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1983

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6-6-1983

### Hydrology: Unraveling the Mysteries of Groundwater Occurrence and Movement

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#### Citation Information

Stetson, Thomas M., "Hydrology: Unraveling the Mysteries of Groundwater Occurrence and Movement" (1983). *Groundwater: Allocation, Development and Pollution (Summer Conference, June 6-9)*. <https://scholar.law.colorado.edu/groundwater-allocation-development-and-pollution/3>

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Thomas M. Stetson, *Hydrology: Unraveling the Mysteries of Groundwater Occurrence and Movement*, in *GROUNDWATER: ALLOCATION, DEVELOPMENT AND POLLUTION* (Natural Res. Law Ctr., Univ. of Colo. Sch. of Law 1983).

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GROUNDWATER:  
ALLOCATION, DEVELOPMENT AND POLLUTION

Fourth Annual  
Summer Natural Resources Law Short Course

Natural Resources Law Center  
University of Colorado School of Law

June 6-9, 1983

HYDROLOGY: Unravelling the Mysteries of  
Groundwater Occurrence and Movement

(Glossary appended)

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I. What is Groundwater?

- A. Water within the earth that supplies wells and springs; water in the zone of saturation where all openings in rocks and soils are filled, the upper surface of which forms the water table. (Webster's Third New International Dictionary of the English Language, Unabridged, G. & C. Merriam Co., 1968.)
- B. Groundwater occurs in openings (pore spaces) between alluvial and sedimentary sands and rocks, in rock fractures (fissure water), in tubular openings in soluble rocks and in openings in lava (solution openings or caverns). (Tolman, C.F., Ground Water, McGraw-Hill Book Company, Inc., 1937.)
- C. The water table, the upper surface of the groundwater body and of the saturated zone, is one of the most important indicia of ground-water occurrence, storage and movement--the "dip-stick" of management of groundwater.

II. Early History of Ground-water Development.

- A. The Bible. O. E. Meinzer, often considered the father of modern day groundwater hydrology, stated that "the twenty-sixth chapter of Genesis...reads like a

water-supply paper." (The History and Development of Ground-water Hydrology, Jour, Wash. Acad. Sci., Vol.24, No. 1, p. 6, Jan. 1934.)

1. The romantic encounters of Rebekah and Issac at a well where she gave him water for his camels. (Gen. 24:11-19, 50-51.)
2. Rachel and Jacob at a well in a field watering sheep. (Gen. 29: 2-3, 9-11.)
3. In the 40 years of wandering in the desert by the Israelites during the Exodus from Egypt they dug wells under the direction of the Lord. Moses smote the rock and a fountain burst forth. (Num. 20: 5-11.)

The Exodus, believed by most Biblical scholars to have taken place in the 13th century B.C., has more recently been alleged by Egyptologist Hans Goedicke to have occurred in the 15th century, B.C.--some 3,500 years ago. (Reader's Digest, April 1983, pp. 133-138.)

- B. The kanats of the Persians (Tolman, Supra, pp. 12-15.)

1. Most extraordinary works of ancient man for collecting groundwater.
  2. Kanats were long tunnels connecting the bottoms of shafts in the high central valleys of Persia. They were dug by human moles.
  3. Thirty-six of these tunnels supplied water to Teheran and the tributary agricultural area. They were 8 to 16 miles long and reached maximum depths of 500 feet below ground surface.
  4. The origins of kanat building is lost in antiquity, but they existed at least as long ago as 800 B.C.
  5. As an interesting aside, Shah Mohammed Reza Pahlavi, in modernizing the development and economy of Iran, had deep wells drilled to develop more groundwater for irrigation. In doing so, the groundwater in some areas was overdeveloped (overdrafted) and some of the ancient kanats dried up. (Personal communication from Ali Shahroody.)
- C. The Egyptians dug wells as early as 2100 B.C., in one instance using 3,000 men to dig 14 wells. (Ground Water and Wells, first

Edition, 1966, Published by Edward E. Johnson, Inc., Saint Paul, Minn., p. 6.)

