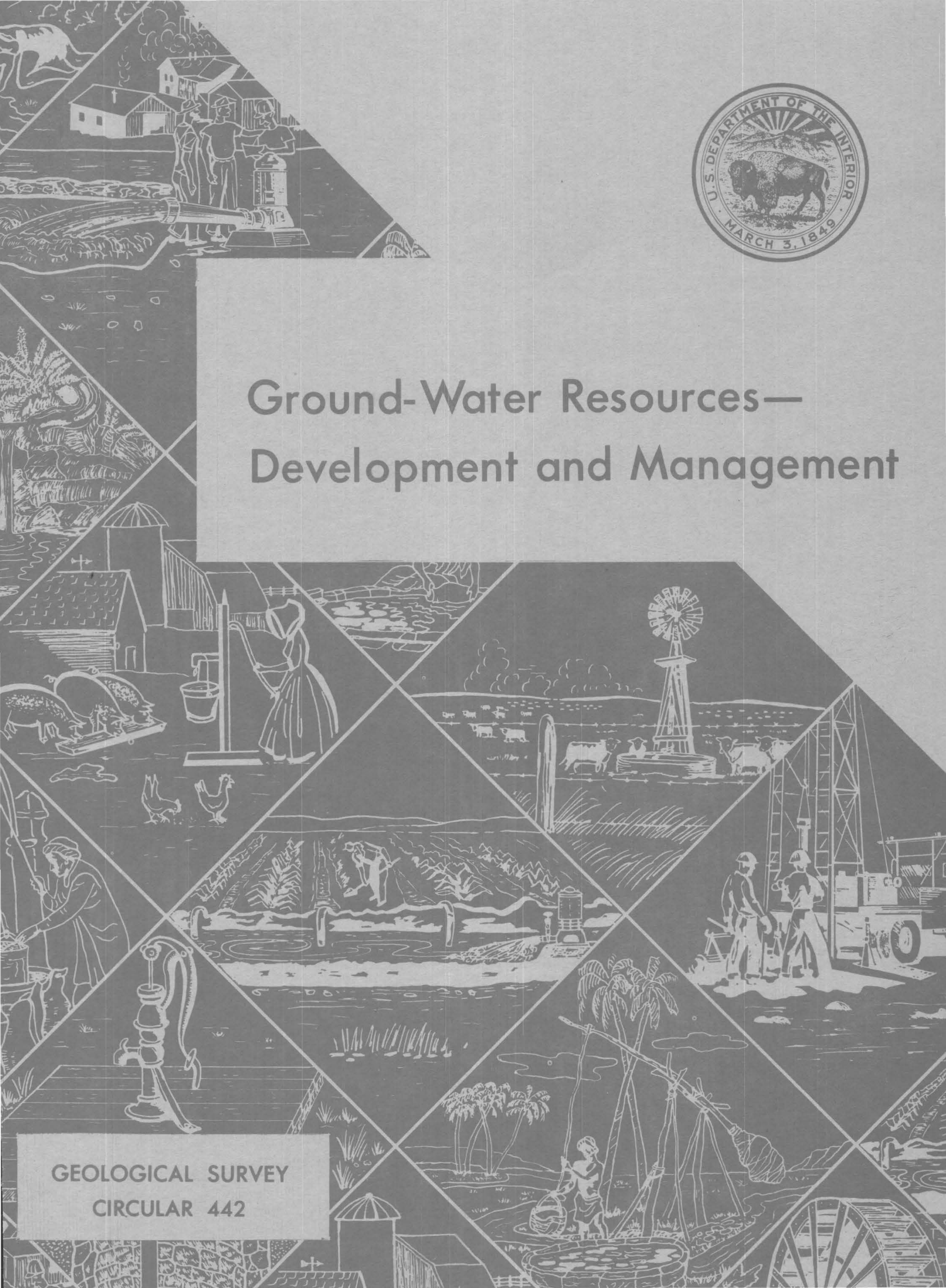
Ground-Water Resources—
Development and Management



GEOLOGICAL SURVEY
CIRCULAR 442

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GEOLOGICAL SURVEY CIRCULAR 442

Washington, D. C. 1961

United States Department of the Interior
STEWART L. UDALL, SECRETARY

Geological Survey
THOMAS B. NOLAN, DIRECTOR

Free on application to the U. S. Geological Survey, Washington 25, D. C.

