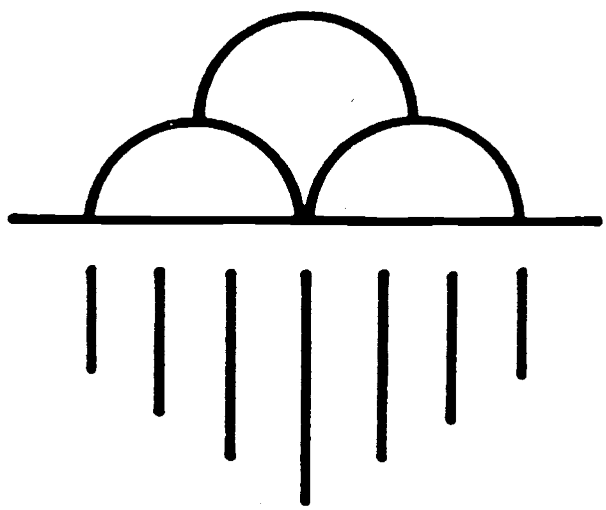
WATER HARVESTING IN ARID LANDS



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Abstract

The use of water harvesting systems in arid lands offers the potential of making lands productive that are now largely unusable due to lack of water for domestic livestock or agricultural use.

As long as there is rainfall a water harvesting system can be designed to collect that rainfall and store it until it can be used for beneficial use. The water harvesting system consists of a catchment and a storage facility. If the water is to be used for agriculture it would also include an agricultural area. The agricultural area could be located within the catchment area or in a separate nearby area.

Many different treatments have been tested for use in catchment construction. These treatments increase the runoff by decreasing the permeability of the surface and or reducing the time the water stays on the surface or amount of water trapped on the surface. A list of the more promising treatments in order of their increasing cost, are: (1)Shaped compacted-earth; (2) sodium-treated shaped compacted-earth; (3) wax-treated shaped compacted-earth; (4) gravel-covered plastic; (5) fiberglass-asphalt chipcoated; (6) asphalt-plastic-asphalt chipcoated; (7) rubberized-asphalt chipcoated; and (8) reinforced-mortar-covered plastic.

The use of compartmented reservoirs make storage of water more efficient. Evaporation and in some cases seepage losses are reduced using the compartmented reservoir by keeping the water concentrated into a volume with as small a surface area as possible. This method of storage when combined with the collection of runoff from a natural surface or with one that is inexpensively treated makes it practical to provide water for supplemental irrigation. This combination is called a water harvesting agrisystem.

Concentration of water in a compartmented reservoir can be accomplished in flat terrain using a pump. If the water is being used at a fast enough rate concentration can also be accomplished by selective removal. Alternatively with topography of a sufficient grade, concentration can be accomplished by gravity.

Evaporation control on the compartmented reservoir can be improved by placing an evaporation control barrier on the "last" compartment, the one in which water is concentrated and has water in it the longest time. This

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enhances the value of the evaporation control barrier and increases the dependable water supply.

A computer model has been developed to help in the design of the water harvesting systems including agrisystems with compartmented reservoirs. This program fits on portable personal computers and can thus be taken by the designer to a field location to develop an optimum design at a minimum cost. The model can be improved through calibration in a given area as systems are installed and data collected.

Introduction

One of the most promising methods of utilizing large tracks of land more effectively in arid and semi-arid regions is the use of water harvesting systems. These systems are a combination of catchment and storage. When used to provide water for agriculture the system also contains agricultural land. The agricultural land can be within the catchment area in the form of strips or in a contiguous area outside the catchment area. The strip type catchment would probably be used where the soil and topography conditions were not limiting in that crops could be grown over the entire area. If good cropping soils are limited then the catchment would be placed on poorer soils outside the planted area. When used to supply water for agriculture this combination is called a water harvesting agrisystem.

Catchment Construction

The least expensive method of catchment is the natural or untreated catchment. Natural basement complex rock outcroppings, exposed clay areas or iron oxide cemented sands that are sometimes available in Africa and elsewhere make excellent natural catchments. In urban areas, rooftops and graded or paved streets are generally available for use at little or no cost. In these cases the main costs of the water harvesting system is the cost of the storage. The author has constructed an urban water harvesting system collecting runoff from the streets at his residence in Tucson Arizona, (Cluff, 1984). This 4-year-old system consists of a 100,000 gallon cement-coated plastic-lined reservoir that stores water until it is used for landscape irrigation. The system has paid for itself by more than $70/month average reduction in domestic water bills.

A list of the most promising methods of catchment treatment in order of their increasing cost, are: (1) Shaped compacted-earth; (2) sodium-treated shaped compacted-earth; (3) wax-treated shaped compacted-earth; (4) gravel-covered plastic; (5) fiberglass-asphalt chipcoated; (6) asphalt-plastic asphalt-chipcoated; (7) rubberized-asphalt chipcoated; and (8) reinforced-mortar-covered plastic.