- D. The American Indians are reported to have dug wells in California hundreds of year ago. The Kamia Indians of Imperial Valley and the Cahuilla Indians of Coachella Valley would excavate, with Mesquite wood shovels and baskets to remove the earth, a sloping trench 50 to 75 feet long and up to 25 feet deep. At the lower end they would dig a circular pit some 15 feet in diameter, with sloping sides and 25 to 30 feet deep. (Heizer, R.F. and Whipple, M.A., The California Indians, Univ. of Calif. Press, Berkeley, 1971, p. 359.) These were called walk-in wells and were usually dug when the water table would decline during drouths. (Handbook of North American Indians, Vol. 8, California, Heizer, R.F., Volume Editor, Smithsonian Institution, 1978, p. 575.)

### III. From Superstition to Understanding.

- A. As late as the seventeenth century it was generally believed that water from springs was not derived from rainfall because there was not sufficient rainfall to supply it and the earth was too impervious for rainfall to penetrate far below the surface. The

ancient Greek philosophers believed that springs were formed by sea water conducted through subterranean channels below the mountains, then purified and raised to the surface. (Ground Water Hydrology, David K. Todd, John Wiley & Sons, Inc. 1959, p. 2.)

B. Tolman wrote: "Centuries have been required to free scientists from superstition and wild theories handed down from the dawn of history regarding the unseen subsurface water, and one should learn to control his impatience at the constant reminders that this is still an age of popular superstition with respect to the occurrence of groundwater. The elementary principle that gravity controls motions of water underground as well as at the surface is not appreciated by all engaged in the development of ground-water supplies." (Tolman, supra, p.22.)

C. Todd indicates that a clear understanding of the hydrologic cycle was achieved by the latter part of the seventeenth century. Pierre Perrault (1608-1680), a lawyer by profession, measured rainfall and estimated runoff of the upper Seine River drainage basin over a 3-year period. He reported in

1674 that the rainfall on the basin was about six times the quantity of water discharged from the river basin. This demonstrated that the previous beliefs that rainfall was not adequate to supply springs and groundwater was false. This finding was soon confirmed by French physicist Edme. Mariotte through his measurements of the Seine at Paris. Meinzer once stated: "Mariotte...probably deserves more than any other man the distinction of being regarded as the founder of ground-water hydrology, perhaps...of the entire science of hydrology." (Todd, supra, p. 3.)

- D. American contributions to ground-water hydrology began near the end of the nineteenth century. Dr. Meinzer probably heads the list of leading contributors to the science of ground-water hydrology through his work with the United States Geological Survey. (Todd, supra, p. 4.)

#### IV. Development of Wells and Pumps

- A. After hand-dug wells, the cable-tool, or percussion, method of drilling is the oldest.

1. First recorded use of percussion drilling was in China, about 600 B.C., in drilling brine wells up to a few hundred feet in depth. By 1500 A.D., holes were drilled to depths of 2000 feet, probably cased with bamboo. (Water Well Technology, Campbell, M.D., and Lehr, J.H., 1973, p. 42; Tolman, supra, p. 12.)
  2. Spring poles were used to drill water and brine wells in the United States in the early 19th century. Colonel Drake drilled the first commercial oil well at Titusville, Pennsylvania, in the 1860's using a steam-powered cable tool rig. This became the principal means of well drilling until early in the 20th century. (Campbell and Lehr, supra, p. 42.)
- B. Rotary drilling was used by the Egyptians in quarrying stone for pyramids. (Campbell and Lehr, supra, p. 50.)
1. By 1823 water wells were drilled in Louisiana with boring tools and the cuttings removed by bailing.
  2. First reference to drilling with rotating tool equipped with hollow

drill rods and circulating fluid to remove cuttings was an English patent to Robert Beart in 1844.

3. United States patents incorporating the hydraulic rotary principles were issued between 1860 and 1900.
  4. The rotary drilling method became common at the beginning of the 20th century.
- C. Suction lift centrifugal pumps were in common use by 1890. Used to pump relatively shallow groundwater or to boost water in distribution systems.
- D. The deep well turbine pump was in common use, at least in southern California, by the early 1900's.
- E. When wells in a free groundwater aquifer are pumped the water level lowers as water is extracted from the immediately adjacent water-bearing material, resulting in a cone of depression surrounding the well. Water outside of the cone of depression moves toward the well to replace the groundwater which is moving into the pumping well. Pumping of confined water reduces pressure in the aquifer and results in movement of water toward the well. Reduction of pres-

sure in the aquifer is reflected by lowering of water levels in non-pumping wells penetrating the confined aquifer. This is called a cone of pressure relief. (See Figures 1 and 2.)

