Paluxy and it is seen that gradually the Paluxy sands must become impregnated with the mineral substances in the Glen Rose water. While the water is used for medicinal purposes by a number of the citizens of Dallas, it is unpalatable as drinking water, and attempts to use it as such have proved unsuccessful. Its temperature is high and the contained salts give it a most unpleasant taste.

By inserting a packer with casing to the surface between the Glen Rose and Paluxy sands the two waters were separated, the mineral water with high temperature coming up inside the pipe and the Paluxy coming up between the pipe so inserted and the well casing. Differences in head and quality and temperature of water were at once noticeable, although the Paluxy waters were to some extent mineralized. The mineral content, however, steadily decreased as the experiment was continued.

RECOMMENDATIONS.

These two examples with the general discussion preceding are sufficient to show the vital character of the problems which they involve, and ought to lead to the following definite results:

1. An accurate log should be kept of every well drilled.

2. Every water-bearing formation should be carefully examined as to its thickness and the quality of the water yielded.

3. The head of each separate water should be accurately determined and its relation established with respect to other waters encountered.

4. The casing should be intact when the well is completed and should be kept so, its condition being determined from time to time by suitable experiments.

5. A change in the head or quality of the water should be interpreted only after the possible effects of defective casing are taken into account.

6. In those States in which the geologic conditions are known to favor contamination through the operation of one or the other of the causes noted herein, laws should be framed making the examination of the well casing and the determination of the exact relations of separate water-bearing strata the duty of each well owner or well driller.

INSTANCES OF IMPROVEMENT OF WATER IN WELLS.

By Myron L. Fuller.

INTRODUCTION.

Instances in which well waters which were pure at the time of drilling have later become mineralized and unfit for use are not uncommon, but cases in which waters originally high in mineral matter have later become fresh and pure are so seldom reported that they excite considerable comment.

Such an improvement in the quality of the water, however, is perfectly natural and is to be expected under certain definite conditions which are somewhat widespread. The water in soaking downward through the ground dissolves a certain amount of mineral matter from the materials with which it comes into contact. The longer the water remains in the ground the more mineralized it tends to become. Where underground circulation is active the water which has been in contact with the soluble materials of the rock is constantly being replaced by pure waters from the surface, and in such instances the ground waters are relatively low in dissolved solids. Where the circulation is slow, on the other hand, the water remains in contact with the surrounding mineral grains for long periods of time and often becomes highly mineralized. Such waters are especially likely to be found in beds which, while porous at the surface, pinch out or become impervious in their lower portions, thus tending to limit or prevent the free downward circulation of the water. Sometimes only a slight circulation is needed to improve the water, especially where it is in materials containing only small amounts of soluble matter. In such instances a single small well may sometimes effect a change in the composition of the water. A number of such instances were brought to light by work conducted under the direction of the writer near Wilmington, N. C., in 1905, and are described in the following paragraphs of this paper. For the facts regarding the wells the writer is indebted to Mr. L. W. Stephenson.

DESCRIPTION OF WELLS.

The wells here described may be taken as types of their class. They are located on the Atlantic coast at a point nearly due east of Wilmington, N. C., 10 miles or more from the city. One of them is on the mainland, near the shore of Greenville Sound, another on the Hammocks, just inside of the barrier separating the sound from the ocean, while the other two are on the barrier beach itself.

TARRYMORE HOTEL WELL.

The well of the Tarrymore Hotel, which is situated on the barrier near the inlet opposite the mouth of Wrightsville Creek, was drilled in 1905 by J. D. Lowry. It is $4\frac{1}{2}$ inches in diameter at the top and $3\frac{1}{2}$ inches at the bottom and has a depth of 195 feet. It passed through alternating beds of sand and thin layers of rock varying from soft to hard. Water was associated with the rock at 65 feet and at the botton of the well, the principal horizon being at the latter point. The water rises to within 4 feet of the surface, or about 5 feet above the level of the sea, the height varying somewhat with the tide. The well yields 25 gallons a minute when pumped.

