Outline of Ground-Water Hydrology

With Definitions

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 494

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Definitions

AR E. MEINZER

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CONTENTS.

ILLUSTRATIONS.

OUTLINE OF GROUND-WATER HYDROLOGY, WITH DEFINITIONS.

By Oscar E. Meinzer.

INTRODUCTION.

FACTS, CONCEPTS, DEFINITIONS, AND TERMS.

The facts or truths on which ground-water hydrology or any other branch of science is based are immutable, but they are not fully known—indeed, they are known in only small fragments.

The concepts of a science are based on the facts or truths that are known or believed to exist. The more fully and accurately the facts of the science are known the more definite and satisfactory are its concepts. Without the complete facts a concept must (1) remain more or less indefinite, (2) be hypothetical, or (3) rest on a fictitious basis. Both hypothetical and fictitious concepts involve assumption of facts that are not known to exist, but they are very different in that one recognizes the lack of knowledge and the other does not. For most concepts the facts are not fully known, but the absence of knowledge does not make it necessary to adopt a fictitious basis. A poor scientist or careless thinker, in the desire to make his concepts definite and complete, is willing to assume as a fact something which he believes is probably true but which has not been conclusively proved. A true scientist, on the other hand, thinks so clearly that he is able to differentiate between what is known to be a fact and what is only probable or hypothetical. Inherently, incomplete knowledge does not necessitate erroneous concepts.

A definition is the expression of a concept by means of language. It should include all that is involved in the concept but nothing more. Obviously there are two kinds of pitfalls for the man who writes definitions—his concepts may be incorrect or hazy, or his command of language may not be adequate to enable him to express even satisfactory concepts accurately and completely. More often than is generally supposed lack of precision in writing is due to the vagueness and inaccuracy of the writer's concepts. The difficulties with language can not be entirely overcome even by the best writers, because of the deficiencies of even so highly developed a language as the English. Many words, when critically examined, are found to be vague and ambiguous in their meaning. Hence, perfection in making definitions is an unattainable ideal. Approximation to what is desired is the best that can be hoped for.

A scientific term is a symbol that represents a scientific concept. It has the same significance as the definition of the concept; it is neither more nor less precise. Scientific terms are not absolutely essential, but they are very convenient, and for this reason they are a real aid in promoting science. In this respect a scientific term is like any other name. It is not essential to a man's existence that he have a name, but human affairs are greatly expedited by giving some individual name to every human being.

It is very useful to have definite terms to denote important scientific concepts, but it is of less consequence what these terms are, provided there is general agreement as to them. It is not a matter of paramount importance whether a baby is called by one name or another, although its elders may have some strong preferences. It is, however, desirable that all concerned should agree on some one name. Intense arguments over names are likely to be amusing rather than serious, for they lack the vital quality of arguments concerning concepts or principles.

As the giving of names is an arbitrary matter, no single criterion for their selection is usually applied or can well be established. Among the principal criteria for the adoption of scientific terms are present use, etymology, original use, convenience, suggestiveness, and distinctiveness. However, none of these criteria can properly be applied to the exclusion of the others. Unanimity in present usage would, of course, be decisive unless possibly the term has been previously used for another purpose; but with respect to terms that are in controversy there is obviously no approach to unanimity, and the question can not generally be wisely decided by a majority vote. Moreover, the citing of authorities does not generally lead to decisive results.

SCOPE AND PURPOSE OF THE PRESENT INVESTIGATION.

In the sixteen years which the writer has devoted almost exclusively to the study of ground water he has become impressed with the large and difficult field that the subject covers and with the variety and complexity of the concepts that it involves. At the same time he has become conscious of a serious lack of terms to express the essential concepts and, back of this and doubtless largely responsible for it, a lack of precision and organization in the concepts themselves.

The present paper had its beginning several years ago, when the writer attempted to put down for his own use precise definitions of some of the terms he employed. This attempt unavoidably led back to the underlying facts and principles and resulted in an effort to organize these facts and principles into a consistent whole. It soon became evident that an attempt merely to assemble the terms in more or less current use and to set down the best possible definitions for these terms would be futile—that the correct and logical procedure would be to attempt to find the concepts involved in this branch of science, determine whether they represent the truth, ascertain their relations to one another, and then state as accurately as the English language will permit what these concepts are; finally, to undertake the troublesome but less vital task of finding terms for the concepts defined.

A few new terms have been deliberately invented, but most of the terms presented in this paper have been previously used. Careful consideration has been given to previous usage, but it has seemed to the writer that to attempt to give the origin and history of each term and references to the authorities would lead to endless and unprofitable complications and would defeat the purpose of the paper. As most terms have been used more or less loosely and many of them in more than one sense, it is obvious that the procedure of defining the concept and then adopting a term to signify that precise concept is likely to be somewhat dogmatic with respect to the term adopted.

Criticisms were invited and received from many authorities, and the original manuscript was revised again and again in the light of these criticisms. Eventually mimeographed copies of the paper were submitted to a large number of men of science, including geologists, hydraulic engineers, chemists, physicists, meteorologists, botanists, students of soil and of agriculture, mechanical engineers, and experts on well drilling. About 50 of these submitted criticisms or suggestions, many of which showed careful consideration of certain phases of the subject and proved to be of very great value. The writer is deeply grateful to all these critics and wishes to acknowledge his obligation to them. The number of critics has become so large that it is hardly practicable to give individual credit to each. Special credit is due to the writer's colaborers in the division of ground water of the United States Geological Survey, who devoted much time to the paper in its early stages; also to Charles H. Lee, who has had much interest in the undertaking and through whom the writer has had the privilege of presenting the subject to the San Francisco and Los Angeles sections of the American Society of Civil Engineers.

Although the statements in this paper are of a concise and positive character, it is not the hope or desire of the writer that they be accepted as the final dicta on the subject, but rather that they should serve to clarify and stimulate thought and lead to wholesome development of a relatively undeveloped branch of science. Even if the present paper should be free of errors—which, of course, it is not—it will some day appear crude and inadequate. At best it is only preliminary to a paper that can be prepared after the fundamental facts of the science and their significant relations have become better known.

The manuscript of this paper at first contained sections on the quality of water and on pumps and other lifting devices, but on account of unsatisfactory features of these sections it was decided to not publish them in their present form. The subject of quality of water is at present under investigation by W. D. Collins, of the United States Geological Survey.

ORIGIN OF TERMS USED.

The following paragraphs contain brief statements as to the origin and availability of some of the terms used and as to most of the terms and classifications that are original with the writer.

The sections on atmospheric water and surface water (pp. 12–17) contain little that is original except the classification of streams and lakes with respect to subsurface water. Perhaps the most significant feature relating to atmospheric water is the emphasis placed on the distinction between actual evaporation and evaporativity—a distinction that is very important in ground-water studies but is not always clearly recognized. None of the terms—*evaporativity* or *potential rate of evaporation; evaporation opportunity* or *relative evaporation*—are original with the writer, but none have become thoroughly established. The term *evaporative power of the air* has been used by Livingston [1] and other botanists for what is called *evaporativity* in this paper. It is, however, open to objection in that it ascribes a power to the air which the air does not really possess. The term *evaporation opportunity* was suggested by R. E. Horton[2] for use as defined in this paper. Meyer [3] uses this term and also the term *relative evaporation.* The term *relative evaporation* is favored by Brooks,[4] who comments as follows:

> *Relative evaporation* is perhaps the more expressive of what this term means, and it is more or less analogous to relative humidity. The fact that relative evaporation is already in use to express the relative losses from evaporation pans of different sizes exposed in the same atmospheric environment should not necessarily preclude such a new application of this term.

The term *vapor-pressure deficit* is obtained from Livingston.[5]

The section on occurrence of subsurface water (pp. 17–30) contains a number of classifications and terms that are either new or stated in somewhat original fashion.

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[1] Livingston, B. E., Evaporation and centers of plant distribution: Plant World, vol. 11, pp. 106–112, 1908.

[2] Horton, R. E., Computing run-off from rainfall and other data; Discussion: Am. Soc. Civil Eng. Trans., vol. 79, p. 1171, 1915; Drainage-basin and crop studies aid water-supply estimates: Engineering News-Record, vol. 79, p. 359, 1917.

[3] Meyer, A. F., The elements of hydrology, pp. 226, 239, 1917.

[4] Brooks, C. F., Monthly Weather Review, vol. 47 p. 810, 1919.

[5] Livingston, B. E., The vapor-pressure deficit as an index of the moisture condition of the air: Johns Hopkins Univ. Circ., March, 1917, pp. 170–175. See also Johnston, E. S., Evaporation compared with vapor-pressure deficit and wind velocity: Monthly Weather Review, vol. 47, pp. 30–33, 1919.

There has been much confusion in the terms that denote the water below the surface and the water in the zone of saturation. The terms *ground water* and *underground water* have been used with bewildering variety of meaning. The term *subsurface water* is not new, but it has been selected in this paper in preference to any similar terms to designate all water that occurs below the surface, thus standing in contrast to *surface water*, which is the water on the surface. The term *ground water* has likewise been selected to designate specifically the water in the zone of saturation. The term *underground water* and its Latin equivalent, *subterranean water*, do not seem to be available for specific definition. They are etymologically equivalent to *subsurface water* but are more often used to designate the water in the zone of saturation or only the water in the deeper parts of this zone. The term *ground water* is understood by many persons to refer only to water in the upper part of the zone of saturation, but it has been used by such eminent geologists as Van Hise [1] and Chamberlin and Salisbury [2] to include the deeper water. Etymologically the water in the zone of saturation is ground water in the sense that it is the basal or bottom water.

The term *phreatic water* was used in French by Daubrée,[3] who, however, included under this term only the water in the upper part of the zone of saturation. The present paper follows Daly [4] in using it to designate all water in the zone of saturation, thus making it an exact synonym of *ground water*. This more general use is etymologically correct, as the term means *well water*—that is, water from the zone of saturation. Used in this sense, it becomes a very valuable term, as is shown in this paper.

Zone of saturation is a well-known term with accurate meaning, but no companion term seems to have been used to designate the overlying zone in which the rocks are not saturated. In the present paper this overlying zone is called the *zone of aeration*, and the water in it *suspended* or *vadose water*. Moreover, the zone is divided into three belts, for which the terms *capillary fringe* (containing *fringe water*), *intermediate belt* (containing *intermediate vadose water*), and *belt of soil water* (containing *soil water*) are proposed. The term *vadose water* was originally used by Posepny [5] to designate the water in the zone of aeration—a very appropriate term for a definite and important concept. Unfortunately the term has been used to include parts or all of the water in the zone of saturation by so many writers that to reclaim it may be impossible, although Daly proposes to

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[1] Van Hise, C. R., A treatise on metamorphism: U. S. Geol. Survey Mon. 47, p. 123, 1904.

[2] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 1, pp. 202-231, 1904.

[3] Daubrée, A., Les eaux souterraines à l'époque actuelle, vol. 1, p. 19, Paris, 1887.

[4] Daly, R. A., Genetic classification of underground volatile agents: Econ. Geology, vol. 12, pp. 495, 499, 1917.

[5] Posepny, F., The genesis of ore deposits: Am. Inst. Min. Eng. Trans., vol. 23, pp. 213, 220, 1894.

return to its original meaning.[1] The proposed term, *suspended water*, is not confused with other meanings, is suggestive of what it stands for, and is accurate in what it connotes.

The terms *specific retention* and *specific yield* are proposed to designate two very important concepts. *Specific retention* is a modification of the term *water-retaining capacity* used by Alway [2] and others; *specific yield* is suggested as an appropriate companion term. The expression *effective porosity* has often been used to mean somewhat the same thing as *specific yield*, but it is apparently unsatisfactory and unavailable for the precise purpose for which the term *specific yield* is here proposed.

The classification of interstices according to origin has been taken from Fuller.[3] The terms *capillary*, *supercapillary*, *subcapillary*, *zone of rock fracture*, and *zone of rock flowage* have been taken from Van Hise;[4] *hygroscopic coefficient* from Hilgard;[5] *wilting coefficient* from Briggs and Shantz;[6] and *moisture equivalent* from Briggs and McLane.[7] The term *aquifer* was introduced from the French by Norton.[8]

In the brief section on origin (pp. 30–32), *connate* is obtained from Lane,[9] *juvenile* from Suess,[10] and *resurgent* from Daly.[11]

The term *water table* (pp. 22, 32) has been widely used, is in general well understood, and is distinctly preferable to other terms used for the same purpose. It is believed that the statement in this paper limiting water tables to permeable beds disposes of an ambiguity that has caused much confusion. The terms *oil-water surface* and *gas-water surface* are taken from the expression *water surface* used by Beal.[12]

In the section on hydrostatic pressure (pp. 37–42) the expression *piezometric surface* is obtained from the French. The expression *isopiestic line* (derived from the same root) has been used by Norton.[13]

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[1] Daly, R. A., op. cit., pp. 494–499.

[2] Alway, F. J., and McDole, G. R., Relation of the water-retaining capacity of a soil to its hygroscopic coefficient: Jour. Agr. Research, vol. 9, p. 27, 1917.

[3] Fuller, M. L., Summary of the controlling factors of artesian flows: U. S. Geol. Survey Bull. 319, pp. 8–15, 1908.

[4] Op. cit., pp. 134–146; Principles of North American pre-Cambrian geology: U. S. Geol. Survey Sixteenth Ann. Rept., pt. 1, pp. 589–603, 1885.

[5] Hilgard, E. W., Silt analysis of Mississippi soils and subsoils: Am. Jour. Sci., 3d ser., vol. 7, p. 16, 1874.

[6] Briggs, L. J., and Shantz, H. L., The wilting coefficient for different plants and its indirect determination: U. S. Dept. Agr. Bur. Plant Industry Bull. 230, 1912.

[7] Briggs, L. J., and McLane, J. W., The moisture equivalent of soils: U. S. Dept. Agr. Bur. Soils Bull 45, 1907.

[8] Norton, W. H., Artesian wells of Iowa: Iowa Geol. Survey, vol. 6, p. 130, 1897.

[9] Lane, A. C., Mine waters and their field assay: Geol. Soc. America Bull., vol. 19, pp. 502–503, 1908; Mine waters: Lake Superior Min. Inst. Proc., vol. 13, p. 63, 1908.

[10] Suess, E., Gesell. deutsch Naturf. und Aertze Verh., 1902, pp. 133–150; Das Antlitz der Erde, vol. 3, pt. 2, pp. 630, 655, 1909.

[11] Daly, R. A., The mechanics of igneous intrusion: Am. Jour. Sci., 4th ser., vol. 26, p. 48, 1908; Genetic classification of underground volatile agents: Econ. Geology, vol. 12, pp. 491, 492,498, 1917.

[12] Beal, C. H., Geologic structure in the Cushing oil and gas field, Okla., and its relation to oil, gas, and water: U. S. Geol. Survey Bull. 658, p. 48, 1917.

[13] Op. cit., pl. 8.

A piezometric surface may be very different from a water table, but the two kinds of surfaces have the same general behavior in many respects. Hence a series of companion terms is desirable, and for this purpose it is proposed in this paper to use the qualifying term *phreatic* to designate features pertaining to a water table and *piestic* to designate similar features pertaining to a piezometric surface.

The term *artesian* has been used in so many ways that to tie it down to any specific meaning is difficult, yet it is too well established and necessary a term to be lightly abandoned. It is widely understood to refer only to water that will rise to the surface, but the preponderance of usage by geologists and engineers is believed to be in the more general sense of water that is under sufficient pressure to rise above the zone of saturation. Essentially this meaning was adopted by both Norton [1] and Fuller [2] after careful investigation of the term. Slichter [3] says: "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." The term *subartesian* has been used by Norton [4] and others.

The term *subnormal pressure* is proposed in this paper to designate the converse of *artesian pressure.* Subnormal pressure is as common a phenomenon as artesian pressure and should be definitely recognized and named. The principle involved was clearly explained by Chamberlin in his classic paper on artesian wells.[5] Related to these two kinds of pressure are the two kinds of confining beds—those in which the water is pressing upward and those in which it is pressing downward. For these the designations *positive* and *negative* are suggested. Perhaps these two qualifying terms are not necessary, but it seems to the writer that it is better to adopt some such specific terms than to use such makeshift expressions as "overlying" and "underlying" or "upward" and "downward" confining beds, which would be ambiguous or misleading in some connections.

The term *perched water* as defined in this paper has been used by Veatch [6] and others. It has also been used to designate the condition for which the term *semiperched* is proposed, and the writer was

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[1] Op. cit., pp. 122–126.

[2] Fuller, M. L., Significance of the term "artesian": U. S. Geol. Survey Water-Supply Paper 160, pp. 9–15, 1906.

[3] Slichter, C. S., quoted by Fuller, M. L., op. cit., p. 10.

[4] Op. cit., p. 125.

[5] Chamberlin, T. C., The requisite and qualifying conditions of artesian wells: U. S. Geol. Survey Fifth Ann. Rept., pp. 139–141, 1885.

[6] Veatch, A. C., Slichter, C. S., Bowman, Isaiah, Crosby, W. O., and Horton, R. E., Underground water resources of Long Island, N. Y.: U. S. Geol. Survey Prof. Paper 44, pp. 56–57, 1906.

at one time favorable toward this extension of the term. Often it is not possible to ascertain whether a body of water is perched or semiperched, although the distinction is a definite and important one. The writer has been criticized for saying that at a given place there may be more than one water table and more than one zone of saturation. This criticism does not, however, seem to him to be valid. It is a well-established fact that in some places there are perched bodies of ground water which are far above the main body of ground water and separated from it by considerable thicknesses of unsaturated permeable rock. Excellent examples in Long Island have been cited by Veatch, and others occur in the Southwest and in the Hawaiian Islands, where some of the perched water is of much economic value. It must be admitted that in such places there is more than one zone of saturation and more than one water table, unless these terms are quite distorted from their ordinary and well-accepted meanings.

The term *ground-water artery* was suggested to the writer by Paul Bailey. It appears to be a very appropriate and useful term.

The section on movement (pp. 42–46) contains chiefly terms that are already widely used. The expressions *effective size of grain* and *uniformity coefficient* were obtained from Hazen,[1] and the term *transmission constant* from Slichter.[2] An effort is made in this paper to restrict the terms *subterranean stream* and *underflow* within somewhat definite limits, in order to preserve them for a useful purpose. There is a strong tendency to make both terms useless by applying them in so general a way that they become practically synonymous with *ground water* and *percolation*. The definition of *underflow* accords essentially with its use by Slichter.[3]

The term *seepage* has been used in many ways. In this paper it is defined to include percolation into or out of soil or rock but not percolation through the soil or rock. This seems to the writer to cover what is usually meant by the term and still to assign to it a rather specific meaning. It leaves the term *percolation* as a correlative but more general term. The qualifiers *influent* and *effluent*, applying to seepage as well as to streams and lakes, are terms of rather self-evident meaning proposed by the writer.

There has been much unprofitable quibbling as to whether any rocks are impermeable, or impervious. If the terms are taken in their absolute, unqualified sense it is probably true that nothing is impermeable, impervious, or impenetrable. These terms, however,

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[1] Hazen, Allen, Experiments upon the purification of sewage and water at the Lawrence experiment station: Massachusetts Board of Health Twenty-third Ann. Rept., for 1891, pp. 429–431, 1892.

[2] Slichter, C. S., The motions of underground waters: U. S. Geol. Survey Water-Supply Paper 67, p. 26, 1902.

[3] Idem, pp. 38–41.

come to have meaning and utility when they are qualified as to the kind of penetrating medium and as to the kind and magnitude of the force acting on this medium. These qualifications are specified in this paper (pp. 20, 44). By qualifying the term *permeability* with the term *hydraulic,* any possible permeability through the agency of molecular or other obscure forces is excluded.

The section on absorption (pp. 46–47) contains little that is original and perhaps nothing that requires explanation. In the section on discharge (pp. 47–56), the classification of discharge is believed to be valuable in clarifying the subject. The terms used are in part original in this paper. The distinctions made by the terms *ground-water* and *vadose-water* and by *hydraulic, evaporation, vegetal,* and *soil discharge* are important, and it is hoped that these terms will be used. The term *phreatophyte* was coined by the writer to designate a well-recognized group of plant species.