V. Occurrence of Groundwater.

A. The hydrologic cycle. Groundwater is a part of the hydrologic cycle. Surface water evaporates, becomes water vapor and is transported through the atmosphere. It then condenses and precipitates to the earth's surface as rain or snow. Part of this precipitation is returned directly to the atmosphere by evaporation and transpiration from the earth's surface or vegetation, part percolates into and through the soil into the zone of aeration and down to the saturated zone, and part of it becomes surface runoff as diffused water or streamflow. The hydrologic cycle is a continuous process resulting from solar energy. (See Figure 3.)

1. In general, the water added to the groundwater is the precipitation minus evaporation and transpiration losses and minus the water discharged from the area as streamflow.

2. Practically all usable groundwater is derived from the atmosphere. (It is often referred to as meteoric water.) There is other underground water, usually at great depths, which is called juvenile water, or new water. It originates as magmatic or volcanic water and is not significant when compared to meteoric, or atmospheric, water. (Tolman, supra. pp. 27-28.)

B. Geologic formations that store and convey groundwater to wells or natural springs are called aquifers.

1. Aquifers are generally separated by aquicludes and aquifuges.

a. Aquiclude is a formation which will absorb water slowly but will not transmit it fast enough to furnish a significant supply to wells or springs. It will not yield water by gravity but will absorb water up to 50 percent of its volume. Clay is an example.

- b. Aquifuge is a rock which is impervious to water, such as granite, quartzite and completely cemented sedimentary rocks.
- C. Groundwater occurs in various forms of storage, generally referred to as basins or reservoirs. These can be groundwater (1) underlying the surface of valleys, (2) underlying bolsons (a topographic basin with centripetal drainage), (3) under and immediately adjacent to streams as subsurface flow, (4) in underground streams, or (5) in large regional aquifers such as the Ogallala and Madison formations.
  - 1. Ground-water aquifers can be multilayered with two or more aquifers underlying one another or portions of one another. (See Figure 4.)
  - 2. Ground-water aquifers can be free or confined.
    - a. A free aquifer is defined as water in the zone of saturation down to the first impervious barrier, moving under control of the water table slope (by gravity).

b. A confined, or artesian, aquifer is a body of groundwater overlain by material sufficiently impervious to sever free hydraulic connection with overlying groundwater except at the intake or forebay. The static water level stands above the water table. Confined water moves under pressure due to the difference in head between the forebay and discharge areas of the confined aquifer. (See Figure 4.)

D. We can only estimate how much groundwater is in storage in the many and various aquifers or reservoirs in the United States. Gross estimates have been made. We know that it is a vast amount. We also know that there is a limit to the amount which can be used without causing adverse or undesirable effects.

1. Ground-water reservoirs probably hold several times as much usable water as the combined capacities of all lakes and surface reservoirs, but we do not have enough information to provide a

reliable estimate as to how much water is in them. (Thomas, Harold E., the Conservation of Ground Water, McGraw-Hill Book Co., 1951.)

2. The Ogallala formation is said to have a storage capacity equivalent to that of Lake Ontario (about 1.327 billion acre-feet). Unfortunately, the Ogallala formation cannot be recharged from the mountain sources which originally supplied it because it has been geologically cut off from those sources for thousands of years. Even precipitation on the 150,000 square miles overlying the Ogallala cannot contribute much recharge because caliche has formed a caprock over much of the water-bearing formation. (You Never Miss the Water Till....The Ogallala Story, Bittinger, M.W. and Green, E.B., Water Resources Publication, Littleton, Colo., 1980.)

#### VI. Groundwater Safe Yield and Overdraft.

- A. Usually surface water and groundwater are considered together in hydrologic studies because together they comprise the total available water supply to an area.

Even in areas where all surface water has been appropriated, it must be taken into consideration in the studies to determine safe annual yield or overdraft of the adjacent or underlying groundwater. (Safe yield of a ground-water basin is the average annual amount that can be extracted from a basin, or aquifer, over a long period of years without causing adverse results.) Two common methods of determining safe yield or overdraft are the inventory method and the change in storage method. Frequently they are used together.

