ARIZONA WATER

By J. W. Harshbarger, D. D. Lewis, H. E. Skibitzke,
W. L. Heckler, and L. R. Kister,
revised by H. L. Baldwin

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1648

U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON: 1966

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

WILLIAM T. PECORA, *Director*

Library of Congress catalog-card No. GS 65–412

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402.

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Why this report was written

Water is a scarce commodity in Arizona, as it is in all semiarid lands. Therefore all possible information about it should be acquired and effectively used for the best interests of all. Man has made great strides in learning how to live in the desert. However, the basic problem still exists—a shortage of usable water to meet the needs of a rapidly growing economy. This report is an effort to help those interested to understand the problem. It discusses the water resources of the State, the current use of this resource, and some methods of relieving the present shortage and avoiding a future shortage.

The report is written in nontechnical terms. Statements about amounts of water and other quantitative information are generalized. The information presented here is neither in the form nor in the detail required for engineering and legal purposes. Although the figures are derived principally from publications of the Geological Survey, the specialist will want to consult those publications and other sources for technical data.


-Mac NE

The Vanished Ones . . .

For many people the word "Arizona" may conjure up a picture of a desert full of thorny trees, brush, and cactus. At the same time, thoughts of modern Phoenix and Tucson come to mind—dramatic skyscrapers designed by leading contemporary architects, luxurious hotels and motels, modern houses with patios and swimming pools. How has this prosperous way of life been achieved in the midst of what we call a desert?

When we think of a desert we often picture acres of windblown sand in the sun, stretching for miles and miles without trees, plants, or flowers. This is often far from a true picture of the Arizona deserts, which after a wet winter may be lush with flowers of every color. Scientists define a desert as a region of sparse vegetation found in areas of low rainfall. Even by this definition, Arizona is far from being wholly a desert.

There are three basic geographic regions in Arizona—Desert Lowlands, Central Highlands, and Plateau Uplands (fig. 1). Two of these, the desert and plateau, have very little rainfall. More than 95 percent of what rainfall there is evaporates very rapidly because of the hot dry climate. More rain falls in the mountains, but unfortunately man cannot live or farm very well on steep slopes. In reality, a good deal of Arizona is arid to semiarid.

Yet civilizations have flourished here. Prehistoric man first came to Arizona between 12,000 and 15,000 years ago, but the earliest culture we know much about dates from about 800 B.C. The Hohokam, who flourished from the beginning of the Christian era to about A.D. 1400, is the most interesting of these ancient cultures because it partly solved the primary problem of Arizona—how to use and manage the scant supply of water to the best advantage. The word "hohokam" means the vanished ones. These people built irrigation canals that diverted water from the rivers and delivered it to the thirsty fields. Several hundred miles of these canals can still be traced—a great achievement by any standards, but an extraordinary one for Indians working with primitive tools. Some of the present-day irrigation canals follow the same courses used by the Indians. The Hohokam grew corn, beans, squash, and cotton. The food surplus produced by irrigation allowed for leisure and the arts of civilization—ball games, textile and pottery-making, sculpture. The Hohokam civilization was the model and inspiration for neighboring tribes. Their achievements demonstrate man's capacity to meet the challenge of a difficult environment, and to manage natural resources wisely.

At some point, however, the Hohokam civilization vanished; how or why we do not know, but most authorities think it was because of a great drought that lasted for several years. Since their irrigation system lacked storage reservoirs, the Hohokam were at a loss to deal with this blow to their way of life, and their civilization faded, leaving the canals behind as inspiration to those who followed.

The first white settlers, too, adjusted their life and economy to the semiarid environment. In 1867, Jack Swilling organized the first "Ditch Company." The canals of this company and of others led the water out on to the fertile flood plain of the Salt River, and the country prospered—at least until the severe droughts of 1897, 1898, and 1899. Again, the lack of water storage proved a weakness in an otherwise excellent irrigation system.

Figure 1. The three major regions of Arizona.

It remained for modern Arizonians to remedy the defect by building dams and reservoirs. They have produced magnificent cities and resorts and great wealth in spite of what once were considered disadvantages—the scarcity of water and the hot dry climate. Water is the problem of living in Arizona, but water in swimming pools and air-conditioners is also the secret of successful adaptation to the climate. The story of Arizona water is the story of man's continuing effort to master the complicated secrets of nature and turn them to beneficial use.

THE PROBLEMS

Evaporation

The "gold" in Arizona's hills is sunshine, the State's greatest natural resource. Health-conscious and sports-loving Americans crave sunshine, and they will spend a great deal of money to get enough of it. They will even create a lavish civilization in a desert for the sake of endless sunshine—and the climate of Arizona is phenomenally sunny. The amount of possible annual sunshine throughout the State ranges from 73 to 90 percent. The average for the State is a startling 80 percent. The humidity is generally very low and there is little wind. To people from other States, this perpetual summer may mean merely a winter tan, or it may mean outdoor living all year round and relief from a lifelong plague of asthma or sinusitis.

But the sun, which blesses Arizona with its light and warmth on the one hand, steals away its water on the other. Anyone driving or flying over the State can see that it is dry. Yet in an average year, the State receives 80 million acre-feet of water from rain and snow. An acre-foot is the amount of water which would cover 1 acre to a depth of 1 foot (326,000 gallons). That is a lot of water! The great rivers—the Colorado, the Gila, the Salt, and the Verde—also add much water to this large amount.

Why shouldn't there be enough water?

The answer lies in one astounding statistic. Of the 80 million acre-feet of water available from precipitation, only a shockingly low 2 million is captured for man's use.

More than 95 percent of the precipitation falling on Arizona is consumed by evaporation and by transpiration (the process by which plants breathe water into the atmosphere). For the United States as a whole, the percentage of loss in this way is about 70.

The high rate of evaporation in the arid Southwest is strikingly shown by a study of evaporation from Lake Mead during 1957. The evaporation loss rate was about 90 inches per year from this reservoir surface. The volume of water evaporated was about 800,000 acre-feet. Evaporation from other reservoirs on the Colorado River, from the channel of the river itself, and from reservoirs within Arizona, amounts to more than 500,000 acre-feet per year.

The total water loss from all reservoirs, though great enough, is small compared with the total evaporation from all the land surface. Rainwater from the sudden storms of summer does not penetrate deeply into the soil. Some of the soil moisture is taken up by plant roots, but most evaporates shortly after a storm. Even when the rain is heavy enough to cause some runoff (water which runs over the surface of the land into streams), part of this water sinks into streambeds. After the storm ends, much of the water retained in the river channel evaporates or is transpired by river-bank vegetation.

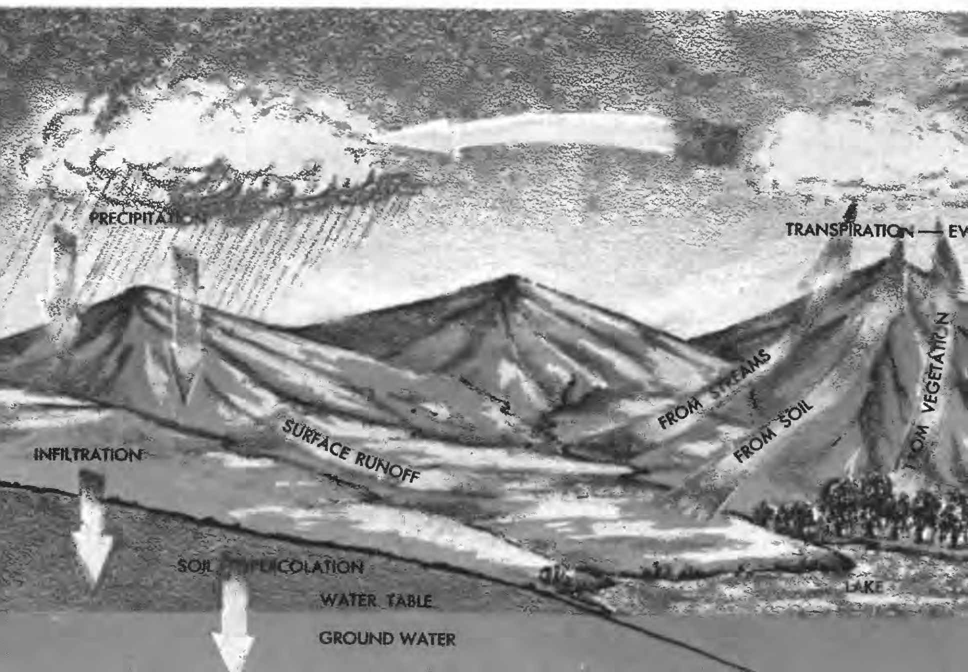
Scarcity of usable water

The high percentage of evaporation causes a scarcity of water available for use by man. Presently, Arizona uses about 7 million acre-feet of water annually, of which about 2 million is from surface water and about 5 million is pumped from the ground. Hydrologists estimate that of the total 7 million acre-feet not more than 3 million is from the renewable supply of surface and ground water. The remaining 4 million acre-feet represents withdrawal of ground water from storage in excess of replenishment.

Demand for water is greatest in the arid valleys in the south, where it is used for light industry and municipal supply as well as for agriculture. Increasing present demands for water are many water-consuming devices, including the all-important air conditioning, which has made the desert a more comfortable place to live. If growth continues at the present rate or at a higher rate, much more water will be needed.

Census Bureau statistics show that the population of the West is growing extremely fast, and Arizona is one of the leaders in this growth. Their figures also show that Arizona is rapidly becoming more urban and industrialized. Nearly 50 percent of all the people in Arizona live in Phoenix or its suburbs, about 25 percent more live in the Tucson area, and the remaining 25 percent are scattered throughout the State. The expanding urban centers are competing more and more with farms for the use of land and water. This trend may continue, and as water rights are acquired by users who can pay the price, more land may be withdrawn from agriculture and put to urban use. Whether it is used to supply farms, homes, or industries, more and more

Figure 2. The natural cycle of water.



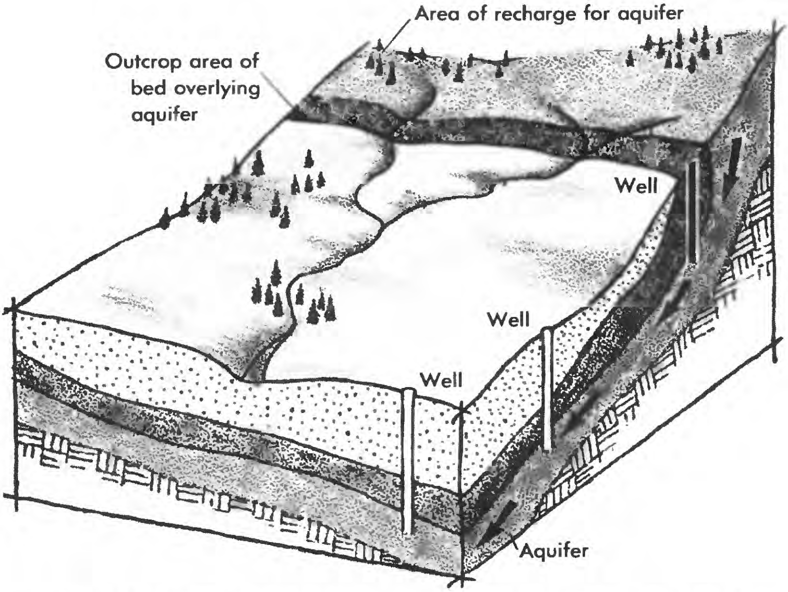


Figure 3. Water-bearing rock strata, or aquifer, underground and at the earth's surface.

ground water is being used, because of the basic water problem—a shortage of usable water that cannot be furnished by existing surface-water supplies.

Ground-water depletion

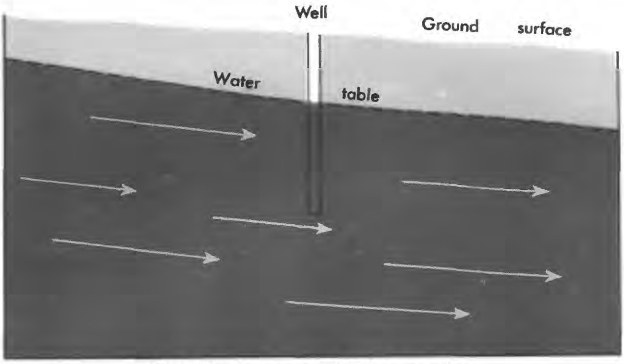
Water evaporates from the land and ocean and is carried as vapor or clouds in the air. Then somewhere it falls as rain or snow, returning to the land or the sea to go through the same wonderful natural cycle all over again (fig. 2). Water from rainfall on any area departs in one of three ways: through the atmosphere as water vapor, as runoff in stream channels, or as ground water. Ground water is all the water clinging to and saturating the rock some distance below the soil surface.

Rainfall enters the ground and starts downward. How this moisture moves through the soil is not fully understood. There is growing evidence that much more of it is returned to the surface, to be evaporated or used by plants, than is commonly believed. When rainfall persists for a long time, however, water may percolate downward and penetrate to the water table and become ground water. Ground water occurs in water-bearing strata of rock called aquifers (fig. 3). The aquifers are replenished, or recharged, by precipitation where they are at or close to the surface. This recharge area may be many miles from the place where the ground water emerges as a spring or is pumped from a well.

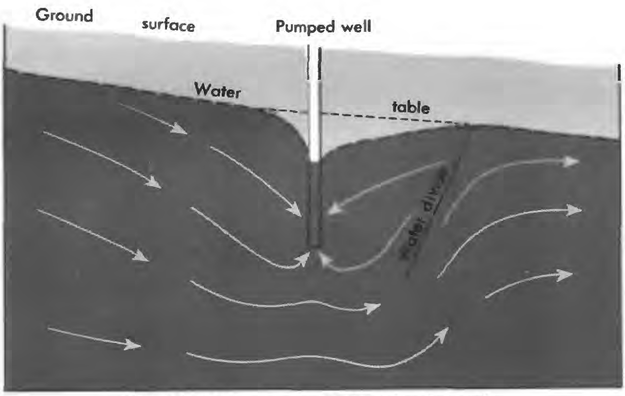
Streams that flow over permeable soils above the water table lose water by seepage into the ground, and this tends to build up ground-water levels. One might say the stream channel has a "leaky" bottom. On the other hand, where the water table is higher than the stream channel, ground water flows into the river. This is called the base flow of a river. Surface streams and ground water are thus connected and form a part of a single hydrologic system. Since streams and ground water are parts of a single system, excessive withdrawal of either one will diminish the other, and heavy pumping in certain areas in Arizona has caused some streams to stop flowing.

Ground water moves very slowly. The total amount of water in underground storage may be very large, but in a highly developed area the volume of flow is usually less than the amount being withdrawn by pumping. The lowering of the water table may be noticeable at distant places only after a long time. The water user's experience, however, may lead him to look upon a ground-water reservoir as an "inexhaustible lake." The ground-water reservoir is not a lake; nor is it inexhaustible, unfortunately. Although it will take many years to realize the full effects of current withdrawals of ground water, it is entirely possible to exhaust the supply eventually.

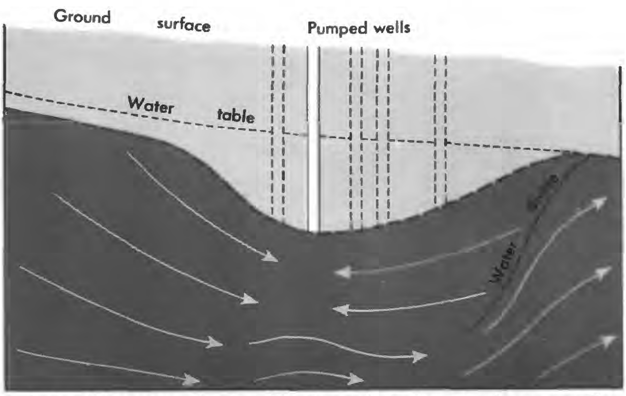
Withdrawal of water from storage underground is quite different from withdrawal of water from a surface reservoir. Water in a surface reservoir moves readily toward the pump, and the lake surface remains nearly level. But underground water moves very slowly toward a pumped well, and the surface slope of the water table steepens toward the well. Thus pumping creates a cone of depression in the water table (fig. 4). The area of depression and shape of the cone depend on the permeability of the water-bearing formation and the rate of pumping. Cones spread outward continually as pumping continues. Theoretically, the cone around a well continually pumped will ultimately lower the water level in all parts of a basin, but in a large basin the final effect would not be achieved for a long time. Where many wells are pumped, the water table is pitted with cones of depression.



Ground-water movement before pumping



Ground-water movement near a pumping well



Regional depression of water table after prolonged pumping by many wells

Figure 4. Ground–water movement in desert basins.

These generally combine to form one very large total cone of depression.

How long can one pump at a given rate? This depends on the amount of water in storage, which is fixed, and the amount of replenishment, which varies. One can choose between pumping at whatever rate is desired until all the recoverable water is gone, or pumping at a rate that will assure a continuous supply for some chosen length of time.

There is one important difference between taking water from a stream and taking it from a lake or ground-water reservoir. The rate at which water can be withdrawn from a stream cannot exceed the flow in the stream, whereas water may be pumped from a lake or underground reservoir at almost any desired rate. The length of time that pumping can continue before the store's reserve is gone depends on how fast we pump. Most geologists and hydrologists who have studied ground water in Arizona believe that the amount of replenishment of the underground reservoirs in the heavily pumped areas is many times less than the amount being withdrawn.

Contrast between irrigated and nonirrigated lands.

Arizona's desert basins contain no lakes; so the water in ground-water reservoirs is the only naturally stored reserve. The ground-water reservoir once stored a volume of ground water roughly equal to the volume of water in Lake Michigan (about 4½ billion acre-feet). Perhaps about 15 percent (700 million acre-feet) of this original volume of water was economically recoverable for use by man, of which about 10 percent (100 million) has been withdrawn, most of it in the last 25 years. Although this is only a small part of the total, it is the most easily and cheaply available part. In ground-water economy, readily available storage is more important than total storage.

Before man arrived on the scene, the water system in the basins of Arizona was in hydrologic balance—inflow equaled outflow. In any given area, inflow includes the total rainfall and the water entering the area by way of streams or by ground-water underflow. Outflow includes water leaving the area as streamflow and as ground-water seepage, and it also includes evapotranspiration loss. Man subtracts the water he uses from some part of this natural system. In doing so, he may draw on the reserves accumulated in ground-water storage. Under man's regime, therefore, outflow may exceed inflow (while storage lasts), and it actually does so in many areas in Arizona.

Salts in the soil

A problem that has received serious attention only recently is the effect of use on the quality of water. Nearly all use of water results in deterioration in the physical or chemical quality of the water when it is returned to the ground or to streams.

The chemical nature of water changes constantly as the water moves through its natural cycle, passing from vapor to cloud to rain or snow, to rivers and underground flow to lakes and oceans, then back into the atmosphere again as vapor (fig. 2). Rain and snow contain gases such as carbon dioxide, oxygen, and nitrogen and may carry small amounts of chloride, sulfate, and nitrate. The gases in rainwater help to dissolve many minerals as the water flows over the ground or percolates slowly through the rocks beneath the surface. The dissolved minerals in water commonly are called salts. This term is used in a chemical sense, however; it does not imply that all these minerals are salt in the ordinary sense, such as table salt (sodium chloride).

Irrigation invariably results in concentration of dissolved mineral matter, or salts, in the return water, because the plants consume a large part of the water applied but only a small part of the salts. Also, mineral fertilizers and soil minerals are carried off in solution in the return water. On heavy soils from which water drains slowly, the moist soil loses much water to evaporation, and this concentrates the salts even more.

In such situations mineral concentrations in the soil may be as much as 100 times the concentrations in the water applied. These high mineral concentrations retard or prevent plant growth. Unless soils are well drained and receive sufficient excess water to flush out the salts, irrigation always increases soil salinity. Eventually the soil may become too highly mineralized for further use.

Soil-salinity problems are rare in areas where rainfall is sufficient to grow crops without irrigation, because the natural water supply flushes the soil. Saline soil is common in the West and Southwest, however, and irrigation increases the problem.

Two methods of meeting the problem have been used. One is to ignore salinity and wring as much profit from the land as possible before abandoning it. The other approach is to make full use of available knowledge—and seek more—on the interrelations of soil chemistry, water chemistry, plant physiology, and soil rehabilitation. Soil and water experts are working hard on these problems, for the problem is already acute.

