Many other folds have been recognized in the rocks of Oklahoma, some of them being the sites of productive oil and gas fields.

WATER-BEARING FORMATIONS

Ground water in Oklahoma occurs in a variety of rock formations—sand, gravel, limestone, dolomite, sandstone, and gypsum. These range in age from Cambrian and Ordovician, represented by the Arbuckle group, to Recent stream-laid sediments. They are not continuous. Where the rocks at or near the surface are porous and permeable and contain no undesirable soluble minerals, moderate to abundant supplies of good water are found. In intervening areas where the rocks are less favorable, only meager supplies, perhaps barely adequate for a farm, domestic, or stock well, will be found. The principal aquifers, or ground-water basins, in Oklahoma are:

- Unconsolidated sediments, mainly sand and gravel
  - Alluvium (along streams)
  - Terrace deposits (western half of State)
- Unconsolidated or slightly consolidated sediments, mainly sand and gravel
  - Tertiary and Quaternary deposits (High Plains)
- Bedrock formations
  - Paluxy sand
  - Rush Springs sandstone
  - Dog Creek shale and Blaine gypsum
  - Garber sandstone and Wellington formation
  - Wichita formation
  - Vamoosa formation
  - Boone formation
  - Roubidoux formation
  - Simpson and Arbuckle groups

Simpson and Arbuckle groups.—The Arbuckle group, of Cambrian and Ordovician age, crops out widely in the Arbuckle Mountains (Murray, Johnston, Pontotoc, and Carter Counties) and less widely in the Wichita Mountains (Comanche, Caddo, and Kiowa Counties). The Simpson group, of Ordovician age, crops out in the Arbuckle Mountains. The rocks dip away from the mountains and within a few miles are so deep beneath the surface that water wells to them are hardly practical and the water is likely to be highly mineralized. The Simpson comprises a thick section of rock strata, but it has a rather narrow outcrop belt because of the steep dips. The limestone and dolomite formations in these groups contain fractures and solution channels from which they yield water through springs and might yield water to wells. Few wells, however, have been drilled because so far the demand for water has been low. Included also are several water-bearing sandstones.

Not uncommonly wells in these groups are artesian, with enough pressure to flow at the surface. Some wells and springs yield large volumes of water, but at other locations the strata are barren of water because of lack of openings to contain it. Hence, the success of a well depends on whether it happens to be drilled where there are openings. For years the city of Ada has obtained its public water supply from Byrd's Mill spring, which issues from the Arbuckle group and is reported to yield from 3 or 4 million to 18 million gallons per day. The water from this spring is very hard, the hardness, exceeding 300 parts per million as calcium carbonate. Water from flowing wells at Lawton, on the south side of the Wichita Mountains, as shown by four analyses, is soft but high in sodium. These same analyses show unusually high fluoride—10 parts per million (Dott, 1942, p. 38).

Roubidoux formation.—The Roubidoux formation, of early Ordovician age, consists of dolomite and interbedded sandstone. At some places two layers of sandstone are present, and at other places three. The formation does not crop out in Oklahoma, but is present in the subsurface rocks of the northeastern part of the State, where it is tapped for water supply mainly in Ottawa County. Its potentialities in that county are discussed by Reed and Schoff (1955). The thickness of the formation in Ottawa County, as indicated by 11 well logs, ranges from 105 to 180 feet and averages 160 feet. The top of the formation was reached at depths ranging from 880 to 1,020 feet below the land surface in the different wells. All the public water supplies and most of the industrial water supplies in the county are drawn from the Roubidoux. Wells yield up to 600 gallons per minute, but drawdowns are large and water levels have declined progressively. The water is generally of the calcium bicarbonate type, moderately hard, and rather low in dissolved solids. The hardness is mostly carbonate (temporary) hardness, and the water can be softened rather easily, if necessary.

