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CONTINUED UTILIZATION OF GROUND-WATER STORAGE BASINS[1]

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Doubtless most of you are more familiar with surface reservoirs, their capabilities and limitations, than you are with ground-water reservoirs. I believe that this is true of people in general, even the experts. And because of our inadequate knowledge of ground-water reservoirs, our use of them creates problems that are rarely if ever encountered in the operation of surface reservoirs. Nevertheless there are many similarities between these two basic forms of water storage, and I should like to point out some of these similarities, as well as some important contrasts.

Actually the chief distinction is that the ground-water reservoirs are filled with rock materials, which in many instances are similar to the sediment which Mr. Brown[3] has shown to be a common disease and ultimate cause of death of surface reservoirs. The sediment carried by most streams is too fine in texture to make a good ground-water reservoir, but nevertheless the water storage in those sediments is appreciable. In Lake Mead on the Colorado River, for instance, the coarse sands that have formed a delta where the river enters the lake are

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1/ Approved by the Director, U. S. Geological Survey, for presentation at the Third World Congress of the International Commission on Irrigation and Drainage at San Francisco, April 29, 1957.

2/ U. S. Geological Survey, Menlo Park, Calif.

3/ Brown, Carl B., Factors affecting the useful life of reservoirs. (Preceding paper presented at Third World Congress of the International Commission on Irrigation and Drainage) ~~at San Francisco, April, 1957)~~

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saturated as the reservoir level rises, and unwatered as the level falls. Because of the water-storage space within these sediments and in other permeable materials forming the bed and banks of the reservoir, the aggregate usable capacity of Lake Mead is about 12 percent greater than the amount calculated from reservoir surveys.

Both surface and subsurface reservoirs hold back water from precipitation that might otherwise flow to some ocean or inland basin within a few days after each storm. And, in either type of reservoir, if we do not use the water, it will either fill the reservoir to overflowing or it will return to the atmosphere by evapotranspiration. Thus we can lose water by not using it. True conservation of water--utilizing it to serve the greatest good of the greatest number in the long run--involves many factors. The efficient operation of reservoirs is one important factor, and the one to which I am limiting myself in this paper.

For efficient management of a reservoir, either of surface water or ground water, one should know the reservoir capacity and have a continuing inventory of the storage in the reservoir, and of the inflow and outflow. And one should know these factors well enough to enable him to anticipate the future and to plan future operations accordingly. With respect to these basic data there is a marked contrast between surface and subsurface reservoirs. Generally we have considerable knowledge concerning these several items at the time we begin to utilize water from a surface reservoir, but this is not true for most ground-water reservoirs. The explanation is, of course, that we must construct a dam before we can fill a surface reservoir, and because of the investment involved, considerable effort is expended in obtaining the data essential for efficient reservoir operation, before any water is used from the reservoir. By contrast, ground-water reservoirs are formed and filled by nature to overflowing before man begins to use the water from them. With a relatively small investment for well drilling, he can develop and use water without bothering to learn anything about the reservoir that is furnishing that water. And for those who would like some measure of the adequacy and sustained yield of ground-water resources, there are the deterrents that the essential data are more difficult and more expensive to collect, and, in the present status of the science of ground-water hydrology, they often provide less definitive answers than do the data pertaining to surface reservoirs. not always