When the well was drilled the water possessed a noticeable salty taste, but after it had been in use for some time the salt became less noticeable and eventally the water became entirely fresh.

LUMINA PARK WELL.

The Lumina Park well is located on the barrier a short distance south of the well just described. It was likewise drilled by J. D. Lowry in 1905, and is 3 inches in diameter and 198 feet deep. The elevation is somewhat lower than that of the Tarrymore well, and the well flows at high tide, although at low tide the water does not quite reach the surface. Twenty-five gallons a minute are obtained by pumping. This well passes through about the same succession of materials as the hotel well and obtains water from similar sand rocks.

When drilled this well also yielded water which was decidedly salty, but on continued use the salt taste gradually disappeared until at the present time the amount of chlorine is not much higher than in the ordinary fresh-water wells of the region.

HAMMOCKS WELL.

The Hammocks well, owned by the Consolidated Railway, Light, and Power Company of Wilmington, was drilled several years ago to a depth of 259 feet. The diameter is 8 inches at the top and 6 inches at the bottom. At 98 feet a cavity was encountered in hard shell rock and yielded a large supply of salty water. This was more or less effectively cased off and the well continued. Later a supply of fresh water began to appear through the larger casing surrounding the smaller one, but it is said that no water was encountered in the 6-inch portion of the well. The water may come from the cavity or along the lower casing from some lower horizon. The data were given from memory, and the cavity may in reality have been struck at a depth considerably greater than was reported, in which case it may possibly be correlated with the horizon in the Tarrymore Hotel and Lumina Park wells. At any rate fresh water is now obtained from some horizon which at the time of drilling yielded salt water or none at all.

QUARANTINE STATION WELL.

The well at the quarantine station is built on piles about half a mile from shore, near the mouth of Cape Fear River. It was drilled some years ago by Mr. De Witt, of Washington, D. C., and has a diameter of about 3 inches and a depth of 400 feet. Its elevation is several feet above high tide. The water level fluctuates with changes of tide, the water generally standing about 2 feet above tide level. It is pumped by steam at the rate of 4,500 gallons an hour.

When the pump is started after standing idle for some time, salt water, similar to that in the wells previously described, is obtained, but after a few minutes the salt rapidly decreases in amount and in less than twenty minutes it can no longer be detected by the taste.

CHANGE IN COMPOSITION.

NATURE OF CHANGE.

In the preceding paragraphs two instances of permanent change in the composition of the water from salt to fresh, under normal conditions of pumping or flow, are described. These changes were exhibited by the Tarrymore Hotel and Lumina Park wells. No analyses of the original waters from these wells were made, but in their saline content they were similar to the water yielded by the well at the quarantine station before pumping, a partial analysis of which is given herewith.

Field analysis of water from quarantine station well before pumping.

[L. W. Stephenson, analyst, 1905.]

	Parts per million.
Iron (Fe)	1.5
Calcium (Ca)	550
Carbonate radicle (CO_3)	195
Sulphate radicle (SO_4)	622
Chlorine (Cl)	8,374

The type of water yielded after the wells have been pumped or have flowed for some time is illustrated by the analysis of water from the C. W. Worth well. This well, which is located near the shore of Greenville Sound, just south of the mouth of Wrightsville Creek and about opposite the Tarrymore Hotel and Lumina Park wells, was drilled in 1904. It is 3 inches in diameter and 152 feet deep and obtained water from a bluish sandstone about 150 feet from the surface. The well is 8 or 9 feet above sea level and flows at the rate of 10 gallons a minute at a height of about 6 feet above the surface, the level varying somewhat with the tide. Like the other wells in the vicinity it was probably salty at the start. A partial analysis of the water now obtained is as follows:

Field analysis of water from C. W. Worth well.

[L. W. Stephenson, analyst, 1905.]