Boone formation.—The Boone formation, also known as the Boone chert and Boone limestone in nearby areas, of Mississippian age, crops out over most of the Ozark area in northeastern Oklahoma, from southern Cherokee and Adair Counties northward across eastern Mayes County, Delaware County, and Ottawa County. It has an average thickness of about 300 feet, contains many fractures and solution cavities, and therefore has relatively high reservoir capacity. Furthermore, it crops out in an area of relatively high precipitation, for Oklahoma, and so acquires a relatively large volume of ground water. The underlying impervious Chattanooga shale stops the downward movement of ground water through the Boone formation, and springs issue where the contact of Boone on Chattanooga comes to the surface (Dott, 1942, p. 38-40). Many wells tap water in the Boone formation in and adjacent to the area of outcrop, but as is true of limestones generally, the success of a well depends in part on chance in encountering fractures and solution openings. As surface contamination may be introduced with the water replenishing this aquifer, and as the Boone, like other limestones, effects little or no purification of the water, frequent bacterial analyses of the waters are desirable where they are used for human consumption. The waters of this limestone are generally moderately hard and of good quality. Analyses of 17 samples of water from wells and springs in Adair, Cherokee, Mayes, Delaware, and Ottawa Counties indicate the following range in principal constituents: dissolved solids, 109 to 274 parts per million; hardness, 26 to 295 parts per million; sodium and potassium, 1.3 to 64 parts per million; bicarbonate, 62 to 205 parts per million; chloride, 4 to 29 parts per million. The availability of ground water in the Boone formation in Ottawa County is discussed by Reed and Schoff (1955).

Vamoosa formation.—The Vamoosa formation crops out in a band extending southwestward from northeastern Osage County to southern Seminole County. It includes sandstone and some conglomerate, interbedded with shale, the whole ranging from 250 to 500 feet in thickness. This formation is believed to yield water more freely at Seminole (from 50 to 150 gallons per minute) than in other parts of its area.

In Creek County the water from this formation has moderate concentrations of calcium, magnesium, and sodium. Westward in Lincoln County and at greater depths down dip, dissolved solids are higher and considerable calcium and sodium sulfate are present. In Seminole and Pottawatomie Counties the concentrates of dissolved solids are about the same as in Creek County, with considerable amounts of sodium bicarbonate (Dott, 1942, p. 40). Analyses show a range in hardness of 12 to 600 parts per million.

Wichita formation.—The Wichita formation, of Permian age, crops out in south-central and southwestern Oklahoma and consists of red shale and sandstone, similar in general character and in part equal in age to the Garber sandstone and Wellington formation of central Oklahoma. This formation has been tapped for industrial water supplies, especially in the oil fields of Garvin County, but the draft on it is light. Yields up to 175 gallons per minute from individual wells have been reported. Water from the Wichita formation is generally low in calcium and magnesium but contains large amounts of sodium bicarbonate, sulfate, and chloride. A median analysis based on 35 published analyses indicates that the water from the lower part is softer, although having a higher concentration of sodium sulfate and carbonate, than that from the upper beds (Dott, 1942, p. 42).

Garber sandstone and Wellington formation.—The Garber sandstone and Wellington formation, of Permian age, consist of layers of sandstone and interbedded shale, and constitute the most important aquifer in central Oklahoma. Water from these beds is utilized in Garfield, Logan, Oklahoma, and Cleveland Counties but to the greatest extent in the latter two, where the thickness of the water-bearing zone is about 400 feet. The waters from these sandstones range from very soft to moderately hard and are generally high in dissolved solids.

Analyses of samples collected in 1954 from the public water supply of Norman and 2 wells of the University of Oklahoma show hardness ranging from about 6 to 32 parts per million; dissolved solids, 326 to 660 parts per million; sodium and potassium, 123 to 391 parts per million; bicarbonate, 278 to 378 parts per million; and fluoride, generally 0.2 to 0.7 part per million. Although yields from individual wells reach a maximum of 300 gallons per minute, the transmissibility of the sandstone is relatively low and the drawdown in pumping wells is correspondingly large. In and near Oklahoma City many industries, large commercial buildings, private homes, and outlying suburban centers rely on this aquifer.

