WATER HARVESTING CATCHMENT AND RESERVOIR CONSTRUCTION METHODS

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Water Resources Contribution No. 2
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DISCUSSION AND CONCLUSIONS

A state-of-the-art summary has been presented of the more promising methods of constructing water harvesting systems. A method of combining the material presented in a rational cost-estimating procedure is given. Presenting cost information is not generally done because of the controversy it sometimes creates in ranking systems according to cost. However, it is essential to the planner to be able to compare with alternate systems and therefore is included. These costs need to be modified to fit the conditions of other countries.

An example was presented that illustrates how the various factors are interrelated. In the example an APAC catchment was used with an APAC membrane seepage control and a wax-impregnated polystyrene floating cover. If a more inexpensive, but less efficient, catchment treatment, such as sodium-treated compacted-earth is used, it would require both a larger area and a larger storage. When all the factors are considered the reduction in unit cost of water utilized is less than one might expect.

This paper introduces to the literature an empirical method of sizing a catchment and storage system to produce a given quantity of water. This empirical method seems to work satisfactorily in southern Arizona but needs to be recalibrated before it can be used in other areas.

Whenever possible, a more detailed hydrologic study should be made in order to size the water harvesting system. With proper design, a water harvesting system can be used to furnish a dependable high-quality source of water at a cost that, in many cases, will be significantly lower than alternative sources.

The costs presented in the paper reflect those of smaller systems that would be used to supply stock water or domestic water on a small scale. For some types of treatment, costs will be considerably less if large systems are constructed. Therefore, extrapolation to large systems should not be made. Independent cost analysis should be made for these larger projects.

The paper demonstrates that there are several viable methods of constructing water harvesting systems that can be cost competitive with more conventional methods of supplying stock or domestic water for small systems. For larger scale systems, the costs would be significantly less than those presented here.

ACKNOWLEDGMENTS

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WATER HARVESTING CATCHMENT AND RESERVOIR CONSTRUCTION METHODS[1]

INTRODUCTION

There is an urgent need for additional water in the arid lands of the world. In many inland areas utilization of ground water far exceeds the recharge rate. The higher yielding streams and available reservoir sites have already been over-developed. The percentage of rainfall utilized beneficially, however, is very small. Most of the rainwater falling on arid lands is absorbed by the soil only to be evaporated due to the prevalent low humidity and high insolation.

One method of greatly improving runoff efficiency and providing water of high quality is to artificially treat the surface of the soil. This increases the runoff which can then be stored until it is needed. A facility designed to catch rainwater using artificial means is called a water harvesting catchment. When combined with a storage reservoir it is referred to as a water harvesting system. Such systems have been in use for several thousand years. Water harvesting was used as early as 3000 B.C. by a large indigenous civilization in the Negev Desert in the Middle East in a region receiving less than 200 mm of rainfall annually. Much progress has been made recently from modest research programs in developing better methods to reduce the cost of water harvesting systems. This paper reports on the most cost-effective methods presently available for both catchment and reservoir construction. Methods of seepage and evaporation control are discussed. The concept of the compartmented reservoir as a means of evaporation control is also elucidated.

[1]Research funds were provided in part by the Office of Water Research and Technology, U.S. Department of the Interior.

CATCHMENT CONSTRUCTION METHODS

Land Alteration

Land alteration has been in existence as a runoff inducement method for thousands of years. Clearing and stone removal were used in the Negev Desert of Israel in ancient times. The stones were used to form low walls against which dirt was placed to create collection channels. These walls followed an approximate contour. When runoff occurred the water collected in channels that directed the water to the various terraced agricultural fields. The terrace walls keps part of the water standing in the field and the surplus went through drop structures to lower terraces (Evanari et al., 1969; National Academy of Science, 1974). This method allowed ancient farmers to grow crops on land that otherwise could not have been utilized for this purpose.

