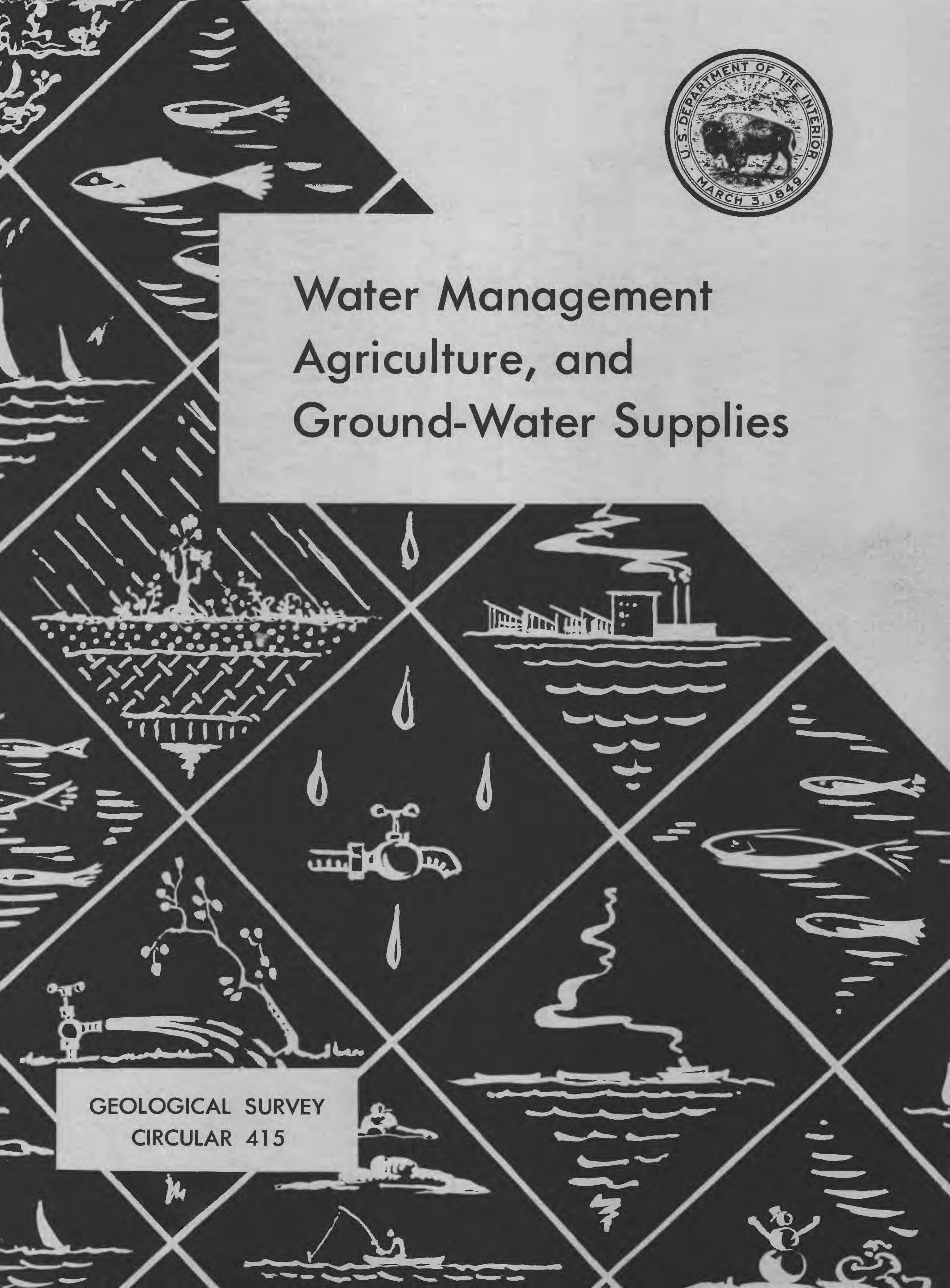
Water Management Agriculture, and Ground-Water Supplies



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Water Management Agriculture, and Ground-Water Supplies

By R. L. Nace

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By R. L. Nace

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ABSTRACT

Encyclopedic data on world geography strikingly illustrate the drastic inequity in the distribution of the world's water supply. About 97 percent of the total volume of water is in the world's oceans. The area of continents and islands not under icecaps, glaciers, lakes, and inland seas is about 57.5 million square miles, of which 18 million (36 percent) is arid to semiarid.

The total world supply of water is about 326.5 million cubic miles, of which about 317 million is in the oceans and about 9.4 million is in the land areas. Atmospheric moisture is equivalent to only about 3,100 cubic miles of water.

