ARID LAND PLANT RESOURCES

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The use of the Compartmented Reservoir in Water Harvesting Agrisystems

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One of the promising ways of increasing both the quantity and dependability of water in arid and semi-arid lands is through water harvesting. For the purposes of this research project it is defined as the artificial treatment of soil to increase the water yield. The water thus produced is captured as surface runoff and stored or put to beneficial use before it evaporates. The combination of a water harvesting catchment and reservoir is called a water harvesting system (Cluff et al., 1972).

Water Harvesting

A summary of the current methods used in water harvesting is given in the Proceedings of the Water Harvesting Symposium held in Phoenix, Arizona, in March of 1974. A summary is also given in a National Academy of Science report (1974). That report and an article by Cluff and Dutt (1975) gives the leading methods as follows:

1. Land alteration (clearing, shaping and compaction).
2. Chemical treatment (sodium salts, silicones).
3. Soil cementation (wax, soil cement, plastic and fiberglass, reinforced asphalt, in situ membranes).
4. Soil covers (gravel-covered plastic sheets, butyl rubber and sheet metal).

An updated list of the more promising of these methods, listed in order of their increasing cost, are: (1) Shaped compacted-earth (or roaded catchments); (2) shaped compacted earth, sodium-treated; (3) compacted-earth, wax-treated; (4) gravel-covered plastic; (5) fiberglass-asphalt-chipcoated (FAC); (6) asphalt-plastic-asphalt-chipcoated (APAC); and (7) rubberized-asphalt-chipcoated (RAC), (National Academy of Sciences, 1974; Frasier, 1975; Frobel et al., 1978).

These methods of treatment greatly reduce costs and increase the efficiency and life of the catchment system. The first two of the above listed methods are inexpensive enough that they are used in conjunction with growing agricultural crops. This is particularly advantageous in marginal dryland areas that need only a small amount of additional water to optimize production. An analogy might be made to the use of fallowing by the wheat farmer in the Great Plains. The author estimates that the wheat farmer spends an equivalent of $5 to 6/ha-cm of water disking his land to provide a mulch. This mulch is needed to store 50 to 75 mm of one-year's precipitation to supplement the precipitation of the next year, in order to produce a crop. This process, in which a farmer plants every other year, is called fallowing. It does not work south of the Texas High Plains because of the excessive evapotranspiration potential. However, concentration of precipitation through water harvesting has the potential of accomplishing the same purpose for approximately the same price with no sacrifice in the net amount of land cropped per year. Furthermore, the system will work in areas where fallowing is impractical.

Hall and Dracup (1970), in reference to Lewis et al. (1969), indicate that far more product per unit of water is possible through the use of concentrated rainwater than through the "relatively inefficient process of streamflow, reservoir, diversion, aqueduct, farm ditch, and irrigation with excess leaching followed by an additional system to dispose of the accumulated salt and drainage water."

The practice of treating watersheds to increase water yield so that crops can be raised is an old one as evidenced by ancient systems in the Negev Desert in Israel (Evenari et al., 1971; National Academy of Sciences, 1974). The ancient dwellers of the Negev utilized the soil profile to store the somewhat erratic runoff. Due to favorable soil conditions this system seems to work most of the time.

In other semi-arid lands with similar rainfall the system does not work as well, with crop failures occurring too frequently for effective commercial agriculture (Fangmeier, 1975; Morin and Matlock, 1975). Morin and Matlock report on the use of a model that does not include surface storage. The use of the model indicates that the distribution of rainfall is more significant than total rainfall after a set minimum amount occurs. This finding supports the hypothesis that for water harvesting to be successful in most semi-arid regions it must be combined with efficient surface storage.