- B. A base period of water supply should be selected that reasonably represents long-term hydrologic conditions and should include both normal and extreme wet and extreme dry periods of years. The base period should be recent and should cover a period with adequate records of hydrologic data. Both the beginning and end of the base period should be preceded by a series of dry years or a series of wet years so that water in transit within the zone of aeration can be minimized.

Precipitation, streambed percolation and applied water enter the zone of aeration and

move by gravity toward the zone of saturation. Water passes through the upper soils zone and if it is not evaporated or transpired by plants it percolates downward to the zone of saturation and becomes an increment of the ground-water supply.

C. The Inventory Method. All items of water supply and demand (inflow and outflow) are accounted for on a monthly or annual basis, depending upon the availability of historic data and the accuracy sought to be achieved.

1. Inflow items

- a. Subsurface inflow
- b. Percolation of precipitation
- c. Streambed percolation
- d. Artificial recharge
- e. Percolation of delivered water from irrigation, municipal and domestic use, and including wastewater.

2. Outflow items

- a. Pumpage
- b. Phreatophytes
- c. Rising water
- d. Subsurface outflow

3. Change in Storage
  - a. Inflow minus outflow equals change in storage
4. Mathematical models, operated by digital computers, are now used to make the many calculations required to determine change in ground-water storage by balancing the many items of inflow and outflow.

D. Change in Storage by the Specific Yield Method

1. Specific yield is the ratio of the volume of water a saturated sediment will yield by gravity drainage to the total volume of the saturated sediment, usually expressed in percent. The specific yield values vary with the type of materials in the aquifer. They are low for clay and consolidated sediments and rocks and high for sand and gravel.
2. Water table elevations are measured and ground-water contour maps prepared to show the change in elevation between the beginning and end of the time period over which change in storage is to be determined.

3. Change in storage is derived by applying the proper specific yield ratio to the volume of change in the water table elevations.
4. If the change in storage is negative, an overdraft condition existed on the basis of water supply and use during the base period. If the change in storage was positive, safe yield was not exceeded on the basis of water supply and use during the base period.
5. To determine safe yield or overdraft under present conditions, or some future condition, of water use adjustment must be made to reflect the increase or decrease in change in storage due to the change in water use over that which existed during the base period.

E. What Causes Overdraft?

1. Ordinarily one would say: "Overpumping ground-water from the basin" But it can be other things too.
2. Change in land use. The San Gabriel Basin in southern California was pumped heavily during the 1920's and 1930's to irrigate citrus groves. After World War

II the area was rapidly urbanized, including the installation of sanitary sewers and the conveyance of the sewage to ocean outfalls. Although annual pumping from the basin after World War II did not exceed the annual pumping before the war, the basin developed overdraft because the return flow from the urban use was exported to the ocean instead of percolating into the basin. Furthermore, urbanization increased valley runoff from precipitation on the valley floor because the former ground surface had been paved over in large part, inhibiting deep percolation of rainfall.

F. Effects of Overdraft

1. Subsidence. This will be discussed later in this course by Mr. Thomas Holzer.
2. Greater pumping lifts. As the water table drops as a result of overdraft, pumping lifts become greater. In today's world of high energy costs, this in itself may result in some

constraints on overdraft. Ten years ago energy costs for pumping groundwater were about \$1 to \$2 per acre-foot per 100 feet of lift. Today they are \$6 to \$10 per acre-foot, depending upon the source of the energy. With overdraft, the pumping lifts stay at deeper levels, even if the overdraft is lessened or reduced to safe yield.

Most groundwater serves the function of holding the usable groundwater at reasonable pumping lifts. In San Gabriel Valley, California, for example, about eight-million acre-feet of fresh groundwater supports the water levels in the upper 100 feet of saturated thickness (about 800,000 acre-feet), which is the portion of the basin that fluctuates in levels and has been used to supply the wells.

3. Intrusion of poor quality water. With overdraft, seawater intrusion can occur or poor quality water from other sources can intrude.