The available and accessible supply of ground water in the United States is somewhat more than 53,000 cubic miles (about 180 billion acre ft). The amount of fresh water on the land areas of the world at any one time is roughly 30,300 cubic miles and more than a fourth of this is in large fresh-water lakes on the North American Continent.

Annual recharge of ground water in the United States may average somewhat more than 1 billion acre-feet yearly, but the total volume of ground water in storage is equivalent to all the recharge in about the last 160 years. This accumulation of ground water is the nation's only reserve water resource, but already it is being withdrawn or mined on a large scale in a few areas.

The principal withdrawals of water in the United Staes are for agriculture and industry. Only 7.4 percent of agricultural land is irrigated, however; so natural soil moisture is the principal source of agricultural water, and on that basis agriculture is incomparably the largest water user. In view of current forecasts of population and industrial expansion, new commitments of water for agriculture should be scrutinized very closely, and thorough justification should be required. The 17 Western States no longer contain all the large irrigation developments. Nearly 10 percent of the irrigated area is in States east of the western bloc, chiefly in several Southeastern States.

Ground water is not completely "self-renewing" because, where it is being mined, the reserve is being diminished and the reserve would be renewed only if pumping were stopped.

Water is being mined at the rate of 5 million acre-feet per year in Arizona and 6 million in the High Plains of Texas. In contrast, water has been going into storage in the Snake River Plain of Idaho, where deep percolation from surface-water irrigation has added about 10 million acre-feet of storage since irrigation began.

Situations in California illustrate problems of land subsidence resulting from pumping and use of water, and deterioration of ground-water reservoirs due to sea-water invasion.

Much water development in the United States has been haphazard and rarely has there been integrated development of ground water and surface water. Competition is sharpening and new codes of water law are in the making. New laws, however, will not prevent the consequences of bad management. An important task for water management is to recognize the contingencies that may arise in the future and to prepare for them. The three most important tasks at hand are to make more efficient use of water, to develop improved quantitative evaluations of water supplies and their quality, and to develop management practices which are based on scientific hydrology.

INTRODUCTION

The poor geographic distribution of water in the world is a principal problem in water management. This is very well known. Yet each year many thousands of published words describe the locally poor geographic and seasonal distribution of water as a fundamental point.

Poor distribution of water is strikingly evident on an ordinary geographic map of the world. The total surface area of the earth is 197 million square miles. About 139 million square miles (70.8 percent) is covered by the world's oceans, about 6.9 million (3.4 percent) by polar icecaps and glaciers, about 330,000 (0.17 percent) by natural fresh-water lakes, and about 270,000 (0.14 percent) by natural saline lakes. About 50 million square miles (about

25.4 percent) is continental and insular dry land. The total land area, including that under ice, lakes, and inland seas is about 57 million square miles. More than two-thirds of the land area is in the Northern Hemisphere. Somewhat more than 18 million square miles (about 36 percent) of the land area is arid to semiarid (table 1).

The inequity in water distribution is indeed drastic. Therefore, before discussing water management, it is pertinent to consider how much water we have to manage. Therefore, some typical water problems and situations will be used to illustrate that the optimum effective use of water can be attained only of it is managed in accordance with scientific principles.

TABLE 1. —WORLD AREA OF ARID AND SEMIARID LAND

[Based on data given by Shantz (1956, p. 4-5)]

Class of land	Area (square miles) based on— Vegetation	Climate
Extremely arid (desert)	2,430,000	2,244,000
Arid	12,900,000	8,418,000
Semiarid	2,720,000	8,202,000
Total	18,050,000	18,864,000

WORLD'S SUPPLY OF WATER

The world's supply of water is estimated approximately as follows. The volume of ocean water is about 317 million cubic miles (or 1.07 x 10^{15} acre ft[1]. (See table 2.) The estimated water volume of polar icecaps and glaciers on the continents is about 7.3 million cubic miles (about 2.47 x 10^{13} acre-ft). Fresh-water lakes contain about 30,000 cubic miles (1.01 x 10^{11} acre-ft), and saline lakes and inland seas contain about 25,000 cubic miles (8.7 x 10^{11} acre-ft). The average amount of water in stream channels at any one time is on the order of 280 cubic miles (9.5 x 10^{8} acre-ft).

Based on an ocean area of 139 million sq mi and a rounded mean depth of 12,000 ft (2.27 miles). A mean depth of 12,450 ft is commonly assumed, but recent surveys indicate that the shallow continental shelves are broader than was once believed and the oceans' ridges are larger; so a somewhat smaller rounded value seems appropriate. One cubic mile=3,379,200 acre-ft=1,101,215,599,200 gal.

