THE COMPARTMENTED RESERVOIR: EFFICIENT WATER
STORAGE IN FLAT TERRAIN AREAS OF ARIZONA

C. Brent Cluff

ABSTRACT

The compartmented reservoir is presented as an efficient method of storing water in areas of Arizona 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.

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 has been utilized in designing several systems including several in Arizona. Through the use of the model, the interrelationship of the parameters have been determined. 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 and 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.

INTRODUCTION

The need for improved methods of water storage in Arizona has long been recognized. This is particularly true in southern Arizona where the high evaporation loss coupled with flat terrain has prevented economical water storage except in rare instances where favorable reservoir sites are available. Most of the favorable sites 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 Arizona 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 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. There is considerable quantities of flood runoff which is not now utilized due to lack of economical storage sites.

C. Brent Cluff is an Associate Hydrologist at the Water Resources Research Center, University of Arizona.

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

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. The research that has been done on evaporation control indicates that the costs of such control in general are prohibitive for use in some major applications such as conventional agriculture (Cluff, 1977b).

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, pumps makes the compartmented reservoir system economically attractive. These pumps can be powered by the power-take-off from a tractor or have their own motor. They are available in capacities of up to 25,000 gpm (5000 cubic meters) per hour. One pump can service several small reservoirs. If tractors are not available a suitable vehicle could be equipped with a pto and used to both transport and power the portable pump. In Arizona, this type of pump can be rented which may be preferred since it is only needed three or four times a year.

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.

THE POTENTIAL OF THE COMPARTMENTED RESERVOIR IN ARIZONA

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 (ΣE) of 5.94 feet (1.81 meter) is used. This is the average pond evaporation measured at the WRRC Field Laboratory 1972-1977 at Tucson, Arizona. It is less, however, than the evaporation in many other parts of the state. A constant consumptive use that would be withdrawn each month is selected so that there is 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 it is impossible to withdraw any water on a continuous basis since all the water would be consumed by evaporation.
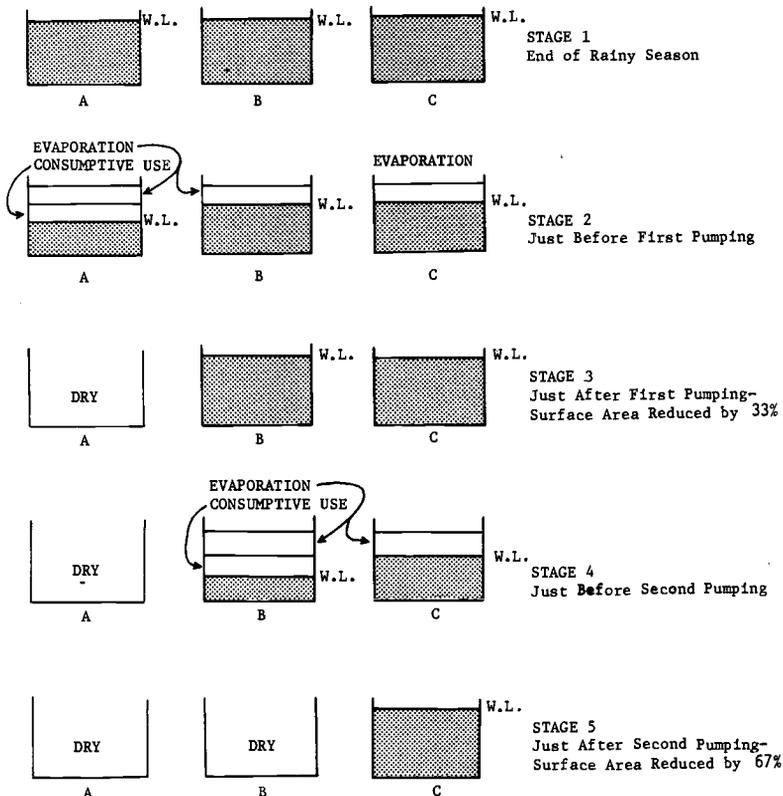
Figure 1. Schematic cross-sectional diagram of a three-compartment
reservoir showing water levels (W.L.) of various stages
in the annual cycle of operation.

    The efficiency can be increased beyond those shown in Figure 2 if all compart-
ments, 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 system. If the depth of B and C are doubled and
quadrupled the efficiency goes up to 70 percent and 82 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 only limitation
in its use on smaller tanks with sloping sides is that the bottom area of the reser-
voir should be a significant percentage of the total surface area of the tank.

