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SURFACE STORAGE FOR WATER HARVESTING AGRISYSTEMS[1]

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Abstract.--This paper is a summary of the various types of methods that can be used to store water for water harvesting agrisystems in arid and semiarid lands.

Supplemental water for irrigation is essential for maximum production. Even though storage of water in flat terrain may be relatively expensive it is generally very cost effective if used for supplemental irrigation with the soil profile serving as the primary source of water storage.

Seepage and evaporation control are discussed. There are several options for seepage control. In general, evaporation control is more expensive. The compartmented reservoir is one way of significantly reducing evaporation at a cost low enough for supplemental irrigation.

INTRODUCTION

Concentrating runoff on cropped areas in arid areas has been done in some parts of the world for several centuries. This practice was being done in the Negev desert in Israel some 4,000 years B.C. (Evenari *et al*. 1971). Surface storage in the form of small reservoirs in conjunction with this type of water harvesting has not been extensively used. The major reason for this has been the difficulty in controlling evaporation and seepage from these small reservoirs.

SUPPLEMENTARY IRRIGATION

The value of applying a small amount of water at a critical time to rainfed agriculture has been documented. Kranz (1979) found in India that the addition of as little as 5 cm of water more than doubled the production from several crops including corn.

In the great plains area, a large section of rainfed agriculture practices fallowing where fields are tilled, but not planted, in order to trap and conserve as little as 2 to 5 cm of rainwater from one year to go with the next year's precipitation so that a crop can be grown. It has been estimated that as much as $60 per acre-foot or $0.05 per cubic meter ($5/ha-cm) of water (1978 dollars) is spent obtaining this supplemental water but without it no crop can be raised (Cluff 1978). In tests by Leubs and Laag (1975) in a 300 mm rainfall area they found that on test plots where half of the land was used as an impermeable watershed there was more barley production in two out of three years than in the fallow-crop system which used the same land area.

Fallowing does not work in the lower latitudes because of high evapotranspiration losses it is virtually impossible to store usable water in the soil profile for shallow rooted crops from one year to the next. Therefore water harvesting or concentrating rainwater directly during the year in which the crop is raised is needed.

The distribution of rainfall in arid and semiarid areas is not very dependable, therefore even with concentration of rainfall through water harvesting, using only the soil profile for storage, there will be crop failures.

Morin and Matlock (1975) 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 semiarid regions it must be combined with efficient surface storage.

One additional factor supporting the use of surface storage in water harvesting is sometimes overlooked. In constructing catchments to concentrate runoff on planted areas there is always a

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natural tendency for placing dikes or retainers to keep the runoff from leaving the planted area until it all infiltrates. This has led to crop damage by cutting off air to the root zone (Leubs and Laag, 1975). When a storage pond below the planted area is used there is not as much need for the retainers. If the runoff rate exceeds the infiltration rate and more water can be stored in the soil profile at the end of the rainfall then the runoff can be pumped back to the head of the field and reapplied.

SEEPAGE CONTROL

Chemical Treatments

Sodium salts such as sodium chloride, sodium carbonate, sodium silicate, and sodium polyphosphate each act as dispersing agents. The cheapest material is sodium chloride. This material has been used effectively for catchment construction to sterilize and reduce infiltration (Cluff and Frobel 1978). In the fall of 1979 a seven-acre salt treated catchment was installed at the Black Mesa Water Harvesting Agrisystem (Cluff 1980). The resulting runoff water is low in dissolved solids; the salt stays with the clay.

The rate of application of sodium salts for reservoir seepage control should be greater than for catchment construction in order to obtain a relatively effective seal against hydrostatic pressures. The application rate depends primarily upon the clay content of the soil, but will usually be 2.6 to 3.9 pounds per square yard (1.0 to 1.5 kg/m^2). Detailed construction methods have been described by Reginato _et al_. (1968). The life of a sodium treated reservoir is dependent on the quality of the water being stored. If the water is low in dissolved solids (less than 500 ppm) and sodium is the predominant ion in the incoming water, the treatment will last for several years. Water relatively high in calcium and magnesium would cause the system to fail in a short period of time. The treatment works especially well when used in conjunction with a sodium treated catchment because the water from the sodium treated catchment carries some dispersed suspended clay. Further, even though the total dissolved solids is less than 200 ppm the water contains more sodium than calcium and magnesium. This assures that a salt treated reservoir using a salt treated catchment would have a long life.