Partly because of this meagerness of basic data on ground water, of ground-water reservoir management commonly runs into difficulties that are rarely encountered in the operation of a surface reservoir. Among these might be mentioned reservoir depletion, where the inflow is insufficient, at least locally, to sustain the ~~aggregate~~ withdrawal by wells~~—in some reservoirs there is a similar depletion in areas of concentrated pumping, even though the inflow to the reservoir is ample to sustain this pumping~~; and deterioration of water quality ~~during~~ resulting from attempts to stop the natural outflow and divert it for beneficial use. It is true that some surface reservoirs have been constructed on the assumption, based on inadequate data, that the inflow would be larger than it acutally turned out to be, and some have run into difficulties because of unexpectedly large ~~unforeseen outflow through~~ discharge by evaporative ~~processes~~ or ~~or~~ by seepage through permeable materials beneath the reservoir, but such difficulties are comparatively rare. Suffice it to say that we have not begun to obtain essential data concerning many ground-water reservoirs until a crisis has developed. Sometimes scientific study has turned up a solution for the problem that will permit perennial utilization. Sometimes development has gone too far, and retrenchment is indicated. But even with an adequate program of collection and analysis of essential hydrologic data--so that we know what has happened ever since the beginning of development and can predict accurately the effects of existing and proposed additional withdrawals--optimum and perennial utilization of a ground-water reservoir is not necessarily assured.

Perennial Use Based on Natural Inflow

Once we have a sufficient mass of hydrologic data, a traditional technique is to derive averages from them. Thus we can compute mean monthly or annual rainfall, average stream discharge, average discharge from a ground-water reservoir, and mean water levels in wells. These averages indicate central tendencies, but alone they are not definitive of the water resources. Average figures are only handicaps if they lead to concepts that the "average" condition--whether flow in a stream, water level in a well, or volume in a reservoir--is something that should be maintained at all costs. As long as precipitation deviates from the average, other elements in the water-resource picture also must also vary.

A major reason for our dependence upon reservoirs--surface or underground--is the great deviations in water supply, especially precipitation and runoff, from the long-term average. The reservoirs, by providing space for storage of the widely varying quantities of natural inflow, should permit us to withdraw water in accordance with our needs, subject to the limitation that, if the reservoir is to serve our purposes perennially, the average withdrawal cannot be greater than the average inflow.

Utilization of surface reservoirs depends upon stopping the natural flow down the channel by damming it, and diverting the water to points of use. Continued utilization of ground-water reservoirs similarly requires diversion of water that would otherwise flow from the reservoir naturally, but this is all done by gradient changes. Pumping in a well or well field lowers the water level until water flows toward the pumps from other parts of the reservoir, instead of toward the natural outlet. Eventually the natural discharge from the reservoir is reduced, or the recharge is increased, or both, but the initial stage of development is likely to involve removal of a considerable volume of water from "permanent" storage, and this will be shown by declining water table or artesian pressure.

In the efficient operation of a fully developed ground-water reservoir, water can be taken and utilized at a fairly uniform rate even though there is great variation in the seasonal and annual rates of recharge. The withdrawals can approach the long-term average rate of inflow, reduced by the amount of natural discharge that is <u>not</u> intercepted. It is a necessary corollary that at some times the sustained withdrawal will exceed the contemporaneous recharge, and the storage in the reservoir will be reduced, perhaps to a small proportion of the storage prior to development. Here is a second situation where the water table or artesian pressure will decline, even under efficient development and operation of a ground-water reservoir.

This is as far as we can go without bringing people into the discussion. Water must abide by certain physical principles, but people are guided by their own special interests, by traditions, and by coded laws and unwritten laws. Although people accept variations in storage in surface reservoirs as an essential part of effective operation, the human reaction to "falling water tables" is almost universally condemnatory. The early users of ground water are understandably averse, because they initially had the advantages of the naturally full and overflowing reservoir--springs, subirrigation, flowing wells, minimum pumping lift--and all these are lost as reservoir storage is reduced. Any lowering of water level means increased cost to well owners, in drilling deeper wells and in pumping water from greater depths. Conservation-minded people who do not depend upon ground water also are likely to favor maintenance or restoration of the natural conditions of full ground-water reservoirs. And some court decisions have indicated that maintenance of a certain minimum water level or artesian pressure is a legitimate attribute of a water right.