The main root zone (about the upper 3 feet) of the soil probably contains at least about 6,000 cubic miles of water (2 x 10^{10} acre-ft). The estimated additional amount of water in the rock crust of the earth is about 1 million cubic miles (3.4 x 10^{12} acre-ft) to a depth of half a mile and an equal amount at the depth between ½ and 2 miles.

The estimated volume of moisture in the atmosphere is equivalent to only about 3,100 cubic miles (1.15 x 10^{10} acre-ft) of water, or enough to cover the entire earth to a depth of only about 1.0 inch.

The data summarized in table 2 show that the total world supply of water is somewhat more than 326 million cubic miles. Though the estimates are inexact, they help to define the magnitude of the problem of water management. About 97 percent of the world's water supply is in the oceans. The conversion of salt water to fresh is a great and intriguing challenge. Even though conversion processes become economically feasible, however, the cost of transportation may prohibit the use of converted sea water by inland areas for a long time. Conversion of locally available salt water may become feasible in some inland areas, and may resolve problems that are locally serious. On the whole, however, the available amount of such water is not sufficient to add materially to regional or national water supplies. Therefore, for an indefinitely long future period, inland areas will receive water from the sea only indirectly and in the same manner that they always have—as vapor carried inland in the air and dropped as rain and snow.

The total volume of water on the land and beneath its surface is only about 9.4 million cubic miles. About 78 percent is locked up in icecaps and glaciers, and about 0.27 percent is in inland saline lakes and seas. Much of the ground water at depths greater than half a mile is economically inaccessible at present or is saline. Thus, less than 3 percent of the world's

TABLE 2. —DISTRIBUTION OF THE WORLD'S ESTIMATED SUPPLY OF WATER

[All quantities rounded]

Location	*Surface area (thousands of sq mi)*	*Volume of water (thousands of cu mi)*	*Percentage of total water*
World (total area)	197,000	-----	-----
Land area	57,500	-----	-----
Surface water on the continents:			
Polar icecaps and glaciers	6,900	7,300	2.24
Fresh-water lakes	330	30	.009
Saline lakes and inland seas	270	25	.008
Average in stream channels		.28	.0001
Total surface water	7,500	7,360	2.26
Subsurface water on the continents:			
Root zone of the soil	50,000	6	0.0018
Ground water above depth of 2,640 ft		1,000	.306
Ground water, depth of 2,640 to 13,200 ft		1,000	.306
Total subsurface water	50,000	2,000	.61
World's oceans	139,500	317,000	97.1
Total water on land		9,360	2.87
Atmospheric moisture		3.1	.0001
Total, world supply of water		326,000	100

water supply is available on the continents, and only about 11 percent of the water on the continents, actually is usable or accessible. Furthermore, the yearly renewal and continued availability of this relatively minute supply of water depend wholly on precipitation from a tenuous bit of water vapor in the atmosphere.

THE UNITED STATES' SHARE OF WORLD WATER SUPPLY

The total land area of the 48 contiguous States, including lakes, is somewhat more than 3 million of the world land area of 57.5 million square miles. On a proportional basis, our share of the world ground-water supply in the upper one-half mile of the earth's mantle is about 5.3 percent, or 53,400 cubic miles (180 billion acre-ft). In contrast, large lakes on the North American Continent contain about 8,000 cubic miles, or about one-fourth of all the fresh surface water on the globe.

Precipitation on the 48 States averages about 30 inches (about 2.5 ft) yearly, and the total yearly volume is about 1,370 cubic miles (4.64 billion acre-ft). Natural annual recharge of ground water may average a fourth of the precipitation, or about 340 cubic miles (1.15 billion acre-ft) yearly. This is a liberal estimate, which many hydrologists wold dispute. However, it indicates the order of magnitude of ground-water recharge.

On the basis of the above estimates, the volume of ground water in storage above a depth of half a mile evidently is equivalent to the total of all recharge during the last 160 years. This estimate is very crude, but whether the true figure is 50, 100, or 200 years is unimportant. The significiant fact is that a reserve of water has been accumulating in the ground-water bank for generations. This is the only real water reserve we have. Annual recharge in any one year is proportionately a very small increment to the total reserve. Now, by pumping, we are placing heavy drafts on the local "branch banks" in some parts of the United States—enough that the manager of the "main bank" must look

Figure 1—Number of acres irrigated in the United States in 1954, by States. The total irrigated area was 29,552,155 acres of a total cropland area of more than 400 million acres.

to the total reserve and estimate how long the drafts can continue. This is the job for water management.

