TM 5-296

WAR DEPARTMENT TECHNICAL MANUAL

GROUND WATER SUPPLY FOR MILITARY OPERATIONS

WAR DEPARTMENT • 1 FEBRUARY 1944

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BY ORDER OF THE SECRETARY OF WAR:

G. C. MARSHALL,
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J. A. ULIO,
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(For explanation of symbols see FM 21-6.)

CONTENTS

CHAPTER 1

GENERAL

1. PURPOSE AND SCOPE. This manual presents fundamental information on the occurrence of ground water and on the location of ground-water supplies for military purposes. It covers the occurrence of water in rocks, the relationships between rock structures and ground-water movement, the location of usable water in coastal zones and desert regions, the occurrence of springs, the quality of water to be expected from various sources, and methods of ground-water reconnaissance. In geologic terms, "rocks" include loose deposits of gravel, sand, silt, and clay, as well as consolidated materials such as granite, basalt, and limestone.

2. THE GROUND-WATER PROBLEM. a. Potable water is essential to all military operations. The usual sources of such water are surface waters such as rivers, creeks, lakes, ponds, and reservoirs, or existing municipal supplies. Where these are inadequate or nonexistent, it is necessary to develop other ground-water supplies.

b. Many areas in subhumid, semiarid, and arid regions have insufficient natural surface-water supplies for military operations for at least a part of the year. Areas falling into this category are most of the Great Plains of the United States; parts of southern Europe; most of North Africa; the greater part of Australia; the plains and plateau areas of China; most of Asia Minor; and much of southern South America. In such areas, the use of water of major streams requires construction of large impounding dams.

c. Most land is underlain by one or more rock formations that will yield at least small perennial supplies of water to wells. In some places, the quantity may be too small to justify attempts at recovery; in others, the water may be too highly mineralized for use. Location of an adequate ground-water supply, therefore, requires a knowledge of the principles controlling the occurrence of water in rock formations. In a new area for which geologic information is not available, the first step in developing a ground-water supply is a geologic reconnaissance (see ch. 7).

d. For most regions of the world some general geologic information is available, and for many areas specific ground-water data exists. One source of such information is the Terrain Intelligence Folios of the Strategic Engineering Studies prepared by the Intelligence Branch, Corps of Engineers, U. S. Army. If available, such folios should be studied before any field investigations in a specific area are made.

3. CLASSIFICATION OF UNDERGROUND WATER. Water beneath the surface of the earth occurs in three zones: the *zone of soil moisture* where water temporarily is held in pore spaces by capillarity and other soil conditions; the *zone of aeration*, or zone of percolation, beneath the soil layer where both water and air are present in the pore spaces; and *zone of saturation*, where all spaces are filled with water. These zones are shown in figure 1. The top of the saturated zone is called the "water table." It is not flat, but has a variable depth beneath the surface, depending upon surface topography, rainfall, direction of water movement, rock structure, and porosity. Water in the zone of soil moisture may evaporate directly or through transpiration by plants, or may percolate downward into the zone of aeration and thence to the zone of saturation. Permeable rocks in the zone of saturation yield water to wells, but wells ending in the zone of aeration produce no water.

4. THE HYDROLOGIC CYCLE. a. The series of processes by which water is circulated from the oceans to the atmosphere and thence

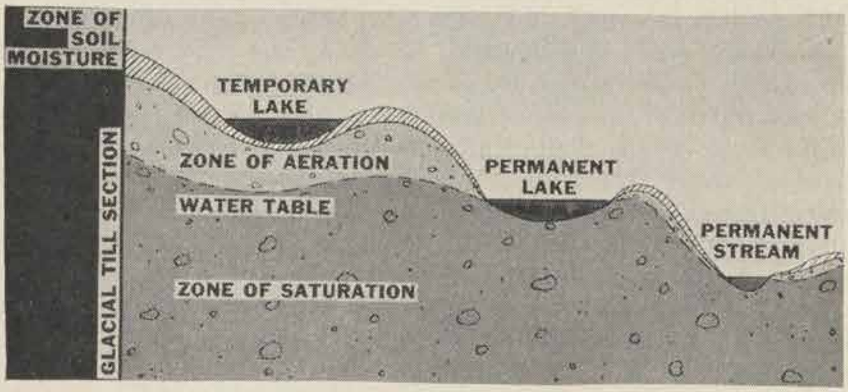


Figure 1. Ground-water and surface-water relationship.

to the surface of the earth and beneath it, is known as the hydrologic cycle (figs. 2 and 3).

b. An understanding of the occurrence of ground water is based on a general knowledge of these processes and their relationships to each

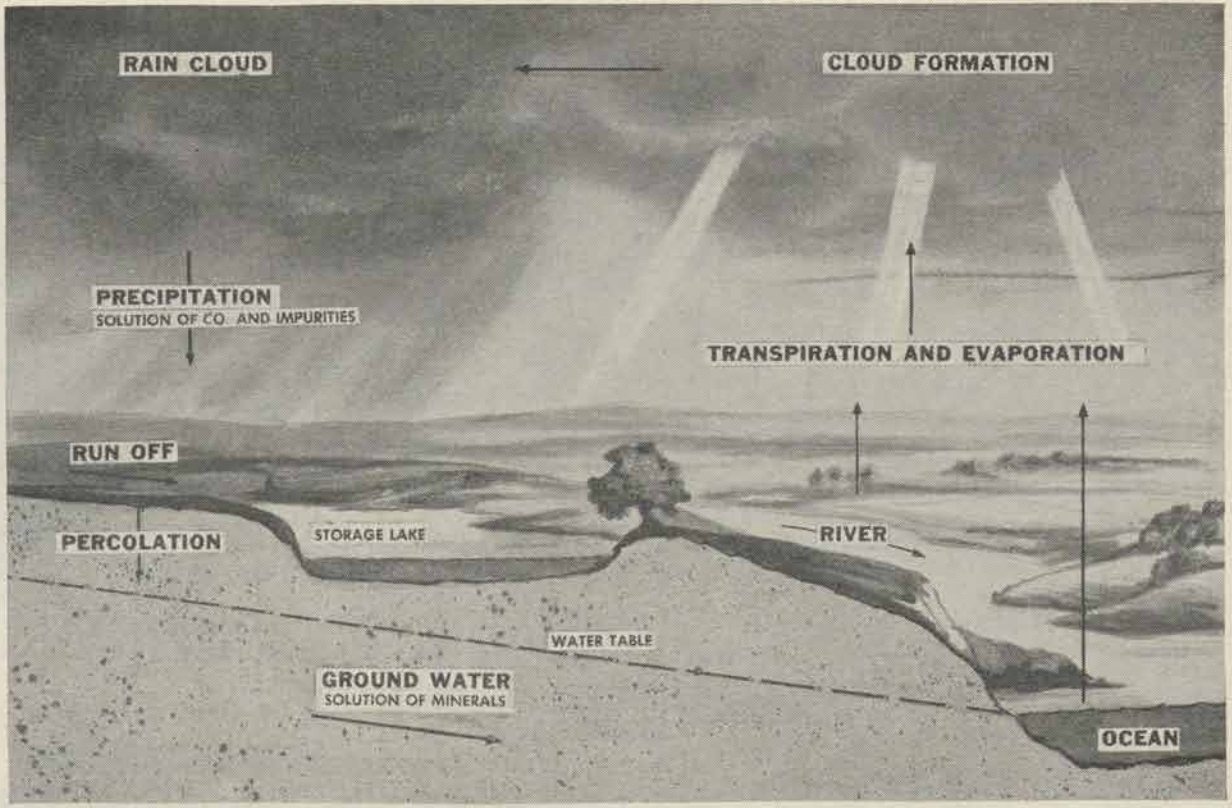


Figure 2. The hydrologic cycle.

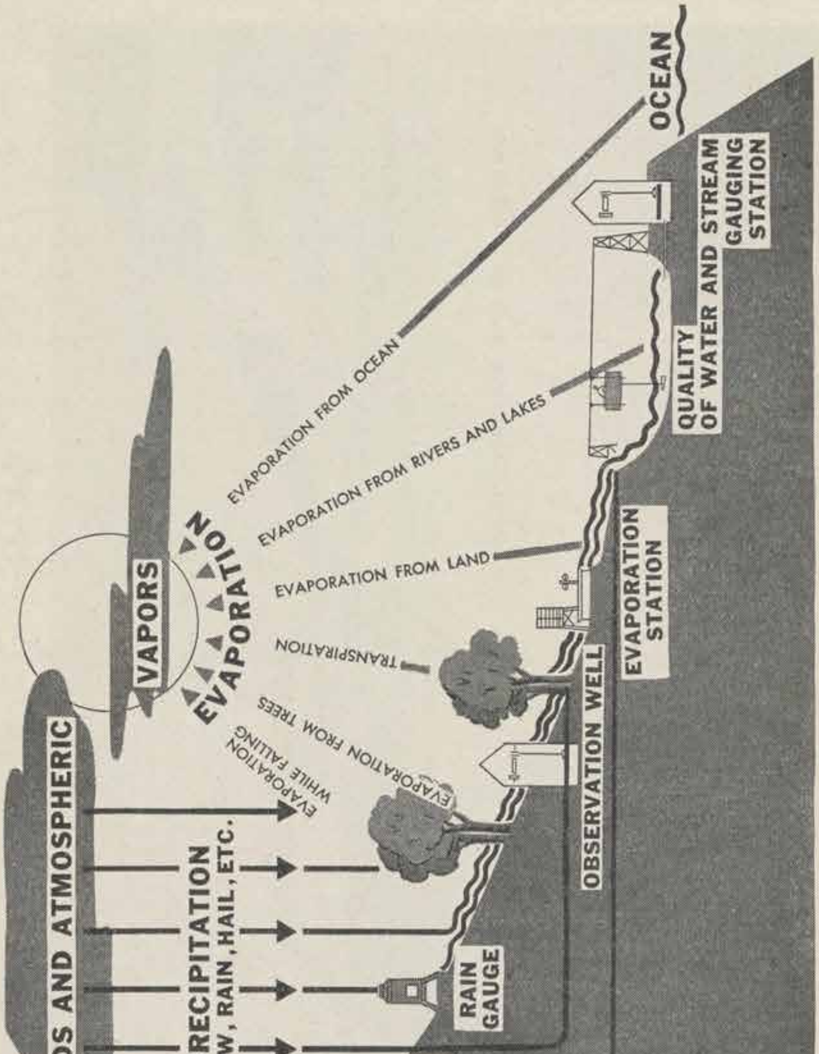


Figure 3. Evaluation of the hydrologic cycle.

other. Basically, the cycle consists of the following processes: evaporation of water from oceans; its condensation to produce cloud formations; precipitation of rain, snow, sleet, or hail upon the land surface; dissipation of the water by direct run-off into lakes and streams, seepage or infiltration of rain water or melted snow into the soil and thence into underlying rock formations and direct evaporation; movement of water through the openings in the rocks; and issue of water at the surface through springs, streams, and lakes. In modern hydrological studies, the quantities and rates of water movement are measured at many points (fig. 3).

c. The cycle usually does not progress through a regular sequence, however, and may be interrupted or short-circuited at any point. Moisture which condenses over the ocean may fall into it as rain. Rain which falls upon a heavily forested area soon may return to the atmosphere by direct evaporation or through transpiration by plants. Jungle-covered islands of the Southwest Pacific are known to produce more evaporation than adjacent areas of ocean. Water which seeps into the soil may be retained for a time by soil capillarity or other means before moving downward through the unsaturated zone to become a part of the ground water.

d. For the purposes of ground-water reconnaissance and development, the relations between the land surface, the unsaturated zone, and the zone of saturation are the most important phases of the hydrologic cycle (fig. 1). Ground water is not static, but moves slowly through pores or other openings in the rock formations. Thus water continuously is moving toward points of discharge and is replenished intermittently by rainfall in intake areas. Rates of water movement are controlled by hydrostatic pressure and permeability. The yield of wells is controlled by hydrostatic pressure, permeability, and thickness of the water-bearing formation.

5. RECOVERY OF GROUND WATER. Ground water is recovered by improving springs or by sinking wells. The development of springs is described in chapter 5. The chief methods of well construction are described in detail in TM 5–297. Purification of water supplies is covered in TM 5–295. Development of water supplies in Arctic and Antarctic areas, where the ground is permanently frozen (perma-frost) requires special procedures which are discussed in Special Report, Strategic Engineering Study No. 62, Intelligence Branch, Office of the Chief of Engineers, March 1943 (prepared by the U. S. Geological Survey).

CHAPTER 2

PRINCIPLES OF GROUND-WATER OCCURRENCE

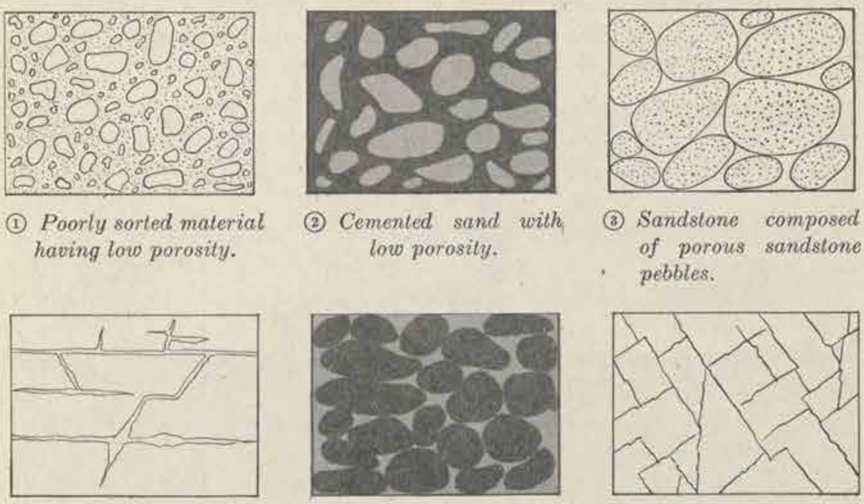
SECTION I

ROCKS AS WATER RESERVOIRS

6. POROSITY OF ROCKS. a. Conditions controlling porosity. The rocks that form the outer part of the earth's crust have many open spaces or voids. These contain the water that occurs below the land surface and which is tapped by springs and wells. The many types of rocks differ greatly in the size, number, and arrangement of their pore spaces and in their ability to contain and yield water. Most rocks have small pore spaces, but some formations have relatively few large openings such as joints (cracks) or caverns. Most rocks have connecting pore spaces which allow water to move from one space to another; but in some, the pore spaces are not connected and this prevents water from percolating from one space to another (see fig. 4). The voids have generally irregular shapes, but different types of rocks have different types of irregularities.

The porosity of a rock is its amount of pore space. Pore spaces or voids range from extremely small sizes to large caverns. Porosity is expressed quantitatively as the percentage of the total volume of the rock occupied by voids. A rock is saturated when all its voids are filled with water; hence, the total volume of water in a saturated rock is practically equal to its porosity.

b. Relation of porosity to arrangement of grains. Deposits of well-sorted, uncemented sand and gravel are highly porous regardless of grain size (fig. 4⑤), but poorly sorted material has a relatively low porosity because smaller grains occupy spaces between the larger ones (fig. 4①). Or, a gravel deposit may be composed of loose pebbles of sandstone or other porous material (fig. 4③), and the aggregate may have very high porosity. Pore spaces in a well-sorted sand or gravel may be filled gradually by deposition of a cementing mineral which reduces the pore space to a small fraction of the original condition (fig. 4②). In contrast, relatively dense rock such as limestone may be made porous by solvent action of circulating water which dissolves it to form cavities and channels (fig. 4④). A hard, brittle rock such as granite, hard limestone, or basalt may be fractured in many places and as a result have considerable water-holding capacity.



① *Poorly sorted material having low porosity.*

② *Cemented sand with low porosity.*

③ *Sandstone composed of porous sandstone pebbles.*

④ *Solution channels in limestone.*

⑤ *Well-sorted sand having high porosity.*

⑥ *Jointed rock (pore space in joints).*

Figure 4. Diagrams showing types of porosity.

7. FORCES CONTROLLING WATER IN ROCKS. The two chief forces that control water in rock formations are gravity and molecular force. Gravity causes water to seep from the surface to rocks deep in the earth and then to travel long distances through sloping or dipping formations. It causes water to issue from springs, to flow into wells, and to accumulate in depressions. If the pore spaces and channels in the rocks are large, the water in them acts according to the ordinary laws of hydraulics; but if the pore spaces are too small, the force of gravity largely is nullified by a counteracting force. This counteracting force is molecular attraction—the attraction of the walls of the small pore spaces for the molecules of water. It is the force which determines whether water may be recovered from a saturated rock. If it is nearly equal to the force of gravity, little or no water can be produced.

8. PERMEABILITY OF ROCKS. The permeability of a rock is its capacity to transmit water under the influence of gravity or hydrostatic pressure. If the water pressure in a permeable rock is equal in all directions, no movement occurs; the system is in equilibrium. If pressure is less in any direction, however, the water moves in that direction. An impermeable rock is one which will not transmit water. Dense, igneous rocks, such as granite or basalt, generally are impermeable. However, water under extremely high pressure may be forced through many substances ordinarily considered impermeable. Permeability, therefore, is a relative term. A coarse gravel which readily allows water to flow through the voids is permeable. Clays

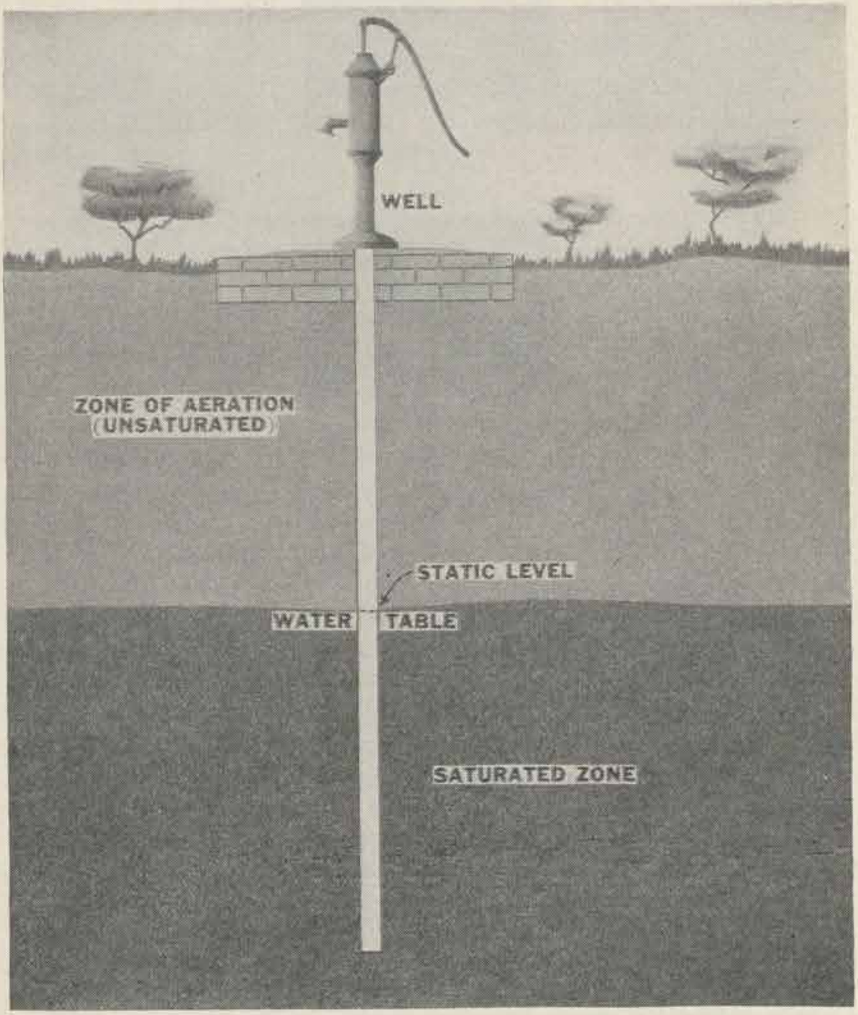


Figure 5. Diagram of well showing relations of static level to water table, zone of aeration, and saturated zone.

and shales which, though saturated, will not transmit water to a well which penetrates them are called impermeable. Various types of rock have infinite gradations between these two extremes. For example, a dense glacial till yields water slowly, but supplies enough water for thousands of small farm wells. Permeable sands in the Gulf Coastal Plain furnish large supplies sufficient for the city of Houston, Texas. After rainfall, the water which infiltrates into the soil moves slowly downward through the zone of aeration, and when it reaches the water table becomes a part of the true ground water. When a well is sunk into the water table in a permeable formation, the level of standing water in the well (static level) is approximately the position of the water table at that point (fig. 5).

