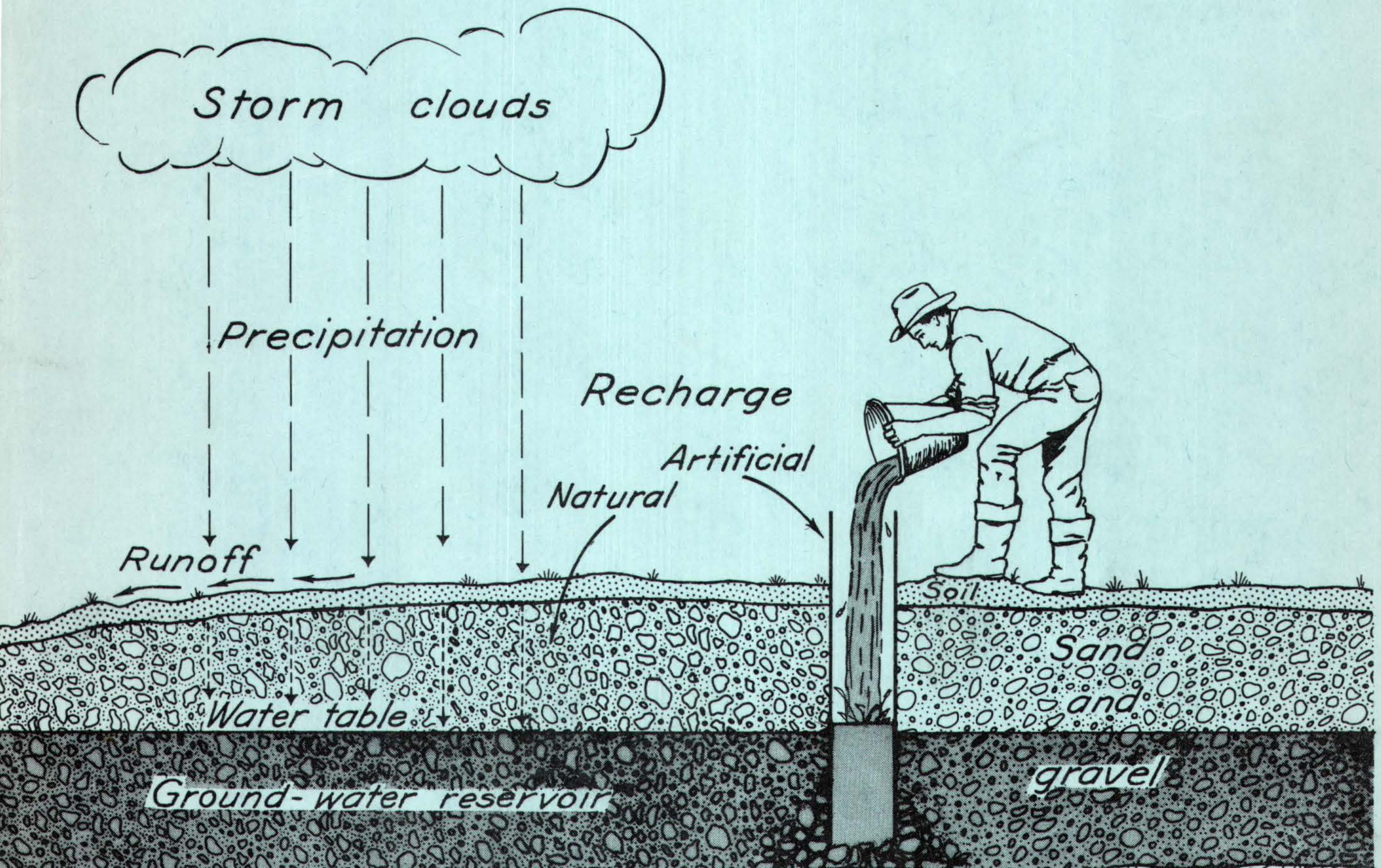
UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

RECHARGING GROUND-WATER RESERVOIRS

By
George H. Taylor



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UNITED STATES DEPARTMENT OF THE INTERIOR

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WATER RESOURCES DIVISION GROUND WATER BRANCH

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INTRODUCTION

Successful artificial recharge of a ground-water reservoir depends upon many factors. Some factors are very complicated and technical. This paper will deal briefly with some of them. For a more comprehensive description of ground-water reservoirs and their artificial recharge, the publications listed at the end of this paper should be consulted.

WHAT IS A GROUND-WATER RESERVOIR?