Dog Creek shale and Blaine gypsum.—The Dog Creek shale and the Blaine gypsum of Permian age, crop out from northern Woods County southward through Woodward, Major, Blaine, Canadian, and Grady Counties, west-northwestward through Comanche, Caddo, Kiowa, Washita, and Beckham Counties, and southward in Greer, Harmon, and Jackson Counties. Only in the last four counties are they known to yield substantial quantities of ground water. There the gypsum appears to have been fractured and then the fractures have been enlarged by the dissolving action of underground water. The water moves rather freely through the resulting relatively large openings, and many wells yielding between 1,000 and 2,000 gallons per minute have been drilled. Yields are erratic, however—a "dry" hole may be drilled 100 feet, or less, from a well of high yield. By conventional standards, the water is too highly mineralized for human consumption, but some of it has been used for this purpose. It also has been used, apparently successfully, for irrigation, which has expanded rapidly since 1950.

Rush Springs sandstone.—The Rush Springs sandstone, of Permian age, crops out in central Oklahoma—Caddo and adjacent counties—in an area of about 2,100 square miles. It is thin near the eastern margin of its outcrop because of erosion, but near the western margin of the outcrop it exceeds 300 feet at places. Although very fine grained, it is abnormally porous because of removal by solution of the cementing materials—calcium carbonate or calcium sulfate. Many analyses of waters from wells in the Rush Springs sandstone in Grady and Caddo Counties indicate that water from this source is satisfactory in quality, although softening would be required for some uses. The ground water in the Rush Springs is used for the public supplies of several towns, and it is used increasingly for irrigation. Despite seeming uniformity of the formation, yields of wells range within wide limits. Some wells yield less than 100 gallons per minute. Others are reported to yield between 500 and 1,000 gallons per minute. In one discharge measurement the yield proved to be about 225 gallons per minute (Davis, 1950).

Paluxy sand.—The Paluxy sand, formation of the Trinity group of Cretaceous age, crops out in southern Oklahoma from western Love County eastward to the Arkansas State line. In part of the area between the northern limit of its outcrop and the Red River, it yields moderately large supplies of water. At many places the water is soft but contains high concentrations of sodium bicarbonate. In so large an area, however, the conditions under which the water enters and moves through the rocks to reach wells are so diverse that no general statement as to quality of the water is adequate. The mineral content of the ground water in the outcrop is certain to differ greatly from the mineral content miles down dip under cover of younger formations, where wells may be 600 feet deep. Water samples analyzed in laboratories of the U. S. Geological Survey have shown that some of the principal constituents range as follows: dissolved solids, 84 to 1,240 parts per million; hardness, 3 to 528 parts per million; sodium and potassium, 1 to 656 parts per million; bicarbonate, 10 to 854 parts per million.

Individual wells in the Paluxy sand yield up to 300 gallons per minute, but some wells pumped at about this rate have been ruined by the sand drawn into them. For a description of the ground water in the Paluxy sand of southern McCurtain County, see Davis (in preparation).

Tertiary and Quaternary deposits.—Calcareous sand, gravel, clay and mixtures thereof, together with caliche, underlie the High Plains and Plains Border sections of northwestern Oklahoma, in Beaver, Cimarron, Texas, Ellis, western Harper, western Roger Mills, and northern Woods Counties. In some reports these deposits have been referred to as the Ogallala formation, of middle Pliocene age, but they subsequently have been found to embrace sediments ranging from the Laverne formation, of early Pliocene age, upward into the Pleistocene. They furnish practically all the water used on farms in the area of their occurrence, and also the principal municipal and industrial water supplies. They are being tapped increasingly for irrigation water, especially in the Panhandle counties—Beaver, Cimarron, and Texas. Observations of water levels were begun about 1938, and the lowest levels were recorded in that year. Little change was recorded until 1941, when a gradual rise began. By May 1953 the net rise of average water level in the Panhandle counties was about 8.5 feet, the trend continuing upward from 1952 notwithstanding a decrease in precipitation that began about 1951. This rise contrasts sharply with the marked decline of water level that has occurred in the irrigated areas of the Texas High Plains, where the reservoir rocks and climate are similar but the pumping is more than 25 times the estimated rate of ground-water replenishment.