Polymeric sealants work best on medium grained soils where the calcium and magnesium content of the water is high. Application of polymeric sealants to existing reservoirs may be done by adding the sealant to the storage water. The rate should be approximately one gallon of sealant to one thousand gallons (3.78 l to 3780 l) of stored water. The preferred method is to add the sealant to a new or emptied reservoir. In this case the soil surface is moistened to a depth of 6 to 12 inches (152 to 304 mm) with water containing the polymeric sealant in a 1:1000 volumetric proportion and then compacted (Boyer and Cluff 1972). The seepage reduction using polymeric sealants is somewhat unpredictable and therefore tests should be made with the particular soil prior to its use.

Bentonite

Good quality bentonite clay, when wetted, swells to several times its original volume. The powdered clay can be mixed with the soil or applied as a layer of pure clay that can be buried or left on the surface. The mixed or buried layer methods are generally more durable than the surface treatment. A minimum treatment rate of one pound per square foot (4.84 kg/m^2) is recommended for soils containing small amounts of sand but application rates can be as much as three to four pounds per square foot (14.5 to 19.4 kg/m^2) in very sandy soil (Boyer and Cluff 1972; Rollins _et al_. 1970).

Alternate wetting and drying cycles reduce the effectiveness of the bentonite seal after about three or four seasons. Therefore, this method should not be used on sites that will be exposed to repeated wet/dry cycles.

Soil Cement

Soil cement may be broadly defined as a mixture of portland cement, natural soil and water. The amount of portland cement required increases as the amount of fine material in the soil increases, but generally averages 7 to 15 percent by volume. The soil should ideally be a well-graded material with 100 percent passing a three-inch (76.2 mm) screen (Portland Cement Association 1968). A soil consisting predominantly of gravel-size particles should not be used for soil cement. If the desired soil type is not available at the site, a source location must be found that has suitable soil.

The top six to eight inches (152 to 203 mm) of soil at the site are first mechanically tilled. Portland cement is then proportionately distributed and mixed into the soil with a rotary tiller and, at the same time, water is added to obtain an optimum moisture content. The mixture is then compacted by rubber-tired road compactors or trucks until the finished thickness - usually 4 to 6 inches (102 to 152 mm) - is obtained. The soil cement must be allowed to water cure (surface is sprayed periodically with hand-held hoses) for up to seven days. A central mixing plant can be set up for large projects requiring imported soil. The finished product is considered to have relatively low permeability and high durability if properly installed.

Synthetic Membrane Liners

Generally, synthetic membranes such as polyethylene (PE), polyvinyl chloride (PVC), butyl and hypalon rubber, and chlorinated polyethylene

(CPE) are more expensive in material costs than is the use of sodium. However, polyethylene liners and in some cases polyvinyl chloride liners will compete very well with soil cement and bentonite, particularly if the materials have to be transported very far. A further advantage of the synthetic membranes is that the probability of success is very high when the membrane is properly installed. This is not always true of other systems. Uncovered butyl rubber has been known to resist atmospheric degradation for more than fifteen years whereas polyethylene and polyvinyl chloride must be covered with earth to insure an acceptable life span. In addition to protecting the membrane from mechanical damage, the earth cover also reduces the seepage significantly through any accidental puncture and is therefore recommended where feasible on all membrane installations. The subgrade must be free of sharp aggregate and vegetation and must be relatively smooth. Proper sealing of the overlap joints is very important when the synthetic membrane is to be used as a seepage control membrane in a reservoir. Mastic and tape are generally used for sealing polyethylene. The other materials, PVC, CPE and butyl or hypalon rubber, can be seamed with solvent-type cements. Detailed construction techniques for synthetic liners may be found in the publication ASAE R340 (1970). In some countries insects, such as termites, might attack a synthetic membrane. In this case it may be necessary to use some type of insecticide. Perhaps a double liner with insecticide between the layers might work.

Concrete Linings

Poured concrete linings, as used in water harvesting storage projects, are generally 2 to 4 inches (51 to 102 mm) in thickness and lightly reinforced with wire mesh. A small batch plant or locally available ready-mixed concrete would be desirable in the construction of a concrete lining. A properly installed concrete lining requires skilled labor and special equipment not always found in remote regions. The concrete should be well cured to help obtain the watertightness and resistance to weathering desired for reservoir linings.