Before discussing the recharge of ground-water reservoirs, either natural or artificial, it is well that we understand just what a ground-water reservoir is. The dictionary defines a reservoir as "A place where anything is stored; especially, a place where water is collected and kept for use when wanted, chiefly in large quantity, as to supply a city, to drive a mill wheel, etc. * * *." There are many kinds of reservoirs, such as our grain bins which are reservoirs for food, the crankcases in our automobiles which are reservoirs for oil to lubricate a motor, and the tanks in which municipal water supplies are stored for future use. In a broad sense our natural lakes are reservoirs in which water is stored by Nature. Lakes supply us with transportation routes, recreation facilities, and water for industrial, municipal, and domestic use. We more often think of a reservoir as an artificially constructed space for the storage of water, such as the reservoir behind a dam built across a stream. Thus, we commonly visualize a water reservoir as being a space that contains nothing but air until it is filled with water. And we commonly think of a reservoir as a space, place, or container that can be seen.

Subsurface water is water that lies hidden beneath the surface of the earth. Not all such hidden water is ground water. The water contained in the unsaturated part of the material below the land surface is called "suspended water" (held in suspension by the attraction of soil and rock particles), a part of which is the soil water that sustains most of our vegetation. Below the zone of suspended water, in many places, are zones of varying thicknesses in which the openings between rock particles--such as in clay, sand, and gravel--are completely saturated. The water contained in this saturated material is ground water. Little or none of the ground water in fine-grained saturated material, such as clay or shale, can be removed except by plant roots, by evaporation, or by very slow drainage. Therefore, this ground water generally is of little use.

When the ground water in saturated material can be recovered for beneficial use, as by pumping from a well, the saturated material is called an "aquifer," which is a technical word meaning "ground-water reservoir." A ground-water reservoir differs from what a reservoir is commonly understood to be. A ground-water reservoir cannot be seen; and it generally is partly filled with material, such as sand and gravel, even though temporarily it may contain no water that is available for withdrawal.

Whether a saturated water-bearing formation is called a ground-water reservoir often depends upon the economy of an area. A zone of saturated material that will yield only a few gallons of water per minute to a well may not be considered to be a ground-water reservoir in an area where another zone of saturated material yields many hundreds of gallons of water per minute for, say, irrigation. In an area of water shortage, however, a similar low-yielding zone of saturated material may yield sufficient water to a well to sustain a farmstead and several head of stock. In such an area, the low-yielding saturated material is of great economic importance and, therefore, is considered to be a ground-water reservoir.

Most ground-water reservoirs can be classified as one of two types: (1) those occurring under water-table conditions and (2) those occurring under artesian conditions. Contrary to popular belief, ground water occurs as underground streams or in underground conduits only under particular geologic conditions. These conditions exist in some dense rocks that contain fractures. Some limestones contain fractures that have been enlarged--sometimes to great size--by water moving through the openings and dissolving the rock material. Lava rocks, especially basalt, also may contain large opening or channels from which ground water is obtained often in large quantities. Ground water in these formations may occur under either water-table or artesian conditions. Knowledge of the type of ground-water reservoir with which we are concerned is very important when artificial recharge of the reservoir is under consideration.

A water-table aquifer, or reservoir, can be defined as one in which the water in a hole or well dug into it will stand at the same level at which the water was found. This situation exists where the saturated materials are unconfined--that is, where they are not immediately overlain by relatively impermeable material, such as a clay bed. The water table is the upper surface of a zone of saturated material except where that surface is formed by impermeable material.

An artesian aquifer, or reservoir, can be defined as one in which the water in a hole or well dug into it will rise above the level at which the water was found. This situation exists where the saturated materials are overlain (and underlain) by relatively impermeable formations. The imaginary surface, or level, to which water will rise at all places in an artesian aquifer is called the "piezometric surface." This surface corresponds to the water table of an unconfined aquifer.

An artesian well may be either a flowing or a nonflowing well, the distinction depending upon the artesian pressure and the level of the land surface at the well. The artesian pressure is created by the difference between the level at which the water is found in the area of recharge and the level at which it is found in the artesian reservoir. A similar situation exists when we empty a washtub through a hose attached to the bottom of the tub: when the end of the outlet hose is above the level of the water, water in the hose will stand at the level of the water in the tub, but will not flow out--it is a nonflowing hose (well); when the end of the hose is below the level of the water in the tub, water flows out of the hose--hence, it is a flowing hose (well).

Figure 1 is a simplified cross section of an imaginary area drawn to illustrate a principal water-table aquifer that grades laterally into an artesian aquifer, which, in turn, is overlain by a shallow water-table aquifer. The figure also illustrates water-table wells, a nonflowing artesian well, and flowing artesian wells. The conditions illustrated are known to exist in some areas within a distance, represented by the width of the figure, of only a few miles; they are not uncommon, especially in western United States. This very simplified illustration illustrates some of the characteristics of a ground-water reservoir that must be well understood if it is to be successfully recharged by artificial means.