Treatments (1) through (3) of the above list are dependent primarily on soil conditions for their water yield efficiency. Rainfall characteristics are also important. Water yield efficiency from treatment (4) is dependent on the depth of gravel cover and rainfall characteristics. For this treatment the first 2.5 mm are absorbed by the gravel cover. This treatment should not be used if most of the rainfall is received in less than 2.5 mm storms. Treatments (5) through (8) will shed nearly 100% of the rainfall provided the treatments are well maintained. The runoff will be essentially free from sediment.

Treatments (1) and (2) are low enough in cost that they can be used for growing lower valued agricultural crops. The more expensive treatments could be used on higher valued crops or where only a relatively small amount of water would be needed at critical times to assure high production. An analogy might be made to the use of fallowing by the wheat farmer of the Great Plains in the United States. The wheat farmer spends an equivalent of $50-60/hectare (U.S. 1985 dollars) disking his land to provide a mulch that reduces evaporation. This mulch is needed to store 50 to 75 mm of this year's precipitation to go with next years precipitation in order to produce a crop. The cost per centimeter of water could be as high as $10-12/hectare-cm. This is a very high unit price for water but the farmers can afford to pay it because otherwise no crop can be grown. This process in which a farmer plants every other year is called fallowing. In North America this process does not work south of the Texas High Plains because of the excessive evapotranspiration potential. Moisture cannot be stored in the soil from one year to the next in hotter climates. However concentration of precipitation through water harvesting on say 50% of the land can in effect produce much more water than the fallowing method and still maintain an equivalent cropping area. Furthermore this system will work in areas where fallowing is impractical.

Lewis et al. (1969) indicated that far more product per unit of water is possible through the use of water harvesting concentrating rainfall for agriculture use than through the "relatively inefficient process of stream flow, 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 computer 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, using Southern Arizona data, supports the hypothesis that in order for water harvesting for agriculture 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 the Trowbridge-Page Experimental Ranch a few miles north of Tucson, Arizona. The site has since been expanded to several acres and three ponds that are operated as a compartmented reservoir. Rainwater is concentrated onto planted strips by shaping, compacting and then treating the contributing catchment with sodium chloride to prevent weed growth and disperses the clay to increase runoff. Erosion is controlled by shaping and utilizing a thin naturally created sand mulch. The excess water is captured and stored in a compartmented reservoir with the "last" compartment additionally protected with a layer of floating foam-filled glass-bottles. The stored water is pumped back during dry periods to water the grapes and deciduous fruit trees planted in the drainage ways on the catchment. The operation of this water harvesting agrisystem over the past 17 years 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 of catchment treatment can be adopted to seepage control. The use of a salt treated catchment will in most soil types completely seal the reservoir into which the sodium-rich clay-laden runoff is collected. Evaporation control which is essential in the storage of water in an arid environment is more expensive than seepage control except for the use of the compartmented reservoir which reduces both seepage and evaporation.

The use of reinforced mortar-covered plastic makes an excellent seepage control barrier. The use of high density polyethylene plastic in 20 to 30 mil thicknesses will give 100% seepage control. This plastic in these thicknesses can be welded together to form a rugged liner. This material generally costs less than other plastic liners with similar characteristics.

Evaporation Control

The process of evaporation requires both a source of energy to vaporize the water and a transfer mechanism such as dry air and wind. Evaporation control methods involve the reduction of surface area to volume ratio, the use of monolayer forming chemicals, the use of suspended or floating covers that either provide a mechanical barrier preventing vapor transfer and/or reduces the sun's energy from reaching the water surface. Mechanical wind breaks can also be used on smaller ponds to reduce evaporation. Vegetative wind breaks might use more water from the pond in evapotranspiration than would be prevented from evaporation from the surface of the reservoir.

Floating Covers

For smaller reservoirs, floating covers seem to have more potential than monolayers formed by long chain alcohol. These covers have been made of many different materials. Methods such as floating thin (4-10 mil) polyethylene plastic sheets (Drew, 1972), concrete slabs made with lightweight aggregate (Eng. News Record, 1966) floating edged sheets of expanded polystyrene (Cluff, 1967) have been tried and largely abandoned. A test at the Water Resources Research Center Field Laboratory consisted of placing crushed expanded polystyrene as a reflective barrier. Evaporation savings were about 50% for the first month, but a heavy wind completely overturned the film and caused it to lose its water repellency and thereby to become wetted. This caused the evaporation savings to drop to approximately 10% making the approach impractical (Cluff, 1977a).