In the classification of springs with respect to the rock structure and the resulting force by which the water is discharged, the recent classification by Bryan [1] is followed, with some exceptions. The subdivision of ordinary springs into *gravity springs* and *artesian springs* and the classification of springs with respect to the character of the openings have been made according to Fuller.[2]

In the section on surface water in relation to absorption and discharge (pp. 56–59) several important distinctions are made, although only a few new terms are introduced. There has been much unfortunate confusion in the designation of streams with respect to permanence in time and continuity in space. In this paper an attempt is made to remove this confusion by defining the terms *perennial, intermittent, ephemeral,* and *interrupted.* It will be noted that the distinctions involved relate chiefly to ground-water conditions.

The general terms relating to wells (pp. 60–68) are all terms with definite and recognized meanings. The term *specific capacity* and the valuable concept for which it stands are obtained from Slichter,[3] who has clearly explained and demonstrated the principle involved.

The classification of wells is rather simple but ought to serve a useful purpose. In the past there has been so great a lack of system in designating wells of different kinds that the name applied to a well may convey no definite information as to its character.

THE PLACE OF GROUND WATER IN HYDROLOGY.

Hydrology is the science that relates to the water of the earth. The water of the earth can be divided into three parts—that which occurs in the atmosphere, that which rests on the surface of the solid

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[1] Bryan, Kirk, Classification of springs: Jour. Geology, vol. 27, pp. 522–561, 1919.

[2] Fuller, M. L., Underground waters for farm use: U. S. Geol. Survey Water-Supply Paper 255, pp. 22–24, 1910.

[3] Slichter, C. S., Field measurements of the rate of movement of underground waters: U. S. Geol. Survey Water-Supply Paper 140, pp. 86–97, 1905.

part of the earth, and that which occurs below the surface. The water below the surface can be divided (with some exceptions) into two parts—that which occurs in the interstices of the rocks and that which is supposed to occur in the earth's interior, where interstices can not exist because of the weight of the overlying rocks and where the water, if any exists there, must be in a sort of rock solution. The interstitial water can, in turn, be divided into that which is above the zone of saturation and that which is in this zone. The science of hydrology can in the same manner be divided and subdivided into several parts.

Although the study of the water of the earth is of vast scientific and practical importance, the science of hydrology, as such, has received comparatively little attention. This seems to be due to the fact that hydrology cuts across the grain, as it were, of several other sciences, and its subject matter forms parts of these other sciences. Atmospheric moisture is in the province of the meteorologist. Surface water is the principal field of the hydraulic engineer and is also of much interest to the geologist and to men in other sciences. The water below the surface is within the general province of the geologist, but that which is near enough the surface to be reached by the roots of plants is of special interest to the students of soils and agriculture. The water in the zone of saturation is in the special province of the ground-water geologist. The water in the interior of the earth, if any exists there, is in the province of the philosophic geologist and volcanologist. The hydraulic engineer is interested chiefly in the surface water and the water in the zone of saturation, because only these two kinds of water occur in large enough bodies for his purposes. That part of the earth which lies above the zone of saturation but too far below the surface to be reached by the roots of plants is a sort of no man's land in hydrology. The water which it contains can not be withdrawn by vegetation; and it can not be recovered through wells because it is held by molecular attraction and will not flow into a well. Hence it is of no use to the farmer or the well driller and is not investigated by the student of soils or of agriculture, and it lies outside of the special field of the ground-water geologist.

Water of the earth and principal sciences relating to it.

1. Water in the atmosphere	Meteorology.
2. Water on the surface	Hydraulic engineering; also geology, oceanography, and hydrography.
3. Water below the surface	Geology and agriculture.
a. Above zone of saturation:	
Within reach of plants	Study of soils and agriculture; also botany.
Not within reach of plants	No man's land.
b. In zone of saturation	Ground-water geology; also hydraulic engineering and other phases of geology.
c. Interior of earth	Geognosy, philosophic geology, and volcanology.

The present paper relates primarily to ground water—that is, to the water in the zone of saturation. It comprises a general outline of the entire subject of hydrology, but this is included only in order to develop the significant relations of the subject of ground water to other branches of hydrology. Its purpose is to state the main concepts of ground-water hydrology and to organize them into one general concept of this branch of the science.

WATER OF THE EARTH.

The term *water* is used to designate both chemically pure water and natural water. *Chemically pure water* (H_2O) is the chemical compound consisting of hydrogen and oxygen combined in the ratio of about eight parts of oxygen to one part of hydrogen by weight. The term *natural water* is used to designate this chemical compound together with the solid, liquid, and gaseous materials which it holds in solution or suspension as it exists in the earth in its natural condition. As these materials differ in quantity, kind, and state of occurrence, natural water is not everywhere the same thing but rather comprises a group of mixtures that may blend into one another. Therefore it is proper to use the term *water* in the plural and to speak of different kinds of natural waters or of different natural waters. Except where confusion might arise the term *water* may be used to designate natural water.

The earth may be divided, with respect to its content of water, into three parts, which may be called the *atmosphere*, the *hydrosphere*, and the *lithosphere*.

The *lithosphere* is that part of the earth which is composed predominantly of rocks (either coherent or incoherent and including the disintegrated rock materials known as soils and subsoils), together with everything inside of this rocky crust. In the lithosphere other materials—chiefly water and gases such as are found in the air—are intermingled with the materials that constitute the rocks and the soils, but rock and soil predominate.

The *hydrosphere* consists of the liquid and solid water that rests on the lithosphere, including, of course, the solid, liquid, and gaseous materials that are suspended or dissolved in the water.

The *atmosphere* is the outer part of the earth, surrounding the lithosphere and hydrosphere and consisting predominantly of air. It contains certain materials which are not air, such as particles of dust and rain drops, but it consists predominantly of air.

The above definitions of lithosphere, hydrosphere, and atmosphere are believed to be the most useful for the purposes of hydrology and to accord as closely to common usage as any others that could be given. It should be recognized, however, that for other purposes these terms have been defined in several somewhat different ways.

According to some authorities the lithosphere is not regarded as extending to the center of the earth; according to some, large permanent ice sheets, such as the ice cap of Greenland, are regarded as belonging to the lithosphere; and according to some, the three "spheres" penetrate one another.

A *land surface*, or *land*, is a part of the surface of the lithosphere which is not usually covered by liquid water.

The water of the earth may be divided, with respect to the "sphere" in which it exists, into three parts—atmospheric water, surface water, and subsurface water. *Atmospheric water* is water which exists in the atmosphere. It may be in gaseous, liquid, or solid state. *Surface water* is water which rests on the surface of the lithosphere. It may be in liquid or solid state. Thus snow and ice at the surface are considered to be surface water. It is the water in the hydrosphere. *Subsurface water* is water that exists in the lithosphere. It may be in liquid, solid, or gaseous state.

Both the atmosphere and the lithosphere are receptacles for water, but their capacity is not unlimited. Water is frequently discharged from the atmosphere into the lithosphere and from the lithosphere into the atmosphere, but any water that is discharged from either of these and is not received by the other remains on the surface until it can be taken into one or the other. The frequent changes in the capacity of the atmosphere are the principal cause of the movements in both surface and subsurface water and the principal agency that prevents the attainment of static equilibrium in the water of the earth.

ATMOSPHERIC WATER.

Water vapor is water in the gaseous state. A space is said to be *saturated* with water vapor if its content of water vapor is the maximum which it can hold at the existing temperature, provided it contains also minute particles of dust or other matter that form nuclei which promote condensation. In the absence of such nuclei a state of *supersaturation* may be possible. The mass of water vapor in a saturated space is such that the vapor exerts the maximum pressure possible at the existing temperature (unless there is supersaturation). If the temperature is lowered some of the water normally changes into the liquid or solid state and the vapor pressure is reduced to the maximum for the lower temperature. If the temperature is raised and no additional water passes into the gaseous state the space becomes *unsaturated.* An unsaturated space has less vapor pressure than the maximum that is normally possible at the given temperature. The difference between the actual vapor pressure and the vapor pressure of a saturated space at the given temperature has been called the *vapor-pressure deficit.*

The term *saturation deficit* has been used to express a closely related concept. The capacity of a given part of the atmosphere for water vapor is nearly the same as that of a like empty space. It is modified only slightly by the presence of the various atmospheric gases.

The *humidity* of a given part of the atmosphere is its condition with respect to its content of water vapor.

The *absolute humidity* of a given part of the atmosphere is the mass of water vapor contained in a unit volume of the atmosphere. It can be expressed in milligrams per liter, grains per cubic foot, or similar units. It can also be expressed in units of pressure which it exerts—for example, in the height of a balanced column of mercury stated in millimeters or inches.

The *relative humidity* of a given part of the atmosphere is the ratio of its content of water vapor to its capacity for holding water vapor at the existing temperature. It is generally expressed as a percentage. The relative humidity of a saturated atmosphere is 100 per cent.

The principal processes involved in the changes that occur in atmospheric water and in the passage of water into and out of the atmosphere are evaporation, condensation, and precipitation.

Vaporization of water is the process by which it changes from the liquid or solid to the gaseous state—that is, the process by which it becomes vapor. *Evaporation* is vaporization that takes place at a temperature below the boiling point. Evaporation is the principal process by which water is converted from surface or subsurface water to atmospheric water. It is also a common process within the atmosphere. It takes place whenever water in the liquid or solid state comes into contact with an unsaturated part of the atmosphere. The term *evaporation* is also commonly used to designate the quantity of water that is evaporated. (See fig. 1.) The rate of evaporation is expressed in depth of water (measured as liquid water) removed from a specified surface per unit of time—generally in inches or centimeters per day, month, or year.

The *evaporativity*, or *potential rate of evaporation*, of a given part of the atmosphere is the rate of evaporation under the existing atmospheric conditions from a surface of water that is chemically pure and has the temperature of the atmosphere. It is expressed in depth of water removed from such a surface in a unit of time. Observations that give continuous records of evaporativity, some of them covering several years, are made at a number of places by the United States Weather Bureau and by other agencies. It is not practicable to maintain at field stations the exact conditions stated in the definition given above, but observations made with the standardized apparatus and methods prescribed by the Weather Bureau give results that approximate more or less closely those which would be obtained if the conditions of the definition were strictly fulfilled. Much of the water of streams and lakes is so nearly pure as to show no appreciable difference in rate of evaporation from that of chemically pure water. Water that contains much dissolved matter evaporates more slowly. The evaporativity of a given part of the atmosphere depends on several conditions, the most influential of which are temperature, relative humidity, barometric pressure, and wind velocity.

The *evaporation opportunity* afforded by a land or water surface in contact with the atmosphere is the ratio of the rate of evaporation

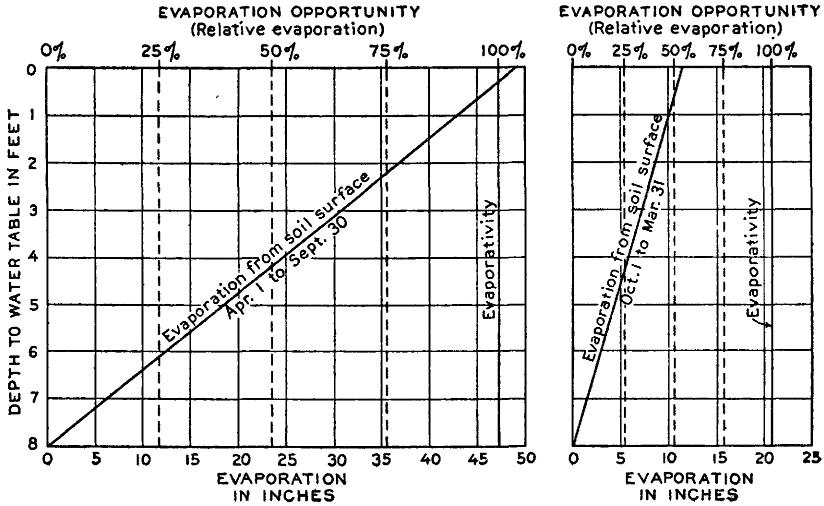

FIGURE 1.—Diagrams showing evaporativity in Owens Valley, Calif., and actual and relative evaporation from soil surfaces covered by salt grass, with different depths to water table. (After C. H. Lee, U. S. Geol. Survey Water-Supply Paper 294, fig. 5.)

from that surface to the evaporativity under the existing atmospheric conditions—that is, the ratio of the actual to the potential rate of evaporation. This ratio has also been called the *relative evaporation.* It is generally stated as a percentage and may be expressed by the formula $E=100\frac{e}{e'}$, where E is the evaporation opportunity, or relative evaporation, e is the actual rate of evaporation, and e' is the evaporativity. (See fig. 1.) Generally surfaces other than pure-water surfaces have evaporation opportunities of less than 100 per cent, but under exceptional conditions of luxuriant vegetation the evaporation opportunity may be more than 100 per cent.

Condensation, as the term is used in hydrology, is the process by which water changes from the gaseous state into the liquid or solid state. It is the reverse of evaporation. It takes place whenever the temperature of a saturated part of the atmosphere is lowered, provided the necessary dust particles or other nuclei of condensation are present.

Precipitation, as the term is used in hydrology, is the discharge of water, in liquid or solid state, out of the atmosphere, generally upon a land or water surface. It is the common process by which atmospheric water becomes surface or subsurface water. It does not include the relatively unimportant processes by which atmospheric water vapor passes without condensation into the soil or rocks. The term *precipitation* is also commonly used to designate the quantity of water that is precipitated. The rate of precipitation is expressed in depth of water (measured as liquid water) precipitated upon a specified surface per unit of time—generally in inches or centimeters per day, month, or year. (See fig. 19, p. 47.)

Rain consists of liquid particles in the atmosphere that have become too large to be held in suspension. The term *rainfall* is used to designate the quantity of water that falls as rain, generally expressed as depth of water in inches or centimeters. It can not be used as a synonym for precipitation without confusion. Snow, sleet, and hail are not rainfall but they are included in precipitation.

An *isohyetal line*, or an *isohyet*, is a line on a land or water surface all points along which receive the same amount of precipitation. Isohyets shown on maps are usually expressed in inches or centimeters of average annual precipitation. A *hyetal interval* is the difference in precipitation represented by two isohyets. If sufficient evaporation data are available it is likewise possible to draw lines of equal evaporativity, equal evaporation, and equal evaporation opportunity.

Classification of atmospheric water.

A. Water in gaseous state (atmospheric water vapor): derived by evaporation.
B. Water in liquid or solid state:
   I. Derived mechanically through the agency of wind: Spray, drifting snow, etc.
   II. Derived by condensation:
      a. In small particles: Cloud and fog.
      b. In larger particles: Rain, snow, hail, and sleet.

SURFACE WATER.

A *drainage system* consists of a surface stream or a body of impounded surface water, together with all surface streams and bodies of impounded surface water that are tributary to it. An artificial drainage system is generally understood to include also the conduits that have been installed below the surface.

A *drainage basin* is a part of the surface of the lithosphere that is occupied by a drainage system or contributes surface water to that system.

A *drainage divide* is the rim of a drainage basin. It is the boundary between adjacent drainage basins. The term *watershed* has been used to mean both drainage basin and drainage divide, and the uncertainty of meaning entailed by this double usage makes the term undesirable.

Run-off is the discharge of water through surface streams. This term has a double use, like *precipitation*, being applied also to the quantity of water that thus runs off. The run-off of a drainage basin is the water that is discharged from the basin as surface water. A drainage basin, by definition, receives no surface water from external areas, but any area that does not constitute a drainage basin is likely to receive as well as to discharge surface water. The run-off of such an area is taken to be the net amount of surface water discharged from the area—that is, the surface water discharged from the area minus that received by the area. If the area discharges less surface water than it receives its run-off may be regarded as a negative quantity. The run-off can be expressed in units of volume, such as gallons, cubic feet, or acre-feet. (An acre-foot is the volume required to cover an acre to the depth of 1 foot—about 325,351 gallons.) The rate of run-off can be expressed in second-feet (cubic feet per second) or in other units.

The run-off of a drainage basin or other area can also be expressed as the depth of a level layer of water equivalent in horizontal extent to the area and equivalent in volume to the net amount of surface water discharged from the area. (See fig. 19, p. 47.) The depth is usually expressed in inches or centimeters. This method of expression is especially convenient for comparing run-off with precipitation and evaporation. The run-off in units of volume of any drainage basin, whether large or small, can be ascertained by measuring the discharge of its trunk stream, but the run-off in depth can be determined only if the size of the drainage basin as well as its discharge is known.

Surface water may be classified as shown in the following outline. Some of the classes given in this outline are more conveniently defined in other connections, as indicated.

Classification of surface water.

A. Land water:
- I. Surface snow and ice; including glaciers, ice sheets, and other bodies of snow and ice that rest directly on the land.
- II. Flowing surface water:
  - *a.* Flowing sheet water.
  - *b.* Streams:
    - With respect to origin:
      1. Natural streams—rivers, creeks, etc. This class can be subdivided according to the geologic history—for example, consequent, subsequent, superimposed, and antecedent streams.
      2. Artificial streams—canals, etc.

A. Land water—Continued.
- II. Flowing surface water—Continued.
  - *b*. Streams—Continued.
    - With respect to permanence (pp. 57–58):
      1. Perennial streams.
      2. Intermittent streams.
         - *a*. Spring-fed intermittent streams.
         - *b*. Surface-fed intermittent streams.
      3. Ephemeral streams.
    - With respect to continuity in space (pp. 58–59):
      1. Continuous streams.
      2. Interrupted streams:
         - *a*. Intermittent interrupted streams.
         - *b*. Perennial interrupted streams.
    - In relation to subsurface water (p. 56):
      1. Influent streams.
      2. Effluent streams.
      3. Insulated streams.
- III. Impounded surface water:
  - With respect to origin:
    - *a*. Naturally impounded bodies—lakes, ponds, etc. This class can be subdivided with respect to the geologic agencies that produce lakes and ponds.
    - *b*. Artificially impounded bodies—reservoirs, etc.
  - With respect to permanence (p. 59):
    - *a*. Perennial impounded bodies.
    - *b*. Intermittent impounded bodies.
    - *c*. Ephemeral impounded bodies.
  - With respect to degree of impounding:
    - *a*. Incompletely impounded bodies:
      1. Bodies which perennially discharge water as surface water.
      2. Bodies which intermittently discharge water as surface water.
    - *b*. Completely impounded bodies. These bodies never discharge water as surface water.
  - In relation to subsurface water (p. 59):
    - *a*. Influent impounded bodies.
    - *b*. Effluent impounded bodies.
    - *c*. Insulated impounded bodies.

B. Ocean or sea water.

SUBSURFACE WATER.

OCCURRENCE.

An *interstice,* or *void,* in a rock or soil is a space that is not occupied by solid mineral matter. An interstice may be occupied by air, water, or other gaseous or liquid material, except that spaces occupied by molten rock are not regarded as interstices. Spaces occupied by ice may for different purposes be regarded in either way, but while the ice lasts they are not really interstices. As the interstices are receptacles for subsurface water they are of fundamental importance in the study of this water. They have great variety in shape, size, and arrangement. Many of them are very irregular.

The interstices are products of the processes which, through the long ages of geologic time, have been at work forming and altering rocks. According to their origin, they can be divided into original and secondary. *Original interstices* are those that were created when the rocks came into existence as a result of the processes by which they were formed; *secondary interstices* are those that were developed by processes that affected the rocks after they had been formed. Original interstices can be divided into those of sedimentary origin and those of igneous origin. Secondary interstices comprise joints and other fracture openings, solution openings, and openings produced by several processes of minor importance, such as the work of plants and animals, mechanical erosion, and recrystallization. The most important interstices with respect to water supplies are the original sedimentary interstices; next to them are the fracture and solution openings.

Outline of principal interstices of rocks and soil.

1. Original interstices:
    a. Sedimentary interstices.
    b. Igneous interstices.
2. Secondary interstices:
    a. Joints and other fracture openings.
    b. Solution openings.
    c. Openings of minor importance, such as those produced by the work of plants and animals, mechanical erosion, and recrystallization.