USE OF WATER

Total water use commonly is estimated in terms of diversions from streams and pumpage from the ground, ignoring the principal use of water—the water derived directly from natural soil moisture. The soil moisture demand for nonirrigated farm land is met largely and directly by precipitation. The water demand for irrigation is, in fact, a demand to increase and maintain soil moisture. Only 7.4 percent of our cultivated land is irrigated (fig. 1), yet withdrawal of water for irrigation about equals industrial wihtdrawls (see fig. 2), and exceeds them if we include conveyance losses in irrigation. Since natural soil moisture is the principal source of water for agriculture, agriculture gets incomparably the largest share of the yearly water supply, even without irrigation.

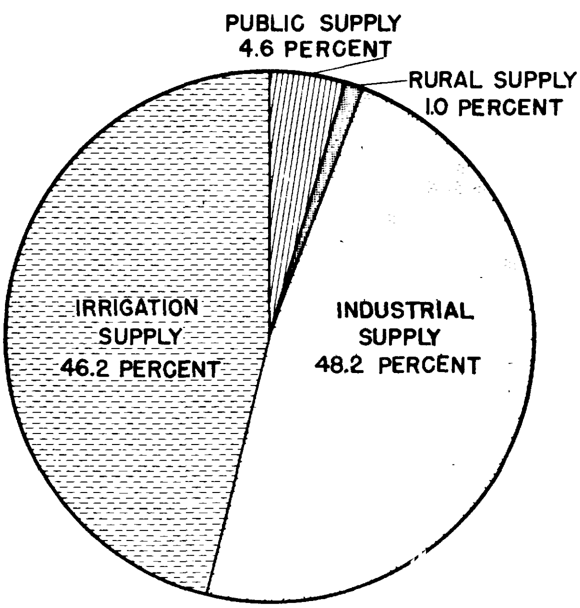

Figure 2—Use of water in the United States in 1958. The use in 1955 was estimated (MacKichan, 1955, p. 16) at 210,500 million gallons per day plus 28,900 million gallons per day conveyance losses in irrigation. In the diagram, total use in 1958 is estimated at 240,000 million gallons a day, not including conveyance losses of 32,400 million gallons a day.

There is nothing wrong with the use of soil moisture by agriculture, especially because we have no other way to use soil moisture. Looking to the future, however, and to the increasingly narrow margin between water supply and water demand, perhaps management and economic and legal authorities will begin to scrutinize very closely all new commitments of water for agriculture. From the standpoint of optimum water use, perhaps the best place to expand agriculture is in areas where its water demand can be met largely and directly by natural soil moisture.

TRENDS IN WATER USE

Trends in water use also deserve close scrutiny. For example, the practice of irrigation is increasing rapidly in the humid Eastern States. We still speak of the "17 Western States" as the home of irrigation; yet more than 9 percent of the total irrigated area in the United States is east of the bloc of western States. Irrigation has become widespread in Florida, Mississippi, Louisiana, and Arkansas, and several other Southern States are developing irrigation rapidly. We now have to reckon with 21 "irrigation States." Extensive use of water for irrigation in the Southeast may become directly competitive with the current trend toward industrialization in that region.

MINED WATER IS NOT SELF-RENEWING

Water is commonly called "a self-renewing natural resource," because a new supply is furnished each year by rainfall. Actually, only the yield of streams and the dependable perennial yield of aquifers is self-renewing. Withdrawn ground water is fully renewed by natural recharge only at places where withdrawal does not exceed the dependable perennial yield. Where the accumulated reserve of ground water is being depleted, the reserve would be renewed only if withdrawals were stopped. Mining of water, in effect, is a gamble by society that some major scientific accomplishment, such as weather modification or desalting of saline water, will provide a new or added source of water when the mine goes dry. In the present state of knowledge, the odds in this gamble cannot be calculated.

SOME SAMPLE WATER SITUATIONS

Texas withdraws about a fifth of all the ground water used in the United States (Sundstrom, 1957). Ground water is the sole source of supply for nearly 600 towns and cities in the State, which is second only to California in the volume of ground-water withdrawls. Use of ground water in Texas for all purposes increased twentyfold in the last 18 years and tenfold in the last 8.

Of the total ground water used in Texas, about 83 percent is for irrigation, 7 percent for industry, 6 percent for municipal supply, and 4 percent for rural domestic and stock supply.