## VII. Sources of Ground-water Pollution

### A. Man-caused Pollution

1. Rainfall flushes man's waste materials from the air, buildings, streets, vegetation and land--including waste materials dumped by man on the earth's surface and buried by man under the surface. These include industrial wastes, agricultural fertilizers and pesticides, and even hospital wastes.
2. Some is discharged directly into surface waters. Some is dumped at legal waste discharge sites. Much is dumped illegally into storm drains, directly onto the ground and at illegal waste sites such as canyons, barrancas, dry creek beds, etc.
3. Before man saw fit to control waste discharge there were all sorts of unregulated dump sites. Old rock and gravel quarries are an example. Many have long since been filled with waste, covered over with earth and the site now developed with housing or otherwise paved over. But the waste is still there, leaching into the groundwater as water from the surface percolates

downward through it or released to the groundwater as the water table rises up through the waste.

4. Nitrates occur in groundwater and can be harmful to infants under three months of age. It causes methemoglobinemia (blue babies) as a result of the reduction of nitrate to nitrite in the digestive tract and the subsequent absorption of nitrite into the bloodstream. The nitrite will combine with hemoglobin to form methemoglobin, which is incapable of carrying oxygen. A significant methemoglobin level in the bloodstream can result in suffocation.

Nitrates leach into groundwater from such sources as domestic sewage, agricultural fertilizers and waste disposal sites.

5. Trichloroethylene (TCE) and Perchloroethylene (PCE) have both been declared by the Environmental Protection Agency and various health departments to be cancer-causing carcinogens in drinking water.

6. Health departments have established maximum limits on concentrations for general physical, general mineral, inorganic chemical, organic chemical, and radioactive contaminants for drinking water. If they are exceeded, it is sometimes necessary to shutdown wells. At other times, the well source may be blended with other water sources to meet the health standard.
7. Today, in addition to monitoring our groundwater sources to assure adequate quantities of water, we must monitor the quality on a regular basis to assure a safe supply--especially in large urban areas dependent upon groundwater.

B. Natural Sources

1. Seawater Intrusion

- a. Where aquifers outcrop on the ocean floor, or in submarine canyons, seawater can become a threat to ground-water aquifers. If the ground-water elevation in the forebay to the aquifer drops below sea-level the seawater can form a wedge intruding into the

aquifer at the interface. The seawater wedge will move in and out depending upon water table fluctuations in the forebay and extractions of water from the aquifer between the forebay and the ocean.

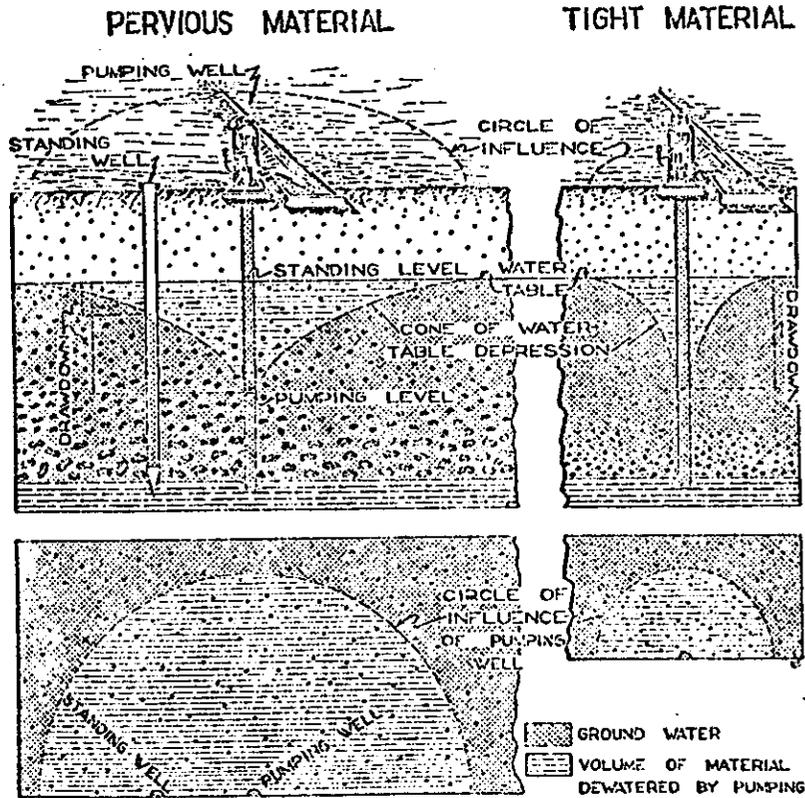
- b. Seawater intrusion has occurred along the coast of southern California. Long lines of injection wells have been constructed near the coast to inject fresh water to drive the seawater out and to create a mound of fresh water between the ocean and the inland portion of the aquifer. It is becoming extremely expensive to operate such projects. In addition to the construction costs of the many injection wells and many miles of pipelines, the annual cost of fresh water to supply these projects is increasing at a

rapid rate. The cost of water to supply the projects in Los Angeles County alone will have risen from about \$2.5 million in 1978-79 to about \$5 million in 1983-84.