For many years more mineral matter has entered the Salt River Valley in the surface-water supply than leaves the area in the outflow. This unfavorable "salt balance" results in a gradual increase in the mineral content of the ground water and deterioration of the quality of the surface outflow. A progressive increase in the dissolved mineral content of the ground-water supplies has been observed for several years in the area between Tolleson and Gillespie Dam. With the beginning of large-scale pumping in the Wellton-Mohawk project area to lower the excessively high water table, water of poor quality with high dissolved-solids content has been delivered to the Colorado River during the winter periods of low flow. The water users in Mexico have claimed over a period of time that their supply was not suitable for irrigation and the Mexican Government asked for relief. The matter has been under consideration by both Governments, and it is expected that a satisfactory method of handling the problem will be worked out.

All these water problems in Arizona are inextricably interconnected and are based on the fundamental facts of weather and climate. Over much of Arizona, precipitation is light and evaporation is high. The scarcity of usable surface water results in depletion of the ground-water reserve. Intensive irrigation is necessary to support a predominantly agricultural economy, and in its turn produces excessive soil salinity.

Climate cannot as yet be changed. Can man change the way he manages the water?

Let us look into the past history of water development in Arizona to see how the present situation arose.

Irrigation canal in the Wellton-Mohawk division of the Gila project.

THE PAST

Growth of water development

As in most parts of the country, early water development in Arizona was rather sporadic. But irrigation in Arizona antedates white settlement; as we have said, the Indians irrigated Arizona land more than a thousand years ago. About 125 miles of prehistoric irrigation canals has been found in the Salt River Valley and in the Gila River valley.

The most enterprising irrigation project of the prehistoric Indians of Arizona was in the Salt River Valley, in a flat fertile area some 15 miles wide and 45 miles long, near the present location of Phoenix. The good soil in this valley, the perennial surface water flowing from the mountains, and the ample sunshine made it a logical place for both prehistoric and modern settlements.

Archeologists say that the Salt River Valley was irrigated as early as A.D. 800. The Indians dug wells to tap shallow ground water, but they relied mostly on rainfall and natural streamflow. Their canal system was identified by surveyors and confirmed in 1929 by aerial survey. The main canals were as wide as 60 feet and could carry enough water to irrigate 250,000 acres, but probably not all the area was irrigated at any one time. Beans, squash, corn, tobacco, and probably cotton were grown.

The Hohokam lived in the southwestern Arizona desert for more than a thousand years. Why they disappeared, or lost their identity as a people, is not known. Archeologists and geologists have their theories, but at present there is no way of establishing precisely what happened. Experts say that the local tree-rings indicate a great drought that lasted on and off through most of the 13th century. The persistence of such a drought might have caused a gradual exodus of the Hohokam people. At the same time, because of the drought, the farmers perhaps irrigated even more intensively than usual. Possibly the land became water-logged, a condition as bad for crops as too little water. Or perhaps, after centuries of use, the land was simply exhausted and laden with salts left by evaporation of the irrigation water. Any one of these conditions, or a combination of them all, might have led to the degeneration of the Hohokam as a cultural entity.

Although we do not know exactly why they vanished, their disappearance probably had something to do with their water and land problems. They responded to the challenge of their environment with intelligence and imagination. Had they been able to construct storage reservoirs, their culture might have lasted until the Spanish came.

As it is, little is known about human history in the Southwest between 1400 and the arrival of the Spanish explorers. After the Spanish, came settlers of English descent. They began to irrigate about 1867, and by 1878 more than 200,000 acres was cultivated. Many of these canals followed the same courses used by the Indians. The drought of 1897–99 forced more than 75,000 acres out of cultivation. By the time Congress passed the Federal Reclamation Act on June 17, 1902, approximately 126,000 acres was under cultivation.

As in any arid land, the development of Arizona was intimately connected with available water supplies. Shortly after the Civil War, pioneers settled along the Gila River, in the Florence area, where water was readily available. Picacho Reservoir, the first of many for storage of irrigation water, was built in 1890 in the Casa Grande–Florence area. By the 1930's it was shown that large amounts of water could be obtained from natural underground storage, and agriculture using water from wells expanded rapidly after World War II.

Diversion dams in southern Arizona.

To assure a constant supply of water for the irrigated land, storage in reservoirs behind dams was necessary. How to finance such facilities was a general problem in the West until the Reclamation Act opened the way for appropriations of money for surveys, planning, and construction. In order to transact business in connection with dam-building, the Salt River Valley Water Users' Association, the first organization of its kind formed to take advantage of the act, was incorporated in February 1903.

Construction of Roosevelt Dam on the Salt River was begun in 1905 and completed in 1911. Two hundred and eighty feet high, it was at that time the highest dam in the world. The dam provided a stable source of water for irrigation, as well as for power generation. Granite Reef diversion dam was built on the Salt River below the mouth of the Verde to divert water from the Salt River into the canal system.

By 1920 Roosevelt Lake had overflowed four times, and much valuable water had flowed unused out of the area. In order to conserve more water, the Water Users' financed and built three additional dams on the Salt River below Roosevelt: Mormon Flat (Canyon Lake) in 1923–25; Horse Mesa (Apache Lake) in 1924–27; and Stewart Mountain Dam (Sahuaro Lake) in 1928–30. The combined capacity of the four reservoirs is about 1,750,000 acre-feet, and their spillways are designed to pass a flood of 150,000 cfs (cubic feet per second). Since 1920, this system has overflowed only once, from April to July 1941.

Irrigation has greatly affected the ground-water situation in the Salt River Valley. Under natural conditions ground-water levels in the Phoenix area were controlled by a rock barrier under the channel of the Salt River at Tempe Narrows. This barrier impounded the ground water; the water table was at the surface along the stream channel; and the ground water discharged into the stream channel. Farther up the valley and along the mountain fronts the water table was deeper. For example, near the Superstition Mountains it was more than 500 feet below the land surface.

In the early 1900's these natural hydrologic conditions were modified. Irrigation water from streams was spread over the land between the mountain fronts and the river. Much of the water entered the ground, recharged the ground-water reservoir, and caused the water table to rise. Because little or no water was pumped from the ground-water reservoir, water levels rose steadily until about 1924 (fig. 5) and farming became difficult because the soil was waterlogged. Drainage wells had to be drilled and pumped to lower the water table.

At first, the drainage water was wasted, but later it was used for supplemental irrigation. In 1929, the Roosevelt Irrigation District built canals and aqueducts to carry off this pumped water, delivering it to lands to the west, where the ground water is poor

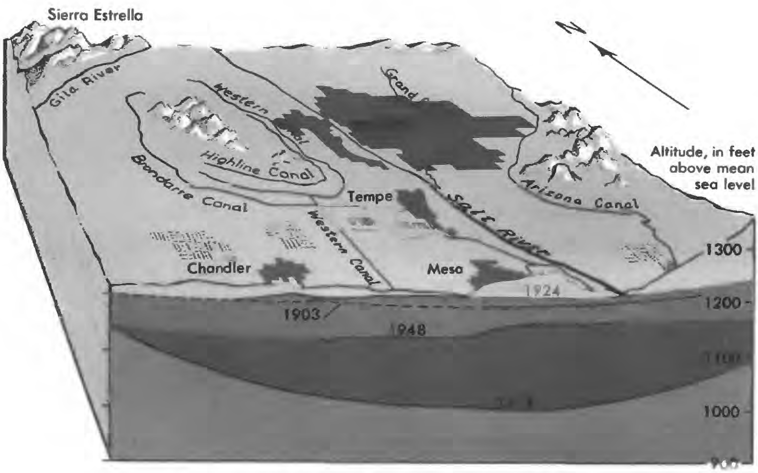


Figure 5. Water table in Salt River Valley.

in quality and no surface water is available. The district also drilled wells along the 30-mile canal and exported water from these wells.

Nowadays, people who live in the vicinity of Phoenix are concerned about this exportation of water because water levels in wells are declining rapidly. Before 1940, irrigation with surface water had caused the water table to rise also in Deer Valley, in lower Paradise Valley, and in the area east of the Roosevelt Water Conservation District. About 1940, however, the cultivated area in the Salt River Valley expanded beyond the region irrigated with surface water, and irrigation water began to be pumped from wells. Thereafter, water levels declined, and in recent years the water table has dropped far below its original level.

During the drought in the forties, additional ground water was pumped to make up shortages in the surface water in the Salt River Valley. After World War II, high prices for farm products stimulated irrigation and increased the demand for water. Today, all available surface-water supplies are in use, and the ground-water reserve is being intensively developed.

Irrigation is practiced in other valleys of Arizona, and other storage dams have been built. Lake Pleasant Dam, the oldest storage facility on the Agua Fria River, was built in 1927 to furnish irrigation water for 50,000 acres in Maricopa County Municipal Water Conservation District No. 1. The storage capacity of the reservoir is 160,000 acre-feet, and the reservoir has overflowed only once, in 1941.

The earliest irrigation in the lower Gila River valley after that by the Indians was started by settlers in the Florence District in 1864. By 1867, 12 canals were delivering water to irrigate 6,000 acres. Settlers began irrigating in the Safford area in 1872 and in the Duncan area in 1879. The Buckeye Canal, on the north side of the Gila about 4 miles below the mouth of the Salt River, began delivery of water in 1888. By 1905 some 29,000 acres was irrigated in the Gila River valley.

Coolidge Dam was built in 1928 to store floodwater. Its lake, known as San Carlos Reservoir, has a capacity of 1,200,000 acre-feet, but the maximum storage attained thus far was 819,200 acre-feet, in 1942. The reservoir has been empty several times.

Gillespie Dam, a diversion structure for the Gillespie Land and Irrigation Co., was completed in 1921 to irrigate 10,000 acres in the vicinity of Gila Bend and Theba. Lack of water has prevented complete development of the irrigation project.

The oldest storage dam on the upper Little Colorado River was built in 1913 but was washed out by a flood in August 1915. Lyman Dam, built in 1920 to serve the St. Johns area, has a reservoir capacity of 30,600 acre-feet and has overflowed only twice, in 1932 and in 1941. Upper and Lower Lake Mary on Walnut Creek, which have a combined capacity of about 35,000 acre-feet, store water for municipal use at Flagstaff.

Yuma Valley has one of the oldest water rights on the Colorado River and uses this river water for irrigating more than 50,000 acres on the flood plain today. By 1904 more than 10,000 acre-feet of water, diverted from the river by pumps and gravity, was used for irrigation. The supply depended, however, on unregulated river flow.

The Yuma Mesa auxiliary project was authorized by the congressional act of January 25, 1917; and work on the Mesa division, which became part of the Gila project, began in June 1936. Water diverted at Imperial Dam now flows about 20 miles by gravity through the Gila main canal to a pumping plant, which was completed in October 1941. The project includes delivery of water to the North Gila division and to the Wellton-Mohawk area, some 50 miles east of Yuma. By 1958, 60,000 acres in the project was being irrigated with Colorado River water. More than 10,000 additional acres is supplied with ground water. Currently, more than a million acre-feet of water is diverted annually from the Colorado River to irrigate more than 125,000 acres near Yuma.

Citrus trees under irrigation, Yuma project.

River water applied to the porous soils of Yuma Mesa contributes to ground-water recharge and has created a unique situation in Arizona—a surplus of ground water. Ground-water overflow from the mesa area has contributed to drainage problems in Yuma Valley. The degree to which mesa irrigation and valley irrigation are respectively responsible for the high water table in the Yuma Valley is difficult to determine.

The story of water development in the lower Santa Cruz basin is the story of agricultural development on a broad plain surrounded by mountains. The basin's main drainageway is the Santa Cruz River, which joins the Gila in Pinal County, southwest of Phoenix. For simplicity, the lower Santa Cruz is divided into four areas: Eloy, Maricopa-Stanfield, Avra-Marana, and Casa Grande–Florence.

Indians and early settlers in the Eloy area used floodwaters for irrigation, and the oldest irrigation wells were constructed in 1914. Many of these wells were abandoned, owing to the high cost of pumping. Then rapid expansion occurred in 1936 and 1937, when cotton prices advanced and low-cost electricity became available for pumping. Some 40 to 50 wells were drilled during this period to irrigate about 18,000 acres of land. By 1963 about 400 wells were in use, furnishing ground water to 75,000 acres.

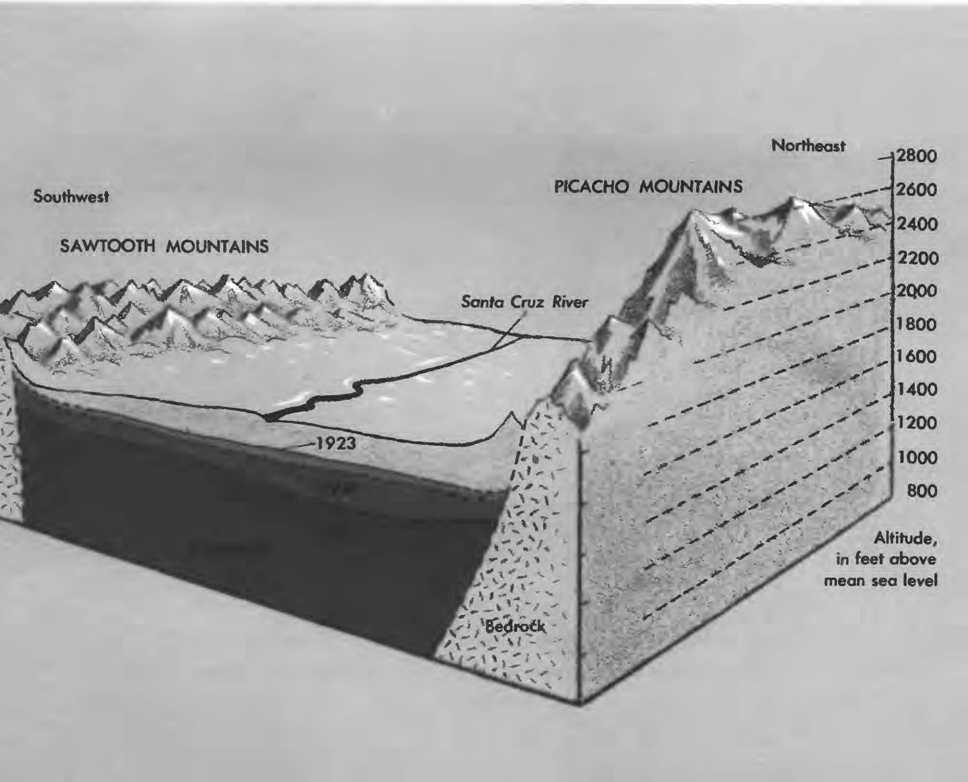
Modern Indians irrigated part of the Maricopa-Stanfield area with floodwater from the Santa Cruz River. Development of ground water began about 1920 and by 1935 about a dozen wells were pumped to irrigate some 2,000 acres. By 1941, 25,000 acres was irrigated and the number of wells rose to 85. In 1963 about 500 wells furnished water for more than 100,000 acres.

Indians used floodwaters for irrigation in the Avra-Marana area long before Arizona became a State. By 1935, however, irrigation had practically ceased because the canals and laterals had been cut so deep by erosion that they could not deliver the water to the surface of the land, and the equipment then available could not lift ground water economically. Ground water was developed in the Avra-Marana area later than in other areas. In the 1950's, rising prices for farm products made the lifting of ground water from greater depths economically feasible. In 1963 some 40,000 acres was under irrigation with ground water pumped from depths as great as 300 feet.

The Casa Grande–Florence area differs from the Eloy and Avra-Marana areas in that surface water is available during part of the year. The Pima Indians have lived here since prehistoric times, and early settlers found them irrigating their land with Gila River water. From 1872 to 1930, because others were irrigating upstream near Florence, the water supply in the Casa Grande–Florence area was inadequate and cultivation of downstream land dwindled. Wells were drilled in 1915 to obtain supplemental ground water. The number of wells in use was about 80 in 1939, nearly 300 in 1942, and more than 500 in 1963.

Several small surface reservoirs and dams have been built in the Casa Grande–Florence area. Picacho Reservoir was constructed by landowners in 1890 and was enlarged in 1956. Water from the Gila River is diverted into this reservoir through an 18-mile canal. Storm runoff from the Picacho Mountains is also captured. Water from this reservoir is used in the vicinity of Casa Grande.

Figure 6. Water table in the lower Santa Cruz basin.



In the Casa Grande–Florence area, about 50,000 acres of Indian lands and 50,000 acres of privately owned lands are included in the San Carlos project, which was authorized by Congress in 1924. By 1930, water was available to the project from the San Carlos Reservoir, but the water supply never has been sufficient to irrigate the entire acreage. Supplemental water for project lands is obtained from wells that discharge into canals and laterals.

Little ground water was pumped in the lower Santa Cruz basin before 1924. The phenomenal expansion of ground-water pumping for irrigation after World War II has caused cumulative decline of water levels in the Santa Cruz basin (fig. 6). The current decline is rapid and in some places has extended to the flanking mountain slopes. The central valley floor is sinking because the dewatered land tends to shrink. Long earth cracks have developed near the mountain flanks. At the margins of the basins, the decline is less than that in areas where pumping is concentrated. If the water table continues to decline in the

Grand Canyon National Park, from Bright Angel Trail.

The Grand Canyon.

central part of the valley, pumping for irrigation may become too expensive to continue. Even before the underground storage supply is exhausted, the high lift necessary may increase the cost to uneconomical levels.

The Colorado River

Almost the entire State of Arizona is in the basin of the mighty Colorado River. Yet so important is water in this part of our country that the use of Colorado River water has been a subject of controversy for more than 30 years.

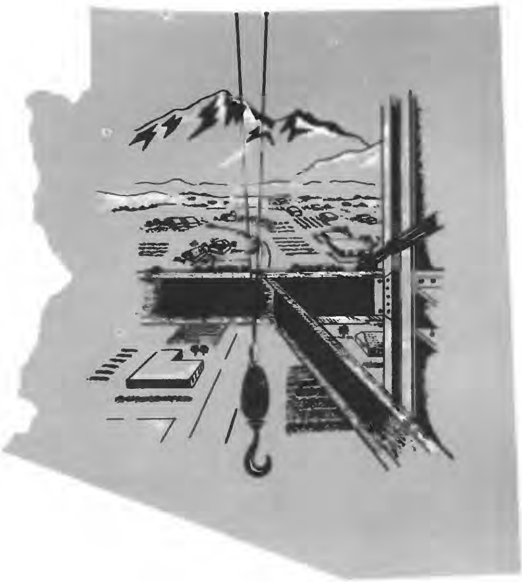
In 1921 Congress authorized construction of Boulder (now Hoover) Dam, an initial effort to prevent floods, store water, develop power, and control flow on the Colorado River. The authorization aroused much controversy among the seven basin States—Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming. Congress was reluctant to pass the authorizing bill unless at least six of the seven States, including California, agreed on how the water was to be divided. In 1922 representatives of the seven States drew up a compact which divided the water between an upper basin and a lower basin, with the point of division at Lees Ferry in northeastern Arizona. The compact allots an average of 7.5 million acre-feet of water per year to the upper basin and a like amount to the lower basin, which includes parts of Colorado, California, and Nevada. In addition, the lower basin is permitted to increase its annual beneficial consumptive use of Colorado River water by 1 million acre-feet of water.

In 1923 all the States ratified the compact except Arizona. Congress then passed the Boulder Canyon Project Act (1928) and the Secretary of the Interior was authorized to let contracts for water and power with States which had ratified the compact. Under the terms of the act, a limitation of 4.4 million acre-feet was set for California, while 2.8 million acre-feet was recommended for Arizona and 300,000 acre-feet for Nevada. Further division was to be made of any surplus. Arizona, California, and Nevada could not reach the agreement suggested by the Congress in the Boulder Canyon Act. In 1952, after several previous legal moves, Arizona filed suit relative to the division of Colorado River water. Subsequently, the Supreme Court rendered an opinion and issued a decree dated March 9, 1964, implementing the opinion. It will probably take several years for water development and use in the lower basin to adjust to the provisions of the Supreme Court decree.

This brief history of water development reveals that almost everywhere in Arizona surface-water supplies are modest or else oversubscribed. The ground-water resource has been used to compensate for the lack of surface water, but intensive ground-water development has resulted in steadily declining water levels in the irrigated areas of Arizona.

The story of water in Arizona to date is one of maximum development with minimum planning or regulation. This trend has produced agricultural products in abundance, as well as all the accompanying benefits of a high standard of living. But the question remains: Can increasing development of ground and surface water continue in its present pattern in the face of the ever rising costs for pumping (because of constantly increasing depth to ground water), and without eventually depleting the ground-water reserve?

Grand Canyon National Park, from Kaibab Trail.