HOW IS A GROUND-WATER RESERVOIR RECHARGED NATURALLY?

Ancient people had many misconceptions about ground water and its source. Many ideas were based upon the occult, the mysterious--even witchcraft. Some of the misconceptions are believed even yet by some persons; they generally are caused by misunderstanding or a lack of information. There is nothing mysterious about the source of ground water. Being generally out of sight, however, its location, nature, movement, and other characteristics are difficult, and sometimes very difficult, to determine. Unlike water on the surface of the earth, which we can see and understand rather well, water under the surface of the earth can be seen only in wells or where it issues as springs, seeps, geysers, and similar discharges. Furthermore, its occurrence and movement are governed to a great extent by geologic conditions--factors with which only a relatively few persons are familiar.

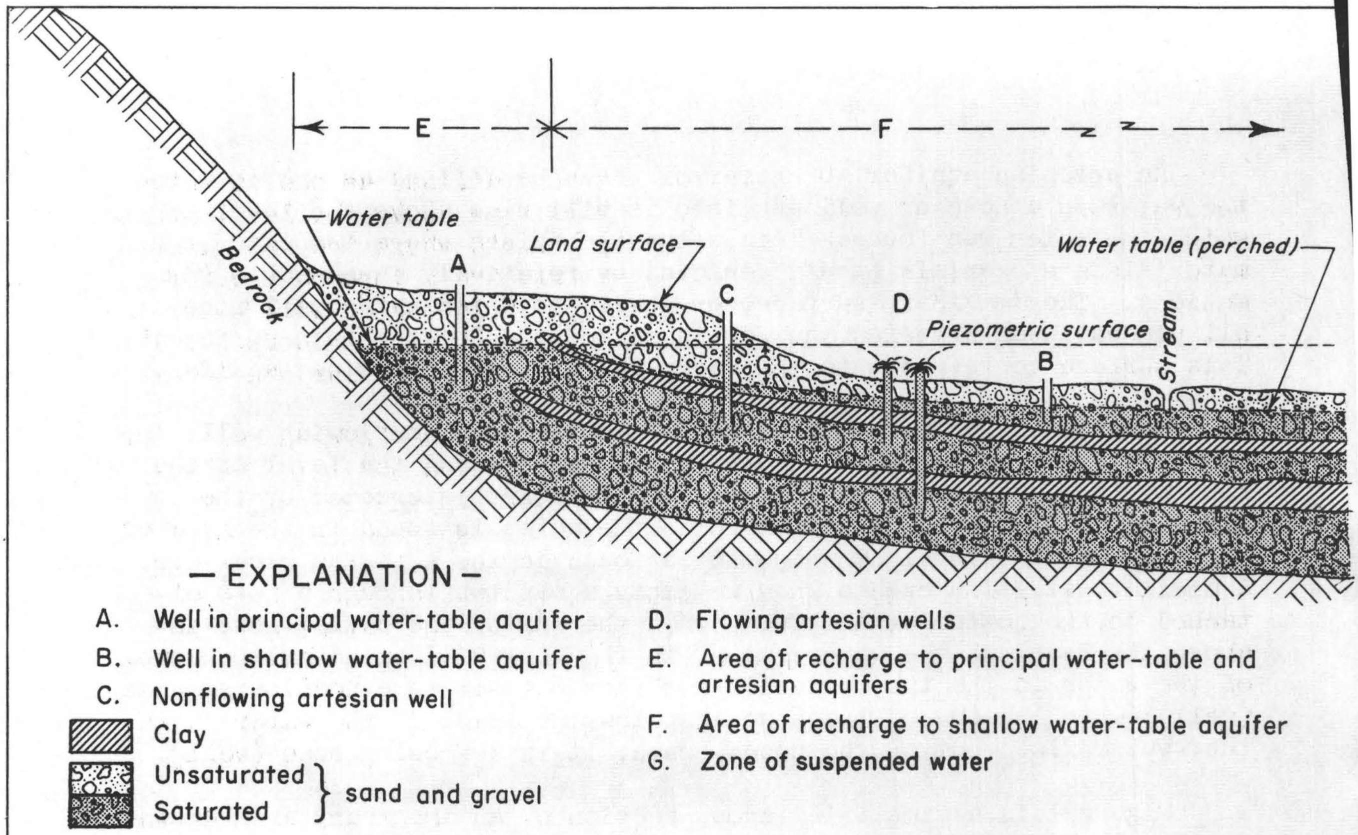

Figure l.-- Partial cross section of a hypothetical valley showing water-table and artesian aquifers

Figure 1.--Partial cross section of a hypothetical valley showing water-table and artesian aquifers.