The hardness of water from these deposits in the Oklahoma Panhandle generally ranges from 200 to 300 parts per million. In other respects the water is of excellent quality. Yields of wells range upward to more than 1,000 gallons per minute. Reports on ground-water resources, primarily in these deposits, have been published for Texas County (Schoff, 1939) and Cimarron County (Schoff and Stovall, 1943).

Terrace deposits.—Like Alluvium, terrace deposits consist of stream-laid sand, gravel, and clay. The identity of the streams making the deposits is no longer apparent in some cases because they subsequently have shifted their channels laterally and have cut to lower levels. In Oklahoma the coarser beds in the terrace deposits generally yield water to wells more freely than does the bedrock, and not uncommonly the water is of better quality. It also may be better than water from alluvium but the quality is by no means uniform throughout the deposits. Replenishment of the ground water in terrace deposits comes mainly from precipitation upon them.

The terrace deposits are of Quaternary age. They occur along the north or northeast sides of the main streams in the northwest quarter of the State, and also in smaller patches in the counties bordering Texas in the southwest quarter. With them is associated much dune sand, which is wind-blown sand drifted in hummocks. Although generally too thin to afford much reservoir capacity and in most localities entirely above the water table, the dune sand contributes significantly to ground-water resources because it soaks up a generous fraction of the rain that falls on it, allowing it to percolate to the water table in the underlying terrace deposits. For descriptions of ground water in terrace deposits, see Reed, Mogg, Barclay, and Peden (1952), Barclay and Burton (1953), and Burton (1953).

Alluvium.—Alluvium is the material deposited by a stream. It may consist of gravel, sand, and clay in any proportion, and it underlies the flood plain or "bottom." It is generally thickest near the middle of a valley and thinnest where the flood plain adjoins the bluffs. It may be more than 100 feet thick along major rivers, but only a few feet thick along small creeks. At many places the alluvium is an excellent aquifer, both because the coarser beds in it will transmit water freely and because replenishment of the ground-water supply is likely to be greater in valleys than in adjacent areas.

Alluvium occurs in long, narrow strips along all streams, but the thickest alluvium, constituting the larger reservoirs, is along the major streams. In the Arkansas River basin these streams are the Arkansas, Canadian, Cimarron, Illinois, Neosho, North Canadian, Salt Fork, and Verdigris Rivers and Wolf Creek; in the Red River basin they are the Kiamichi, Little, North Fork, Red, Salt Fork, and Washita Rivers and Muddy Boggy Creek.

These streams drain areas underlain by different rock formations having diverse mineral constituents. The Alluvium, therefore, differs greatly from place to place, and not all of it contains water of good quality. At places man's activities have led to pollution of the ground water as well as the surface water. The alluvium along the North Canadian River downstream from Oklahoma City, for example, has been so polluted by disposal of oil-field brines that the city of Shawnee had to abandon its wells in the alluvium. Above Oklahoma City, however, many towns use ground water from the alluvium, among them El Reno, which requires some 2 million gallons per day. For descriptions of ground water in alluvium, see Reed and Schoff (1951), and Mogg, Schoff, and Reed (in preparation).

SOME PRINCIPLES OF THE OCCURRENCE OF GROUND WATER

The principles governing the occurrence and movement of ground water have been described in detail by Meinzer (1923, 1923a) and have been restated in many publications of the U. S. Geological Survey and others. The paragraphs that follow have been adapted from these sources, to which the reader should refer if a fuller statement is desired.

POROSITY AND PERMEABILITY

The rocks within reach of drilling machines contain many open spaces, called voids or interstices. These open spaces are the receptacles for the water found below the land surface and recovered in part through wells and springs. Rocks differ greatly in the number, size, and arrangement of their interstices, and hence in their properties as containers of water (fig. 1). The occurrence of ground water, therefore, is determined by the character, distribution, and structure of the rocks, together with the climate and topography.