Cluff et al. (1972) and Dutt and McCreary (1975) report on a one-acre system installed at Page Ranch north of Tucson, Arizona, in which rain water is concentrated into planted strips by shaping, compacting and treating the contributing catchment to prevent weed growth. Erosion is controlled by shaping and utilizing a thin, naturally created sand mulch. The excess water is captured and stored in a covered reservoir and pumped back during dry periods to water the grapes and deciduous fruit trees planted in the drainage ways on the catchment. The system has had ample water since it was installed in 1970. The resulting runoff water from the salt-treated catchment is of high quality with the sodium being trapped by the clay in the soil on the catchment (Dutt and McCreary, 1975). The above type of system, or one in which the treated catchment is separate from the planted area as described by Morin and Matlock (1975), when combined with surface water storage is referred to as a water harvesting agrisystem. The operation of the system shows that efficient surface storage of water is essential to maximize production.

Efficient storage of surface water in small reservoirs requires both evaporation and seepage control. Many of the same methods used above can be adapted to seepage control and other methods are available. Evaporation control which is essential in storage of water is more expensive. It will be discussed in more detail in the next section.

Evaporation Control

The concept of concentrating water to reduce evaporation loss is not new, and the literature contains some references concerning this method. The process of evaporation requires both a source of energy to vaporize the water and a transfer mechanism, a greater vapor pressure at the water surface compared to that of the air above. This transfer mechanism, and consequently evaporation, is accelerated by wind.

The various methods of evaporation control reported by Veihmeyer (1964) are:

1. Surface-area reduction.
   a. Constructing reservoirs with a minimum ratio of area to storage volume.
   b. Storing water "in one large reservoir instead of several small ones."
   c. Proper selection of reservoir sites
2. Mechanical covers. (Roofs, floating rafts and windbreaks.)
3. Surface films. (Oil and long-chain fatty alcohols.)

On first reading, item 1b could be interpreted as the direct opposite of the compartmented reservoir concept. However, Veihmeyer bases his summary in part on an article by Beadle and

Cruse (1957) in which "concentration of water into single reservoirs" is said to be a method for retarding evaporation. Another method listed by Beadle and Cruse is the "elimination of shallow water areas." The compartmented reservoir concept provides a systematic method of concentrating water, thus eliminating shallow water areas. The other reference used by Veihmeyer is Freese (1956) who also stresses concentration of water and indicates that this might be done by selecting a good site. Freese gives an example of the operation of three reservoirs in Abilene, Texas, where the water was concentrated in a lower lake. In essence, this is a gravity-fed separated-compartmented reservoir system (Cluff, 1977a). Freese also gave an example of the savings that could result in filling in the shallow areas of a lake near Fort Worth, Texas. He determined that saving water worth $0.19/m^3 would justify filling in the shallow areas in the lake up to a depth of 0.98 m even though the fill would cost $0.33/m^3 per year. Fort Worth is in a 1,220 mm net annual evaporation area.

Garstka (1962) indicated that elimination of the shallow areas by diking may result in greater evaporation savings than that indicated by comparison of the ratio of the water surface due to temperature reduction of the water.

To the above list by Veihmeyer should be added a fourth category of energy-reducing treatments such as coloring the water, shading by suspended materials and floating reflective barriers such as perlite, that may or may not be a vapor barrier. Cooley (1970, 1975) did considerable research in this area. In a joint research program, Cooley and Cluff (1972) determined that while lighter than water initially, floating perlite does become saturated over a period of time and loses its buoyancy, rendering the method impractical.

Surface films formed by long-chain alcohols received considerable attention during the late 1950s and early 1960s. The research was sponsored and coordinated by the U.S. Bureau of Reclamation (Garstka, 1962). Several land grant universities were involved: Colorado State (Hayes, 1959), Arizona (Cluff, 1966), Utah State (Israelson and Hansen, 1963), Oklahoma State (Crow, 1961) and Texas Tech (Meinke and Waldrip, 1964). The U.S. Geological Survey also conducted experiments (Cruse and Harbeck, 1960). During these studies, the use of alcohol to prevent evaporation was perfected to the point where it could be used in several physical formulations in conjunction with various methods of application including use of airplanes. However, due to wind problems, the unit cost of achieving evaporation control greatly increases as the residual time on the reservoir decreases. The system is much more economical on large reservoirs than on small ones. Generally the value of water is much greater in small reservoirs than larger ones so at the present time no commercial applications are being made.