9. WATER TABLE. The water table usually is slightly higher under higher land areas than under lower ones. In depressions such as swamps, permanent lakes, and streams, the water table lies above the land surface; the shore lines are lines of contact where the water table passes under the land surface. From the land surface downward to the top of the saturated zone, the rocks contain some moisture, but are not saturated. This is called the "zone of aeration," or "unsaturated zone." If an impervious bed occurs between the land surface and the water table, a zone of saturation may exist above the water table. The water in this zone is called "perched water," and may be sufficient in quantity to supply wells and springs.

10. CAPILLARY FRINGE. In drilling wells in any granular materials such as silt or silty sand, a zone of increased moisture invariably is encountered just above the water table. This zone is called the "capillary fringe"; it is a result of the molecular attraction of the silt particles for the water in the small pores. The capillary fringe may be 5 to 10 feet thick in clays or shales, but is thin in permeable coarse sands and gravels. In sinking wells, the capillary fringe usually is identified by an increase of moisture in the cuttings. Generally it indicates that the water table is near.

11. WATER-YIELDING CAPACITY OF ROCKS. a. Importance of water-yielding capacity. In locating sites for wells, an understanding of the probable rates of yield from the important types of water-bearing rocks must be applied to each problem. Not all the water in a permeable rock will flow into a well penetrating it; a large proportion remains in the rock. To estimate the amount of water that can be pumped from a given formation, the volume of specific yield for each foot of draw-down must be estimated. This can be determined by pumping tests on test wells or completed wells. All estimates of yield must be based on specific yield, not on porosity.

b. Aquifer. An aquifer is a rock formation which will furnish enough water for a specific practical purpose. It has the same meaning as "water-bearing formation" or "water-bearing stratum." It is a relative term because a good aquifer for farm wells may be inadequate for a municipal supply or for a battalion or regiment.

SECTION II

TYPES OF ROCKS AND THEIR WATER-BEARING PROPERTIES

12. ORIGIN AND CLASSIFICATION OF ROCKS. a. General.
(1) The earth's crust consists of a great variety of rock materials ranging from loose formations such as gravel, sand, and clay to hard, dense rocks such as limestone, granite, and quartzite. Geologists call these and related earth materials, "rocks."

(2) The rocks at and near the surface generally are looser and more easily penetrated by drilling tools than are those at greater depth. At great depths, in most places several miles below the surface, the pressure renders all rocks extermely dense and closes practically all pore spaces. The large stores of ground water are at depths between these extremes. In some regions weathering has disintegrated, fractured, and broken the rocks from the surface downward several hundred feet or more. In other areas, rapid erosion by glaciers or run-off waters have carried the weathered materials away so rapidly that fresh, unweathered rock lies at the surface. Constant transportation and deposition by surface waters have formed large concentrations of loose materials in river valleys, inclosed basins, and along seacoasts. These materials are known as alluvial deposits. Recent volcanic activity in some regions has produced deposits of lava, volcanic ash, and rock fragments of endless variety.

(3) The driller may encounter a variety of rock conditions; therefore, the personnel responsible for locating and drilling wells for military use should have an understanding of the water-bearing possibilities of all important rock formations. Rocks can be divided roughly into two large groups: unconsolidated or uncemented rocks: and bedrocks or consolidated rock. No sharp distinction between the two groups can be made, since partly consolidated formations are intermediate between them.

(4) With respect to origin, rocks are divided into three large classes: igneous rocks, formed by solidification of molten materials; sedimen-

tary rocks, produced by deposition of rock debris from weathering of plant and animal remains; and metamorphic rocks, formed by the action of great heat and pressure on existing igneous or sedimentary rock formations.

(5) Because of their differences in texture, porosity, and structure, these three great classes of rock have fundamentally different water-producing properties.

b. Igneous rocks. Igneous rocks are formed by the cooling and solidification of molten material. If solidification occured beneath the surface, the formation is called "intrusive rock"; if it occurred on the land surface, the formation is called "extrusive rock." Igneous rocks vary widely in texture from glassy rocks through felsitic types made up of crystals of microscopic size, to granitic types which may have crystals several feet long. Rocks which have cooled too rapidly for crystals to form have a glassy texture. Sizes and arrangements of grain affect porosity. Most igneous rocks however, have practically no porosity except in fractures and they are poor water sources. Some igneous formations, such as lava flows, contain numerous large openings such as bubble holes, tunnels, caverns, and cracks formed during cooling.

c. Sedimentary rocks. The sedimentary rocks are grouped into three classes: fragmental (clastic) deposits derived from debris produced by weathering of other rock formations; organic deposits from plant or animal remains; and chemical deposits produced by deposition from solution.

(1) The clastic deposits include formations containing particles of all sizes from clay to huge boulders, and may be grouped according to the types of materials which they contain or the method of deposition. The coarse varieties include beds of boulders or pebbles which may have more or less rounded shapes. A large proportion of the gravel deposits in many places is composed of silica in the form of quartz, chert, or flint, because these minerals are stable, hard, and highly resistant to weathering. Pebbles of most igneous rocks in gravels weather relatively fast and occur commonly in a rotten or decayed condition.

(2) Sand also commonly contains a high proportion of silica minerals, but locally may contain concentrations of any other mineral.

(3) Clays consist of extremely small particles, and feel smooth and plastic when moist. They are derived from the decomposition of other rock minerals. Silt is intermediate in size of grain between sand and clay.

(4) The well-sorted fragmental deposits have been transported by water or wind in such a way as to produce sorting according to size

of grain. In a river system, the coarse gravels usually are laid down near the sources in headwater areas, sands predominate in the middle courses and silts and clays are more abundant near the mouth of the stream. In contrast, transportation by glacial ice involves no sorting action; hence true glacial deposits (tills) contain boulders, sand, silt, and clay unsorted.

(5) The clastic deposits may undergo any type or degree of cementation or consolidation after they are laid down. Thus gravel, when cemented, becomes conglomerate; sand may become quartzite; clay becomes shale or slate. All degrees of cementation or compaction may be found in various deposits, and the degree of compaction has important influences upon the water-bearing properties.

d. Metamorphic rocks. The chief types of metamorphic rocks are slate, quartzite, marble, schist, and gneiss, all of which occur in many different varieties.

(1) Slate is produced from shale by great heat and pressure and has good cleavage which allows it to split into thin layers. It is much harder than shale, and more resistant to weathering.

(2) Quartzite is a dense, hard rock composed of sand grains or pebbles of quartz thoroughly cemented by silica. It has the highest resistance to weathering of all common rocks, and a low porosity. If it is fractured, the joints may provide some porosity.

(3) Marble is formed by compaction and reforming of the crystals in a limestone. It has low porosity, but is subject to solution by ground water and may have extensive caverns.

(4) Schist is produced by the extreme alteration of shale or any other rock under great heat and pressure. It has a typical parallel arrangement of flat grains and is known by the most conspicuous mineral which it contains; for example, "mica schist."

(5) Gneiss is formed from an igneous rock by heat and pressure which cause some rearrangement and banding of minerals.

13. VOIDS AND OPENING IN ROCKS. a. General. Voids in rocks can be divided into two large classes according to origin: original and secondary. The original voids were produced when the rock was formed and are chiefly pore spaces between the grains. Secondary voids consist of cracks, solution cavities, root holes, and animal burrows, cavities resulting from erosion, and other less important types.

b. Original sedimentary openings. Original sedimentary openings are spaces between adjacent grains of a sedimentary rock. Since most sediments are composed of fragments that have been worn and partly rounded by abrasion, even when they are packed tightly in a sedimentary deposit, there is a considerable volume of open spaces between them (fig. 4⑤). *These openings are the most important sources of ground water.* Well-sorted deposits have high porosity regardless of the size of fragments; poorly sorted deposits have the lowest porosity (fig. 4①, ③, and ⑤). The sizes of these openings range from microscopic pores in clays, which will yield no water, to spaces a few inches wide which yield water freely. In sediments the average size usually is a small fraction of an inch, but such openings usually allow water to move freely.

c. Original voids in igneous rocks. Original voids in igneous rocks include small cavities within crystals, small spaces between crystals, bubble holes produced by escaping gases, and cavities produced by cooling and movement in lava flows. The small cavities between and within crystals are of little importance as water containers because they are not interconnecting. The gas cavities and caverns in lava flows, however, have large aggregate volume in some formations and are important sources of water for springs and wells. These features can be seen in outcrops or on the surface.

d. Joints and fracture spaces. Practically all solid rock formations are broken by cracks called joints. These can be seen in natural outcrops, road cuts, and quarries. If the joints are numerous and somewhat open, they are good channels for water movement and may yield important quantities of water. Thin, porous zones between individual beds in a sedimentary rock may extend long distances and intersect other joints to provide good water reservoirs even in a dense rock such as quartzite or granite. (See fig. 4.)

e. Solution cavities. Openings of two kinds are produced by water penetrating original cavities: Those resulting from chemical decomposition followed by removal of dissolved minerals; and those resulting from solution and removal of a soluble rock such as limesstone Chemical decomposition is most common in igneous rocks. The resulting material is largely clay. The resulting cavities are small and yield little water, but in some regions produce enough for small wells. Openings produced by solution and removal of material in soluble rocks occur in limestones, dolomites, gypsum, and salt. If water circulation continues for long periods, large caverns may be formed. The caverns and channels first form along joints and bedding planes; later they merge to form a network of large, irregular cavities. Solution cavities are important sources of ground water.

14. WATER-BEARING PROPERTIES OF ROCKS. a. Gravel and conglomerate. (1) Gravel is one of the best water-yielding formations. In North America and Europe gravel beds yield more water than all other types of formations combined. A coarse gravel without much fine material has high porosity, high permeability, and high specific yield. The yield from wells 1 foot in diameter and 50 feet or more deep ending in good gravel beds ranges as high as 2,000 gallons per minute. Such gravel beds occur in outwash deposits around the margins of the great glacial drift sheets of northern United States and Europe, in intermountain basins, and around shore lines which receive coarse rock debris from swift-flowing streams. If the gravel has been cemented, however, or if it contains much silt or clay, it is not a good water producer. Figure 6 illustrates a porous beach gravel near Nantucket, Massachusetts.

Figure 6. Porous beach gravel near Nantucket, Massachusetts.

(2) The best gravel beds consist mainly of durable, resistant materials such as quartz pebbles, limestone or dolomite fragments, or chert. Gravel containing many igneous rock fragments, shale pebbles, or much mica, is not a promising aquifer. Such content often can be determined by study of outcrops in or near the area.

b. Sand, sandstone, silt, and quartzite. (1) Sand and sandstone rank next to gravel as water-bearing formations. They generally have more uniform texture and extend over much greater areas than gravels. The porosity of clean sands ranges as high as 40 percent.

(2) Water moves less rapidly through sands than through gravels, but a good sandstone well may yield as much as several hundred gallons

per minute. In many wells special screens and other devices must be used to exclude sand grains from the well and from the water pumped from it. See TM 5–297 for methods of drilling and developing wells in sands.

(3) Sandstones, like gravels, must be fairly well sorted and open-textured to be good water producers. A fine, silty sand or a sand containing much clay lacks porosity and generally will not furnish usable amounts of water.

(4) Cementation occurs readily in sandstones and obstructs much of the pore space. Some partly cemented sandstones, however, are better water producers because the cement prevents sand grains from moving into the well under pumping. When cementation by silica has been thorough, the pore space is so reduced that the rock is not an abundant water-producer. Such rocks are called "quartzites" and are hard, brittle, and massive formations. Although they have low porosity, commonly they have extensive joint systems which will furnish some water. In such a formation, the yield of a well depends upon the number and size of joints intersected by the hole, and deeper wells generally produce proportionally more water than shallower ones.

c. Loess. Loess is a fine, unstratified, buff-colored silt consisting of angular particles. It is soft, but will stand in high, vertical walls, Generally it is regarded as a wind-deposited formation. Loess has high porosity and is a good soil material but because of capillarity yields extremely little water to wells.

d. Clay, shale, and slate. (1) True clays are the end products of weathering of many igneous rock minerals. They consist of extremely small particles which retain water even under strong hydrostatic pressure. Clays are so soft and plastic that joints or cavities which form soon close completely. Unless a clay formation contains lenses of sand it is unproductive. Of all rocks, clays are the poorest sources of water.

(2) Shale, which is formed by compaction of clay, also is a poor source of water, but in some areas provides a source for small domestic wells.

(3) Slate is too dense to be a satisfactory water-producer, but since most slate formations have joints and cleavage planes they yield usable water in some regions. In areas of slaty rock, such as southern Maine, most wells must be drilled about 500 feet deep to provide a yield of 25 gallons per minute.

e. Till. (1) Deposits of mixed rock material carried by glaciers are called glacial drift. Material deposited directly by melting ice is known as boulder clay or till. The part carried by streams flowing from the ice is called outwash gravel. Impermeable clay beds are formed in glacial lakes, and loess deposits and sand dunes are formed by wind action upon other glacial materials.

(2) Ordinary till commonly has low permeability and low specific yield, and varies widely in texture and composition. Scattered lenses and irregular bodies of gravel within a large till mass contain abundant water, but they are difficult to locate. Some till formations consist largely of sand and gravel and are good water sources. Since glacial deposits cover large areas of northern North America, Europe, and Asia, till is an important source of water in parts of many countries.

f. Poorly sorted alluvial deposits. Alluvial deposits laid down by running water are the best-sorted sediments and generally good water-producers. Many of them, however, were formed intermittently by flash run-off in arid and semiarid regions such as the intermountain basins of western United States. These mountain-valley deposits are of heterogeneous texture, with some well-sorted sand and gravel in the main stream courses, and mixed boulders, sand, and clay in intervening areas. Productive wells may be drilled in sediments which are covered by later deposits. Test drilling frequently is required to locate a good well of this type. Poorly sorted alluvial deposits occur in mountainous regions on all the continents. Some intermountain basins have water tables at great depths—in some places more than 1,000 feet below the surface. To get an abundant yield, wells in poorly sorted alluvium frequently must be "developed" after drilling is completed. (See ch. 9, TM 5-297.)

g. Limestone and related rocks. (1) Some limestones are excellent aquifers; others are entirely unproductive, depending on variations in size and number of solution cavities. Differences in porosity between grains have little effect. Also, some limestones are productive in some places, and yield little or no water in others.

(2) Some newly formed limestones consisting of loose aggregates of calcium carbonate fragments have much pore space between the fragments. As soon as water circulation is established in the formation, however, these pore spaces tend to fill with carbonate cement leached from the rock and redeposited by ground water. Older limestone formations generally are more dense than younger ones. However, the same solutions which deposit cement between the grains dissolve channels and cavities along joints and bedding planes as water circulation develops.

(3) Solution and cavern formations develop most rapidly in the zone of aeration above the water table, but the cavities thus formed are not available as water-producers unless later they are brought below the water table. The best aquifers among limestones are those which have had the following history:

(*a*) Deposition of a large limestone formation beneath the sea.
(*b*) Cementation and compaction.
(*c*) Elevation above water table.
(*d*) Enlargement of joints and bedding planes by ground water solution.
(*e*) Rise in ground-water level, submerging cavernous zone.

(4) Frequently, test drilling is necessary in locating limestone wells, for any one hole may miss all water-bearing channels entirely.

(5) *Marble* has approximately the water-producing properties of hard limestone.

(6) *Dolomite,* a less soluble variety of limestone containing magnesium, also is a good water-producer if it contains solution cavities.

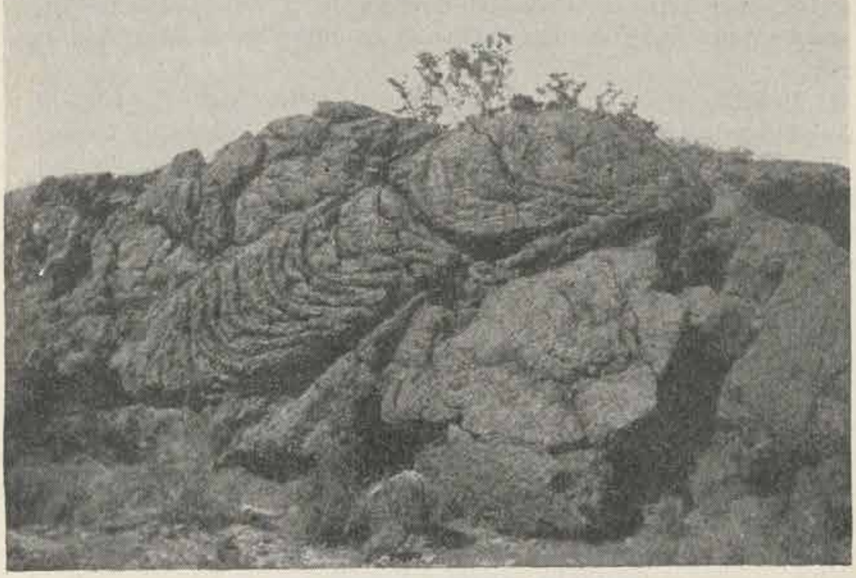


Figure 7. Rough surface of a basalt flow

(7) *Chalk,* a soft, fine-grained limestone, is an important source of water in Europe, where it is abundant, but is scarce in North America.

h. Salt and gypsum deposits. Saline deposits occur as impurities in shale and limestone formations, and in a few places as thick beds. Practically all waters derived from them are too highly mineralized for use except as sources of mineral salts.

i. Coal and peat beds. In most localities, coal and peat beds below the water table contain usable water. The water may be clear or brownish in color, and in some places contains sulphur.

j. Basalt. Basalt, a heavy, fine-grained, dark-colored, lava-flow rock, is one of the most important water sources. Water in basalts occurs in large joints, tunnels, and zones of spongy rock between individual flow sheets. In the Hawaiian Islands, the City of Honolulu obtains water from more than 100 wells in basalt which yield an average of about 400 gallons per minute per well. Many large springs also occur in basalt formations. Not all basalt formations furnish abundant water, but in unexplored areas they are worth investigating. The rough surface of a basalt flow is illustrated in figure 7.

k. Rhyolite and related fine-grained rocks. (1) Rhyolite is a fine-grained, lava-flow rock containing more silica than basalt and having less importance as a water-producer. Rhyolites and related rocks contain fewer large openings than basalt and have less definite water zones between successive flow sheets. Their weathered upper parts supply small amounts of water to dug wells in western United States.