Interstices may be more or less arbitrarily divided, with respect to their size in relation to the range of molecular forces, into capillary, supercapillary, and subcapillary interstices.

A *capillary interstice,* with respect to water in distinction from other liquids, has the following limits of size: (1) It is small enough for water to be held in it at a considerable height above the level at which it is held by hydrostatic pressure, the phenomenon involved (*capillarity*) being due to the attraction of the molecules in the walls of the interstice for the molecules of the water (*adhesion*) and the attraction of the molecules of water for one another (*cohesion*). (2) It is large enough to preclude the attraction of the molecules of its walls from extending across the entire space which it occupies. The upper limit of size is indefinite, and any limit that may be fixed must be arbitrary; the size determined by the lower limit is so minute that the limit is necessarily involved in obscurity. Interstices large enough to permit cross currents and eddies are not classed as capillary.

A *supercapillary interstice* is one that is larger than a capillary interstice. It is so large that water will not be held in it far above the level at which it is held by hydrostatic pressure and that water moving in it may form cross currents and eddies.

The arbitrary character of the distinction between capillary and supercapillary interstices is due to the following conditions: (1) Absence of any mathematical limit to the size of openings in which capillarity is exhibited, (2) possible differences in capillarity produced by different materials and by different surfaces of the same material, (3) differences in capillarity produced by differences in temperature and in the quantities of different substances dissolved in the water, (4) indefiniteness as to the limiting size for cross currents and eddies, and (5) the lack of relation between the criterion of capillary rise and that of cross currents and eddies. The indefiniteness as to the limiting size for cross currents and eddies is due not only to the great variety in the shape of interstices but also to the fact that the tendency to form cross currents and eddies increases with the velocity of the moving water. Notwithstanding the indefinite character of the boundary between capillary and supercapillary interstices, the distinction is a valuable one because of the great importance of capillarity in the behavior of subsurface water. Supercapillary interstices include large openings such as joints and caverns.

A *subcapillary interstice* is one that is smaller than a capillary interstice. It is theoretically so small that, at least in some parts, the attraction of the molecules of its walls extends through the entire space which it occupies. The water in these interstices is supposed, therefore, to be held by adhesion—a force presumably comparable to that which holds together the molecules of the rock—and to be immovable except by forces that greatly exceed the pressure usually found in subsurface water. The conditions existing in these interstices are, however, only very imperfectly understood and are largely a matter of speculation.

Interstices may be divided, with respect to their relations to one another, into *communicating interstices* and *isolated interstices.* To the latter class belong the *inclusions* found in quartz and other minerals.

A rock or soil is *saturated* with respect to water if all its interstices are filled with water. A saturated rock or soil contains all the water that it is capable of holding.

The *porosity* of a rock or soil is its property of containing interstices. The porosity of a rock or soil can be quantitatively expressed as the ratio of the aggregate volume of its interstices to its total volume. This ratio is usually stated as a percentage.

If the specific gravity of water is taken as unity, the porosity of a sample of rock or soil may be expressed, in percentage, by the following equations:

$$P=100\left(\frac{w}{V}\right)=100\left(\frac{V-v}{V}\right)=100\left(\frac{S-a}{S}\right)=100(b-a)$$

where P is the porosity, w is the volume of water required to saturate the sample when it is dry, V is the volume of the sample, v is the aggregate volume of the solid particles that make up the sample, S is the weighted average of the specific gravities of the minerals of which the solid particles consist, a is the specific gravity of the dry sample, and b is the specific gravity of the saturated sample.

The *zone of rock fracture* is the upper part of the lithosphere in which rocks are under stresses less than those required to close their interstices by deformation of the walls of the interstices.

The *zone of rock flowage* is the deep part of the earth in which all rocks are under stresses exceeding their elastic limits. In this zone the rocks undergo permanent deformation and are said to flow; hence in this zone interstices are absent or insignificant. The depth at which such conditions exist has not been conclusively determined but seems to be many miles.

The *zone of fracture and flowage* is intermediate in position between the other two zones. It is the zone in which the strongest rocks behave as in the zone of rock fracture and the weakest as in the zone of rock flowage.

Rocks may be divided, with respect to their penetrability by water, into permeable or pervious rocks and impermeable or impervious rocks.

A *permeable* or *pervious* rock, with respect to subsurface water, is one having a texture that permits water to move through it perceptibly under the pressure ordinarily found in subsurface water. Such a rock has communicating interstices of capillary or supercapillary size.

An *impermeable* or *impervious* rock, as the terms are used in hydrology, is one having a texture that does not permit water to move through it perceptibly under the pressure ordinarily found in subsurface water. Such a rock may have subcapillary interstices or isolated interstices of larger size. It may possibly also have small communicating capillary interstices. A rock that is impermeable under the conditions that have been specified may not be impermeable to water under a hydrostatic pressure in excess of those found in subsurface water. It may also allow water to move through it under the influence of other forces, such as molecular attraction.

A rock that is otherwise permeable may become impermeable by the filling of its interstices with ice. A permeable rock may be impenetrable by water under pressure in the position in which it exists because its interstices are filled with gas or with petroleum or other liquid that has no avenue of escape. Permeable rocks under these conditions may be said to be *inert* with respect to water, in somewhat the same sense as the impermeable rocks. Permeable rocks that are not in the inert condition may for purposes of contrast be designated *functional permeable rocks.*

The lithosphere above the zone of rock flowage may be divided, with respect to the occurrence of subsurface water, into a zone of saturation and a zone of aeration (fig. 2). The *zone of saturation* is the zone in which the functional permeable rocks are saturated with water under hydrostatic pressure. The *zone of aeration* is the zone in which the interstices of the functional permeable rocks are not (except temporarily) filled with water under hydrostatic pressure; the interstices are either not filled with water or are filled with water that is held by capillarity. Impermeable bodies may be within the zone of saturation or within the zone of aeration, but they are in a sense not functional parts of either zone. If an impermeable body lies between a saturated and an unsaturated body it is rather arbitrarily considered to be in the zone of aeration. Oil-bearing and gas-bearing bodies generally lie deep within the zone of saturation.

The gases in the interstices of rocks and soil can be divided, with respect to occurrence, into three classes—subsurface or interstitial air, natural gas, and included gas. The term *subsurface air* is applied to the gases in the interstices of the zone of aeration that open directly or indirectly to the surface and hence communicate with the atmosphere. Subsurface air is therefore essentially under atmospheric pressure and has a composition more or less like that of atmospheric air. The term *natural gas* is applied to gases that are entrapped in interstices in the zone of saturation—that is, prevented from escape to or communication with the atmosphere by an overlying effectively impermeable bed. A body of natural gas is generally under hydrostatic pressure transmitted by the water from below. For this reason it is partly in solution in the water or in any petroleum that may intervene between the water and the body of gas. Because of its isolation from the atmosphere its composition has no relation to that of atmospheric air. The term *included gas* may be applied to the gases in the isolated interstices of either zone.

In most parts of the earth there is only one zone of aeration and one zone of saturation, the zone of aeration being above the zone of saturation. In some places, however, there are two or more zones of each kind (figs. 14 and 15, pp. 41, 42). If there are two zones of aeration the lower one is between an upper and a lower zone of saturation. Water that saturates the soil immediately after a rain or before the deeper frost has left the ground in the spring produces a temporary zone of saturation. Water in transit from the surface to a zone of saturation may for convenience be regarded as passing through a zone of aeration or may be regarded as an irregular and perhaps temporary projection of the zone of saturation.

A *water table* is the upper surface of a zone of saturation except where that surface is formed by an impermeable body (fig. 2). No water table exists where the upper surface of a zone of saturation is formed by an impermeable body.

The water above the zone of rock flowage includes that which occurs in the interstices (*interstitial water*) and that which exists in more intimate relation to the mineral matter (water in solid solution, etc.). The interstitial water may be divided into (1) *ground water* or *phreatic water,* which is the water in the zone of saturation, (2) *suspended* (subsurface) *water* or *vadose water,* which is the water in the zone of aeration, and (3) *subsurface ice,* or *interstitial ice.* (See fig. 2.) In sinking a well it is considered that the zone of saturation is reached at the point where water first enters the well. This water is ground water.

The term *ground water* may be regarded as meaning the basal or bottom water. The term *phreatic water* may be regarded as an exact synonym of *ground water,* although it was originally used in a slightly different sense. *Phreatic* is derived from a Greek word meaning "a well." It serves a useful purpose in supplying a convenient root for terms relating to ground water. The terms *underground water* and *subterranean water* are sometimes used as synonymous with *ground water* and sometimes as synonymous with *subsurface water* in general. They are etymologically equivalent to *subsurface water.*

Subsurface ice, or *interstitial ice,* is ice that occurs below the surface of the lithosphere. It may be formed from the freezing of either saturated or unsaturated rock or soil or from the covering of a bed of surface ice or snow by a mantle of rock débris. It may be either temporary or perennial. Functionally it is like any other solid constituent of a rock or soil, and it can therefore not properly be classed with either ground water or suspended water.

The term *internal water* may be applied to the water in the interior of the earth, where the pressure of overlying rocks is so great that interstices can not exist (fig. 2). *Magmatic water* is water that exists in a magma or molten rock. Magmatic water and internal water may be largely the same, but it seems convenient to have two different terms to express the somewhat distinct concepts that are involved. A magma is believed to be a solution of its constituent minerals in one another. The water which it contains, in molecular or dissociated condition, is believed to be one of the constituents of the solution. To the extent that water occurs in the zone of rock flowage it is presumably present in some such miscible condition.

The zone of aeration may be divided, with respect to the occurrence and circulation of its water, into the belt of soil water, the intermediate belt, and the capillary fringe (fig. 2).

The *belt of soil water* is the part of the lithosphere, immediately below the surface, from which water is discharged into the atmosphere in perceptible quantities by the action of plants or by soil evaporation (figs. 2 and 20). This belt differs greatly in thickness with different types of soil and vegetation, being only a few feet thick where the surface is covered with grass or ordinary field crops but much thicker in forests and in tracts that support certain deep-rooting desert plants. The water in this belt is called *soil water.* It is of great importance to the agriculturist because it is the water

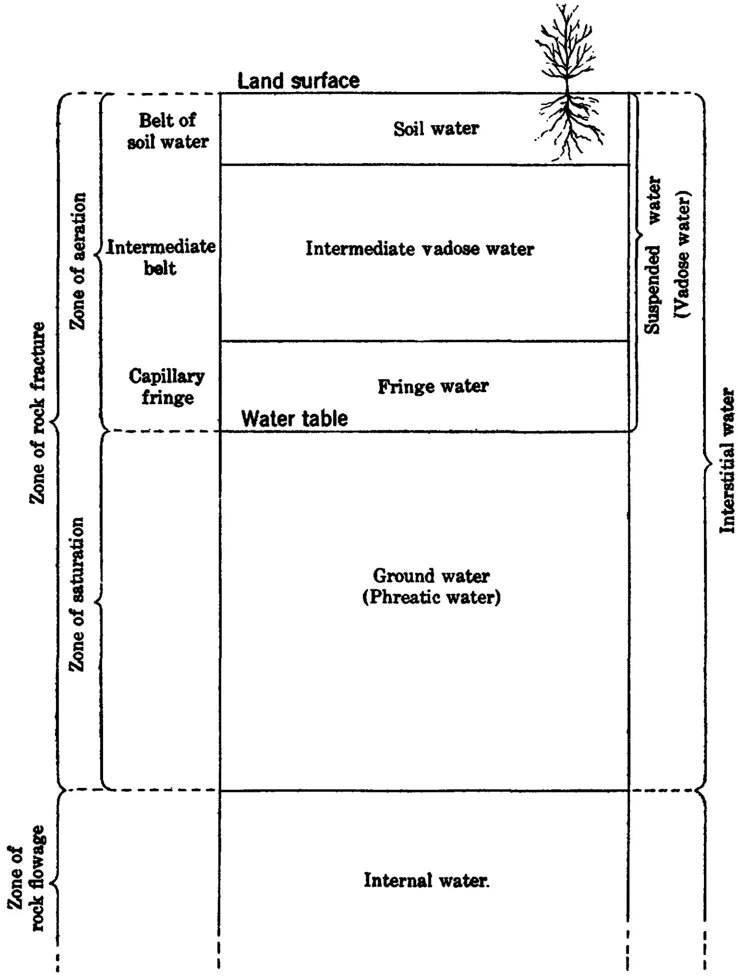

FIGURE 2.—Diagram showing divisions of subsurface water.

that is near enough the surface to be available to the roots of plants. Elaborate series of soil-water determinations extending through periods of years have been made by students of agriculture to determine the lower limits of the belt of soil water under various conditions of crops and cultivation and to investigate the absorption, movement, and discharge of soil water.

Soil water may be divided, with respect to its availability to plants, into water that is available for growth and water that is not available for growth. The latter is so firmly held by adhesion or other forces that it can not be absorbed by plants rapidly enough to produce growth.

The *wilting coefficient* of a soil is the ratio of (1) the weight of water in the soil at the moment when (with gradual reduction in the supply of soil water) the leaves of the plants growing in the soil first undergo a permanent reduction in their water content as the result of a deficiency in the supply of soil water to (2) the weight of the soil when dry. This ratio is expressed as a percentage. By permanent reduction, or permanent wilting, is meant a condition from which the leaves can not recover in a saturated atmosphere without the addition of water to the soil. (See fig. 3.)

The wilting coefficient is equivalent to $100\left(\frac{d}{W}\right)$, where d is the weight of water in the soil when permanent wilting begins and W is the weight of the soil when dry. The water in excess of that which remains when permanent wilting begins may be regarded as water available for growth, although this assumption is probably only approximately correct.

Hygroscopic water is the water in the soil that is in equilibrium with atmospheric water vapor. It is essentially the water which molecular attraction can hold against evaporation. When a dry soil is brought into contact with the atmosphere it absorbs water from the atmosphere, and this water, after absorption, is known as hygroscopic water.

The *hygroscopic coefficient* of a soil at a given temperature is the ratio of (1) the weight of water which at that temperature the soil will absorb if, after completely dry, it is placed in free contact with a saturated atmosphere until equilibrium is established, to (2) the weight of the soil when dry. This ratio is expressed as a percentage and may be expressed by the formula $100\left(\frac{h}{W}\right)$, where h is the weight of water that will be absorbed by the dry soil when placed in a saturated atmosphere and W is the weight of the soil when dry. The hygroscopic coefficient is usually somewhat smaller than the wilting coefficient. (See fig. 3.) The hygroscopic coefficient of a soil at a given temperature is a function of the soil only, but the quantity of hygroscopic water required for equilibrium in a given soil changes with the temperature and the relative humidity of the air and is therefore a function of both soil and air.

The *moisture equivalent* of a soil is the ratio of (1) the weight of water which the soil, after saturation, will retain against a centrifugal force 1,000 times the force of gravity, to (2) the weight of the soil when dry. This ratio is stated as a percentage, and may be expressed by the formula $100\left(\frac{c}{W}\right)$, where c is the weight of the water that remains in the soil after it has been saturated and then subjected to a

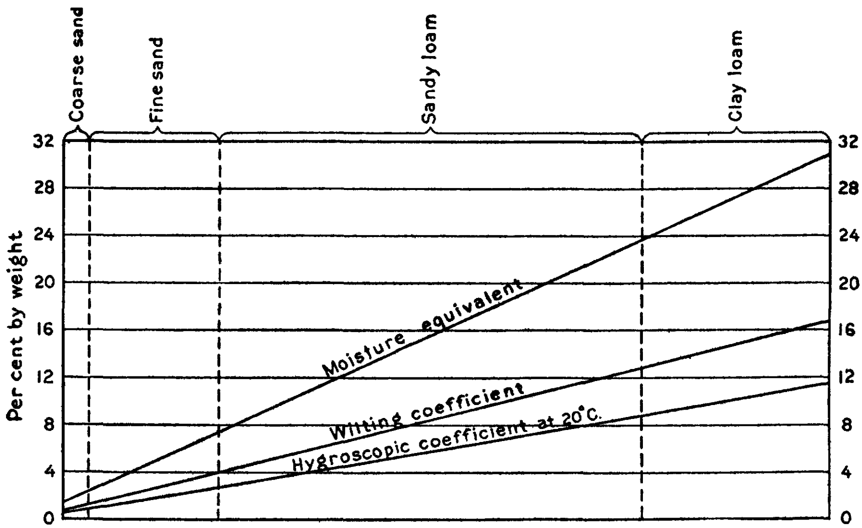

FIGURE 3.—Diagram showing relations of hygroscopic coefficient, wilting coefficient, and moisture equivalent in certain materials of different textures tested by Briggs and Shantz (U. S. Dept. Agr. Bur. Soils Bull. 230, 1912). The material is evenly graded from coarse at the left to very fine at the right.

centrifugal force 1,000 times the force of gravity, and W is the weight of the soil when dry. The moisture equivalent is an arbitrary ratio used in indirect determinations of the hygroscopic and wilting coefficients of soils (fig. 3). It may also be found useful for estimating the specific retention (p. 29).

According to the usual practice of students of soil and agriculture, the wilting coefficient, hygroscopic coefficient, and moisture equivalent are expressed in percentage by weight. Consequently these ratios can not be directly compared with the porosity, which is expressed in percentage by volume, but they can be converted into a comparable form by being multiplied by the specific gravity of the dry soil.

The *capillary fringe* is a belt that overlies the zone of saturation and contains capillary interstices some or all of which are filled with water that is continuous with the water in the zone of saturation but is held above that zone by capillarity acting against gravity (figs. 2 and 20). Experiments have shown that in cylindrical tubes the height at which water is held by capillarity is inversely proportional to the diameter. Hence, the thickness of the capillary fringe depends on the texture of the rock or soil. The fringe is relatively thin if it consists of materials in which all the capillary interstices are large. Materials that have only subcapillary interstices are impermeable and are not regarded as having any capillary fringe or as forming a functional part of such a fringe. In materials whose interstices are all supercapillary the capillary fringe is practically absent. However, permeable materials that do not have some capillary interstices are exceptional. The thickness of the capillary fringe in silty materials has frequently been observed to be about 8 feet; in very fine-grained materials it is even thicker, and in coarse sand it is considerably thinner. In digging or boring wells it is generally not difficult to recognize the point at which the capillary fringe is reached. It is correctly interpreted by well diggers and borers as an indication that the water table is near. In digging through the capillary fringe the water content and wet appearance generally increase downward because progressively larger interstices are filled with water. However, all this water is held against gravity by molecular attraction and hence does not flow into the well. Not until the water table is reached does water enter the well. Molecular attraction can not hold all the water in the capillary fringe against evaporation, however, and therefore the walls of a shallow dug well may become relatively dry even where it passes through the fringe. The water in the capillary fringe may be called *fringe water*.

The *intermediate belt* of a zone of aeration is the part that lies between the belt of soil water and the capillary fringe (figs. 2 and 20). Water that sinks into this belt is either drawn downward by gravity to the underlying zone of saturation or is drawn by molecular attraction into the capillary and perhaps subcapillary interstices in the intermediate belt, where it may become nearly or entirely stationary. The water in the intermediate belt may be called *intermediate* (*vadose*) *water*.

Both the belt of soil water and the capillary fringe are limited in thickness by definite local conditions, such as character of vegetation and texture of rock or soil, but the intermediate belt is not thus limited. It is the residual part of the zone of aeration. It may be entirely absent or may attain a thickness of several hundred feet. Where the thickness of the zone of aeration is equal to only the aggregate thickness of the belt of soil water and the capillary fringe these two belts come into contact with each other, the intermediate belt wedging out, and discharge of ground water into the atmosphere begins. Where the zone of saturation approaches still nearer to the surface and the zone of aeration becomes still thinner the belt of soil water includes part or all of the capillary fringe and may even extend into the zone of saturation. Where the height that water will rise by capillarity is equal to or greater than the thickness of the zone of aeration the capillary fringe comes as near the surface as is permitted by the discharge by plants and soil into the atmosphere. Where the belt of soil water extends into the capillary fringe the water may be regarded as both soil water and fringe water. Where the belt of soil water extends into the zone of saturation or includes a temporary zone of saturation the water is regarded as both soil water and ground water (fig. 20, p. 48).