Here is where the hydrologist needs all the basic data he can muster, and sufficient analysis of them so that he knows what they signify. He must be able to show whether a specific reservoir has been developed and is being operated so that it becomes part of a modified hydrologic cycle, capable of sustaining the developed yield or even an increased withdrawal perennially; or whether withdrawals are so great that they can be sustained for only a few years or decades. If he finds the latter to be true--that is, the developed demand exceeds the perennial supply--the alternatives are to reduce withdrawals and use of water, or to import water from regions of surplus.

Importation of Water

It is possible to sustain perennially an economy in which the water requirements exceed the natural supplies available locally, by importations from more abundantly watered regions. Importation brings up a major question, which is more in the realm of philosophy than of hydrology: Shall the Water go to the People, or Shall the People go to the Water? Generally people in humid regions would say that those who want water should be located where water is available according to their needs--and if they want lots of it, choose the largest rivers or lakes. People who glory in the continuous sunshine of arid regions are just as fervent in their feeling that water should be delivered to them to meet their requirements. Right now we in California are engrossed in a question arising in the California plan to transport water from surplus areas in the northern half of the state for use in the water-deficient southland: Who shall have priority to this water, and if and when there is insufficient water to satisfy all, which region is to be guaranteed water? In a broader sense, the people in all arid regions depend at least in part upon water that originated as precipitation somewhere else. Here in the western United States we live in the water-deficient lowlands rather than in the more humid mountainous areas.

If the question is answered affirmatively as to whether importation and artificial addition to local water resources are permissible, storage may be provided in either surface or ground-water reservoirs. Cyclic storage in ground-water reservoirs is an important part of the

California water plan, and it is likely to be of increasing importance in many other places. Artificial recharge of ground-water reservoirs is therefore a subject of increasing importance and interest. Although some artificial-recharge projects have been unsuccessful, and suggest that we need to know much more about recharge, there is abundant evidence that we have increased recharge in many places. Irrigation with surface water has resulted in increased storage in underlying ground-water reservoirs in many places in the West, and "evaporation" pits for oil-field brines have added water, unfortunately ~~but unavoidably~~ salty, to some ground-water reservoirs. Where several individuals have rights to water from a certain reservoir it may be necessary to prove that the operations by one of them have resulted in artificial recharge, and how much. This would not be difficult if the recharge is through wells leading directly into the reservoir, but the effects of pits, ponds, surface channels or ditches, spreading basins, or "over-irrigation" would need to be evaluated quantitatively.

Nonrenewable Storage

The water in some ground-water reservoirs constitutes a nonrenewable resource. An outstanding example that comes to mind is the High Plains south of the Canadian River in Texas and New Mexico, where the ground water in storage is estimated to have been initially of the order of 400 million acre-feet, but where the average replenishment is a hundred thousand acre-feet a year or thereabouts. We are now mining that water at a rate approaching 6 million acre-feet a year.

The High Plains are admittedly exceptional in some respects: a fossil land surface now cut off by erosion from the Rocky Mountains that produced the source materials for them, and a fossil ground-water reservoir which if emptied would require ~~thousands~~ many hundred of years to refill at current rates of recharge. But throughout the West there are ground-water reservoirs in arid basins, which are similar in that ~~where~~ the volume of fresh water in storage is many times--even hundreds of times--the average annual replenishment under the climatic conditions that have prevailed in recent centuries.

Here, as with the surface reservoir sites, comes the question of timing--whether in the interests of civilization in the long view we should not reserve some of these irreplaceable stores of water for future generations. The answer of the present generation, as of the generations preceding it, has generally been that it will take advantage of the natural resources as it finds them and has need for them. In the High Plains, for instance, where climate and soils are suitable for a permanent grazing agriculture but where there is sufficient water to permit only one or two generations to reap the profits of irrigated cotton, the decision has been in favor of the present generation reaping those profits. The saving factor for future generations is that Nature seems to be able to hold back some of her secrets for them.

The areas dependent entirely on nonrenewable water storage have a time limit to their use of water, determined simply by dividing the total volume of stored water by the net annual depletion in storage. Their hopes for permanency of water supply depend upon our success in getting more water to the area than Nature now provides, perhaps by weather modification, perhaps by importation of fresh water from other areas or by importation of demineralized ocean water.