(2) Volcanic glass (obsidian) is extremely dense, and is important as a source of water only in a few areas where it is extensively fractured.

l. Granitic rocks. (1) The term "granitic rocks" is applied to coarse-grained igneous rocks of widely differing composition. They all are similar in yielding little water near the surface and practically none at greater depths. *Where granitic rocks lie several hundred feet below other rocks, drilling deeper for water usually is futile.* In granitic rocks water occurs in small spaces of the weathered part of the rock near the ground surface, and in joints that extend to greater depths. The deeper water can be recovered only by drilled wells 200 feet or more deep, but the shallow water is recovered best by large-diameter wells, usually dug or drilled. In areas of granite not exposed to rapid erosion there is gradual gradation from decayed and disintegrated rock at the surface to fresh rock at depths of 100 feet or more. Lateral tunnels radiating from the well shaft have substantially increased the yield in some wells dug in weathered granite.

(2) Deep wells drilled in granite in the same locality vary greatly in their individual yields because water is obtained from joints and the penetration of numerous joint openings by any one well is largely a chance occurrence. Sometimes the success of such wells may be increased by locating them with reference to joint systems as observed in nearby outcrops. Drilling deeper than 400 feet in granitic rocks generally is not justified, for at greater depths the joints are fewer and smaller.

m. Gneiss and schist. Gneiss and schist have about the same water-bearing properties as the granitic igneous rocks. Their joint systems, however, are less well developed, so most of their water occurs at shallower depths than in granites.

n. Volcanic sediments. Volcanic sediments include volcanic conglomerates, formations of angular fragments, and volcanic ash beds. In many places they are porous enough to yield water. In the Pacific Islands, Mexico, and Central America many springs issue from this type rock. Cinder beds are most productive, and in many places they yield large supplies of water to wells.

SECTION III

STRUCTURES OF ROCKS AND THEIR WATER-BEARING PROPERTIES

15. ROCK FORMATIONS. a. The earth's crust consists of layers, or strata, of various types of rocks overlying more massive igneous or metamorphic rocks. In some regions, erosion has removed the overlying stratified rocks, exposing the massive, usually deep-lying, rocks at the surface.

b. A rock formation is a distinct unit of the crust of the earth having a specific age or other distinguishing characteristics. Thicknesses of stratified rock formations range from a few to several hundred feet and may extend laterally hundreds of miles either at the surface or beneath other rocks.

16. GEOLOGIC SECTIONS. a. Nearly everywhere the sedimentary formations, together with any igneous flow rocks, occur in orderly sequence, with successively younger rocks overlying older formations. Widespread and thick series of formations were deposited when portions of the continents were covered with sea water. Some regions have received many successive lava flows during periods of volcanic activity either beneath the sea or on the land surface. Large areas of all the continents have received land deposits by the action of streams, lakes, glaciers, or wind. The physical properties and the remains of plant and animal life (fossils) of each formation indicate the conditions under which it was deposited.

b. In drilling a deep well, different formations may be penetrated, the youngest at the surface and successively older ones at greater depths. Exceptions to this sequence occur where folding of the strata has overturned some beds and left a part of the series inverted, where igneous rock masses have been intruded between older formations, and where faulting has occurred.

c. All possible information (well log) on the rocks penetrated by the well should be collected during drilling. Descriptions of the rocks and indications of all possible water sources should be recorded. Dug wells allow the best opportunity to study the section, but rock samples can be collected from bored and drilled wells. Methods of reconnaissance, location of wells, sampling, and maintenance of records are outlined in chapter 7.

17. STRATIFICATION. Sedimentary rock formations generally consist of relatively thin beds or layers of rock extending over wide areas, sometimes thousands of square miles. The Dakota sandstone of Upper Cretaceous age is one of the most productive and well-known aquifers of the United States. It bears plentiful water at accessible drilling depths over an area of approximately 150,000 square miles in Minnesota, North and South Dakota, Iowa, Nebraska, and Kansas, as well as in scattered areas of the Rocky Mountain States. In many places, however, it is highly mineralized. For a typical log of a well in the Dakota formation in northwestern Iowa see table I. Figure 8 shows the position of the water-bearing formations as they should appear in a general section of regional strata.

TABLE I. *Log of old city well at Sioux City, Iowa**

Formation	Material	Thickness (feet)	Depth to base of formation (feet)
Glacial drift	Sandy clay	35	35
	Gravel, fine (water)	13	48
Dakota	Shale, gray	32	80
	Sandstone, fine, gray (water)	36	116
	Sandstone, yellow	20	136
	Shale, pink and blue	11	147
	Shale, gray and blue	21	168
	Sandstone, coarse (water)	67	235
	Sandstone, fine, gray	27	262
	Pyrite and lignite	31	293
	Sandstone, fine gray	2	295
	Sandstone, white, fine	19	314
	Sandstone, dark, coarse	33	347
	Sandstone, coarse	11	358
	Sandstone, coarser	3	361
	Sandstone, very coarse (water)	10	371

*Norton, W. H., Hendrixson, W. S., Simpson, H. E., Meinzer, O. E., Underground Water Resources of Iowa, U. S. Geol. Surv. Water Supply Paper 293, 1912, p. 893.

18. LATERAL GRADATION OF STRATA. a. The character of sedimentary rock formations commonly changes from one locality to another because of differences in conditions under which they were deposited. Along a shore line, swift, inflowing streams may carry

SECTION	THICKNESS (FEET)	FORMATION	CHARACTER
	1000	PIERRE	BLACK SHALE
	200	NIOBRARA	CHALKY LIMESTONE
	550	CARLILE	SHALE WITH CONCRETIONS
	65	GREENHORN	LIMESTONE, GRAY
	900	GRANEROS	SHALE, DARK GRAY
WATER	200	DAKOTA	SANDSTONE
	100	FUSON	SHALE AND SANDSTONE
	25	MINNEWASTA	LIMESTONE
WATER	150	LAKOTA	SANDSTONE
	50	MORRISON	SHALE
WATER	100	UNKPAPA	SANDSTONE
	200	SUNDANCE	SHALE AND SANDSTONE
	600	SPEARFISH	SHALE AND SANDSTONE (RED)
	50	MINNEKAHTA	LIMESTONE, GRAY
	100	OPECHE	SHALE, RED
WATER	400	MINNELUSA	SANDSTONE
	300	PAHASAPA	LIMESTONE
	50	ENGLEWOOD	LIMESTONE
	50 TO 150	DEADWOOD	SANDSTONE AND SHALE
			GRANITE, SCHIST, GNEISS

Figure 8. Columnar section of rocks in the Southern Black Hills of South Dakota showing water-bearing formations.

a mixed load of sediment ranging from gravel to silt, clay, and salts in solution. The gravels and sands are deposited near shore where they may be redistributed by shore currents. In deeper water, fine silts are deposited, and in clear water farther from shore, chemical deposits such as limestone may be laid down. A typical section of beds in the West Gulf Coastal Plain of Texas in shown in figure 9.

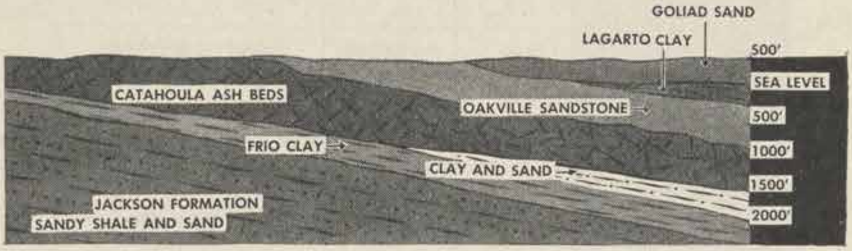


Figure 9. Cross-section of coastal plain formations in Duval County, Texas.

b. The most rapid lateral gradations occur in alluvial deposits at the foot of mountain ranges or other steep slopes where swift, intermittent streams deposit their loads quickly. In such deposits even wells drilled within a few hundred feet of each other may have quite different logs. In such cases, individual beds cannot successfully be correlated (see ch. 7) in adjacent wells. The records of two neighboring wells in an alluvial fan formation of the Santa Clara Valley of California, given in tables II and III, show the variety of materials in such formations.

TABLE II. *Log of Alameda Sugar Company well in the Santa Clara Valley near San Francisco, California**

Lithology	Thickness (feet)	Depth (feet)	Lithology	Thickness (feet)	Depth (feet)
Soil	10	10	Yellow clay	14	182
Yellow clay	6	16	Blue clay	15	197
Sand	4	20	Blue clay, sandy	4	201
Blue clay	12	32	Blue clay	19	220
Yellow clay	16	48	Yellow clay	6	226
Sand	3	51	Sand	9	235
Gravel	12	63	Yellow clay	12	247
Yellow clay	34	97	Blue clay	8	255
Sand	18	115	Yellow clay and gravel	2	257
Gravel	5	120	Gravel	3	260
Yellow clay, sandy	18	138	Gravel, fine	1	261
Blue clay	19	157	Gravel, coarse	3	264
Gravel	3	160	Gravel	2	266
Yellow clay	6	166	Bedrock	------	------
Gravel	2	168			

*Clark, William O. Ground Water in Santa Clara Valley, California. U. S. G. S. Water Supply Paper 519, 1924, p. 93.

TABLE III. *Log of Alameda Sugar Company well No. 1, near Alvarado, California*

Lithology	Thickness (feet)	Depth (feet)	Lithology	Thickness (feet)	Depth (feet)
Soil	7	7	Gravel	2	194
Sand	2	9	Yellow clay	1	195
Blue clay	18	27	Yellow clay, sandy	12	207
Yellow clay	5	32	Yellow clay, gritty	5	212
Yellow clay, gritty	11	43	Yellow clay	4	216
Yellow clay	2	45	Sand	8	234
Yellow clay, sandy	6	51	Gravel	3	237
Sand	10	61	Yellow clay	11	248
Sand and gravel	3	64	Yellow clay, sandy	9	257
Gravel	6	70	Sand	2	259
Yellow clay	8	78	Blue clay	6	265
Blue clay	8	86	Sand	4	269
Blue clay, sandy	6	92	Gravel	5	274
Yellow clay	17	109	Yellow clay, sand	2	276
Sand	5	114	Gravel	13	291
Sand and gravel	1	115	Yellow clay	2	293
Blue sandy clay	10	125	Gravel	2	295
Blue clay	23	185	Yellow clay	25	320
Blue clay, sandy	5	190	Yellow clay, sandy	14	334
Quicksand	2	192	Sand	2	336

19. ORIGIN OF FORMATIONS AS RELATED TO THEIR WATER-BEARING PROPERTIES. a. a much better evaluation of the nature and water-bearing properties of a formation can be made if the origin of the formation is known. In general, glacial drift is poorly stratified and is a poor water source, till usually having no stratification whatever. Gravels and sands laid down by glacial streams are good water producers, though they may or may not be well stratified.

b. Alluvial deposits characteristically have poor stratification. They occur in valleys, interior basins, or at the foot of steep slopes. They include much water-bearing sand and gravel. The best-stratified deposits are those in the ocean or in lakes. They commonly extend considerable distances laterally and have few local irregularities, hence the nature of the formation in one area can be used as a guide to its identification or exploitation in another.

20. CORRELATION OF FORMATIONS. a. General. Correlation is the determination of the relative ages of formations in different localities. If a certain bed does not occur in outcrops continuously from one place to another, identification must be made by fossils or physical characteristics. Usually this is a simple problem when distances between outcrops are short, as on two sides of a narrow valley, but it is not safe to correlate two similar limestone beds in localities 50 miles apart. A comparison of fossils is the best positive means of correlation. Certain formations, however, display typical properties over wide areas and occur uniformly in the same position in a series of other rocks.

b. Available data. For the development of ground-water supplies the best available data is a series of well logs from the area. Many of the records kept by drillers and well owners are inaccurate, but data of this type always have some value.

c. Collection of samples. Samples of drill cuttings taken about every 5 feet and at every change of formation give the best data for recording the log and correlating it with logs of other wells. All samples should be free from contamination by foreign material and properly labeled.

d. Study of rock samples. Where laboratory facilities are available, the samples of well cuttings should be studied in detail with a petrographic microscope to identify and determine the typical minerals of all the formations. In the field, however, the chief minerals usually can be identified by hand lens, and by hardness and acid tests as described in chapter 7. When a series of wells for military operations is drilled in areas where laboratories are not available, careful field studies of all samples should be made and all data tabulated for future reference.

e. Possibilities of error. All precautions should be taken to eliminate errors in measurement of depths, location of water zones, and identification of formations during drilling. Insufficient or irregular sampling is one of the main causes of error. Some types of rock or entirely different composition may "feel" the same in drilling; hence, if sampling is omitted while "making" 20 feet or more of hole, an entire bed, possibly water-bearing, may be missed. Any material in the cuttings which is foreign to the rock being penetrated should be studied carefully. It may mean a thin bed of entirely different composition has been penetrated.

21. INCLINATION OF STRATA. Most rock strata are inclined at various angles to a horizontal plane. Slight dips of many formations are caused by original deposition in a sloping position. In such areas as the Atlantic and Gulf Coastal Plains some increase in steepness of these original dips has been caused by gentle uplift. Steep dips usually are a result of large earth movements occurring after the strata were laid down. A series of gently dipping beds in Duval County, Texas, is illustrated in figure 9. The actual dip of these formations is about 50 feet per mile southward toward the Gulf Coast; this dip is exaggerated in the diagram. Many of the large, water-bearing formations of the United States, such as the Saint Peter sandstone, the Dakota sandstone, and the Niagaran dolomite, have dips of less than 10 feet per mile over wide areas. The determination of dips is an important factor in identification and correlation of aquifers.

22. FOLDS. **a.** In most regions the dips in the rock strata are not simple and uniform, but vary in both angle and inclination. These irregularities or flexures in rock formations are known as "folds." The various types and parts of folds are known by a series of special terms. An *anticline* is a fold in which the formations dip downward from a central axis (fig. 10(1)). A *syncline* is a fold in which the strata incline upward from a central axis (fig. 10(2)). A series of folds, consequently, is a series of anticlines and synclines. A *monocline* is a fold or steplike structure in which the dip extends for a relatively long

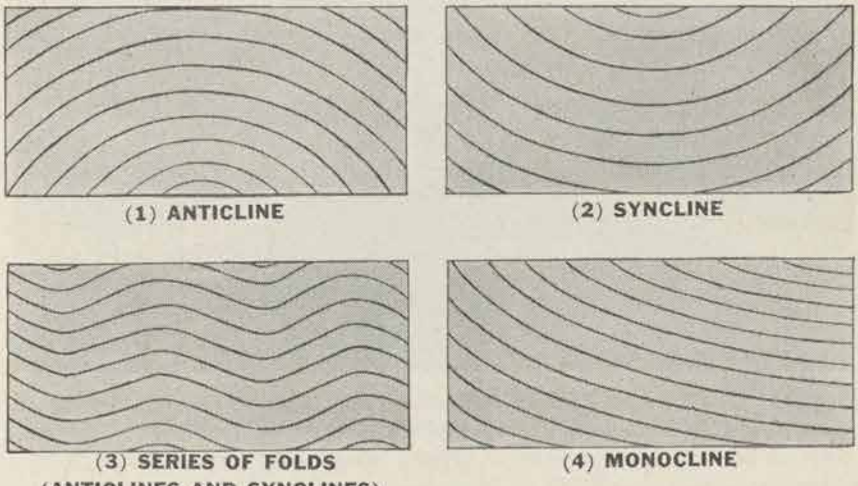


Figure 10. Types of folds.

distance in one direction (fig. 10(4)). A *dome* is an uplifted area from which the rocks dip downward in all directions, as in the Ozark uplift of Missouri. A *basin* is a structural depression where the dips incline upward in all directions from a center, as in the coal basin of Illinois.

b. Much more detailed information of geologic sections, structures, and dips is required in a region of folded rocks than in one where the dips are uniform and relatively gentle. In a series of folded rocks, the water table may extend across the structures in such a position that in some localities a permeable bed is below the water table and in other localities is above it. Flowing wells are more likely to occur in areas of dipping rocks than in areas of flat-lying strata (see fig. 9).

23. UNCONFORMITIES. In most regions, two or more series of rocks normally are separated by unconformities. An unconformity is a break in the rock sequence representing a long period during which little or no deposition occurred. During this period, the rocks may have been severely eroded, folded, and tilted or broken by faulting. Later beds were deposited on the old eroded surface. If, before the later deposition, the older formations had been folded or tilted, the two series would have entirely different dips and strucures, as shown in figure 11. This results in entirely different ground-water situations

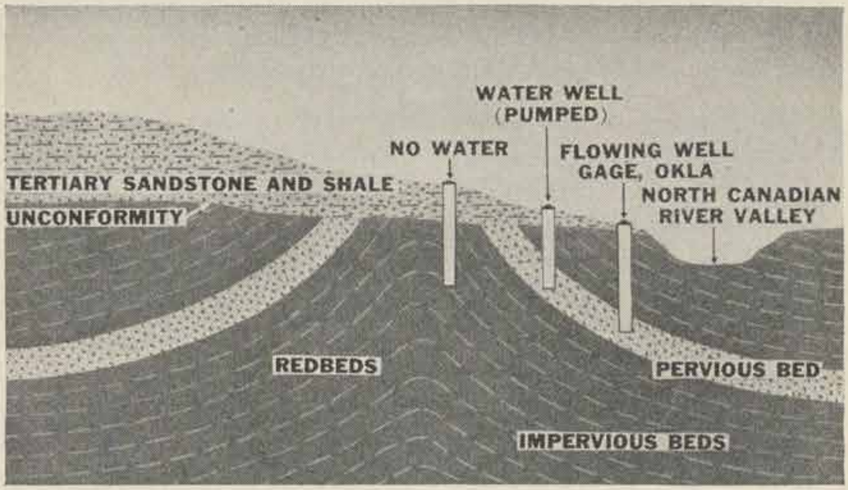


Figure 11. Ideal cross-section of formations near Gage, Oklahoma, showing the effect of unconformity and folded structures on well locations.

in localities within the same general area. Wells in one locality may penetrate a good pervious formation, but only a few miles away this formation may be absent.

24. JOINTS, VEINS, AND MINOR STRUCTURES. a. A joint is a natural crack or fracture in a rock formation. If the rocks have been displaced by movement along a fracture the structure is called a fault. Joints are characteristic of hard rock formations, and they have important water-bearing properties. Two, three, or more directions of jointing may occur in a solid rock formation such as granite or hard limestone, and the spacing of joints may range from a few inches to several yards. Joints usually are more abundant and more open near the ground surface, decreasing in number with depth. Some zones of a rock formation may have many more joints than others, and

Figure 12. Quarry in jointed limestone.

consequently are better water reservoirs. A quarry in jointed limestone is illustrated in figure 12.

b. Veins are joints or fissures filled with minerals; these usually are of later origin than the surrounding rock.

25. FAULTS. a. General. Faults are normal faults (fig. 13①), and reverse or thrust faults (fig. 13②), depending upon the direction of movement. The diagrams in figure 13 indicate the effects of faulting which has elevated the beds on one side so the pervious bed is above the water table. Faults of limited extent contain little water, but large open ones may contain large supplies.

b. Impounding effects of faults. Some faults are filled with impervious clay or pulverized rock and act as dams to ground-water movement. In clay-filled faults, a pervious bed may be saturated on one side of the fault and unsaturated on the other.

c. Faults as water reservoirs. Faults not filled with impervious material may be good water conduits and may yield abundant water to wells which penetrate them. The fault planes, which may be enlarged by ground-water action or which may consist of zones of shattered rock, form good reservoirs.

