This is important since none of the subsurface contributions from the watersheds could be measured. Could the entire outflow of the basins have been measured we might well expect to find even greater increases in runoff both during and after the storm period.

To test the effect of the treatment on peak discharges, unit discharges were computed for these flows and were plotted as ordinate and abscissa on a graph of A versus B discharges in second-feet per acre. This is shown for the Diamond Range watershed in Tehama County in Figure 5. The locus of the points indicate that a slight increase in unit discharges has been effected by the treatment. This has not been the case in all of the study areas.

It appears evident from these considerations that vegetation management may have a significant effect upon the runoff characteristics of watershed so treated. The data available at the present time are only for small watersheds ranging in size from less than one to approximately twenty acres. Current studies include watersheds up to 4,000 acres in area which will, we believe, give a more realistic picture of the situation since the larger areas will permit the inclusion of all runoff and not just the surface components. As was suggested earlier the scope of vegetation manipulation for watershed management is rapidly developing. Should this program become of large enough scale to include major portions of stream systems, it will be necessary to recognize these facts in the utilization of streamflow records. Further studies along these lines are now under way and will be continued in an effort to isolate in great detail the effects of various watershed management practices on the hydrologic characteristics.

MAXIMIZING RIVER BASIN BENEFITS BY CONJUNCTIVE OPERATION OF SURFACE AND GROUND-WATER RESERVOIRS

by

Frank B. Clendenen[1]

Much has been said about the great conflict of reservoir purposes in water resources development. This is due primarily to the competition among these purposes for the limited storage capacity. Students of water resources development are familiar with the difficult proposition of affording flood control along with conservation, power generation, and recreation on a storage scarce stream. Flood control desires empty reservoirs while the interests of the other three purposes require the opposite; a highly paradoxical situation. The solution has taken the form of a compromise with the calculation of an operation schedule to maximize the benefits of the reservoir. Thus an operation schedule with a variation in flood control reservation with time, thereby releasing such reservation for conservation wholly or partially when the dangerous season is past, is the usual compromise on California Sierra streams. From a second examination of these four principal purposes of western water resources development it is apparent that actually, if sufficient storage were available, these purposes are not at odds. Conservation desires the control of all waters for beneficial use, flood control desires the control of all peak flows and is fully satisfied if they can all be detained in storage; hydroelectric power generation favors full reservoirs for scheduled release; and recreation interests are best served by increased water surface area of reservoirs and firmed minimum flows in streams. These all are benefited by storage of water. This is an obvious point; yet at times in the planner's quandary over proper allocation of existing or proposed storage capacity he seems to forget this point.

Storage capacity being in large part the solution to problems of water resources development, it behooves the developer for the future to inventory water storage capacity and requirements to determine proper planning for future development. In California this immense task has been performed by the California Department of Water Resources. The future requirements for water have been compiled and presented in State Water Resources Board Bulletin No. 2 and the inventory of

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water and storage capacity are found in State Water Resources Board Bulletins number 1 and 3 respectively. These investigations found the quantity of water sufficient for ultimate purposes but surface reservoir capacity sadly lacking. The major areas of reservoir shortage are the Central Valley where sufficient water originates but economic surface storage capacity is not obtainable and the South Coastal area where topography has provided insufficient surface storage sites for local development let alone the needs for controlling the great quantities of imports required for ultimate conditions. The Colorado Desert and the Lahonton Areas lack surface storage capacity to regulate imports that are needed for their development. California is blessed indeed, having in each of these areas great quantities of ground-water storage capacity. Of the estimated 100 million acre feet of useable ground-water storage capacity contained within a 200 foot depth in the Central Valley only about one-third will be required for ultimate needs if this storage capacity is operated in conjunction with the surface reservoirs. The quantity of subsurface reservoir capacity required in the South Coastal area is readily available but as for the Colorado Desert and Lahonton Areas while there appears to be ample capacity in their valley alluvium, further investigation must be made prior to firm estimates of such capacity.

It is therefor a fact that in many regions where surface storage is insufficient for present or future water resources development requirements ample ground-water storage capacity is economically available. If this additional storage capacity could be utilized in the same manner as is surface storage the principal purposes of: water conservation, flood control, power generation, and recreation could all be met with a high degree of mutual satisfaction. Of course, ground-water reservoirs differ markedly from surface reservoirs in many respects. The main differences of economic significance generally faced in ground-water reservoirs are:

1. Slow rate of filling or recharge.
2. Low rate of discharge requiring consumption of energy.
3. No associated power generation.
4. Little evaporation loss.
5. Tremendous magnitude of storage.
6. Water quality problems.
7. "Stored" water is usually moving.