    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 24.9 percent of the initial storage to
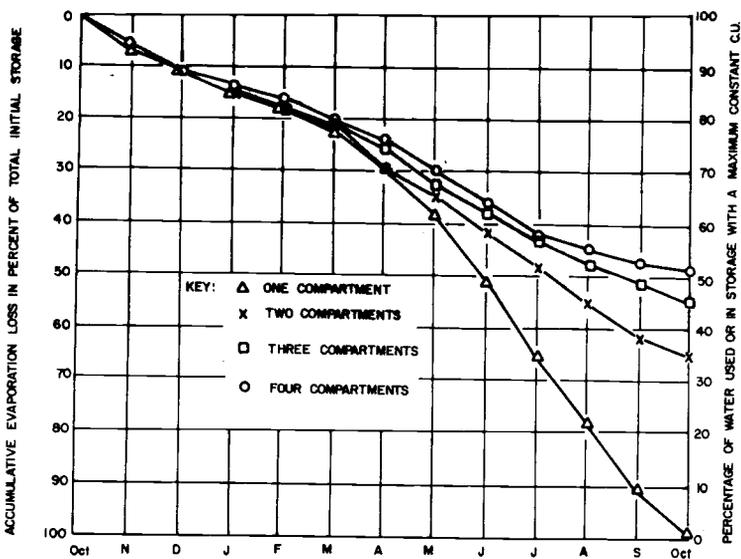obtain a 45.0 percent efficiency when the water is used on a constant basis. This

Figure 2.   Evaporation Loss for Compartmented (but undeepened) Reservoirs with a
Constant Volume and Area, a Maximum Constant Consumptive Use and a
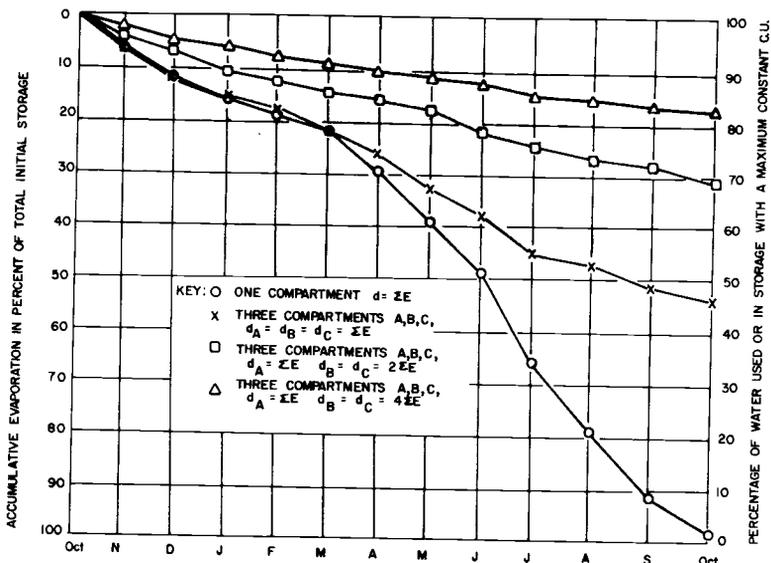Depth Equal to Annual Evaporation Loss at Tucson, Arizona.

Figure 3.   Evaporation Loss in Percent of Total Initial Storage for Compartmented
Reservoirs with a Constant Volume, Varying Depth and a Maximum
Constant Consumptive Use (Tucson, Arizona).

amounts to pumping 56.2 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 first understood 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 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 National (Cluff, 1976) in support of the Fundo Cancelillero, 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 6.5 acre-foot (8100 m^3) two-compartmented livestock reservoir dug by mules, to a 162 acre-foot (200,000 m^3) 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.

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 (1977a).

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 agri cultural 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 that the reservoir system 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.

Additional improvements have been made since the model was developed in the fall of 1976. The model has been used to design compartmented reservoir systems using a minimum amount of data. The model has been used on several reservoir systems in Arizona, Coahuilla, Mexico and Mali, West Africa. These systems ranged in size from a 4.9 acre-foot (6,000 m^3) stock tank to a 72,964 acre-foot (90,000,000 m^3) reservoir system in Arizona designed to store excess floodwater in the Santa Cruz River near Tucson for
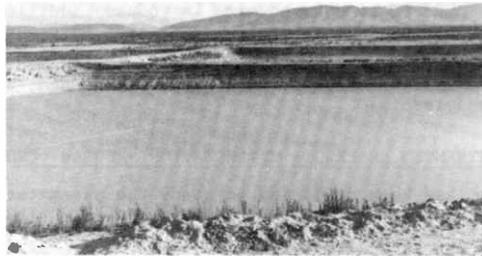
Figure 4.   Four Compartmented Reservoir System near Parras,
            Coahuilla, Mexico, with a 162 acre-foot (200,000 m^3)
            Capacity.   -- Above: Under Construction.
            Below: Completed System.

proposed agricultural use.   In the latter example, 23 years of daily runoff data at the
Cortaro gaging station was used in CROP-76.   This computation showed that a reservoir
system consisting of six 12,160 acre-feet (15,000,000 m^3) compartments only 16.4 feet
(5 meters) deep could effectively re-regulate the erratic flood flows so that approxi-
mately 50 percent of the water could be beneficially used on a continuous basis to
irrigate 1760 acres (704.0 hectares).   A single compartment reservoir of the same
depth would be dry approximately 10 percent of the time without any beneficial consump-
tive use.