26. RELATION OF TOPOGRAPHY TO GROUND WATER. Low, flat plains generally have a relatively flat water table, often near the surface. In most flat areas, springs are rare. In hilly or mountainous regions, however, the relief of the water table tends to be higher under higher land areas, as indicated in figure 3. Springs are more numerous in hilly regions because the water table intersects the land surface in numerous places.

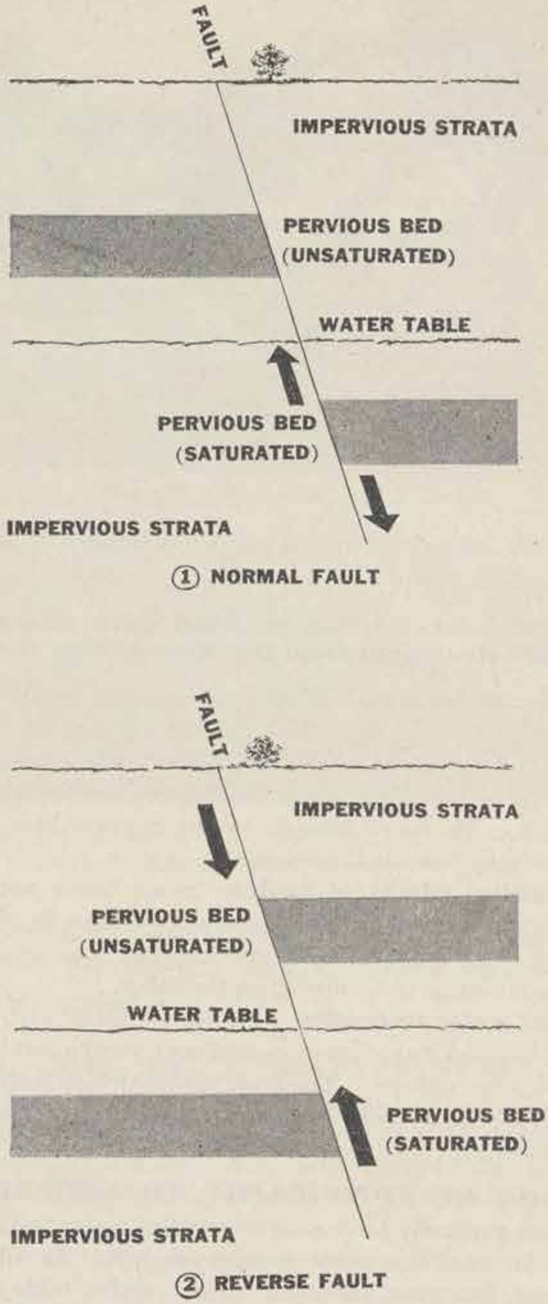


Figure 13. Diagrams of faults (arrows show direction of displacement).

SECTION IV
MOVEMENT OF GROUND WATER

27. LAMINAR AND TURBULENT FLOW. Water in the small spaces between the grains of permeable rocks moves slowly but constantly toward the direction of least pressure. This type of movement is called "laminar flow." "Turbulent flow" occurs where water flows in more open cavities or channels such as caverns, underground streams, or river beds. Turbulent flow is more rapid, and forms eddies and constantly changing currents.

28. DARCY'S LAW. The rate of flow of water through the particles of permeable rocks varies directly with the hydraulic gradient. This relationship is known as Darcy's law, after the scientist who discovered it; it has been verified by the United States Geological Survey in exhaustive laboratory tests.

29. DIRECTION AND RATE OF GROUND-WATER MOVEMENT. Water in permeable rock formations commonly moves from areas of intake down the hydraulic gradient to a point of discharge into a lake or stream, to a spring, through the soil into roots of plants, or to other points of exit. The water may move only a few hundred yards to a nearby spring, or hundreds of miles through a widespread aquifer The usual rate of movement varies from about 5 feet per day to 5 feet per year, but rates as high as 420 feet per day have been measured by the United States Geological Survey.

30. HEAD IN RELATION TO WATER MOVEMENT. a. In a detailed investigation of an area for underground water it is desirable to prepare a contour map of the ground-water surface. Such a study requires considerable test drilling where wells are scarce, and may not be possible in some military operations. In unconfined aquifers, such as glacial drift or fractured limestones near the surface, the direction of water movement usually is downward with the slope of the land surface. This is an important consideration in shallow wells when sources of contamination, such as latrines, are present in the area.

b. In sedimentary rocks, where the aquifers are confined, the water-bearing beds follow the *regional* dips or structures. The direction of water movement in these aquifers may not be down the dip in any particular locality but depends upon the hydraulic head from a distant point, possibly from an intake area many miles distant. In artesian structures, the depth to the water-bearing formation may have no relation to the surface topography. Water rises to various heights in artesian wells, depending upon the amount of hydraulic head in the aquifer. Contour maps showing pressures in water-bearing formations have been prepared for some regions where detailed ground-water surveys have been made, but such maps probably will not be available for most areas of military operation in the present war.

31. PERMEABILITY OF ROCKS. The hydraulic permeability of a porous rock material is its property of permitting passage of fluids through its pore spaces. The degree of permeability or rate at which this movement occurs is called the coefficient of permeability.

Tests based on an arbitrary standard show a range of permeability in natural rocks from less than 0.0002 to more than about 90,000, but the range in most water-bearing rocks which supply wells is from 10.0 to 5,000.0.

32. STORAGE IN RELATION TO WATER MOVEMENT. a. Ground water is the largest source of fresh water. The U.S. Geological Survey and other agencies have measured the water output from the Carrizo sand in a 60-mile belt of irrigated truck-farming land in southwest Texas. The average output of the combined wells in this area is about 24,000,000 gallons per day, and the average rate of movement through the formation is about 50 feet per year. Considering the dimensions of the formation, each mile of the Carrizo sand extending from its outcrop toward the Gulf of Mexico contains enough stored water to supply about 24,000,000 gallons per day for 100 years. Most of this water, however, cannot be recovered by wells.

b. The slow circulation of ground water from intake areas through the permeable formations to points of discharge can be compared to the flow of surface water in streams toward a lake. The underground aquifers act both as channels and as reservoirs. Where movement of water is active the quality of water generally is good. Where it is slow, it may be salty either from dissolved rock minerals or from sea water still inclosed within the rock formation.

c. Without constant or intermittent recharge, the water in rock formations gradually would be exhausted. As indicated in chapter 1, the circulation of water through the rocks is a part of the hydrologic cycle. During periods of deficient rainfall in intake areas, the amount of water entering the rocks is less than average, and the consequent decrease in output of wells near the intake area has been noted in some cases within a period of months following the dry season. Wells far from the intake area may not be affected. Slow variations in rates of movement, head or pressure, and possible yield at well locations, occur constantly in any underground water system.

SECTION V

ARTESIAN CONDITIONS

33. GENERAL ARTESIAN CONDITIONS. An *artesian well* is one in which the water rises to some height above the rock from which it issues. Water may or may not flow from the top of the well. The term has been used loosely in some areas to mean any deep well. Fundamentally an artesian condition is one in which the water in a rock formation is confined under hydrostatic pressure. In some localities the pressure, when originally tapped, has been sufficient to force water 100 to 200 feet into the air above the well. The basic conditions for artesian flow are: a permeable bed to contain and conduct the water; relatively impervious formations above and below the aquifer to confine the water; an intake area where water enters the permeable bed; and a structure or dip which produces hydrostatic pressure upon water in the lower areas of the water-bearing formation. These conditions are illustrated in figure 14. If the intake area is high enough above the point of outflow, the well will flow. The amount of pressure or head always is subject to friction losses as the water moves through the rock.

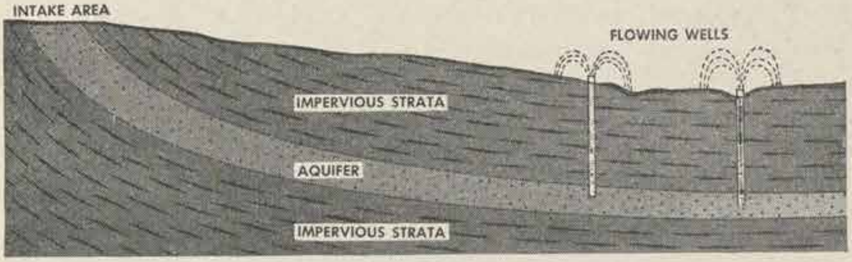


Figure 14. Theoretical section showing artesian conditions.

34. ARTESIAN CONDITIONS IN INTERIOR PLAINS. a. General. Artesian conditions in large interior basins occur in wide, relatively flat structures in which most of the beds are nearly horizontal. Water drawn from wells in such systems may have been in slow transit through the rocks for many years.

b. Northern Mississippi River Basin. The stratified rock systems in the northern Mississippi River Basin comprise a large, relatively shallow artesian basin. In this great structure, the sandstones and some of the limestones are the water-bearing beds, and the intervening shales are the confining beds. The strata are nearly flat in the greater part of the basin, but recharge of the pervious beds occurs in some elevated areas such as the Ozark uplift in Missouri, the Baraboo Region of central Wisconsin, and the Giants Range divide in northern Minnesota. Since the areas of intake are not high mountains but relatively low elevated areas, the flowing wells are confined chiefly to the larger valleys. Wells in the Mississippi Valley and some of the larger tributary valleys originally flowed several hundred gallons per minute, but in most places heavy draft has reduced the flow and head. The deepest strata in the interior basin commonly contain salt water which has remained in the rocks since the formations were deposited beneath sea water. In these deeper formations, circulation has been slow or stagnant, and fresh water has not penetrated them in large quantity. In formations within a few hundred feet of the surface, however, ground water circulation has been active, and the quality of water from wells in the shallower zones is good.

c. Great Plains of Western United States. In the central and northern Great Plains, several sandstone formations of Cretaceous age extend great distances beneath overlying strata. Large beds of impervious shales retain the water in the sandstones. The intake areas are on high slopes around the Black Hills of South Dakota, the front ranges of the Rocky Mountains, and other uplifts.

35. ARTESIAN CONDITIONS IN COASTAL PLAINS. a. Artesian wells have been developed on long stretches of coastal plains, usually in relatively young rock formations. Continental borders which have appreciable coastal plain areas have been uplifted from the ocean in relatively recent geologic periods. The original dip of the strata toward the seas has been increased along some coasts by gentle tilting during uplift. The resulting structure provides inland intake areas and a downward gradient toward the sea.

b. Artesian conditions exist at most places along the Atlantic and Gulf coastal plains of the United States. The aquifers are sands, limestones, and gravels, and the inclosing beds are clays, shales, or other impervious formations. The aquifers probably discharge fresh water into the sea at some points. In other places where the pressure is lower, sea water backs up into the lower part of the aquifer and the system remains relatively static. Figure 9 illustrates a typical coastal plain formation in south Texas where the Goliad sandstone is a well-known aquifer.

36. GLACIAL DRIFT. a. The glacial drift that covers a large part of northern United States provides water for many flowing wells. The principal aquifers are the scattered and irregular sand and gravel deposits confined within the till. Many of the individual till sheets are bordered by low ridges of sand and gravel, called moraines, which furnish good intake areas. As the water table is near the surface over much of the drift area, the conditions in some of the deeper valleys are favorable for artesian flow.

b. Artesian systems in drift generally are small and localized, the intake areas in many places being no more than a few hundred yards from the points of discharge. The head usually is low, and the flow often is irregular, depending upon the seasonal rainfall.

37. VALLEY-FILL ARTESIAN WATER. a. The intermountain valleys and basins of mountainous regions are favorable sites for flowing wells. Water is contained in sands and gravels of alluvial materials deposited by swift intermittent streams flowing down the high

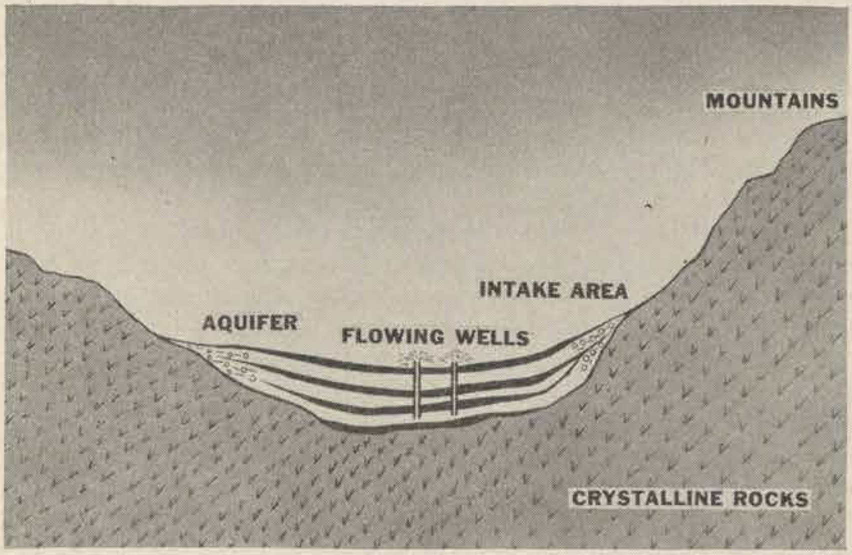


Figure 15. Ideal cross-section showing artesian conditions in the San Luis Valley of southern Colorado.

slopes and spreading out upon the valleys. Impervious beds are sills, clays, and silty sands, some of which are old lake deposits. In these systems, the intake areas are on mountain slopes, where rainfall is more abundant than in the valleys.

b. The San Luis Valley of southern Colorado (fig. 15) is one of the best examples of valley-fill artesian flow in the United States. According to a survey made by the United States Geological Survey, there were in 1936 more than 6,000 flowing wells in this valley.

CHAPTER 3

COASTAL GROUND WATER

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38. INTRODUCTION. a. General. (1) Coastal ground water is one of the most important sources of supply for human use. It has been heavily exploited, and much information on depth of wells, yields, and quality of ground water has been accumulated. Where military operations along a sea coast require ground water, cities supplied by wells are good sources of information.

(2) Coasts are divided into three classes according to geological conditions affecting ground water: coasts underlain by porous, loose materials such as sand or gravel; coasts underlain by hard rocks with joints and fissures; and coasts underlain by alternate pervious and impervious formations.

b. Definitions. A *shore* is the zone over which the water line migrates, or the zone between high and low tides. It includes, however, an additional strip covered by water only during storms. A *coast* is a broader zone of variable width, extending landward from the shore. The seaward limit of the exposed coast is the *coast line*.

39. CHIEF PROBLEMS. a. Locating coastal ground water generally is not difficult, but the water quality and yield are affected by many complex conditions. Coastal wells may be affected in two principal ways: they may become salty from encroachment of sea water, and the water level may rise and fall with the tides. The first of these is the more serious problem, for salty water is unfit for most human use and water too salty for human consumption usually is injurious to automotive cooling systems, locomotive boilers, and other types of machinery.

b. The problem of contamination by salt water is affected by several conditions. Among these are the width of the zone in which sea water saturates the formations, the depth at which sea water may occur at various distances from the shore, and the effect of pumping which causes salt water encroachment. The availability of coastal ground water also is affected by stream flow, humidity, seasonal and total rainfall and temperature.

c. The only accurate method of determining the saltiness or degree of the contamination of the water is by chemical analysis. The average concentration of dissolved solids in sea water is about 35,000 parts million (3.5 percent) and most of the salts are chlorides.

40. KNOWN CONDITIONS IN IMPORTANT COASTAL AREAS. On most coasts, fresh water can be obtained from shallow wells near shore, but deep wells even farther from shore are somewhat salty. This is because the deeper sands which carry salt water are overlain by a zone of fresh water constantly supplied from land sources. On other coasts a porous bed containing fresh water is overlain by a zone of salt water separated from it by an impervious bed.

41. RELATIONS BETWEEN SALT WATER AND FRESH WATER. a. General. (1) Fresh water is lighter than salt water and occupies the upper part of the sand in which both are present, tending to float on the salt water. The position of contact is determined by the head of the fresh water above sea level and by the relative specific gravities of the two liquids. This relationship is shown in figure 16(A) and (B).
(2) Where two liquids of different specific gravities fill a U-tube, the heights of the two columns above the point of contact are inversely proportional to the specific gravities.
The same balance of pressure occurs in a small island or peninsula composed of permeable sand. Figure 16(B) shows a cross section of a small, sandy island where fresh water is supplied by rainfall. The salt water entirely surrounds the island and extends under it, but the hydrostatic head of the fresh water and the resistance of the pores in the sand prevent the salt water entering the middle zone and mixing with the fresh water. Ordinarily the excess fresh water from the rainfall flows under pressure into the ocean at the shores of the island. In calculations of salt and fresh water levels the average specific gravity of sea water (1.025) is used.
(3) If a sandy island is underlain by an impervious stratum the fresh water is impounded or perched as shown in figure 16(C). Most coasts have alternating beds of pervious and impervious material, as indicated in figure 16(D). The contacts between salt water and fresh water in the various pervious strata depend upon the hydrostatic pressures of fresh water in each.

b. Effect of pumping. (1) The amount of fresh water that can be pumped from a coastal formation partly exposed to salt water depends upon the local conditions, the types of well, the rates of pumping, and the rate of recharge of the sand by fresh water. Any de-

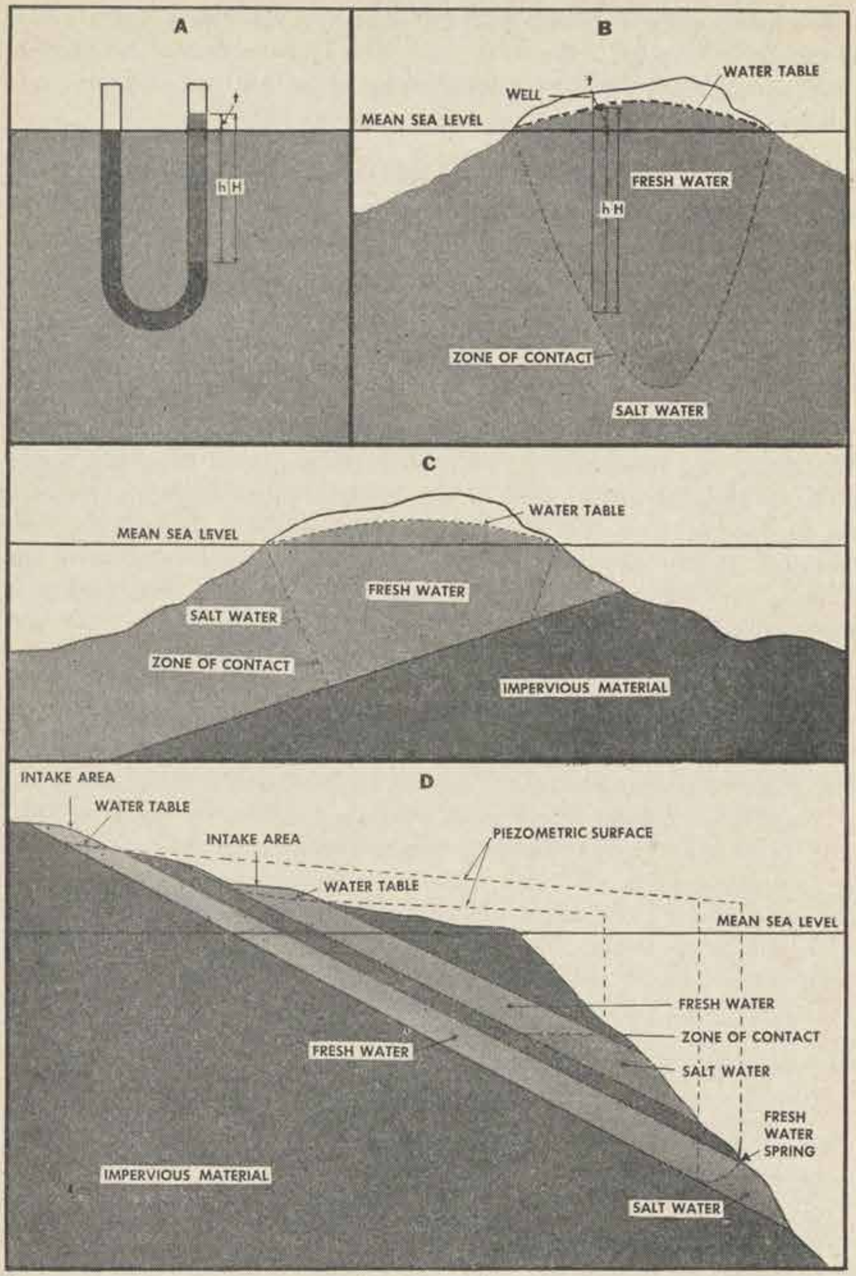

Figure 16. Relation between fresh water and salt water in water-bearing sands when not disturbed by pumping. (A) U-tube showing balance between liquids of different specific gravities, (B) section through an island composed entirely of sand and surrounded by salt water. (C) section through a sand island underlain by impervious material, (D) section through a coastal plain composed of alternate layers of pervious and impervious materials.

crease in the head of fresh water, either by pumping or by decrease in rainfall, allows a rise in the level of the salt water. The "cone of depression" produced in the fresh-water level around a well allows a corresponding rise in the underlying salt water. If heavy pumping is continued, the well produces salt water. The difference in the specific gravities of salt water (1.025) and fresh water (1.0) is so slight that even a small change in fresh-water head causes large changes in the level of contact. A fresh-water head of 5 feet above sea level is enough to hold back sea water to a depth of 200 feet below sea level.