Out of 8 million acre-ft of ground water withdrawn in Texas in 1956, about 2 million acre-feet was intercepted water that otherwise would have been discharged by natural means. As withdrawals increase in the future, the proportionate draft on ground-water storage will increase.

An irrigation survey of the High Plains of northwestern Texas (Sherrill, 1958) showed that 4,752,570 acres was irrigated in that area in 1958 (fig. 3), all with ground water and water from small local lakes. Out of 45,522 irrigation wells, 33,766 were lifting water more than 125 feet. More than 1,000 new wells were added in that year. The phenomenal growth of pumping coincided with a 10-year drought in that part of Texas, and the drought obviously supplied a strong stimulus to ground-water development.

Runoff is very small in the High Plains area, and most of the water supply is underground. About 6,348,000 acre-ft of water was pumped in this area in 1956 (Texas Board of Water Engineers and others, 1958, p. 28–29). Pumpage in 1958 probably was about 7 million acre-ft.

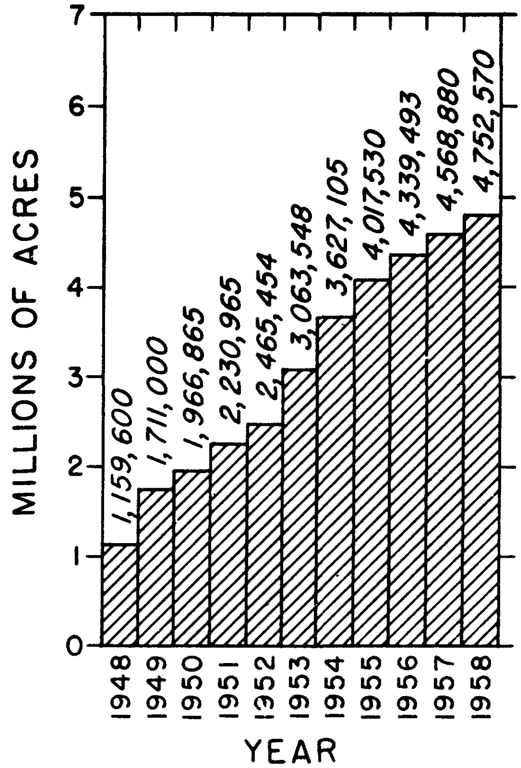

Figure 3—The irrigated acreage in the High Plains of Texas increased 362 percent in the 10 years after 1948.

The principal bulk of pumpage since the beginning of pumping (mostly since 1948), was a draft on reserve storage because natural discharge of ground water has not lessened appreciably. The increasing draft on ground water is reflected in increased pumping lifts and lowered yields from wells (fig. 4). Water is being mined rapidly in this area. Unquestionably, the mining is profitable now, and this kind of operation is self-regulating to some extent. As pumping lifts increase and well yields decline, costs rise and economic factors may force a balance between water supply and water use. The balancing may entail social and economic adjustments. To what extent can management aid orderly adjustment and assure optimum use of the water?

Quite a different situation has developed on the Snake River Plain of Idaho, where irrigation development, using water from the Snake River, became rapid soon after 1909. The plain was underlain by a very large body of natural ground water, overflow from which was discharged through springs into the Snake River below the irrigated area. Excess irrigation water that was applied to the land filtered into the ground, joined the ground-water body, and was discharged through the springs. The capacity of the ground-water reservoir was so great that water levels did not generally rise much, but the average aggregate rate of discharge from the springs increased from about 3,800 cfs to about 5,500 cfs in a quarter of a century.

A somewhat specialized situation prevailed in the Twin Falls (south side) tract on the Snake River Plain, where ground water originally occurred only at considerable depth. During the first 25 years of irrigation on this 200,000-acre tract, the water table rose 200 to 300 feet and at least several hundred thousand acre-feet of water went into underground storage.