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By C. S. Conover

Presented August 24, 1960, to Ground Water Section of the Western Resources Conference, Boulder, Colo.

The need for broader appreciation, evaluation, and management of our ground-water resources is becoming more evident every day. Also, as development of our water resources approaches a finite limit, it becomes evident that ground waters and surface waters must be developed and managed as one water supply. This integration, like the solution of many other problems, is easier said than done.

Effective development and management of ground water, whether singly or in conjunction with surface water, requires knowledge and appreciation of its physical environment. Though ground water and surface water are phases of the hydrologic cycle and therefore are interdependent, their prime common denominator is the fact that both are wet. There are other common factors, of course, such as chemical character, but many of the physical situations in which ground water and surface water exist are quite different. It is only because they are different that we have water during dry periods. Mother nature planned it this way, and if man is to make maximum use of ground and surface waters he must fully understand and tailor his actions to take advantage of these different environmental factors.

Take storage, for example. In most areas, the volume of ground water in storage is several times that of surface water. In the United States as a whole, the quantity of water in underground storage, within half a mile of the land surface, is several times that in all the large lakes of the North American Continent and more than 100 times the annual runoff of streams in the United States (Nace, 1960, p. 3). Though the volume of ground water in storage is large, its natural rate of replenishment is small in comparison. For the United States as a whole, several hundred years would be required to replenish the stored ground water, whereas streams are replenished seasonally. An outstanding example of large storage and small replenishment is offered by the southern High Plains in Texas and New Mexico. Overall, the ground water in storage in the Texas portion is about 200 million acre-feet, but if exhausted it would take considerably more than 1,000 years to replace (U.S. Senate Select Committee on National Water Resources, 1960a, p. 15).

The rate of movement of ground water also contrasts sharply with that of surface water. Generally, ground water flows inches or feet per day, whereas the flow in streams is measured in feet per second or minute. The contrast in rates of flow is illustrated by the movement of ground water in the aquifer supplying Houston, Tex. Houston, the largest city of the United States dependent mainly on wells for municipal supply, is served by an aquifer having a better-than-average capability for transmitting water. Even so, a cross section of the aquifer 45 miles wide and 600 feet thick is required to transmit 80 mgd (million gallons per day) to the Houston area at a hydraulic gradient of 10 feet per mile. New York City obtains three times as much water from Croton Reservoir through a pipeline less than 14 feet in diameter (Thomas, 1951, p. 98).

The flow in streams is such that water from a large area can be gaged at a single location. Surface reservoirs also can be gaged at a single location. However, permeable earth materials offer significant impedance to flow of ground water, with the result that a ground-water reservoir (aquifer) must be gaged at many points if the status of the resource is to be evaluated. Water-level measurements in a single observation well may indicate conditions in only a small part of an aquifer.

Though stream channels are not simple conduits, they can be easily mapped and measured. The same is not true of aquifers. Aquifers are composed of a wide range of earth materials deposited by many geologic processes. The very nature of geologic processes insures that the materials composing aquifers will vary in character both laterally and vertically. Formations that are water bearing (aquifers) in one locality may change laterally to become nonwater bearing (aquicludes) in another area. Several aquifers may be present in a particular area, separated vertically by aquicludes, and both water-table and artesian conditions may exist. The source of water to and the area of discharge from an aquifer may be distant or nearby. Therefore, aquifers are not easily mapped. However, they must be mapped, their water-bearing characteristics determined, and their hydrologic regimen evaluated before decisions can be made as to optimum development and management of the ground-water resource over a long period of time.

Water is commonly referred to as a renewable resource. Strictly speaking, this is true. However for many ground-water reservoirs, especially those in the arid and semiarid parts of the country, the question of renewability is academic so far as the life span of present water users is concerned. Even in humid areas, ground water withdrawn from wells is renewable by natural recharge only where the wells are so placed that natural discharge is reduced or natural recharge increased by an amount equal to the net consumptive use. If the wells cannot be ideally located—or, even if they are but the net consumptive use of water exceeds the natural discharge (recharge) of the aquifer—then the reserve can be renewed only if the withdrawals are reduced or stopped.