This type of contoured catchment can be used on steeper slopes. Altering the land surface by removal of all vegetation and rocks will increase runoff substantially and requires no real skill or equipment. However, some type of surveying equipment would be useful for establishing collection channels on the contour.

Compacted Earth

In order to increase runoff and reduce weed growth, smoothing and compaction can be added to the clearing and rock removal mentioned above. Compaction is most effective when the earth is shaped to provide ridges sloping toward collection channels. This type of catchment has been named the "roaded catchment" since it appears to be an array of roads.

The compacted earth or "roaded catchment" is one of the most basic catchment construction techniques. It requires no synthetic treatment materials; its success depends totally on site conditions and availability of equipment. The technique has been used on a large scale in Western Australia since 1948.

Availability of equipment such as a road grader, a rotary rock rake and large vibratory drum roller is important in reducing costs of a compacted earth catchment (Cluff, 1974). However, substitution of hand labor for shaping and smoothing and use of an automobile driven back and forth for compaction has been successful. A compacted earth catchment can yield 35 to 50 percent runoff efficiency if properly constructed. Figures 1 and 2 show construction of a compacted earth catchment located in southern Arizona. This catchment was compacted following a one-half inch (12.5 mm) rainfall.

Any soil type which can be compacted to form a monolithic hard or crusted surface is suitable for compacted earth catchments. In general, the soil should contain not less than 3 percent clay and not more than 25 percent gravel retained on a 3/16 in. (3.8 mm) screen (Carder, 1970). Unsuitable soil types include heavy clays, friable clays, coarse gravels with little clay content, and loose sands with no clay subsoil. All compacted earth catchments must be compacted when moist to provide an optimum runoff surface. This moisture can be obtained from natural rainfall to keep costs to a minimum. Current recommendations on roaded catchments call for a 20 ft to 33 ft (6.1 m to 10.1 m) road width; side slope of 5-15 percent; and road and collecting channel gradients 2 percent at the upper end and reducing with length to a minimum of 0.25 percent (Carder, 1970). Compacted earth catchments are difficult to maintain in areas where there is considerable plant growth.

Chemical Treatments

Sodium salts, when mixed into the upper portion of the soil profile, tend to reduce the permeability of the soil by dispersing the clay fraction. These salts may be referred to as dispersing agents and include, but are not limited to, sodium chloride, sodium carbonate, sodium silicate and sodium polyphosphate. An accurate soil analysis should be made to determine the clay content and type. Once the type and amount of clay in the soil is known, the amount of salt to be used can be calculated. As a general rule, however, during catchment construction sufficient

Figure 1. CONSTRUCTION STEPS IN A COMPACTED EARTH CATCHMENT.

a. Above: Road grader removes the desert shrubs and does initial shaping and smoothing.

b. Below: Final smoothing is done using a rock rake. This can also be used to mix salt into the soil.

Figure 2. COMPACTED EARTH RUNOFF PLOT (H-5), ATTERBURY EXPERIMENTAL WATERSHED, NEAR TUCSON, ARIZONA.

a. Above: Installing graveled cover plastic liner for drainage while compacting.

b. Below: Completed catchment.

salt is applied in order to sterilize the soil to prevent weed growth. This will generally require 5 tons per acre (11.4 metric tons per hectare).

These chemical treatments work only on the clay fraction and will not be effective if the soil is coarse-grained. Sodium-treated catchments are also susceptible to erosion unless well-compacted. Dispersing agents can be applied by hand labor if fertilizer spreaders or grain drills are not available. If the soil is properly compacted after application the runoff efficiency will be greatly increased (Cluff, 1974). In general, the site is cleared and shaped as indicated above in the roaded catchment section. After the salt is applied it can be mixed into the upper inch of soil by hand or mechanized rotary rock rake (Figure 1) however successful treatment has been made without mixing. In this case the first rainfall dissolves the salt and carries it into the soil. Following a rainfall of at least one-half inch (12.5 mm) the catchment is compacted. Figure 3a shows the effect of compaction on runoff from a compacted-earth sodium-treated (CEST) catchment. Figure 3b illustrates that the sodium treated catchment can be used for agriculture. The sodium becomes adsorbed onto the clay particles; thus the quality of the resulting water is very good. The quality generally drops to less than 200 ppm after the initial one or two runoff events. The initial runoff is usually less than 1000 ppm. Sodium salts can be used to treat soils having a clay content in the range of 5 to 30 percent. Sodium is also effective in seepage control on expanding-type clays when the clay content is above 15-20 percent.

