THE COMPARTMENTED RESERVOIR: A METHOD OF EFFICIENT WATER STORAGE IN FLAT TERRAIN

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ABSTRACT/SUMMARY

The compartmented reservoir is presented as an efficient method of storing water in areas having a relatively flat terrain where there is a significant water loss through evaporation. The flat terrain makes it difficult to avoid large surface-area-to-water-volume ratios when using a conventional reservoir.

This paper demonstrates that large water losses through evaporation can be reduced by compartmentalizing shallow impervious reservoirs and in flat terrain concentrating water by pumping it from one compartment to another. Concentrating the water reduces the surface-area-to-water-volume ratio to a minimum, thus decreasing evaporation losses by reducing both the temperature and exposure of the water to the atmosphere. Portable, high-capacity pumps make the method economical for small reservoirs as well as for relatively large reservoirs. Further, the amount of water available for beneficial consumption is usually more than the amount of water pumped for concentration.

A Compartmented Reservoir Optimization Program (CROP-76) has been developed for selecting the optimal design configuration. The program was utilized in designing several systems. Through the use of the model, the interrelationship of the parameters have been elucidated. These parameters are volume, area, depth, and slope of the embankment around each compartment. These parameters interface with the parameters describing rainfall and hydrologic characteristics of the watershed.

The water-yield model used in CROP-76 requires inputs of watershed area, daily precipitation, daily and maximum depletion. In addition, three sets of seasonal modifying coefficients are required either through calibration or estimated by an experienced hydrologist. The model can determine runoff from two types of watersheds, a natural and/or treated catchment. Additional inputs of CROP-76 are the surface water evaporation rate and the amount and type of consumptive use.

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Because of the large number of parameters it was found that repeated runs of the model are necessary to determine a near optimum design in a reasonable amount of time. The model computation time for the CDC 6400 computer for a 45 years length of record is less than ten seconds per run for the usual design. Usually no more than four or five computer runs were needed for design purposes. CROP-76 was used on several typical systems including a water harvesting agrisystem. The following general observations were made: (1) The rate of increase of efficiency of storage decreases as the number of compartments increase; (2) there was no significant difference in evaporation loss by varying the relative size of compartments provided the side slope, depth, total number of compartments and the total combined volume remained constant; (3) the increase in efficiency due to the use of the compartmented system decreases as the depth of the reservoir increases, becoming insignificant for depths of 20 or more meters; and (4) the use of a compartmented reservoir provides efficient storage for a water harvesting agrisystem.
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INTRODUCTION

The need for a low-cost, efficient method of water storage in semi-arid and arid lands has long been recognized. The high evaporation loss coupled with flat terrain has prevented economical water storage except in rare instances where favorable reservoir sites are available. These favorable sites in most parts of the world have been utilized but the demand for water is far from satisfied and will continue to increase in the future.

IMPORTANCE OF IMPROVED STORAGE OF WATER

The importance of improved water storage can be verified easily by aerial flights over dry areas prior to the onset of the rainy season. These flights reveal that most small storage reservoirs are dry or close to it. An examination of many of these reservoirs by the author in Arizona and northern Mexico, as well as West Africa, has revealed that the average depth generally is less than the average annual water evaporation rate. This condition prevents withdrawal of water on a constant-rate basis and any chance of carry-over storage from one year to the next.

The importance of constructing deep reservoirs has long been known but there are several constraints which normally have prevented the construction of deep reservoirs. These are:

1. The grade of the bed of the contributing stream. Any conventional storage must be below the bed.

2. Shallow soils. These make excavation difficult.

3. Construction equipment. The equipment has constraints which restricts the depth.

4. Seepage control. This becomes more difficult in deeper reservoirs.

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5. Erosion control on the steep banks. The problem increases with deeper reservoirs.

6. Safety constraint. Unless excavated, deeper reservoirs pose more danger to downstream occupants than shallow reservoirs.

7. Financial constraints. Deep reservoirs usually cost more money per unit-volume of storage than shallow reservoirs.

The dozer tractor commonly is used for constructing small reservoirs. The deeper a dozer excavates into the ground the greater is the unit cost. It has been the author's experience, when using a 1:2 embankment slope, that building a reservoir deeper than six meters is very expensive. This six-meter depth is usually accomplished with a three-meter cut combined with a three-meter embankment. Due to the constraint imposed by the grade of the stream the upper bank generally serves no useful purpose other than as a spoil area; hence, the effective depth is three meters or less.