Year-to-year declines in water level are the usual condition in many of the developed aquifers of the West. Persistent declines are evidence of depletion of ground-water resources. Whether the depletion is localized or aquifer-wide, and whether it is temporary or will persist for periods equal to or greater than long-term climatic cycles, depends upon the local geohydrologic situation. Lowering of water levels is a natural consequence of pumping of wells, so that even in humid areas of abundant recharge there are declines of water level.

In areas of shallow-lying ground water, particularly in many stream valleys of the West, rank growths of phreatophytic vegetations consume large quantities of water. The area of phreatophytes in California, Arizona, New Mexico, Nevada, Utah, and Colorado currently is estimated as 7 million acres. These plants consume 10 to 12 million acre-feet a year. The area of phreatophytes in New Mexico and Arizona is almost 1 million acres, and the water consumption is $2\frac{1}{2}$ to 3 million acre-feet per year (U.S. Senate Select Committee on National Water Resources, 1960b, p. 2). Not only do these plants waste large amounts of water, but the water transpired is virtually pure. The chemical character of the water remaining therefore has deteriorated. Salvage of this wasted water by such measures as eradication of the vegetation and construction of drains is only partially effective. However, in many areas capture of this wasted water could be easily accomplished and would be a natural consequence of the lowering of water levels caused by pumping. If wells are located with the objective of salvaging water, then the net usable supply can be increased and the quality improved. However, if wells are installed with water supply as the only objective, then their location may be such that the pumped water comes from ground-water storage or from streamflow. If so, the individual well owner benefits temporarily at the long-term expense of all water users.

Use of ground water may provide an increase in water supply through the medium of recirculation. This is particularly true in irrigated areas, where a significant portion of the water applied to the crops may infiltrate to the ground-water body. It is then pumped to the land surface for reuse by the same individual or his neighbors. Reuse of surface water is on a downstream basis, each succeeding user receiving a supply diminished in quantity and less acceptable in quality. Recirculation of ground water, though it may take place on the same property, likewise diminishes the quantity and deteriorates the quality. In an aquifer, the continued recirculation of water results in an accumulation of dissolved salts, whereas in a stream the water of diminished quality is flushed downstream. Thus, in many areas of ground-water development, the accumulation of salts in the water poses a more serious threat to the life of the resource than does the decrease of supply. The Wellton-Mohawk area of the Gila River basin in Arizona illustrates such deterioration through recirculation. In 20 years the concentration of salts in the ground water there increased from 7,000 to as much as 16,000 ppm (Thomas, 1951, p. 59).

Development and management of ground-water resources, to provide the optimum use of the water for the benefit of a large segment of the population and for the greatest period of time, therefore should be based upon scientific hydrology and tailored to the geohydrologic characteristics of the particular aquifer in question.

Many aquifers may be classified, with respect to development and management, into two broad categories: those which have large storage but negligible recharge and which are not intimately related to streams, and those associated with streams. By proper management, a dependable supply of water of acceptable quality can be developed on a virtually perennial basis from aquifers of the second class—that is, those associated with streams. Aquifers of the first class can yield only a small perennial supply once their storage is depleted.

Aquifers under the first category—those having large storage and little recharge—correspond generally to those having "reservoir" problems as discussed by Thomas (1951, p. 35). In such aquifers to limit the use of water to the rate of recharge is not feasible because of (a) the large demand, (b) the very small recharge, or (c) aquifer characteristics such that natural discharge cannot be diverted or stopped feasibly by development. These are the aquifers where water is being mined, and must be mined, if the water resource is to serve a useful purpose. The problem is to recognize the mining situation and to manage the resource for the greatest good over the longest possible time. A large number of developed aquifers in the West fall into this category. Included in the areas of current or potential ground-water mining are the southern High Plains of Texas and New Mexico; the northern High Plains in Oklahoma, Colorado, and Nebraska; and many of the intermontane valleys of New Mexico, Arizona, California, Nevada, and Utah.