2. Brackish and Saline Water

- a. In many areas brackish and saline water is found at depth underlying and adjacent to fresh groundwater. Excessive extractions of the fresh water permits the brackish or saline water to intrude.
- b. Poor quality groundwater adjacent to fresh groundwater at the interface of two or more aquifers can result in degradation in quality of the fresher water due to variations in extractions among the aquifers.
- c. Poor quality perched groundwater can find its way down to the better quality aquifers through improperly abandoned wells and through the perforations in

casings of wells where the well was not properly sealed through the perched water. This is one reason that municipal wells are required to be sealed to prevent shallow water and surface drainage from entering the well.

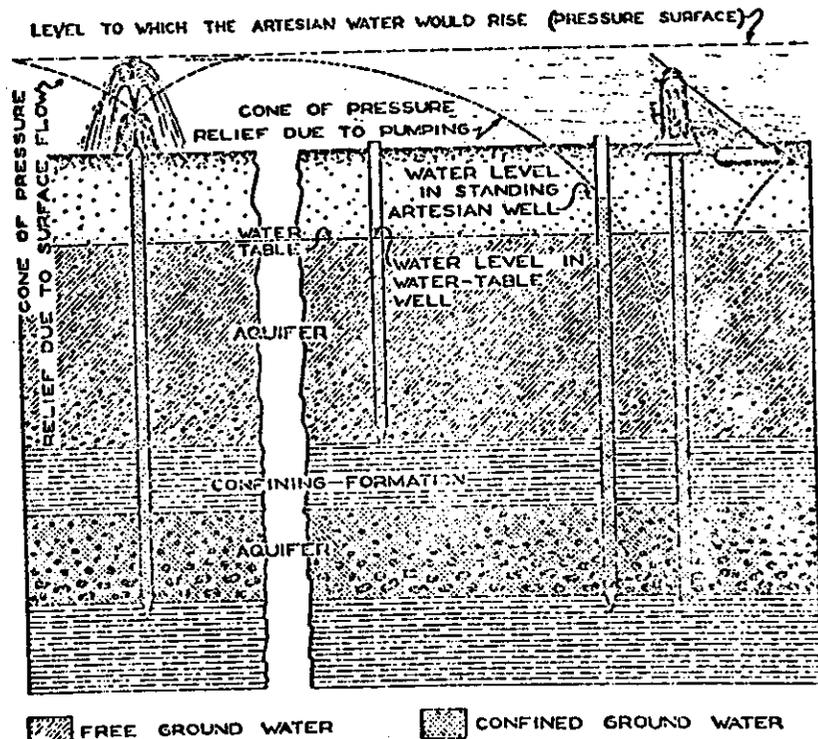


PLAN AT ELEVATION OF WATER TABLE

Hydraulic features caused by pumping a water-table well. For simplicity the area of influence is bounded by a circle and the popular term circle of influence is used instead of the preferred term area of influence.