THE PRESENT

Water resources

The most outstanding characteristic of Arizona is diversity—of scenery, climate, weather, and streamflow, as well as plant and animal life. The climate is related to the mountains and plateaus and to the prevailing westerly winds. The cold desert country to the north offers scenic beauty to the tourist and provides limited pasturage for grazing sheep and cattle. In the hot deserts of the south, agriculture and industry flourish where water is diverted from streams or pumped from underground storage.

Annual precipitation in Arizona ranges from about 3 inches in the desert to 30 inches in the mountains. Streamflows are very erratic, fluctuating widely from year to year. Because of this variability, storage of surplus water is vital to water management in Arizona.

A glance at the map (see fig. 1) will show that Arizona is naturally divided into three major regions: the Desert Lowlands in the south, the Central Highlands running east-west across the State, and the Plateau Uplands in the northern half of the State. Water conditions and water problems are different in each of these three regions because of differing geographic and geologic conditions.

The rugged, mountainous central region has been carved by streams into spectacular landforms (fig. 7). The Mogollon Rim, a distinctive feature of grandeur and prominence, extends more than 200 miles through the central part of the State and ranges in height from several hundred feet to more than 2,000. Its brow is the divide between the drainage systems of the Little Colorado and Gila Rivers. Springs along the base of this south-facing escarpment feed water into the Gila, Salt, and Verde Rivers.

Principal Gila River tributaries that rise in the Central Highlands include the Verde River, which flows southeastward through the central part of the State, and the Salt River, which drains the eastern area lying south of the Mogollon Rim.

Precipitation in the mountains ranges from 10 to 35 inches annually (fig. 8). Westerly winds cool as they rise over the steep mountain slopes, form clouds, and create a virtual squall line along the rim's crest from late morning until late evening during the summer. Similar conditions may prevail during the winter and cause heavy snowfall. Melt water from snow provides a large part of runoff late in the spring.

Water from the Central Highlands flows southward in the Salt and Verde Rivers and northwestward in the Little Colorado River. The Salt River and Tonto Creek join in the highlands (fig. 9) and discharge to the lowlands through the narrow Salt River gorge east of Phoenix. The Salt and the Verde Rivers carry most of the surface-water yield from the region, and the gorge funnels most of this water to the Phoenix area.

Surface runoff varies widely from place to place in the mountains, owing to differences in precipitation, temperature, and terrain. South and immediately west of Mount Baldy, precipitation exceeds 25 inches a year (fig. 8), and the average annual runoff is about 4 inches. ("Four inches of runoff" means a volume of water equivalent to a layer 4 inches deep over the entire watershed.) West of Baldy, along the upper reaches of Forestdale and Carrizo Creeks, annual rainfall exceeds 20 inches, but runoff is less than 1 inch. Farther west, in upper Tonto Creek basin, runoff is more than 2 inches. The average for the Salt River drainage system above Roosevelt Lake is 2.8 inches, or somewhat more than 600,000 acre-feet a year.

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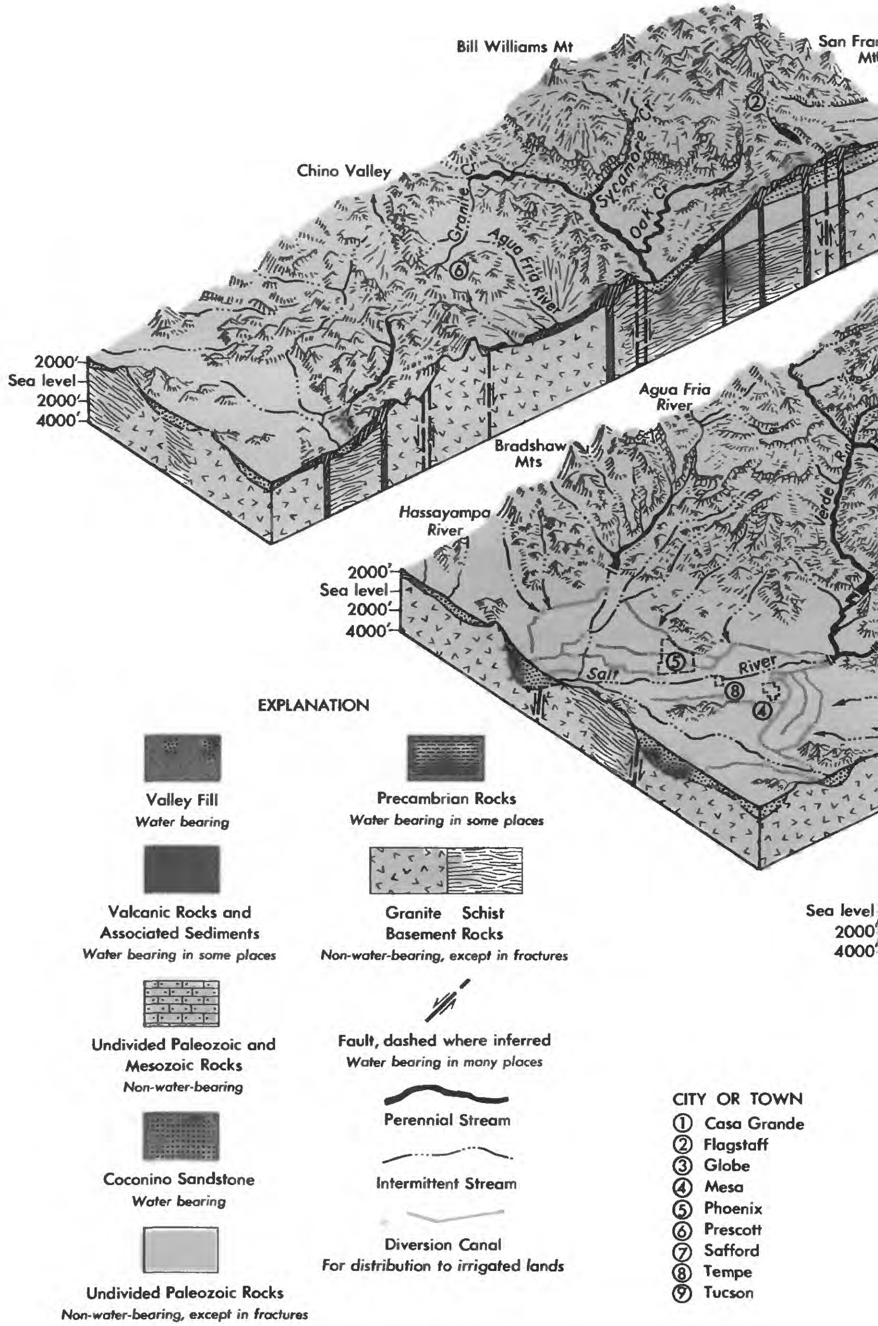
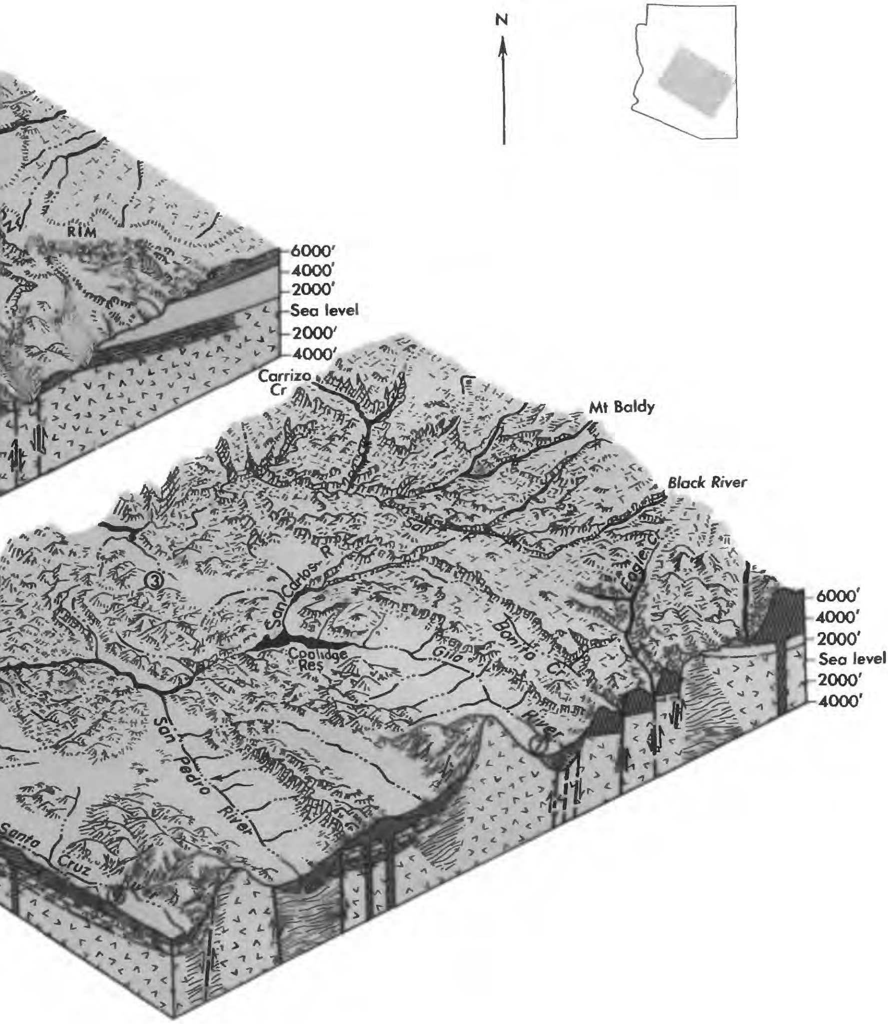


Figure 7. The Central Highlands of Arizona.


N
RIM
6000'
4000'
2000'
Sea level
2000'
4000'
Carrizo Cr
Mt Baldy
Black River
Salt R
San Carlos R
Coolidge Res
Gila
River
Bonito Cr
Eagle Cr
San Pedro River
Santa Cruz
3
6000'
4000'
2000'
Sea level
2000'
4000'

The streamflow characteristics of the Verde River basin, in the western part of the province, resemble those of the Salt River. Several upstream tributaries, such as Oak and Granite Creeks, have an average annual runoff of about 4 inches (fig. 9). At the mouth of the Verde, the annual average is only 1.4 inches, or 500,000 acre-feet. Because Agua Fria and Hassayampa Rivers drain areas at lower altitude, their runoff is considerably less—around 0.5 inch.

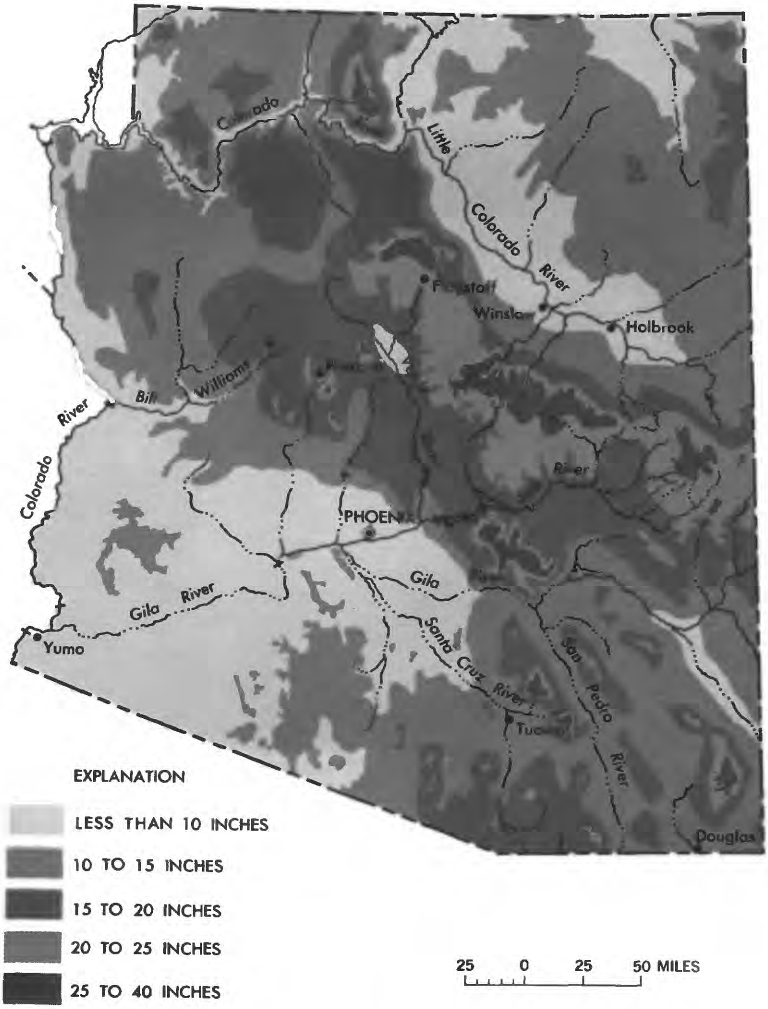


Figure 8. Average annual precipitation.

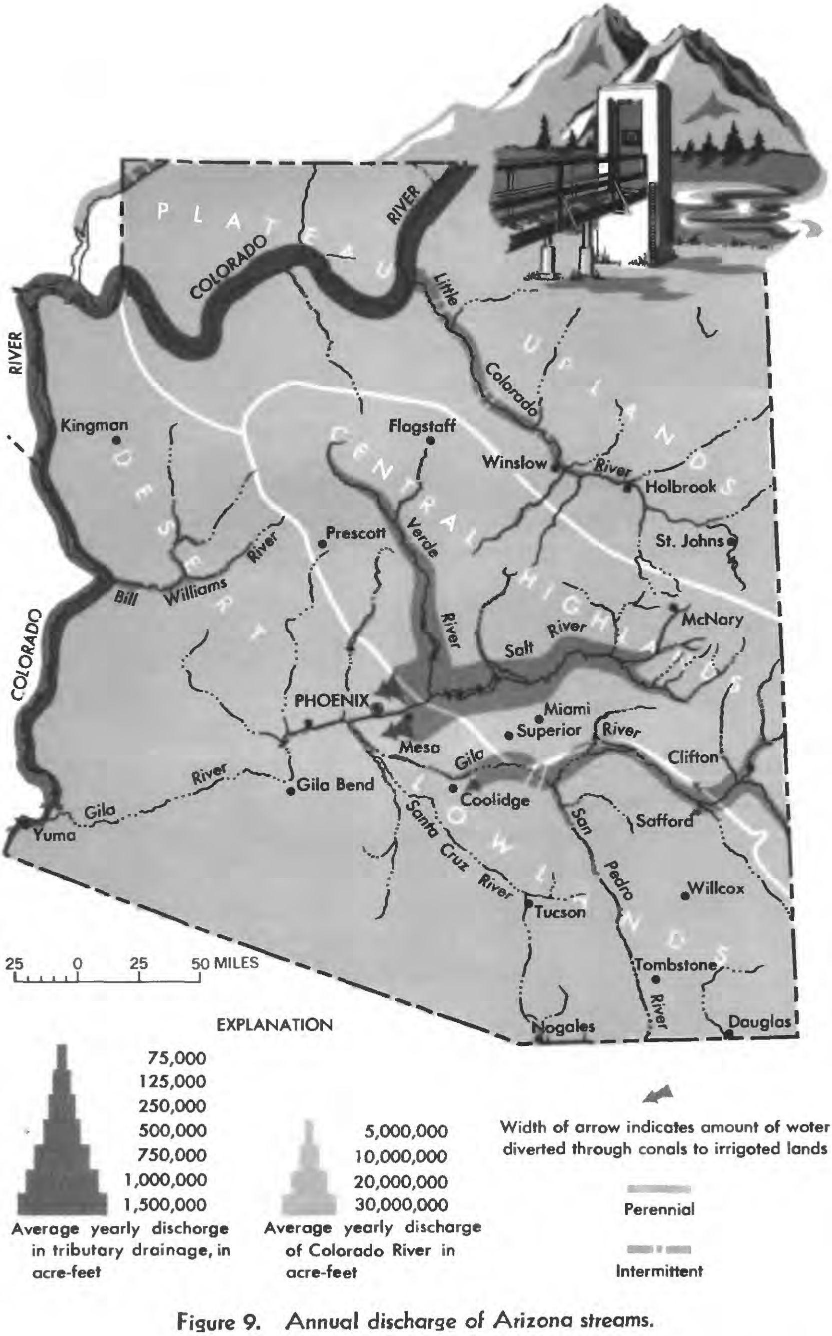


Figure 9. Annual discharge of Arizona streams.

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The San Francisco and San Carlos Rivers and Eagle Creek are the main drainageways in the southern part of the Central Highlands, from which streams flow southward to join the Gila above Coolidge Dam. Their average annual runoff is less than 0.6 inch.

Most floods in the central highlands are caused by storms moving eastward from the Pacific coast, most frequently in winter or early spring. The largest flood of record on the Salt River, in February 1891, had a peak flow of 300,000 cfs (cubic feet per second) just below the mouth of the Verde. The peak discharge of this flood is about the same as that of the largest flood known to have occurred on the main stem of the Colorado River. This widespread storm also caused the maximum flood of record (46,000 cfs) at Planet, on the Bill Williams River in the western part of the State.

The second greatest flood on record occurred in November 1905, when peak flow of the Verde River near its mouth was 96,000 cfs. Floods were widespread also in January 1916, and on several streams these rank variously as second or third highest in the last 70 years. Other noteworthy floods occurred in February 1937, March 1958, March 1941, and January 1952.

Storms originating in the Gulf of Mexico occasionally cause unusual floods. A peak flow of 27,000 cfs on August 1951 is the maximum for the Hassayampa River since 1938. The same storm caused the highest recorded summer peak on Tonto Creek, 31,000 cfs, the fourth highest of record since 1941. Another unusual summer storm occurred in August 1954, sending a maximum flow of 43,000 cfs down Queen Creek.

In general, flood stages from winter storms are persistent, and stream discharge may remain high for several days. Floods from summer storms rise rapidly to a sharp peak, followed by rapid decline.

Sixty percent of the annual runoff in the Salt River occurs between January and April, compared with 15 percent between July and September. Runoff in the Verde is 65 and 15 percent during the same periods. Minimum flows usually occur just before the summer rains, in June or early July. June runoff in the Salt and Verde Rivers averages only 3 percent and 1.5 percent of the annual total.

An outstanding characteristic of the Phoenix area is the extreme variability of the annual runoff (fig. 10) in the Salt River.

Runoff ranged from a low of 290,000 acre-feet in 1900 to a high of 5,200,000 in 1905. Base flow before intensive development is reflected in the annual lows of June and October. Base flow as used here refers to ground water that is discharged into streams. The slow movement of this water sustains the discharge and enables streams to continue flowing even when there has been no rain for a long time.

Three main rock types occur in the mountains: sedimentary, igneous, and metamorphic. Each of these has a different physical makeup, and each differs from the others in its ability to store and transmit water and in the chemical quality of its water. Igneous rocks are formed from the molten rock, or magma, which pushes through crevices in the earth's crust and solidifies. Sedimentary rocks are made from the sediments laid down by ancient rivers and winds. Metamorphic rocks may have begun as igneous or sedimentary rocks, but heat, time, pressure, and sometimes water have changed them into another kind of rock.

Igneous rocks in the Central Highlands are mostly granite. Among the metamorphic rocks, schist and gneiss are common. These rock varieties are nearly impervious to water and have little capacity for water storage except where they are intensively fractured.

The sedimentary rocks that form the Mogollon Rim consist of firmly consolidated sandstone, siltstone, claystone, and limestone. These rocks can store large quantities of water. But because they have low permeability, they are slow to absorb water or to yield it up once it is absorbed.

A large part of the rim is formed by the Coconino Sandstone, a major and widespread aquifer beneath the plateau. In many places, it is several thousand feet below the land surface, and in some places the water may contain too much chloride to be of use.

Many springs near the base of the rim discharge from the Coconino Sandstone or the underlying Supai Formation. Several springs occur along faults. The discharge from about 150 of these springs, totaling some 180 cfs, sustains the perennial flow of many small streams to the south.

Flagstaff lies near the base of the volcanic San Francisco Mountain. The city obtains part of its water supply from wells in the Coconino Sandstone in areas where faults and other fractures provide avenues for replenishment from precipitation. Permeable volcanic rocks, which form a large part of the land surface around Flagstaff, locally supply much water. Water from the surface moves freely through the volcanic rocks and recharges underlying beds.

A few valleys in the mountains contain alluvium, which is silt, sand, gravel, or similar material deposited by running water. Alluvial deposits are capable of storing ground water. Though these valleys extend for many miles, the alluvial deposits are shallow, and they do not contain as much water in storage as do basins to the south.