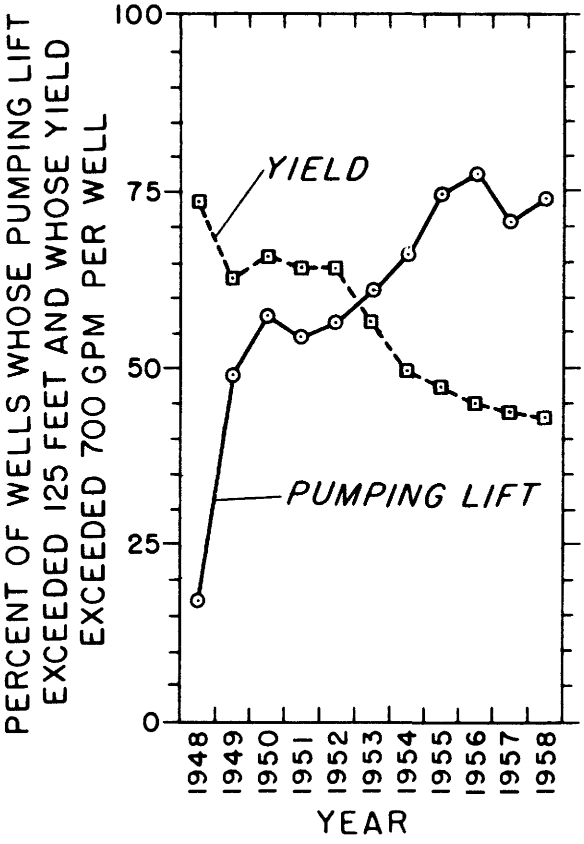

Figure 4—In 1948 there were 8,356 wells in the High Plains of Texas; only 17.5 percent of these lifted water more than 125 feet and 74 percent yielded more than 700 gallons per minute per well. In 1958 the number had increased to 45,522 and the percentages had changed to 74 and 43 respectively.

Water was not mined on the Snake River Plain. It was put in the bank. The increase in storage beneath the whole plain was on the order of 10 million acre-feet. This was not planned; it merely happened as an incident to irrigation with surface water. Further irrigation expansion is under way, using water from the ground, including extensive private developments and the first large Federal reclamation project that is based on ground-water irrigation.

Consider the tremendous capacity of the basalt aquifer in the 10-million acre area of the plain east of the longitude of King Hill, Idaho. Normal precipitation on this plain, averaged for the entire area, is about 10 inches. In much of the area the amount is only about 7 inches. Probably, less than an inch of precipitation, on the average, becomes direct recharge—about 680,000 acre-feet yearly. Most perennial replenishment of the ground water is by underflow from adjacent highlands. The estimated volume of saturated aquifer is 10^{10} acre-feet, in which the estimated total water content is 2×10^9 acre-feet. This is roughly a thousand times the combined storage capacity of all the surface reservoirs on the Snake River, above King Hill —one of the most completely regulated large rivers in America. Much of this ground water is in capillary pores and could not be extracted by gravity drainage into wells. The extractable volume probably is about 5×10^8 acre-feet, or about 135 times the storage capacity of the surface reservoirs.

The currently unconsumed perennial yield of the aquifer in the Snake River Plain is about 4.2×10^6 acre-feet. If spread out in the zone of saturation east of King Hill, this water would occupy a thickness of only 8.4 feet, or about 1 or 2 percent, of the aquifer. All the remaining water is potentially recoverable and is in what amounts to "dead storage." Of course, only part of this water is effectively available, but this area offers a tremendous opportunity for scientific water management.

Entirely different problems are illustrated in California. Among many situations created by pumping, two are chosen to illustrate the diversity of water problems: land subsidence caused by dewatering of aquifers; and intrusion of sea water into fresh-water aquifers in certain coastal areas.

Land subsidence has occurred widely in the San Joaquin Valley of California, and less widely in the Sacramento and Santa Clara Valley areas. The rate of subsidence in recent years has been as much as 0.8 foot per year, and this subsidence in some areas is attributed to lowering of the artesian head in pumped aquifers (Poland and Davis, 1958). Little imagination is needed to visualize the consequences of subsidence in terms of disturbed drainage and irrigation systems and other effects. Factors other than dewatering of aquifers also cause subsidence of the land, as is shown by several examples in California. Wetting of noncompacted soil and subsoil by irrigation has caused compaction and subsidence in the Central Valley. Subsidence has deranged certain canal systems in the Central Valley. Oil-field development at Long Beach has caused subsidence, and some land in that area is now below sea level.

Sea-water invasion of aquifers is a common problem in coastal areas of many seaboard States. Invasions of sea water in about 20 ground-water basins along the coast and inland bays of California have been observed for about 35 years (Baumann, 1953, p. 521). Not until 1950, however, were systematic experiments begun at Manhattan Beach, Redondo Beach, and El Segundo to combat the invasion by creating a fresh-water mound or ridge, inshore from the sea, to retard or stop the invasion. Two methods were used: recharging the aquifer through spreading grounds at Redondo and El Segundo to sustain water levels generally, and recharge through batteries of injection wells at Manhattan Beach, to create a ground-water mound—a barrier to invasion. The results from small-scale water-spreading, were inconclusive; those from recharging wells were more positive. Much remains to be done in California and many other places, to rescue aquifers from marine invasion and to forestall further invasion.