	Parts per million.
Iron (Fe)	1
Calcium (Ca)	200
Carbonate radicle (CO_3)	224
Sulphate radicle (SO_4)	None.
Chlorine (Cl)	85

The analysis of the water from the quarantine-station well before pumping may probably be taken as typical of the salty waters obtained from the wells in this region when drilled, while that of the water from the Worth well represents the maximum purity likely to be attained in these wells. Between the two there will be all gradations, one of which is represented by a second analysis of water from the quarantine-station well, made on a sample taken after pumping twenty minutes at the rate of 4,500 gallons an hour. This is as follows:

Field analysis of water from quarantine-station well after pumping.

[L. W. Stephenson, analyst, 1905.]

	Parts per million.
Iron (Fe)	1
Calcium (Ca)	209
Carbonate radicle (CO_3)	122
Sulphate radicle (SO_4)	36
Chlorine (Cl)	298

The decrease of mineral matter in the water of the quarantine-station well is gradual, and the water is unquestionably even lower in chlorine after pumping for thirty minutes than after twenty minutes.

It will be noted that the relative as well as the absolute amounts of the mineral ingredients of the fresh waters are entirely different from those of the saline waters. From over 8,000 parts per million at the start the amount of chlorine, for instance, may fall to less than 100, while the sulphates may decrease from 600 to nothing. At the same time the carbonates may actually increase, notwithstanding less than a tenth of the original total solids is present.

CAUSE OF CHANGE.

The change of the water from salt to fresh is believed to be due to the drawing in of fresh supplies from the surface after the exhaustion of the mineralized waters by pumping or by their natural removal through flowing wells. Whether the salinity was due to originally included sea water, to salt dissolved from the sediments, or to a penetration of sea water now going on can not be absolutely determined. The high percentage of calcium present, amounting to over 500 parts per million, indicates that sea water was not the only source of the salinity, since such water rarely carries over 5 parts per million.

The ease with which the salt water was removed and the composition of the water itself suggest that the derivation of the salinity from contemporaneous leakage of salt water is very improbable. Some of the salts may come from imprisoned sea water, but the general character of the waters indicates that solution of matter from the deposits in which they occur or from beds with which they have been in contact is the predominating factor in determining their composition.

It is evident that the wells, although striking the water bed below the limit reached by the active circulation of the surface waters, were not beyond the limit of feeble circulation, for otherwise the mineral content of the water would have been much higher and more nearly that of the deep wells at Wilmington, in which the salinity approaches if it does not exceed that of ordinary sea waters.

APPLICATION OF PRINCIPLE.

The principle that originally inclosed sea or other highly mineralized waters may be removed by flowing or pumped wells is one which may prove to be of broad application to waters in the Coastal Plain and similar regions elsewhere. It means that a well should not necessarily be regarded as a failure if only salt water is obtained at the start. Instead of abandoning and plugging such a well it should be allowed to flow as freely as possible. No harm to underground supplies will in such instances be brought about by allowing free flow, while, on the other hand, as shown by the wells described, fresh water may be drawn into the water-bearing bed as the salt water is removed and a valuable well eventually secured. After the water has become fresh the flow or pumping, as the case may be, should be regulated and only enough water to meet actual needs taken. Otherwise the drain on the ground water may become so severe that the supply will be exhausted, as has often been the case.

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CLASSIFICATION OF THE PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

[Water-Supply Paper No. 160.]

The serial publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of the United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists may be had on application.

Most of the above publications may be obtained or consulted in the following ways:

1. A limited number are delivered to the Director of the Survey, from whom they may be obtained, free of charge (except classes 2, 7, and 8), on application.

2. A certain number are delivered to Senators and Representatives in Congress for distribution.

3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they may be had at prices slightly above cost.

4. Copies of all Government publications are furnished to the principal public libraries in the large cities throughout the United States, where they may be consulted by those interested.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports. This paper is the fifty-eighth in Series O, the complete list of which follows (PP=Professional Paper; B=Bulletin; WS=Water-Supply Paper):

SERIES O, UNDERGROUND WATERS.

WS 4. A reconnaissance in southeastern Washington, by I. C. Russell. 1897. 96 pp., 7 pls. (Out of stock.)

WS 6. Underground waters of southwestern Kansas, by Erasmus Haworth. 1897. 65 pp., 12 pls. (Out of stock.)