The efficiency of storage is defined as the percent of water going into storage that is available for a desired beneficial use on a fixed demand basis. This efficiency can be increased by reducing evaporation loss. As indicated in the literature review in the next section, some research has been done on evaporation control which indicates that the costs of such control in general are prohibitive for use in some major applications such as conventional agriculture.

This study shows the advantages of controlling evaporation loss through the use of the compartmented reservoir. Using this system, the surface area to depth ratio is reduced by keeping the water concentrated. The increase in average depth reduces the amount of solar energy input into the reservoir as well as the exposure to the atmosphere thus reducing evaporation loss.

Figure 1 is a schematic drawing of a three-compartmented reservoir system. The reservoir consists of a receiving compartment which is called A. This compartment is located below the stream grade and therefore is usually shallow. Compartments B and C are shown as being smaller in surface area but deeper in depth. This reservoir is operated as follows: As runoff occurs during the rainy season, water is pumped from compartment A to fill compartments B and C. Water is first withdrawn for consumptive use from compartment A until the evaporation and seepage losses from B and C are equal to the remaining water in A. At this time, the pump is used to move the remaining water in A to fill the unused capacity of B and C. This eliminates further evaporation and seepage losses from A. Water is then withdrawn as needed for consumptive use from B until the water remaining in B is equal to the unused capacity in C. At this time, the pump is used again to move the remaining water from B into C. This eliminates further evaporation and seepage losses from B. At this point, C is filled and A and B are empty. A spillway would be needed from compartment A to protect the safety of the system. All inner dikes would have to be built higher than the maximum water level determined by the elevation of the spillway.
The compartmented reservoir concept can be applied to existing reservoirs or new ones. Since a pump will be used in flat terrain, all compartments other than the receiving compartment can be made deeper by building the embankments above the stream grade.

The recent development of portable, low-lift, high-capacity, tractor-operated pumps makes the compartmented reservoir system economically attractive. These pumps are powered by the power-take-off (pto). They are available in capacities of up to 5000 cubic meters per hour. One pump can service several small reservoirs. If tractors are not available a suitable vehicle such as a British Land Rover could be equipped with a pto and used to both transport and power the portable pump.

If the general slope of the topography is greater than three or four percent, the concept of a gravity-fed compartmented reservoir can be used. The compartments of this reservoir are separated by a sufficient distance to develop enough hydraulic head so that one compartment can be completely drained by a gravity pipeline or an elevated canal into the second and succeeding compartments. This reservoir system could be operated as before but without a pump.

Surface storage reservoirs in semiarid regions are usually fed by intermittent flood flows. However, in some cases, there may be a base flow going into compartment A. In this case, the base flow would be used to satisfy consumptive demands. The remainder, if any, could be pumped into storage on a continuous basis.

THE POTENTIAL OF THE COMPARTMENTED RESERVOIR

The potential of the compartmented reservoir is demonstrated in Figures 2 and 3 under idealized conditions.

Figure 2 illustrates the use of compartments of equal size in a reservoir of depth equal to the evaporation loss. The reservoir is assumed to be filled by runoff only once a year, with no additional input. In this figure and Figure 3, an annual evaporation depth (zE) of 1.636 meter (m) is used. This is the evaporation for Parras, Coahuilla, Mexico and is close to the evaporation loss in Tucson, Arizona. It is less, however, than the evaporation in other parts of the world. A constant consumptive use that would be withdrawn each month is selected so that there would be no water remaining in the reservoir at the end of the year. This value is determined by trial and error. It is called the maximum constant consumptive use. For the single compartment (the typical reservoir) this consumptive use value is zero. When the depth of the reservoir is equivalent to the annual evaporation loss is is impossible to withdraw any water on a continuous basis since all the water would be consumed by evaporation.