THE MEANING OF WATER PROBLEMS

The few examples given above of widely contrasting situations emphasize the basic fact that water development in the United States has been mainly a laissez-faire process, in accord with the individualistic tradition inherited from the pioneers. Surface-water users commonly have been forced by the high cost of construction to join hands in development projects. Most ground-water users have gone independent ways. Each class of users tends to regard its source of water as distinct from the others. In many areas, however, overdevelopment is now forcing recognition of the unity of water as a single resource. For example, a water authority in one Western State recently ruled that permission to pump new wells in a certain area would be conditioned on concurrent purchase and release of rights to an equal amount of surface water.

The situations here described illustrate that development which is based on a selfish philosophy leads to situations which could be avoided because we have at our disposal the scientific knowledge needed for the guidance of water management. Certain highly developed areas in the Southwest today face a situation which eventually will confront all highly developed areas that depend heavily on ground water: water is being withdrawn at a rate that cannot be continued indefinitely, yet the demand is increasing. What is the future of these areas after the recoverable reserve of ground water is exhausted? The High Plains of Texas has or will have this problem. Will the plains one day revert to their native condition?

A reverse and favorable situation exists in the Snake River Plain, which contains what is probably the largest naturally unified water system in North America. The reserve of ground-water storage has been building up unseen, owing to irrigation, and today the ground-water resource is virtually undeveloped. The area offers a great opportunity for scientifically guided development and management of the total water resource.

The situation in southern California also has some important lessions. Although the problems of salt-water encroachment have been appreciated and studied for many years, no permanent or general solution has been found. Much of the scientific knowledge and data necessary for solution are available, but management in many parts of the country is not sufficiently sensitive to scientific principles to attempt effective use of them. This leads us to the real problem for water management.

THE CHALLENGE TO WATER MANAGEMENT

Reportedly, there are more than 500 principal local water-supply agencies in the United States, and there is a host of minor ones. Texas alone has about 500 water agencies, including irrigation districts and other small agencies. Each State has several State agencies with responsibilities for water, and about 25 Federal agencies have important responsibilities or concern with water. All these agencies have made and are making decisions and taking actions that commit water or affect its quality and availability. Some of these decisions and actions may have prejudiced the future.

Several recent forecasts indicate that the national water requirement will double by 1975 or 1980. In how many States could withdrawal be doubled? How could the withdrawals be made? What will be done if such withdrawals are not possible?

In view of forecasts of the national water demand, some commentators say that our main problem is where to get the water and still have enough for expansion in the next generation. But is it? Three things seem more important: more efficent use of the water we already have developed; improved quantitative evaluation of water supplies and their quality; and scientific management.

MORE EFFICIENT USE OF WATER

Projections of history are the basis for most forecasts of future water use. But history is an index of the future only in those things over which we exercise no control. With scientific water conservation and management and more efficient use of water, most of or all the increased demand during the next 10 to 20 years might be met without material increase in our gross water demand.

During the 40 minutes, it takes to read this paper, about 100,000 acre-feet of water has flowed from the United states back into the sea from whence it came. How much did we get out of it before it returned to the sea? Water uses in the United States are generally rather lavish, though there are some notable specific exceptions. Abundant data show that many current uses of water are wasteful, some extremely so.

In one area in the arid West, comprising 1 million irrigated acres, the water diverted for irrigation, averaged for the whole area, was about 6.6 feet in the 1957 water year. Some districts in the area used up to 10 feet of water. On the other hand, the potential evapotranspiration in that area, computed by the Thornthwaite method, is about 2.2 feet. About 0.2 to 0.4 feet of the requirement is supplied directly by precipitation, and only 1.8 to 2.0

feet is needed from irrigation. Thus, the efficiency of water use is about 30 percent or less. Increasing the efficiency even to 50 percent would free enough water to irrigate more than 600,000 acres of new land—more new land than seems to be suitable for irrigation in that area. The whole potential irrigation expansion in this area by, say, 1975 could be met without additional gross water demand. In this area, much of the excess irrigation water gets into the ground-water reservoir and is available for reuse. But it is not necessarily available at the places where it could best be used. Moreover, the cost of pumping could be avoided by more effective use of the water while it is still at the surface.

A few miles from the area just considered, in an area having about the same potential natural water demand, farmers irrigate some crops successfully with less than 2.0 feet of water and pride themselves on their ability to make a crop with what others would look upon as a starvation ration of water.