For smaller reservoirs inexpensive floating covers appear to have more potential (Cluff, 1966). Many floating-cover methods such as polyethylene sheets (Drew, 1972), concrete slabs made with lightweight aggregate (Eng. News Record, 1966) and floating edged-sheets of expanded polystyrene (Cluff, 1967) have been tried and abandoned. A test by the author consists of placing crushed expanded polystyrene as a reflective barrier. Evaporation savings were about 50% for one month, but a heavy wind completely overturned the film and caused it to become wetted. This caused evaporation savings to drop to 10%, making the approach impractical (Cluff, 1977a).

Among the leading floating-cover methods are the use of wax blocks (Cooley, 1975), foamed butyl rubber (Dedrick et al., 1973) and weatherized sheets of expanded polystyrene together to form a continuous raft (Cluff, 1972). More recently the expanded polystyrene sheets have been impregnated with wax to prevent waterlogging and to "weatherize" the sheets (Cluff, 1977b). This patented process has worked well for waterproofing, and appears to resist oxidation. No problems were encountered during the first summer. However, in the second summer of testing a windstorm occurred during air temperatures in excess of 45°C in which the melted wax on the surface trapped darker soil than had been encountered before. This darker soil appears to have accelerated deterioration. The various remedies that are being considered are: (1) Add a layer of light colored sand to surface immediately following wax impregnation; (2) Remove excess wax from the surface after impregnation; (3) Use a wax with a higher temperature melting point; or (4) Use a surface treatment on top of the waxed foam.

These leading methods of evaporation control are all too expensive to use for conventional agriculture (Cooley et al., 1973). However, as will be described later, their use in conjunction with a compartmented reservoir appears to be very cost effective.

The Compartmented Reservoir

As shown above, the principle of reducing the surface area of reservoirs to control evaporation appears to be documented in the literature. The author has failed to find any writings by other researchers, however, concerned with the division of a conventional reservoir into compartments and the systematic pumping or transfer or water between compartments to achieve evaporation control through reduction of surface area. The author first discovered the relatively large savings that can be achieved from such a system while serving as a consultant in the Sahel in Mali, Africa.

The Sahel contains hundreds, perhaps thousands, of small, shallow, natural depressions called "mares" that are filled each year during the rainy season. As long as the water is there it is heavily used by the many surrounding villages. However, due primarily to high evaporation loss, only a relatively small amount of the water is beneficially consumed and the mares soon dry up.

A determination was made of the savings of dividing the mare into two compartments, a receiving compartment and a deeper one. This concept had been proposed earlier by Gordon Dutt and co-workers at the University of Arizona. The extension of this idea to three or more compartments of equal or close-to-equal depth was a result of the African consulting trip. At that time, it was found that significant savings could be achieved by compartmentalization even without deepening.

A schematic of the compartmented reservoir is outlined in Fig. 1.