(2) In developing a water supply along a sea coast, therefore, it is advisable to sink enough wells to yield about twice the required amount of water. Pumping of any one well should be restricted according to draw-down, for, if draw-down is maintained substantially below sea level for extended periods, salt water will enter the well. The pumping rate should not exceed the rate of recharge.

(3) The effect of pumping a well in a sand island is shown in figure 17(A) and (B). As the head of fresh water is lowered by pumping, the salt water rises in a point or peak beneath the well. This point might be called a salt-water point of elevation. It is confined to the area of influence of pumping around the well. If it rises to the bottom of the well casing, salt water is pumped.

(4) In an artesian sand, as shown in figure 17(C), pumping a well affects much less the line of contact between salt water and fresh water. If pumping does not exceed the rate of intake in the artesian sand the line of contact is not changed. Figure 17(C) shows two wells in different artesian sands. One has been pumped at a higher rate than it has been recharged with fresh water, and hence salt water has entered it. The other has been pumped at a lower rate; in it the line of contact between salt and fresh water has not changed.

c. Contamination in shallow wells. (1) On most coasts, shallow wells ranging in depth from 20 to 50 feet are either dug or driven, and usually end in sand. Contamination can be distinguished roughly in the field by the following scale. The presence of 25 to 100 parts per million of chloride generally indicates a percentage of sea water. Chloride in a proportion of 300 parts per million can be tested readily and indicates definite contamination, but such water can be used for drinking and, in emergencies, can be used for short periods in automotive cooling systems. Water containing 500 to 1,000 parts per million of chloride is unpalatable. It should not be used in any type of machinery except marine motors.

(2) In shallow wells the zone of diffusion between fresh water and salt water is narrow (less than 100 feet wide) unless affected by heavy pumping. A small sandy island or narrow peninsula, where

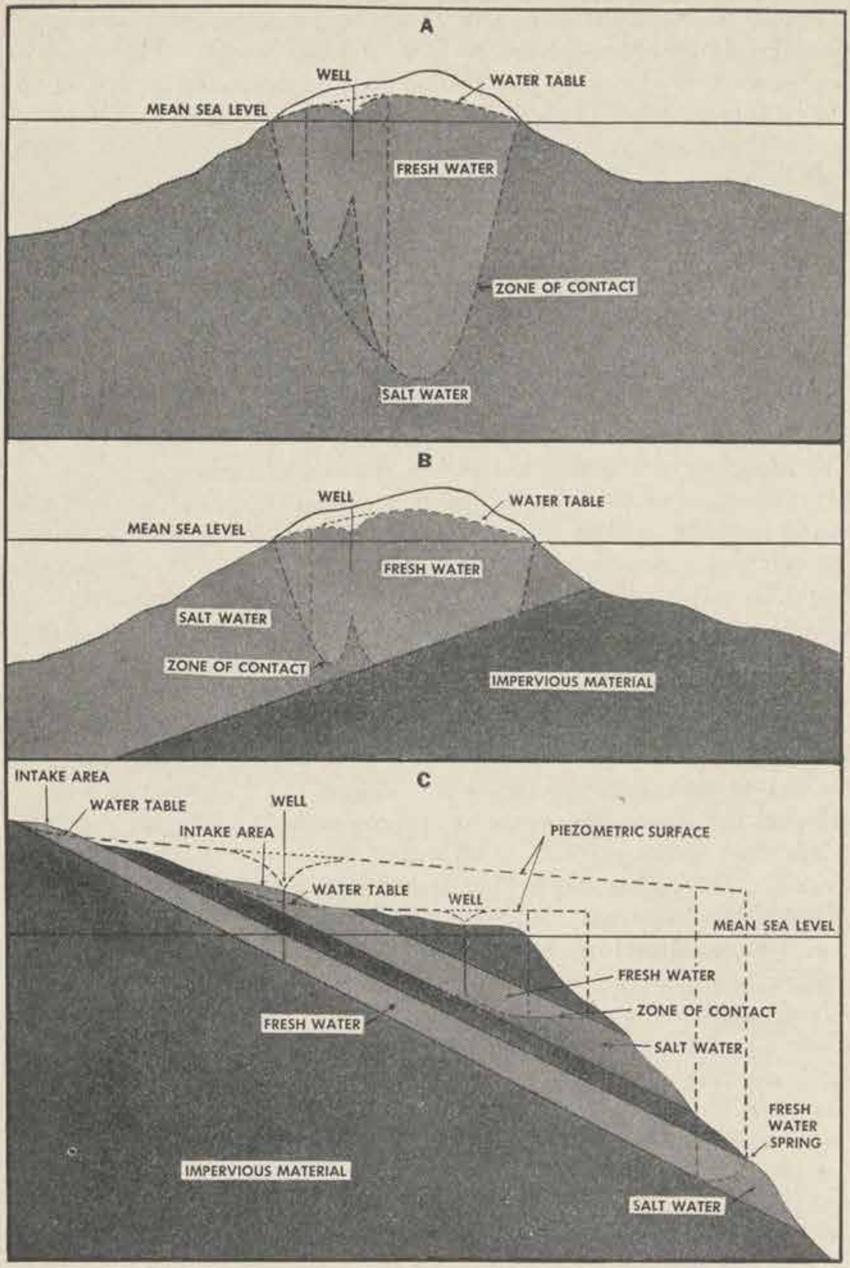

Figure 17. Effect of pumping water from wells in sand exposed to salt water contamination: (A) in an island composed of sand, (B) in a sand island underlain by impervious material, (C) on the coast of a large land area where artesian sands are confined between impermeable strata.

the area is measured in acres, generally has near the surface a body of fresh water supplied by rainfall (fig. 17(A) and (B)). Along shores of large bodies of land which have a permanent water table, fresh water occurs to the edge of the high-water line of the tides, and on sandy beaches fresh water may seep from the beach sand at low tide. In the zone of contamination the water becomes more salty during high tides and freshens during low tides.

d. Contamination in deep wells. (1) In coastal areas underlain by massive, jointed rocks the conditions are different from those in areas underlain by unconsolidated materials. The coast in the vicinity of New Haven, Connecticut, is an example of extensive ground-water development in jointed rocks.

(2) Nearly all the drilled wells in the New Haven coast area produce water from joints. Many of these wells were failures because salt water was encountered at all depths below the water table. The relations between salt and fresh water in the joints and crevices are obscure in many places; one well may yield fresh water while a neighboring one of the same depth produces only salt water. In general, the danger of contamination increases with depth. However, deep wells more than 500 feet from the coast usually do not encounter salt water.

e. Tidal marshes. Tidal marshes are poor sites for wells because the land surface is unfavorable and the water usually is salty both in the marsh and in the rock formations beneath it. The saltiness of the marsh usually is less than that of the ground water, especially in tidal marshes along river mouths where fresh water is discharged continually.

f. Bars and spits. Most bars, spits, and barrier beaches are unfavorable locations for wells because the ground water in them is somewhat salty. The sand composing such features is extremely porous, and high waves carry salt water over large parts of small bars, saturating them with sea water. Large barrier beaches such as that of the western Gulf Coast, however, have enough area to maintain shallow fresh-water wells.

g. Effects of joints in bedrock. In a body of jointed and fractured rocks along a coast, sea water enters the rocks through joints and may penetrate some distance inland. This penetration varies with the pressure relationship between fresh water and salt water, and the line of contact is typically irregular. The extent of penetration by sea water can be determined only by consulting existing well records or by test drilling.

h. Effect of recent silt deposits. At a number of other places along the Atlantic Coast, deposits of recent mud have been laid down by streams flowing into the sea. This has provided an impervious cover over porous sands in the estuaries. The sands beneath this cover contain fresh water under low head from nearby land areas, and can be tapped by shallow wells. This condition exists in many harbors.

i. Other influences such as tides and temperatures. Fluctuations of water levels with the tides have been recorded in wells along many seacoasts. In wells near shore the fluctuations may range from a few inches to several feet. Wells in fractured rock formations generally are affected to about the same extent as wells in pervious sands. Higher temperature increases evaporation and accelerates seepage and percolation. A seasonal rise in ground-water level from heavy rainfall may increase the head of fresh water and thus cause seasonal increases in fresh-water yield.

CHAPTER 4

DESERT GROUND WATER CONDITIONS

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42. GENERAL CONDITIONS. a. Most of the desert regions of the world are characterized by scattered mountain ranges separated by basins filled with alluvial sediments derived from the mountains. The sediments are favorably situated for absorbing water that falls as rain or snow, and for receiving water from rain which falls on the mountains and flows out into the basins. Therefore, in practically all such basins, a permanent zone of saturation occurs in the lower part of the valley fill, and this water can be tapped by wells. As most of the desert basins have interior drainage, evaporation is the only means of discharging the water that enters the sediments. In the lowest part of each basin generally there is an area in which ground water discharges by evaporation, leaving salt concentrations in the rocks near the surface. Prospecting for water in such basins, therefore, is a problem chiefly of locating water of good quality and avoiding the common salty waters.

b. In a few desert regions, such as parts of northern Africa and interior Australia, the topography was developed on high plateaus without conspicuous mountain ranges. Such regions do not favor the accumulation of thick deposits of alluvium. Furthermore, the absence of mountains results in an extremely low rainfall throughout the region. There is little percolation of water into unconsolidated surface deposits. The supplies of ground water near the surface are meager, and the possibility of developing ground water depends upon the existence of deep-lying aquifers which transmit water from distant intake areas.

c. In such desert areas, a knowledge of the regional geology is essential for the development of ground water. If a geologic reconnaissance (see ch. 7) indicates that a deeply buried artesian aquifer may be present, test-drilling to great depth to tap it may be justified. Deep drilling generally is not justified if the area is underlain by hard crystalline rocks such as granite, schist, and slate.

d. In some desert areas for which little geological information is available, probably there are undeveloped supplies of good ground water at depths of several hundred feet or more. In such areas in Asia, Africa, and South America special attention should be given to areal geology, because test drilling to depths below those reached by native wells may be justified.

43. DESERT PHYSIOGRAPHY. a. Topography. Because most desert regions have a basin-and-range type of topography, the conditions of that type are described in the following paragraphs. Such a region is composed of great waste-filled valleys separating mountain ranges rising to 5,000 feet or more above the valleys, many of which are interior basins with no river outlets. Some of the basins have minor mountain ranges within them. The desert valleys are partly filled with rock debris washed out from the ranges by intermittent, often torrential, streams. At the margins, where the slopes decrease, the mountain streams slacken in speed and deposit large quantities of coarse, angular rock fragments. This results in a series of coarse, fan-shaped, alluvial deposits along the mountain flank. Most of the out-flowing water sinks and disappears into these deposits. The lowest parts of the closed desert basins receive from the uplands the storm water not lost by seepage or evaporation.

b. Playa lakes. The thin sheets of muddy water which accumulate in the basins remain for days or weeks until the water evaporates

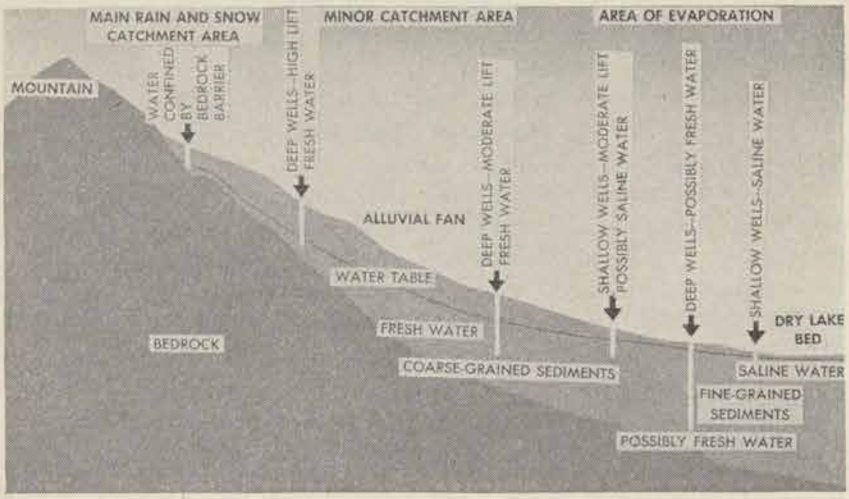

Figure 18. Cross section showing ground-water conditions in a typical desert basin.

or sinks into the surface sediments. As a result the basins receive accumulations of silt, clays, and salts. These barren clay flats are called "playas" or "playa lakes." They have smooth, flat, lake-basin topography. For a cross section showing the relations between the mountains, the basins, and the playa lakes, see figure 18. The surface of some playas holding water in the subsurface sediments always is moist. That of playas from which subsurface water escapes downward through crevices in bedrock below the sediments is dry except for short periods following rains. In the moist playas, salt water generally occurs near the surface, but fresh water may underlie it. Figure 19 is a photograph of the Mohave Basin and Soda Lake in California.

Figure 19. View of Mohave Basin and Soda Lake, California.

c. Ground-water occurrence. The typical desert basin can be divided into three principal segments according to ground-water occurrence: the mountain range, which contributes most of the runoff, but has little ground water; the upper alluvial slopes, consisting of coarse debris and containing ground water at some depth; the valley fill in the lower parts of the basin, which contains most ground water (see fig. 15). The water in the central part of the basin, however, may be alkaline or salty. Some water can be obtained in the mountains, but the quantity in the rock generally is small. Fresh ground water usually can be obtained by drilling in the alluvial slopes at some depth, sometimes as much as several hundred feet. In unexplored basins, some test drilling will be necessary as the thickness and character of the sediments varies greatly from place to place.

44. PLANTS AS INDICATORS OF GROUND WATER. a. Principal species that tap ground water. Desert plants can be useful to anyone who seeks water. Some plants are adapted to extreme economy of moisture and exist where only light, infrequent rains occur and where no ground water occurs near the surface. Other plants usually grow only where they can send roots down to the water table. Some species have uncertain significance or are difficult to interpret as ground-water indicators. The plants that use ground water form a distinct group in desert regions but in more humid areas become less distinct as water indicators. Many plants which use ground water in deserts will spread to moist places along irrigation ditches, and in some localities they also can use soil moisture in the unsaturated zone. In spite of many complicating conditions it is definitely recognized that certain plants customarily tap ground water and others do not. The ground-water plants commonly occur in a zone around the central playa of a desert basin. There they indicate a belt of shallow ground water. In most places the center of the playa is barren of vegetation because of the alkaline clays at its surface.

(1) RUSHES, SEDGES, AND CATTAILS. Rushes, sedges, and cattails commonly grow where surface water is visible in swamps or pools or where the water table is near the surface. Generally they cannot survive dry periods.

(2) REEDS AND CANE. The common reed grass Phragmites occurs along streams and ponds and where ground water is near the surface. It has tall, jointed stalks sometimes 10 feet high, with green leaves at the tops.

(3) WILD RYE. Numerous species of wild rye occur in rich soils where ground water is near the surface, and also where rainfall is abundant. They can use either ground water or soil moisture.

(4) SALT GRASS. Salt grass (fig. 20) is one of the most reliable and useful of the shallow ground-water indicators.

(5) RABBIT BRUSH. (Chrysothamnus graveolens). In the deserts of Nevada, Utah, and California the common rabbit brush (fig. 21) is a conspicuous ground-water indicator. It is a shrub with whiplike branches and gray-green leaves, and in late summer has yellow blossoms resembling those of goldenrod. Rabbit brush generally indicates ground water at a depth less than 15 feet.

(6) GREASEWOOD (SARCOBATUS VERMICULATUS). The black greasewood (figs. 20 and 22) is one of the best and most conspicuous indicators of ground water in all of the northern desert areas of the United States. It should not be confused with the creosote bush (Covilla tridentata) which usually does not tap ground water. This species of greasewood grows in bushes 1 to 8 feet high, and has a deep, strong, blue-green color which makes a vivid contrast with the sages. It can send its tap roots to depths of 30 to 40 feet to tap ground water.

Figure 20. Salt grass (Distichlis) in foreground, black greasewood (Sarcobatus) in background, near Nelson, Nevada.

Figure 21. Rabbit brush (Chrysothamnus) near Grantsville, Utah.

(7) MESQUITE AND RELATED PLANTS. Mesquite can send its tap root along moist belts to a depth of about 50 feet to tap ground water, but it also can adapt itself to use soil moisture in upland areas. It occurs widely in southwestern United States and in the southern half of South America. In general, the smaller mesquite indicates a greater depth to ground water.

(8) ALFALFA. Alfalfa grows best where ample water is available, but it can send down roots 60 feet or more to use ground water. It does not produce abundant foliage where the depth to the water table is more than 15 feet, but it is a good ground-water indicator. It grows wild in Persia, central and western Asia, and northern Africa.

(9) WILLOW. Most common varieties of willow use ground water either at the surface or near it. Two species have been known to obtain water from depths of 6 to 11 feet. One variety, the desert willow, uses either soil moisture or ground water at depths of 50 feet, and is not a reliable ground-water indicator.

(10) COTTONWOOD. The common cottonwood trees are reliable indicators of ground water in the arid parts of western United States and other countries. The desert varieties commonly occur where the water table is 20 feet or less below the surface.

(11) BERRY BUSHES AND WILD ROSES. The buffalo-berry bush, elderberry and gooseberry bushes, and the large hackberry are known through western United States as ground-water indicators. The buffalo-berry bush has been known to send down roots 50 feet to tap ground water. Wild roses grow in variety of environments, but in arid regions they may indicate the presence of shallow ground water.

(12) WASHINGTON PALM AND OTHER PALMS. Palms (fig. 23) are reliable ground-water indicators especially in desert oases of Africa and Asia Minor. In the hot, arid region of southwestern California their occurrence invariably indicates a spring or ground water within a few feet of the surface. Because palms grow to heights of 50 feet or more they can be seen for miles as sign posts of shallow ground water.