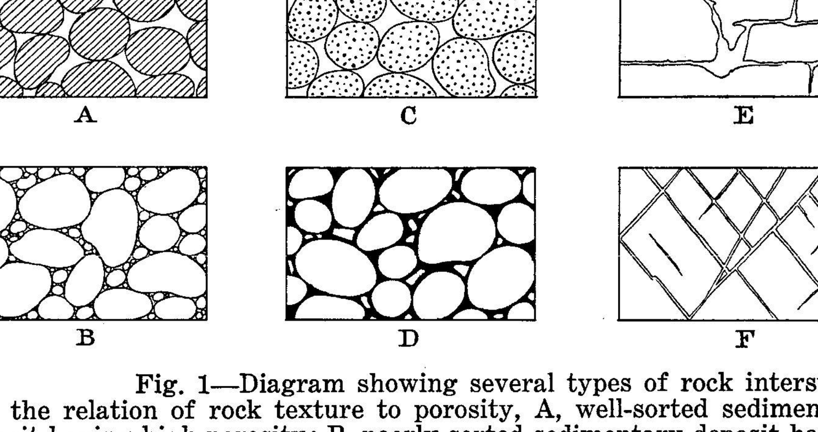

Fig. 1—Diagram showing several types of rock interstices and the relation of rock texture to porosity, A, well-sorted sedimentary deposit having high porosity; B, poorly sorted sedimentary deposit having low porosity; C, well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a high porosity; D, well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; E, rock rendered porous by solution; F, rock rendered porous by fracturing (After Meinzer).

The amount of water that can be stored in a rock depends on the volume of pore spaces in the rock—that is, the porosity, which is expressed as a percentage of the total volume of the rock. Well-sorted deposits of unconsolidated silt, sand, or gravel have high porosity regardless of the size of the constituent mineral grains. Poorly sorted deposits have lower porosities because small grains fill the openings between the large grains, reducing the amount of open space. The openings in some well-sorted deposits of sand and gravel may be partially filled with cementing material, which reduces the porosity. Hence sandstone and conglomerate, which are consolidated rocks, are likely to have less porosity than sand and gravel, which are unconsolidated. Solution openings and fractures may give a high porosity to an otherwise dense rock and, hence, may be of great practical importance.

Although the capacity of a rock to contain water is determined by its porosity, its capacity to yield water is determined by its permeability, which is defined as ability to transmit water under hydraulic head. Rocks that will not transmit water are said to be impermeable. Silt, clay, or shale may be well sorted and have high porosity, but because of the minute size of their pores will transmit water only very slowly. If shale is fractured, however, the fractures may transmit water in moderate quantities. Well-sorted gravel or sand containing relatively large openings that communicate freely with one another will transmit water readily. Sandstone will also transmit water readily if its openings have not been obstructed by cementing material. Part of the water in any deposit is not available to wells because it is held against the force of gravity by molecular attraction—that is, the water adheres to the walls of the pores.

The amount of water available to wells depends on the saturated thickness, the lateral extent, and the permeability of the water-bearing material. It also depends on how much of the water contained in the rock will be released, in contrast with the water held in the rock by molecular attraction. The amount of water that can be pumped perennially without progressive depletion of ground water in storage depends on the amount of replenishment (recharge).

THE WATER TABLE

Below a certain level the interstices of the permeable rocks are generally saturated with water under hydrostatic pressure. These rocks are said to be in the zone of saturation. The upper surface of this zone is called the "water table" except where the upper surface is formed by impermeable rock (fig. 2). When a well is sunk, it remains empty until it enters a saturated permeable bed—that is, until it enters the zone of saturation. Then water flows into the well. If the rock through which the well passes is all permeable the first water that is struck will stand in the well at about the level of the top of the zone of saturation—that is, at about the level of the water table. If the rock overlying the bed in which the first water is struck is impermeable, the water may be under pressure which will raise it in the well to some point above the level at which it was struck. In such a place there is no water table, and confined (artesian) conditions are said to exist.