Seldom can a person actually see a ground-water reservoir being naturally replenished, or recharged. Natural recharge generally occurs in one of two ways. Perhaps the greatest amount of ground-water recharge occurs when precipitation falls on the earth's surface and a part of it moves downward through the earth's mantle until it reaches the water table. Even an artesian aquifer, in nearly all cases, is recharged over an intake area under which a water table exists (area E in fig. 1). In some areas, as illustrated, two or more artesian aquifers lying at different depths may be replenished through the same recharge area.

Ground-water reservoirs, especially those in arid regions, often are recharged by water seeping downward through porous streambeds that lie over the reservoir. As in figure 1, a stream having a porous bed and flowing from left to right would lose water to the ground and would recharge not only the principal water-table aquifer but also the artesian aquifers. Likewise, it would recharge the shallow water-table aquifer as it flows across area F.

If a stream extends below the water table, as it generally does in humid regions, and often does in parts of arid and semiarid regions, it acts most of the time as a drain instead of a source of recharge, and there are springs and seeps along its bottom and edges. These springs and seeps drain water from the ground-water reservoir which lies upstream from them and which may have been recharged by water from the same stream some distance above the springs.

The beds of some lakes and ponds are sufficiently porous to permit water to move through them to underlying ground-water reservoirs. Conversely, other lakes and ponds receive water from a ground-water reservoir through seeps and springs. In some areas, depressions or pockets in the land surface intersect the water table, and ponds or lakes are formed. The water surface in such a lake is at practically the same level as the water table, and the lake is called a "water-table lake."

Natural recharge to ground-water reservoirs results from precipitation or surface water moving through the soil and underlying material to the water table. Thus, in addition to a knowledge of the type of ground-water reservoir that is to be recharged by artificial means, an understanding of the geologic formations and the method of natural recharge in the area is essential.

WHY RECHARGE A GROUND-WATER RESERVOIR ARTIFICIALLY?

When a new land is settled, the first residents establish their homes along or near bodies of surface water, such as streams or lakes, which serve as sources of water supply. Later, for convience or for other reasons, shallow wells are dug where the water table lies close to the land surface, as in a stream valley. As the population increases and industries are established, more and more water is used. Not only is water used for more purposes, but the per capita use grows by leaps and bounds. In some areas the use of water has increased during the last several decades from a few to hundreds of gallons per day per person. The national per capita use of water is currently well over 700 gpd (gallons per day), including water used for industry and irrigation but excluding that used for hydroelectric power. The increasing use of water has caused more and more to be obtained from ground-water reservoirs. In some areas, more ground water is being withdrawn than is being recharged by natural methods. Here, artificially recharging the reservoirs would help sustain and perhaps expand the current economy.

During past years, more dependence has been placed upon ground-water reservoirs in the arid and semiarid areas of the western United States than in the humid and semihumid areas of the eastern United States. This has been caused by a scarcity of surface water, by droughts, and, especially, by an increasing recognition of the availability of ground water for irrigation. However, as the population, industries, and requirements for water have increased, ever greater use of ground water has developed in the eastern United States. Local shortages of surface water for industrial and municipal use and, in recent years, a growing interest in irrigation in the eastern United States have increased the use of ground water materially.

The absence of sediment and other suspended material in ground water makes it more desirable than surface water for many uses. As it has a more constant temperature and generally is cooler in summer, ground water is preferred for use as a cooling medium. The great expansion of air conditioning in recent years has placed a huge demand upon ground-water reservoirs. The use of ground water for irrigation likewise has grown remarkably during recent years. For example, during the 1950's the number of irrigation wells in Nebraska increased by about 25 percent each year until, in 1959, the State had more than 24,000 irrigation wells.

The increasing use of ground water has caused ground-water levels to decline in some areas to a point where the water in the ground-water reservoirs is being exhausted or where the cost of pumping from increasing depths is becoming prohibitive. This is not a new situation, for it occurred in local areas many years ago, especially in the western United States. Among the first to experience the effects of declining water levels were irrigated areas in California. Later there were declines on Long Island, where much ground water is pumped for municipal and industrial supply and air conditioning. As more ground water has been used, the areas of shortage have spread to other parts of the United States.

This does not mean that we are running out of ground water throughout the Nation; it simply means that in some areas more water is being removed from the ground-water reservoir than is being put back into it by Nature. In some areas the situation is only a temporary one, which will be corrected during periods of less demand and greater precipitation. In other areas, such as the parts of the High Plains in Texas and New Mexico where intensive irrigation by ground water has been developed during the past 2 or 3 decades, the depletion is permanent. In the High Plains the water pumped each year represents water that has been added to the ground-water reservoir by Nature over a period of many decades. In effect, the ground water in these areas is being mined, and locally the reservoirs will be depleted within a relatively few years or decades with no possibility of being refilled naturally for many years, even for centuries. As in a surface-water reservoir, more water cannot be removed from a ground-water reservoir than is added to it without lowering the water level. If withdrawals persistently exceed additions, the supply eventually will be depleted.