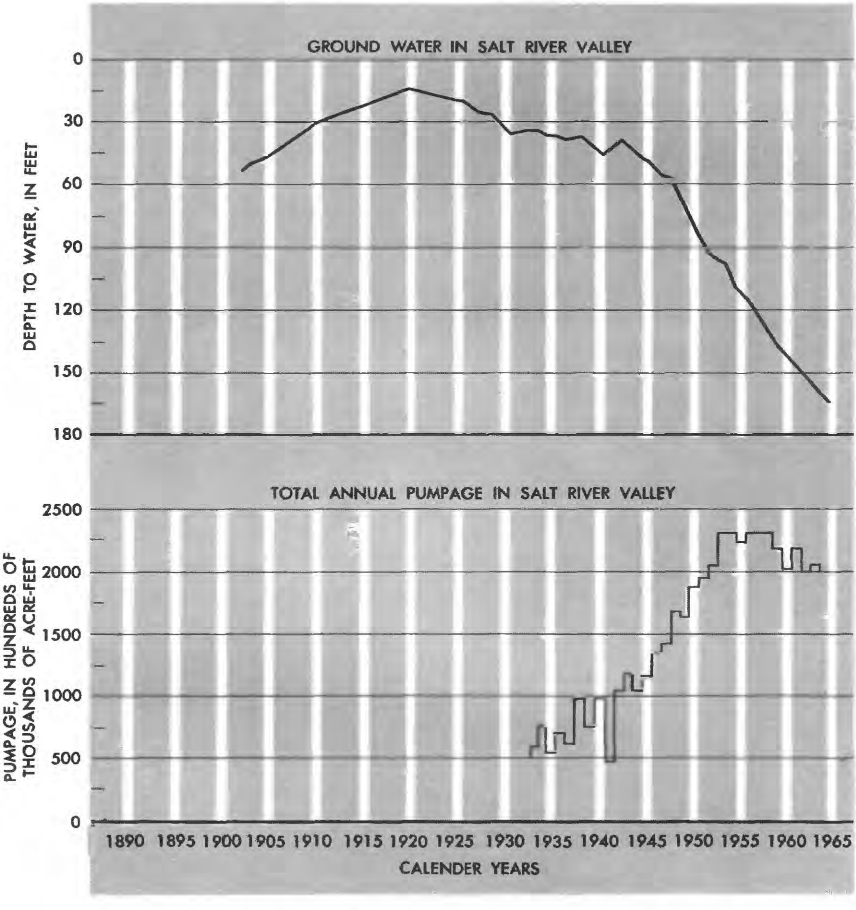
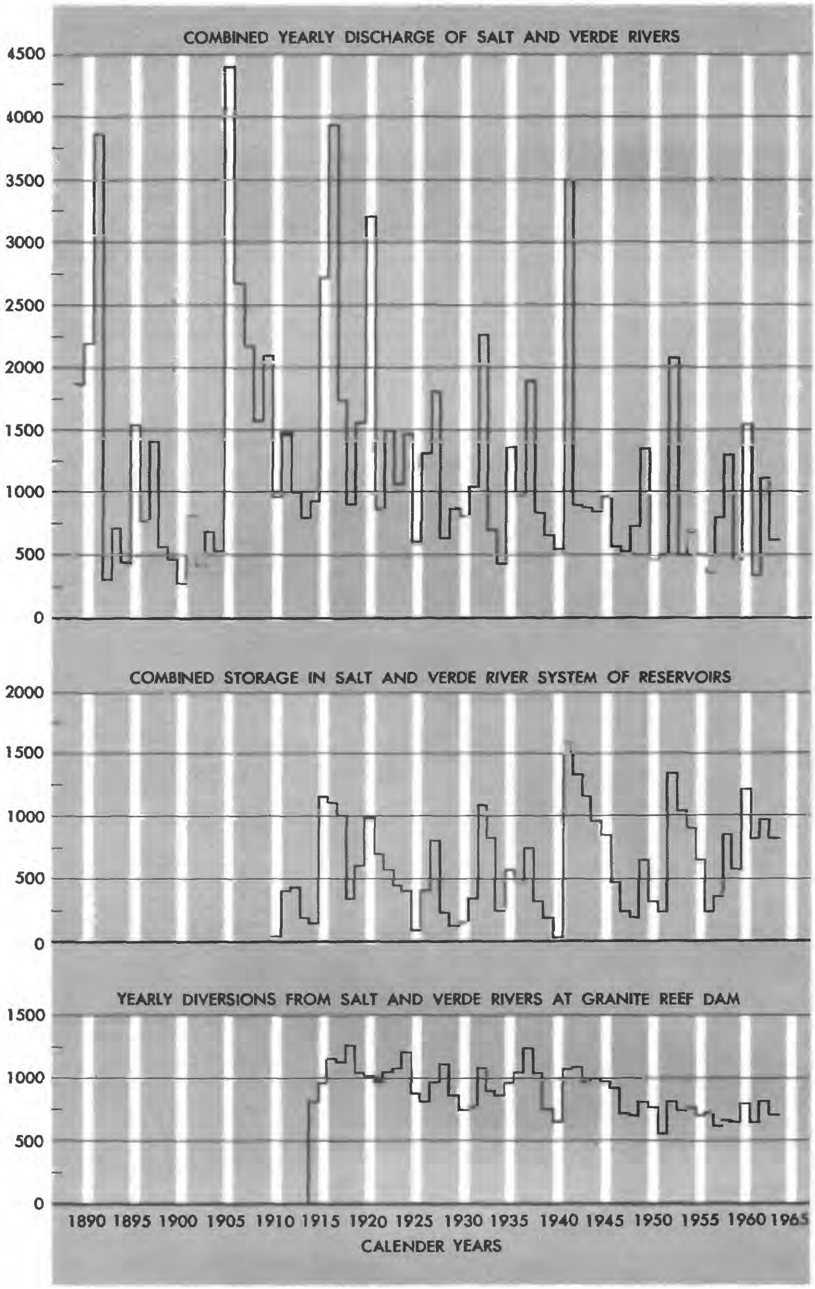


Figure 10. History of ground and surface water in Salt River Valley.



COMBINED YEARLY DISCHARGE OF SALT AND VERDE RIVERS
4500
4000
3500
3000
2500
2000
1500
1000
500
0
COMBINED STORAGE IN SALT AND VERDE RIVER SYSTEM OF RESERVOIRS
2000
1500
1000
500
0
YEARLY DIVERSIONS FROM SALT AND VERDE RIVERS AT GRANITE REEF DAM
1500
1000
500
0
1890 1895 1900 1905 1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965
CALENDER YEARS

Alluvial sediments in Safford Valley contain ground water, but the potential yield is small because most of the sediments are fine grained. Only the shallow unconsolidated material, about 80 feet thick along the Gila River, will yield water readily. Although hydrologic conditions in the upper part of the Verde River valley generally resemble those in the Safford Valley, there are many local differences that affect the quality and quantity of ground water obtained from the valley sediments.

Plantlife varies widely with climate and altitude. Nowhere in the State are variations more pronounced than in the Central Highlands. In many places temperature, precipitation, soil types, and other environmental factors favor luxuriant growth.

As you leave the Desert Lowlands behind and climb upward, the first noticeable change in vegetation is the occurrence of chaparral along the base of the mountains, where moisture is somewhat more plentiful. Chaparral includes a wide variety of shrubs such as live oak, manzanita, desert ceanothus, sumac, buckthorn, and silktassel. Grasses are more abundant in the chaparral zone than at lower altitudes, but the main grassland zone is higher.

Vegetation in the highlands.

Many parts of the upper grassland zone have been invaded by juniper. Where this tree is well established and its density adjusted to the available water supply, little moisture is left for grass. The ground beneath the trees is barren. Ponderosa pine predominates at altitudes between 6,000 and 8,000 feet. Above 8,000 feet are spruce, fir, and aspen. Each zone merges gradually with its neighbor, and there is no distinct line of demarcation between the several zones. Pine may occur with spruce and fir in the upper part of the ponderosa zone and with juniper in the lower. Each tree zone has an understory of shrubs and grasses.

When rain or snow falls in forests some is intercepted by vegetation. A shower may wet an entire tree thoroughly; yet no water reaches the ground under the tree. After the shower the water soon evaporates. Vegetation probably intercepts considerably more snow than rain. Snow may lodge thickly on the needles and branches of conifers, and much of it evaporates unless blown off by the wind.

Although we have no good measure of how much water is intercepted by forest vegetation, we do know that the amount

is substantial. More information about interception of precipitation by vegetation is needed.

Geology, topography, and climate influence the quality of surface and ground water. The quality of water at a point in a stream depends to some extent on the upstream conditions, and the character of the water will change from place to place. The chemical and physical changes in surface waters can be easily detected over short time intervals, hours or days. Whereas, changes in the quality of ground water, owing to the complex relations of the materials through which it flows, occur over much longer periods of time.

The numerous small mountain creeks flow swiftly; they carry cool, fresh water and are usually free of sediment because the water flows over granite, schist, and volcanic rocks, which do not erode easily. During periods of storm runoff, however, the streams contain large amounts of sediment. In the upper reaches of the streams, the water contains little dissolved minerals.

Springs in the Salt River below Cibecue Creek contribute small amounts of highly mineralized water to the Salt River and to a few of its tributaries above Roosevelt Lake. Nevertheless, the quality of water released at Stewart Mountain Dam is good because fresh floodwaters are mixed with the saline spring water in the Salt River reservoirs.

Below Stewart Mountain Dam the average concentration of dissolved salts was less than 700 ppm (parts per million) between 1951 and 1957. (Parts per million is one way of expressing the weight of dissolved matter in a solution. One part per million equals 8.34 pounds of dissolved solids in a million gallons of water.) In the course of a year, more than 400,000 tons of salts are carried by the Salt River below Stewart Mountain Dam. The Gila River at Kelvin carries about 142,000 tons per year, and the average load of the Verde below Bartlett Dam is about 110,000 tons (fig. 11).

The plateau in the northern part of Arizona represents almost 40 percent of the total area of the State—a vast expanse of magnificent scenery. The climate is cool and the country arid. This is the land of the Navajo, the domain of the Little Colorado River. The gently sloping surfaces, covered with a thin mantle of soil and sparse grass, provide grazing land for sheep, a major

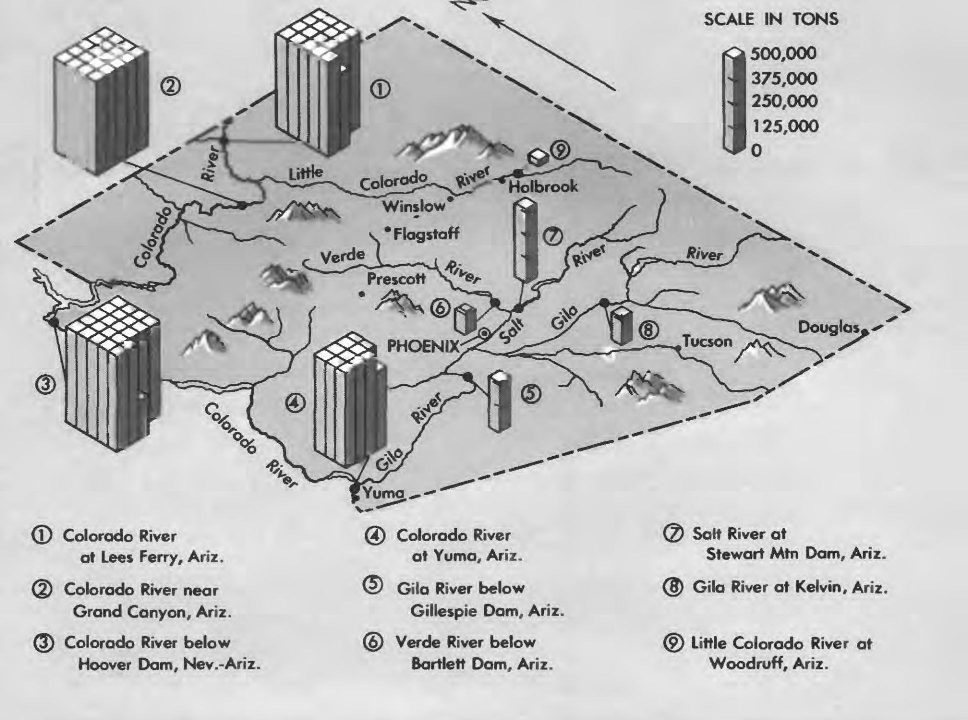


Figure 11. Average loads of dissolved salts in Arizona streams.

factor in Navajo economy. Another factor is the scanty water supply.

The ribbon of high precipitation that extends along the brow of the Mogollon Rim in the mountains bends northward past San Francisco Mountain to the Kaibab Plateau, where it supports forests of juniper and pine. Spruce, aspen, and fir grow at higher altitudes.

The Colorado River flows across the northwest part of the State, where it has sculptured the inspiring spectacle of the Grand Canyon. Persons from all over the world have seen the ancient colored rocks and marveled at the depth of the tremendous chasm. To the east the Little Colorado, an important upland tributary, flows along a shallow valley to Grand Falls, where it tumbles into a deep gorge. Throughout the plateau, erosion has carved the rocks into a great variety of landforms such as Monument Valley and the Painted Desert. The natural coloring in this part of the State is exceptionally vivid.

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Junction of the Colorado and Little Colorado Rivers and south rim of Grand Canyon at Grand Canyon Village.

Almost all perennial streams which flow across the plateau originate in the mountains, where precipitation is high along the Mogollon Rim. Melting of winter snows tends to prolong the flow in some streams, but during the summer most of the streams flow only after rain.

The canyons of the Colorado and Little Colorado cut through several thick aquifers which discharge water as springs. Surface runoff and discharge from springs constitute the perennial water yield of the plateau. Some of the water is good in quality, some is very salty. Little of it is captured for beneficial use.

Because evaporation is high, streams here yield very little water in proportion to the sizes of their drainage areas. A typical example is the Little Colorado River, which drains a vast area of over 26,000 square miles, yet is intermittent through most of its course. (See fig. 9.)

Streams that flow northward lose a small part of their water by seepage into the ground. The rocks near the surface transmit water very slowly; so downward movement is slow, and much of the water is evaporated or transpired from the soil zone near the surface. The ground water also moves very slowly—a few inches a day at most. Much of the water remains in the ground for many centuries before it is discharged. Generally, wells on the plateau yield little water; however, there are marked exceptions where local geologic conditions favor high productivity. Most of the ground-water supply of the plateau is undeveloped, and full development may never occur because of the difficulty of extracting the water from the ground.

The principal area of natural discharge for ground water in the uplands is near the junction of the Colorado and Little Colorado Rivers. There, Blue Springs discharge about 160,000 acre-feet of water annually into the Little Colorado.

Geologic conditions, as well as sparse rainfall, tend to keep the plateau arid, with only scanty vegetation. The Chinle Formation of Triassic age forms a large part of the ground surface. This formation consists of fine-grained siltstone, claystone, and some sandstone and limestone. In the Hopi Reservation, Cretaceous shale and sandstone are the main surface rocks. Here, the Little Colorado River obtains its large sediment load from these easily eroded formations.

Fractured limestone, which forms the surface rocks between Winslow and Flagstaff, permits water to percolate from the land surface downward into the underlying Coconino Sandstone (fig. 12). These subsurface units, the Coconino Sandstone and the

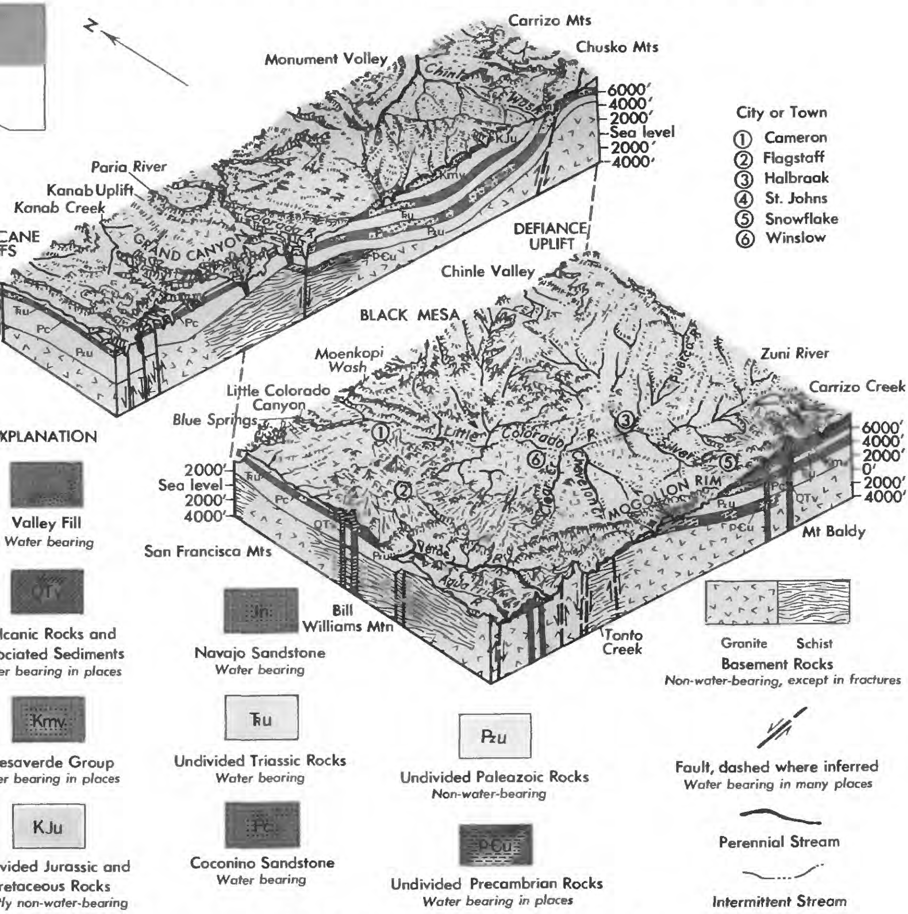
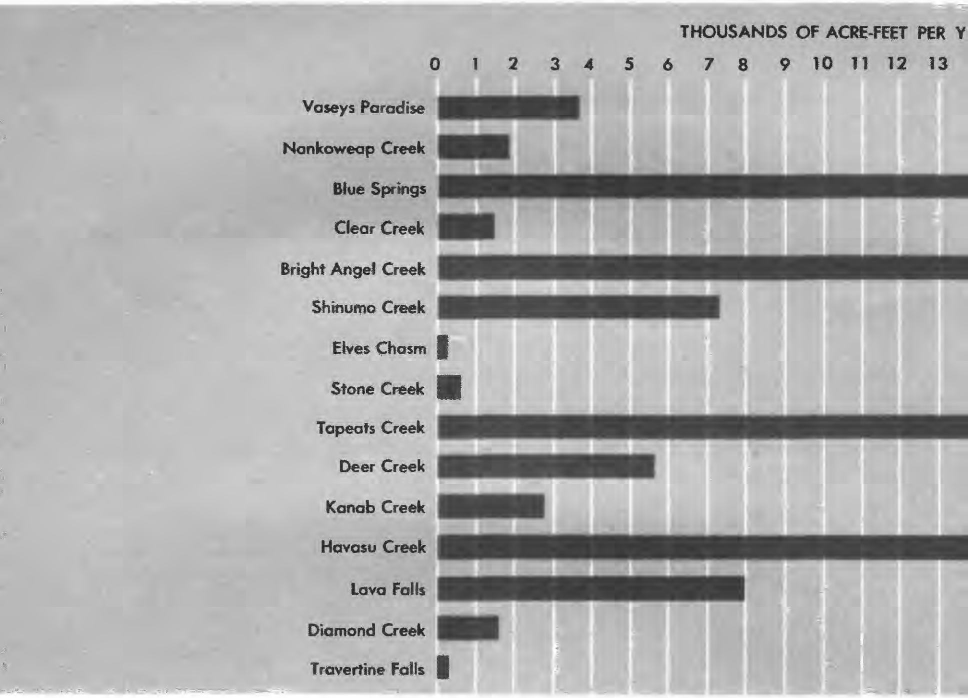


Figure 12. Geology of the Plateau Uplands.



upper part of the Supai Formation, are the main aquifers and yield water to wells and springs throughout the region. Another feature of the region is "aquicludes," rock units or layers of fine-grained materials through which little or no water can move. Such an impervious layer overlying an aquifer leads to the development of artesian pressure in the water-bearing formation.