The reservoir embankment surface and reservoir bottom must be smoothed and properly compacted to grade. The equipment and methods used will depend on the characteristics of the subgrade soil. Expansive subgrade soils should be avoided in colder regions because of membrane damage by frost action. Detailed construction specifications can be obtained from the Portland Cement Association (1962).

Reinforced mortar-covered plastic is another concrete lining method in which polyethylene or polyvinyl sheeting is used as the effective seepage control membrane and the wire mesh-reinforced mortar is the protective cover. The plastic must be properly sealed at the overlaps to prevent any seepage since some cracking in the mortar does occur. Plastic, wire mesh-reinforcement and mortar are all run continuously into an anchor trench at the top of the reservoir slope to prevent slippage of the liner on the slope. The mortar is added in sufficient thickness to cover the wire mesh. Generally an average of 0.75 inch (19 mm) is used to cover 20 gage stucco wire. A 1.0 inch (25.4 mm) mesh size is generally used. Larger openings increase the difficulty in keeping the wire buried in the cement mortar. With a mesh up to one inch mortar can be dumped on the surface and spread with rakes. Only a light trowelling is required, thus reducing the amount of hand labor needed. Fewer cracks occur when using coarse, washed concrete sand than fine plaster or mortar sand (Cluff 1975).

The mortar-covered plastic membrane liner can be effectively installed using only hand labor with a minimal amount of equipment. The mortar can also be applied using gunite equipment, when available. This type of lining can be constructed with mortar-covered sides and an earth-covered bottom which would cut construction cost considerably.

Asphalt Linings

Unlike water harvesting catchment linings, asphalt can be used in reservoir construction without reinforcement as long as the lining is covered with soil. The most successful unreinforced asphalt linings have been catalytically blown asphalt or air-blown asphalt cements of the 50-70 penetration range (Hoiberg, 1965). The amount of asphalt membrane material required will vary with the type of subgrade but will not be less than 1.5 gal/yd^2 (6.8 l/m^2) applied by conventional asphalt-distributor spraying techniques.

The asphalt membrane must be covered with a protective soil cover of sufficient depth to prevent atmospheric degradation or mechanical damage. Using fine cover materials, such as sand, on the top of the asphalt and then adding coarse grained gravel or cobbles provides an erosion resistant surface suitable for banks.

Exposed asphalt-fiberglass linings have been successfully used for small ponds (Myers _et al._ 1974). The asphalts used can be either cutbacks (solvent based) or emulsions (water based). Either anionic or cationic emulsions can be applied by spraying or brooming, using industrial floor brooms with soft bristles. Cutbacks usually have to be heated to 150° F (65.6° C) minimum and applied by spraying.

If spraying, a 0.25 gallon per square yard (1.1 l/m^2) tack coat is first applied, followed by the 0.75 to 1.0 oz per square ft (0.025 to 0.033 kg/m^2) fiberglass matting. An additional 0.5 gallons per square yard (2.26 l/m^2) of asphalt is then applied over the matting.

If brooms are utilized the tack coat is not used, but rather the glass is placed directly on the ground and asphalt broomed across the top.

After this first treatment, a seal coat of asphalt-clay roofing type emulsion is applied at a rate of approximately 0.33 gallon per square yard (1.51 l/m^2). This method does, however, require a return trip to the reservoir to complete the treatment.

One advantage of the asphalt-fiberglass treatment is that the broom method can be used, thus avoiding the use of specialized equipment. The fiberglass, however, may not be readily available in many countries.

When the asphalt-polyethylene-asphalt-chip-coated treatment (APAC) is to be used as a reservoir lining for seepage control, 6 mil polyethylene is recommended with the asphalt applied at approximately twice the catchment rate. In addition, it is also necessary to seam the joints by placing mastic between the overlapped plastic sheeting. A protective soil cover of 6 inches (152 mm) or more is recommended (Frobel and Cluff 1976).

Asphalt concrete provides the best type of durable, waterproof, erosion-resistant hydraulic lining but its cost may be prohibitive in all but large municipal reservoirs. Care must be taken to insure proper mix design and subgrade preparation. The lining is placed by standard paving machines and by special equipment or hand methods on side slopes.

Asphalt-rubber utilizing shredded rubber from tires can also be used for seepage control (Frobel et al. 1977). Laboratory tests reveal that this material has considerable potential for seepage control. The material has good weathering properties and stays flexible over long periods of time.