Thus, if we wish to withdraw more water from a ground-water reservoir each year than, on the average, is added by Nature each year, we must find some way to add the difference.

Preventing depletion is not the only reason for trying to augment natural recharge. Pumping large amounts of water from ground-water reservoirs that are adjacent to and connected with bodies of salt water, such as the ocean, causes the water table to be lowered in some places to a level where the salt water moves into the fresh-water reservoir. When salt water invades a ground-water reservoir, that reservoir may be virtually ruined for all future use as a fresh-water reservoir. Removal of the salt generally requires so much fresh water to flush it out that such reclamation may be beyond any known practical means.

We have a choice of two ways to retard or stop intrusion of salt water. First, we can reduce the withdrawal (pumpage) to an amount less than the natural recharge. The economy of many areas has been built around the ground-water supply, however, and such a reduction of pumpage would result in great economic loss. Second, we may be able to recharge the ground-water reservoir artificially and raise the level of the water table or create a ground-water mound, or dam, between the salt and fresh water. This may be the only practical way to prevent further encroachment of the salt water. Artificial recharge for this purpose is becoming a necessity and a common practice in several areas, such as in California, Florida, and New York.

Repressurizing oil fields ("water flooding") to aid in the recovery of oil has been practiced for many years. This practice is, in essence, a form of artificial recharge. Some of the water that is pumped under pressure into abandoned oil wells, or into wells drilled for the purpose, goes to replace the brine that has been removed from the oil-bearing formations. Some replaces the oil that has been removed. It also serves to displace and float out oil that clings to the rock particles of the oil-bearing formations, thus increasing the amount of oil that can be recovered.

The removal of large quantities of water from a ground-water reservoir may cause the land surface overlying the reservoir to subside in some areas. Large-scale removal of oil from oil reservoirs may cause similar land subsidence. This lowering of the land surface has amounted to tens of feet in some places. Land subsidence due to the pumping of ground water or oil has caused extensive damage to surface construction in California in the San Joaquin Valley and in the vicinity of the Los Angeles harbor, in Mexico City, in Japan, and in other areas. Much research and experimentation has been undertaken toward a solution of these subsidence problems. Artificial recharging or repressurizing of underlying ground-water or oil reservoirs serves to arrest or slow down such subsidence. Research to date, however, indicates that it will not restore the original level of the land surface.

Water stored in a ground-water reservoir is subject to little or none of the evaporation that helps to deplete surface reservoirs. In some areas, evaporation will remove water from a surface reservoir each year equal to a depth of 6 feet or more over the entire reservoir. Basinwide, the building of more and more surface reservoirs can reach the point of diminishing returns: That is, the evaporation from all the reservoir surfaces can equal or even exceed the water that can be stored in an additional surface reservoir. On the other hand, water stored in a ground-water reservoir is not subject to evaporation losses so long as the water table is kept below the land surface a distance exceeding the thickness of the capillary fringe. This distance generally is within the range of 4 to 12 feet. Thus, greater conservation of water can result when it is stored underground than when it is stored on the land surface.

Some plants obtain considerable water by sending their roots into the capillary fringe. To avoid loss of ground water through transpiration by those plants, the water table may need to be held at depths as great as 20 or 25 feet below the land surface. This is especially important if the plant is nonbeneficial, such as salt cedar.

Many areas are underlain by unsaturated porous materials. Some of these materials are potential ground-water reservoirs if they can be artificially filled with water. This has been done in the past, sometimes unintentionally as a byproduct of irrigation activities, as will be noted later.

Some ground-water reservoirs can hold temporarily (a matter of months and even years) much more water than normally is stored in them. Because of the relatively low rate of ground-water movement (commonly a few hundred feet per year), temporarily stored water often can be recovered by pumping before it reaches points of natural discharge. Even though it might not be recovered by pumping, its slow, uniform rate of natural discharge will serve to maintain the flow in streams during periods of below-normal precipitation and low surface runoff. In some areas, therefore, storing water in a ground-water reservoir, even one that is not being depleted, is a good water-conservation practice. The underground storage of surplus water, especially during periods of high surface runoff, has been practiced for many years in California. The practice has more recently been adopted in other areas. Full conservation of the Nation's fresh-water resources eventually will involve much wider adoption of the practice.

HOW IS ARTIFICIAL RECHARGING DONE?

Ground-water reservoirs are artificially recharged by two principal methods: (1) spreading water over the land surface and (2) pouring or injecting water into wells. Running water into pits is an intermediate method similar in some respects to both of the principal methods, but it generally is classed as a type of water spreading.