Among the other floating-cover methods tested have been the use of wax blocks (Cooley, 1975), foamed butyl rubber sheets (Dedrick et al., 1973) and surface treated sheets of expanded polystyrene tied together to form a continuous raft (Cluff 1977b). Expanded polyethylene sheets have been found to absorb water that reduces the strength and life of the material. This waterlogging characteristic also fosters weed growth. In order to weatherize the rafts and prevent waterlogging with subsequent weed growth the method of wax impregnation was developed and patented by the author. The sheets of polystyrene are dipped in molten wax, the wax fills up the open pore spaces in the material. This method effectively prevents waterlogging but if excess wax is left on the surface it will melt in the hot summer sun and attract dust which darkens the surface and increases the temperature causing an accelerated weathering.

The concept of wax impregnation is presently being used in conjunction with a reinforced mortar coating that has, over the past four years, been very effective. The final concrete coating can be applied while the raft is floating on the water. This provides an integral long-lasting evaporation cover that is very resistant to vandalism. It is an evaporation control technique that should last as long as other features of a water supply system. The platform can easily be used to mount photovoltaic systems that can easily be rotated to track the sun. The energy that previously evaporated water can be collected and used beneficially so that the same reservoir system can supply both water and energy.

Floating Spheres

Another promising method of evaporation control is the use of floating spheres which can be made out of plastic, glass or ceramics. Glass bottles, available as a waste product in developing countries, can be used. A particularly suitable material available in most third world countries is clay which can be converted into ceramic spheres. Flattened ceramic spheres can be wax impregnated to prevent water from seeping in. When floated on the surface of the water they have been found to reduce evaporation by 70%. The spheres generally cover about 85% of the surface of the water thus they are 82 % effective in reducing evaporation over the net area that is covered. The use of ceramic or glass spheres will provide an evaporation control method that will last indefinitely. One ceramic expert from Brazil claimed that if the ceramic sphere was properly made and properly fired it would last over 1000 years floating on water unless the sphere was broken. Initial tests have shown the ceramic spheres appear to be rugged enough to withstand floating on the surface of the water. Sufficient numbers of spheres need to be applied to the surface of any reservoir to reduce wave action against the shoreline. If this is done the spheres could even be used on larger reservoirs. These ceramic spheres can be made by hand molding methods, by plaster of paris molds or by using a potters wheel. The range in size has been from a molded sphere, 7.5 cm in diameter, to a hand molded sphere made on the banks of the Nile River in Sudan that is 45 cm in diameter. The best shape when using a mold made out of plaster of paris appears to be a flattened sphere about 25 cm in diameter and 10 cm high. The ceramic sphere is wax-impregnated with molten wax to water proof them. The wax goes into the pore space of the ceramic so it is long lasting and very effective. This inexpensive technique was discovered at the University of Arizona when experimenting with ways to waterproof evaporation control spheres but has a use throughout the ceramic industry whenever water proofing is needed.

Compartmented Reservoirs

The principle of reducing the surface area to volume ratio of reservoirs to control evaporation appears to be documented in the literature. However the concept of the division of a conventional reservoir into compartments and the systematic pumping or transfer of water between compartments to achieve evaporation control through reduction of surface area has not been extensively reported. The author began working with the concept in 1975 as a result of a consulting trip to the Sahel in Mali. A computer program has been developed to design these systems (Cluff, 1977). Several compartmented reservoirs have been built in Mexico, Arizona, Brazil and Thailand. It was not until a consultant trip to Sudan in the summer of 1985 that the author discovered that the British had constructed hafirs similar in principle to the compartmented reservoir.

A relatively large three compartmented hafir was constructed in El Obeid, Sudan in 1940. This system has operated successfully for over 46 years. The town of El Obeid has grown to a size of over 200,000 people so the Sudanese government built a second 4 compartmented hafir system in 1977. This water storage system was studied using the compartmented reservoir optimization program, CROP84 (Cluff, 1985). The computer model showed that the hafir system worked very well in most years. Without the concentration of the water made possible by the hafir the town of El Obeid would run out of water almost every year. The hafir involves the construction of smaller deeper compartments next to a collection compartment. The maximum surface elevation of both the collection compartment and the deeper hafir is the same. The concept involves interconnecting pipelines with gates between the compartments. The gates are opened at the beginning of each rainy season. The floods then fill up both the collection compartment and the deeper smaller compartments. When the rainfall season ends the gates are closed and the smaller efficient compartments are kept full by pumping. After the receiving compartment is dry, water is withdrawn from one of the remaining compartments. The water is always kept concentrated in as few as compartments as possible by pumping water from the least efficient into the most efficient compartments.