The aquifers in this region are not very productive, but the people living on the plateau depend upon them. The Navajo Sandstone supplies water in the western part of the reservation, but it thins out eastward and is absent in the eastern part. Erosional features also are important. For example, the Cretaceous sandstones which yield water in Black Mesa are absent elsewhere. Near the Colorado River, where these rocks have been eroded, little ground water is available.

Annual runoff from the plateau is generally less than 0.3 inch, except in streams originating just north of the Mogollon Rim and those rising just south of the Kaibab Plateau. The principal streams north of the Mogollon Rim are Clear Creek, Chevelon Fork, Show Low Creek, and the West Fork of the Little Colorado River northeast of Mount Baldy. Runoff from headwaters of

Figure 13. Discharge of springs in the Grand Canyon area.

these streams ranges from 2 to 4 inches, but the average is less than this from areas near the Little Colorado.

The average annual runoff in Clear Creek at the mouth is 1.6 inches and in Chevelon Fork only 0.6 inch. Runoff from the headwaters of Silver Creek is about 3 inches, but consumptive use on more than 6,000 acres of land irrigated from it reduces the average annual runoff at the mouth to only 0.3 inch. Similarly, the flow of the upper Little Colorado passes through many small reservoirs, and the water is used to irrigate about 6,700 acres upstream from Lyman Reservoir. Measured just above the reservoir, the average annual runoff is only 0.3 inch. The large expanse of arid lands on the north side of the Little Colorado, mostly in Navajo and Hopi Indian Reservations, has an average annual runoff of less than 0.25 inch.

Many tributaries enter the Colorado River between Lees Ferry (Lees Ferry is approximately the dividing point between the upper and lower basin States), and the head of Lake Mead. Most of the tributaries flow only during periods of heavy rainfall, but several are fed by springs and are perennial (fig. 13). The total contribution of these springs to the Colorado is not known exactly but must be about 300,000 acre-feet per year. The largest contributor is Blue Springs, which emerge about 10 miles above the mouth of the Little Colorado and yield some 160,000 acre-feet of water annually, and about 500,000 tons of dissolved salts. The second largest group emerges in Havasu Creek just above Hualapai, a tributary draining from the south side of the Colorado River near the western part of Grand Canyon National Park. The second group contributes about 45,000 acre-feet per year to the Colorado.

Bright Angel Creek and Tapeats Creek (Thunder River) originate below the Kaibab Plateau on the north side of the Colorado. On the basis of surface drainage area their apparent average annual runoff at the mouth is 5 to 10 inches. This indicates that the streams are fed from springs whose water probably comes from precipitation in the high plateau area beyond the surface drainage boundary. Bright Angel Creek contributes an average of 26,000 acre-feet per year to the Colorado River. The estimated annual flow in Tapeats Creek is about 50,000 acre-feet.

We noted earlier that the main aquifers on the plateau are fine-grained sandstones with alternating layers of siltstone and claystone. Even the beds which yield little water play an important role in ground-water occurrence. Beginning with the formations at greatest depth (fig. 14), we find the following more important aquifers:

The Supai Formation contains alternating beds of sandstone, siltstone, and mudstone nearly impervious to water.

The Coconino Sandstone is of Permian age and underlies nearly all the area. It averages about 600 feet in thickness, but thins eastward to about 200 feet. The formation consists of fine well-sorted sand which was deposited by ancient winds. (By well sorted we mean that the grains are all about the same size. Well-sorted formations hold more water than poorly sorted ones.) In places, the formation is fairly impervious.

The Navajo Sandstone of Jurassic age is the aquifer next in importance to the Coconino. It is fine grained and well sorted and contains only a small amount of cemented material. It consists of ancient dune deposits, and it is the principal water-bearing formation in the western part of the Navajo Reservation. Wedge shaped, the formation is about 1,500 feet thick

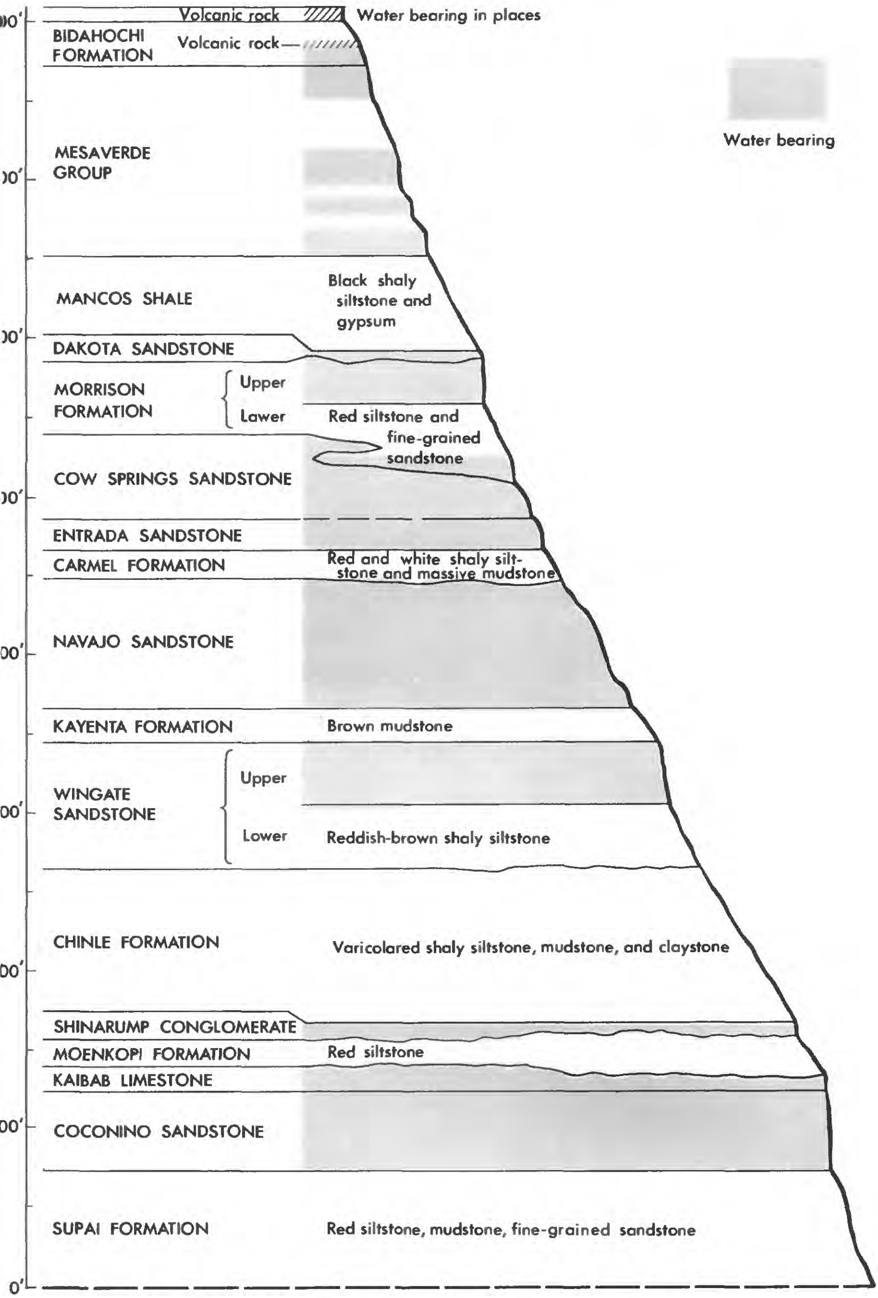


Figure 14. Rock formations in Navajo country.

near Lees Ferry and thins southeastward and disappears near Ganado.

The Mesaverde Group is a series of sandstone, shale, and silt units of Cretaceous age. These yield a small amount of water in the Black Mesa area.

Sedimentary and volcanic (igneous) rocks in the Springerville–St. Johns area are water bearing, but their storage capacities are small. The volcanic materials are porous and act as collectors, enabling water to percolate into the underlying sediments. Ground water is obtained also from shallow alluvium along major drainage systems such as that of the Little Colorado and its tributaries in the Navajo and Hopi country (fig. 12). Storage capacity of these deposits also is limited. The fine-grained character of the alluvial material is not favorable for sustained large yield through wells. Well yields range from a few gallons per minute to 200 gpm.

The main aquifers in the plateau uplands contain large amounts of water, but the rocks are low in permeability and do not readily yield large quantities of water. Wells seldom yield as much as 300 gpm.

Where sandstone aquifers have been faulted and jointed, additional storage space and greater permeability are provided. At such places these aquifers will yield considerably more water. Such conditions prevail near Flagstaff, St. Johns, and Snowflake. Similarly, a few miles east of the confluence of the Little Colorado and the Colorado, faulting probably accounts for a large spring flow from the Coconino Sandstone in the Black Mesa basin.

Although ground water occurs widely in the uplands, its chemical quality is varied, and much of it is unfit for use (fig. 15). Some rocks that contain good water yield only small amounts. The variation in quality is accounted for by differences in the mineral composition of the rocks through which the water moves. At places, water in the Coconino Sandstone is too highly mineralized, and in much of the region the water is too far below the surface for development under present economic conditions. An 1,800-foot well penetrating this aquifer northwest of Holbrook yields water containing more than 10,000 ppm of chloride. Although excellent water is available from the Coconino in its recharge areas, there is little hope for developing large supplies of good quality in the central part of Black Mesa basin.

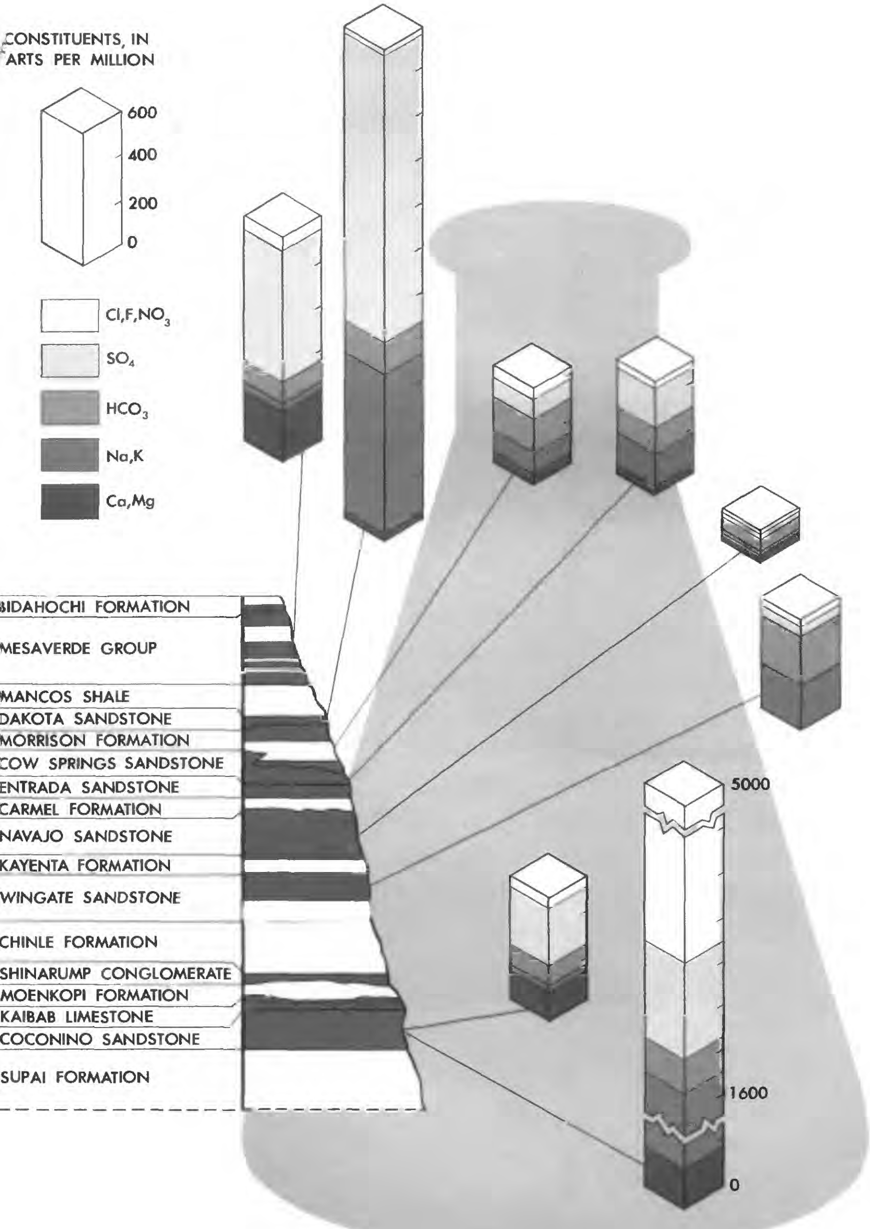


Figure 15. Analyses of representative ground waters from important water-bearing rocks in the Plateau Uplands.

Streams on the plateau carry more sediment than those in any other part of the State, for the rocks that form much of the surface there are easily eroded. The amount of sediment added to the Colorado by its tributaries is tremendous. The Paria and the Little Colorado yield an average of 14 million tons each year. Sediment yield of streams in the uplands varies greatly, owing to runoff fluctuations. Half the annual load of suspended sediment in the Little Colorado and Paria sometimes is moved in a day or two, and more than nine-tenths of the annual load may be carried in a month. Measured near Grand Canyon, the average annual load of sediment in the Colorado River is more than 150 million tons (fig. 16).

Stream water becomes salty where it comes in contact with rocks composed of easily dissolved minerals such as common salt and gypsum. Dissolved salts in waters of the larger upland rivers usually amount to less than 700 ppm. On the other hand, water in some of the smaller intermittent streams contains 1,000 to 2,000 ppm. But flows of the more highly mineralized waters are small compared to those of the Colorado; so the mineral waters are diluted in the purer waters of the Colorado.

The Desert Lowlands contain more than 80 percent of the State's population. Many persons prefer living and working where the climate is hot and dry the year round. For agriculture, the hot climate provides one of the longest growing seasons in the United States, and the rapidly increasing population provides an adequate labor supply. Thus, the Desert Lowlands furnish favorable conditions and an unusually attractive setting for healthful living, prosperous agriculture, industry, and mining. Here is a typical boom society on the receiving end of the westward movement.

There are fewer visible evidences of water shortage here than in many areas of the country considered to be far richer in water. About 7 million acre-feet of water is diverted or pumped yearly for irrigating about a million acres in this region. Industry and municipalities use about 300,000 acre-feet and another half a million acre-feet could be put to good use immediately. Almost 2.25 million is obtained from surface water—1.25 million from the Salt, Verde, and Gila Rivers impoundments and nearly 1 million diverted from the Colorado north of Yuma.

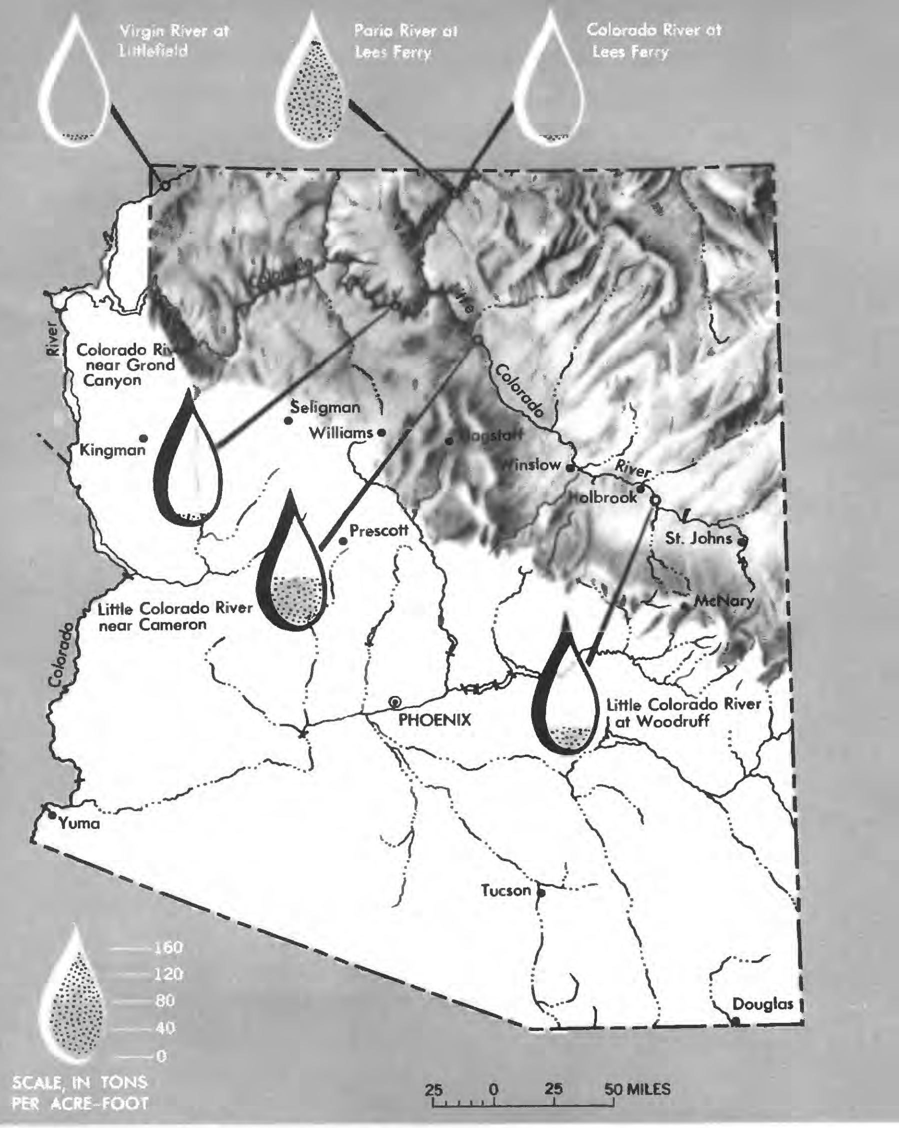


Figure 16. Average loads of suspended sediment in streams on the Plateau Uplands.

Nearly 5 million acre-feet of the water now used annually comes from ground-water reservoirs. The areas of ground-water exploitation are in different stages of development. Ground-water supplies in some limited areas are practically unused, but are suitable for tapping at any time. Others are highly developed, or overdeveloped.

Consider surface-water supplies in the Salt, Gila, and Santa Cruz Rivers (fig. 9). Under natural conditions, the upper reaches of these streams lost water by percolation into the ground, thus feeding the ground-water system along the southern edge of the highlands. In turn, the ground-water system fed the downstream reaches of the stream where the water table was higher than the stream elevation. The natural recharge of ground water has been curtailed by upstream water use; so ground-water levels in the region would decline even if no ground water were pumped. However, ground water *is* being pumped; the decline of water levels is accelerating; and continued lowering is expected. Owing to curtailment of upstream runoff and the consequent decrease in ground-water discharge into the streams, the downstream reaches have long since ceased to carry water.

In the Desert Lowlands, precipitation is highest, of course, on the high mountain ranges. Near the top of the Catalinas, precipitation averages more than 30 inches annually, and the average yearly runoff is close to 5 inches. At the other extreme, precipitation is less than 5 inches and runoff is almost nil in the southwestern part of the State. Annual runoff from the driest 15,000 square miles in the lowlands area averages less than 0.1 inch. The headwater areas of the San Pedro, Santa Cruz, and other large tributaries of the Gila River yield about 0.5 inch of runoff per year, but in downstream areas yields decrease to an average of 0.25 inch at Winkelman and Tucson. Runoff averages about 0.15 at Whitewater Draw, 0.1 inch along San Simon Creek, and 0.25 inch along the Bill Williams River at Alamo.

There are no large storage reservoirs for surface water in the Desert Lowlands. Several detention dams in San Simon basin were installed to reduce headward cutting of stream channels and to trap sediment that otherwise would be carried to the Gila. These structures have no operating gates, and they store water only for short periods. The capacity of Picacho Reservoir on the San Carlos project is about 18,000 acre-feet. It stores floodwater from the Florence–Casa Grande Canal. Many small stock ponds are scattered through the region, but most of these have surface areas of less than 2 acres. A great deal of water evaporates from these ponds; however, their effect on total water yield has not yet been evaluated.

Streamflow in the Desert Lowlands occurs mostly as flash runoff following thundershowers. A few lowland streams rise at higher altitudes, where snowmelt furnishes part of the runoff.

High in some mountain areas precipitation is more than 25 inches annually. Streams originating there generally have perennial headwaters, but where they emerge on the alluvial basins, much water is lost by evaporation and infiltration. In the downstream reaches the flow is intermittent. (See fig. 9.) In desert areas the flow dwindles to nothing.