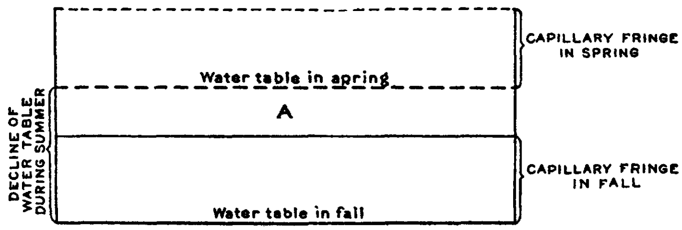

FIGURE 4.—Diagram illustrating gravity ground water. The water that drains out of a given body of rock at A when it passes from the zone of saturation to a position above the capillary fringe is gravity ground water.

Ground water may be divided, with respect to the force by which it is controlled, into gravity ground water and ground water that is not under the control of gravity.

The *gravity ground water* of a body of rock or soil in the zone of saturation is the water that would be withdrawn from the body by the direct action of gravity if the zone of saturation and the capillary fringe were moved downward through the body until both were entirely below it and remained in that position a specified period, no water being received by the body and none lost by it except through the pull of gravity (fig. 4). As the draining would, according to certain experiments, continue during an indefinitely long period, though at a continually decreasing rate, the term gravity ground water is indefinite unless an arbitrary period of draining is adopted. The amount of water that drains out also varies with the temperature and the mineralization of the water.

The water that is retained in rock or soil after the gravity ground water has drained out is no longer ground water but has become vadose water. Most of the *retained water* is held by molecular attraction, but a part may be held in isolated interstices or by other more or less obscure forces, and a part remains as water vapor occupying interstices from which liquid water has been withdrawn. (See fig. 5.) Essentially, the retained water is that held by molecular attraction against gravity, whereas the hygroscopic water is that held by molecular attraction against evaporation.

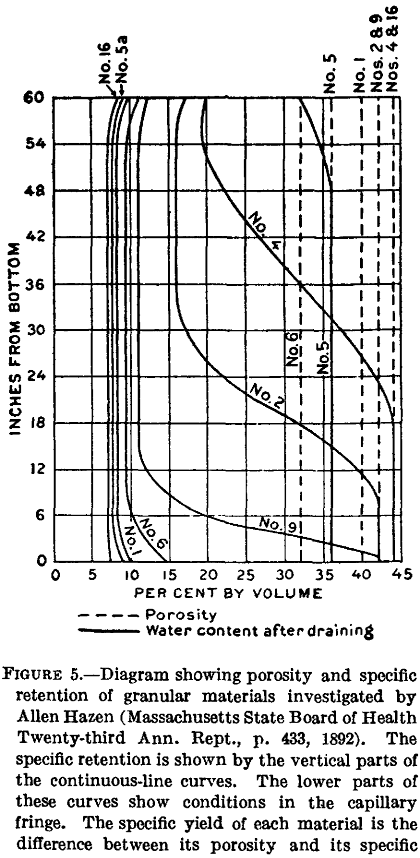

FIGURE 5.—Diagram showing porosity and specific retention of granular materials investigated by Allen Hazen (Massachusetts State Board of Health Twenty-third Ann. Rept., p. 433, 1892). The specific retention is shown by the vertical parts of the continuous-line curves. The lower parts of these curves show conditions in the capillary fringe. The specific yield of each material is the difference between its porosity and its specific retention.

The gravity ground water is of special interest to the student of ground water, because it is the water that is available for recovery by man through wells and springs. On the other hand, the retained water is of special interest to the student of agriculture, because it is the water that remains after the temporary zones of saturation produced near the surface by precipitation have disappeared and that is therefore the principal supply of water for vegetation.

The *specific yield* of a rock or soil, with respect to water, is the ratio of (1) the volume of water which, after being saturated, it will yield by gravity to (2) its own volume. This ratio is stated as a percentage and may be expressed by the formula $Y = 100\left(\frac{y}{V}\right)$, in which Y is the specific yield, y is the volume of gravity ground water in the rock or soil, and V is the volume of the rock or soil. (See fig. 5.)

The term *effective porosity* has been used to mean about the same as specific yield, as here defined, but it is generally used in a somewhat more general though closely related sense. The *effective porosity* of a rock or soil may thus be defined as the ratio of (1) the volume of water, oil, or other liquid which (after being saturated with that liquid) it will yield under any specified hydraulic conditions to (2) its own volume. Students of agriculture regard this term as inappropriate because it is the retained water and not the gravity water that is generally effective in producing plant growth.

The *specific retention* of a rock or soil, with respect to water, is the ratio of (1) the volume of water which, after being saturated, it will retain against the pull of gravity to (2) its own volume. It is stated as a percentage and may be expressed by the formula $R=100\left(\frac{r}{V}\right)$, where R is the specific retention, r the volume of water retained by the rock or soil against the pull of gravity, and V the volume of the rock or soil. (See fig. 5.)

By students of soil and agriculture the specific retention, or *water-retaining capacity*, as they sometimes call it, is so defined as to be expressed as a percentage of the dry weight. Ambiguity can be avoided by stating, when necessary, whether the specific retention is expressed by volume or by weight. To convert the specific retention of a rock or soil expressed by weight into the specific retention by volume multiply it by the specific gravity of the rock or soil.

The specific retention and specific yield of a rock or soil, as above defined, are not the same as the percentages of water that would respectively be retained and yielded by the same material if a small isolated sample of it were saturated and then allowed to drain. In such a sample the percentage of water yielded would be less than the specific yield. This difference results from the fact that a short capillary tube filled with water and held in an upright position may hold all the water, whereas a longer tube of the same diameter may allow a part of its water to drain out, because the height of the column of water that can be held by capillarity is limited. The communicating interstices of a rock or soil may form irregular capillary tubes. In a small sample these tubes are short and may hold their water; in nature, however, they are likely to be indefinitely long and hence to be drained down to a certain level above the water table, determined by their diameters. The principle involved can be illustrated by many familiar examples. For instance, if a blanket is washed, put through a wringer, and then deposited in a basket it may hold all the moisture remaining in it. If, however, it is hung up, so as to have a longer vertical range, it may soon become very wet at the bottom and begin to drip. The methods for determining specific retention have been so little standardized that when the term is used a statement should be made as to the methods employed, especially as to size of sample and period of draining. For some experiments it may be expedient to work with small samples.

Classification of subsurface water with respect to occurrence.

- I. Interstitial water:
  - A. Suspended water (vadose water):
    - *a.* Soil water:
      - 1. Water available for growth.
      - 2. Water not available for growth.
        - (a) Water that can be removed by evaporation.
        - (b) Water that can not be removed by evaporation (hygroscopic water).

I. Interstitial water—Continued.
  A. Suspended water (vadose water)—Continued.
    b. Intermediate vadose water.
    c. Fringe water.
  B. Ground water (phreatic water):
    a. Gravity ground water.
    b. Ground water not under the control of gravity.
  C. Subsurface ice (interstitial ice).
II. Water in the mineral matter of the rocks above the zone of rock flowage (solid solution, etc.).
III. Internal water (and magmatic water above the zone of rock flowage).

The term *rock formation* is used to designate a part of the lithosphere that is more or less distinct (lithologically or structurally and hence genetically) from other parts. To a considerable extent a formation is an arbitrary unit. The term *water-bearing formation* is a relative term used to designate a formation that contains considerable gravity ground water. It is commonly used with more or less reference to the economic value of the formation as a source of water supply. Few if any formations are entirely devoid of gravity ground water, but those that do not contain enough to be of consequence as a source of supply are not rated as water bearing. Hence, it may happen that in a region that is underlain by formations yielding large quantities of water a formation that will yield only meager quantities will not be classed as water bearing, whereas in a region that is nearly destitute of available ground water a similar formation may be thus classed. An *aquifer* is a formation, group of formations, or part of a formation that is water-bearing. The term *ground-water reservoir* is used as a synonym of aquifer. The terms *water-bearing bed, water-bearing stratum,* and *water-bearing deposit* are also used.

A *structure contour* of the upper or lower surface of an aquifer is a line on that surface all points along which have the same altitude. The altitude is generally expressed in feet or meters above or below mean sea level. The structure contours shown on a map generally indicate equal intervals of altitude.

A line on a land surface all points along which are the same vertical distance above the upper or lower surface of an aquifer may be called an *isobath* of the specified surface, or merely a line of equal depth to the surface. The isobaths shown on a map may collectively be called lines showing depths to the specified surface.

ORIGIN.

The origin of the water of the earth, like the origin of many other things, is largely lost in obscurity. The question of the origin of the water involves questions relating to the origin of the earth itself and to the poorly understood processes that take place in the earth's interior. Classification and definitions relating to origin are therefore almost unavoidably based in part on hypotheses instead of on demonstrated facts of nature, and they may be confusing if used when other hypotheses are assumed.

Interstitial water may be divided, with respect to its origin, into water of external origin and water of internal origin.

Interstitial water of external origin is that which is derived from atmospheric or surface water. It may be divided into absorbed water, connate water, water of dehydration, and water derived from resurgent water. Different kinds of *absorption* are described on page 46. The absorbed water includes much the largest part of all known interstitial water. It is by far the most valuable for both water supply and agriculture.

Connate water is water that has got into a rock formation by being entrapped in the interstices of the rock material (either sedimentary or extrusive igneous) at the time the material was deposited. It may be derived from either ocean water or land water.

Water of dehydration is water that was once in chemical combination with certain minerals and has been by later chemical changes set free as water. Most though perhaps not all of this water is of external origin. The chemical process of hydration, or taking water into chemical combination with minerals, occurs at the surface and also for some distance below the surface, where it consumes chiefly absorbed water.

The term *meteoric water* refers to water that is in or derived from the atmosphere. It has been used in various ways, sometimes to include all subsurface water of external origin and sometimes to include only that derived by absorption, excluding especially the connate ocean water. It does not seem to be available for specific definition with respect to subsurface water.

Interstitial water of internal origin is that which is derived from the interior of the earth and has not previously existed as atmospheric or surface water. It is commonly called *juvenile water.* If water of internal origin is discharged to the surface and then reenters the soil or rocks it may be classed as water of external origin. There is much difference of opinion as to the abundance of water of internal origin, some authorities believing that the atmospheric and surface water is largely derived from the interior and others doubting whether there is any magmatic water except that of external origin.

Two kinds of water of internal origin may be distinguished—(1) that derived from *primitive water,* or water that had been imprisoned in the interior (in either molecular or dissociated condition) since the formation of the earth, and (2) that created by the chemical combination of primitive hydrogen with oxygen of external origin.

Internal water and magmatic water above the zone of rock flowage may be divided, at least theoretically, into primitive water and resurgent water. Primitive water is defined above. The term *resurgent water* is used to designate magmatic water of external origin. The term is extended to apply also to such water after it has been expelled from the magma to rock interstices or to the surface.

Classification of subsurface water with respect to origin.

- A. Interstitial water:
    - I. Water of external origin:
        - *a.* Absorbed water (see p. 46):
            - 1. Influent seepage (water of infiltration):
                - (a) Capillary seepage.
                - (b) Supercapillary seepage.
            - 2. Flow of streams into sink holes or other large openings.
            - 3. Absorbed by capillarity.
            - 4. Derived by hygroscopic absorption.
            - 5. Inflow of atmospheric water vapor.
        - *b.* Connate water:
            - With respect to origin of water:
                - 1. Derived from ocean water.
                - 2. Derived from land water.
            - With respect to kind of rock in which water was entrapped:
                - 1. Water in sedimentary rocks.
                - 2. Water in extrusive igneous rocks.
        - *c.* Water of dehydration (in part).
        - *d.* Water derived from resurgent water.
    - II. Water of internal origin (juvenile water):
        - *a.* Derived from primitive water.
        - *b.* Derived from chemical combination of primitive hydrogen with oxygen of external origin.
- B. Internal water (and magmatic water above the zone of rock flowage):
    - I. Primitive water.
    - II. Resurgent water.

WATER TABLES.

A *water table* is the upper surface of a zone of saturation except where that surface is formed by an impermeable body (fig. 2).

An *oil-water surface* is a surface that forms the boundary between a body of ground water and an overlying body of petroleum that saturates the rock. A *gas-water surface* is a surface that forms the boundary between a body of ground water and an overlying body of natural gas. Both kinds of surfaces generally occur within the zone of saturation, the petroleum or gas being trapped under a cover of effectively impermeable rock. As the gas and water are in contact with each other the gas is necessarily under the hydrostatic pressure of the water at the depth at which it exists and is therefore greatly compressed. Likewise, a *gas-oil surface* is a surface that forms the boundary between a body of petroleum and an overlying body of natural gas. Some question exists as to the extent to which these boundaries are definite surfaces. Where there is considerable hydrostatic pressure much gas will go into solution in the water and oil before it will form a body of gas.

A *contour of a water table* is a line on the water table all points along which have the same altitude (figs. 6 and 7). The altitude is generally expressed in feet or meters above mean sea level. The contours shown on a map generally represent equal intervals of altitude.

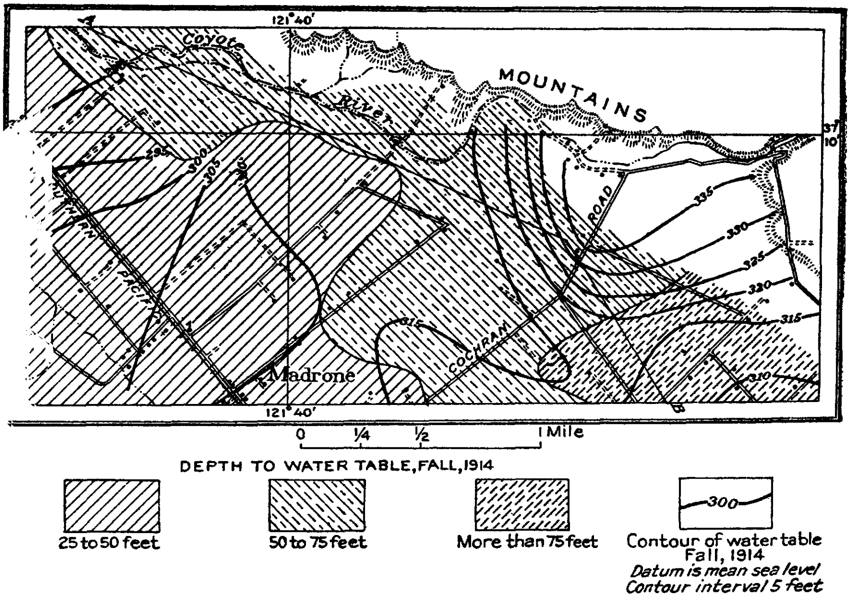

FIGURE 6.—Map of a part of Santa Clara Valley, Calif., showing contours of water table and depths to water table in the fall of 1914. (After W. O. Clark, U. S. Geol. Survey Water-Supply Paper 400, pl. 6, 1917.) *A-B*, Line of profile in figure 8.

A *gradient of a water table* at a given place in a given direction is the rate of change of altitude per unit of distance in the water table at that place and in that direction. If the direction is not mentioned it is generally understood that the direction of maximum rate of change is meant. If the rate of change is uniform between two points the gradient is the ratio of the difference of altitude between the two points to the horizontal distance between them. The gradient can be expressed in percentage, in feet per mile, or in other ways.

A *profile of a water table* is a vertical section of the water table. It is the line along which a given vertical plane intersects the water table (fig. 8).

A line on a land surface all points along which are the same vertical distances above the water table may be called an *isobath* of the water table, or merely a line of equal depth to the water table. The isobaths shown on a map may collectively be called lines showing depths to the water table. The expressions "lines of equal depth to water" or "lines showing depth to water" are not permissible because they lack specific meaning. (See figs. 6 and 18.)

A *ground-water divide* is a line on a water table on each side of which the water table slopes downward in a direction away from the line (figs. 6, 7, and 8). It is analogous to a divide between

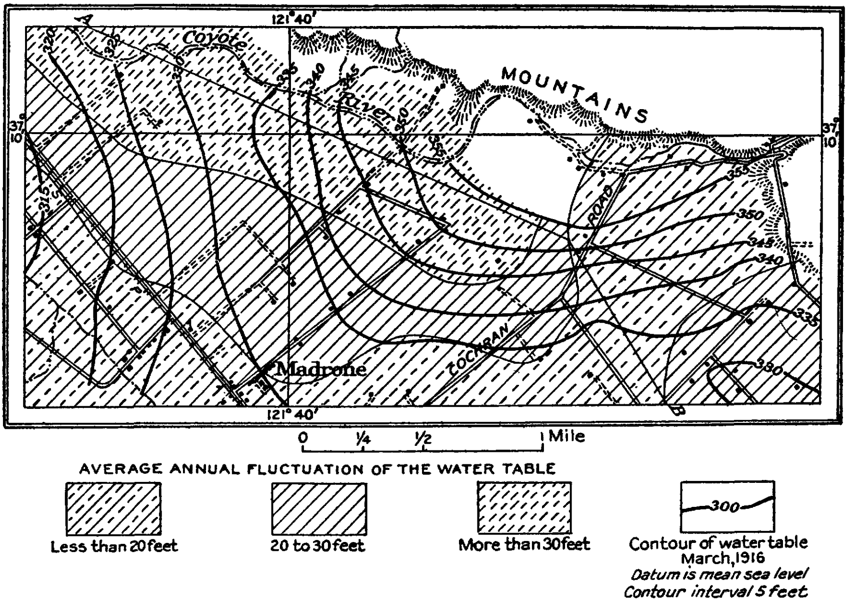

FIGURE 7.—Map of a part of Santa Clara Valley, Calif., showing fluctuations of the water table and its position during the high stage in March, 1916. (After W. O. Clark, op. cit., pl. 7.) *A-B*, Line of profile in figure 8.

two drainage basins on a land surface. The water moves in the direction of the slope—that is, in opposite directions on opposite sides of the divide. Generally a ground-water divide is found nearly below a surface-drainage divide, but in many localities there is no relation between the two.

The *rise of the water table*, or the *phreatic rise*, is the upward movement of the water table. The *decline of the water table*, or the *phreatic decline*, is similarly the downward movement of the water table. The *fluctuation of the water table*, or *phreatic fluctuation*, is the alternate upward and downward movement of the water table (fig. 9). Such movement is caused chiefly by irregularities in the rates at which water is taken into and discharged from the zone of saturation.

It is characteristic of the water table in all areas that have been investigated.

A *period of rise* is the time during which the water table is moving upward continuously or has a general upward trend, and a *period of decline* is the time during which it is moving downward continuously or has a general downward trend. A *cycle of fluctuation*, or *phreatic cycle*, is the total time occupied by a period of rise and a succeeding period of decline (fig. 9). The most common kinds of cycles are *daily*, *annual*, and *secular* cycles. Daily cycles are due to daily variations in transpiration, evaporation, atmospheric pressure, and temperature. Annual cycles occur because of differences between different seasons in the rates of transpiration,

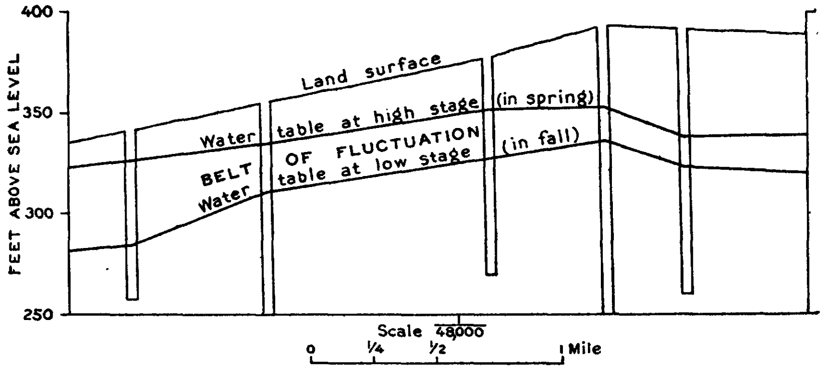

FIGURE 8.—Profiles of water table along line *A-B* in figures 6 and 7. (After W. O. Clark, op. cit., fig. 9.)

evaporation, and precipitation, in the accumulation or melting of snow, and in the presence or absence of frost in the ground. They are most distinctly marked in regions such as California, where there are strongly contrasting rainy and dry seasons. A *secular cycle* is one that covers a period of predominantly rainy years alternating with a period of predominantly dry years. It is composed of a number of annual cycles, just as an annual cycle is composed of many daily cycles.