The compartmented reservoir also is effective when all compartments are the same depth. A schematic showing the operation of the compartmented reservoir is shown in Figure 1. 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 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 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 downstream to protect the system. All inner dikes would have to be built higher than the maximum water level. Pipes between compartments to facilitate initial filling are optional.

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 both figures an annual evaporation depth of 1.81 meter 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 than evaporation in many other areas of the world. 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 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 to 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.

The compartmented reservoir concept can be applied to existing reservoirs or new ones. In Brazil it has been found that new compartmented reservoir systems can be built for about 20 percent less than a one compartmented reservoir of the same total volume. The reason for this is that the construction of the inner dikes reduces the distance that excavated material has to be moved.

Portable low-lift, high-capacity propeller pumps make 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 5000 cubic meters per hour. One pump can service several reservoirs. Smaller propeller pumps are also available. These could be connected to photovoltaic panels or powered with wind energy. These smaller pumps are generally constructed so that they float on the water. A 3.5 horsepower pump can lift as much as 120 cubic meters per hour. It is available in the US for less than $1200 (1985 US dollars).

If the general slope of the topography is greater than 3-4 percent 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.

The use of the compartmented reservoir 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 usable water from any given watershed. These parameters are a function of the seepage and evaporation losses. If needed, a floating cover such as a reinforced mortar coated foam platform or floating ceramic spheres can be used on the "last" compartment. This is the compartment that has water in it for the longest period of time and would normally only go dry during periods of extreme drought. This greatly increases the amount of firm water at a reasonable price as compared to covering the entire surface of the typical reservoir.

Compartmented Reservoir Optimization Program (CROP86)

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 involves first using a routine called RAMOD to determine the daily runoff data using daily rainfall and a knowledge of the soil conditions, size and drainage patterns on the watersheds. Runoff data is summarized and stored in a weekly array. This data is used in Compartmented Reservoir Optimization Program or CROP. The most recent version is CROP86. 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 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 to 5 percent. An additional constraint is that the reservoir system provide water for the desired beneficial use for a specified minimum amount of time. The typical minimum amount is approximately 95% of the time. The size of the watershed is increased and/or the reservoir size is either increased or decreased to meet the consumptive use for the minimum amount of time. Contrary to conventional design it has been found using the model that a reduction in storage size generally will provide more water since there will be fewer losses. If there are constraints on these parameters either areal or monetary then the size of the cropping area is reduced.

A soil moisture-accounting routine has been built into CROP86. The amount of water in the soil profile available to the roots of the crop are accounted for. A root function simulates the growing plants increasing the available soil moisture as the crop grows. Whenever the soil moisture level reaches a specified level and there is water stored in the reservoir an irrigation occurs. An irrigation efficiency factor is applied.

There are too many design parameters to obtain a satisfactory design in a single run of the computer, within a reasonable processing time. The optimum design can be generally be obtained by a skilled operator within 3 or 4 runs.

This design system has been used in several countries around the world including Mali, Mexico, Brazil, USA, Thailand, India, Sudan, Kenya and Tanzania. Many of these examples will be included in a USAID publication that is now being written.

Summary and Discussion

Water Harvesting Systems can make many areas available for human habitation. It can reduce the drudgery of millions of people now forced to carry water great distances. It can open up large areas of land for cultivation and improve the production on marginal dry lands presently being used around the world. With so much potential why hasn't it been more widely accepted? One reason appears to be that there is no water harvesting technique superior to all others. Each area needs to be carefully evaluated before a recommended design can be made. The use of the personal computer can make the design of water harvesting system more optimal. By using historical data fairly accurate prediction can be made of the operation and water production from the systems. With the more accurate advance prediction, it should be possible to get better support from funding agencies and institutions.

The use of a compartmented reservoir system in areas of flat terrain provides a relatively low-cost efficient method of storage as compared with a conventional single compartmented reservoir. The system can be used to store excess water during rainfall events to be used as supplemental irrigation. Wherever naturally occurring excess water is not available runoff can be created using treated catchments.

Water storage efficiencies of 40 - 50 percent 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 and would go dry. Even higher savings are possible at a cost within the economics of supplemental irrigation if an evaporation cover is placed on the "last" compartment. The use of reinforced mortar- coated foam platform or flattened hollow ceramic spheres appear to be long-lasting evaporation control measures suitable to be used for water harvesting systems.

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 requires the pumping of 25% of the initial storage to obtain a 45% water use efficiency. 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 much less than pumping groundwater due to the very low pumping lift. Fortunately the cost of low head pumping can be dramatically reduced using efficient propeller pumps. The cost of photovoltaic power to power these pumps has also been reduced in the past few months. This combined method of pumping due to its efficiency, long life and low maintenance should always be considered when installing a compartmented reservoir system that requires pumping. In some areas the use of wind energy would be the appropriate technology to use.

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