WATER HARVESTING AGRISYSTEMS USING COMPARTMENTED RESERVOIRS

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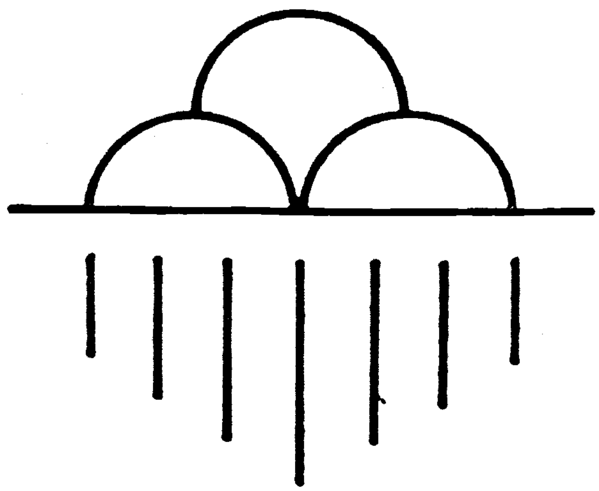

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Abstract

The use of compartmented reservoirs make storage of water for water harvesting agrisystems more efficient. Evaporation and in some cases seepage losses are reduced using the compartmented reservoir by keeping the water concentrated into as small a surface area as possible.

The compartmented reservoir can be used to store excess runoff water and provide supplemental irrigation for rainfed agriculture. A conventional reservoir can be retrofitted into a compartmented reservoir at the time of cleaning by building earthern embankments either in the reservoir or adding compartments outside. Experience in Brazil has shown that a compartmented reservoir can be built for 20 percent less cost than the typical reservoir in flat terrain. The reason for this is that intermediate embankments needed to form the compartmented reservoir provide a place to deposit excavated material. This provides a place to deposit the excavated material and reduces the distance that earthmoving equipment need to move the material.

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.

Excess runoff water from planted areas can be stored in compartmented reservoirs until needed for supplemental irrigation of the crop. Moisture available for the crop and excess runoff can be increased by means of strip farms. The land is cleared and shaped so that runoff from a fallow strip can be directed to the planted strip of crop with the excess going into storage for later use. Runoff can also be stored from treated or untreated natural watersheds that are not cropped.

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A computer model has been developed to help in the design of the water harvesting 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 increasing food production in arid and semi-arid regions is the use of water harvesting agrisystems. These systems are a combination of a treated catchment, surface storage and an agricultural area. By converting marginal dryland areas into water harvesting agrisystems agricultural production can be improved through supplemental irrigation of the crop during critical stress periods.

Catchment Construction

If there is not sufficient runoff to supply supplemental irrigation then catchment areas must be set aside and treated to increase runoff. In this way a land resource is converted to a water resource. These catchment areas can be strips of land within the agricultural area or a contiguous area outside of the planted 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 within a contiguous area outside the planted area.

A list of the more promising methods of catchment treatment 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; (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 cm of water could be as high as $10-12/hectare-cm. This is a very high unit price for water but the farmers will pay it because otherwise no crop can be grown. This process, in which a farmer plants every other year, is called fallowing. This process does not work south ot 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) 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 somwhat 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 that 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 onto 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 reservoir protected from excessive evaporation with a floating layer of foam filled glass bottles. This water is pumped back during dry periods to water the grapes and deciduous fruit trees planted in the drainage ways on the catchment. The system has been expanded. It has had ample water since it was completed 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. The operation of this water harvesting agrisystem over the past 15 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 construction 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 storage of water is usually more expensive.

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. Wind breaks can also be used on smaller ponds to reduce evaporation. Vegetative wind breaks might use more water from the pond than they would save.

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 polyethylene sheets (Drew, 1972), concrete slabs made with lightweight aggregate (Eng. News Record, 1966) floating edge sheets of expanded polystyrene (Cluff, 1967) have been tried and largely abandoned. A test by the author 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 become wetted. This caused 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 continous raft (Cluff 1977b). Expanded polyethylene sheets have been found to absorb water that reduces the strength and life of the material. This water logging 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 three years, been very effective. The final concrete coating can be applied while the raft is floating on the water. This povides an intergral 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 photovotaic 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 ceramic. 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 loss by 70%. The use of ceramic or glass spheres will provide an evaporation contol method that will last indefinitely. One ceramic expert claimed that if the ceramic sphere was properly made and properly fired it would last over 1000 years floating on water unless of course the sphere was broken. Initial tests have shown that 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, by plaster of paris molds or by using a potters wheel.

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 covered. 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 found the concept of the compartmented reservoir was similar to the hafir constructed by the British in Sudan.

A relatively large hafir was constructed in El Obeid in 1940 The town of El Obeid has grown to a size of over 200,000 people so the Sudanese government built a second hafir system in 1977. This water storage system was studied using the compartmented reservoir optimization program, CROP84 (Cluff, 1985). This 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 recieving 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.