Consider the southern High Plains of Texas and New Mexico as an example of a problem of development and management of an aquifer having a large volume of water in storage, but only a small unit rate of replenishment.

The southern High Plains, or Llano Estacado, lies south of the Canadian River in Texas and New Mexico. It has a total area of some 30,000 square miles. Conspicuous escarpments form the east and west borders. The north border is the deep canyon of the Canadian River. The Ogallala formation is the aquifer, and its boundaries are essentially those of the High Plains. The Ogallala is thin or absent in some areas but is more than 600 feet thick in other areas. The total water potentially available from storage in the Texas portion in 1958 was about 200 million acre-feet (Cronin, 1959, p. 11), but the annual average rate of recharge is only about 50,000 acre-feet. Storage and recharge in the New Mexico part of the High Plains are perhaps a third as great. Thus, total storage in the southern High Plains was perhaps 250 to 275 million acre-feet in 1958. About 40 million acre-feet had already been pumped, and the current rate of pumping is more than 100 times the recharge. Obviously, limiting development to the rate of recharge would mean that the large volume of water in storage would not be utilized. Further, even if it were decided so to limit the development, it would be physically almost impossible to carry out the decision if the premise were that doing so would result in a perennial water supply. The only means of developing water from an aquifer on a perennial basis is to locate wells so that, over a long time, the natural discharge can be stopped, and therefore diverted to the pumps, or the recharge can be increased, or both, in an amount equivalent to the consumptive use.

Most of the discharge from the High Plains occurs along or near the eastern escarpment. Originally some discharge occurred from ground-water lakes such as at Portales, N. Mex., and near Muleshoe, Tex. Over most of the Plains the water table is more than 50 feet below the land surface, and lowering of water levels in these areas cannot induce more recharge. Therefore, it is not physically possible, except in small areas, to locate wells on the High Plains so that the water pumped will come other than from storage.

The lowering of water levels caused by pumping from a water-table aquifer such as the Ogallala formation is transmitted laterally at a slow rate. The major lowering of water level occurs in the vicinity of the well.

The areal spread of the cone of depression is independent of the pumping rate and is a function of time and the hydraulic characteristics of the aquifer. An increase in pumping, or localized heavy pumping, such as caused by many wells in one locality, deepens and steepens the cone of depression. The water can be pumped at such a rate that it is virtually exhausted in the area of heavy pumping, yet water levels are affected only slightly and slowly a few miles away. For example, pumping on the High Plains has been concentrated in the areas where the land is suitable for irrigated farming and where adequate wells can be obtained. As a consequence, water levels have declined more than 100 feet in some of these areas and an average of more than 50 feet under whole counties (Cronin, 1959, p. 10), yet in areas of little or no pumping the water levels have not declined, or have declined only a few feet.

The general solution to the problem of optimum development of ground water in areas of mining is therefore twofold: conservative pumping from adequately spaced wells. The exact rate and spacing are a matter of decision which must take into account the aquifer characteristics and which revolve essentially around philosophical and long-term economic considerations. A long-term, stable development permits amortization of capital expenditures for farm equipment, city and highway development, schools, etc. Also of importance, a long-term, stable development permits the economy of the region to evolve to a level such that conservation and rectification measures can be undertaken. In the final analysis, all conservation and rectification measures are economic - a balancing of cost with benefits, either locally, regionally, or nationally. Some conservation and rectification measures require research, and research takes time - time bought by managed development to permit a stable, growing economy to pay for the research.

An example of management that recognizes the two factors of time and spaced development in ground-water mining is afforded by regulatory measures set up by the New Mexico State Engineer in the Lea County portion of the High Plains. Regulation in Lea County is based essentially upon assuring a firm minimum 40-year life of extractable water, for agricultural papers. It is accomplished on a township basis by taking into account the recoverable water under each township.