The *highest stage of the water table*, or *phreatic high*, at a given place and for a given cycle of fluctuation is the highest altitude reached by the water table at that place in that cycle. It is generally expressed in feet or meters below the land surface or above mean sea level. The *lowest stage of the water table*, or *phreatic low*, is likewise the lowest level reached by the water table (fig. 9). These concepts give rise to various qualifying terms such as annual, daily, average annual, and average daily.

The *belt of fluctuation of the water table*, or the *belt of phreatic fluctuation*, is a part of the lithosphere which, because of the fluctuation of the water table, lies a part of the time in the zone of saturation and a part of the time in the overlying zone of aeration (figs. 7, 8, and 9). This expression may be used to designate a belt whose limits are fixed by the total known fluctuation at each point of observation or a belt whose limits are fixed by the fluctuation in a given cycle or other period. Its volume, for a given region or aquifer, is generally expressed in acre-feet. The net amount of ground water gained by a given region or aquifer during a specified

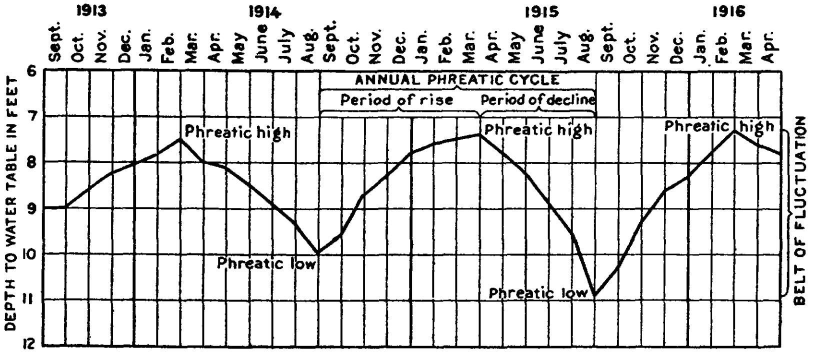

FIGURE 9.—Diagram showing fluctuation of the water table at Jones ranch, Big Smoky Valley, Nev.

period of rise or lost during a specified period of fall may be calculated approximately by multiplying the volume of this belt for the period by the specific yield.

The vertical position and thickness of a belt of fluctuation can be shown on a map by means of two sets of contours of the water table, one showing its position at the date of the highest stage and the other its position at the date of the lowest stage. Its thickness

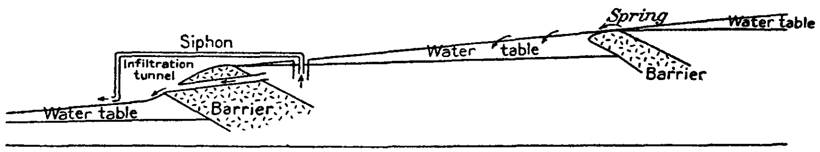

FIGURE 10.—Diagrammatic section showing ground-water dams, an interrupted water table, a contact spring, an infiltration tunnel, and a well from which water is drawn with a siphon. Based on conditions in Tularosa Basin, N. Mex.

can also be shown directly by means of lines of equal fluctuation (figs. 6 and 7).

A *wave of the water table*, or *phreatic wave*, is a rise of the water table that progresses horizontally away from an area where in certain periods exceptionally large supplies of water are added to the zone of saturation.

A *ground-water dam* is a body of material which is impermeable or has only low permeability and which occurs below the surface in such a position that it impedes the horizontal movement of ground water and consequently causes a pronounced difference in the level of the water table on opposite sides of it. Such a dam may be either natural or artificial. A water table that has a pronounced descent along such a dam may be called an *interrupted water table.* If ground water spills over such a dam it may be said to produce a *ground-water cascade.* (See fig. 10.)

HYDROSTATIC PRESSURE.

The *hydrostatic pressure* at a given point in a body of water at rest is the pressure exerted by the water at the point. The hydrostatic pressure of ground water is generally due to the weight of water at higher levels in the same zone of saturation. Ground water is generally in motion, but except where the conditions are artificially modified the motion is generally so slow that no appreciable error is involved in regarding the pressure which it exerts as hydrostatic. However, the pressure in a given aquifer differs from point to point, decreasing in the direction of movement, because of the friction resulting from the viscosity of the water and consequently the conversion of potential energy into heat and perhaps other forms of kinetic energy in overcoming this friction.

The *pressure head* of water at a given point in an aquifer is its hydrostatic pressure expressed as the height of a column of water that can be supported by the pressure. It is the height that a column of water rises in a tightly cased well that has no discharge. The pressure head is commonly expressed with reference to the land surface at the well or to some other convenient level. Thus, it is proper to say that at the surface the pressure head is 25 feet, meaning that the pressure is sufficient to lift the water in a tightly cased well to a level 25 feet above the surface (fig. 11).

Rarely water will rise higher in a well than its pressure head, because of the presence of bubbles of gas in the water. In most such places the gas was probably originally in solution in the water but escapes out of solution as the pressure decreases. The resulting bubbles reduce the specific gravity of the water and gas mixture below that of water, and hence the water rises higher than it would under the same pressure if the column contained no gas.

The *hydrostatic level,* or *static level,* of water at a given point in an aquifer is the level that passes through the top of a column of water that can be supported by the hydrostatic pressure of the water at that point. It is the level to which water will rise in a well under its full pressure head. It can be expressed with reference to any convenient datum—for example, it is proper to say that the static level is a certain number of feet above or below the land surface, the water table, or mean sea level (fig. 11).

The *piezometric surface* of an aquifer is an imaginary surface that everywhere coincides with the static level of the water in the aquifer. It is the surface to which the water from a given aquifer will rise under its full head (figs. 11 and 12). If at any given place the water from different depths in the aquifer will rise to different levels the aquifer has more than one piezometric surface.

An *isopiestic line* of an aquifer is a contour of the piezometric surface of the aquifer. It is an imaginary line all points along which have the same static level. Its position may be described in any convenient unit and with reference to any convenient datum, but is most commonly expressed in feet or meters above mean sea level. A *piestic interval* is the difference in static level between two isopiestic lines. (See fig. 12.)

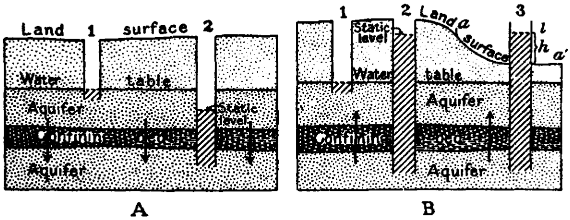

FIGURE 11.—Sections showing hydrostatic pressure in aquifers and wells. In A the lower aquifer has subnormal head, its piezometric surface is below the upper surface of the zone of saturation, the resultant hydrostatic pressure on the confining bed is downward, and the bed may be called a negative confining bed. Both wells are nonartesian. The water in the upper aquifer is semiperched—it belongs to the same zone of saturation as the lower aquifer. In B the lower aquifer has artesian head, its piezometric surface is above the upper surface of the zone of saturation and in some places above the land surface, the resultant hydrostatic pressure on the confining bed is upward, and the bed may be called a positive confining bed. No. 1 is a nonartesian well, No. 2 a subartesian well, and No. 3 a flowing well. The static level of the water in the lower aquifer at the intake of well No. 3 is at *l*, and its pressure head with reference to the land surface is the vertical distance *h*. *aa'* is an area of artesian flow.

The *hydraulic gradient*, or *pressure gradient*, of an aquifer at a given place in a given direction is the rate of change of pressure head per unit of distance at that place and in that direction. If the direction is not mentioned it is generally understood that the direction of maximum rate of change is meant. If the rate of change is uniform between two points the hydraulic gradient between these points is the ratio of the difference in the static level between the points to the horizontal distance between them. The hydraulic gradient can be expressed in percentage, in feet per mile, or in other ways.

A *hydraulic profile* of an aquifer is a vertical section of its piezometric surface.

Ground water may be said to have *artesian*, *normal*, or *subnormal pressure* or *pressure head*, according as its static level is above the upper surface of the zone of saturation, at this surface, or below this surface (fig. 11).

Artesian water is ground water that has artesian pressure head. It is ground water that is under sufficient pressure to rise above the zone of saturation. An *artesian aquifer* is one that contains artesian water. An *artesian basin* is a geologic structural feature or combination of such features in which water is confined under artesian pressure.

A piezometric surface may be an *artesian-pressure surface*, which is above the upper surface of the zone of saturation; a *normal-pressure surface*, which coincides with the upper surface of the zone of saturation; or a *subnormal-pressure surface*, which is below the upper

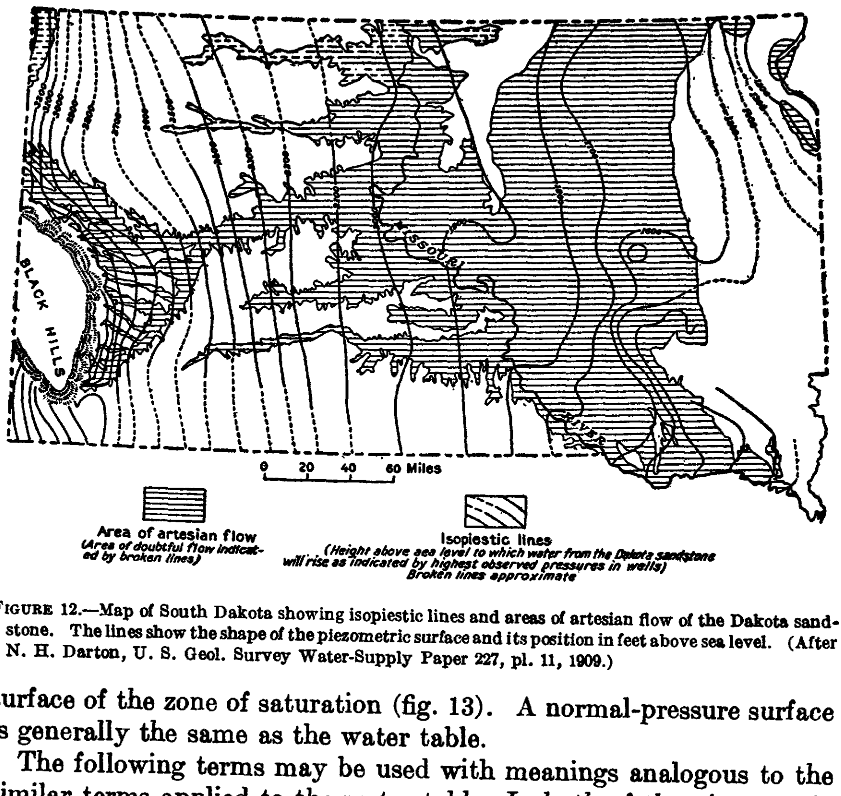

FIGURE 12.—Map of South Dakota showing isopiestic lines and areas of artesian flow of the Dakota sandstone. The lines show the shape of the piezometric surface and its position in feet above sea level. (After N. H. Darton, U. S. Geol. Survey Water-Supply Paper 227, pl. 11, 1909.)

surface of the zone of saturation (fig. 13). A normal-pressure surface is generally the same as the water table.

The following terms may be used with meanings analogous to the similar terms applied to the water table: Isobath of the piezometric surface; rise, decline, and fluctuation of the static level, or piestic rise, decline, and fluctuation; period of piestic rise or decline; piestic cycle; highest and lowest stages of the static level, or the piestic high and the piestic low; line of equal piestic fluctuation; belt of piestic fluctuation; and piestic wave. If it is desired to avoid these technical terms, more expanded expressions may be used, such as "lines showing the depth below the surface at which water stands in wells."

An *area of artesian flow* is a land or water surface which lies below a piezometric surface. It is an area in which the water of some underlying aquifer is under sufficient pressure to rise above the surface (fig. 13). An area in which the water rises to the surface because of the presence of gas can not properly be called an area of artesian flow but may be called an *area of gas-lift flow* or may be designated by means of a brief description of the conditions.

A *confining bed* of an aquifer is one which, because of its position and its impermeability or low permeability relative to that of the aquifer, gives the water in the aquifer either artesian or subnormal head.

Confining beds may, at least theoretically, be divided, with respect to their effectiveness, into *impermeable confining beds* and *permeable confining beds*. Permeable confining beds produce artesian or subnormal head, not by preventing percolation but by retarding it.

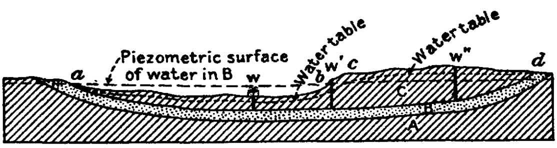

FIGURE 13.—Diagrammatic section of an artesian basin. The formation B is an artesian aquifer. The formation A is a confining bed—probably negative, although there is nothing in the illustration to prove this definitely. The formation C is a confining bed which is permeable, at least in its upper part, where it has a water table. It is positive from *a* to *c* but negative from *c* to *d*, where the water table is semiperched. The area *ab* is an area of artesian flow. Three wells are shown: W is a flowing well; W' is a subartesian well; W″ is a nonartesian well whose water has subnormal pressure head.

They are much more abundant than impermeable confining beds. There is probably no confining bed that is strictly impermeable over any wide area.

Confining beds may be divided, with respect to the vertical direction in which they are effective, into *positive confining beds* and *negative confining beds*. A positive confining bed is one that prevents or retards upward movement of ground water where the underlying water has a higher static level than the overlying water and where there is, therefore, a resultant upward pressure. Artesian head is maintained by confining beds of this class. A negative confining bed is one that prevents or retards downward movement of ground water where the overlying water has sufficient head to produce a resultant downward pressure. Such a bed generally maintains subnormal head in the underlying water. It may also be essential in maintaining artesian head in the overlying water. (See fig. 13.)

Ground water is said to be *perched* if it is separated from an underlying body of ground water by unsaturated rock. Perched water belongs to a different zone of saturation from that occupied by the underlying ground water. Its water table is a *perched water table*, in distinction from that of the lower zone of saturation, which is called the *main water table*. Rarely more than one body of perched water may occur at different altitudes in the same locality. (See figs. 14 and 15.)

Perched ground water may be divided, with respect to its permanence, into temporary perched water and permanent perched water. Numerous temporary bodies of perched water of very short duration are produced near the surface by rain and melting snow. These are especially noticeable in the spring before the frost has left the ground, when the frozen soil acts on a small scale as a nearly impermeable negative confining bed. Many examples could also be given of permanent bodies of perched water.

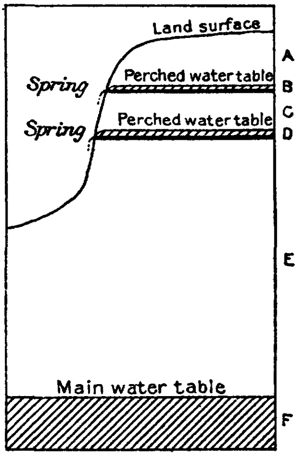

FIGURE 14.—Diagrammatic section showing two bodies of perched water at Kapapala ranch, Kau district, Hawaii. The rocks shown are essentially all permeable lava except at B and D, where thin, nearly impermeable beds of volcanic ash are represented by the black lines. Thin but economically important zones of saturation (the shaded zones at B and D) occur at the high levels of the springs, where perched water is held up by the deposits of ash that form negative confining beds. The main zone of saturation (F) occurs much lower. The intervening spaces (A, C, and E) are not saturated and hence constitute three zones of aeration. Vertical distance shown amounts to several hundred feet.

Ground water may be said to be *semiperched* if it has greater pressure head than an underlying body of ground water, from which it is, however, not separated by any unsaturated rock. Semiperched water belongs to the same zone of saturation as the underlying water, and therefore where it occurs there is only one water table, which may be called a *semiperched water table*. Semiperched water, like perched water, is underlain by a negative confining bed of either permeable or impermeable type. The underlying water has subnormal head. (See fig. 11; also *cd* in fig. 13.)

If, after the water table is struck in drilling a well, the well contains water at all depths which it reaches but the water level in the well sinks below the original water table, then the water table is of the semiperched type and the deeper water is under subnormal head. This is true whether the well is cased or uncased. If the well is uncased and it loses all its water after having passed through a water-bearing bed, the rock at the bottom of the well is probably unsaturated and is receiving the perched water that was penetrated at a higher level. If the well is tightly cased and it yields no water after having passed through a water-bearing bed, it may end in an impermeable bed or in a permeable bed that is unsaturated. If water poured into the well all drains out the well evidently ends in an unsaturated bed and the overlying ground water is perched.

A *ground-water artery* is a more or less tubular body of permeable material incased in a matrix of less permeable or impermeable material and saturated with water that is under artesian pressure. The term is especially applicable to deposits of gravel along ancient stream channels that have become buried in less permeable alluvial material under alluvial fans. Each of these gravel trains heads at the apex of an alluvial fan, where it obtains the principal supply of water, and it may branch as it passes beneath the lower parts of the fan, where its water, under artesian pressure, may ooze out through the capillary or other interstices of the matrix. In their general structure and manner of functioning these ground-water arteries closely resemble the arteries in animals.

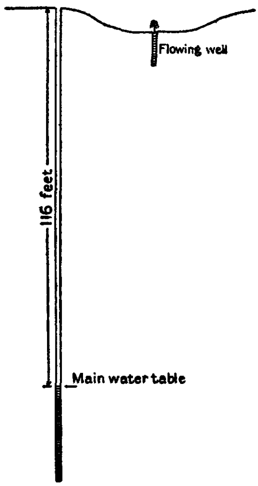

FIGURE 15.—Diagrammatic section showing a shallow flowing well supplied by a body of perched water far above the main body of ground water that supplies the deep well. Based on conditions in Sulphur Spring Valley, Ariz. Vertical distance shown, about 150 feet.

A ground-water artery is entirely surrounded by a confining bed. The outward percolation of water through this bed under artesian pressure may be called *dispersion* from the artery. A ground-water artery has a piezometric surface with piestic fluctuations, cycles, and waves, which follow promptly the causal conditions, whereas the water table of the matrix has phreatic fluctuations, cycles, and waves, which lag much behind the causal conditions.

MOVEMENT.

Movements of subsurface water include percolation, flow of water through large openings, capillary migration, and circulation of water vapor.

Percolation of water through a rock or soil is the movement, under hydrostatic pressure, of water through the interstices of the rock or soil, except the movement through large openings such as caves.

The flow of water through large openings in the rocks may be produced directly by gravity, like the flow of surface streams, or by hydrostatic pressure, like the flow of water through pipes.

Capillary migration of water through a rock or soil is the movement of liquid water produced by the molecular attraction of the rock material for the water. It occurs in the zone of aeration and is most pronounced in those parts of the capillary fringe that come into contact with the belt of soil water, where there is a constant removal of water at the top of the fringe by evaporation or plant absorption and a constant replenishment at the bottom, where the capillary fringe comes into contact with the zone of saturation. A familiar illustration of this process is the rise of kerosene in the wick of a lamp.

Circulation of water vapor through a rock or soil occurs in the zone of aeration, chiefly through interstices that communicate with the atmosphere. It is produced largely by (1) changes in atmospheric pressure, which result in alternate compression and expansion of the subsurface gases, (2) changes in temperature, which produce convection currents, (3) subsurface evaporation, which results both in gaseous diffusion and in differences in density that produce circulation, and (4) rise and fall of the water table, which displaces subsurface gases or draws in air.

Percolation may be regarded as consisting of *capillary percolation* (percolation through capillary interstices) and *supercapillary percolation* (percolation through supercapillary interstices). The velocity of water through a large pipe varies, at considerable velocities, approximately as the square root of the hydraulic gradient; the velocity through a very small pipe or through a somewhat larger pipe at very low velocities varies approximately as the hydraulic gradient. Likewise, it has been shown by experiment that the velocity of slowly moving water through a rock having small interstices varies approximately, but not exactly, as the hydraulic gradient, but that the velocity of water moving more rapidly through a large opening varies approximately as the square root of the hydraulic gradient. However, no sharp distinction can be made between capillary percolation and supercapillary percolation on the basis of the controlling law of flow.