The spreading of water for artificial recharge is done in several ways. The water can be distributed by means of dams and dikes over a "spreading ground" which is suitably graded for the purpose. It can be spread over irrigated fields in amounts greater than are needed to supply the crops. The water can be put into pits or basins dug for the purpose. Furrows and ditches can be constructed and water run slowly through them and allowed to seep into the ground. Water can be stored temporarily in surface reservoirs during periods of high streamflow and later released at a rate that does not exceed the percolation capacity of the streambed.

Abandoned sand and gravel pits can be used to receive water, which then seeps from them to the ground-water reservoir. The best way to spread the water in a particular area depends upon many factors, such as the percolation rate of the streambed, of the bed of the basin or pond, or of the spreading ground; the quality and quantity, and the rate of flow, of the water available for recharge; the geology of the spreading ground and of the ground-water reservoir to be recharged; and the value of lands available for recharge.

Several ground-water reservoirs are being recharged by the pit method. One of the cities where this method is used is Peoria, Ill. Briefly, a pit 35 feet deep was dug to the gravel aquifer underlying the city, exposing a horizontal cross section of about 7,900 square feet. Water is diverted from the Illinois River, the sediment removed, and the water chlorinated. It is then run into the pit, where it percolates through a renewable sand bed in the bottom of the pit and into the ground-water reservoir.

The earliest record of a project planned to spread water over a recharge area in the United States to replenish a ground-water reservoir is that of the Union Water Co., Denver, Colo., in 1889 (Michelson, 1934). In California, recharge water began to be spread on the alluvial fan of Santiago Creek in 1896, and on the Santa Ana River fan in 1900. These latter projects, enlarged and improved, now are of major importance in the conservation of water and the recharge of ground-water reservoirs in those areas. Similar methods of ground-water recharge are now practiced in many other areas in California and elsewhere in the United States.

Artificially recharging ground-water reservoirs by pouring or injecting water into wells is perhaps the most difficult of the methods used, especially if the reservoir is to be recharged at a relatively high and continuous rate. One of the outstanding examples of artificial recharge through wells is that on Long Island, N. Y. Here, much ground water is used for cooling purposes and the large withdrawals in the western part of the Island caused an alarming lowering of the water table below sea level under an area of many square miles. This, in turn, caused an intrusion of salty sea water into the fresh-water aquifers. Under State legislation, many millions of gallons of water is now being returned, after use, to the ground-water reservoir through hundreds of recharge wells and several pits. In addition, surface runoff from some highly urbanized areas is recharged through several storm-water disposal basins.

Another outstanding and more recent example of artificial recharge through wells is along the ocean beaches near Los Angeles. Here, the ground-water reservoir is recharged by injecting fresh water into a series of wells drilled in a line parallel to and a little distance back from the beach. The wells were drilled especially for this purpose after extensive research and experimentation. The recharge water causes a ground-water dam, or ridge, to be formed below the land surface, which prevents further intrusion of the sea water into the fresh-water aquifer.

The examples just given, though outstanding, are typical of many other artificial-recharge operations throughout the United States.

WHAT ARE THE REQUIREMENTS FOR SUCCESSFUL ARTIFICIAL RECHARGING?

The factors that govern the success of artificial recharge of a ground-water reservoir vary with the method used. The best method to be adopted in turn varies with local conditions, such as the type of reservoir (water-table or artesian), the source of natural recharge, the natural direction and rate of movement of the ground water, the topographic conditions, the amount and quality of the water available for recharge, the percolation characteristics of the material underlying the proposed recharge area, and many other similar or related factors. The factors in one situation will be different from those in another.

An adequate supply of good-quality water is, of course, the first requirement. Note that the supply of water should be not only adequate but of good quality. This latter requirement is of utmost importance, especially if the recharge water is fed directly into the ground-water reservoir through wells or shafts or through the bottom of pits directly in contact with the water-bearing materials, or is spread over recharge areas where the depth to the water table is only a few feet. Ground-water reservoirs can easily be contaminated with polluted water, and once introduced the contamination may persist for a long time. Ground water nearly always is moving from areas of recharge toward points or areas of discharge. Thus, contaminated water placed in a ground-water reservoir not only will ruin the reservoir at the point of entrance or under the area of recharge but may cause contamination of the ground water many hundreds of feet down gradient. The more porous and permeable the materials of the aquifer, the more rapid the spread of contamination. In very permeable material, such as very coarse gravel or fractured or cavernous limestone or basalt, the contamination may move miles in a few days or weeks.