Such farsighted regulated management of ground-water mining assures a stable development and economy and also allows the time needed to investigate and institute conservation and rectification measures. Such measures could include (a) increasing recharge, (b) improving water-application practices, (c) substituting crops of lower water requirements, (d) changing from an agricultural to an industrial economy, (e) utilizing (perhaps demineralizing) inferior waters for certain industrial processing, (f) importing surface water, and (g) transporting ground water from undeveloped to developed areas.

Transporting ground water from undeveloped to developed areas to alleviate local shortages is a distinct possibility in some areas of the High Plains, especially for municipal and industrial supplies. Amarillo and Lubbock, Tex., are doing so, and Portales, N. Mex., is favorably situated to transport water from the sand-dune area to the north. A significant part of the High Plains is underlain at less than plow depth by cemented sediments called "caliche" which are not suitable for agriculture. The formation of the caliche rocks in these areas may be said to have effectively saved water for the future, and the rocks therefore may be "worth their weight in water" to the economy of the Plains.

Aquifers of the second category with respect to development and management—that is, those associated with streams—correspond to those having "watercourse" problems and generally to those having "pipeline" problems as discussed by Thomas (1951, p. 36). These are aquifers in which the amount of water that can be developed is sufficiently large to warrant management on a perennial basis. The ground water in these aquifers is related to surface streams, either directly along a stream reach or indirectly through spring flow or other natural discharge.

The prime requisites for development of water from an aquifer on a perennial basis are as follows: (a) the location and character of the discharge areas are such that pumping from wells can effectively reduce the natural discharge from the aquifer, and (or) (b) recharge to the aquifer can be increased in the recharge area or induced in the discharge area. Development can be perennial if the net consumptive use of developed water does not exceed the sum of (a) natural discharge stopped and (b) recharge induced or increased, by virtue of the development or by other artificial means.

Ground-water reservoirs in alluvial valleys of essentially perennial streams, wherein the surface and ground waters are intimately related, fit this category. Examples of such are the Middle, the Rincon, and the Mesilla Valleys of the Rio Grande in New Mexico and the Duncan-Virden and the Safford Valleys of the Gila River in New Mexico and Arizona. In Colorado the South Platte and Arkansas River Valleys and some of their major tributaries also fit this category.

In such valleys, surface water is usually applied to irrigate the lands. A part of the surface water infiltrates to the ground-water body and returns to the stream through drains and by ground-water seepage. The amount of water available for net consumptive use is essentially equal to the difference between the inflow, primarily that brought in by the stream, and the outflow that must be allowed by virtue of prior water needs and rights downstream (and by the necessity of maintaining salt balance). In many such valleys, the valley consumptive use of water exceeds the beneficial consumptive use because of the areas of native phreatophytic vegetation. For example, in 1936 the consumption by irrigated lands in the Middle Valley of the upper Rio Grande was 157,000 acre-feet, whereas the total consumptive use was 583,000 acre-feet (Natural Resources Committee 1938, p. 91).

Streamflow in such valleys is occasionally inadequate for the needs, in spite of regulation by surface reservoirs. Consequently, wells have been installed. As these wells commonly are located at a spot convenient to provide water, evapotranspiration by native vegetation is reduced little if any; accordingly, net consumptive use of the pumped water results in either diminution of streamflow or reduction in ground-water storage, or both. Before pumping is undertaken in most such stream valleys, ground water feeds the streams. After pumping lowers the water table the ground-water accretion to the streams is reduced or, more frequently, the gradient of the water table is reversed so that the stream loses rather than gains water. Water shortages downstream are thereby increased, and individuals downstream who are able also install wells to satisfy their water needs. Because of this extraction from storage, the stream will continue to lose water even after normal inflow to the valley is resumed. Therefore, pumping will be continued until such time as increased efficiency in water use, reduction of nonbeneficial losses, and inflow of excess surface water result in replenishment of ground-water storage.