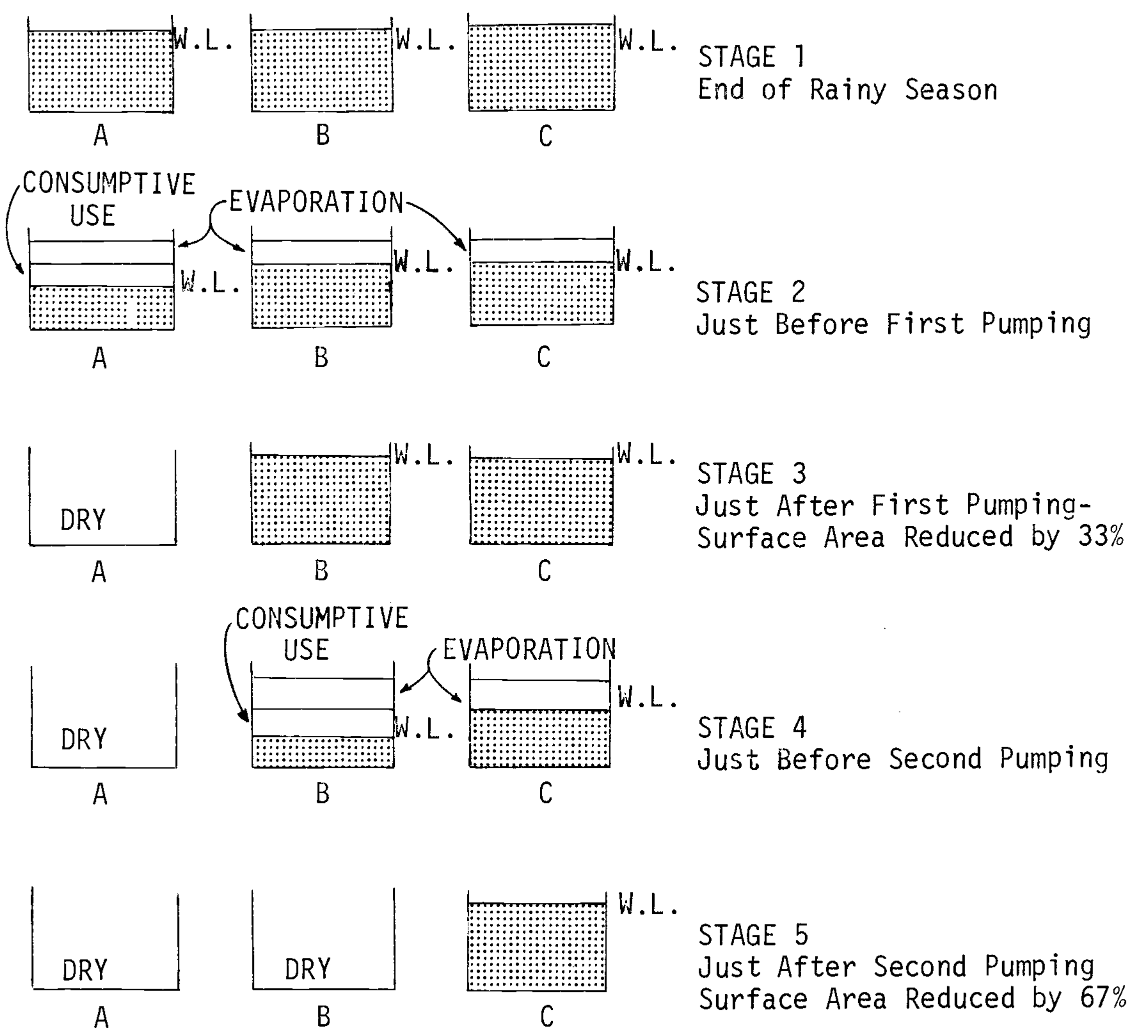


Figure 1. Schematic cross-sectional diagram of a three-compartment reservoir showing water levels (W.L.) of various stages in the annual cycle of operation.

The reservoir consists of a receiving compartment (A) which is located below the stream grade and therefore is usually shallow. Compartments B and C are shown as being smaller in surface area but of greater depth. This reservoir is operated as follows: As runoff occurs during the rainy season, water is pumped 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 comsumptive 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 potential of the compartmented reservoir is demonstrated in Figs. 2 and 3 under idealized conditions.

Fig. 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 both figures an annual evaporation depth (ΣE) of 1.81 m is used. This is the average pond evaporation measured at the Water Resources Research Center 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.