Seepage is the percolation of water through the surface of the lithosphere or through the walls of large openings in it, such as caves or artificial excavations. The term *infiltration* has essentially the same meaning. Seepage may be divided, with respect to the direction in which it takes place, into *influent seepage* (seepage into the lithosphere) and *effluent seepage* (seepage out of the lithosphere). Seepage may also be divided, like percolation in general, into *capillary seepage* and *supercapillary seepage.*

A *subterranean stream* is a body of flowing water that passes through a very large interstice, such as a cave or cavern, or a group of large communicating interstices—for example, the openings from which the tubular spring shown in figure 22 issues. The term does not apply to percolating water.

An *underflow conduit* consists of a permeable deposit which underlies a surface streamway, is more or less definitely limited at its bottom and sides by rocks of relatively low permeability, and contains ground water that percolates approximately downstream (fig. 16).

Underflow is the movement of ground water in an underflow conduit. The term is also used to denote the rate of discharge of ground water through an underflow conduit—generally in second-feet (cubic feet per second).

The *hydraulic permeability* of a rock or soil, with respect to water, is its capacity for transmitting water under pressure. For some rocks and soils it is different in different directions This capacity can be quantitatively defined as the rate of discharge of water through a unit cross-section area of the rock at right angles to the direction of flow if the hydraulic gradient is unity. Under the name *transmission constant,* it has been expressed as the discharge in cubic feet per minute through each square foot of cross-section area when the

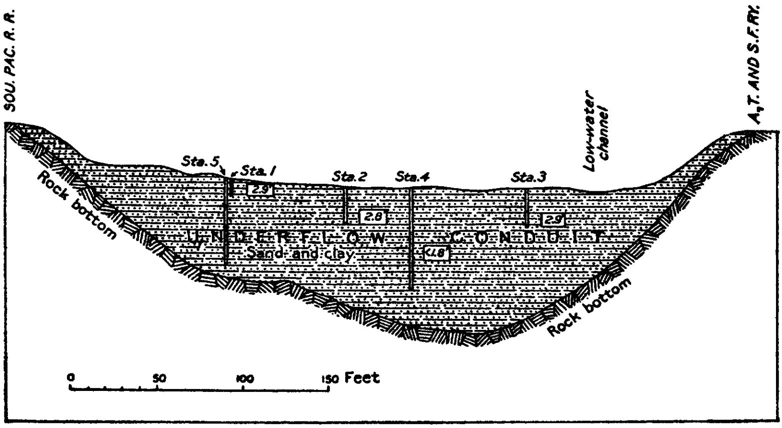

FIGURE 16.—Cross section of gorge of Rio Grande above El Paso, Tex., showing the underflow conduit. (After C. S. Slichter, U. S. Geol. Survey Water-Supply Paper 141, fig. 2.) Numbers give the velocity of the ground water in feet a day.

hydraulic gradient is 100 per cent. Thus expressed, the transmission constant is unity if the discharge is 1 cubic foot per minute through each square foot of cross-section area, with a hydraulic gradient of 1 foot difference in head for each foot the water travels.

The *coefficient of viscosity* of water is a quantitative expression of the friction between the molecules of the water when in motion. It can be defined as the amount of force necessary to maintain a unit difference in velocity between two layers of water at a unit distance apart. The coefficient of viscosity varies somewhat with several factors. It decreases rapidly with increase in temperature. The capacity of a rock or soil to transmit water varies inversely as the coefficient of viscosity of the water. Hence it varies with the temperature of the water, which is generally the same as the temperature of the rock or soil through which the water passes and may for this reason be considered an attribute of the rock or soil as it exists in nature. The transmission constant of a rock or soil is therefore not the same for different temperatures; it is greater for high than for low temperatures.

The *effective size of grain* of a rock or soil is the diameter of the grains in an assumed rock or soil that has the same transmission constant as the rock or soil under consideration and is composed of spherical grains of equal size and arranged in a specified manner. The term has practical application only to materials that are composed chiefly of more or less rounded grains. A material composed of uniform spherical grains may range in porosity, according to the manner of arrangement of the grains, between 25.95 and 47.64 per cent. Hence

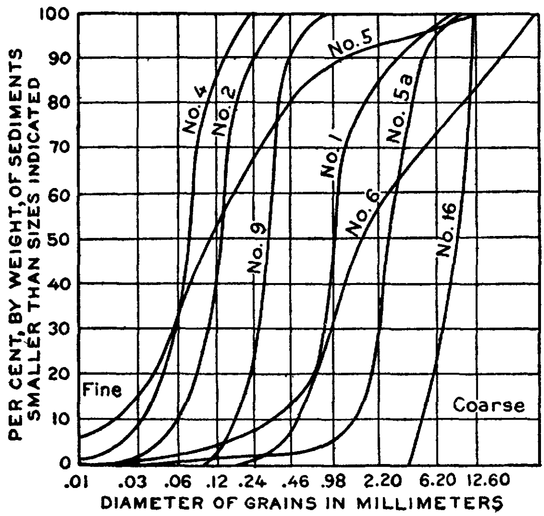

FIGURE 17.—Diagram showing sizes of grains in eight granular materials shown in figure 5. (After Allen Hazen, Massachusetts Board of Health Twenty-third Ann. Rept., p. 430, 1892.)

it also has a considerable range in permeability. The manner of arrangement can be indicated by stating the porosity.

An indirect method that has been used for estimating the effective size of grain, and hence the transmission constant, of appropriate material is to determine, by the use of sieves of known mesh or by other methods, the approximate diameter of a grain which is just too large to pass through a sieve that allows 10 per cent of the material, by weight, to pass through, and to assume that this diameter is the effective size of grain. According to this method the effective sizes of the materials plotted in figure 17 are indicated by the points where the curves cross the 10 per cent line. Experiment has shown, however, that this method may give results that are largely in error.

The *uniformity coefficient* of a granular material is an expression of the variety in the sizes of the grains that constitute the material. It may be defined as the quotient of (1) the diameter of a grain that is just too large to pass through a sieve that allows 60 per cent of the material, by weight, to pass through, divided by (2) the diameter of a grain that is just too large to pass through a sieve that allows 10 per cent of the material, by weight, to pass through. This definition does not imply that the sizes of grains are necessarily determined by means of sieves. The uniformity coefficient is unity for a material whose grains are all of the same size, and it increases with variety in size. In figure 17 the 60 per cent points as well as the 10 per cent points can be determined by inspection. Obviously the more nearly uniform the grains of a material are the steeper will be its curve.

ABSORPTION.

Absorption of water by the lithosphere includes influent seepage, flow of streams into sink holes or other large openings, absorption by capillarity, hygroscopic absorption, and inflow of atmospheric water vapor. Influent seepage is defined on page 43; hygroscopic water on page 24. Absorption by seepage is also called *infiltration*.

Intake or *recharge* of ground water comprises the processes by which water is absorbed and is added to the zone of saturation. These terms are not applied to the absorption of water that reaches only the belt of soil water or the intermediate belt of the zone of aeration. Water that reaches the capillary fringe of course makes direct contribution to the zone of saturation—that is, to the supply of ground water. The terms *intake* and *recharge* are also used to designate the quantity of water that is added to the zone of saturation. The expressions *increment of ground water* and *increment to an aquifer* are used in the same sense. These quantities are generally expressed in gallons or acre-feet.

An *intake area* of an aquifer is an area where water is absorbed which eventually reaches a part of the aquifer that is in the zone of saturation (fig. 18). In nearly all land areas water is at certain times absorbed, but in many places the absorbed water penetrates only to the belt of soil water or perhaps to the intermediate belt. The term *intake area* is not applied unless the water reaches the zone of saturation. The boundaries of many intake areas are of course indefinite. The intake of an aquifer is *direct* if the absorbed water first reaches the zone of saturation in the aquifer and *indirect* if it first gets to the zone of saturation in some other formation and thence percolates into the aquifer.

The *catchment area* of an aquifer comprises its intake area and all areas that contribute surface water to the intake area. For example, the intake area of an aquifer may be only a narrow belt along the edge of a mountain range where the aquifer crops out, but its catchment area may include the entire group of mountainous drainage basins that discharge into or across this belt. In the region shown in figure 18 the catchment area consists of the intake area and the mountain area tributary to it.

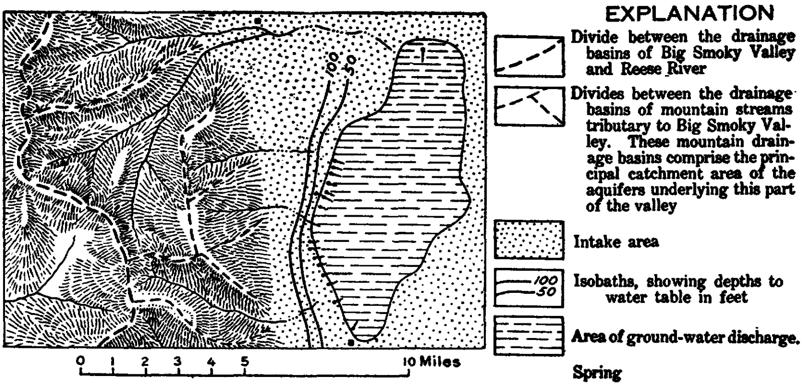

FIGURE 18.—Map of a part of Big Smoky Valley, Nev., and tributary mountain area, showing intske and discharge of ground water.

The intake from a catchment area can be expressed as the depth of a level layer of water having the same horizontal extent as the catchment area and equivalent in volume to the quantity which it supplies to the zone of saturation. This method of expression is

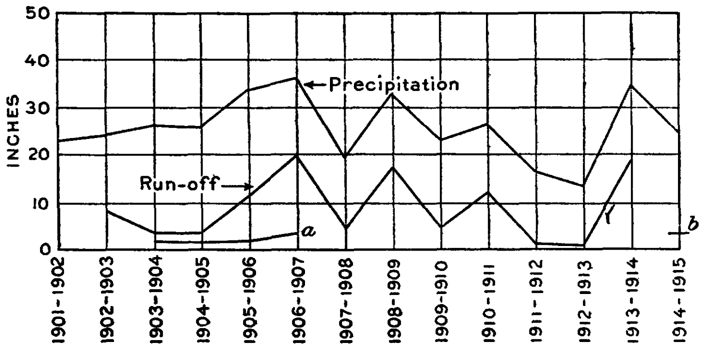

FIGURE 19.—Diagram showing precipitation on mountainous area of drainage basin of Coyote River, Calif., also run-off and ground-water recharge from the area, expressed in inches on this area in each year for which records are available. *a*, Ground-water recharge between upper and lower gorges, Santa Clara Valley, based on measured losses in stream flow; *b*, ground-water recharge in Santa Clara Valley, based on measured rise of water table. (After W. O. Clark, Water-Supply Paper 400, fig. 9.)

convenient for comparison of intake from an area with precipitation on the area and with evaporation and run-off from the area. (See fig. 19.) The intake of an aquifer can also be expressed as the depth of a layer of water having the same horizontal extent as the aquifer.

DISCHARGE.

Discharge of subsurface water may be divided into *ground-water discharge*, or *phreatic-water discharge* (discharge of water from the zone of saturation), and *vadose-water discharge* (discharge of soil water not derived from the zone of saturation) (fig. 20).

Ground-water discharge may be divided into hydraulic discharge and evaporation discharge.

Hydraulic discharge of ground water is discharge of water in the liquid state directly from the zone of saturation upon the land or into a body of surface water. Hydraulic discharge may be divided into discharge through springs and discharge through wells, infiltration ditches, and infiltration tunnels. A *spring* is a place where, without the agency of man, water flows from a rock or soil upon the land or into a body of surface water. Definitions of *well*, *infiltration ditch*, and *infiltration tunnel* are given on page 60.

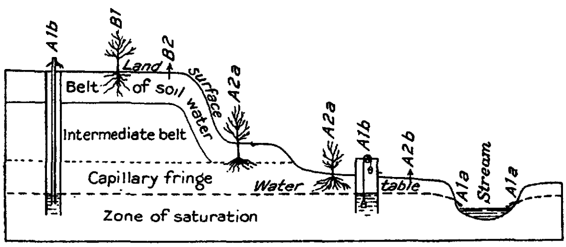

FIGURE 20.—Diagrammatic section showing different kinds of discharge of subsurface water. (See table of classification.) A, Ground-water or phreatic-water discharge: A1a, spring; A1b, well; A2a, phreatophyte; A2b, soil which is acting like the wick of a lamp in drawing water from the zone of saturation. B, Vadose-water discharge: B1, ordinary plant, the roots of which do not extend to the capillary fringe: B2, soil above the capillary fringe, which is losing moisture by evaporation.

Evaporation discharge of ground water is discharge into the atmosphere, in the gaseous state, of water derived from the zone of saturation. Evaporation discharge may be divided into vegetal discharge and soil discharge.

Vegetal discharge of ground water is discharge through the physiologic functioning of plants. The water may be taken into the roots of the plants directly from the zone of saturation or from the capillary fringe, which in turn is supplied from the zone of saturation. It is discharged from the plants by the process of *transpiration*. The depths from which plants will lift ground water vary greatly with different plant species and with different soils and conditions of water supply. Investigations show that certain kinds of plants will lift ground water from depths as great as 50 feet.

Soil discharge of ground water is discharge through evaporation directly from the soil or rocks. The water is, for the most part, lifted by capillarity from the zone of saturation nearly to the surface, where evaporation takes place. Obviously discharge of this kind can occur only where the water table is close to the surface.

The distinction between discharge through springs and evaporation discharge is entirely definite. A spring, however small it may be, if protected from evaporation and absorption by plants, will form a body of surface water. On the other hand, vegetal and soil discharge can be accomplished only by evaporation, and hence they can never produce surface water. Although vegetal and soil discharge of ground water are quantitatively important they have received less attention than discharge by springs because they are less conspicuous, and they do not, like springs, produce water supplies that can be utilized for human consumption. Considered in its economic bearing, ground water disposed of by soil discharge is wasted, and that disposed of by vegetal discharge produces plants that may be of little or no value or may be of considerable value. In arid regions, where it is desired to make maximum use of the supply of ground water, the effort is often made to reduce vegetal and soil discharge of the ground water to a minimum, in order to have as large a supply as possible available for recovery through wells.

Vadose discharge of subsurface water is all accomplished by evaporation. It consists of vegetal discharge and soil discharge. In agriculture, especially in arid regions, it is desirable to reduce soil discharge to a minimum and to raise the kinds of crops that will yield the largest financial returns per unit quantity of water given off by transpiration.

The classification of different kinds of discharge of subsurface water is summarized in the following table:

Classification of discharge of subsurface water.

A. Ground-water or phreatic-water discharge:
  1. Hydraulic discharge:
    a. Discharge through springs.
    b. Discharge through wells, infiltration ditches, and infiltration tunnels.
  2. Evaporation discharge:
    a. Vegetal discharge.
    b. Soil discharge.

B. Vadose-water discharge:
  1. Vegetal discharge.
  2. Soil discharge.

The extent to which subsurface water can be discharged by the several agencies and processes of discharge is shown by the following table:

Summary of agencies and processes for the discharge of subsurface water.

Agency.	Process.	Kinds of water that can be discharged.
Springs, wells, infiltration ditches, and infiltration tunnels.	Hydraulic discharge...	Gravity ground water.
Plants....................	Vegetal discharge.....	All water that can be removed by hydraulic discharge. Also the vadose water in excess of that represented by the wilting coefficient. Also some of the water that is not available for growth.
Soil (by direct evaporation).	Soil discharge.........	All water that can be removed by hydraulic and vegetal discharge. Also all other water except the hygroscopic water that is in equilibrium with the atmospheric water vapor.

Springs may be divided into different classes on the basis of various characteristics, among which are (1) character of openings through which the water issues, (2) rock structure and resulting force that brings the water to the surface, (3) lithologic character of the aquifer, (4) geologic horizon of the aquifer, (5) "sphere" into which the water is discharged, (6) quantity of water discharged, (7) uniformity in the rate of discharge, (8) permanence of the discharge, (9) quality of the water, (10) temperature of the water, and (11) features produced by the springs or otherwise related to them.

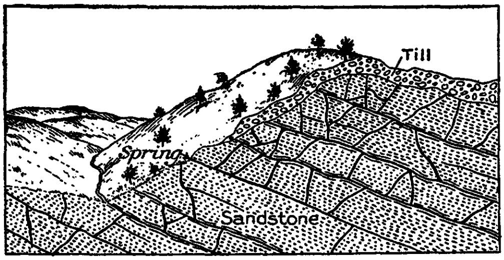

FIGURE 21.—Diagrammatic section showing a fracture spring. (After H. E. Gregory, U. S. Geol. Survey Water-Supply Paper 232, fig. 22.)

With respect to the character of the openings through which the water issues, springs may be divided into three general classes—seepage or filtration springs, fracture springs, and tubular springs. A *seepage spring*, or *filtration spring*, is one whose water percolates from numerous small openings in permeable material. Many of these springs have a very small discharge, but others yield freely. The term *seepage spring* is often limited to springs with small discharge; the term *filtration spring* may be applied without limitation as to yield. Any considerable area in which water is seeping to the surface is called a *seepage area.*

Fracture springs and *tubular springs* are springs whose water flows from relatively large openings in rocks. The term *fracture spring* is used where the opening or openings consist of joints or other fractures (fig. 21). The openings in these springs are more or less sheetlike. Springs issuing from large fissures may be called *fissure springs.* Springs issuing from joints may be called *joint springs.* The term *tubular springs* is used where the opening or openings consist of more or less rounded channels, such as solution passages in limestone or gypsum (fig. 22) or natural tunnels in basaltic lava. All these different types of springs grade into one another.

With respect to the rock structure and the resulting force by which the water is discharged, springs may be divided, at least theoretically, into springs whose water is brought to the surface through pressure produced by gravity acting on the water, and springs whose water is brought to the surface through pressure produced by other, more obscure agencies that are operative deep within the earth.

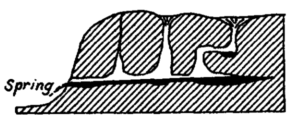

FIGURE 22.—Diagrammatic section showing a tubular spring caused by the discharge of a subterranean stream from a system of solution openings.

Springs due to pressure produced by gravity may be divided into gravity springs and artesian springs.

A *gravity spring* is one whose water does not issue under artesian pressure but which is due to an outcrop of the water table. The water of such a spring percolates from permeable material or flows from large openings in a rock formation, under the action of gravity, as a surface stream flows down its channel (figs. 23 and 24).

An *artesian spring* is one whose water issues under artesian pressure, generally through some fissure or other opening in the confining bed that overlies the aquifer (fig. 25). Such springs, by definition, occur only in areas of artesian flow, where the piezometric surface is above the land surface.

Gravity springs may be divided into depression springs, contact springs, and fracture and tubular gravity springs with openings so large that the distinction as to the presence or absence of an effective contact rock can not be applied.

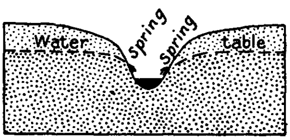

FIGURE 23.—Diagrammatic section showing a depression spring.

A *depression spring* is one whose water flows to the surface from permeable material simply because the surface extends down to the water table (fig. 23).

A *contact spring* is one whose water flows to the surface from permeable material over the outcrop of less permeable or impermeable material that retards or prevents the downward percolation of the ground water and thus deflects it to the surface (figs. 10 and 24). Contact springs may be subdivided according to the character of the features that bring the water to the surface.