The efficiency can be increased beyond those shown in Figure 2 if all compartments, other than the receiving compartments, are made deeper. This is possible due to the use of the pump. This improvement in efficiency due to deepening is shown in Figure 3 for a three-compartment
Figure 2. Evaporation Loss for Compartmented (but undeepened) Reservoirs with a Constant Volume and Area, a Maximum Constant Consumptive Use and a Depth Equal to Annual Evaporation Loss.
Figure 3. Evaporation Loss in Percent of Total Initial Storage for Compartmented Reservoirs with Constant Volume, Varying Depth and a Maximum Constant Consumptive Use.
If the depth of B and C are doubled and quadrupled the efficiency goes up to 68 percent and 80 percent respectively. This is contrasted with zero percent for the shallow single compartmented reservoir.

The above illustrations are idealized in that the reservoirs are filled once a year with no additional input. If seepage is controlled, the same savings would apply regardless of the total size of the reservoir system. It is readily apparent that the compartmented reservoir concept can be applied to reservoirs of all sizes, from small, livestock watering tanks to large reservoirs for agricultural use.

The amount of pumping required in a compartmented reservoir is relatively low compared to the water savings effected. For instance, the three-compartmented reservoir, with all compartments equal in depth to the evaporation loss, illustrated in Figures 2 and 3, requires the pumping of 20.8 percent of the initial storage to obtain a 42.5 percent efficiency when the water is used on a constant basis. This amounts to pumping 48.9 percent of the water beneficially utilized. This assumes that the water can be withdrawn by gravity flow for use from all compartments. The cost of pumping would be generally much less than pumping groundwater due to the low pumping lift.

The full concept of the compartmented reservoir was conceived by the author in the summer of 1975 while serving as a consultant for the Wunderman Foundation in the Sahel Region of Mali in West Africa. At this time an earlier concept of pumping from a shallow to a deeper compartment was expanded to include multiple compartments and repeated pumping. The discovery was made at this time that significant savings could be made just by dividing a reservoir into compartments and keeping the water concentrated. Deepening all compartments other than the receiving one was found to increase the efficiency.

The concept evolved as an attempt to help solve a critical water storage problem in Mali, Africa. Ten different sites were surveyed and recommended designs were made using a small programmable calculator (Cluff, 1975). Following his return from Africa, the author spent six months in Mexico working for the Food and Agricultural Organization (FAO) of the United Nations (Cluff, 1976) in support of the Fundo Candelillero, an action agency of the Mexican Government. Eleven compartmented reservoirs were built by the above agencies in the state of Coahuilla, Mexico, during the six-month period the author served as a consultant. More have been built since that time. These reservoirs range in size from a 8,100 m³ two-compartmented livestock reservoir dug by mules, to a 200,000 m³ four-compartmented reservoir constructed using D-7 dozers. This largest reservoir which is used for agricultural purposes is shown in Figure 4. One small gravity-fed separated compartmented reservoir also was constructed.

The use of the compartmented reservoirs introduces additional design parameters for effectively using and storing water from any given watershed. The number of compartments and their depth and size relative to each other must be considered in order to maximize production of water from any given watershed. These parameters are a function of the seepage and evaporation losses. If needed, a floating cover can be used on the last compartments.
Figure 4. Four Compartmented Reservoir System near Parras, Coahuilla, Mexico, with a 200,000 m³ Capacity. -- Above: Under Construction. Below: Completed System.
COMPARTMENTED RESERVOIR OPTIMIZATION PROGRAM (CROP-76)

A computer model has been developed to study the parameters involved in the compartmented system and their relationship to each other using historical data. This model is briefly described in this section, with examples of its use. A more complete description can be found in Cluff (1977).

The computer model converts daily historical rainfall data into runoff data from either a natural and/or a treated watershed. Runoff data is summarized and stored in a weekly array. The compartmented reservoir is subjected to a domestic and/or agricultural demand as well as evaporation losses. The design parameters of the compartmented reservoir can be adjusted so that the "optimum" reservoir system would be selected. The definition of an optimum reservoir is "the system that would have the highest storage efficiency under the constraints imposed." The definition of the storage efficiency is the percent of water that passes into the storage system that is available for a desired beneficial use on a constant demand basis.