Because of these listed differences in ground-water reservoir characteristics relative to surface reservoirs, the method of operation must vary accordingly. Conjunctive operation of surface and ground water reservoirs is the term applied to that operation of all project reservoir capacity resulting in maximum project economy, all factors considered. Efficient economic operation has always been the criterion of water resources development, but in connection with use of ground water reservoirs this criterion has not always been maintained. For the most part ground-water development has been accomplished by individuals with little conception of ground-water hydrology. Perhaps the main factor in maintaining rather independent operation of surface and subsurface reservoirs has been the different system of water rights that has developed for ground water and surface water. All reservoir development has been by appropriative rights while ground-water rights are correlative for overlying land owners. Thus the rather familiar problem of the appropriator developing a surface water supply with neighboring pump operators taking the project seepage without sharing in the surface development cost has developed. Because a project frequently needs deep drainage by pumps and since early developers did not plan on using this seepage there has been little conflict in the past. In fact, this was the beginning of conjunctive operation. But now with the surface appropriator needing to use ground-water reservoirs for further stream regulation, problems have evolved. Generally the problem is solved, or rather left at a state of compromise, where the surface water developer relys mainly on surface firm yields with some adjunctive ground-water use, while the ground-water pumper continues to develop what he can. The result is that the ground water reservoir is not operated according to plan. Actually the subsurface reservoir ends up regulating the annual project seepage and the natural recharge. With conjunctive operation the ground-water reservoir will in addition do much cyclic storage of surface stream flows.

With respect to conjunctive operation how are the four main purposes of water resources development affected?

Water Conservation

Great storage capacity and little evaporation make ground-water reservoirs exceptionally well suited for cyclic storage. Slow rates of recharge greatly limit storage efficacy as in most areas where additional storage is needed water development has proceeded to the state where the remaining water occurs sporadically in great volumes for short durations. Thus we have the adverse relationship of slow acceptance by the vast cyclic storage reservoir with the great volume to be stored occurring for short durations. The obvious solution is to use surface storage capacity which has in most cases no limit to its recharge capacity for regulating the greater flows of the surface streams with transfer of storage to the ground-water reservoir as rapidly as economic recharge will permit. In such a manner a high degree of conservation can be obtained. Such a conjunctive operation of surface and ground-water storage capacity would vary among projects and with time in schedules of surface discharge, ground-water recharge, pumping and other functions of operational features according to the pertaining economic conditions.

But here is another paradoxical situation. Usually where increasing water development needs are being felt most all available surface storage capacity has been appropriated for the usual type surface operation wherein firm water yields and firm power production is sought with reservations for flood control and with no plan for producing a greater firm yield by operation in conjunction with ground-water storage capacity. Initial stages of conjunctive operation of projects planned for ultimate requirements might well be operated for firm power and water yields from the surface reservoir as the object of conjunctive operation is the greatest net benefit for the project for the time in question. The problem that presents itself is that of assuring future water resources development by insuring the required flexibility for future conjunctive operation. Eventually, when economics dictate, the smaller firm yield of the surface reservoir must be reduced for the greater conjunctive yield of surface and subsurface reservoirs. Unless the flexibility that will be ultimately required is stipulated in initial project planning, rigidities of ownership and ensuing from practice might make it extremely difficult to obtain the greater yield.

Flood Control

As with conservation of water, flood control requires storage capacity with practically no limit on recharge rates for controlling sudden great stream flows. Usually there is a limited amount of economic surface storage capacity available and flood control has to share this capacity with the other reservoir purposes. With conjunctive operation most cyclic storage is performed in the ground-water reservoir thereby the surface reservoir is relieved of this function resulting in freeing a great capacity for additional flood control purposes. The conservation of all flood waters would completely satisfy both purposes but in most cases, even with conjunctive operation, some spill will occur during flood periods because of limited economic storage capacity. Therefor with conjunctive operation surface reservoirs will start each flood season at much lower stages than would obtain with conventional operation. During the critical flood danger months of November and December greater protection from floods would exist.