The water that is presumably brought to the surface through pressure produced by obscure agencies that are operative deep within the earth is probably largely of internal origin. The springs that yield this water are generally thermal (p. 54) and discharge at nearly uniform rates, without great seasonal fluctuations. Many of them occur along faults or other structural features that may allow water to rise from great depths. High temperature, uniform discharge, and structure that may allow water to rise are, however, also characteristic of artesian springs. Absence of any structural feature that could lead the water from the surface to the necessary depth and under sufficient head to return it to the surface is regarded as evidence that the spring is not an artesian spring but belongs to this class. Springs of this class may be divided into those associated with volcanism and those due to fractures that extend deep into the earth in localities not affected by volcanism.

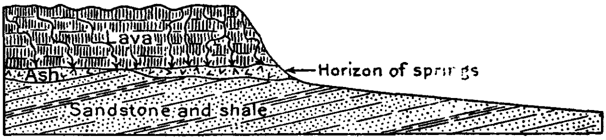

FIGURE 24.—Diagrammatic section showing a contact spring.

The classification of springs with respect to the rock structure and resulting force by which the water is discharged is summarized in the following table:

Classification of springs with respect to rock structure.

A. Springs due to pressure produced by gravity acting on the water:
   1. Gravity springs:
      a. Depression springs.
      b. Contact springs.
      c. Fracture and tubular springs with openings so large that the criterion as to contact is not applicable.
   2. Artesian springs.

B. Springs due to pressure produced by obscure agencies that are operative deep within the earth:
   1. Springs associated with volcanism.
   2. Springs associated with fractures that extend deep into the earth.

With respect to the lithologic character of the aquifer that yields the water, springs may be divided into various classes—for example, limestone springs, sandstone springs, quartzite springs, and lava springs.

With respect to the geologic horizon of the aquifer that yields the water, springs may be divided into various classes—for example, St. Peter sandstone springs and Knox dolomite springs.

With respect to the "sphere" into which the water is discharged, springs may be divided into subaerial springs and subaqueous springs.

With respect to quantity of water discharged, springs are sometimes divided into strong springs and weak springs, or into large springs and small springs. However, these terms are used in a relative sense without any recognized quantitative limits. As the rate of discharge of different springs ranges from a small fraction of a gallon a minute to hundreds of thousands of gallons a minute, it is obvious that so simple a scheme of classification is inadequate. The most consistent and universally applicable classification would be one based on a decimal scale and on the metric system, as shown in the first table below. However, for practical purposes in the United States the classification shown in the second table may be more useful. In the United States there are about 10 springs of the first magnitude according to the first classification, and about 50 according to the second classification. Under either scheme the designation of a spring may refer to the average discharge of the spring or to its discharge at a specified date.

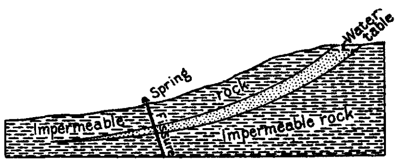

FIGURE 25.—Diagrammatic section showing an artesian spring.

Classification of springs with respect to discharge.

1. Classification based on the metric system.

Magnitude.	Discharge in metric or C. G. S. units.	Discharge in English units (approximate).
First	10 cubic meters per second or more	353 second-feet (cubic feet per second) or more.
Second	1 to 10 cubic meters per second	35 to 353 second-feet.
Third	0.1 to 1 cubic meter per second (100 to 1,000 liters per second.	3.5 to 35 second-feet.
Fourth	10 to 100 liters per second	158 gallons per minute to 3.5 second-feet.
Fifth	1 to 10 liters per second	16 to 158 gallons per minute.
Sixth	0.1 to 1 liter per second (100 to 1,000 cubic centimeters per second).	1.6 to 16 gallons per minute.
Seventh	10 to 100 cubic centimeters per second	1.25 pints to 1.6 gallons per minute.
Eighth	Less than 10 cubic centimeters per second	Less than 1.25 pints per minute.

2. Classification suggested for practical use in the United States.

Magnitude.	Discharge.
First	100 second-feet or more.
Second	10 to 100 second-feet.
Third	1 to 10 second-feet.
Fourth	100 gallons per minute to 1 second-foot (448.8 gallons per minute).
Fifth	10 to 100 gallons per minute.
Sixth	1 to 10 gallons per minute.
Seventh	1 pint to 1 gallon per minute.
Eighth	Less than 1 pint per minute (less than 180 gallons or about 5 barrels a day).

With respect to variability of discharge, springs may be divided into constant, subvariable, and variable springs.

The *variability* of a spring may be quantitatively stated as the ratio of its fluctuation to its average discharge. Thus, it can be expressed by the formula $V=100\left(\frac{a-b}{c}\right)$, where V is the variability (in percentage), a is the maximum discharge, b is the minimum discharge, and c is the average discharge. Obviously the variability as calculated from existing records of discharge will tend to be less than the actual or absolute variability. If only a few measurements have been made, the calculated variability may be so much too small that it entirely misrepresents the spring. Therefore no statement as to the variability of a spring is usually reliable unless many measurements of its flow have been made in different years and in different seasons or unless a gaging station has been maintained at the spring for a period of a few years. It is, however, permissible to speak of the variability of a spring within a designated period.

From the variability as expressed by the formula, a *constant spring* may be defined as one having a variability of not more than 25 per cent, a *subvariable spring* as one having a variability of more than 25 but not more than 100 per cent, and a *variable spring* as one having a variability of more than 100 per cent.

With respect to permanence of discharge, springs may be divided into *perennial springs* (springs that discharge continuously) and *intermittent springs* (springs that discharge only during certain periods but at other times are dry or do not exist as springs). All intermittent springs are variable, but perennial springs may be constant, subvariable, or variable.

A *geyser* may be regarded as a special kind of intermittent spring in which the discharge is caused at more or less regular and frequent intervals by the expansive force of highly heated steam.

A *periodic spring* is a special kind of spring which has periods of relatively great discharge at more or less regular and frequent intervals. Periodic springs resemble geysers somewhat in their rhythmic action but are due to an entirely different cause. All or nearly all occur in regions underlain by limestone, and their rhythmic action has been supposed to be due to natural siphons in the rock. Periodic springs may be perennial or intermittent.

Springs have been divided according to various more or less elaborate systems of classification based on the quality of the water which they yield. Special interest in classification on this basis is due to widespread popular interest in the supposed therapeutic value of certain spring waters.

With respect to the temperature of the water, springs may be divided into thermal springs and nonthermal springs. A *thermal spring* is one whose water has a temperature appreciably above the mean annual temperature of the atmosphere in the vicinity of the spring.

Thermal springs may be divided into hot springs and warm springs. A *hot spring* may be regarded as one whose water has a higher temperature than that of the human body—that is, higher than about 98° F. A *warm spring* may be regarded as a thermal spring whose water has a lower temperature than that of the human body.

Nonthermal springs may be divided into (1) those whose waters have temperatures approximating the mean annual temperatures of the atmosphere in the localities in which they exist, and (2) those whose waters are appreciably colder. The term *cold spring* is frequently used as a synonym for *nonthermal spring*, especially in localities where there are also thermal springs. According to the best usage, however, the term *cold spring* is applied only to a nonthermal spring of the second class—that is, to a spring whose water has a temperature appreciably lower than the mean annual temperature of the atmosphere in the vicinity of the spring.

Topographic features that are produced by or otherwise related to certain springs have given rise to distinctive names such as *pool springs* and *mound springs*. Pool springs discharge from deep pools, many of which are probably related to faults. A pool may assume somewhat the shape of a jug because of a peripheral platform that is developed over the water at the surface by vegetation and sediments blown in by the wind. Mound springs may be produced, wholly or in part, by the precipitation of mineral matter from the spring water; or by vegetation and sediments blown in by the wind—a method of growth common in arid regions. A pool spring may in the course of time develop a mound composed of a felt-work of vegetable matter and entrapped sediments built over the pools.

A *phreatophyte* is a plant that habitually obtains its water supply from the zone of saturation, either directly or through the capillary fringe (fig. 20). Although the distinction between phreatophytes and other plant species is not entirely definite, it is known that in arid regions the phreatophytes form a fairly definite group. After further investigation it may be possible to separate phreatophytes into groups, such as *halo-phreatophytes*, which are alkali-resistant, *xero-phreatophytes*, which are able to resist drought when necessary, and *meso-phreatophytes*, which do not have these special properties.

An *area of ground-water discharge* is one in which ground water is discharged either through springs or through evaporation from plants or soils. Such areas in arid regions can be shown on maps with considerable accuracy, but in humid regions distinction is less practicable. (See fig. 18.)

Evaporation discharge from a given area can be expressed in volume of liquid water (generally in gallons or acre-feet). It can also be expressed in depth of water removed, generally in inches or centimeters. (See definitions relating to evaporation, pp. 13–14.)

The term *safe yield* is employed to designate the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible. It can be expressed in gallons or acre-feet per day or year or in second-feet (cubic feet per second). In some places it is practicable to determine the safe yield per unit of area of the land surface above the productive aquifer.

SURFACE WATER IN RELATION TO ABSORPTION AND DISCHARGE.

With respect to intake and discharge of ground water, streams or parts of streams may be divided into influent streams, effluent streams, and insulated streams. (See fig. 26.)

A stream or stretch of a stream is *influent* with respect to ground water if it contributes water to the zone of saturation. The upper surface of such a stream stands higher than the water table or other piezometric surface of the aquifer to which it contributes.

A stream or stretch of a stream is *effluent* with respect to ground water if it receives water from the zone of saturation. The upper surface of such a stream stands lower than the water table or other piezometric surface of the aquifer from which it receives water.

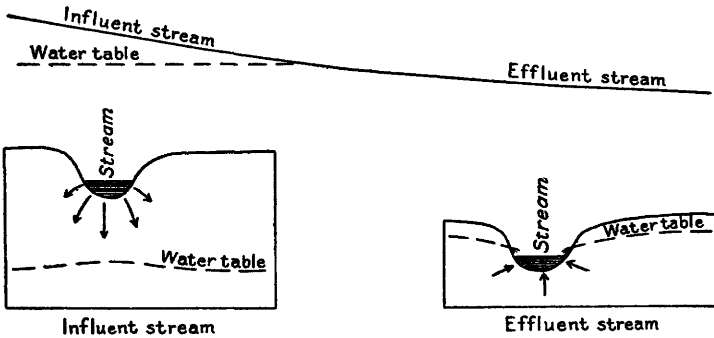

FIGURE 26.—Diagrammatic sections showing influent and effluent streams.

A stream or stretch of a stream is *insulated* with respect to ground water if it neither contributes water to the zone of saturation nor receives water from it. It is separated from the zone of saturation by an impermeable bed.

A stream may in certain parts be influent, in others effluent, and in still others insulated. Moreover, at the same point it may be alternately influent and effluent because of fluctuations in the surface of the stream or in the water table. Influent and effluent streams are sometimes simply called *losing* and *gaining* streams, respectively.

The *evaporation area* of a stream is an area consisting of the surface of the stream itself and a wetted belt on each side through which water supplied by the stream passes into the atmosphere. Evaporation discharge from the stream takes place by evaporation from the water surface, by evaporation from the adjacent moist soil, and by transpiration of plants whose roots absorb water derived from the stream. The term evaporation area has application chiefly to influent streams in arid regions (fig. 27).

The loss of water from an influent stream may be divided into discharge into the atmosphere and discharge into the lithosphere (absorption). The absorption is generally accomplished chiefly by seepage and is frequently called seepage.

The water absorbed from a stream may be divided into water that does not reach the zone of saturation and water that contributes to ground-water recharge. The former may be the larger part in streams that flow only a short time after rains; the latter is likely to be the larger part in influent streams that flow continuously or during long periods.

The rate of total discharge of water from a given part of a stream and the rates of discharge into the atmosphere, lithosphere, and zone of saturation may be expressed in units of discharge per unit length of stream (generally second-feet per mile). The rates of discharge into the lithosphere and zone of saturation may also be expressed in units of discharge per unit of seepage area.

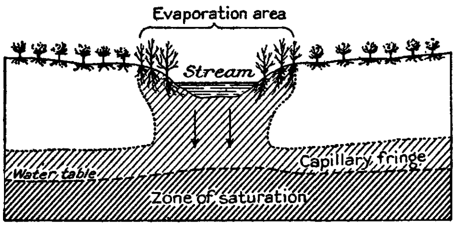

FIGURE 27.—Diagrammatic section showing evaporation area of an influent stream in an arid region. Arrows show percolation of water from the stream to the zone of saturation. Light shading shows parts that receive water by capillary migration from the stream, from the zone of saturation (proper), or from the gravity water on the way from the stream to the zone of saturation (which produces, in a sense, an irregular extension of the zone of saturation). The plants in the evaporation area of the stream are supplied by water from the stream; those outside of this area depend on the local rain for their meager water supply.

The term *perched* may be applied to streams in the same way as it is applied to ground water. Thus a perched stream, or stretch of a stream, is either an influent or an insulated stream that is separated from the underlying ground water by a zone of aeration.

With respect to permanence, streams may be divided into perennial streams, intermittent streams, and ephemeral streams. (See fig. 28.)

A *perennial stream*, or stretch of a stream, is one which flows continuously. Perennial streams are generally fed in part by springs, and their upper surfaces generally stand lower than the water table in the localities through which they flow.

Intermittent streams may be divided, with respect to the source of their water, into spring-fed intermittent streams and surface-fed intermittent streams.

A *spring-fed intermittent stream*, or stretch of a stream, is one that flows only at certain times when it receives water from springs. The intermittent character of streams of this type is generally due to fluctuations of the water table whereby the stream channels stand a part of the time below and a part of the time above the water table. This is the ordinary type of intermittent stream.

A *surface-fed intermittent stream*, or stretch of a stream, is one that flows during protracted periods when it receives water from some surface source, generally the gradual and long-continued melting of snow in a mountainous or other cold tributary area. The term may be arbitrarily restricted to streams or stretches of streams that flow continuously during periods of at least one month.

An *ephemeral stream*, or stretch of a stream, is one that flows only in direct response to precipitation. It receives no water from springs and no long-continued supply from melting snow or other surface source. Its stream channel is at all times above the water

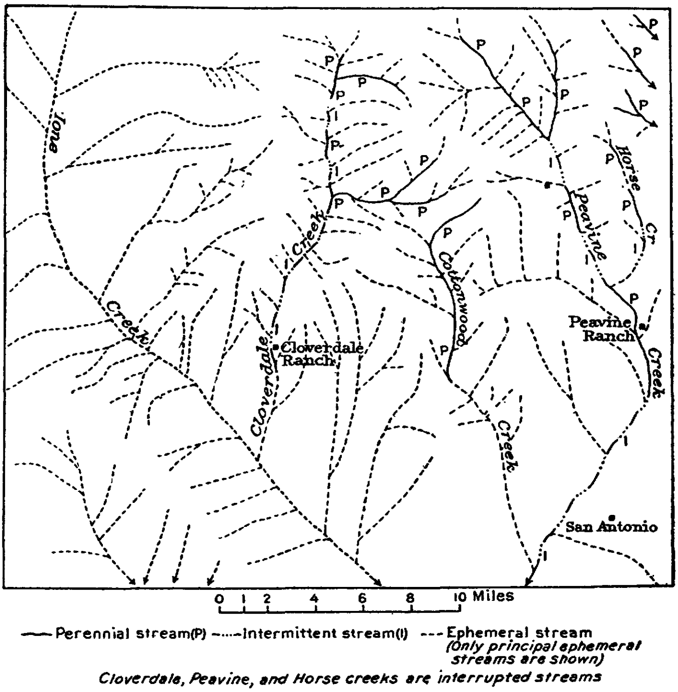

FIGURE 28.—Map of a part of Tonopah quadrangle, Nev., showing perennial, intermittent, and ephemeral streams. (After J. E. Blackburn, topographer. U. S. Geological Survey topographic map.)

table. The term may be arbitrarily restricted to streams or stretches of streams that do not flow continuously during periods of as much as one month.

With respect to continuity in space, streams may be divided into continuous streams and interrupted streams. An *interrupted stream* is one which contains (*a*) perennial stretches with intervening intermittent or ephemeral stretches or (*b*) intermittent stretches with intervening ephemeral stretches. These two classes of interrupted streams are designated, respectively, *perennial interrupted streams* and *intermittent interrupted streams*. A *continuous stream* is one that does not have interruptions in space. It may be perennial, intermittent, or ephemeral, but it does not habitually have wet and dry stretches. (See figs. 28 and 29.)

Run-off consists of two components—direct run-off and ground-water run-off. *Direct run-off* is that part of the run-off which consists of water that has not passed beneath the surface since it was last precipitated out of the atmosphere. *Ground-water run-off* is that part of the run-off which consists of water that since its last precipitation has existed as ground water.

Ground-water run-off may be regarded somewhat arbitrarily as consisting of two components—*permanent* and *temporary*. At the lowest stage of a stream the run-off is generally all or nearly all derived from ground water, and at this stage the ground-water contribution to the stream is generally the least. Therefore, in general, the permanent ground-water run-off is represented approximately by the minimum rate of discharge of surface water.

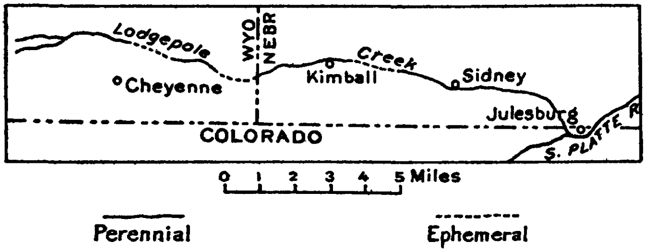

FIGURE 29.—Map of Lodgepole Creek, an interrupted stream with four perennial and three ephemeral stretches.

Certain terms can be applied to lakes, ponds, and other bodies of impounded surface water with meanings somewhat analogous to those of similar terms applied to streams. Lakes and ponds are influent, effluent, or insulated with respect to ground water in the same sense as streams are. They have evaporation areas. All lose water by evaporation, and many by surface discharge. If they are influent to an aquifer they also lose water by seepage. The rates of evaporation and seepage may be expressed in units of discharge (for example, second-feet), in units of discharge per unit area of the lake or pond (for example, second-feet per square mile), or in depth of water removed from the lake or pond per unit of time (for example, inches or centimeters per day, month, or year). Some lakes and ponds are perched with respect to the ground water beneath them. Lakes and ponds may be classified as perennial, intermittent, and ephemeral; or as permanent (the same as perennial) and temporary (including both intermittent and ephemeral).

WELLS.

GENERAL DEFINITIONS.

A *well*, in strict sense of the term, is an artificial excavation that derives some fluid from the interstices of the rocks or soil which it penetrates, except that the term is not applied to ditches or tunnels that lead ground water to the surface by gravity. It is applied, however, to excavations from which water can be drawn by means of siphons.

Wells may be divided into various classes according to the fluid that is produced—for example, water wells, oil wells, gas wells, and salt wells (producing brine). Water wells are so much the most common and the most important class that unless otherwise specified the term *well* may be understood to denote a water well. A water well necessarily extends into the zone of saturation.

The term *natural well* is used to designate an abrupt depression in the land surface, not made by human agency, which extends into the zone of saturation but from which water does not flow to the surface except by an artificial process. Such a feature is not a well in the strict sense, but the name has become firmly established and can be used without danger of confusion. Most ponds, swamps, lakes, and other bodies of impounded surface water extend into the zone of saturation, but natural wells are distinguished from ordinary features of this class in having smaller water surfaces, being deeper in proportion to their water surfaces, and having steeper sides.

An *infiltration ditch* is an artificial ditch which extends into the zone of saturation and through which water flows by gravity from the zone of saturation to the land surface or into a sump or well. An *infiltration tunnel*, or *infiltration gallery*, is an artificial tunnel with like properties. (See fig. 10.)

The expression *well record* is used in a general sense to denote any concise statement (tabular or otherwise) of the available data regarding a well. A *well log* is a record of the beds of rock that were passed through in sinking the well, listed in the order in which they were penetrated. It generally includes statements as to the thickness, lithologic composition, and water-bearing characteristics of the beds and is, in a sense, a chronologic record of what was found in sinking the well.

The *intake* of a well is the opening or group of openings through which water passes into the well from the water-bearing beds that it penetrates. The intake may also be called the *infiltration area* or *seepage area* of the well. The *mouth* of a well is the orifice at the upper end of the well, generally at or near the surface, through which access is had to the interior of the well.