Fig. 3 illustrates the added advantage of having both the effect of deepening and compartmentalization. Efficiency of water use goes up to as high as 84% when two of the compartments are deepened four times the evaporation loss. This increase in depth in a compartmented system when pumping is used can be achieved by diking rather than the excavation required in a conventional reservoir. This deepening however may increase seepage so that the most cost effective design would be the single depth compartmented reservoir system.

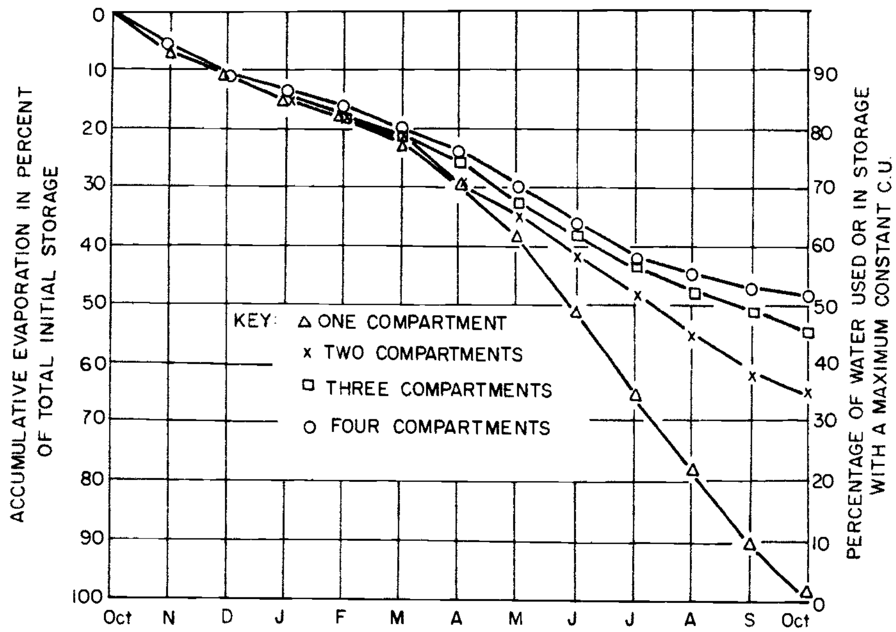


Figure 2. Evaporation Loss for Compartmented (but undeepened) Reservoirs with a Constant Volume and Area, a Maximum Constant Consumptive Use and a Depth Equal to Annual Evaporation Loss at Tucson, Arizona.