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 recieving 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 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

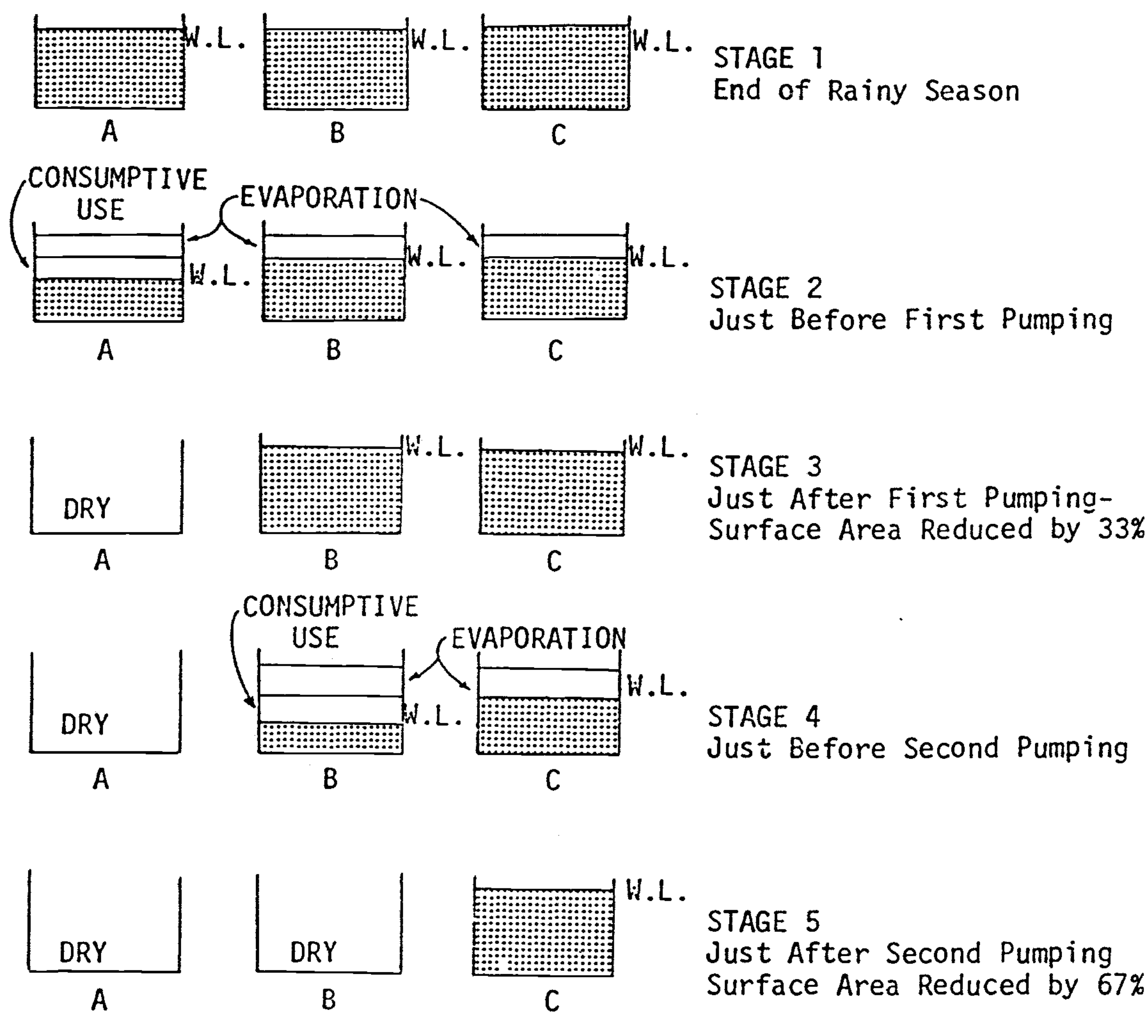

Figure 1. Schematic cross-sectional diagram of a three-compartment reservoir showing water levels (W.L.) of various stages in the annual cycle of operation.