WS 7. Seepage waters of northern Utah, by Samuel Fortier. 1897. 50 pp., 3 pls. (Out of stock.)

WS 12. Underground waters of southeastern Nebraska, by N. H. Darton. 1898. 56 pp., 21 pls. (Out of stock.)

WS 21. Wells of northern Indiana, by Frank Leverett. 1899. 82 pp., 2 pls. (Out of stock.)

WS 26. Wells of southern Indiana (continuation of No. 21), by Frank Leverett. 1899. 64 pp. (Out of stock.)

WS 30. Water resources of the lower peninsula of Michigan, by A. C. Lane. 1899. 97 pp., 7 pls. (Out of stock.)

WS 31. Lower Michigan mineral waters, by A. C. Lane. 1899. 97 pp., 4 pls. (Out of stock.)

WS 34. Geology and water resources of a portion of southeastern South Dakota, by J. E. Todd. 1900. 34 pp., 19 pls.

WS 53. Geology and water resources of Nez Perces County, Idaho, Pt. I, by I. C. Russell. 1901. 86 pp., 10 pls. (Out of stock.)

WS 54. Geology and water resources of Nez Perces County, Idaho, Pt. II, by I. C. Russell. 1901. 87-141 pp. (Out of stock.)

WS 55. Geology and water resources of a portion of Yakima County, Wash., by G. O. Smith. 1901. 68 pp., 7 pls. (Out of stock.)
WS 57. Preliminary list of deep borings in the United States, Pt. I, by N. H. Darton. 1902. 60 pp. (Out of stock.)
WS 59. Development and application of water in southern California, Pt. I, by J. B. Lippincott. 1902. 95 pp., 11 pls. (Out of stock.)
WS 60. Development and application of water in southern California, Pt. II, by J. B. Lippincott. 1902. 96–140 pp. (Out of stock.)
WS 61. Preliminary list of deep borings in the United States, Pt. II, by N. H. Darton. 1902. 67 pp. (Out of stock.)
WS 67. The motions of underground waters, by C. S. Slichter. 1902. 106 pp., 8 pls. (Out of stock.)
B 199. Geology and water resources of the Snake River Plains of Idaho, by I. C. Russell. 1902. 192 pp., 25 pls.
WS 77. Water resources of Molokai, Hawaiian Islands, by Waldemar Lindgren. 1903. 62 pp., 4 pls.
WS 78. Preliminary report on artesian basin in southwestern Idaho and southeastern Oregon, by I. C. Russell. 1903. 53 pp., 2 pls.
PP 17. Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian, by N. H. Darton. 1903. 69 pp., 43 pls.
WS 90. Geology and water resources of a part of the lower James River Valley, South Dakota, by J. E. Todd and C. M. Hall. 1904. 47 pp., 23 pls.
WS 101. Underground waters of southern Louisiana, by G. D. Harris, with discussions of their uses for water supplies and for rice irrigation, by M. L. Fuller. 1904. 98 pp., 11 pls.
WS 102. Contributions to the hydrology of eastern United States, 1903, by M. L. Fuller. 1904. 522 pp.
WS 104. Underground waters of Gila Valley, Arizona, by W. T. Lee. 1904. 71 pp., 5 pls.
WS 110. Contributions to the hydrology of eastern United States, 1904; M. L. Fuller, geologist in charge. 1904. 211 pp., 5 pls.
PP 32. Geology and underground water resources of the central Great Plains, by N. H. Darton. 1904. 433 pp., 72 pls. (Out of stock.)
WS 111. Preliminary report on underground waters of Washington, by Henry Landes. 1904. 85 pp., 1 pl.
WS 112. Underflow tests in the drainage basin of Los Angeles River, by Homer Hamlin. 1904. 55 pp., 7 pls.
WS 114. Underground waters of eastern United States; M. L. Fuller, geologist in charge. 1904. 285 pp., 18 pls.
WS 118. Geology and water resources of east-central Washington, by F. C. Calkins. 1905. 96 pp., 4 pls.
B 252. Preliminary report on the geology and water resources of central Oregon, by I. C. Russell. 1905. 138 pp., 24 pls.
WS 120. Bibliographic review and index of papers relating to underground waters, published by the United States Geological Survey, 1879–1904, by M. L. Fuller. 1905. 128 pp.
WS 122. Relation of the law to underground waters, by D. W. Johnson. 1905. 55 pp.
WS 123. Geology and underground water conditions of the Jornada del Muerto, New Mexico, by C. R. Keyes. 1905. 42 pp., 9 pls.
WS 136. Underground waters of the Salt River Valley, by W. T. Lee. 1905. 194 pp., 24 pls.
B 264. Record of deep-well drilling for 1904, by M. L. Fuller, E. F. Lines, and A. C. Veatch. 1905. 106 pp.
PP 44. Underground water resources of Long Island, New York, by A. C. Veatch and others. 1905. 394 pp., 34 pls.
WS 137. Development of underground waters in the eastern coastal plain region of southern California, by W. C. Mendenhall. 1905. 140 pp., 7 pls.
WS 138. Development of underground waters in the central coastal plain region of southern California, by W. C. Mendenhall. 1905. 162 pp., 5 pls.
WS 139. Development of underground waters in the western coastal plain region of southern California, by W. C. Mendenhall. 1905. 105 pp., 7 pls.
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WS 142. Hydrology of San Bernardino Valley, California, by W. C. Mendenhall. 1905. 124 pp., 13 pls.
WS 145. Contributions to the hydrology of eastern United States; M. L. Fuller, geologist in charge. 1905. 220 pp., 6 pls.
WS 148. Geology and water resources of Oklahoma, by C. N. Gould. 1905. 178 pp., 22 pls.
WS 149. Preliminary list of deep borings in the United States, second edition, with additions, by N. H. Darton. 1905. 175 pp.
PP 46. Geology and underground water resources of northern Louisiana and southern Arkansas, by A. C. Veatch. 1906.
WS 153. The underflow in Arkansas Valley in western Kansas, by C. S. Slichter. 1906. 90 pp., 3 pls.