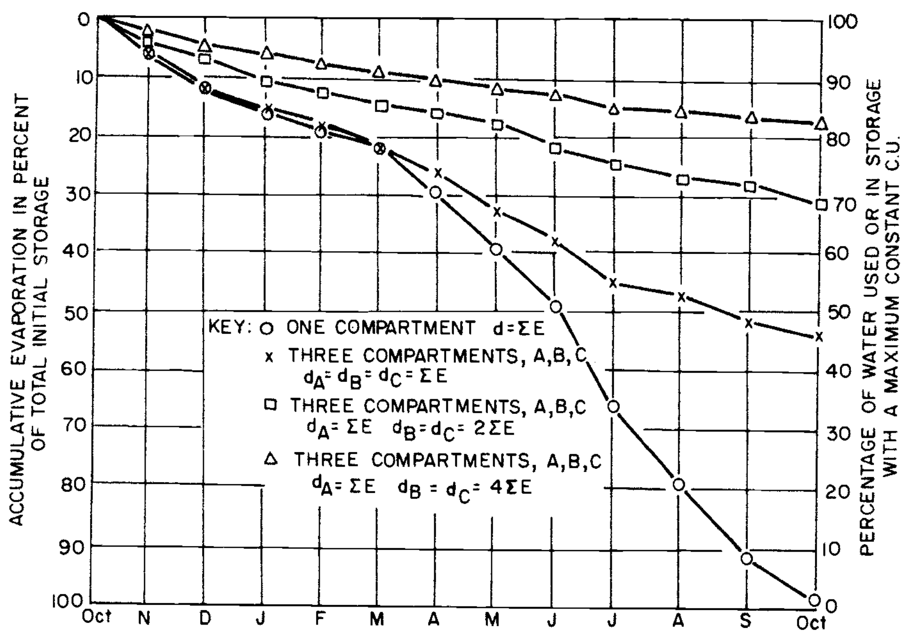


Figure 3. Evaporation Loss in Percent of Total Initial Storage for Compartmented Reservoirs with a Constant Volume, Varying Depth and a Maximum Constant Consumptive Use (Tucson, Arizona).

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, thus greatly reducing costs.

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 (pto) from a tractor or have their own motor. They are available in capacities of up to 25,000 gpm (5,000 m^3/hr). 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. For smaller systems, a 3.5 horsepower, 600 gpm (120 m^3/hr) floating pump costing less than $800 (U.S.) is available.

If the general slope of the topography is greater than 3-4% 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 a canal into the second and succeeding compartments. This reservoir system could be operated as before but without a pump.

In Mali, Africa, ten different sites were surveyed and recommended designs were made using a small programmable calculator (Cluff, 1975). After returning 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 Coahuila, 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 m^3 two-compartmented livestock reservoir dug by mules, to a 200,000 m^3 four-compartmented reservoir constructed using Caterpillar D-7 dozers. The larger reservoir was used for agricultural purposes. One small gravity-fed separated compartmented reservoir was also constructed.

Five small, two or three-compartmented systems have been built on or near the Papago Reservation, near Tucson. In addition, an approximate 10 ha water harvesting agrisystem with a three-compartmented reservoir system is nearing completion at Black Mesa on the Navajo Reservation in Northern Arizona. It is being constructed on coal mine spoils in cooperation with the Navajo Tribe, the School of Renewable Natural Resources, University of Arizona, the U.S. Bureau of Mines, and Peabody Coal. The Black Mesa design was based on use of a computer model described below.

The use of the compartmented reservoirs introduces additional design parameters for effectively using and storing water from any given watershed or catchment area. 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. These are the compartments that contain water the longest period of time.

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 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 comstraints 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 4-5 percent. An additional constraint is that the reservoir system provide water for the desired beneficial use for a specified minimum, usually 95 or 96% 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; Coahuila, Mexico; and Mali, West Africa. These systems ranged in size from a 6,000 m^3 stock tank to a 90,000,000 m^3 reservoir system in Arizona designed to store excess floodwater in the Santa Cruz River near Tucson for proposed agricultural use.

CROP-76 was used to verify the design of a 20 ha water harvesting agrisystem which has been constructed at the San Francisco Ejido near Parrus, Coahuila, Mexico. The surface soil of the 20 ha area has been shaped and compacted. Plantings of grapes and pistachios have been made in an artificially depressed drainage area (Gavande et al., 1976; Cluff, 1977a). 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 (Fig. 4).