When water is spread over recharge areas on the land surface, however, the danger of contamination is greatly reduced, especially if the water table lies a considerable number of feet below the land surface and the material through which the water percolates has a relatively low percolation rate. Under some circumstances, even water rather badly polluted by sewage and industrial waste will be purified by percolation through several tens of feet of relatively fine-grained material if the time of travel from the land surface to the water table is of 1 or 2 weeks' duration. Spreading such water for purification as well as for recharging purposes has been successful. However, unless done on a strictly controlled basis, the use of polluted water to recharge ground-water reservoirs should not be attempted.

A very undesirable and potentially dangerous method of artificially recharging ground-water reservoirs has been tried when the potential contamination, perhaps permanent, that could be introduced into the reservoir was not recognized. This method consists of drilling a hole or well, with no professional advice, into the bed of a relatively small pond or lake and draining the water into it. Such water, especially in temporary rain or flood ponds, is likely to be highly contaminated, and if the practice is continued it may ruin an otherwise excellent source of water. Fortunately, such recharge efforts are generally shortlived because the water supply is small and because the recharge hole or well commonly becomes so clogged with sediment that it will cease to take in water.

If the water to be used for recharging is found, by a competent chemist or bacteriologist, to be impure, the impurities may possibly be removed by chlorination or other means. Because chlorination is an effective and relatively inexpensive process, its use for most recharge water should be considered. By proper treatment and purification, even sewage water can be made acceptable for recharge by most methods. This is being done near Azusa, Calif., where about 450,000 gpd of the effluent from a sewage-treatment plant is spread over and sunk into the alluvial fan of the San Gabriel River. Much research has been and is being done along these lines, and in areas of acute water shortage the reclamation and reuse of considerable quantities of sewage water as a water-conservation measure is not at all unlikely in the near future.

Perhaps the next most important item to be considered is the geologic setting--what are the geologic formations that make up the aquifer and the surrounding material? Other factors being equal, the better the geologic conditions are understood the more likely a successful recharging operation can be designed. For anything other than a relatively unimportant operation, the advice and services of qualified hydrologists should be obtained to make a thorough study of the ground-water reservoir to be recharged. Such studies would consider the physical features of the area and of the ground-water reservoir, and probably would also include economic factors to aid in the determination of the best method to be used.

If, in a particular situation the spreading method can be used, the quality of the recharge water will be a less critical factor. Even though water that is somewhat polluted may be used in the spreading method, all or most of any sediments or solids in the water should be removed by passing the water through settling basins before spreading it on the recharge area. Sediments in even light concentrations may necessitate frequent and expensive cleaning of the infiltration area.

When the best available spreading area has a lower percolation rate than desirable, water loss through evaporation from the spreading area may be relatively great. If the same water-surface area is maintained, the quantity lost by evaporation will be the same with a low percolation rate as with a high rate. Thus, the percentage of the total water supply lost through evaporation increases as the percolation rate decreases. This factor may be especially important when the conservation of water is a principal objective of a recharging operation, or when the cost of frequent cleaning of the spreading area to maintain the percolation rate is prohibitive.

Artificial recharge through wells has been found to be troublesome in some areas and under some conditions. Most of the difficulties are caused by the clogging of the recharge well with the sediment in the recharge water, by the growth of bacteria and algae in the water, or by the precipitation in or around the well of mineral matter from the recharge water. Frequent cleaning and redevelopment of the recharge well or treatment of the recharge water generally is required. However, the appropriate treatment is difficult to determine. Much research has been and is being done to determine the necessary treatment of water to make its use in recharge wells successful. An outstanding example of this type of research is that being carried on in the rice-field areas of Arkansas.

ARTIFICIAL RECHARGE AS A BYPRODUCT

The artificial recharge of ground-water reservoirs, in many instances, has been accomplished unintentionally and as a byproduct of other activities. Sometimes the effect has been detrimental and sometimes it has been beneficial.

Oil-field wastes, such as brines, have been stored in open pits to be evaporated. However, in many places some of the liquid has seeped from the storage ponds and recharged the underlying ground-water reservoir. These wastes, containing high concentrations of various salts, have polluted the water in some ground-water reservoirs to the extent that it has become unfit for most uses. Since recognition of this danger in the use of evaporation pits, active steps have been taken by oil companies as well as by regulatory agencies to insure disposal of the wastes by other methods. These include making certain that surface ponds used to store the wastes are tight enough to prevent seepage from them. Also, much oil-well waste is being returned to oil-bearing or other saline formations by pumping it through wells. This method of disposal often gives two benefits: safe disposal of wastes, and re-pressurizing of oil-bearing formations, which helps to recover more oil and tends to reduce land subsidence.

When soil water evaporates or is used by plants, most of the salts that were in the water accumulate in and at the surface of the soil, sometimes to the point that plant growth is affected. To prevent this accumulation of salts on irrigated lands, more water than is needed for plant growth is applied to irrigated crops. On nonirrigated croplands, precipitation generally exceeds plant requirements during some parts of the year. The excess water in both situations percolates downward, leaches out the salts and recharges the ground-water reservoir. Thus, successful irrigation over long periods results in unintentional and unavoidable recharge of underlying ground-water reservoirs.