A few small field installations have been made with some success. More field testing is needed before the asphalt rubber can be widely used. The material has the disadvantage that specialized equipment is needed for its application.

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 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 are:

1. Surface-area reduction.
    a. Proper selection of reservoir sites.
    b. Constructing reservoirs with a minimum ratio of area to storage volume.
    c. Diking off shallow areas.
    d. Compartmented reservoir.
2. Reflective methods (floating reflective beads, dyes, etc.)
3. Surface films. (Oil and long-chain fatty alcohols.)
4. Mechanical covers. (Roofs, floating rafts and windbreaks.)

Surface-area Reduction

Surface area to volume ratio can be reduced by proper selection of a site, diking off shallow areas or in the case of smaller reservoirs deepening through excavation. This generally increases the seepage rate.

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.

The compartmented reservoir which will be discussed in detail in the next section takes advantage of this temperature reduction.

Reflective Methods

Reflective barriers include 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.

A test by the author consists of placing crushed expanded polystyrene as a reflective barrier. Evaporation savings were about 50 percent 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 percent, making the approach impractical (Cluff 1977a).

Surface Films

Surface films formed by long-chain alcohols received considerable attention during the late 1950's and early 1960's. The research was sponsored and coordinated by the U.S. Bureau of Reclamation. Several land grant universities were involved: Colorado State, Arizona, Utah State, Oklahoma State and Texas Tech. The U.S. Geological Survey also conducted experiments. 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

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 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 potential of the compartmented reservoir is demonstrated in figure 2 under idealized conditions.

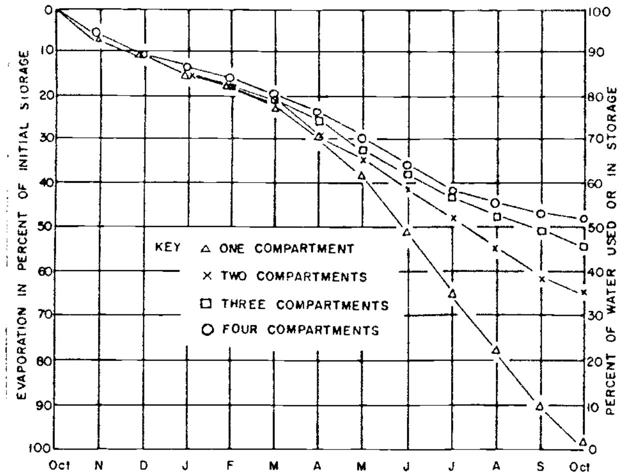


Figure 2. Evaporation loss for compartmented reservoirs with a constant volume and area, a maximum constant consumptive use and a depth equal to annual evaporation loss at Tucson, Arizona.

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 the figure 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.

This type of graph could be made anywhere in the semiarid and arid conditions and would illustrate the potential of compartmented reservoirs for evaporation control.

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 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 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. 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 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.

Mechanical Covers

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.

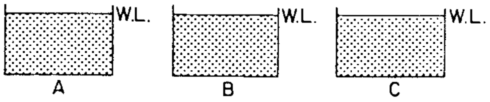
Among the leading floating-cover methods are the use of wax blocks (Cooley 1975), foamed butyl rubber (Dedrick *et al*. 1973) and weatherized sheets of expanded polystyrene together to form a continuous raft (Cluff 1972). More recently the expanded polystyrene sheets have been impregnated with wax to prevent water logging 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 have been considered are: (1) Use a wax with a higher temperature melting point; or (2) Use a surface treatment of high temperature wax such as polyethylene; or (3) use wax impregnated lightweight concrete (Cluff 1980b). These leading methods of evaporation control are generally too expensive to use for conventional agriculture. However, as will be described later, their use for supplementary irrigation or in conjunction with a compartmented reservoir appears to be very cost effective.

The Compartmented Reservoir

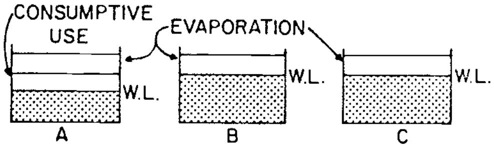
As shown above, the principle of reducing the surface of reservoirs to control evaporation appears to be documented in the literature. The author has failed to find any writings by other researchers, however, concerned with the division of a conventional reservoir into compartments and the systematic pumping or transfer of 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 water is beneficially consumed and the mares soon dry up.