Jojoba Water Harvesting Agrisystems

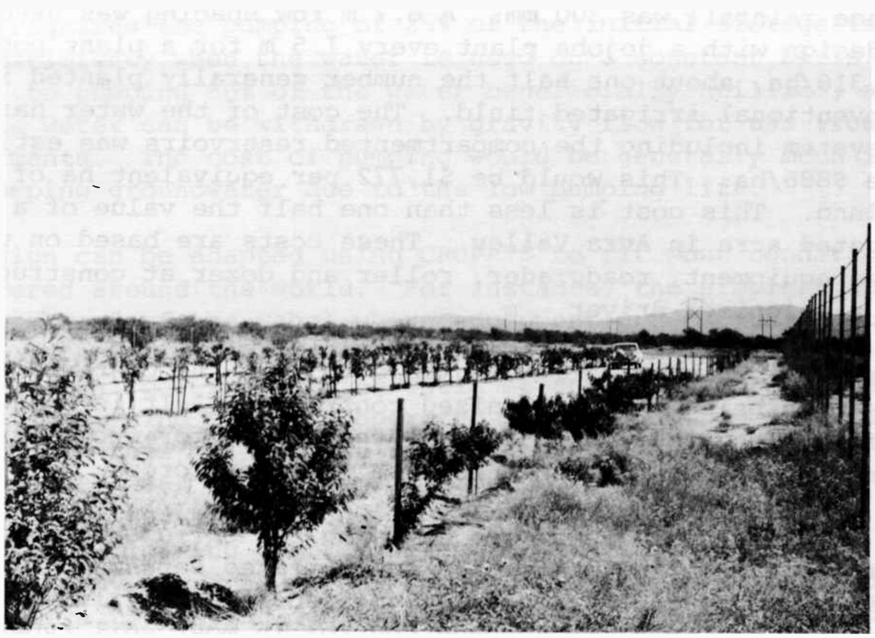
CROP-76 was also used to design a 16 ha jojoba water harvesting agrisystem for use on a piece of retired farmland (Cluff and Foster, 1978). The design used was a shaped compacted earth salt treated catchment feeding water into drainage ways in which jojoba is planted. The excess water is stored in a three-compartmented reservoir. This design was based on a one-acre jojoba water harvesting agrisystem that was established at Sells on the Papago Reservation in 1974 (Cluff, 1978). This design was similar to the one-acre system at the Page Experimental Ranch installed in 1970 (Fig. 5). In the Sells jojoba system, three treatments were tested, sodium, APAC and wax. The growth of jojoba on the sodium treated plot was as good or better than the other two more expensive treatments.

The 16 ha design was for a parcel of retired farmland owned by the City of Tucson and is located in the Avra Valley 32 km west of Tucson. The city has been purchasing and retiring the farmland to obtain a water supply. The land has since become an ecological disaster with dust and windblown tumbleweeds causing problems for adjoining neighbors. The salt treated jojoba water harvesting system offers an economic, viable method of land management to correct the above conditions without using groundwater.

The simulation using CROP-78 (the improved CROP-76) indicated that a three-compartmented reservoir with a combined surface area of 0.4 ha and holding 14,100 m^3 would assure sufficient water to achieve maximum jojoba growth and production.

Figure 4. Water Harvesting Agrisystem in Mexico.

Above: A Compartmented Reservoir
Below: Pistachio (left and grape (right) plantings in catchment areas.



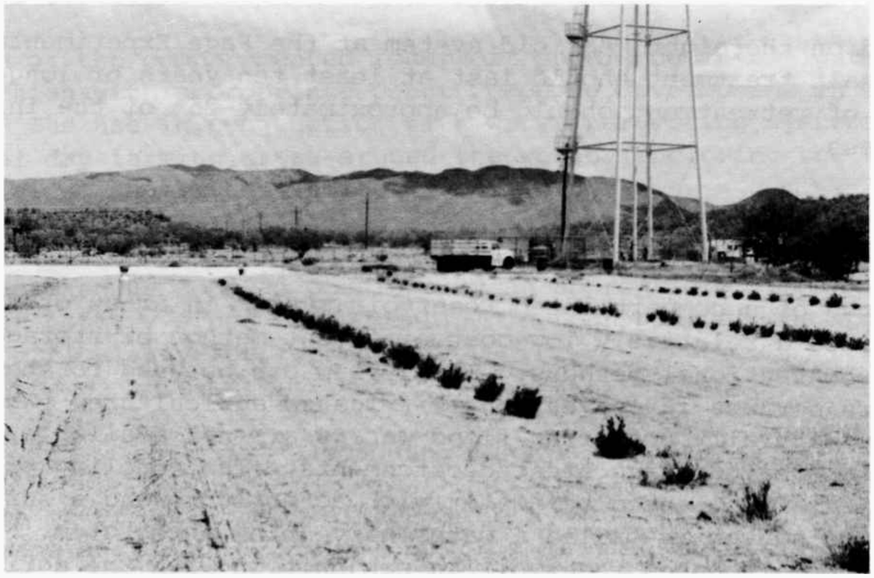


Figure 5. Water Harvesting Agrisystems in Arizona

Above: Page Experimental Ranch. Note sale treatment for grapes in background versus untreated grassy area around fruit trees in foreground.