Storms originating in the Gulf of Mexico reach the southeastern corner of Arizona first and often drop their moisture over the mountainous headwaters of San Simon Creek, Whitewater Draw, and the San Pedro and Santa Cruz Rivers. Except for Whitewater Draw, these streams flow northwestward and join the Gila River. Whitewater Draw flows southward to join the Yaqui River in Mexico. These streams derive about three-fourths of their total annual runoff from thunderstorms in July, August, and September.

As floodwaters move downstream, several factors operate to decrease the flood peak and decrease the volume of runoff. These factors are: infiltration, evaporation, channel storage (the amount of water in the stream channel at any time), channel retention (the water required to fill the voids in the porous materials of the stream channel), and bank storage (water that seeps into the stream banks during high stages and drains back into the stream at lowered stages). In Arizona the decrease in volume of runoff is tremendously important. For example, runoff of floodwaters in the Santa Cruz River in August 1954 showed a loss of more than 2,000 acre-feet between Nogales and Cortaro (see fig. 17), a distance of 82 miles. No water at all reached the mouth of the Santa Cruz west of Laveen.

Below Cortaro, agricultural developments along the Santa Cruz use surface water for irrigation. But because there are no storage reservoirs on the stream, only a small percentage of flood runoff can be used. Natural losses of water between Cortaro and Laveen are high. In 1954, for example, some 53,000 acre-feet passed Cortaro, but only 9,400 passed Laveen, 94 miles downstream.

Below Gillespie Dam the Gila River traverses the area of lowest precipitation in the State, and natural channel losses are

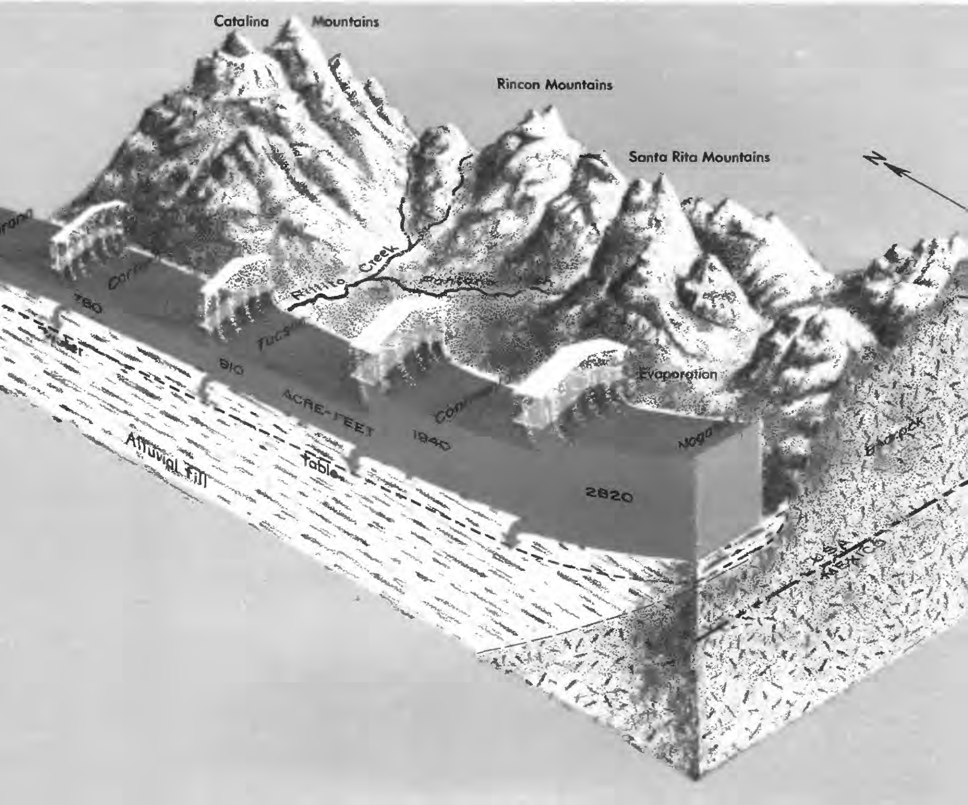


Figure 17. Disposition of water during a single flood, Santa Cruz River, August 23–25, 1954.

high. For example, from July 19 to September 10, 1955, 102,000 acre-feet flowed past Gillespie Dam, but only 11,000 acre-feet passed Dome, 146 miles downstream. Moreover, the flow at Dome probably included some waste water from the Wellton-Mohawk irrigation project. The highest runoff year of record at Gillespie Dam was 1941, when 1,036,000 acre-feet passed the dam, but only 590,000 passed Dome. Because precipitation and flood runoff are low and channel losses high, the lower reaches of the Gila are dry during long periods. During the decade between September 1941 and September 1951, there were only 3 days when any surface flow passed the Dome gaging station.

Before 1880 many streams in the arid Southwest were depositing sediment along their lowland courses. In the decades that followed they began to erode and to entrench their channels through those sediments. The most extensive trenching came in the late eighties, but the process is continuing in many areas.

Cutting of the Santa Cruz channel between Calabasas and Tucson was first noted in 1909. According to local residents, the flood plain was once covered with sacaton grass, and the river channel was insignificant. During floods, water spread over most of the grassy flood plain, and tules grew in boggy places. Late in the 1880's, ditches and cattle trails were enlarged by floods, and the present channel began to develop. At Tucson it is now 100 to 300 feet wide and 12 to 15 feet deep.

San Simon Creek also has an interesting history. In the 1880's, when settlers from Utah reached the area, the present steep-walled channel did not exist. Trenching reportedly started in 1883 when the settlers excavated a channel 20 feet wide and 4 feet deep at Solomon to confine floodwaters. Since then the channel has been scoured 20 to 30 feet deep and has extended itself upstream about 60 miles.

No single cause is responsible for the start of this erosion in this channel or others. Whether the principal cause was climatic change, overgrazing, exceptional floods (as in 1891), or some combination of causes, the fact remains that many stream channels in the lowlands changed radically. A complete analysis of the hydrology of this region would require a study of its erosional history as well as study of the subsurface conditions.

Figure 18 shows the geologic features of a typical area in the Desert Lowlands. Granite, gneiss, and schist are the principal rocks in the mountain blocks, but a few areas contain unmetamorphosed sedimentary rocks. Some of the mountain blocks are capped with volcanic rocks dating from recent time—a most unusual feature. Some volcanic materials locally were erupted perhaps no more than 10,000 years ago. Most volcanic rocks are much older.

Geologists can reconstruct the history of erosion and deposition during past eons. The mountain blocks in the Desert Lowlands were pushed upward, and the basins were lowered by earth movements. These movements were accomplished by breaking (faulting) of the rocks along the edges of the mountains or by folding and warping. The basins were further excavated by

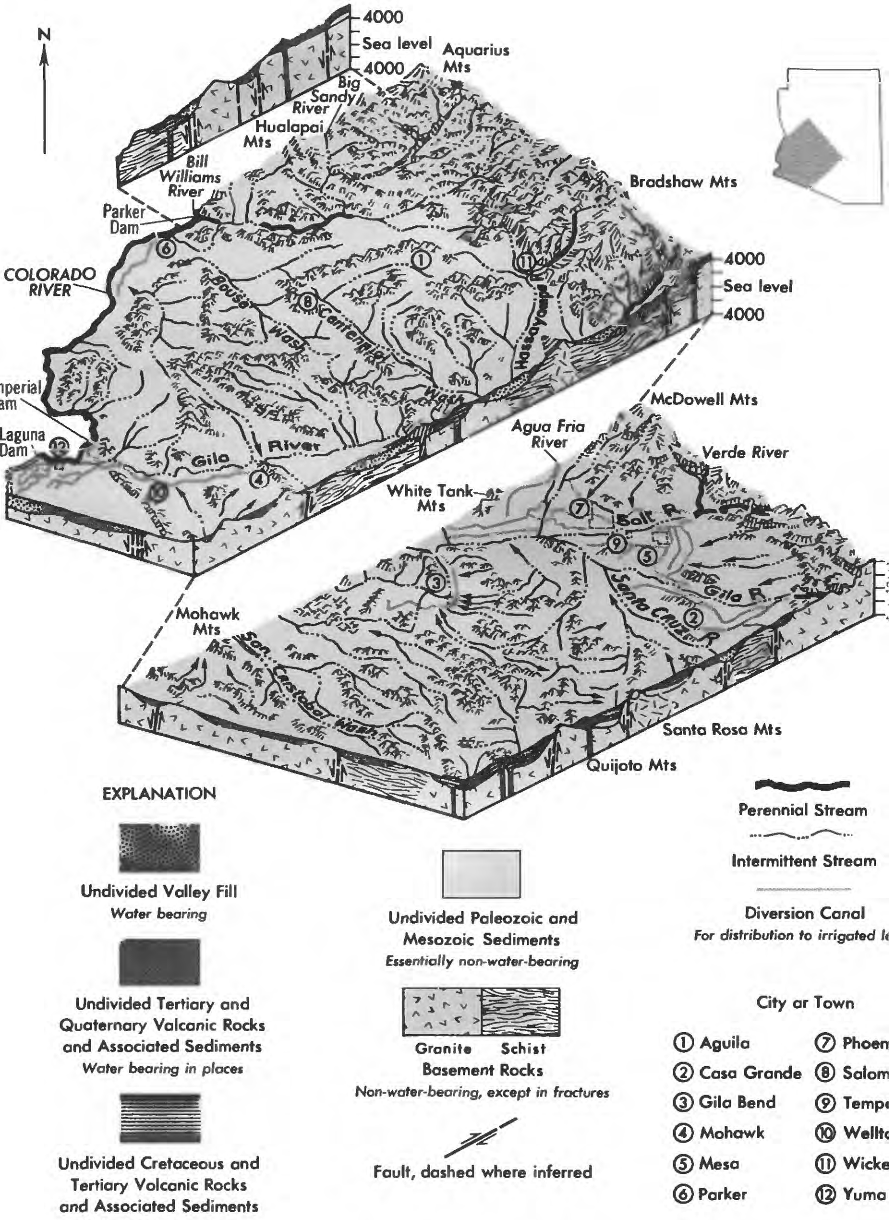


Figure 18. Geology of the Desert Lowlands.

stream erosion that preceded the accumulation of alluvial sediments. Earth movement continued during the period of sedimentation. Volcanic eruptions also were common, and in places the volcanic rocks are interlayered with alluvial material; the interlayering indicates that some eruptions occurred while sedimentation was in progress. The prehistoric drainage pattern in the lowlands probably was quite different from that of today, and the ancient pattern has important bearings on the present occurrence of water.

Most alluvial valleys in Arizona passed through three principal stages of erosion and sedimentation. As is shown in figure 19, coarse sand and gravel were deposited on the floor of an ancient valley. The Arizona climate was more humid then than it is now, and large fresh-water lakes occupied the basins after the old gravel was deposited. Clay and silt beds accumulated in these lakes. These deposits rest on the old gravel in many places. Later the mountains were pushed upward and the lakes were drained. Subsequently, rapid erosion of the mountains again provided coarse materials which were deposited as valley alluvium. Erosion and sedimentation are continuing in the modern stage.

Permeability and porosity are among the most important physical characteristics of water-bearing materials. "Permeability" is a measure of the ease or difficulty with which water passes through the materials. "Porosity" is a measure of the ability of the rock to store water. "Porosity of 25 percent" means that 25 percent of a mass of earth or rock is pore space.

Fine-grained substances like clay, silt, and very fine grained sandstone may be highly porous, but the pores are generally very small; so these materials are poorly permeable or impermeable. On the other hand, gravel may contain less pore space, but the pores are large. Some gravel is so permeable that it will transmit millions of times as much water as dense clay whose porosity is relatively large.

Within the alluvial deposits the range in permeability is wide. Moreover, each kind of material contains particles of several sizes. Gravel, for example, may be composed largely of boulders, cobbles, and pebbles, but the deposit may also contain sand and clay. The fine sediments fill the spaces between coarse particles and reduce the porosity.

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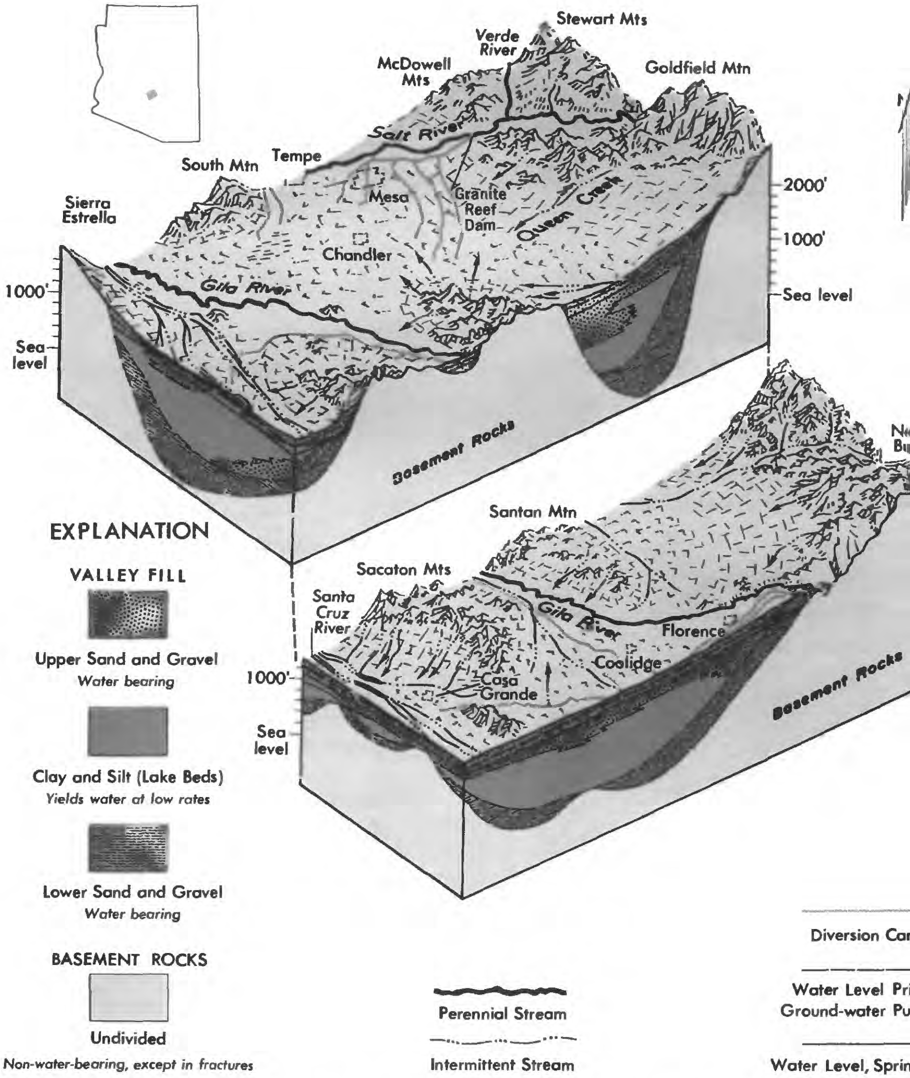


Figure 19. Alluvial basins in central Arizona.

Alluvial materials in the desert basins of Arizona are unconsolidated or poorly consolidated, and they are far more porous than the aquifers on the plateau. Porosities of the alluvium range from 10 to 40 percent, and the average is about 25 percent.

The porosity of water-bearing material is a measure of the amount of water in the material, but it is not a measure of the amount that can be removed. Rocks may have high porosities but yield little or no water if the pores are very small. Small pores hold water tenaciously, and the water moves through them very slowly. This is true of many lakebed deposits in alluvial basins. The porosity may be 50 percent or more, but the pores are so small that water moves through them extremely slowly. Time is thus an important factor in the yield of wells. Though the amount of water in an aquifer may be very large, one cannot withdraw water from a well faster than the water can move through the ground to the well.

The mantle of alluvial sediment, where it is present in the Central Highlands, averages only a few tens of feet in thickness, whereas in the Desert Lowlands its thickness ranges up to thousands of feet (fig. 19). Water that is discharged from the mountains into the basins seeps through the sandy floors of the basins and moves downward by gravity and becomes ground water. During past millennia, the ground water filled a large share of the pore space in sediments under the desert basins—filled them to overflowing in some places. Today, however, the amount of water seeping underground from mountain-born streams, plus a small amount of rainfall that enters the basin sediments directly, is inadequate to replace the water that is discharged naturally and that is pumped by man.

Use of water

Arizona uses more than 7 million acre-feet of water annually, and more water will be needed to provide for growth, if it continues at the present rapid rate. Even now, for every 7 gallons of water withdrawn from the State's "water bank," only 2 is from surface water. The remaining 5 is obtained from reserves of water stored underground in the alluvial basins.

How is this 7 million acre-feet of water used?

The major beneficial use of water in Arizona is for irrigation, a process which by its very nature results in evaporation and transpiration of water. From 1936 to 1963, canals diverted an average of 1,250,000 acre-feet of water each year from streams other than the Colorado River. During 1948–63 annual gross diversions from the Colorado River ranged from 680,000 to 1,750,000 acre-feet. Surface return flows averaged more than 350,000 acre-feet;

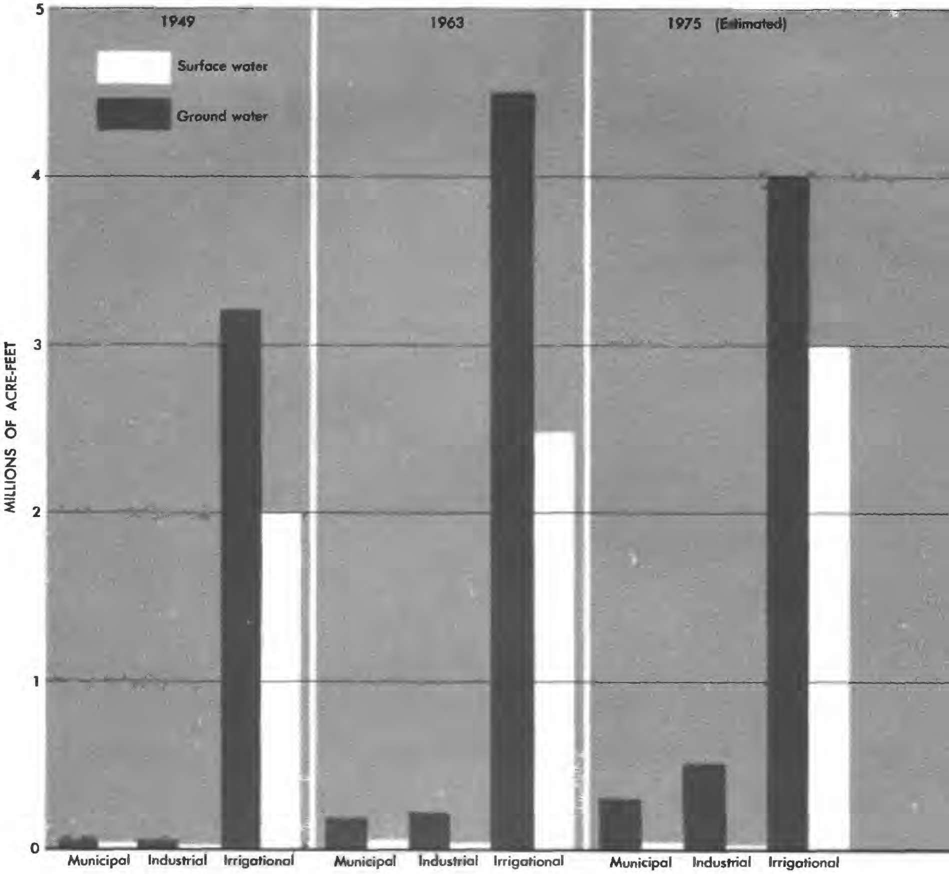


Figure 20. Use of water.

so the net diversion did not exceed 1,400,000 acre-feet. The 1963 net diversions of surface water for Arizona irrigation totaled about 1,900,000 acre-feet per year (fig. 20).

Many small ponds have been built by farmers and ranchers to intercept and store surface water in ephemeral stream courses. Each pond captures most of the water reaching it. Livestock consumes very little of the trapped water, but the loss of water by evaporation is great.

The amount of water controlled by these ponds is unknown, but there are a large number of them, and they may be partly responsible for declining streamflow during the past 20 years.