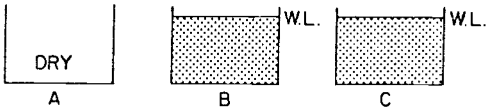
A schematic of the compartmented reservoir is outlined in figure 1.



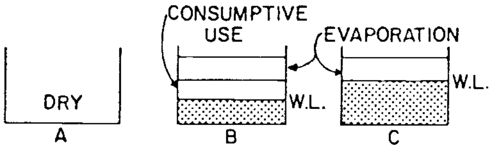
STAGE 1
End of Rainy Season



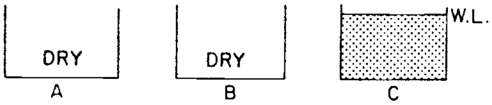
STAGE 2
Just Before First Pumping



STAGE 3
Just After First Pumping-
Surface Area Reduced by 33%



STAGE 4
Just Before Second Pumping



STAGE 5
Just After Second Pumping-
Surface Area Reduced by 67%

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.

small gravity-fed separated compartmented reservoir was constructed in addition to a compartmented system to store water for a 20 ha water harvesting system at the Ejido San Francisco del Bareal located near Parrus, Coahuilla.

Computer Model

A computer model has been developed to study the parameters involved in the compartmented system and their relationship to each other using historical data. A more complete description can be found in Cluff (1977a). In this dissertation the model was used to study many proposed systems using actual data. These computer runs verified the simplified estimation of savings indicated in figures 1 and 2. The results from the operating of the computer program indicated that these savings were dependent upon proper sizing, thus it is important to use the model whenever a compartmented reservoir system is used.

This model was also used to size the three compartment reservoir system at the Black Mesa Waterharvesting Agrisystem (Cluff 1980). This system is fed using a 3 ha salt treated catchment and a 3.3 ha fiberglass reinforced asphalt chip catchment. 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. It is solar powered using a 1200 watt floating photovoltaic concentrator.

Economics

It is beyond the scope of this review to cover the economics. The cost of the various methods of seepage and evaporation control as well as a simplified method of sizing for small projects is found in Cluff and Frobel (1979). Large projects should be costed out separately since there is usually considerable savings in buying materials in large quantities.

Summary

Supplementary irrigation generally will provide more in return that it costs provided simplified storage methods are used.

The NaCl treated catchment feeding into a salt treated compartmented reservoir offers a storage methods that should be cost effective for most crops. A floating cover on the "last" compartment will greatly enhance the efficiency of the compartmented system. This is much more cost effective than a cover on a conventional reservoir.

Additional work needs to be done of floating covers for evaporation control but at the present time either wax impregnated lightweight concrete or foam capped with polyethylene thermal wax appear to be the leading methods. Floating solar collectors can simultaneously provide power and reduce evaporation.

It is important in designing any surface storage system that a hydrologic analysis be made if possible using some type of computer model to estimate the correct size. The cost of such an analysis is usually very small in relation to the cost of constructing a water harvesting agrisystem.

REFERENCES CITED

American Society of Agricultural Engineers. 1970. Installation of flexible membrane linings. ASAE R340.

Boyer, D. G., and C. B. Cluff. 1972. An evaluation of current practices in seepage control. Arizona American Water Resources Association. Proceedings, Vol 2.

Cluff, C.B. 1966. Evaporation reduction investigation relating to small reservoirs. Technical Bulletin 177, Agricultural Experiment Station, University of Arizona.

Cluff, C.B. 1972. Patchwork quilt halts evaporation loss. Arizona Cattle Log, Arizona Cattle Association, Phoenix, Arizona.

Cluff, C.B. 1974. Engineering aspects of water harvesting research at the University of Arizona. Water Harvesting Symposium, March 26-28, ARS-W-22, ARS, USDA.

Cluff, C.B. 1975. Surface water storage potential in the Nara and Songa areas of Mali. Summer project, 1975. Unpublished Consultant's Report, Wunderman Foundation, New York.

Cluff, C.B. 1976. Agro-industrial training, research and extension in arid zones. Report of the Expert Consultant in Hydrology, United Nations Development Program, UNDP/MEX/74/003. Unpublished Consultant's Report, submitted to FAO, United Nations, Rome, Italy.

Cluff, C.B. 1977a. The compartmented reservoir - a method of efficient water storage. Ph.D. Dissertation, Department of Civil Engineering. Colorado State University.