Continual application of excess water may raise the water table close enough to the land surface to permit evaporation from the capillary fringe, which exists above all water tables. This evaporation causes salts to accumulate on the land surface, generally in the low-lying areas, of many irrigation projects some time after irrigation has begun. Drainage works are necessary in some parts of most irrigation projects to prevent this. Because some of these initially productive areas cannot be drained economically, they become wasteland. Examples of such wasteland can be seen in the Helena Valley in Montana; in the Cache Valley in Utah; in the Shoshone River basin in Wyoming; in the North Platte River valley in Nebraska; in the Belle Fourche irrigation project in South Dakota; and in many other places.

In some places, "overirrigation" is practiced deliberately to recharge ground-water reservoirs--that is, the irrigated areas are used to grow crops and to spread water. Obviously, the practice is followed only where it is economically feasible and where it does not cause waterlogging.

Unplanned artificial recharge has been and can be highly beneficial. Benefits do occur on different parts of an irrigation project where detrimental results also occur. A good example of this is the Shoshone Irrigation Project in Wyoming. Here, seepage and overapplication of irrigation water damaged some low-lying lands, and at the same time a normally dry, porous formation underlying part of the project area became saturated and was thus converted into a ground-water reservoir, from which many farm wells draw water for domestic and stock use. The town of Powell, Wyo., has been provided a municipal ground-water supply as a result of this unplanned artificial recharge.

Another outstanding example of unplanned artificial recharge is one near Twin Falls, Idaho, where seepage from land irrigated with water from the Snake River has increased the water stored in the ground by several million acre-feet. Over a period of about 50 years, this artificial recharge raised the water table more than 200 feet, coming so close to the land surface in some places that drains had to be built to prevent waterlogging of the land.

Other examples could be cited, in foreign countries as well as in the United States. Many irrigation projects are now planned, however, to avoid the damaging effects and to take advantage of the beneficial effects of artificial recharge from irrigation seepage.

The discharge of industrial wastes into surface streams, ponds, and lakes has caused unexpected damage to ground-water reservoirs. As mentioned previously, seepage from stream channels naturally recharges many ground-water reservoirs. When the water in these streams is polluted, it can pollute the water in the ground-water reservoirs, as it has done in many places. For example, the discharge of phenol wastes into the Caloosahatchie River has necessitated abandonment of some municipal wells at Fort Myers, Fla. The accumulation of pulp-mill waste on a streambed may impede the natural recharge to a ground-water reservoir that supplies water to wells upon which the same or other industries depend for water, as has happened in Michigan. The dumping of oil-well brines into the Canadian and Arkansas Rivers in Oklahoma has contaminated not only the streams but also the water in nearby wells.

In recent years, the widespread use of synthetic detergents has created problems in places where detergent-bearing waste water is discharged into septic tanks or is dumped into ponds or streams that are natural sources of recharge to a ground-water reservoir. Pumping from wells agitates the ground water and the detergent causes froth. Much research has been done on water-supply problems caused by detergents in waste water, and more is needed.

More universal understanding of the dangers to ground-water reservoirs of dumping waste into streams and other surface-water bodies has resulted in progressively greater consideration of waste-water-disposal methods. In many places, disposal methods are controlled by State and Federal laws.

WHAT DOES ARTIFICIAL RECHARGE COST?

The cost of artificial recharge depends upon many factors and varies widely. Generally, the operation is not feasible unless water has become scarce enough to justify considerable expense to augment the ground-water supply or conserve the total supply. Even though the cost may be great, it may be less than that to import water from a distant source. The most expensive method, per gallon of water recharged, generally is that of recharging through wells. The least costly generally will be that of one of the water-spreading methods. However, the cost of land for water spreading in concentrated residential or industrial areas may be prohibitive; here, if done at all, recharging through wells may be the least costly method. Because of the many and variable conditions affecting the cost of artificial recharge, general estimates are not practical; each situation is a separate problem. The estimate of cost should be made by persons qualified by training and experience in ground-water hydrology. It is urged that any person or group of people considering the artificial recharge of any ground-water reservoir--whether for the disposal of wastes, the replenishment of the reservoir, or the conservation of water--seek the advice and assistance of qualified ground-water hydrologists. A number of consulting geologists and engineers located throughout the United States can give these expert services.

SELECTED REFERENCES

U.S. Geological Survey water-supply papers may be purchased for a nominal sum from the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C. References marked with an asterisk (*) are out of print; however, copies can be consulted at many of the larger public and university libraries and at many of the Geological Survey's offices, one or more of which are located in nearly every State.

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