(13) FOREST TREES. Some species of birch, sycamore, live oak, and alder are known to tap ground water in dry valleys, but most of them also can use soil moisture in regions of low rainfall.

b. Desert plants that do not commonly tap ground water. Some of the common desert plants that do not indicate ground water are the cacti, most of the yuccas, big sagebrush, and creosote bush. They occur in large areas of arid western United States and some of them occur on other continents. They can live by using extremely

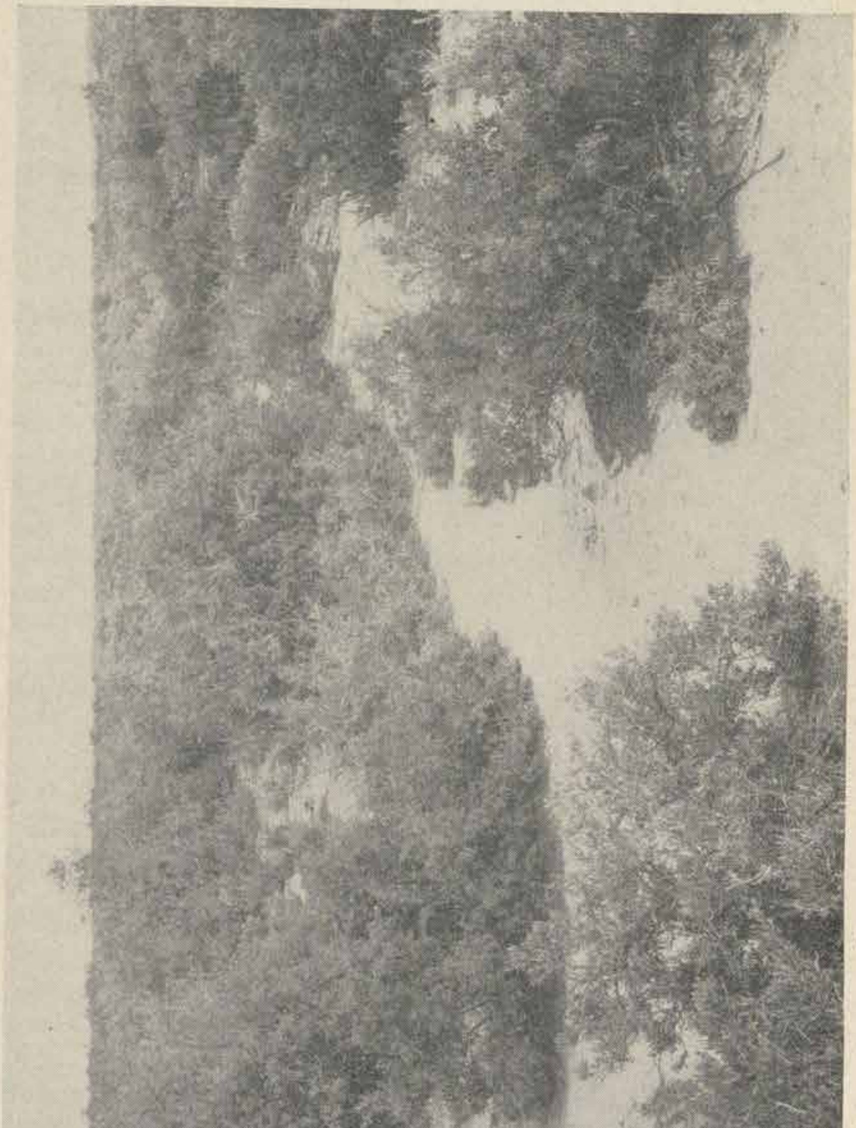

Figure 22. Black greasewood (Sarcobatus) near Montrose, Colorado.

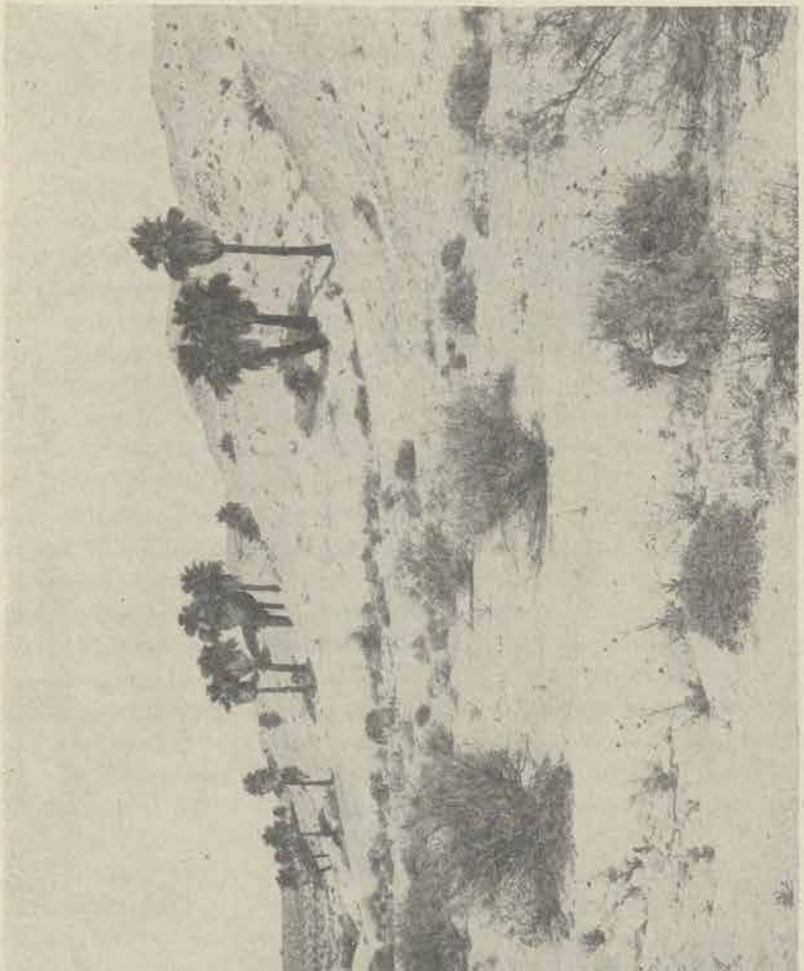

Figure 23. Desert palm near Indio, California.

small quantities of moisture derived from the soil, and many of them remain in a dormant condition for months.

c. Value of plants as indicators of ground water. (1) TO SHOW OCCURRENCE OF GROUND WATER. The usefulness of plants to show occurrence of ground water depends largely upon the presence or absence of the ground-water species in the area under investigation. An area that has in abundance several types of plants that use ground water probably is worth further investigation. If no ground-water plants are present, ground water is absent or lies at depths approaching 60 feet or more.

(2) TO SHOW DEPTH TO GROUND WATER. The occurrence of various species of ground-water plants indicates roughly the depth of the water table. Approximate maximum depths of root growth for common types of ground-water plants are given in **a** above. These limits are indefinite because the depth of root penetration is affected by tightness of the soil and other factors. The lower limits are more indefinite than the upper ones. Palms and salt grass, however, normally indicate that water may be obtained by digging with spades or boring with augers. With few exceptions the greatest depth from which ground water can be lifted by plants is about 50 feet.

(3) TO INDICATE QUALITY OF GROUND WATER. Some plants furnish an indication of quality of ground water, as well as its presence and depth. In many places, reeds, sedges, and rushes indicate good quality water. In most places pickleweeds, tamarisk, and a few other plants indicate highly mineralized water. Palm trees and greasewood may be present where the water is good or where it is highly mineralized; their value as indicators of water quality is doubtful. Mesquite, shrubs, and trees that grow in more humid regions usually indicate good water.

CHAPTER 5

SPRINGS

45. GEOGRAPHIC AND TOPOGRAPHIC OCCURRENCE OF SPRINGS. **a.** In most humid regions such as the eastern part of the United States, the British Isles, and northern Europe, the streams have many branches which are fed by many small springs along their courses. Streams which drain limestone areas generally receive water from fewer but larger springs.

b. In areas of young glacial drift, such as the Great Lakes region of the United States, the Scandinavian countries, and parts of north-central Europe, a substantial part of the total ground-water discharge occurs by direct evaporation from the soil and through transpiration of plants. This proportion is higher in summer and lower in winter. The surface of the younger drift has few through streams but many lakes and swamps. The water table is near the surface, and small springs are numerous.

c. In subhumid and semiarid regions, springs generally are few and small. They are especially scarce in areas where extensive shale formations or other impervious beds form the surface rock. In semi-arid and arid regions evaporation rates are high. Large inland plateaus in such regions commonly have few springs.

d. In and near high mountains springs generally are numerous because rainfall on mountain slopes is relatively high and in most mountain systems percolation downward is limited by large, impervious rock masses. Water from rainfall or melting snow percolates downward through rock debris and superficial crevices, encounters solid, impervious formations, and moves along the impervious surface to a point of issue along a slope.

e. As a result of surface run-off and spring flow from mountains much water moves to the desert basins, as described in chapter 4. Belts of springs occur around some of the basins.

46. CLASSIFICATION OF SPRINGS. Springs originate under so many different conditions and in so many kinds of rock that no simple classification is possible. Some of the chief characteristics by which springs are classified are:

Character of spring opening.
Rock structure and resulting pressure.
Type of water-bearing rock.
Geologic age of water-bearing rock.
Environment into which water is discharged.
Quantity of water discharged.
Type of flow fluctuations.
Quality of water.
Temperature of water.
Features produced by springs.

a. Character of spring opening. In respect to type of spring opening three classes of springs are recognized: *seepage springs*, where

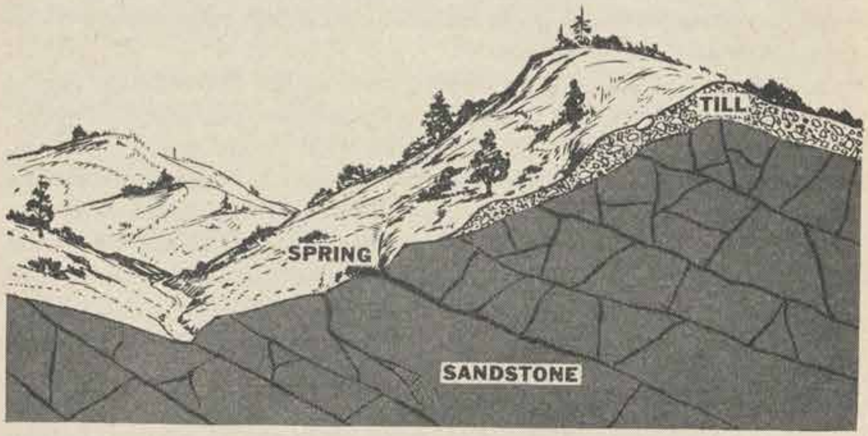

Figure 24. A fracture spring.

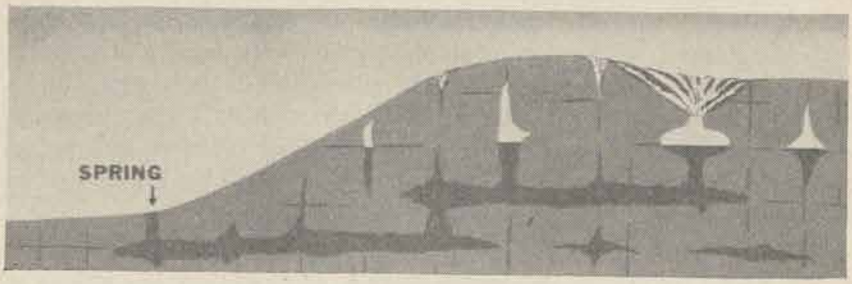

Figure 25. Tubular spring in creviced limestone.

water percolates slowly through many small openings; *fracture o fissure springs,* where water issues from a joint in the rock formation (fig. 24); and *tubular springs,* where water issues from a solution tunnel, as in a limestone (fig. 25), or from an original tunnel, as in lava.

b. Rock structure and resulting pressure. Two principal types of spring are recognized according to rock structures and pressures: *gravity springs*, where the water flows by gravity from a higher

Figure 26. Type of gravity spring.

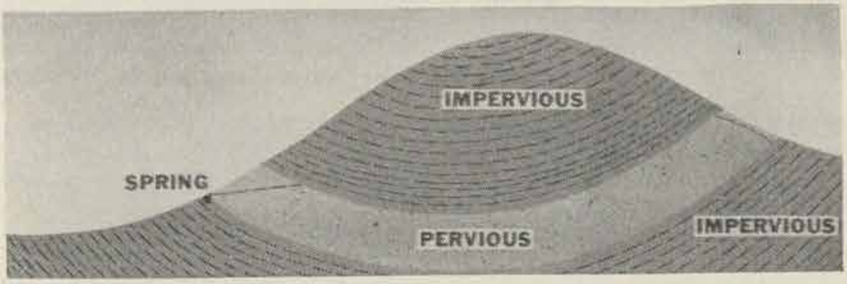

Figure 27. Inverted-siphon artesian spring.

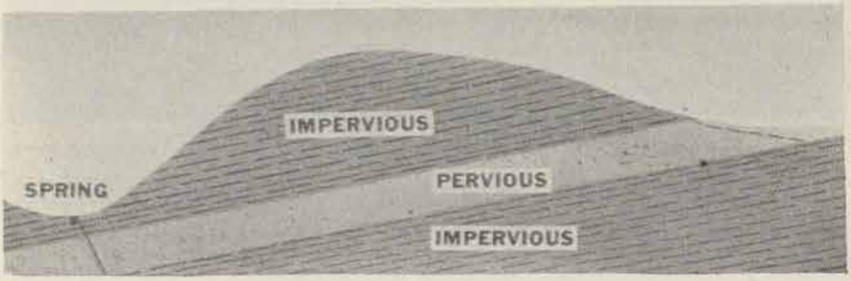

Figure 28. Fracture artesian spring.

point of intake to a lower point of issue (fig. 26); and *artesian springs*, where the water issues under hydrostatic pressure (figs. 27 and 28). Gravity springs may issue in depressions, from contacts between two rock formations, or from various types of opening in the rocks.

c. Type of water-bearing rock. Springs are known by the type rock from which they flow, as sandstone springs, lava springs, limestone springs, and others.

d. Geologic age of water-bearing rock. Some springs are known by the formation of rock from which they flow, as Dakota sandstone springs and Niagaran limestone springs.

e. Environment into which water is discharged. A classification according to environment into which spring water flows includes subaqueous springs (issue under water), valley springs (fig. 29), alluvial-slope springs (fig. 30) and others. The springs shown in figures 25 and 26 also can be called gravity springs.

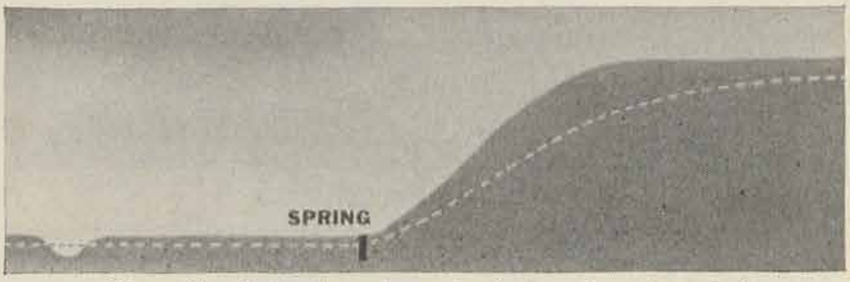

Figure 29. Valley-depression spring (a type of gravity spring.)

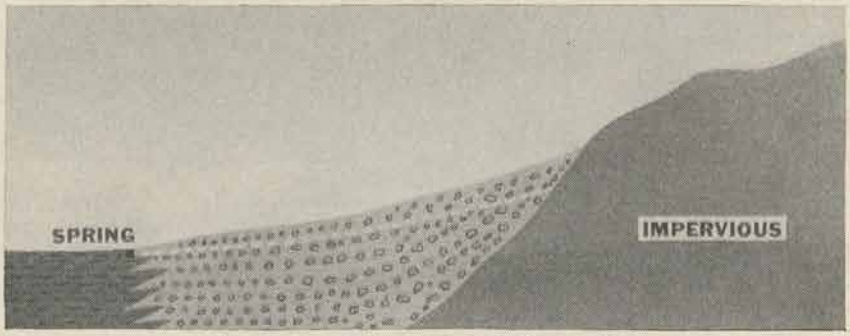

Figure 30. Spring at foot of alluvial slope.

f. Quantity of water discharged. Small, slow-flowing springs are called "seeps," but no special terms are applied to springs of larger free flow.

g. Types of flow fluctuations. With regard to fluctuations in flow springs are divided into perennial, or permanent, springs and intermittent springs, which discharge only at certain seasons or periods. All perennial springs vary somewhat in rate of flow. Geysers are a special type of intermittent spring.

h. Quality of water. The composition of water issuing from springs is used in dividing them into types, such as sulfur springs, salt springs, and mineral springs.

i. Temperature of water. Warm and hot springs usually originate at some depth in contact with bodies of hot volcanic rock. Cold springs have temperatures slightly above the average annual temperature of the air in the vicinity.

j. Features produced by springs. Some springs deposit mounds or rims of mineral matter and are known as mound springs or pool springs.

47. DEVELOPMENT OR IMPROVEMENT OF SPRINGS. a. Objectives of spring development. Springs are improved or developed to increase the available flow, to protect the water quality, and for convenience in using the water. The chief means of developing springs include building a basin to collect the water, clearing or enlarging contributing channels, and making a protective covering for the water. Details of the structures required to develop various type springs differ according to the size and type of flow, types and structures of water-bearing formations and adjacent rocks, and types of spring openings. Methods of development of various types of spring are suggested in the following subparagraphs.

b. Methods of development. (1) GRAVITY SPRINGS. (*a*) *Depression springs.* Springs which flow from the rocks under force of gravity and collect in depressions can be collected in boxes or basins of wood, tile, or concrete if the pool is in unconsolidated material. The collecting box should be large enough to impound most of the flow, and should have small slots or openings to admit water. It should be sunk into the ground so its top is slightly above the surface, and for military use should be about 5 feet wide, 10 feet long, and 5 feet deep. The long dimension should be at right angles to the surface slope to aid collection of water. The box should have a tight cover to retard evaporation and to prevent contamination. If the installation is on a steep slope of loose rock the supply of water may be increased by constructing tunnels leading upslope from the spring into the water-bearing formation. The tunnels can be filled with cobbles or boulders to prevent caving. Depression springs in hard rocks generally cannot be developed on a large scale, but the spring basin should be enlarged. Water leading from a long, fissure opening can be collected in shallow trenches and diverted into a closed top collecting pool.

(*b*) *Contact springs.* Where water issues from the bottom of a pervious formation over an impervious floor, any one of four general types of spring may occur: that in which both formations are soft or unconsolidated; that in which the overlying rock is unconsolidated and the underlying formation consolidated; that in which the overlying rock is consolidated and the underlying rock is soft and unconsolidated; that in which both formations are consolidated, as a permeable sandstone over a dense limestone. In contact springs the water moves toward the openings as a wide, thin sheet, and issues at the contact in a long line of seeps or springs. The object of developing contact springs is to divert to one point all the water issuing from a long length of the contact zone. In springs of the first two types, a ditch can be dug in the overlying formation along the contact and the water directed into a basin or box at a lower elevation. Another method is to dig tunnels into the overlying formation, using the top of the impervious formation as a floor. In some cases, subsurface dams of wood or concrete have been constructed at right angles to the direction of flow to divert water to the central tunnel. If the unconsolidated formation is 10 feet or more thick a dug well extending through it, with the bottom on the impervious formation, may be more practical than a system of tunnels. For springs of the third type, tunnels or ditches can be dug into the impermeable formation below the contact and the water diverted into a collecting basin. In the fourth type, where both formations are hard rock, a shallow trench or groove can be chipped out along the contact to divert the water into a central collecting basin at a lower level.