The great value of accurate stream forecasting to conjunctive operation cannot be over emphasized. With such forecasts water can be retained in surface storage for power generation and surface water distribution during dry years. Conversely during wet years, surpluses can be efficiently received and disposed with minimum spill.

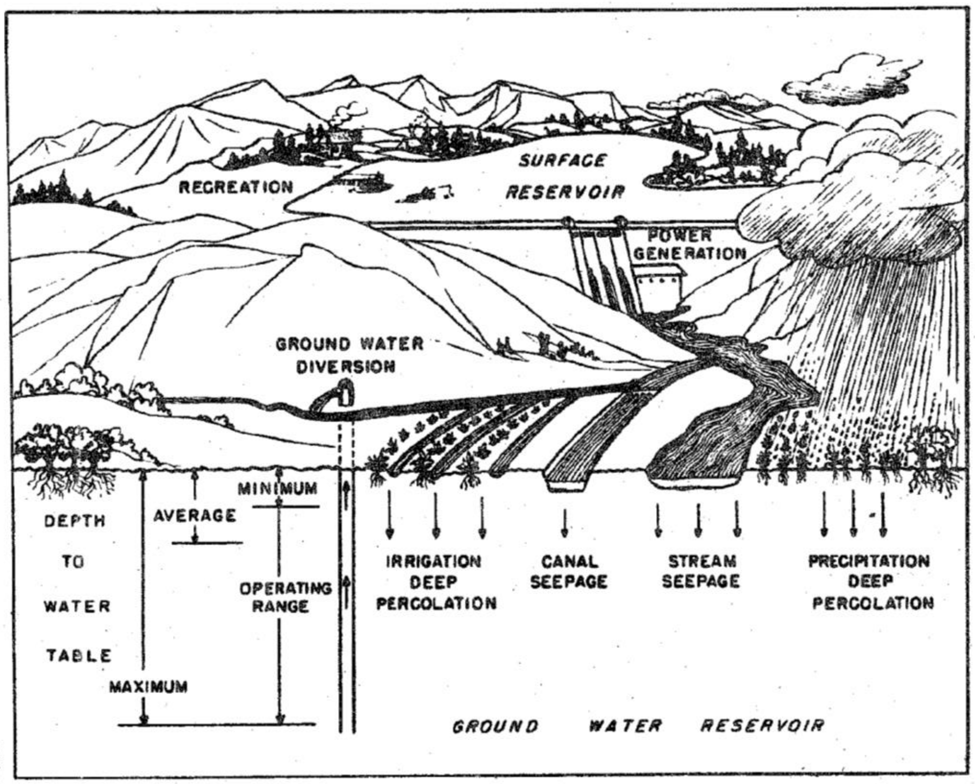
Hydroelectric Power Generation

A basic tenet of conjunctive operation is the placing of surface storage into the ground-water reservoir as fast as economically feasible to make available empty reservoir capacity for river control. This reduces power value in two ways. First, the lowering of stage reduces the head on the power plant. Second, the performance of cyclic storage in the ground-water reservoir decreases the firm yield of power to that of the minimum flow year.

A compensating factor favorable to power generation is the much greater quantity of regulated reservoir discharge within the installed capacity of the power plant. Thus if there could be pumped storage to regulate the untimely occurrence of the power and to firm the dry year production the power value would be enhanced. Surface reservoir releases to coincide with pump power requirements and to cut off the peak of the seasonal requirement would decrease both the need of installed pumping and power generating capacity. Total effect of conjunctive operation on power values is dependent on the various economic factors and could be favorable as well as unfavorable.

Recreation

Discharging surface reservoirs to near empty stages every year is not advantageous to recreational use. Nevertheless for the same quantity of surface water developed there is less change in surface storage per year with conjunctive operation than with surface storage alone. Since ulti-