In the operation of the model the design parameters are usually adjusted so that the amount of overflow plus excess water is kept below a specified amount, usually 4 or 5 percent. An additional constraint is the requirement that the reservoir system is required to provide water for the desired beneficial use for a specified minimum, usually 95 or 96 percent of the time. The consumptive demand is reduced if necessary in order to fit the above constraints.

A water harvesting agrisystem option has been built into CROP-76. Under this option a soil moisture-accounting routine is used to account for storing water in the soil in addition to storing excess water in the compartmented reservoir system.

There are too many design parameters to obtain a satisfactory design in a single run of the computer, within a reasonable processing time. The design, however, can be obtained by repeated computer runs by a skilled operator who helps the computer in its selection of the parameters that will meet the constraints.

The 76 was added to the CROP acronym of the model since it was developed in 1976. It also serves as a reminder that there are additional improvements that can be made. However the model has been used to design compartmented reservoirs systems using a minimum amount of data. The model has been used on seven reservoir systems in Arizona, Coahuilla, Mexico and Mali, West Africa. These systems ranged in size from a 6,000 m³ stock tank to a 90,000,000 m³ reservoir system in Arizona designed to store excess floodwater in the Santa Cruz River near Tucson for proposed agricultural use. In the latter example, 23 years of daily runoff data was used in CROP-76. This computation showed that a reservoir system consisting of six 15,000,000 m³ compartments—only 5 meters deep could effectively re-regulate the erratic flood flows so that approximately 50 percent of the water could be beneficially used on a continuous basis.
A single compartment reservoir of the same depth would be dry approximately 10 percent of the time without any beneficial consumptive use.

CROP-76 has also been used to verify the design of a 20 hectare water harvesting agrisystem which has been constructed at the San Francisco Ejido near Parrus Coahuilla. The surface soil of the twenty hectares has been shaped and will be compacted this summer. Plantings of grapes and pistachios have been made in the artificially depressed drainage area. Excess water from both the artificial catchment and a natural watershed will be stored in a three compartmented system for use in the dry season. Ten years of daily precipitation data was used in CROP-76. This simulation indicated that the reservoir system would be dry only three weeks during the ten year period. There was, however, ample soil moisture during this period to maintain full production.

The use of CROP-76 also showed the advantages of using a floating cover in conjunction with the compartmented reservoir system. In one simulated example a floating cover was placed on the last compartment of a six compartmented system. The cover was placed over only 16 percent of the area but increased the dependable water supply from the system by 50 percent.

By making repeated runs with CROP-76 using different climatic regimes a better understanding of the inter-relation between parameters has been obtained. It was found that there is not much advantage in making the compartments different sizes. They can all be made the same size without reducing their efficiency.

The effect of the compartmented system on reservoir efficiency diminishes as the depth of the reservoir increases. The effect becomes negligible for depths greater than 20 meters. Also the rate of increase in efficiency diminishes as the number of compartments increase. Usually there is little to be gained by having much more than six compartments for the larger reservoirs and three or four compartments for smaller reservoirs.

It was also determined that the reservoir efficiency is relatively sensitive to the design of the system. In order to obtain the highest efficiency the system should be designed to match the amount and frequency of input to the consumptive demand. This is also true of shallow conventional reservoirs.

An extensive economic study of the compartmented system has not been made. The storage costs are site dependent, however a preliminary analysis shows that the cost of water from an intermediate size or large compartmented reservoir should be less than a conventional moderate depth irrigation well. This intermediate size reservoir would be between 200,000 to 400,000 cubic meters in capacity. The storage costs are significantly reduced if the reservoir is located in a soil type where seepage is negligible or where seepage control can be easily obtained by an inexpensive treatment such as sodium chloride.
DISCUSSION AND CONCLUSIONS

This study has shown that the use of a compartmented reservoir can provide efficient storage of water in areas of flat terrain and high evaporation loss. For intermediate and larger systems the unit cost of water should be low enough to permit its use for conventional agriculture. The system has been successfully used in conjunction with a water harvesting agrisystem. This use should make it possible to continuously cultivate large areas which could not be economically farmed any other way. Old projects that have been studied and then discarded due to poor storage efficiency should be re-evaluated. Existing reservoirs in high evaporation areas should be examined to see if storage efficiency can be increased. Any future studies of projects involving storage of water in flat terrain should include an analysis of a compartmented reservoir system.

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