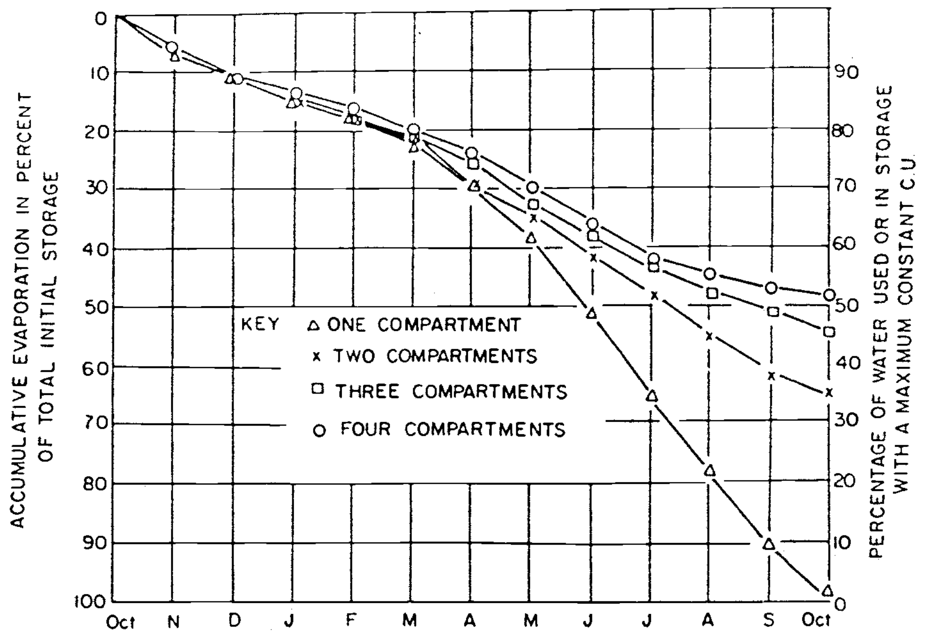

Figure 2. Evaporation Loss for Compartmented (but undeepened) Reservoirs with a Constant Volume and Area, a Maximum Constant Consumptive Use and a Depth Equal to Annual Evaporation Loss at Tucson, Arizona.

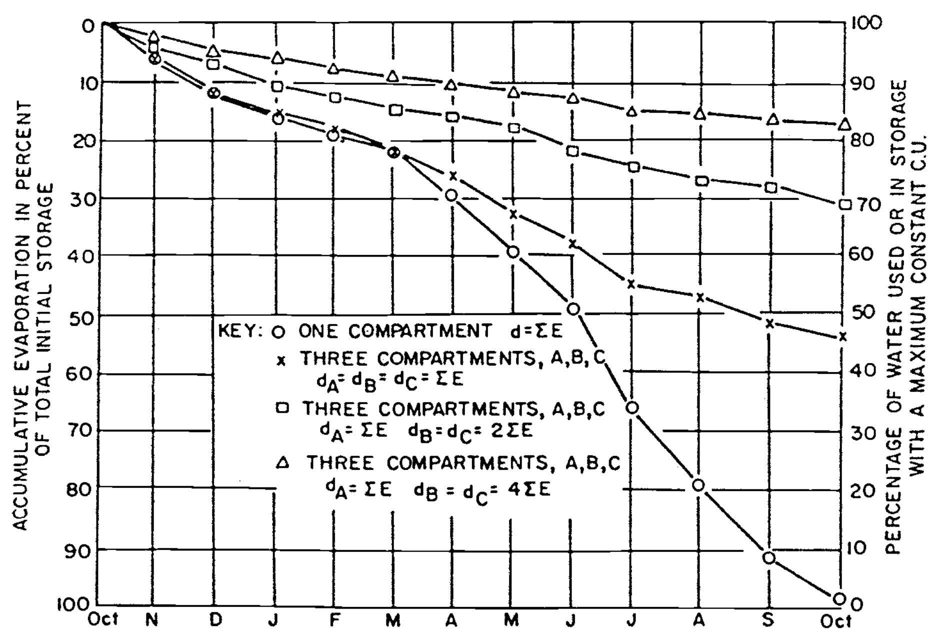

Figure 3. Evaporation Loss in Percent of Total Initial Storage for Compartmented Reservoirs with a Constant Volume, Varying Depth and a Maximum Constant Consumptive Use (Tucson, Arizona).

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 comsumptive 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 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 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 (CROP84)

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 it use. A more complete desciption 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. 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 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 minimum amount is 95 or 96 % of the time. 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 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 CROP84. 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 surface water 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 and most recently Sudan. Data has been collected for Morocco and runs will be made there in the near future. Specific examples from these countries will soon be available as a result of a USAID sponsored project.

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 a conventional single compartment reservoir. The system can be used to store excess water during rainfall events to be used as supplemental irrigation. Wherever naturally occuring excess water is not available runoff can be created using treated catchments. The coupling of this artificial or naturally collected runoff with agriculture and a surface storage system is called a water harvesting agrisystem. The use of a compartmented reservoir system, refered to as a hafir in Sudan, in conjunction with the agrisystem can be very cost effective. Water use efficiencies of 50 -60 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. 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 in water harvesting agrisystems.

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.

CROP84 can be used in most personal computers to design optimum water harvesting agrisystems. Its use is important to avoid as much as possible uneconomical designs. The calibration of this computer model can be improved as data is collected from water harvesting agrisystems.

The requirement of a pump can be met in several different ways. Alternate energy sources such as photovoltaic or wind would be recommended particularly in the more remote areas where petroleum may not always be available in the future. The propeller pump is recommended to reduce the amount of energy needed for low-head pumping.

In conclusion it is recommended that addional water harvesting agrisystems need to be installed in Morocco and other countries to stabilize agricultural production from marginal dryland areas.

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