(c) *Large-fracture or tubular springs.* As large-fracture or tubular springs commonly occur in hard, consolidated rocks, little can be done to increase the flow at any one point, but a collecting basin can be constructed and sealed to the underlying rock. In some localities, ditches can be dug to lead the discharge from nearby springs into a central reservoir.

(2) ARTESIAN SPRINGS. Artesian springs occur only in zones of artesian flow where the water issues under pressure. If the spring opening covers a small area a concrete or brick basin can be built around it. If the water issues from fissures, covered ditches can be dug to conduct it to a central basin.

(3) PRESSURE SPRINGS FROM DEEP SOURCES. Pressure springs from deep sources originate either from volcanic rocks or from deep sources of uncertain origin. Usually they issue from hard rocks, and can be developed by any of the methods mentioned above for consolidated rocks.

d. General precautions for spring developments. Special precaution should be used in blasting to increase spring yield or to construct basins. Blasting in unconsolidated rocks may shift sand or gravel in such a way as to divert the spring flow to a different point.

In unconsolidated materials, digging usually is more economical. In hard rocks, blasting may open new fractures which divert water entirely away from the spring or may create fractures in the underlying impervious rock, thus draining the water from the aquifer at that point. A general rule in spring development is to cover all ditches, basins, and outlets to and from the basin to prevent surface contamination and to retard evaporation. Pipes should be used to conduct the water from the basin to the point of use. Nearby surface sources of contamination should be investigated and eliminated if the spring water is to be used for drinking.

CHAPTER 6

QUALITY OF WATER

48. MINERAL QUALITY. a. Natural processes controlling mineral quality of water. (1) Water falling upon the earth begins at once to dissolve the minerals of the soil and rocks with which it comes in contact. It does so while moving from the surface to the water table and continues as it moves through the rocks as part of a body of ground water. The quantity and character of the mineral matter so dissolved depend upon the chemical composition and the physical structure of the rocks, the temperature, the pressure, the duration of the contact, and the materials already in solution. The solvent action of the water is assisted by carbon dioxide derived from the atmosphere as the water falls as rain or snow, or from the soil through which it passes, where it is formed by organic processes.

(2) Highly mineralized water in rock formations may be water derived from rain or snow (meteoric water) that has dissolved a large amount of soluble material in traveling from the land surface to the point at which it is found. It may have passed either for a relatively short time through rocks containing a large proportion of soluble material, or for great distances and during a long time through rocks containing smaller quantities of soluble material. On the other hand, the highly mineralized water may be "connate water," that is, water trapped in the sediments when they were deposited and never flushed out by fresher waters from above. If the sediments were deposited in the sea, obviously the connate water will be highly mineralized. In many places highly mineralized water consists of connate water that has been diluted but not entirely removed by fresher water of meteoric origin. In such places rocks of low permeability generally have water of high salinity, and rocks of high permeability have water of low salinity, because the connate water has been flushed out more completely from the more permeable portions, in which the movement of water is more vigorous.

(3) For many purposes, the usefulness of water depends on the amount and nature of the dissolved materials. Water containing more than 1,000 parts per million of dissolved solids is likely to con-

tain enough of certain salts to make it unsuitable for human use, and generally it is better to use water containing not more than a few hundred parts per million. However, human beings can tolerate for short periods water containing 2,500 parts per million of dissolved solids, or even more. Waters of poor mineral quality generally are found in wells or springs in the lowest parts of closed basins. Waters from mountain springs or wells usually are good.

b. Physiological effects of common mineral substances in water. (1) Most waters that are not positively distasteful can be drunk in small quantities without harmful effects if they do not contain bacterial contamination. In large quantities, however, highly mineralized waters may cause serious physiological disturbances which, though usually only temporary, may be fatally weakening. The most dangerous waters usually are so distasteful they cannot be swallowed. Waters producing such ill effects usually contain large quantities of sodium sulphate (Glauber's salt), magnesium sulphate (Epsom salt), sodium carbonate, or sodium chloride (common salt). Waters containing large quantities of the sulphates of sodium or magnesium are bitter. They may quench thirst but they have a laxative effect which, if they are used in large quantities, may be serious. Waters containing large amounts of sodium carbonate have a characteristic soapy taste and cause a burning sensation in the mouth. They produce a nauseating effect. Waters with much sodium chloride taste salty and, drunk in quantities, are nauseating.

(2) A total concentration of 2,500 parts per million of dissolved solids is about the maximum that can be tolerated in drinking water by human beings. If much magnesium or sodium sulphate, sodium carbonate, or sodium chloride are present, the maximum tolerable concentration is about 1,500 parts per million. People can become accustomed to drinking mineralized waters, but continued use of them is harmful.

c. Sources of important mineral substances in water.
(1) Silica is an important constituent of all rocks except limestones, but in natural waters usually it is present in quantities less than 30 parts per million. Silica is one of the constituents that contribute to the formation of scale in boilers, but is of little significance in other ordinary uses of water.

(2) Iron is dissolved from most rocks and to some extent from water pipes. Quantities of iron greater than one part per million usually precipitate when the water is exposed to air. Some waters containing iron salts are corrosive. Waters with much more than about 0.2 part per million of iron are objectionable because they stain clothes, enamel, and porcelain.

(3) Calcium and magnesium are somewhat alike in chemical properties but differ in physiological effects. Calcium is dissolved mainly from limestone, dolomite, and gypsum. Magnesium is dissolved mainly from dolomite, although some may come from deposits of magnesium sulphate. Calcium and magnesium cause hardness, and contribute to the formation of scale in boilers. Natural waters usually have more calcium than magnesium.

(4) Sodium and potassium, called the alkalies, are dissolved from practically all rocks. They have similar chemical and physical properties. The quantity of potassium usually is small in proportion to the sodium.

(5) Carbonate and bicarbonate result from solution of carbonates by waters containing dissolved carbon dioxide. Few natural waters contain carbonate but most contain bicarbonate. These are the hard waters.

(6) Sulphate is derived from gypsum, from deposits of sodium and magnesium sulphate, and to some extent from the oxidation of sulphides. Some sulphate waters are corrosive.

(7) Chloride is dissolved from most rocks and soils. Sea water generally contains 18,000 to 20,000 parts per million of chloride. The United States Public Health Service recommends 250 parts per million as a limit for chloride in potable waters. Waters appreciably higher in chloride content can be used but they become progressively more objectionable for drinking as the chloride content increases.

(8) Nitrate is dissolved mainly from oxidized organic material. Natural waters usually contain small quantities of it.

(9) Fluoride, derived from fluorine minerals, is present in many ground waters, the quantity ranging from a fraction of a part to several parts per million.

(10) The most common objectionable properties of water are high iron content, hardness, and corrosiveness. The most corrosive waters generally are soft. Hard waters generally are not corrosive. Hard waters can be made suitable for boiler use and washing by softening. Man can tolerate extremely hard water for drinking unless the hardness results from magnesium sulphate or chloride.

d. Chief methods of treating mineralized waters. The chief methods of treating and purifying water are discussed in TM 5–295.

49. SANITARY QUALITY. a. Most surface waters are polluted. They must be purified to make them safe for drinking. This also is true of many ground waters at shallow depths in unconsolidated materials, and especially of waters in fissured and creviced rocks such as limestone and basalt. Such rocks may transmit polluted water for miles without purifying it, whereas water passing through porous materials such as sand and sandstone generally is purified by filtration. The distance water must move before bacteria are destroyed depends on several factors, among them the size and shape of the pore spaces through which it moves. Coarse gravel may be no better filter than fissured limestone and basalt. In its natural state, ground water in granular materials below impermeable confining beds generally is bacteriologically pure.

b. Well drilling and spring development invariably introduce bacteriological contamination into the water; hence, wells and developed springs should be sterilized with chlorine or other germicides, and thoroughly pumped out, before the water is used for drinking.

c. In many places, especially in swampy areas of regions of high rainfall and warm climate, shallow ground water may contain relatively small quantities of mineral matter but large quantities of organic matter in solution. Such water generally has a musty or otherwise objectionable taste. Boiling will not remove the organic matter entirely, and chlorination may form compounds with stronger tastes than those in the raw water. Although such waters are objectionable for drinking, they can be used safely after being sterilized properly.

50. SANITARY PROTECTION OF DRILLED WELLS. a. General conditions. (1) The protection of drilled wells is a problem that begins before the well is sunk, for a proper well site may be the controlling factor in insuring a continued supply of sanitary water. The factors to consider in choosing a site are distance from existing sources of pollution; location with reference to flooding; direction of movement of ground water; character and thickness of material lying above water-bearing formation; and character, depth, and water-bearing properties of formations to be tapped. Local conditions vary so widely that to overlook any one of these factors may seriously impair the quality of the water.

(2) Contamination may enter a well either from the surface or underground, and hence a well is properly constructed only if pollution is excluded from both these sources. The proper methods of finishing a well at the surface are relatively simple and are essentially the same for most types of well, regardless of the system of drilling used. To prevent underground contamination, special methods of finishing have been developed. Most contamination at the surface enters the well through the well opening. Hence the space between the casing and the pump pipe must be tightly sealed with a well seal or a suitable

bushing and packing gland. The annular space between the wall of the hole and the well casing also should be securely sealed to prevent the downward percolation of surface water or waste.

(3) The casing of a drilled well should extend at least a foot above the general level of the surrounding ground or pump-room floor, or above the bottom of the pump pit, if used. In some States, pump pits are prohibited at wells intended for public use.

(4) Protecting a well from underground contamination primarily involves excluding polluted ground water or highly mineralized water that is unsuitable for use. Defects that permit underground contamination are insufficient, faulty, or improperly seated casing, and defective sealing between casings of different sizes.

(5) Casing requirements are different for each well. The problem of protecting a well under water-table conditions is somewhat different from that arising under artesian conditions. Most contamination is at the water table; hence, a water-table well should be cased to a point below the lowest level ever reached by the water table when the well is pumped. Shallow formations carrying water in solution channels, fractures, and crevices are not suitable sources of supply unless the water is chlorinated, because such passages afford little or no filtering action.

(6) Because a more or less impervious formation usually overlies an artesian aquifer, artesian water is contaminated by direct percolation from above only as contamination may enter directly through existing wells or through space between the well wall and the casing. Hence, an artesian well generally should be cased tightly from the ground surface to the water-bearing formation it taps, though under certain conditions the casing of a deep well may be securely seated in an impervious formation above the water-bearing stratum.

(7) Improperly seated casing permits contamination to enter the well from higher levels of polluted ground water or highly mineralized water. Such water may percolate down through the space between the wall of the hole and the casing. The remedy is to seat the casing securely in an impervious formation above the water-bearing stratum. If this cannot be done, the casing should be cemented tightly in the hole by one of the special methods devised for such work (see TM 5-297).

(8) Unless the space between casings of unequal diameters is sealed effectually, highly mineralized waters detrimental to the supply may enter. Proper construction requires that such casings overlap by at least one joint and that a suitable seal of lead or similar material be used to close the space between them. To insure absolute protection, the inner casing can be extended to the surface.

b. Special methods for protecting casings. Since casing deteriorates, and conditions sometimes make ineffective the usual procedure for shutting out polluted or highly mineralized water, special methods have been devised for sealing and protecting the casing with cement. These methods are described in TM 5-297.

c. Chlorination of completed wells. Chlorinating new wells is an essential part of good construction, particularly where the well is intended as a source for a municipality or for military forces. During construction, considerable contamination may be introduced into the well on the drilling tools or the well casing, or by using gravel from polluted sources. Contamination on the tools is not avoided easily, but gravel can be freed from contamination by washing with chlorine solution. A well may be chlorinated under pressure or simply by introducing a strong solution of chloride of lime into it with a dump bailer. The former procedure probably is the more effective but requires special pumping equipment usually not available with cable-tool drilling machines. Under most conditions, chlorination by use of a dump bailer is adequate; but if the hydrostatic head is not excessive and if the well remains contaminated after a thorough pumping following a dosing with a dump bailer, chlorination under pressure may be desirable.

CHAPTER 7

GROUND-WATER RECONNAISSANCE

SECTION I

SOURCES OF INFORMATION

51. SPECIAL REPORTS ON SPECIFIC AREAS. a. One of the most valuable sources of information on general geology and ground water in foreign areas of military operations is a series of Terrain Intelligence Folios prepared by the Intelligence Branch, Corps of Engineers, in cooperation with the U. S. Geological Survey. These folios contain data on resources, industries, and engineering problems of the countries, regions, or islands covered. They include maps of topography, geology, and ground-water provinces, and tables of information on water supplies of all important cities and towns. If no other references for an area are at hand, the Terrain Intelligence Folio for that region can be used as a reliable guide for developing a ground-water program for troop units.

b. General information on sources and use of water in foreign countries can be obtained from survey reports by the Military Intelligence Division, War Department.

c. The Office of Strategic Services, Research and Analysis Branch, has prepared topographic intelligence studies on a number of foreign areas.

d. Some general information on water supply is included in field monographs on various countries by the Division of Naval Intelligence, U. S. Navy Department. More specific information on water sources appears in a series of reports on water resources data by the Bureau of Yards and Docks, U. S. Navy Department.

e. British sources of general information and ground-water data for various countries include the Inter-Service Topographical Department reports and the Inter-Service Information Series.

52. LOCAL AUTHORITIES. In any foreign country, the national and state or provincial geological survey reports usually are the best sources of information on geology and ground-water supply. Some reports of the U. S. Geological Survey are available for all possessions of the United States.

53. MAPS AND AERIAL PHOTOGRAPHS. Base maps, topographic maps, and geologic maps are prepared by the Corps of Engineers, U. S. Army, and the U. S. Geological Survey, for all large areas of military operations where such information is available. Many of these maps are of small scale and cover extensive areas; they should be supplemented by local maps or aerial photographs when ground-water reconnaissance is begun. Photomaps, described in TM 5–240, are prepared by the U. S. Army Air Forces and the Corps of Engineers for detailed tactical and developmental operations in the various theaters of operations.

54. GENERAL REFERENCES. A list of references on general ground-water geology and hydrology is presented in appendix I.

SECTION II

FIELD RECONNAISSANCE

55. TYPES OF RECONNAISSANCE. a. General. (1) Since location and development of ground water are essentially geologic problems, ground-water reconnaissance is basically a type of geologic surveying. The paragraphs below may be used as a guide for engineer officers in developing ground water for troops.

(2) Ground-water reconnaissance usually involves study of rock structure and topographic forms; location and study of springs and other water at or near ground surface; plotting on a map all points where field studies are made; assembling all available information on local wells; and locating sites for wells.

b. Instruments. (1) Many different instruments are used in geologic surveying, depending upon the type of work and the degree of accuracy required. For most types of geologic reconnaissance the Brunton and Gurley compasses are most convenient. They consist of a metal case, folding open sights, a swinging clinometer, a small spirit level, and an accurate compass. They are used for measuring direction, for determining dip and strike of rock formations, and for hand-leveling if a hand level is not available. Since neither compass is regularly issued to engineer troops other instruments are used for most ground-water work.

(2) The standard Army compass and the Abney level can be used in conjunction for most purposes served by the Brunton compass. The uses of the Abney level and the standard compass for ordinary surveying are described in TM 5–235. If an altimeter is available (see TM 5–235), it will save time in measuring difference in elevation.

(3) Where base maps are inadequate a plane table with either the open-site or telescopic alidade (TM 5–235) can be used to locate important features and to map topography.

c. Measurement of dip and strike. (1) *The dip of a rock formation is the angle of inclination of a rock stratum or formation with a horizontal plane.* The direction of dip always is measured at right angles to the strike. *The strike of a rock stratum is the direction of the line of intersection of its surface with a horizontal plane* (see fig. 31).

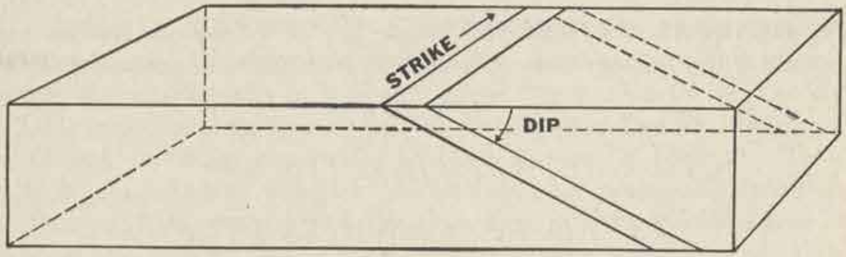

Figure 31. Block diagram showing dip and strike.

(2) The clinometer of the Abney level can be used to measure dip in the same way as to measure angle of land slope, except the angle of dip always is downward. The compass should be held so the line of sight extends parallel to the bedding planes or other features of the stratification and the bubble on the swinging arm is centered to establish the horizontal. Then the angle between the line of sight and the horizontal, as read on the scale, is the dip of the rock formation. A dip less than 3° is difficult to read and generally should be expressed in feet per mile of slope. The direction of strike at several different points should be obtained with a compass on a flat surface. The readings should be averaged, because rock formations have many irregularities.

d. Traverses. (1) The types of traverse which may be required for a reconnaissance of ground-water possibilities are many and varied, depending upon the base maps available, the scope or size of the water-development program, and the accessibility of the area. If roads are well distributed, most of the reconnaissance can be made with a light truck or automobile. If the topography is rugged and roads are lacking, the field work may be done on foot or by horse.

(2) The first step should be preliminary inspection of the entire area to be investigated. The main features of topography, drainage, rock outcrops, vegetation and other indications of ground water should be noted and their approximate positions plotted on the base map. Existing wells and springs should be located.

(3) Before locating sites for wells the important ground-water features should be investigated in detail and plotted accurately on the base map. The routes of detailed traverses should be planned to allow all outcrops of possible water-bearing formations to be studied and their relations to topography and intake areas understood. Routes of surveys, extent of outcrops, and trends of ridges, valleys, and bluffs should be determined by compass traverses, especially if a topographic map is not available. Relative elevations of important points should be determined by hand level or by an altimeter.

(4) The following outlines give essential procedure for compass traverse and plane-table traverse:

(*a*) Compass traverse involves using a compass for direction, pacing for distance, barometer for elevation, and notebook for plotting. Positions throughout the traverse are referred to a few control stations on the base map, which is ruled with both north-south and east-west coordinates. Set the compass for true azimuths or bearings. Determine the elevation of the starting point or assume an arbitary elevation. Record the barometer reading at least 30 minutes before leaving the starting point and again when beginning the traverse. The starting point can be called Station 1, and plotted upon the map. Find the bearing or azimuth of a line from Station 1 to Station 2, and plot this line on the map. Pace toward Station 2, stopping when necessary to make offsets, to examine important features, and to record necessary data. Scale and record distances from the starting point to the stops. Continue pacing until Station 2 is reached. At Station 2, record the distance from Station 1. Check the bearing or azimuth by backsight on Station 1, if it can be seen. Read the barometer and determine the elevation of Station 2. Locate a point on the map for Station 3 and proceed as before.