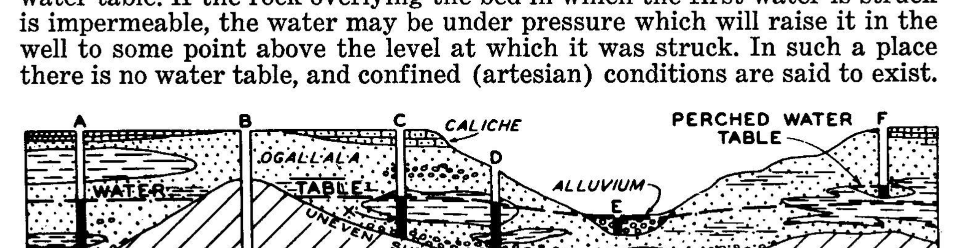

Fig. 2—The water table. Diagram to show the occurrence of ground water in the Tertiary and Quaternary sediments of northwestern Oklahoma ("Ogallala" formation). A, well penetrates a considerable thickness of pervious, saturated sand and gravel, separated into two water-bearing zones by a lens of clay; B, a hill on the uneven surface of the redbed basement rises above the water table, so that all of the "Ogallala" is dry; C, well encounters a lens of impervious clay at the level of the water table and remains dry until permeable sand is penetrated at X; D, well encounters two clay lenses, and driller reports two water-bearing beds, but total thickness of saturated permeable materials is about the same as at C; E, valley has been cut deeply, drawing the water table down, the stream has a permanent flow derived from the ground-water reservoir, and the well beginning in valley fill (alluvium) obtains water at slight depth; F, well obtains small supply of water in a perched reservoir.

The water table is not a level surface but has irregularities comparable with and related to those of the land surface, although it is less rugged. It does not remain in a stationary position but fluctuates up and down. The irregularities are due chiefly to local differences in gain and loss of water, and the fluctuations are due to variations from time to time in the gain or loss.

The water table is not to be regarded as a single continuous surface, but rather as a great many small and interconnected surfaces. Each impervious mineral grain that happens to be at the level of the water surface breaks the continuity of the water table. It is only in the voids or pores that the water table is present. In sandstone the water surfaces are numerous, small, and close together. Where the ground water is in fractures in rocks that otherwise are solid and impervious, the water table consists of small, irregular, rather widely separated water surfaces. Where fractures have been enlarged by solution, some of the water surfaces may be relatively large, but they are similarly irregular and widely separated. Taken all together, the solution openings are likely to be a small fraction of the entire volume of the rock—that is, the porosity is low.

CONFINED (ARTESIAN) WATER

Artesian or confined conditions are said to exist where a water-bearing bed is overlain by an impermeable or relatively impermeable bed and where the top of the aquifer is below the level of the water table in the outcrop area (fig. 3). Water enters the water-bearing bed at the outcrop and percolates slowly downward to the water table and then down the dip in the water-bearing bed beneath the overlying confining bed. Down dip from the outcrop area the water exerts considerable pressure against the confining bed, so that when a well is drilled into the water-bearing bed the pressure causes the water to rise in the well. Because of loss in head resulting from friction as the water percolates down the dip, the water level will not rise to an elevation as high as that of the water table in the outcrop area. Where the land surface is low enough the artestian pressure may be sufficient to raise the water above the surface, and flowing wells may be obtained. Because the upper surface of the saturated zone is formed by an impermeable bed and the water in wells will rise above it, this portion of the aquifer has no water table. The imaginary surface defined by the height to which artesian water will rise in wells is known as the piezometric surface.