A study of the effects of pumping in the Rincon and Mesilla Valleys of the Rio Grande in New Mexico showed that pumping would need to be continued for 4 years after a return to normal surface supply following a 5-year period of 50-percent-normal surface supply. In the absence of excess surface water, pumping there would need to be continued, even in years of normal surface supply, unless the debt to ground-water storage could be gradually reduced by more efficient use of the pumped water and the reduction in pumping that would be made possible. It was shown that ground water obtained by pumping in the Rincon and Mesilla Valleys (where losses from areas of native vegetation are small) does not represent an additional supply or new source of water, but rather a change in method, time, and place of diversion of the supply already available (Conover, 1954, p. 2, 122, 126). During the period of shortage of project water supply in the surface reservoirs, individual farmers utilized the ground-water reservoir by pumping of wells. As a natural consequence the ground-water reservoir was replenished later from project water supply by stream losses and infiltration from irrigated lands. Pumping in such circumstances therefore is, in effect, borrowing on future water supplies.

This unplanned, though somewhat effective, use of the ground-water reservoir in conjunction with the surface stream benefits those who have wells but works a hardship on those who have only surface-water rights. Planned development and management of ground water in stream valleys can increase the water supply by salvaging nonbeneficial losses in areas of shallow water and will facilitate using the ground-water reservoir in conjunction with the surface supply to the maximum benefit of all water users. Such planned development and management necessitates locating and pumping of wells in harmony with the surface system. If such is properly done a perennial water supply can result.

Proper location of pumps includes placing wells in areas of shallow water to capture water used by native vegetation, and spacing of wells so that the storage of ground water can be manipulated. Operation of pumps in conjunction with the surface supply entails pumping during periods of deficient surface supply at a rate such that the ground-water reservoir can be replenished during periods of excess surface supply. A fully managed ground-water and surface-water supply not only will maintain but will increase the firm supply because of (a) the savings in evaporation resulting from storing surface water underground, (b) the capture of floodwaters by surface reservoirs made vacant by storing water underground, (c) the reduction of evapotranspiration losses by phreatophytes, and (d) the recirculation of water by pumping.

Because of the large volume of water in underground storage in many alluvial valleys, as compared with the volume of surface reservoirs, a fully managed integrated system would be capable of providing a firm supply that would span climatic cycles a decade or two long. Theoretically, it is possible to control a supply to the extent that no water would be allowed to flow to the oceans. However, such a system is not desirable or feasible, as the salt content of the water would increase and the economy of the region would suffer. A managed system should therefore provide for flushing out excess salt during periods of excess precipitation and runoff.

The population of the 17 Western States is expected to continue to increase at a rate exceeding the national average. The present 43 million population of these States is expected to reach 108 million in 40 years (U.S. Senate Select Committee on National Water Resources, 1960c, p. 9). The need for industrial, municipal, and agricultural water likewise is expected to increase. Competition for the limited water supply will dictate systematic planning, coordination, and integrated development and management of water supplies.

Integrated development and management of surface and ground water will require a better understanding of our ground water resources and the nature and extent of the aquifers. The nature of ground-water investigations is changing as the demand for water increases and the limit of the ground-water resources is approached. Only some 30 years ago most ground-water investigations went no further than to determine the occurrence of water—that is, where could wells be drilled, and what might be their expected yield? The concentrated development of wells in some areas of the West brought questions of well interference and the need for quantitative studies of the effects of pumping. Such questions prompted Theis to develop his well-known nonequilibrium formula in 1935. The trend toward full development of ground-water resources and integration with surface-water development is creating a demand for means of analyzing masses of geohydrologic data and parameters to provide a basis for choosing among alternate plans for aquifer development. Electrical analog models offer promise of providing solutions to complex problems. Development of such equipment for analyzing aquifer systems is now well advanced, and examples of their use are forthcoming. The results will be only as good as the number and quality of data fed into them will permit, however, and in many cases the necessary data will cost a lot of money to acquire.

In summary, optimum development and integrated management of ground waters, singly and in conjunction with surface waters, promises to solve perplexing water problems of the West. But the solution will be neither easy nor inexpensive. The public, as well as those responsible for water-resource development and management, must be informed and convinced of the need and value of such measures. Large sums will have to be spent to acquire the needed information on the ground-water reservoirs and their relation to the streams, and in many States substantial new legislation will be needed to provide the basis for planned water management.

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INT.DUP.,D.C.61 87721