WS 154. The geology and water resources of the eastern portion of the Panhandle of Texas, by C. N. Gould. 1906. 64 pp., 15 pls.

WS 155. Fluctuations of the water level in wells, with special reference to Long Island, New York, by A. C. Veatch. 1906. 83 pp., 9 pls.

WS 157. Underground water in the valleys of Utah Lake and Jordan River, Utah, by G. B. Richardson. 1906. 81 pp., 9 pls.

WS 158. Preliminary report on the geology and underground waters of the Roswell artesian area, by C. A. Fisher. 1906. 29 pp., 9 pls.

PP 52. Geology and underground waters of the Arkansas Valley in eastern Colorado, by N. H. Darton. 1906. 90 pp., 28 pls.

WS 159. Summary of underground-water resources of Mississippi, by A. F. Crider and L. C. Johnson. 1906. 83 pp., 10 pls.

PP 53. Geology and water resources of the Bighorn basin, Wyoming, by C. A. Fisher. 1906. 69 pp., 14 pls.

WS 160. Underground-water papers, 1906, by M. L. Fuller. 1906. 104 pp., 1 pl.

The following papers also relate to this subject: Underground waters of Arkansas Valley in eastern Colorado, by G. K. Gilbert, in Seventeenth Annual, Pt. II; Preliminary report on artesian waters of a portion of the Dakotas, by N. H. Darton, in Seventeenth Annual, Pt. II; Water resources of Illinois, by Frank Leverett, in Seventeenth Annual, Pt. II; Water resources of Indiana and Ohio, by Frank Leverett, in Eighteenth Annual, Pt. IV; New developments in well boring and irrigation in eastern South Dakota, by N. H. Darton, in Eighteenth Annual, Pt. IV; Rock waters of Ohio, by Edward Orton, in Nineteenth Annual, Pt. IV; Artesian-well prospects in the Atlantic coastal plain region, by N. H. Darton, Bulletin No. 138.

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