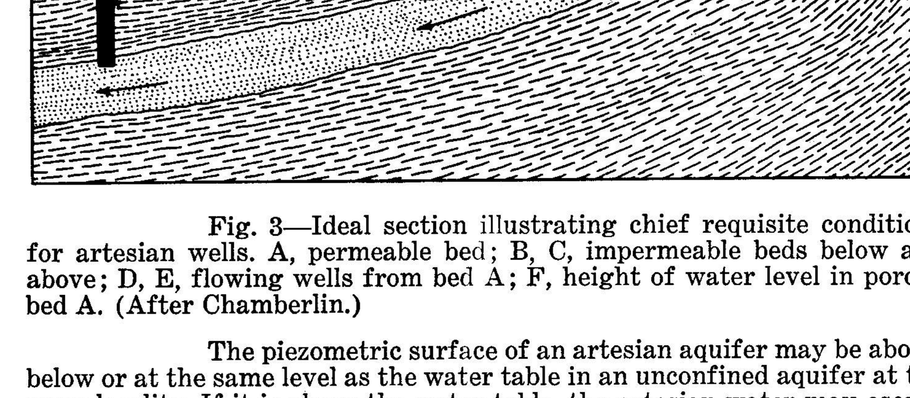

Fig. 3—Ideal section illustrating chief requisite conditions for artesian wells. A, permeable bed; B, C, impermeable beds below and above; D, E, flowing wells from bed A; F, height of water level in porous bed A. (After Chamberlin.)

The piezometric surface of an artesian aquifer may be above, below or at the same level as the water table in an unconfined aquifer at the same locality. If it is above the water table, the artesian water may escape into the unconfined aquifer through unplugged or leaky artesian wells or through the confining layer itself if the latter is leaky. If the piezometric surface is below the water table, the water from the unconfined aquifer may drain into the artesian aquifer through leaky artesian wells or through a leaky confining layer. If the piezometric surface and the water table happen to be at the same level, or if there is no connection between the aquifers, no interchange of water can occur.

Oklahoma has many artesian aquifers, and a few are of considerable importance as sources of water, but the conditions for flow at the surface are found at but few places. When deep wells first were drilled in Ottawa County they overflowed, but under heavy draft the water levels declined and pumping has been necessary for many years. A few wells overflow at Sulphur, Murray County, on the north side of the Arbuckle Mountains, and at Lawton, Comanche County, on the south side of the Wichita Mountains. It is likely that wells at other localities on the flanks of the mountains would flow. Flowing wells have been drilled at a few other places in Oklahoma, but flowing wells are the exception rather than the rule.

RECHARGE AND DISCHARGE OF GROUND WATER

The principal source of water in the earth is precipitation on the outcrops of permeable rocks. Other sources are influent seepage from streams crossing the outcrop, and movement underground from outside areas. The replenishment of ground water is known as recharge. It is often expressed as a percentage of the annual precipitation, or as equivalent to a layer of water, usually measured in inches of depth, spread uniformly over the area. It may range from a small fraction of an inch in some areas to many inches in others. It may equal only a small percentage of the annual precipitation, or more than 50 percent. In the same county, it will differ from township to township, from section to section, and from acre to acre, but the movement of water underground tends to equalize the recharge for large areas.

The amount of water entering the ground depends first on the amount of precipitation. Obviously, little rain means little opportunity for recharge. If rain comes as gentle to moderate showers, a larger fraction of the water can go into the soil and rock than if it comes in heavy or protracted storms that quickly fill the uppermost openings and furnish water faster than it can be absorbed. Light, loose, sandy soils will absorb more water than will heavy clay soils. The absorption will be relatively high on gentle slopes but much less on steep slopes where runoff is dominant. Vegetation favors absorption by retarding runoff and by loosening the soil so that it is more permeable, but it uses part or all of the water, transpiring it to the atmosphere instead of letting it percolate to the water table. In winter a larger fraction of the precipitation will reach the zone of saturation than in the heat of summer because evaporation is less and transpiration ceases. The first rain after a prolonged drought will add little or nothing to the ground-water supply because the soil must be saturated before any water can sink below it. Thick rock formations that dip at low angles have more surface exposed to receive water from precipitation than formations of equal thickness that dip at steep angles, and rocks of course, uniform texture, or with extensive systems of fractures, will take in water faster than rocks that are fine grained, uneven textured, or unbroken.

Streams crossing the outcrop will contribute water if their channels are above the water table, but otherwise will receive water from the underground reservoir. Recharge may be accomplished artificially by putting water into aquifers through infiltration beds or through wells.

Ground water moves slowly through the rocks from the places of recharge or intake, to points of discharge at lower altitudes. Although the path followed by any given molecule of water may be circuitous, the net result is movement down the slope of the water table, or, in the case of confined water, down the slope of the piezometric surface. Discharge of ground water occurs naturally through springs, into channels of effluent streams, through use by plants that can send their roots down to the water table, and by evaporation where the water table is near the surface. It occurs artificially through wells by pumping or artesian flow, or by drainage into ditches or other man-made excavations.