ELEMENTS OF CONJUNCTIVE OPERATION

PLATE I

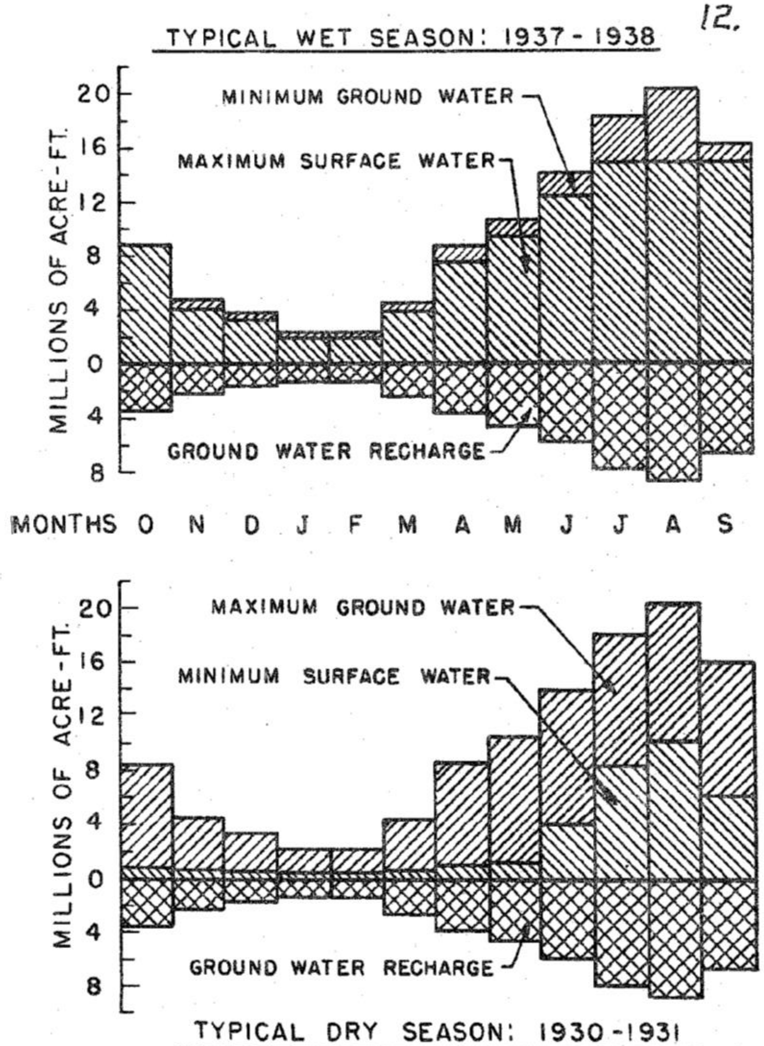


PLATE 2 VARIATION OF SURFACE AND GROUND WATER DIVERSION CONJUNCTIVE OPERATION:
EAST SIDE SAN JOAQUIN VALLEY

mately all economic surface reservoir sites will be used, the actual difference in recreational values will be small and assuming ultimately, if not now, that water will be the critical item its development will have to take precedence over recreation. As with conservation, during initial stages of development reservoirs can be kept near full to increase recreational and power benefits.

From this brief analysis it appears clear that conjunctive operation of basin or project storage capacity is the means of maximizing river basin benefits. A significant advantage of conjunctive operation is its adaptability to stage development. Surface reservoirs not lending themselves to stage development generally should be constructed to ultimate size. Thus in the initial stages of development surface reservoir operation would differ little from that of the usual operation. Only after the firm yield of the surface reservoir and its attendant ground water development have reached their full use would the firm yield of the surface component be reduced to increase the conjunctive yield.

In considering values under ultimate conditions it appears certain that water conservation and flood control will out-rank hydroelectric power and recreation. Since water will still originate on the mountain slopes and be used primarily on the valley floor, power generation will increase with development regardless of manner of operation. In a similar manner most all reservoirs are recreation centers notwithstanding the manner of operation and since the number of more attractive mountain reservoirs constructed principally for power development will increase, recreational use of water resources will increase as population pressure grows.

Conjunctive operation of surface and ground-water reservoirs is dependent on two important rates of water movement relative to the subsurface reservoir: (1) into storage, recharge and (2) discharge, usually pumpage from the reservoir. The latter, discharge, has received much attention and is fairly well cared for; recharge, though it has been practiced for many years, has only recently received attention commensurate with its importance to resources development. This operational feature is generally the bottleneck in conserving water in ground-water reservoirs. One reason for the difficulty, as has already been explained, is due to the manner and duration of occurrence of undeveloped water and the lack of reservoir capacity for its regulation. Under conditions of conjunctive operation most recharge occurs as incidental recharge.