        The size of this reservoir can be reduced and the efficiency of storage increased
if the percentage of floodwater diverted into the reservoir system is reduced.   This
was studied by Wicke (1978) when CROP-76 was used to develop a appropriate design for
re-regulating excess flood flows at the Cortaro Gaging Station on the Santa Cruz
River to recharge wells on a continuous basis in Avra Valley.

        Compartmented reservoirs appear to be very cost effective when used in the al-
luvial valleys of Arizona where recharge of the ground water table is needed.   In this
case seepage control would not be needed since any addition to the ground-water table
could be beneficially used.

        CROP-76 has also been used to verify the design of a 50 acres (20 hectare) water
harvesting agrisystem which has been constructed at the San Francisco Ejido near Parrus,
Coahuilla, Mexico. The surface soil of the twenty hectares has been shaped and compact-
ed.   Plantings of grapes and pistachios have been made in the artificially depressed

70

drainage area. Excess water from both the artificial catchment and a natural water-shed will be stored in a three compartmented system for use in the dry season. Ten years of daily precipitaton 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 pro-duction. See Figure 5.

Figure 5.   Fifty acre (20 hectare) water
harvesting agrisystem in Coahuilla,
Mexico with compartmented reservoir
in the foreground.

CROP-76 has also been used to design similar water harvesting systems for use with the growing of jojoba, an oil-bearing desert shrub, on retired farmland in Avra Valley near Tucson, in cooperation with the Office of Arid Lands Studies, University of Arizona. This analysis indicates that these systems approach economic viability when using the compartmented reservoir to reduce the effects of variable rainfall on pro-duction. There has been some commercial interest shown in developing this type of rainfed agriculture in Arizona.

The use of CROP-76 also showed the advantages of using a floating cover in con-junction 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 compartmentes 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.

71

Four small compartmented reservoir systems for stock purposes are under construction at the Papago Indian Reservation. These are retrofits of older, inefficient systems. With this approach a smaller, lined compartment is located next to a typical earth stock tank. In this two-compartmented system the water is first collected in the old stock tank and then pumped or siphoned over into the lined compartment. Many earthen tanks in Arizona could become perennial sources of water for stock purposes, if modified in this way.

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 162 to 324 acre-feet (200,000 to 40,000 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

The use of a compartmented reservoir can increase the efficiency of water storage in flat terrain areas of Arizona. It has considerable potential in improving the efficiency of earth stock tanks. For intermediate and larger systems the cost of water should be low enough to permit its use for storage of flood flows to supplement existing irrigation projects. It appears to have considerable potential for use in conjunction with water harvesting agrisystems on farmland retired due to falling water tables. This is particularly true if desert plants such as jojoba are used.

A selected number of existing and new reservoir sites in Arizona are presently being studied to provide additional examples of the improvement in efficiency available through use of the compartmented reservoir. Any future studies of projects involving the storage of water in flat terrain should include the possibility of using a compartmented reservoir system.

ACKNOWLEDGMENTS

REFERENCES

Cluff, C. B. 1975. Surface Water Storage Potential in the Nara and Songa Areas of Mali, Summer Project, 1975, Unpublished Consultants Report, Wunderman Foundation, New York, N. Y.

Cluff, C. B. 1976. Agro-Industrial Training, Research and Extension in Arid Zones, Report of the Expert Consultant in Hydrology, United Nations Development Programs, UNDP/MEX/74/003, Unpublished Consultants Report, Submitted to FAO, United Nations, Rome, Italy.

Cluff, C. B. 1977a. The Compartmented Reservoir: A Method of Efficient Water Storage, Dissertation, Civil Engineering, Colorado State University, Ft. Collins, Colorado.

Cluff, C. B. 1977b. Evaporation Control for Increasing Water Supplies, UNITAR Conference on Alternative Strategies for Desert Development and Management, Sacramento, California, May 31-June 10, 1977.

Wicke, H. D. 1978. A Preliminary Feasibility Analysis of Artificial Recharge in Avra Valley, Arizona with Santa Cruz Flood Flows, Master's Thesis, Department of Hydrology and Water Resources, University of Arizona.