After World War II the amount of ground water used for irrigation increased tremendously. In 1949 about 3.25 million acre-feet of ground water was used for agricultural purposes. This increased gradually to a peak of nearly 4.75 million acre-feet in 1953, then dropped off slightly from 1953 to 1963. About 4.5 million acre-feet was used for irrigation in 1963. The increase in irrigation with ground water is illustrated in figure 20. Figure 21 shows the main agricultural areas in Arizona and how much

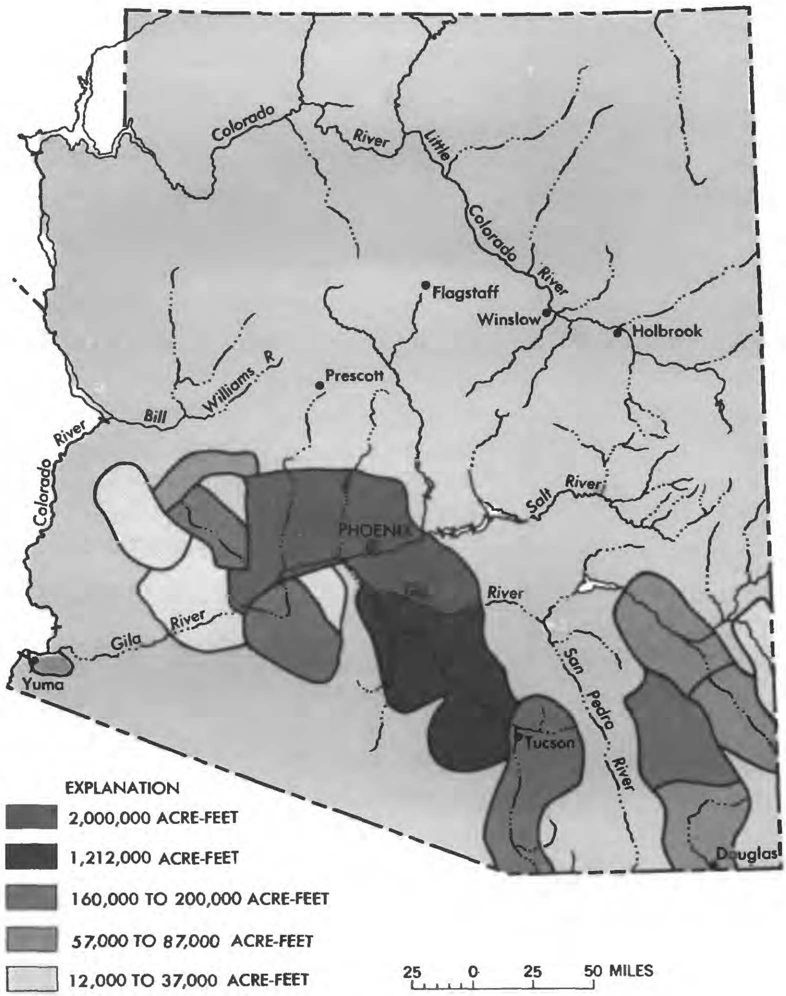


Figure 21. Ground-water pumpage for irrigation, 1963.

water was pumped in each during 1963. More than 75 percent of all the ground water used in 1963 was pumped in Maricopa and Pinal Counties.

Most irrigation pumps are within irrigated areas. Where transport ditches are lined, transmission loss of water is small. Ordinarily, irrigation water is applied somewhat in excess of the amount needed for optimum growth of crops, and some of the surplus returns by deep percolation to the subsurface reservoir. The amount of irrigation water returned to ground storage is an important item in the water budget, but data on the amount returned are not easy to obtain. Under some conditions the return may amount to one-quarter of the water applied for irrigation.

The chemical quality of irrigation waters apparently did not concern water users for many years. However, attention has recently been given to the relation of water quality and productivity of irrigated lands. Through the combined efforts of many individuals and State and Federal agencies, a fair knowledge of the factors necessary for successful irrigation has been accumulated. Nevertheless, much remains to be learned about the control of harmful salts in soils and irrigation water.

Lands with adequate water are valuable. Because water is scarce and therefore relatively costly, the agricultural trend has been toward such high-value crops as top-grade, long-staple cotton, citrus, melons, figs, dates, and lettuce. The long growing season permits double cropping with other products that also yield a cash return. High water costs encourage efficient use of irrigation water, and profitable crops are grown in some places with 3 acre-feet or less per acre.

Large areas of fertile land in the lowlands still are desert, lacking only water to make them productive. Some of this land is being developed as additional wells are drilled, but there is more than enough land to use all the water that can be made available. Meantime, steady decline of the water table is a clear warning that there may be a ceiling on development. While new lands are placed in production, other land which had been cultivated is being retired. Retired land reverts quickly to desert.

The Indian names of some Arizona towns attest to the fact that the early settlers were very conscious of the importance of their water supply. Tucson, for example, meant the place of "dark springs," Todilto Park stood for "sounding" or "splashing" water, and Todokozh Spring means "saline" spring or "sour" water.

But modern society and urban living impose demands on water supply undreamed of by the first settlers. Large population concentrations in arid regions create especially difficult water-supply and development problems. Municipal use has become a significant part of total water use in Arizona only in recent years. Municipalities used 40,000 acre-feet in 1949 and more than 200,000 in 1957. The increased use is related directly to population growth. Larger urban areas like Phoenix and Tucson account for more than 80 percent of the total municipal use.

Most municipalities in Arizona use ground-water reservoirs for their principal public supplies. Phoenix, which diverts 70,000 acre-feet of water per year from the Salt and Verde Rivers, is an exception. This is the largest single development of surface water for a municipal supply in Arizona. Other municipal uses of surface water are small. Some water from the Black and San Francisco Rivers is diverted to supply the Morenci mines and the communities of Clifton and Morenci.

Ground-water development is usually less expensive, and surface supplies are not always available. Surface water usually requires filtration and purification, whereas ground water is less susceptible to contamination and commonly requires less treatment. For many places surface water would have to be transported over long distances.

Most Arizona cities drill wells for water supply. This is true of Tucson, Flagstaff, Prescott, Winslow, and Safford. Even Phoenix has turned to wells in the city to supplement the supply from the Verde River. Tucson once used Santa Cruz River

Irrigation at Yuma project and young citrus groves in the Gila project.

water, but the river ceased to flow long ago. Tucson's entire supply is now obtained from wells.

Practically all surface waters in Arizona streams have been appropriated for irrigation. As a result ground water has had to be developed for urban use. The settlement of water rights, whether for surface water or ground water, is a serious problem for each expanding community.

Arizona's largest and fastest growing urban area is Phoenix, the State capital. This city is proud of its streets, parks, homes, and business section. Green lawns, shade trees, and flowering plants flourish everywhere. Swimming pools dot the landscape. Phoenix is said to be as completely air conditioned as any community in the West. Nearly every home and place of business is equipped with an air conditioner. These comforts use much water. Situated in a desert environment, the city is virtually an oasis with metropolitan comforts. Within the canal system the land is green; beyond the canals is the desert.

Each year more and more winter visitors become residents of Phoenix. The population increased from 92,000 in 1946 to 173,000 in 1958, nearly doubling in little more than a decade. Meanwhile, water use more than doubled. As of mid-1963 the population was 507,000.

The fast-growing city of Phoenix.

Phoenix is fortunately situated for municipal water development. The Salt River Canyon is a very convenient hydrologic funnel through which flows the State's principal perennial water supply (though the Colorado River flow is greater, only part of it can be used in Arizona). A part of the water for the city is obtained from the Salt and Verde Rivers just above and below their junction; this water is collected in horizontal galleries and vertical wells in alluvium near the river channel or pumped directly from the rivers. From these it is pumped to a large water-treatment plant just above Granite Reef Dam and thence by pipeline to Phoenix. Water from canals, and from wells within the city limits, supplements this supply.

In 1946 an average of about 18 mgd (million gallons per day) came from the Verde, and another 5 mgd was pumped from wells to obtain the daily average of 22.5 million gallons. By 1963 the average use increased to about 120 mgd. About 33 mgd came from the Verde and Salt Rivers. Another 31 mgd was taken from the Water Users' canal system at Squaw Peak pumping plant; most of this water came from the Verde and Salt Rivers. The remainder was ground water. Pumpage varies greatly throughout the year. On January 3, 1963, for example, the city used 45 million gallons of ground water; while on July 25 of the same year, it required about 100 million.

The municipal supply system serves about 95 percent of greater Phoenix. The wells produce a little more than 1,500 gpm each, and the average pumping lift is about 250 feet.

Water from the Verde and Salt Rivers is good in quality. It contains only 300 to 400 ppm of dissolved solids. But ground water pumped near Phoenix contains 700 to 800 ppm. The ground water must be treated before large quantities can be put in the city water system. Therefore, the city prefers to draw on the Verde River for as much of the total supply as possible.

All water in the Verde River has been appropriated, and most of it goes into the irrigation system of the Salt River Valley Water Users. Yet Verde River water has always been an important factor in the economy of Phoenix, and two large dams have been built on the river to impound the supply and regulate streamflow. Phoenix lies in the middle of the Water Users' project, and urban growth has caused a reduction of land under cultivation in the project. New city subdivisions are sprouting on formerly agricultural land. By paying the Salt River Valley Water Users' Association for these rights, Phoenix has obtained additional water from the Verde and Salt Rivers.

Tucson nestles among the Catalina, Rincon, Santa Rita, and Tucson Mountains, near the northern end of the upper Santa Cruz Valley. One hundred years ago, Tucson consisted of a few homes along the Santa Cruz River. Water was readily available from surface streams and shallow wells. But even then it was not cheap, and was sold by the cupful from goatskin bags and hide-lined barrels by street vendors.

The city is a few miles south of the confluence of the Santa Cruz River and the Rillito-Pantano drainage system, which receives surface flow from the Catalina and Rincon Mountains. Less than 1 percent of the precipitation falling in this area yields flood runoff, and local recharge to ground water is only a few thousand acre-feet annually. Much of the flood runoff in the Santa Cruz River evaporates or is transpired, and Tucson depends upon ground water to provide for its people, airbases, factories, and other enterprises. No surface water is used for municipal needs in the Tucson area, but a project has been proposed to direct flood runoff from Rillito Creek over a geologic barrier of impermeable rocks into Tucson's sandy ground-water reservoir.

Most of the city wells produce about 500 gpm each, but their range is wide. Withdrawals have been heavy in recent years, partly because of intermittent periods of severe drought and partly because of municipal expansion. The water table is declining in the Tucson area; the decline indicates that pumpage from storage exceeds natural replenishment.

Geologically, the alluvial deposits in the Tucson basin are typical of those in similar areas throughout the Desert Lowlands. Dense rock surrounds the basin on three sides. Lofty Mount Lemmon, 9,185 feet, is only 40 miles from the city. Alluvial beds constitute the ground-water reservoir in the Tucson basin. Local rock units vary in their water-yielding capacity, but the geology is complex and needs study to determine the amount of water that may be withdrawn.

Tucson plans eventually to obtain additional water from outside the urban area. This will entail additional expense for water transmission.

Flagstaff is fortunate in having surface-water as well as ground-water supplies. Located in the northern part of the Central Highlands, this community receives about 25 inches of precipitation annually. Water from Lake Mary has supplied the city for many years, but there were shortages in years when precipitation was low. At times during Flagstaff's early history, water had to be hauled in. Shortly after World War II, owing to population increase and scanty rainfall, the city had to develop additional supplies.

The information then available about ground water in the area was not encouraging. However, after an investigation by the U.S. Geological Survey, several exploratory holes were drilled. The study showed that both the Coconino Sandstone and the Supai Formation contain water at considerable depth and that both the amount of precipitation and the geologic environment were favorable for recharge of the ground-water supply. The mantle of permeable volcanic rocks and cinders allows water to percolate from the surface through the ground to the underlying sandstone. The investigation indicated that adequate water would be available in a fault zone southwest of the city. The first well produced about 300 gpm. Three additional wells on Woody Mountain produce 300 to 700 gpm. The water must be pumped from depths of more than 1,000 feet, however. Recharge conditions are very favorable in the newly developed well field, and natural replenishment along the fault zone assures long-term availability of water. Preliminary tests indicate that the fully developed well field may produce 5 to 6 mgd. Another 1.5 mgd in normal years is available from surface-water storage at Lake Mary. Thus, the community now has a dependable supply that is adequate for considerable growth and expansion.

The Safford area, along the upper Gila River in southeastern Arizona, includes the towns of Safford, Solomon, Central, Pima, and Thatcher. These municipalities obtain water from streams and wells. As population increases, increased demands are met by sinking new wells. Nearby river water cannot be tapped because downstream users have prior rights to the water.

Safford's municipal system obtains ground water from alluvial aquifers along Bonita Creek, a Gila River tributary. The water-collection system consists of an infiltration gallery 4 miles above the mouth of Bonita Creek. This gallery provides 900 to 2,500 acre-feet annually. Small emergency supplies are available from wells near the mouth of Bonita Creek. Water from the Safford wells is poor in quality. Surface water impounded by a small dam on the northeast slope of Mount Graham provides another emergency supply, but water from this source is not dependable because of the wide variations in surface runoff.

Safford is cooperating with the Geological Survey in an effort to develop additional water in the volcanic rocks along Bonita Creek. Currently, the city is engaged in a drilling program to develop additional water supplies from wells above the infiltration gallery on Bonita Creek.

At San Manuel on the San Pedro River, water for a recently developed copper mine, mill, smelter, and townsite is obtained entirely from wells. About 4,000 gpm is pumped from six 1,000-foot wells in valley-fill deposits near the river. About 350 gpm is distributed to the town for domestic and public use. The remainder, supplemented by 3,000 gpm pumped from San Manuel mine, is used for mill and smelter operations.

Water management at the San Manuel mine is a good example of efficiency in water use. All water pumped from the mine is put to use, and waste water from tailings and other sources is recirculated. Wells along the river are pumped to produce make-up water equivalent to less than 25 percent of the amount needed to operate the plant.

A recent study of the geology and ground water of the Hopi and Navajo Reservations was started by the Geological Survey in cooperation with the Bureau of Indian Affairs. The geologic work was hardly under way in 1950 when drought occurred. A well-drilling program was begun immediately. About 300 wells were drilled in 7 years, and as geologic knowledge of the reservations increased, the proportion of dry holes decreased, and the percentage in 1957 was practically zero. Some of the deepest wells tap water under artesian pressure, and in some the pressure is great enough to cause the wells to flow.

The yields of all wells are low. A yield of 200 gpm is high for this area. Commonly, the yields average 10 to 15 gpm, but these are adequate for present domestic and stock supplies.

Today the water requirements on the reservations are being met by development of ground water through geologic exploration. Water supplies developed with the aid of geologic information have resulted in the establishment of industrial plants on the reservations.

Manufacturing and mining have increased considerably in the State in recent years, and demand for water has consequently increased. Total demand is small, however, compared to industrial demands in other parts of the Nation. In 1963, industry, including mining, used about 200,000 acre-feet of ground water in Arizona. This represents a 500 percent increase since 1949. The main water use in manufacturing is for cooling and sanitation, and only about 10 to 15 percent of the water used is consumed. The remaining 85 to 90 percent is available for reuse.

Assurance of a permanently adequate water supply is essential to an industrial plant. Treatment of water enables some industries to use water that in its native condition is unsuitable. Improved technology permits economical treatment of water that formerly could be treated only at prohibitive cost.

For industry the acceptable amount of dissolved solids in water ranges widely. Water for brewing, for example, may contain as much as 1,000 ppm of dissolved solids, where for candy-making, it should contain no more than 100. Calcium, magnesium, sodium, bicarbonate, sulfate, and chloride are the predominant constituents in most untreated water. The amounts of these various constituents determine whether or not it is suitable for specific industrial needs. Hardness, defined as the soap-consuming property, probably is the most familiar chemical characteristic of water. In some manufacturing processes, hardness can cause considerable trouble. The formation of scale in boilers is an example. Hardness is not the problem it once was in washing, however, now that synthetic detergents have come into widespread use.

Much of the water used by industry for cooling, separation processes, and other nonconsumptive operations is available for reuse. But nearly all uses of water cause at least some deterioration in its quality. Many kinds of use warm the water, and this is to be considered a form of pollution. Warm water may kill fish and water plants. Many manufacturing processes add contaminating chemicals to the water. However, industrial pollution of water so far is a minor problem in Arizona, except in certain local instances.

Recreational facilities for water sports are greatly in demand as a result of the growth in population, the increasing number of vácationing tourists, and more leisure time for more people. Water-based recreation now appears to be more popular than ever before and to be expanding faster than any other kind of sport. In States such as Florida and Minnesota, water-based recreation can depend on thousands of miles of natural shoreline on lakes, streams, or the ocean. But in Arizona and other States in the Southwest, relatively few natural lakes can be found. Where they exist, they are often at very high altitudes—4,500 feet or more. A simple tally of reservoirs can almost sum up the easily accessible bodies of water available for recreation in Arizona. However, those in search of water-based recreation are not deterred by the scarcity of natural lakes. To enjoy their favorite sports, they will drive hundreds of miles to a reservoir, many carrying boats with them. Tourism now ranks third among the State's industries.

Speed-boating, Lake Mead Recreational Area.

More than 17 million acres of land in Arizona is owned for all the people by the Federal Government. Most of this Federal land is available for recreation, although little of it has been developed for this purpose. Colorful desert and deep mountain forests in the care of the National Park Service are available for people trying to "get away from it all." Lake Mead behind Hoover Dam is the largest artificial lake in the world, with a shoreline of 550 miles; other, smaller reservoirs—Mohave, Imperial, Roosevelt, Apache, Sahuaro, Lyman, San Carlos—are used for water-based recreation. Lake Powell, formed by the giant Glen Canyon Dam, is rapidly rising and extending upstream; the Glen Canyon National Recreation Area will attract thousands of sportsmen and vacationers. Many other recreation areas in Arizona are administered by the State or operated by private enterprise. Every year more Americans are visiting Arizona in search of sunshine, sport, and a rest from the sights and sounds of crowded cities.

Many of these artificial lakes are stocked with fish from the State's hatcheries, and of course fishing is excellent in Arizona's mountain lakes and streams. White River and lakes and streams in the mountains offer fine sport for the fisherman. Because Arizona's larger rivers have been so drastically modified by dams and reservoirs, State and Federal agencies are working to protect the fishery potential and develop it further. Desirable species must be introduced into the artificial lakes; access

Fishing below Davis Dam on the lower Colorado.

must be provided for fishermen; and the problems of multiple recreational use must be solved.

If the population of Arizona continues to grow as trends indicate, more recreational reservoirs will be needed, as well as wetlands and bodies of water for propagating waterfowl and fish for the hunters and fishermen. The first and biggest problem will be obtaining sufficient supplies of water of suitable quality. Other problems follow in the wake of that one. Recreational use of a body of water implies at least a minimum standard of quality, both sanitary and esthetic. On the basis of this standard, recreational use of water may not be compatible with other uses, such as disposal of wastes, navigation, and waterpower. Some of the recreational uses conflict with each other. Motorboats and water skiers can be a menace to swimmers, and most types of water sport interfere with fishing in the same area. Recreational waters may have to be, and sometimes are, zoned to prevent such conflicts.

The benefits derived from recreational use of water are mostly intangible ones. It is difficult, if not impossible to assess the economic value of water for recreation. However, maintenance of sanitary standards, installation of docks and ramps, and supervision of public use all cost money. In water-hungry States, individuals are willing to pay for the privilege of using these facilities, as the revenues collected by Water Districts, National Park Service, and National Forest Service attest. For whatever purpose new reservoirs are constructed in the future, their use for recreation will have to be considered.

Some results of present use

The greatest demand for water in the State occurs in the Desert Lowlands in the southern part of the State. About 80 percent of the population and more than 90 percent of Arizona's irrigated acreage are concentrated here. During 1963, according to the Geological Survey's "Annual Report on Ground Water in Arizona," water levels in nearly all the developed basins in this part of the State continued to decline. As in past years, the greatest declines again occurred in the Salt River Valley, in Maricopa

County, and in the lower Santa Cruz River basin. Lesser declines of the water table occurred in other areas.

Observation wells in the irrigated areas of Arizona continued to record falling water levels. In the Salt River Valley during the 5-year period 1958–63, the water level declined as much as 60 feet. Other areas recorded similar sharp water-level declines. In the Eloy area the maximum 5-year decline was about 60 feet, and in the Stanfield-Maricopa area, about 100 feet. The Casa Grande–Florence area receives supplies of surface water from the Gila River (168,000 acre-feet in 1963); nevertheless, the ground-water level declined 40 feet in the 5-year period 1958–63. In the Kansas Settlement area of the Willcox basin, the decline in the year 1962–63 alone was as much as 50 feet.