Recharge has been classified as natural and artificial. Artificial recharge being that attributable to man's activity. Artificial recharge can be divided into deliberate and incidental. Deliberate artificial recharge occurring as a result of activity performed for recharge and incidental artificial recharge being a by-product of an activity performed for some other purpose. As depicted in Plate 1 natural recharge is the deep percolation of unconsumed precipitation and stream seepage. Deliberate artificial recharge may be achieved by several means: (1) stream modification and controlled flow (2) spreading ponds, basins, or ditches, (3) wells and shafts of various types, (4) controlled pumping to induce greater inflow and (5) operation of distribution systems and reservoirs in off-season periods. Incidental artificial recharge may be a by-product of: (1) irrigation, as deep percolation (2) water conveyance, as ditch, pipe, stream and reservoir seepage and (3) of ground-water pumping, as induced inflow from streams and other sources by steepened hydraulic gradients.

The development of a pump pattern throughout a service area and a distribution system such as to enable water service from either the ground-water or surface reservoir transforms incidental recharge from a constant source of drainage water to a great recharge device. Thus during wet years most of the area is served from surface supplies with only the minimum pumping thus placing most all incidental recharge along with natural recharge in storage while in dry years, when the cyclic storage is needed to provide that which is lacking on the surface, ground-water supplies are drawn upon. Plate 2 depicts a wet and dry year operation. The operational technique is in large part dependent on accurate stream flow forecasts.

In the preliminary studies included in the ground water appendix to California State Water Resources Board Bulletin Number 3, commonly known as "The California Water Plan", no deliberate artificial recharge was resorted to in conjunctively operating the entire Central Valley ground-water storage capacity to provide for ultimate needs. It must be noted that this study was performed on a regional basis and that therefore there probably are areas within the large regions where the regional average rates of canal seepage and irrigation deep percolation used, do not obtain; thus deliberate artificial may under ultimate conditions be an important facet of operations in this valley, even as it is now.