Cluff, C.B. 1977b. Evaporation control for increasing water supplies. Alternate Strategies for Desert Development and Management, California, May 31-June 10.

Cluff, C.B. 1978. The use of the compartmented reservoir in water harvesting agrisystems. Proceedings of the International Arid Land Conference on Plant Resources (Texas Tech University, Lubbock, Texas, Oct. 8-15, 1978).

Cluff, C.B. 1980. Water harvesting systems, a method of reclamation for mine tailings. Mine Tailings Reclamation Workshop (Univer of Arizona, Tucson, Arizona, April 23-2

Cluff, C.B. 1980b. Low cost evaporation control using wax impregnated foam. Project Completion Report. OWRT Project No. A-091-ARIZ. Water Resources Research Center, University of Arizona, Tucson.

Cluff, C.B., and R.K. Frobel. 1978. Water harvesting catchment and reservoir construction methods. Water Resources Contribution No. 2. Water Resources Research Center, College of Earth Sciences, University of Arizona, Tucson.

Cooley, K.R. 1970. Energy relationships in the design of floating covers for evaporation reduction. Water Resources Res. 6(3): 717-727.

Cooley, K.R. 1975. Evaporation suppression for conserving water supplies. Proceedings of the Water Harvesting Symposium (Phoenix, Arizona, March 26-28, 1974). ARS W-22, Agricultural Research Service, U.S. Dept. of Agriculture.

Cooley, K.R., and C.B. Cluff. 1972. Reducing pond evaporation with perlite ore. Amer. Soc. of Civil Engineers, Journal of the Irrigation and Drainage Division 98 (IR2): 255-266.

Drew, W.M. 1972. Evaporation control: a comparative study of six evaporation restriction media. AQUA, State Rivers and Water Supply Commission of Victoria.

Engineering News Record. 1966. Concrete slabs cut reservoir losses. 177(15): 140.

Evenari, M., L. Shana and N. Tadmore. 1971. The Niger: the challenge of a desert. Harvard University Press, Cambridge, Massachusetts.

Frobel, R.K., and C.B. Cluff. 1976. Plastic reinforced asphalt seepage barrier. Journal of the Irrigation and Drainage Division, September.

Frobel, R.K., C.B. Cluff, and R.A. Jimenez. 1977. Development of a low cost asphalt-rubber membrane for water harvesting catchments and reservoir seepage control. Project Completion Report, OWRT Project No. A-075-ARIZ.

Garstka, W.U. 1962. The Bureau of Reclamation's investigations relating to reservoir evaporation loss reduction. Symposium on Water Evaporation Control. Council of Scientific and Industrial Research and UNESCO South Asia Science Cooperation Office, Poona, India.

Hoiberg, A.J. 1965. Bituminous materials: asphalts, tars and pitches. Vol. II, Part I, Interscience Publishers, New York, N.Y.

Krantz, B.A. 1979. Small watershed development for increased food production. International Crops Institute for the Semiarid Tropics, Hyderabad, India. ICR79-0019.

Leubs, R.E., and A.E. Laag. 1975. Water harvesting for barley in a 30-cm winter rainfall area. Proceedings of the Water Harvesting Symposium (Phoenix, Arizona, March 26-28, 1974). ARS W-22, U.S. Department of Agriculture.

Morin, G.C.A., and W.G. Matlock. 1975. Desert strip farming--computer simulation of an ancient water harvesting technique. Proceedings of the Water Harvesting Symposium (Phoenix, Arizona, March 26-28, 1974). ARS W-22, U.S. Department of Agriculture.

Myers, L.E., and G.W. Frasier. 1974. Asphalt-fiberglass for precipitation catchments. Journal of Range Management, Vol. 27(1).

Portland Cement Association. 1962. Concrete for hydraulic structures. CB6-2, Chicago, Illinois.

Portland Cement Association. 1968. Soil cement linings for water reservoirs. Los Angeles, California.

Reginato, R.J., L.E. Myers, and F.S. Nakayama. 1968. Sodium Carbonate for reducing seepage from ponds. WCL Report No. 7. United States Water Conservation Laboratory, Agricultural Research Service, Phoenix, Arizona.

Rollins, M.B., and A.S. Dylla. 1970. Bentonite sealing methods compared in the field. Journal of the Irrigation and Drainage Division, Proceedings American Society of Civil Engineers, 196, (IRS).