A serious side effect of the decline of water levels due to intensive pumping is land-surface subsidence. Land subsidence or sinking has been suspected for some time in Arizona, but has now been confirmed in the Eloy area of Pinal County. Measurements indicate that by 1960 the land surface had sunk more than 3.5 feet along the Southern Pacific railroad 2½ miles northwest of Eloy. Nearly all this subsidence took place after 1934, during the period of ground-water development. Canals, bridges, and other structures that require a level grade can be seriously affected by subsidence.

Waterlogging is still another ground-water problem of recent significance, but rather different from most of Arizona's water problems. In areas where irrigation water is diverted from the Colorado River, water levels have risen. For example, in the Yuma Mesa area, water levels in wells rose 1 to 4 feet in 1960–61. A ground-water mound has developed beneath the mesa, making a drainage system necessary. Nine drainage wells were installed in 1961, and water levels now are declining slightly. In the same way, the water levels in the Wellton-Mohawk area rose as much as 24 feet from 1956 to 1961. The resultant waterlogging made it difficult to grow crops successfully. A network of drainage wells was established in 1961 to pump the surplus water, which is then discharged to the Gila River, and water levels are declining.

THE FUTUR

Without large-scale water development, Arizona's wealth would be centered chiefly in livestock and mining, and each would operate on a much smaller scale than it does now. With water development, the personal income of Arizonians passed the $3.1 billion mark in 1962, according to the Valley National Bank. Development of water supplies contributes materially to the State's prosperity, which is based on agriculture, livestock raising, manufacturing, mining, and tourism. Perhaps of more importance, the availability of water helps to stabilize a diverse and well-rounded arid-land economy.

Of all the States, Arizona has had the largest percentage gain in population in the 20th century. In 1963 the population of Arizona was 1,545,000—a gain of nearly 76 percent in 10 years. According to students of population trends, this figure will increase to more than 2 million by 1975.

The available labor force, coupled with the natural advantages of the State, will attract industry at an increasing rate. This will be largely dry industry, an example of which is the electronics manufacturing that has developed in Phoenix and Tucson. The phenomenal growth in manufacturing is due to several factors: inland location away from target areas, a reserve of skilled labor, and a dry climate. In some manufacturing processes, humidity control is very important.

The number of retired persons seeking to move to Arizona may increase. One of the first planned retirement communities was established at Youngtown, Ariz. Since then they have been organized in other parts of the State. One problem in Arizona is land acquisition. Over 85 percent of Arizona land is publicly owned, and patented lands amount to less than 8 acres per person, considerably below the national average.

Estimates of the population in the year 2000 range from 8 to 14 million! Of course, even if these forecasts are reliable, population growth alone does not ensure prosperity. Capital must be invested and employment assured. According to recent studies, Arizona leads the Nation, not only in rate of population growth, but also in rates of income growth, employment growth, farm-income growth, and manufacturing growth.

Predictions of future municipal and industrial water demand vary widely, depending on estimates of future population and industrial development and estimates of per capita use. By 1975, if per capita use remains constant, municipal and industrial water demand is expected to double, but if per capita use continues to increase at its present rate, this demand may be about 1 million acre-feet per year.

How will enough water be obtained?

Surface waters are intensively used already, mostly for agriculture. Ground water is also being intensively developed. Continued depletion of ground water will probably lower water levels gradually, until the water is so deep that it would cost more to pump than could be regained by selling the crops the water irrigated. Because of declining water levels, farmland is being converted to residential tracts and industrial plots in the Salt River Valley. The finest agricultural land in the valley, including citrus and date groves, is becoming subject to the bulldozer. This does release irrigation water for domestic use—and acre for acre domestic uses consume less water than agricultural uses. However, as more desert areas are developed, the demand for water in these more than compensates for any additional water released from agricultural use.

Some studies show that water produces more wealth when used to support people and industry than when it is used for agriculture, but this may vary depending on local conditions. In water-short areas, competition for water is keen, and the long-term advantage rests with water uses that yield the greatest financial return.

In recent years, dry industry has become important in Arizona's economy. Dry industry needs water only for air conditioning and sanitary purposes. The amount of water needed to irrigate an acre of land for farming might meet the needs of a large factory where many persons work. Industry can probably obtain this water from deep wells, while a farmer might find the same water too expensive because of high pumping costs. The gross return from agriculture averages about $50 for each acre-foot of water used. Even with crops of the highest cash return, $14 is often considered to be about as much as agriculture can spend per acre-foot on water. On the basis of average dollar yield, industry in many areas is capable of paying a higher price for water than agriculture.

The cost of municipal water ranges widely throughout the State. Retail prices in most communities are between 25 cents and 1 dollar per thousand gallons. In many areas, especially in the north, the cost of obtaining water for domestic and livestock purposes is high. Several municipalities have increased their water rates because of rising costs, and this trend will probably continue. Currently, a few communities charge from $1.00 to $1.80 per thousand gallons. In one town, to which water is hauled, the price is $3.25 per thousand. Price per acre-foot ranges between $80 and $320 in most Arizona communities.

The vital need for additional water in Arizona is recognized by most of its citizens. If additional water cannot be obtained, the alternatives are continued depletion of the ground-water reservoir, or reduction in water use (with consequent possible dislocations in the economy), or more efficient and conservative use of the available supply. Of these alternatives, logic points to the last one.

Several methods have been proposed to reduce or prevent water waste. An intensive program of watershed management might salvage some water by removal of nonbeneficial vegetation. Willow, saltcedar, and other trees that line creeks are major water users.

It is not easy to eradicate saltcedar. Burning does not destrov the roots, and next year's growth is more vigorous. Chemical agents of destruction tend to get into ground water and endanger water supplies near stream channels. Chopping saltcedar down activates the soil, reduces overgrowth, and encourages young vigorous growth in succeeding seasons.

One efficient method of destroying saltcedar is to lower the water table quickly beyond reach of its roots. In the Gila River below Gillespie Dam, large areas of nonbeneficial plants have had their water supply reduced by a rapid drop in the water table, and the growth is much thinner than it used to be. Such a remedy, however, cannot be practically applied over the whole State.

The watershed-management program might include eradication of juniper and piñon, thinning stands of ponderosa pine, cutting among the spruce and fir to reduce transpiration of water, and eradication of chaparral. Cleared areas would be seeded to grass in the hope that grass will eventually cause a smaller evaporation loss than did the woodlands. However, modification of native vegetation brings its own problems, which would have to be considered. In any event, large-scale eradication programs might best be deferred until research data now being collected are available to provide a basis for forecasting the actual results of such measures.

Nonbeneficial water-loving vegetation on the Gila River.

Saltcedar along the Gila River.

Control of evaporation is another method of water conservation. Arizona has more than 17,000 miles of mapped stream channels. Some channels are in narrow gorges in impervious rock; others are underlain by porous sand and gravel in broad open valleys. Some streams flow continuously; others flow infrequently and only immediately after rain. Many miles of additional channels are not shown on maps. A large number of valleys are barren; others are choked with water-loving plants. Between these two extremes are an infinite number of conditions. However, there is one common characteristic of channels in Arizona—large amounts of water are lost through evaporation.

Concurrent records of streamflow on the Gila River at Gillespie Dam and at Dome are available since 1921. When compared, the records of annual runoff at the two sites give some idea how much water is evaporated. The greatest recorded loss, 600,000 acre-feet, occurred in 1941. Most of this water was evaporated, but of course unknown amounts were transpired or contributed to recharge.

Laboratory research suggests that evaporation from the surface of reservoirs, at least, can be reduced under some circumstances by more than 25 percent through the application of a chemical film. Research is now underway both to improve methods and to evaluate results. There is some evidence that the treatment is more practical on small than on large bodies of water. If this is confirmed by further work, evaporation control may have applicability to the thousands of small reservoirs and ponds throughout the State. In addition, evaporation reduction can be achieved by careful location and design of new reservoirs. It is well established, for example, that a deep pond of small surface area loses less water by evaporation than a wide shallow pond of the same capacity. Because deep tanks retain water longer, they also serve the rancher better.

One of the most practical ways to increase the availability of water supplies is to capture water and put it underground. Floodwaters as well as base flow could be captured and transported by lined canals or conduits to the areas of need, for example, where ground-water withdrawals have been large. The water could then be recharged into dewatered sediments by means of wells (fig. 22).

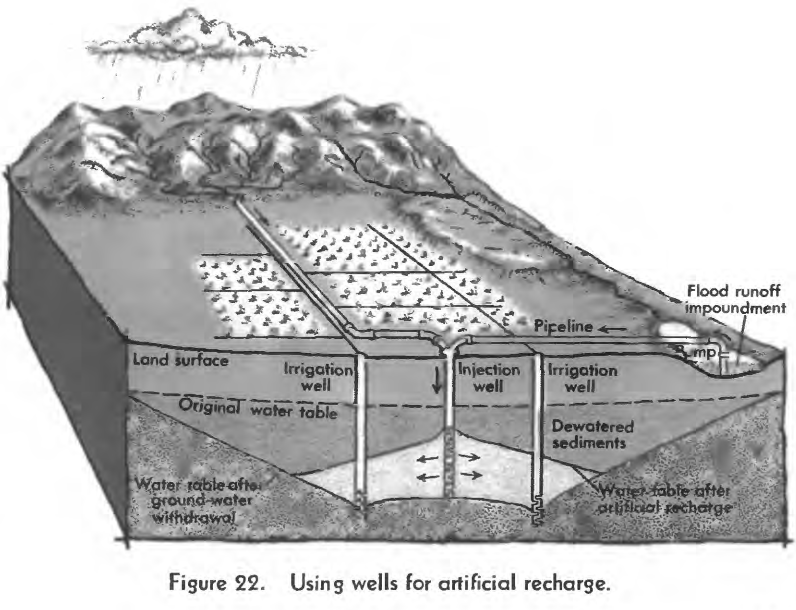


Figure 22. Using wells for artificial recharge.

Many engineering, geologic, legal, and economic problems would have to be solved to make this method practical. Amounts of water that could be salvaged and points of most efficient impoundment would have to be determined. The water might have to be desilted before it is fed underground. Experiments in Texas and elsewhere indicate that silt allowed to go underground tends to seal the surrounding material and reduce a well's intake capacity. Chemical reactions also tend to reduce capacity.

Desalination of brackish water would provide another source of water supplies. Cost of conversion is presently about 1½ times the cost of present-day municipal water in Arizona. But for some uses the cost of converting the brackish ground-water reserves may not be an impossible obstacle.

To achieve any of these salvage methods, some measure of State or local responsibility would be necessary. At present, the ground-water resource continues to be exploited without any particular management other than the water users' needs at the moment. Attempts to control ground-water draft by legislation have been unsuccessful. The State legislature has restricted the drilling of wells to supply new irrigation developments in four "critical areas," but heavy pumping continues in these. New developments have been started in other basins, despite the prospect of eventual depletion.

The interrelation of surface and ground water must be recognized, and the technique of joint management developed. To this end, the laws governing water rights may have to be modified. Most water law developed at a time when the science of hydrology was little understood, and the law has not kept abreast of scientific advances.

One legal development of great importance was the ruling of the Secretary of the Interior in 1961 withdrawing from entry of certain desert lands in the public domain. This will tend to limit development in public lands and thus not add still further drafts on heavily used ground-water resources.

Another major step needed is basinwide management planning of the water resources, both surface and ground water. This need is especially critical in the Gila, Salt, San Pedro, and Santa Cruz River valleys where the greatest overdevelopment has taken place and where most of the ground-water basins are interconnected in varying degrees. Hydrologic studies on a basinwide basis would be required in support of the planning program. A recent innovation in ground-water studies that can be of great assistance in basinwide planning is the electric-analog model. Such models duplicate the hydraulic regime effectively on a laboratory scale. This makes it possible to try various alternate solutions to a given problem without the time and expense of extensive field tests.

For many years Arizona has pursued a course of depletion of its ground-water reserves. The Nation has followed exactly the same course in regard to its oil resources. Without controls on production or well spacing, each oil producer tried to produce as much oil as possible as soon as possible, before the oil was exhausted. Presently the ground-water resource is being exhausted at a rate greater than it is being replenished. Yet utilization of the resource is an indispensable part of the State's economy. Unplanned, rapid depletion of ground-water storage, however, can be very inefficient. Rapid depletion results in rising power costs owing to increased pumping lift and in excessive maintenance costs owing to the need for frequent lowering of pumps and deepening of wells. Land subsidence is another common result of overdraft of ground water.

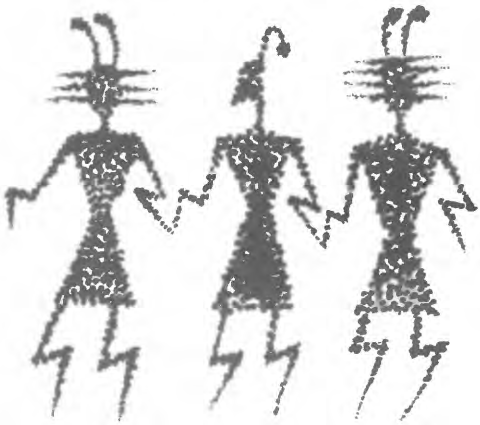
Planned management of ground-water development can soften or prevent a blow to the local economy. Now may be the time to decide whether to continue the unregulated and haphazard development of this resource or to modify and regulate it.

We need information on the present total supply, the extent of the reserves, and the rate of depletion that will provide the most efficient exploitation. We need a better understanding of the hydrologic system, and the physics, or mechanics, of water movement. All the disciplines in water resources should be harmonized and merged to achieve a clear understanding of Arizona's hydrologic system.

After the magnitude of the total supply is known, some questions that are difficult to answer still remain. What will be the cost of water? What economic pursuits will be able to pay the price? What will happen when the water level drops down to the impervious layers or lakebed deposits? Some of these questions cannot be answered; others require information about the occurrence of water itself. The hydrologic data should be studied, analyzed, and interpreted so that management will have sound information on which to base decisions. As Secretary Udall has said before the American Water Works Association, Philadelphia, Pa. (June 20, 1962):

> Neither new laws nor new planning groups will create water where none existed before, or restore it where it has been mined; nor will they restore the quality of water that has deteriorated. Neither new laws nor new development schemes will necessarily prevent the consequences of bad management. The first need is not new regulations, but intelligent management.

History contains documented accounts of many civilizations that attained a high degree of progress, but declined or even became extinct when their water supplies were exhausted. Several notable examples are in the Middle East. The facts in the lesson are clear; however, Arizona need not suffer a similar decline in productiveness. Armed with a knowledge of water resources, informed citizens will be better able to plan for and evaluate prudent water management in Arizona.



FOR MORE INFORMATION ABOUT—

Basic Water Facts, Principles, and Problems:

A primer on water, by L. B. Leopold and W. B. Langbein, a special report by the U.S. Geological Survey: Washington, D.C., U.S. Government Printing Office, 50 pages, 1960.

A primer on ground water, by H. L. Baldwin and C. L. McGuinness, a special report by the U.S. Geological Survey: U.S. Government Printing Office, 26 pages, 1963, reprinted 1964.

National water resources and problems, by R. E. Oltman and others: U.S. Senate (86th Congress, 2d session) Select Committee on National Water Resources, Committee Print 3, Washington, D.C., U.S. Government Printing Office, 42 pages, 1960.

Arizona, its people and resources, edited by Jack L. Cross, Elizabeth H. Shaw, and Kathleen Scheifele: Tucson, Ariz., The University of Arizona Press, 385 pages, 1960.

Progress report of the committee on quality tolerances of water for industrial uses, by E. W. Moore: Journal New England Water Works Association, volume 54, 271 pages, 1940.

Ten rivers in America's future: Report of the President's water resources policy commission, volume 2, 801 pages, 1950.

Arizona Resources:

The Colorado River, Proposed report of the Secretary of the Interior: Bureau of Reclamation, U.S. Government Printing Office, 295 pages, 1946.

Bill Williams River and tributaries, Arizona: 78th Congress, 2d session, House Document 625, U.S. Congress, House Committee on Food Control, 29 pages, 1944.

The Hoover Dam Documents, by R. L. Wilbur and Northcutt Ely: 80th Congress, 2d session, House Document 717, 936 pages, 1948.

The Technical and Scientific Background:

Annual report on ground water in Arizona: Arizona State Land Department, Water resources reports.

Analysis of basic data concerning ground water in the Yuma area, Arizona, by R. H. Brown, J. W. Harshbarger, and H. E. Thomas: U.S. Geological Survey open-file report, 117 pages, 1956.

Erosion and sedimentation in the Papago country, Arizona, with a sketch of the geology, by Kirk Bryan: U.S. Geological Survey Bulletin 730–B, pages 19–90, 1923.

Soil salinity problems along the Rio Grande in New Mexico and Texas, by C. W. Chang, *in* Problems of the upper Rio Grande: International Arid Lands Symposium and Conference, held in 1955 at University of New Mexico and New Mexico Institute of Mining and Technology, U.S. Commission for Arid Resource Improvement and Development Publication 1, page 5, 1957.

Significance of carbonates in irrigation waters, by F. M. Eaton: Soil Science, volume 69, pages 123–133, 1950.

Use of water by bottom-land vegetation in lower Safford Valley, Arizona, by J. S. Gatewood, T. W. Robinson, B. R. Colby, J. D. Hem, and L. C. Halpenny: U.S. Geological Survey Water-Supply Paper 1103, 210 pages, 1950.

Diagnosis and improvement of saline and alkali soils, by L. A. Richards and others: U.S. Department of Agriculture Handbook 60, 160 pages, 1954.

Phreatophytes, by T. W. Robinson: U.S. Geological Survey Water-Supply Paper 1423, 84 pages, 1958.

Rainfall and runoff in the upper Santa Cruz drainage basin, by H. C. Schwalen: University of Arizona, Arizona Agricultural Experiment Station Technical Bulletin 95, pages 421–472, 1942.

Water in the Santa Cruz Valley, by H. C. Schwalen and R. J. Shaw: University of Arizona, Agricultural Experiment Station Bulletin 288, 119 pages, 1957.

Compilation of flood data in Arizona, 1862–1953, by Winchell Smith and W. L. Heckler: U.S. Geological Survey open-file report, 113 pages, 1955.

Ground-water resources of the Santa Cruz Basin, Arizona, by S. F. Turner and others: U.S. Geological Survey open-file report, 84 pages, 1943.

Ground-water resources and problems of the Safford Basin, Arizona, by S. F. Turner and others: U.S. Geological Survey open-file report, 28 pages, 1946.

Use of water by phreatophytes in 2,000-foot channel between Granite Reef and Gillespie Dams, Maricopa County, Arizona, by S. F. Turner and H. E. Skibitzke: American Geophysical Union Trans., volume 33, number 1, pages 66–72, 1952.

The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah, by H. E. Gregory: U.S. Geological Survey Water-Supply Paper 380, 219 pages, 1916.

Ground water in the Gila River basin and adjacent areas, Arizona—a summary, by L. C. Halpenny and others: U.S. Geological Survey open-file report, 224 pages, 1952.

Use of ground water in Arizona, by J. W. Harshbarger, *in* Climate and man in the Southwest : Contribution 6, Program in Geochronology, University of Arizona Press, pages 51–68, 1958.

The Navajo country, Arizona-Utah-New Mexico, by J. W. Harshbarger, C. A. Repenning, and J. T. Callahan, *in* The physical and economic foundation of natural resources, Part 4, Subsurface facilties of water management, and patterns of supply—Type area studies: House of Representatives, Interior and Insular Affairs Committee, pages 105–131, 1953.

Quality of water of the Gila River basin above Coolidge Dam, Arizona, by J. D. Hem: U.S. Geological Survey Water-Supply Paper 1104, 230 pages, 1950.

Saline soils, their nature and management, by O. C. Magistaad and J. E. Christiansen: U.S. Department of Agriculture Circular 707, 1944.

University of Arizona, Agricultural Experiment Station (annual), Arizona agriculture: Agricultural Experiment Station Bulletins.

Quality of surface waters of the United States, U.S. Geol. Survey (annual): U.S. Geological Survey Water-Supply Papers.

Surface water supply of the United States, Colorado River basin, U.S. Geological Survey (annual): U.S. Geological Survey Water-Supply Papers.

Water levels and artesian pressures in observation wells in the United States, Southwestern states: U.S. Geological Survey Water-Supply Papers.

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U.S. GOVERNMENT PRINTING OFFICE: 1966 O—681-100