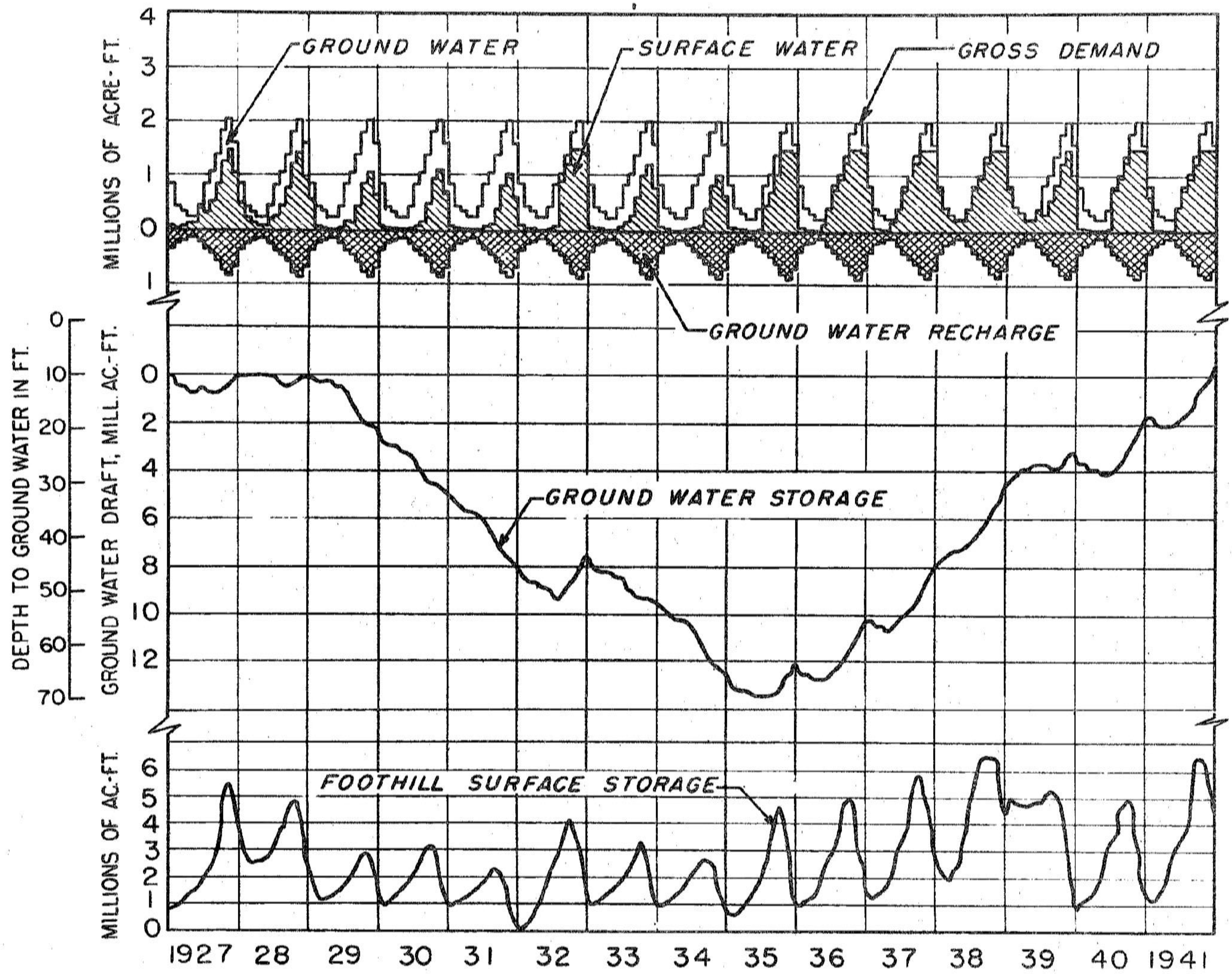


PLATE 3 CONJUNCTIVE OPERATION OF SURFACE AND UNDERGROUND STORAGE OF THE SAN JOAQUIN VALLEY EAST SIDE

Plate 3, "Conjunctive Operation of Surface and Ground-water Reservoir of the San Joaquin Valley Eastside" depicts the monthly operation for the water year 1927 through 1941 for an area from the Mokelumne river south to and including the Kern river. The area was designed to require about 11.5 million acre feet annually which is ninety percent of the mean annual impaired foothill runoff of these streams. As can be seen in Plate 3, conjunctive operation obtained this high degree of conservation with only 6.5 million acre-feet of foothill surface because of the 13.8 million acre feet of ground-water storage capacity used. Upstream storage affords some regulation.

It appears quite certain that conjunctive operation of all basin storage capacity is not only the means of maximizing river basin benefits but for regions similar to California's Central Valley is the only way ultimate water requirements can be economically provided.

RESERVOIR EVAPORATION CONTROL

By

Raymond E. Kerr, Jr.1/

It is particularly appropriate to discuss the subject of evaporation from reservoirs at a meeting involving the Colorado River hydrologists, since the stimulation for some of the most useful work on evaporation that has been published stemmed from the evaporation problem in Lake Mead. The interesting and effective work on evaporation control now under way at the Bureau of Reclamation Engineering Laboratories in Denver was fairly directly initiated by situation in Lake Mead. I shall return to a discussion of the role played by these investigations in a later part of this paper.

My purpose at this time is to give a general background and review of the current state of the science of evaporation control and the hope that we may hold out for effective application to large reservoirs. I make no pretense at being a qualified chemist and much of the future work to be done lies strictly in the domain of chemical engineering. However, we do believe that evaporation is a subject that lies in the proper domain of the meteorologists and that there is a serious contribution that we can make to the full attainment of the efficient application and maintenance of an evaporation reducing film.

The civil engineer can provide many methods of known and unquestionable efficiency in the reduction of evaporation losses simply by reducing the ratio of the exposed water surface to the total volume of water contained. Where evaporation rates are known it is a simple matter to calculate the cost-benefit ratio and to determine the economical alterations to the engineering design of the reservoir and its collection and distribution systems in view of the present and predicted cost of water. Reduction of the surface-to-volume ratio may be accomplished by deepening the reservoirs, filling the banks higher with water, eliminating shallow area, and so forth, and this ratio may be reduced to zero by roofing. Roofing is, of course, expensive and generally uneconomical except in small reservoirs where sanitation is also an important factor, and in practice not as effective as the theory would indicate. Furthermore, the multiple use of many reservoirs complicates the application of these methods, even where the cost-benefit ratio is favorable. For example, a chain of shallow lakes would provide far better conditions for recreation and for wild fowl than would a single steep sided reservoir. Every surviving hydrologist has learned the power of various organizations of sportsmen and wild life conservationists.

The use of polyethylene sheets, perhaps laminated with other materials to increase its efficiency as a vapor barrier has been suggested as a possibility of considerable merit. Although the mass production of this material is lowering the cost to the point where this procedure may become economically feasible, the objection in the case of multiple purpose reservoirs remains, since it would obviously frustrate the ducks should they decide to alight on a polyethylene covered lake.

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