QUANTITATIVE EVALUATION OF WATER SUPPLIES

A recently published report on ground water states that "only after years of development may the effects of overdevelopment become evident." Similar statements appear in many reports. They are true in the present state of knowledge. But "after years of development" is too late. To determine "the effects of overdevelopment" is to determine the course of history—to describe a problem without solving it. The "solution" applied "after years of development" often is the adoption of some drastic control or of some new law.

Some water planners now advocate drastic changes in State laws and policies about water rights. Rather than grant rights in perpetuity, they would assign rights for consuming uses of water for terms of say 10 or 25 years; rights for nonconsuming uses might be for 25 to 50 years.

These are signs of the times, and new laws undoubtedly are needed. But laws will not 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. Generations might be required to rehabilitate a contaminated aquifer, because ground water moves very slowly. New laws will not prevent the consequences of bad management. So the first need is not laws but intelligent management.

Many people seem to believe that our main problem is to locate ground-water supplies. This was true a generation ago, but it is true no longer. Although techniques can be improved, we have good methods for locating water supplies and can find them just about wherever they exist. The real problem of today is twofold: to determine the quality of water and its quality; to manage the water in accord with principles of hydrology. The continuing problem is how to manage a total water supply, a small part of which is perennially self-renewing, but which is largely a nonrenewable resource.

SCIENTIFIC MANAGEMENT

Water—all water—is a single resource. Almost everyone knows that pumping from a flood plain near a river can deplete the flow of the river. But this is only a small part of the problem. Pumping anywhere affects the total available water. Management requires the study of whole regions, not merely of basins or districts.

Another example will illustrate the point—namely, the 11-county tristate area adjacent to the lower Delaware River, including Philadelphia, Pa., Camden and Trenton, N. J., and Wilmington, Del. Barksdale and others (1958, p. xii) estimate that current withdrawal of ground water in the region is somewhat more than 200 million gallons per day. More than 1 billion gallons per day could be developed within the region, and additional water could be developed outside the region and imported if the need arose. The report shows that recharge from the Delaware River, induced by heavy pumping, contributes a substantial part of the total ground water now drawn from the Raritan and Magothy formations. Increased pumping of ground water would increase recharge. Therefore, maintenance of good quality in the river water is necessary, both for its own sake and to preserve the quality of the ground water.

Deepening of the Delaware River channel from Philadelphia to Trenton, which has been proposed, would increase the opportunity for interchange of water between the river and the adjacent aquifers. Whether this would be beneficial or detrimental to the quality of the ground water would depend on the quality of the water in that reach of the river. River water of acceptable quality would augment the ground-water resources of the region. If salt water from the ocean or contamination from other sources depreciates the quality of the river water, actual and potential ground-water supplies aggregating about 250 million gallons per day would be endangered. Therefore, a proposal has been made to construct a low dam on the river near the head of Delaware Bay, to prevent incrusion of salt water.

This kind of situation calls for aggressive, intelligent management, and the report that has been cited outlines a scientific basis for developing management plans as further scientific studies continue.

"Management through knowledge" should be a watchword. Management of ground water and surface water jointly as a unit resource should be expanded and continued. Each kind of water has peculiar advantages. What are the advantages in this case or that? How do we apply hydrology to the profitable use of water so as to safeguard the total resource? How can efficiency of use be improved?

Joint management of surface-water and ground-water storage is an especially efficient scheme of management. But management—including legal principles—fails to permit this because stored ground water cannot be reserved for withdrawal solely by intended users.

New techniques have been proposed, such as rain-making, salt-water rectification, and evaporation suppression. We could review and assess their place in the future. But at long last this conclusion is inescapable: There is no panacea for problems; no hydrologic magic will substitute for scientifically sound hydrologic management.

THE ULTIMATE CRITICAL PROBLEM

Many means are available for conserving water supplies and making less wasteful use of them. Rather than add to the voluminous literature on this topic, it seems to be more important to clinch one fact: The ultimate critical water problem of the United States—and of the world—is ground-water supply. This is fairly obvious from table 2; the rough estimates of which are sufficiently realistic to warrant sober reflection.

The yearly disposition of rainfall on the United States probably is somewhat more than one-third each to runoff and soil moisture, and about one-fourth to ground-water recharge. Each part is the total we can count on having perennially for human requirements. Eventually, our water use will approach the total recoverable from precipitation; we will convert salt water to fresh on a large scale; and we may have some control of the weather to increase precipitation. Meantime, we will have drawn heavily on the accumulated reserve of ground-water storage. As is shown by table 2, ground water in natural storage is our principal reserve in fresh water, and for a long time to come the extent to which we can conserve and manage that reserve will be the deciding factor in development.

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