Here I should like to modify my statement that the present generation has decided in favor of using nonrenewable storage for its own advantage, because it is likely that few people are aware that there was any decision to make. The manner of development and utilization of natural resources is a matter for all society to decide, and therefore a matter of national and state policy. Policies have been fairly well defined with respect to various aspects of development and use of water resources, but especially as to ground water we are hampered by our inadequate understanding of the capabilities and limitations of specific reservoirs. As a result, development may proceed for several years before we become aware that one reservoir has been yielding water entirely from nonrenewable storage, another from storage that is replaced each year, and still another from storage that is replaced only in years of excessive precipitation or runoff.

Filling of Reservoir Space

Ground-water reservoirs have some of the problems mentioned by Mr. Brown in his discussion of surface reservoirs. For example, some of the storage space in ground-water reservoirs can be filled by sediment, though not in the same way. The evidence of this is in subsidence of the land surface. There has been a substantial subsidence of land overlying ground-water reservoirs in half a dozen areas in California, and also in Texas and Nevada. This subsidence may be so gradual and extensive that residents in the locality are not aware of it. And doubtless subsidence has occurred in other areas of intensive pumping from wells, and we will learn of it only by releveling to bench marks whose elevations were determined prior to the intensive ~~development~~ pumping. The subsidence in many areas results from compaction of sediments that ~~had been saturated, but were~~ have been partially unwatered by the pumping.

It is possible that some of this storage space may be regained if the sediments are resaturated, but more probably ~~that~~ there has been some permanent loss of reservoir space because of the compaction. We need to know more about the mechanics and effects of subsidence, and research on the problem is now in progress by the U. S. Geological Survey in cooperation with the California Department of Water Resources. It is likely that we may have to accept the loss of some reservoir space through compaction and subsidence--like the loss of surface reservoir space by sedimentation--as one of the unavoidable costs of reservoir utilization.

Some of the storage space within ground-water reservoirs may also be filled with undesirable or unusable water, derived perhaps from an ocean or saline lake, or from a formation bearing saline water, or by the infiltration of water contaminated during nonconsumptive use, or of waste waters. There is some analogy here to surface reservoirs, where the stored water becomes more mineralized during periods of minimum inflow and progressive loss by evaporation. However in surface reservoirs the undesirable water can be more easily drained out or made usable by mixing with inflowing water of better quality. Thus, the inflow of undesirable water to a ground-water reservoir is a more serious and ~~permanent~~ longer lasting problem.

Nonconsumptively used waters in arid regions merit special attention. Such waters include especially the return seepage or return flows from irrigation, and also the sewage and waste waters from cities and industries. These waters can be reused, perhaps several times, but their quality deteriorates with each use. In humid regions these waters, when they become unsuitable for further use, may be discharged into surplus waters flowing out to sea. In many places, however, particularly in arid regions of interior drainage, these contaminated waters may find their way into ground-water reservoirs. We are aware of the importance of maintaining a suitable "salt balance" in irrigated soils, and to do this some water must be reserved for the purpose of carrying off the saline residues and disposing them where they cannot contaminate our resources of fresh ground water or surface water.

Conjunctive Use of Surface and Subsurface Reservoirs

Surface and ground-water reservoirs serve the same broad purpose of holding back the water provided by precipitation at highly varying rates, and releasing it more in accordance with human needs. Certainly in many places, and probably as a general rule, this broad purpose could be better achieved by conjunctive operation of the two types of reservoirs than by their separate and independent operation. In fact, such conjunctive operation can overcome some of the difficulties encountered in operation of multipurpose surface reservoirs, and also in pumping so heavily from subsurface reservoirs that reserves are seriously depleted.