(*b*) Plane-table traverse involves determining direction by open-sight alidade, distances by pacing, vertical distances by clinometer, contours by referring to differences in elevation, and plotting by oriented plane table (see TM 5–235). It requires the same basic conditions as the compass method, and also that both Station 2 and another control point (K) be visible from Station 1. At Station 1 set up the plane table and orient it by backsight to K. Sight at Station 2—and 3 if possible—and draw a line to Station 2. Determine the slope angle from Station 1 to Station 2, and record it. Determine and plot azimuths to any other important point. Find positions of several contour points between Stations 1 and 2, and sketch contours. Pace the distance from Station 1 to Station 2, record necessary information and plot important points. Find slope angles and directions, and record offsets to important features. Scale the distance to Station 2 and make corrections for slopes if necessary. At station 2 set up the plane table and back-sight on Station 1 for alignment. Select a suitable point for Station 3 and continue as before.

56. USE OF BASE MAPS. a. For most ground-water surveys, the best type of base map is a topographic map with a scale not less than 1:63,360, similar to the U. S. Geological Survey quadrangle maps, 1:62,500. The positions of outcrops, the extent of each rock formation at the land surface, and the borders of alluvial formations can be plotted on such a map; and their relations to topography immediately are evident.

b. Aerial photographs, aerial mosaics, and photomaps are good base maps, but they show elevations less positively than topographic maps. Photomaps are adequate base maps for most geologic work, and the commonly used scale 1:20,000 is satisfactory in most areas. The military grid can be used for reference to important points of the survey and for reporting well locations.

57. OUTCROPS. a. The best places to find outcrops are cliffs, steep slopes, hilltops, stream banks, shore lines, road cuts, and artificial excavations such as quarries. In prospecting for ground water special study should be given the common types of water-bearing rock such as sands, sandstones, gravels, fractured and cavernous limestones, porous basalts, and highly fractured formations of any type.

b. Before making a detailed study, each outcrop first should be observed as a whole. Its extent and its general relationship to its surroundings should be determined and plotted on the base map. In the detailed study of an outcrop at least the following points should be noted:

(1) Type or types of rock.

(2) Stratification—thickness and dip of all visible beds.

(3) Porosity and probable water-bearing characteristics.

(4) Grain size and degree of sorting.

(5) Contacts between formations.

(6) Possible unconformities.

(7) Degree of cementation.

(8) Joint systems—spacing, amount of open space, and arrangement.

(9) Possible cavernous conditions.

c. Often the best method of recording information is to sketch a cross-section of the outcrop, with appropriate notes opposite each bed. Fossils are important means of correlating sedimentary rocks, but inexperienced persons are likely to be misled by mistaking for the same species similar types in different localitites.

d. All outcrops in the area under investigation should be traced or "walked" as far as possible. Any seeps or zones of moisture should be studied and traced, because the rock from which they issue probably will yield water at other places.

58. SURFICIAL GEOLOGY. Determination and mapping of the surface extent of various rock formations in simple in areas of flat-lying beds, and highly complex where rocks are tilted, faulted, or folded. If an area is covered with glacial till, the map of surface outcrops shows only one formation over the entire area. If the rocks dip steeply in one direction, the surface outcrops are in straight belts or bands. More resistant rocks tend to produce ridges and other elevations in topography, while softer beds tend to occupy low places and the lower flanks of slopes. When the common rocks in an area have been studied at their outcrops their surface extent should be determined to identify properly the surface formations at sites where wells are to be drilled. For identifying and mapping rock formations at the surface the following five types of observation have greatest value:

a. Rock type. Classification as to origin, igneous, sedimentary, or metamorphic, is made first at important outcrops. The rock may have conspicuous minerals, such as mica, or typical colors which can be seen where soils are thin or in minor outcrops such as creek banks.

b. Topography. Rock formations have typical topographic forms throughout an area. Such characteristic topographies are caused by different degrees of hardness and resistance to weathering. Thus, hard sandstones tend to occur on high ridges. A resistant limestone appears in ledges or benches along valley sides, with more gentle slopes on softer beds above and below it.

c. Vegetation and soils. Typical plants occupy the areas of distinct rock formations and, together with the soils, are good guides to the underlying rock. Sandstones typically have sandy soils which in some areas support forest growth. In many areas, limestones have dark or gray clay soils. Some metamorphic rocks have soils abundant in mica. When characteristics such as these have been identified with rocks of an area they can be used as good guides to mapping.

d. Stratification. A typical sequence such as sandstone, limestone, and shale in an outcrop can be used to identify beds on the surface. The order of bedding shown in the outcrops can be expected elsewhere. If a conspicuous bed can be located on a slope, the adjacent beds can be located even if they do not crop out.

e. Fossils. In many sedimentary rocks fossils furnish a basis for accurate correlation from one place to another, but successful use of this method requires much study and practice.

59. EXISTING WELLS AND SPRINGS. Posssibly the most important item in a ground-water survey is a complete tabulation of information on existing wells and springs. This can be assembled while investigating the geology and topography of the area. Locations of all wells and springs should be plotted on the base map. Natives of the area, especially owners and users of the wells, should be consulted whenever possible, and the drilling records of drillers who operate in or near the area should be obtained. The following items should be tabulated for each well so far as possible:

Type of well (drilled, bored, or other).
Kind of casing (and screen if used).
Total depth.
Depth at which water first was found.
Depth of all water zones in well.
Present static level of water.
Amount of water produced.
Draw-down of water when pumped.
Complete log of the well. (For form of a well log see tables I and II.)
Date constructed.
Elevation, or relative height, at the curb.

60. PREDICTION OF LOGS. a. The prediction of the log as to total depth and depth to water in a proposed well is important in military operations because the time involved, the amount of casing needed, and the type pump required, all depend upon the characteristics of the new well.

b. All the information assembled in the ground-water reconnaissance must be used in predicting the log. If the well is to be at the same elevation as an existing well for which the log is known, it should have a similar log and water-producing capacity. If no local well records are available, and only a thin rock section is exposed in the surrounding area, only an indefinite prediction can be made. For such wells some test drilling may be necessary.

61. LOCATION OF WELLS. **a.** The final decision on locating a new well is based upon all the information obtained by the reconnaissance survey. If the best water prospects have been found in shallow alluvial sediments in a valley several possible locations should be selected, because alluvial sediments vary markedly from place to place (see fig. 15). If the first location does not yield enough water, test holes may be necessary to supply large troop units. If water for temporary use during beach landings along a coast is required, shallow drive-point wells can be sunk within an hour. Larger supplies can be developed farther inland as the troops advance. This procedure was followed in North Africa and Sicily when American troops landed in 1943. Enough water for immediate use was obtained on the beaches.

b. Upland sites for shallow wells should not be nearer than 250 yards to high bluffs or deep valleys, because water usually percolates more rapidly from formations exposed in nearby outcrops.

c. Surface-water seepage and contamination can be minimized by locating on well-drained sites, but isolated high points or hills should be avoided because of the deeper drilling required.

SECTION III

SUBSURFACE CORRELATION

62. TEST DRILLING. **a.** The purpose of test drilling is to obtain information on depth to water, amount of water, thickness and character of rocks, and nature of deeper water zones. Test drilling is necessary in undeveloped regions where surface water is scarce and few wells have been drilled. Some areas of operation in the present war have required considerable test drilling and almost certainly more will be needed, especially if operations are expanded in Asia and Asia Minor.

b. In this paragraph the term "test drilling" is used to include boreholes, dug pits, and experimental driven wells. The choice of equipment depends upon the conditions and depths required. In soft formation which do not cave badly the post-hole or Ivan auger, operated by hand, is effective to depths of 50 to 60 feet. In beach sands and sandy alluvial deposits, the water yield can be tested by small drive points to depths of 100 feet or more but such wells do not give exact information on the formations penetrated. The Army's drilling machines can sink test holes 1,000 feet or more, but unless the need for water is acute and there are no other promising prospects within a reasonable distance, test drilling deeper than 500 feet generally is not advisable.

c. The most promising sites should be drilled first. In a desert basin, for example, first attention should be given to favorable sites in the central or lower part of the basin around the playa lake. If water at all depths in that locality is too salty or too scarce an entirely different location, such as the alluvial slope around the sites of the basin, should be prospected. In an alluvial valley where the climate is semiarid or subhumid, several holes located to represent a cross section of the valley should be drilled before abandoning the valley as a source of water.

d. Deep drilling in granite and related rocks generally is useless. If water is not found in a weathered surface zone or in overlying rocks, deeper drilling should not be attempted.

63. SAMPLING. a. Collecting samples. Samples of the rocks penetrated by test holes should be collected at vertical intervals not greater than 5 feet. In auger holes, samples can be taken by gouging the material from the bottom of the auger blade, after pulling the auger from the hole. In dug holes, a continuous section can be sampled from the wall of the hole. In drilled wells, sampling methods differ with the type of machine. With the percussion machine a clean sample can be collected from the bailer when it is first pulled from the hole after a "run." With the rotary drill, samples of the mud can be collected at intervals, then washed for examination (see TM 5–297). Samples should be saved in cloth bags or other containers and labeled accurately according to depth.

b. Study of samples. (1) All samples from each well should be studied carefully and the field descriptions recorded in a notebook with other data on the well. If laboratory facilities are available, they should be used for more detailed study. For test-drilling programs and drilling jobs requiring several wells, it is necessary to know the depths where previously prospected water-bearing beds will be found. This knowledge can be gained only where the successive formations can be identified as the well is drilled. *Correlation of rock strata means the identification of specific beds of formations at separate points,* it is the most important objective of test drilling.

(2) A few simple tools can be used to advantage in studying well samples, or rocks in outcrops. They are a small hand lens, an ordinary pocketknife, a small bottle of dilute hydrochloric acid, and a small glass plate.

(3) The proper identification of rocks depends upon the identification of their constituent minerals, but with the aid of simple hardness, color, and other tests, anyone can distinguish some of the large rock groups.

(*a*) *Sandstones* and other sandy rocks typically have an abundance of quartz grains, which appear glassy under a hand lens and are hard enough to scratch glass.

(*b*) *Limestones* are composed largely of calcium carbonate grains, which effervesce freely when treated with dilute hydrochloric acid.

(*c*) *Dolomites* are composed of calcium and magnesium carbonate; the grains effervesce only slightly when treated with dilute hydrochloric acid. Calcite (limestone) and dolomite grains can be scratched by an ordinary knife point.

(*d*) *Silts, clays, and shales* are composed of particles so small they cannot be distinguished clearly with an ordinary hand lens. Their colors range from black through red, green, and gray, to white.

(*e*) *Igneous rocks* have a high proportion of silicate minerals, most of which are harder than a knife blade. Samples of drill cuttings in igneous rocks generally are composed of sharp, angular particles. *Granites* and related rocks have light gray or pink color, and *basalts* typically are dark gray, or greenish.

(*f*) *Metamorphic rocks* may be composed of practically any combination of minerals, but they have high average hardness and characteristic structures—slaty, banded, or crumpled.

64. TESTING WELLS. **a.** Except in emergencies, such as beach landings, where no other water is available, wells should not be used until both quality and yield have been tested. Quality of water is tested with the standard Army filtration-unit test sets (see TM 5–295).

b. The yield of wells is tested by bailing or pumping and by measuring the water in a container of known volume, such as an oil drum, or by a meter attached to the pump discharge pipe. For small yields of 4 to 8 gallons per minute in shallow wells a hand-pump test lasting at least 1 hour should be made and the draw-down measured about every 15 minutes. Motor-driven pumps should be used for testing deep wells and wells of larger yield, and the test runs should be continued for several hours. If the yield is too small, additional wells should be sunk. For descriptions of pumps and their operation, consult TM 5–297 and instruction sheets furnished with Army pumping equipment.

SECTION IV

REPORTS

65. REPORTS. Upon completion of a ground-water study and development project, the officer in charge should prepare a complete report of the operation which can be used as a guide in later water projects in the vicinity or in adjacent areas. The report should contain all details of the reconnaissance study, the test drilling, final drilling, and testing of wells, and a copy of the field map used in the work. The following outline may be used as a guide to preparing the ground-water report:

OUTLINE FOR GROUND-WATER REPORT

I. Methods used in field study.
- A. Traverses (show on base map).
- B. Equipment.

II. Previous reports on the area (references).
- A. Army or Navy reports.
- B. Local reports or records.

III. General description of the area.
- A. Location.
- B. Topography and drainage.
- C. Climate and vegetation.
- D. Rock formations—types, thicknesses, structures, chief water-bearing zones.

IV. Existing wells and springs.
- A. Location and distribution.
- B. Individual well records.
    1. Depth, elevation, and type of well.
    2. Yields.
    3. Logs.
    4. Age.

V. Test drilling.
- A. Locations and elevations.
- B. Equipment used, and sizes of holes.
- C. Log records and sample descriptions.
- D. Records of water zones.
- E. Report of pumping tests.
- F. Quality of water.

VI. Final wells.

Same items as for test wells.

VII. Later history of wells as they are used (to be added at some later date).

APPENDIX I

GEOLOGIC TIME TABLE

Geologic time is subdivided into eras, periods, epochs, ages, and smaller units. The corresponding names for the rock bodies are groups, systems, series, stages, and smaller units. The order of the following time scale is in stratigraphic sequence, with the oldest at the bottom and successively younger periods toward the top.

Era or group		*Period or system*
Cenozoic	Recent	Quaternary
	Pleistocene	
	Pliocene	Tertiary
	Miocene	
	Oligocene	
	Eocene	
Mesozoic	Cretaceous (Upper Cret.)	
	Comanchean (Lower Cret.)	
	Jurassic	
	Triassic	
Paleozoic	Permian	
	Pennsylvanian	
	Mississippian	
	Devonian	
	Silurian	
	Ordovician	
	Cambrian	
Proterozoic	Keweenawan	
	Animikian	
	Huronian	
	Algomian	
	Sudburian	
Archeozoic	Lawrentian	
	Keewatin	

APPENDIX II

GLOSSARY

Aeration, zone of. The zone above the water table, usually below the soil layer, in which the pore spaces are filled partly with air and partly with moisture. Also, *zone of percolation.*

Alluvial deposits. Sediments deposited on land by water and wind and associated plant and animal agencies.

Anticline. A fold in which the beds dip downward in two directions from a central axis.

Aquifer. A rock formation which yields a usable amount of water to wells or springs.

Arid. Dry. An arid climate is one in which the average annual rainfall is less than 10 inches.

Artesian. An artesian condition is one in which water is in a confined rock formation under hydrostatic pressure.

Basalt. Dark-colored, heavy, fine-textured igneous rock formed at or near the ground surface, usually as a lava flow.

Basin. A rock structure in which the strata dip downward in all directions toward a center.

Capillarity. The force of attraction of extremely small openings upon liquids.

Chalk. Soft, relatively pure limestone of uniform texture.

Chert. A noncrystalline mineral composed of silica (SiO_2), the same composition as quartz.

Clastic rock. A fragmental rock composed of pieces or fragments of other rocks.

Clay. Fine-grained unconsolidated clastic rock having a majority of particles less than 0.005 inch in diameter.

Conglomerate. Coarse-textured, cemented, clastic rock in which the individual fragments are chiefly pebbles or cobbles. A cemented gravel.

Consolidated rock. Hard, solid rock.

Contamination. Mixing of undesirable (unpotable) substances, such as salt, with water.

Correlation. The identification of correct ages of rock beds or formations in wells or separated outcrops.

Dip. Angle of downward inclination of a rock formation from the horizontal.

Dolomite. A sedimentary rock similar to limestone but having magnesium carbonate chemically combined with calcium carbonate.

Dome. A rock structure having dips in all directions from a center.

Extrusive. An igneous rock that has cooled and solidified on the surface of the earth.

Fault. A fracture in rocks along which movement has occurred.

Fault, normal. A fracture along which movement has displaced the overhanging side downward.

Fault, reverse. A fracture along which movement has displaced the overhanging side upward.

Felsitic. Like felsite. Fine-textured, light-colored igneous rocks.

Flint. A noncrystalline silica mineral similar to chert.

Fold. A rock structure in which the beds incline upward or downward from a central axis. See *anticline* and *syncline*.

Glacial drift. A general term including all deposits made by glaciers and glacial streams.

Gneiss. Coarse-textured, banded, metamorphic rock produced from other rocks by great heat and pressure.

Granite. Coarse-textured, light-colored igneous rock containing quartz and feldspar.

Gypsum. A sedimentary rock mineral consisting of hydrous calcium sulfate.

Humid. A humid climate is one which has an average annual rainfall of 30 inches or more. See *subhumid*.

Hydrologic cycle. The hydrologic cycle is a series of processes by which water and condensed moisture circulate from the oceans, through the atmosphere, into surface-water and ground-water reservoirs, and return to the oceans.

Igneous rock. Rock which has formed by cooling and solidification from a molten condition.

Intrusive. An igneous rock formation which cooled beneath the earth's surface.

Joint. A fracture in a rock stratum or formation.

Laminar flow. Smooth flow in fluids, as between grains in a rock. *See* turbulent flow.

Lateral gradation. Changes in character and thickness of a rock formation from one locality to another, usually resulting from differences in local conditions of deposition.

Lava. Igneous rock which cools upon the surface of the earth.

Limestone. A sedimentary rock formation composed chiefly of calcium carbonate.

Lithology. Refers to rock composition and texture.

Loess. Wind-deposited accumulation of angular, silt-size particles.

Marble. A metamorphic rock altered and recrystallized from limestone by heat and pressure.

Metamorphic rock. A rock which has been altered by great heat and pressure.

Mica. A type of silicate minerals having high luster and platy form.

Molecular force. The force of attraction of surfaces for adjacent fluids.

Monocline. A step-like bend in otherwise uniformly dipping beds.

Obsidian. Volcanic glass.

Perched water. Relatively small concentrations of ground water above an impermeable layer in the zone of aeration.

Permafrost. Permanently frozen ground in arctic and antarctic regions.

Permeable. A permeable rock is one which will transmit water.

Pervious. Synonomous with permeable.

Playa. A basin containing temporary lake water, usually in desert environment. Also, an area of discharge of ground water by evaporation.

Pollution. Bacterial impurities in water.

Porosity. The proportion of open spaces in a rock in relation to its total volume.

Potable. Drinkable (liquids).

Pyrite. A metallic rock mineral composed of iron sulfide.

Quartz. A hard, crystalline rock mineral composed of silica.

Quartzite. A hard, metamorphic rock composed chiefly of quartz.

Reconnaissance:

Geologic. Preliminary field examination of geologic features.

Ground-water. Preliminary field examination of ground-water features.

Sandstone. Sedimentary rock chiefly composed of sand grains.

Saturation. A condition in which all pore spaces in a rock are filled with water. *Zone of saturation.* The zone where all rock cavities are filled with water.

Schist. Metamorphic rock having thin laminations and exhibiting one or more conspicuous minerals. It is formed from other rocks by heat and pressure.

Sedimentary rock. Rock formed at the surface of the earth from fragments of other rocks by water, wind, and associated biological agencies.

Semiarid. A semiarid climate is one with average annual rainfall of 10 to 20 inches.

Shale. A fine-grained sedimentary rock having abundant clay minerals.

Silica. A chemical compound, silicon dioxide, abundant in rocks.

Silt. A textural term for sediment having grain sizes smaller than sand but larger than clay.

Slate. A metamorphic rock formed from shale by great heat and pressure.

Static level. In a well, the level at which water stands when it is not pumped.

Specific yield. The volume of water which a rock will yield in proportion to its total volume.

Stratification. Bedding in a sedimentary rock.

Subhumid. A subhumid climate is one with average annual rainfall of 20 to 30 inches.

Syncline. A rock structure in which the strata dip in two directions toward an axis.

Till. An unstratified, unsorted glacial deposit.

Transpiration. Evaporation through the action of plants.

Turbulent flow. Free flow of fluids in open channels. It is characterized by eddies and cross currents.

Unconformity. A break representing an interval of erosion between two rock strata or formations.

Water table. The upper surface of the saturated zone.

APPENDIX III

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