Below: Papago Indian Reservation planting of jojoba at Sells soon after planting. APAC treatment in foreground, salt treatment on right.

The simulation was done for a 31-year period, 1945-1975. The average rainfall was 300 mm. A 6.7 m row spacing was used in the design with a jojoba plant every 1.5 m for a plant population of 2,310/ha, about one half the number generally planted in a conventional irrigated field. The cost of the water harvesting agrisystem including the compartmented reservoirs was estimated to be $886/ha. This would be $1,772 per equivalent ha of irrigated farmland. This cost is less than one half the value of a typical irrigated acre in Avra Valley. These costs are based on use of rented equipment, roadgrader, roller and dozer at construction rates with a unionized driver.

Farmers have historically been able to keep the cost of repetitive tasks much below those unionized contractors. It is felt that an efficient farmer could install the system for much less thus making the process suitable for use with many crops.

This low cost can be achieved by using the efficient compartmented reservoir in combination with a salt-treated catchment. The salt-treated catchment provides a sodium dispersed clay liner which eliminates the need for seepage control in most soil types. The runoff from the salt treated catchment is of excellent quality (less than 200 ppm dissolved solids). The water, however, will be higher in sodium content than calcium plus magnesium. This assures a long life for the sodium-dispersed clay reservoir liner.

Based on the eight year old system at the Page Experimental Ranch, the salt treatment should last at least ten years or longer. The cost of retreatment should be approximately 25% of the initial process.

Summary and Discussion

The use of a compartmented reservoir system in areas of flat terrain provides a relatively low-cost efficient method of storage as compared with conventional methods. The system can be used to store flood-waters for use in conventional irrigated agriculture. Where sufficient naturally occurring flood waters are not available, runoff can be created using treated catchments. The coupling of this artificial collected rainwater with agriculture and a surface storage system is called a water harvesting agrisystem. The use of a compartmented reservoir in conjunction with the agrisystem appears to be very cost effective. Efficiencies in excess of 50-60% are easily obtained with the compartmented reservoir, whereas a conventional reservoir of the same depth covering the same area would not even be able to sustain its own evaporation loss. Even higher savings are possible at no significant increase in cost if an evaporation cover is placed on the "last" compartment.

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 Figs. 2 and 3, requires the pumping of 25% of the initial storage to obtain a 45% efficiency when the water is used on a constant basis. This amounts to pumping 56% of the water beneficially utilized, assuming 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 design can be adapted using CROP-78 to fit most conditions encountered around the world. For instance, the simplest approach in the "mares" of the Sahel where equipment and capital is scarce is merely to divide up the mare using low dikes constructed with hand or animal power. Pumping could be done using appropriate hand, animal, wind or solar operated pumps. The floating pumps described in this paper might be the appropriate technology to use.

Although the floating pump requires fossil fuel, the amount of fuel needed is very low. A 20-year supply could be purchased and stored on site or a trust fund set aside for fuel purchases to assure the success of the project.

If more equipment and capital are available, the systems can be made deeper, thus increasing the efficiency but not necessarily the cost-effectiveness.

The use of the compartmented reservoir should be investigated in conjunction with appropriate plant resource development in arid lands. Its use in conjunction with water harvesting systems in marginal dry farming areas around the world (including the Texas High Plains) should be studied.

A demonstration project in Africa somewhere in the Sahel should be undertaken as soon as possible by an appropriate funding agency and host country since the potential in that part of the world looks particularly intriguing.

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