A *well section* may be a *vertical section* or a *cross section* (a section in a horizontal plane). The *cross-section area* of a well is the area occupied in a cross section by the interior of the well. Most wells have circular cross sections, and the size of such a well is commonly expressed by giving its diameter.

The *drawdown* of a well from which water is being discharged at a given rate is the lowering of the water level or the equivalent reduction in the pressure of the water in the well caused by the withdrawal of water (fig. 30). In a well that discharges by artesian pressure the reduction in pressure can be measured by means of a pressure gage. In a well that is pumped by suction the reduction in pressure can be measured by means of a vacuum gage; this method is applicable especially if the casing is used as the suction pipe. The drawdown is generally expressed in feet or meters.

When the well is at rest there is equilibrium between the pressure of the water outside the well and the pressure of the water inside. The pressure on the inside may be reduced by lowering the water level, by removing the atmospheric pressure in a well pumped by suction, or by relieving the pressure at the mouth of a well that discharges by artesian pressure. When the pressure on the inside is reduced the equilibrium is destroyed, and there is a resultant inward pressure, in consequence of which water flows into the well. It is obvious, therefore, that drawdown is invariably present when a well is yielding water.

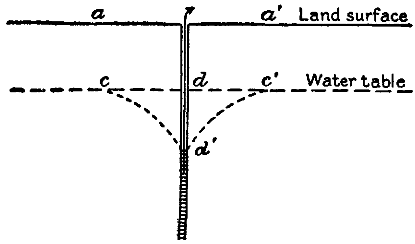

FIGURE 30.—Diagrammatic section of a well that is being pumped, showing its drawdown (*dd'*), cone of influence (*cc'd'*), and area of influence (*aa'*).

The *area of influence* of a well from which water is being discharged at a given rate is the land area that has the same horizontal extent as the part of the water table or other piezometric surface that is perceptibly lowered by the withdrawal of the water (fig. 30). The area of influence for a given rate of discharge may vary with the period of withdrawal and with the rate of recharge.

The *cone of influence* of a well from which water is being discharged at a given rate is the depression produced in the water table or other piezometric surface by the withdrawal of the water (fig. 30). If the aquifer is nearly uniform in shape and texture in the vicinity of the well this depression has somewhat the form of an inverted cone whose apex is at the water level in the well while discharge is in progress, whose height is equal to the drawdown, and whose base is the original water table or other piezometric surface within the area of influence.

The discharge of a well is almost invariably produced either by artesian pressure or by the operation of a pump or other lifting device. (See pp. 66–67.) The term *artesian discharge* is used to designate the process of discharge from a well by artesian pressure, and also the quantity of water thus discharged. In some wells the artesian pressure is aided by the buoyancy of natural gas that enters the well with the water. The term *pumpage* is used to designate the quantity of water withdrawn from a well by means of a pump.

The *capacity* of a well is the rate at which it will yield water. It can be expressed in gallons per minute, in second-feet (cubic feet per second), or in other units. Four kinds of capacity are recognized—total capacity, tested capacity, artesian capacity, and specific capacity.

The *total capacity* of a well is the maximum rate at which it will yield water by pumping after the water stored in the well has been removed. It is the rate of yield when the water level in the well is drawn down to the intake.

The *tested capacity* of a well is the maximum rate at which it is known to have yielded water without appreciable increase in drawdown. If the well has been tested with the water level drawn down to the intake—that is, by pumping all that the well will yield—the tested capacity is the total capacity. It is, however, seldom practicable to pump a well of large capacity at a sufficiently rapid rate to draw its water level down to its intake.

The *artesian capacity* of a well is the rate at which it will yield water at the surface as a result of artesian pressure.

The *specific capacity* of a well is its rate of yield per unit of drawdown. The term is applied only to wells in which the drawdown varies approximately as the yield. In such wells the specific capacity can be estimated by dividing the tested capacity by the drawdown during the test. Thus, if in such a well the yield is 250 gallons a minute and the drawdown is 10 feet, the specific capacity can be stated as 25 gallons a minute for each foot of drawdown, or, if the units involved are known, it is sufficient to say that the specific capacity is 25.

A well will always yield water at a greater rate immediately after a period of rest than after there has been continuous discharge for some time. This increase in yield is due to the accumulation of water in or near the well during the period of rest. After the accumulated water has been disposed of, the rate at which water enters the well is nearly equal to the rate at which it is discharged (provided the forces that produce discharge remain uniform), although there may be a small persistent difference that will result in a gradual decrease or increase in capacity. Therefore, any accurate statement of capacity must be based on observations made after both the rate of discharge and the drawdown have become nearly constant. Moreover, on account of the gradual changes that may be developed by protracted discharge, the statement, to be entirely reliable, must give the results of several observations made at stated intervals during a considerable period of relatively stable conditions.

Interference of two or more wells occurs when their cones of influence come into contact with one another, thereby decreasing the specific capacities of the wells (fig. 31).

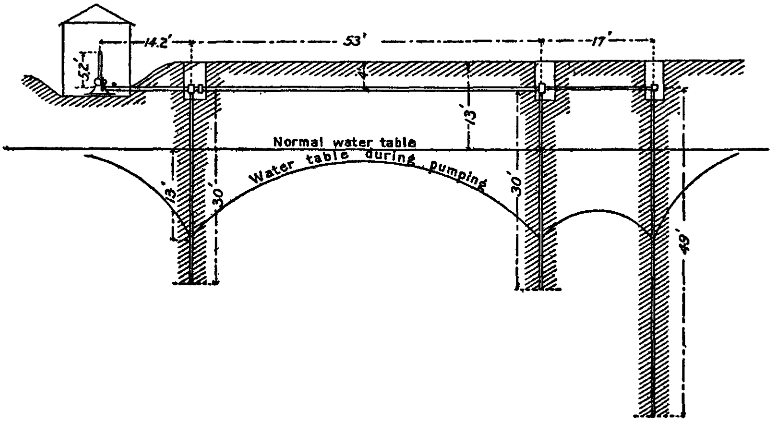

FIGURE 31.—Section showing interference of wells in a pumping plant near El Paso, Tex. (After C. S. Slichter, U. S. Geol. Survey Water-Supply Paper 141, fig. 12.)

CLASSIFICATION.

Wells may be divided into various classes according to any of the following characteristics: Method of sinking, method of finishing or developing, shape of cross section, size of cross section, depth, character of the bed that yields the water, geologic horizon of the bed that yields the water, capacity, head of the water, quality of the water, direction in which the water is moved, and grouping of wells.

With respect to the method of sinking, wells may be divided into dug wells, bored wells, drilled wells, and driven wells.

A *dug well* is one that is excavated by means of picks, shovels, and spades or by means of a steam shovel or other dredging or trenching machinery. Dug wells are generally more than 2 feet in diameter or width.

A *bored well* is one that is excavated by means of a hand or power auger, the material being brought up, for the most part, by the auger. This term is frequently used, especially in England and Australia, to designate various kinds of drilled wells, but much ambiguity will be avoided if it is used in the restricted sense as here defined, which conforms to the most common American usage. Bored wells are generally between 1 and 36 inches in diameter.

A *drilled well* is one that is excavated wholly or in part by means of a drill, either percussion or rotary, which operates either by cutting or by abrasion, and in which the materials are brought up by means of a bailer, sand pump, or hollow drill-tool, or by a hydraulic or self cleaning method. Drilled wells are generally between 1 and 24 inches in diameter. The principal drilling methods are outlined in the following table and are described in Water-Supply Paper 257.[1]

Outline of principal methods of drilling.

[Asterisk (*) indicates methods most largely used at present.]

A. Percussion methods:
- 1. Drillings removed with bailer:
  - *a.* Standard cable (or solid-tool) method.*
  - *b.* Portable cable (or solid-tool) method.*
  - c. Pole-tool method.
- 2. Drillings forced continuously upward through hollow drill rods—self-cleaning method.
- 3. Drillings held in hollow drill tool, which is periodically withdrawn:
  - *a.* Mud-scow (or California) method.*
  - *b.* Punching method.
  - *c.* Core-drill method.

B. Abrasion methods (diamond, calyx, chilled-shot, etc.)

C. Hydraulic methods:
- 1. Jetting (or hydraulic percussion) method.*
- 2. Hydraulic rotary method.*

A *driven well* is one that is constructed by driving a casing at the end of which there is a drive point, without the aid of any drilling, boring, or jetting device (fig. 32). The term is not properly applied to drilled wells. Driven wells are generally between 1 and 3 inches in diameter.

With respect to the method of finishing, wells may be divided into cased wells, uncased wells, and partly cased wells.

Cased wells and partly cased wells may be divided, according to the material and construction of the casing, into various groups—for example, wells with heavy iron (or steel) "casing" or "pipe," sheet-iron (or steel) casing, double stovepipe casing, board or plank casing, log casing, brick casing, stone casing, cement casing, and burnt-tile casing.

Cased wells may be divided, with respect to the character of their intakes, or openings through which the water enters, into at least three classes—open-end wells, screened wells, and perforated-casing wells. An *open-end well* is one into which the water enters only at the lower end of the casing, near the bottom of the well, this end being left unobstructed by a screen or other device. A *screened well* is one into which the water enters through one or more screens other than perforated casing. A *perforated-casing* well is one into which the water enters through holes in the casing. The name is most commonly applied to wells cased with iron or steel or with boards or cement, but it is applicable to wells with casings of other types.

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[1] Bowman, Isaiah, Well-drilling methods: U. S. Geol. Survey Water-Supply Paper 257, 1911.

Cased wells may be divided, with respect to the development of their aquifers, into at least three classes—unmodified cased wells, natural-strainer wells, and gravel-wall wells. A *natural-strainer well* is one which taps an aquifer of imperfectly assorted and at least partly incoherent material and whose specific capacity has been increased by the withdrawal of much of the fine-grained part of the material in the immediate vicinity of the well. A *gravel-wall well* is one which taps an aquifer of incoherent material and whose specific capacity has been increased by the introduction of gravel, crushed tile, or other coarse-grained material around the intake of the well. (See fig. 33.)

With respect to the shape of cross section, wells may be divided into various classes, such as circular wells, square wells, and oblong wells. Circular wells form by far the largest class and include all bored, drilled, and driven wells. With respect to diameter, circular wells may be designated by stating the diameter—for example, a 6-inch well.

Wells may also be divided, with respect to diameter or size of opening, into open wells, tubular wells, and combination wells.

An *open well* is one that is large enough to allow a man to enter it and to descend in it to the water level. Wells of this class are generally dug wells 3 feet or more in diameter or width.

A *tubular well* is a circular well that is too small to be entered by a man. Wells of this class are generally less than 2 feet in diameter. They include practically all drilled and driven wells. Bored wells may be rather arbitrarily divided between the two classes according to their diameters. Tubular wells may be arbitrarily divided into large tubular wells (more than 8 inches in diameter at the top), medium tubular wells (more than 3 inches but not more than 8 inches in diameter at the top), and small tubular wells (3 inches or less in diameter at the top).

A *combination well* is one that consists of an open well and one or more other wells or infiltration tunnels that communicate with it.

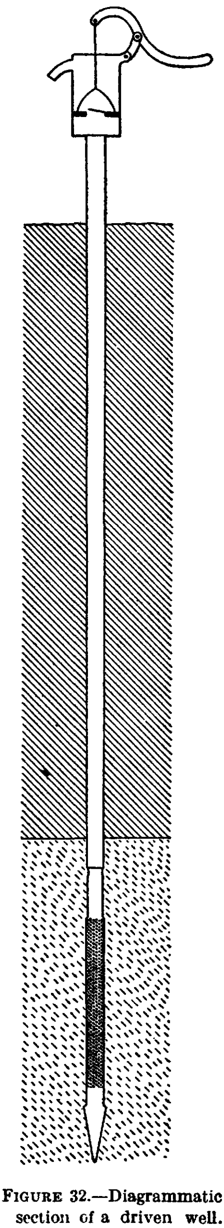

FIGURE 32.—Diagrammatic section of a driven well. (After A. J. Ellis, U. S. Geol. Survey Water-Supply Paper 374, fig. 9.)

With respect to depth, wells are frequently divided into shallow wells and deep wells, but no logical basis has been found for this classification, and it appears to be impracticable to select a delimiting depth that will be generally useful.

With respect to the character of the material that yields the water, wells may be divided into various classes—for example, rock wells, sand wells, and gravel wells. Moreover, rock wells may be subdivided into various groups—for example, sandstone wells, limestone wells, quartzite wells, granite wells, and basalt wells.

With respect to the geologic horizon of the aquifer that yields the water, wells may be divided into various classes—for example, Cretaceous wells, St. Peter sandstone wells, and Niagara limestone wells.

With respect to capacity, wells are frequently divided into strong wells and weak wells. However, no quantitative basis for this classification has been recognized, and there is probably none that would be generally useful.

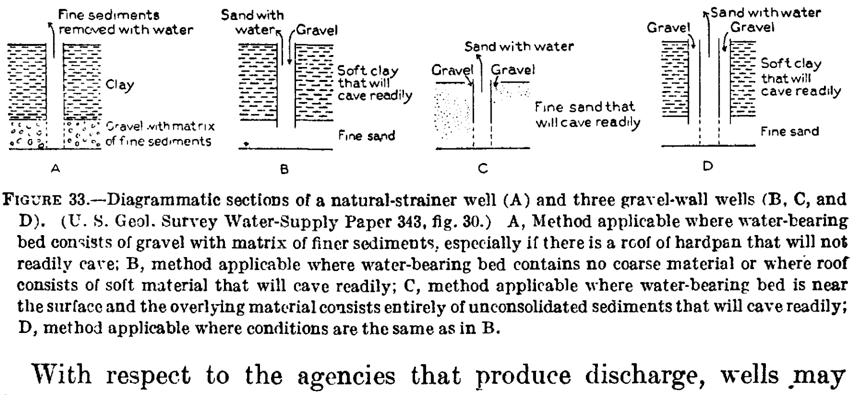

FIGURE 33.—Diagrammatic sections of a natural-strainer well (A) and three gravel-wall wells (B, C, and D). (U. S. Geol. Survey Water-Supply Paper 343, fig. 30.) A, Method applicable where water-bearing bed consists of gravel with matrix of finer sediments, especially if there is a roof of hardpan that will not readily cave; B, method applicable where water-bearing bed contains no coarse material or where roof consists of soft material that will cave readily; C, method applicable where water-bearing bed is near the surface and the overlying material consists entirely of unconsolidated sediments that will cave readily; D, method applicable where conditions are the same as in B.

With respect to the agencies that produce discharge, wells may be divided into flowing wells and nonflowing wells.

A *flowing well* is one that discharges water at the surface without the application of a pump or other lifting device. (See figs. 11 and 13.) Flowing wells may be divided, with respect to the agency that produces the flow, into artesian flowing wells and gas-lift flowing wells. An *artesian flowing well* is one whose water is lifted by hydrostatic pressure above the land surface at the well (without the introduction of gas). A *gas-lift flowing well* is one whose water is not under sufficient hydrostatic pressure to be lifted above the land surface without the introduction of gas but is caused to rise above the surface because of the buoyancy of natural gas mingled with the water. The gas is generally dissolved in the water before it reaches the well, but it passes out of solution when the pressure on the water is reduced in or near the well. *Artesian water power* is the power developed at the mouth of an artesian flowing well by the pressure of the water discharged from the well. Artesian flow may be either perennial or intermittent. Wells that discharge only in rainy seasons or only when the atmospheric pressure is low have intermittent flow.

A *nonflowing well* is one that does not discharge water at the surface except through the operation of a pump or other lifting device. The term *pump well* is often applied to wells of this class. Nonflowing wells may be divided, with respect to the pressure head of the water, into *subartesian wells*, whose water rises by hydrostatic pressure above the zone of saturation but not to the surface, and *nonartesian wells*, whose water does not rise above the zone of saturation. (See figs. 11 and 13.)

With respect to the quality of the water, no complete classification of wells is recognized, and perhaps none is needed except such as logically follows a classification of the water itself. Certain classes, not mutually exclusive and not quantitatively defined, are frequently recognized—for example, soft-water wells, hard-water wells, salt wells (yielding brine), and sulphur wells (yielding hydrogen sulphide).

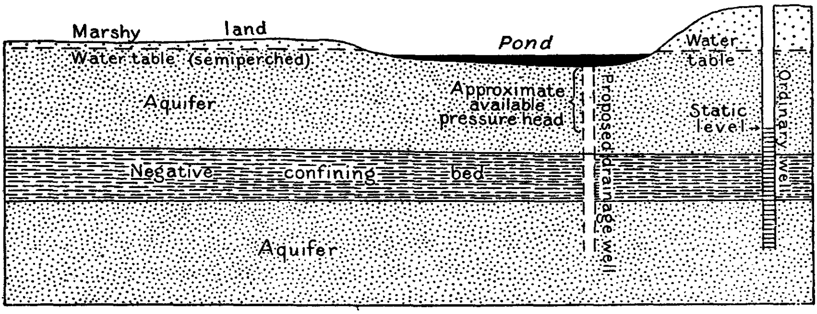

FIGURE 34.—Diagrammatic section showing conditions that will permit drainage of marshy land through inverted wells. Drainage through wells would also be practicable if the marshy land had a perched water table.

An *inverted well* is one in which the movement of water is in the reverse direction of that in ordinary wells, water being admitted at or near the top of the well and discharged into a permeable bed through one or more openings at lower levels. The term is commonly extended to include excavations that discharge into permeable beds even if they do not reach the zone of saturation.

Two kinds of inverted wells may be recognized—*inverted drainage wells* and *recharge wells*. They are alike in construction and operation but differ in purpose, a drainage well being put down for the purpose of draining swampy land or disposing of storm water, sewage, or other waste water at or near the surface (fig. 34), and a recharge well being put down for the purpose of increasing the ground-water supply by conducting surface water into an aquifer (fig. 35). Inverted drainage wells have long been in use in many localities, chiefly for draining swampy land and disposing of water in wet cellars. Recharge wells have recently received attention in connection with plans for conserving the water supply in arid regions. Not all drainage wells are inverted, for drainage is also accomplished by pumping from wells and even by means of flowing wells.

It is possible to drain swampy land by means of an inverted well only where the water-bearing bed that produces the swampy condition is underlain by a zone of aeration or by an aquifer with subnormal pressure head. The *available pressure head* of an inverted well whose lower or discharge openings are in a zone of saturation is the vertical distance between the level at which the water to be drained off is admitted and the water level in the well when the well is not receiving drainage water (figs. 34 and 35). The *available pressure head* of an inverted well whose discharge openings are in a bed that is permeable but not saturated is practically the vertical distance between the level at which the water to be drained off is admitted and the average level of the discharge openings. The available pressure head of an inverted well is functionally the converse of the drawdown of an ordinary well.

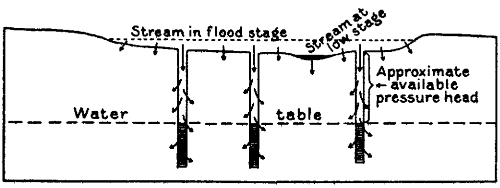

FIGURE 35.—Diagrammatic section showing recharge wells along an influent stream and the manner in which they increase the rate of recharge during flood stages when much water would otherwise run to waste.

The *inverted capacity* of a well is the maximum rate at which it will dispose of water admitted at or near its upper end, by discharge through openings at lower levels. If these lower openings are in a zone of saturation the inverted capacity is approximately the product of the specific capacity multiplied by the available pressure head. The rate of yield of wells is sometimes estimated by drillers by pouring water into them and noting the rate at which the water disappears. In this method the general principle is recognized that the permeability of an aquifer is the same whether it is delivering water to or receiving water from a well.

A *gang* or *battery* of wells is a group of wells from which water is drawn by a single pump or other lifting device. A group of wells that are pumped by compressed air from a common source may be regarded as forming a gang.

A *well field* is a tract of land especially devoted to wells. The term is applied chiefly to tracts that have many wells used for obtaining large public, industrial, or irrigation supplies. The wells of a well field may be arranged in one or more gangs or may be pumped individually.

INDEX OF TERMS.

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