In surface reservoirs constructed for flood control, the prime requisite is space to hold the flood runoff of heavy storms, and that space must be emptied as soon as one flood is past to be ready for the next flood. Wherever this water can be used for artificial recharge of a ground-water reservoir, the water is conserved and can be made available for future requirements.

As pointed out by Mr. Brown, surface reservoir sites are a limited resource. On some streams they are so limited that only a part of the average annual runoff can be stored. Wherever ground-water reservoirs are available to accept some of this runoff, they serve an important purpose in conservation. The surface reservoir, by receiving water at highly variable rates and releasing it at rates more suitable for recharge, is an essential part of the conjunctive operation. Conjunctive operations may also reduce some of the conflicts of interests of various types of water users--those who want water released during the growing season for irrigation, or throughout the year for municipal or industrial use, or at varying rates in accordance with hydroelectric power demand, or maintained at certain levels in lakes for recreation. Wherever water released for various purposes can be stored in ground-water reservoirs, it may be made available to other users when they need it, which may be months or years after the time of release from a surface reservoir.

Wherever the annual evaporation greatly exceeds precipitation--that is, in any arid region--there is a ~~net~~ water loss from surface reservoirs due to evaporation. Thus, even with a maximum of surface storage facilities, we cannot save and use all the water that flows into surface reservoirs, and ~~this is characteristic of~~ unfortunately the loss is greatest in the places where water is most in demand and most valuable. Here the conjunctive use of ground-water reservoirs, if available, promotes water conservation, for the water stored underground ~~can be~~ is largely, or even entirely, beyond the reach of evapotranspirative processes. Ground-water reservoirs constitute the only means of conserving a major portion of runoff in desert regions for future use, because about half that runoff is likely to be lost from surface reservoirs, either by overflow of small ones, or by evaporation from those large enough to capture the water from maximum floods.

Summary

I believe that to the question assigned to me, whether we can hope for continued utilization of ground-water reservoirs, I can answer a qualified "yes." The word "continued" presupposes the existence of the ground-water reservoir, which I interpret as meaning permeable, saturated rock materials capable of yielding water to wells in quantities suitable for irrigation or for industrial or municipal use. Such reservoirs probably underlie only a minor fraction of the total land area of the earth, and thus we are speaking of areas that probably total considerably less than half of each continent.

The qualification to the affirmative answer is that our present scientific understanding indicates effective management for perennial use to be possible; but effective management requires detailed hydrologic data that we do not now have for the great majority of ground-water reservoirs, and it requires also an awareness on the part of the public and government that the alternatives are depletion and eventual exhaustion of fresh ground-water resources, and in many places, contamination by brines or other unusable water.

The affirmative answer is a generalization for ground-water reservoirs as a group, and this is a composite group with tremendous diversity and variation among its individual members. When the question is asked as to the possibility of perennial utilization of specific ground-water reservoirs, the answer may range from yes to no, with all degrees of certainty or doubt. For some ground-water reservoirs there is hydrologic evidence that their perennial utilization can be assured, for others there is evidence that the resource will be exhausted or become unusable within a limited period. The potentialities of many ground-water reservoirs are shadowed by doubts, and will need the light of more hydrologic information and analysis before they can be determined.

We know that the haphazard development of ground water by individual initiative, which has been characteristic at least in the United States, has not been conducive to the most efficient operation of ground-water reservoirs. In some places efficient operation will require different well locations and different rates of draft from those now extant. And many ground-water reservoirs can be more fully utilized if their natural replenishment is supplemented by artificial recharge whenever surplus water is available. This brings us to the benefits that may be realized by conjunctive management of surface and ground water, and reservoirs for each, with the objective of providing water for the greatest benefit to mankind.

In conjunction with the need for adequate hydrologic data as a basis for effective reservoir operation, there is need for education of the public concerning these data, and for greater understanding by all concerned of the physical principles involved in efficient operation of ground-water reservoirs. In many localities the water users and their lawyers, rather than the present unplanned pattern of development and use, are the chief deterrents to effective utilization of a ground-water reservoir.