From: Ground Water, Tolman, C.F.,  
McGraw-Hill Book Co., 1937

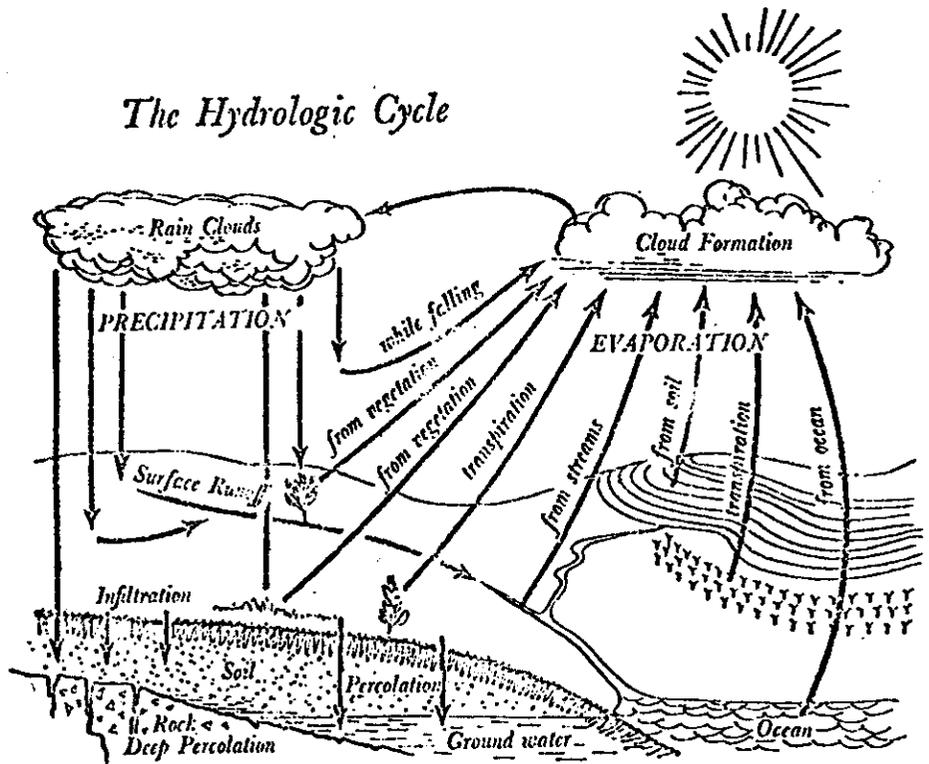
Figure 2



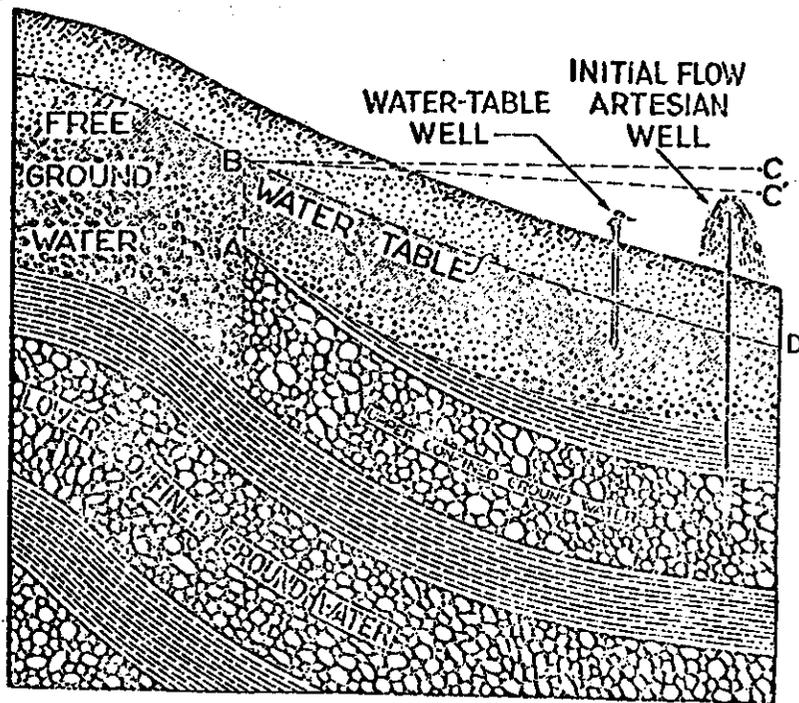
Hydraulic features caused by surface flow and by pumping of confined-water well. Initial flow (prior to development of cone of pressure relief) shown by light lines above adjusted flow (dark lines).

From: Ground Water, Tolman, C.F.,  
McGraw-Hill Book Co., 1937

### The Hydrologic Cycle



From: The Yearbook of Agriculture, 1955,  
"Water", U.S. Department of  
Agriculture



—Comparison of free and confined ground water. *BC*, theoretical static level of confined water body; *BC'*, pressure gradient, indicates actual static level in wells piercing the conduit.

From: Ground Water, Tolman, C.F.,  
 McGraw-Hill Book Co., 1937