Under natural conditions, the recharge to an underground reservoir is approximately balanced by the discharge from it. Hence, a measure of the natural discharge is a rough measure of the recharge.

EFFECT OF PUMPING

When a well in an unconfined aquifer is pumped the water level in it is lowered, a hydraulic gradient is set up toward it from all directions and water flows into it. The water table around it assumes a shape somewhat like an inverted cone, which is called the cone of depression.

As pumping continues, the cone of depression expands and water from progressively greater distances percolates toward the well. If no recharge occurs, the cone will continue to expand, although at a decreasing rate, until the limits of the formation are reached, or until the water level in the well approaches the bottom of the formation. Recharge to the formation may halt the development of the cone of depression. If the rate of discharge is less than the ability of the aquifer to deliver water to the well, and if the well is pumped continuously at a constant rate, the cone of depression will reach a state of dynamic equilibrium. The cone then will expand during droughts and shrink during periods of recharge.

The lowering of the water table at any point within the cone of depression is directly proportional to the rate of pumping. That is, other conditions being the same, the drawdown at a certain distance from a well being pumped at 200 gallons per minute will be twice the drawdown caused by pumping at 100 gallons per minute.

When a well in an artesian aquifer flows or is pumped, a similar but not identical situation develops. The water level is lowered, a hydraulic gradient is set up toward the well from all directions and water flows into the well. A cone of depression in the piezometric surface results and water levels decline in other wells tapping the same aquifer within the cone. This cone is defined by the water levels in wells and it may be depicted on maps just as if it were in a water-table aquifer. Nevertheless, it is an imaginary cone because the piezometric surface is imaginary. Between wells no water surface is present at the level where the surface should be because the impermeable confining layer prevents the water from rising to it. To the user of an artesian well, however, this cone and the effects related to it are of great practical significance. Other conditions being the same, the cone for an artesian aquifer will be deeper and will expand more rapidly than the cone in a water-table aquifer.

Much has been done to translate these hydraulic effects into quantitative terms useful in planning the development of ground-water resources. For a general statement of methods, see Meinzer and Wenzel (1942) or Wenzel (1942). Applications to Oklahoma aquifers are discussed by Davis (1950, 1955, and in preparation), Schoff and Reed (1951), Reed, Mogg, Barclay, and Peden (1952), Barclay and Burton (1953), Reed and Schoff (1955), and Mogg, Schoff, and Reed (in preparation).

CHEMICAL CHARACTER OF GROUND WATER

All ground waters contain mineral matter dissolved from the rocks and soils with which they have come in contact. The quantity of dissolved mineral matter in the water depends primarily on the type of rock or soil through which the water has passed, the length of time of contact, and pressure and temperature conditions. In addition to these natural factors are others connected with human activities, such as infiltration from streams and wells used for disposal of sewage and industrial waste.

Samples of ground water are collected during field investigations, and the results of chemical analyses are published in ground-water reports. For chemical analyses of ground water in localities not covered by such reports, see Smith (1942), Dover (1953), and Laine, Schoff, and Dover (1951).

REFERENCES

Most of the publications dealing with ground water in Oklahoma are listed below. Also included are a few of the fundamental papers on the occurrence and movement of ground water. Reference is made in the preceding text to some but not all of the papers in the list.

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Burton, L. C., 1953, Ground water in terrace deposits of central Beckham County, Oklahoma: (typewritten), 182 p., 5 pls., 2 figs., 3 tables.

Davis, L. V., 1950, Ground water in the Pond Creek basin, Caddo County, Oklahoma: Okla. Geol. Survey, Min. Rept. 22, 23 p., 1 pl., 5 figs.

———, 1955, Geology and ground water of Grady and northern Stephens Counties, Oklahoma: Okla. Geol. Survey, Bull. 73. 184 p., map.

———, Geology and ground water of southern McCurtain County, Oklahoma: Okla. Geol. Survey, Bull., (in preparation).

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