Wax Treatments

Another relatively cheap material for constructing water harvesting catchment areas is paraffin wax. Pulverized paraffin wax of a low melting point, 120-150°F (49 to 65°C), can be hand applied to a smoothed soil surface at the rate of approximately one to two pounds per square yard (0.54 - 1.08 kg per square meter) (Cooley *et al.*, 1976; Fink *et al.*, 1973). In areas characterized by high soil temperatures, two days are generally

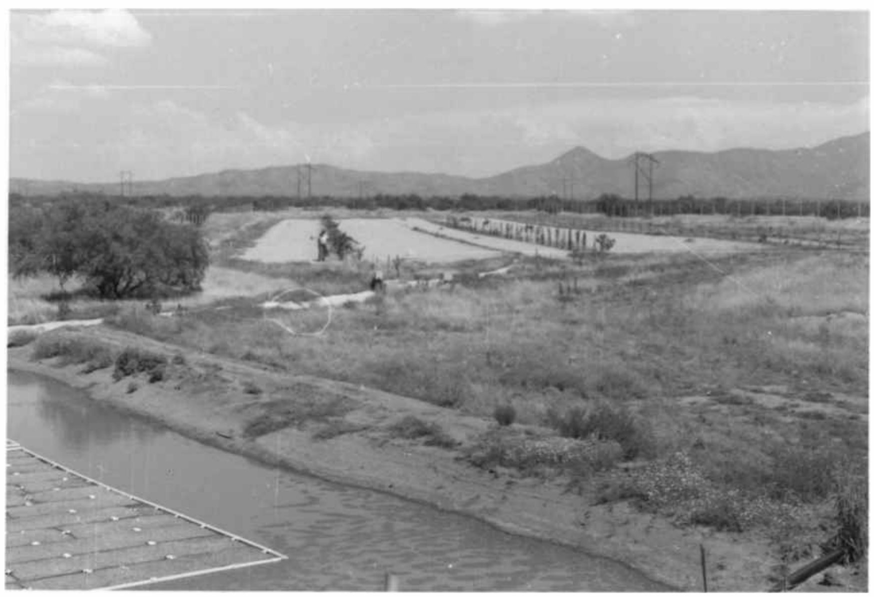


Figure 3. COMPACTED EARTH SODIUM TREATED CATCHMENTS, ARIZONA.

a. Above: Left side compacted, right side uncompacted. Papago Indian Reservation.

b. Below: Water harvesting agrisystem at Page Ranch, Arizona.

adequate to melt the wax into the soil producing a semi-stabilized, water repellant surface treatment. A runoff efficiency of 90 percent has been observed on several different soil types. For best results the wax should be applied to shaped, compacted soils. Paraffin treated plots were used successfully to establish trees on mine spoils and were found to provide a substantially greater amount of soil moisture to the growing plants than did untreated plots (Aldon et al., 1974). Since this use of paraffin is relatively new, its life expectancy on various soil surfaces is unknown; however, some plots are still effective after five years. It has been demonstrated that paraffin treatment is best suited for sandier soils and does fail on some soil types. As an alternative to hand distribution of pulverized wax, melted paraffin can be readily applied by spray methods. Paraffin acts as a water repellent only and will not resist hydrostatic pressures. Therefore, its use as a seepage control method in water storage structures is not recommended.

Synthetic Membranes

As soon as plastic and butyl rubber membranes became available in the 1950's they were tested for water harvesting. The plastics, both polyethylene and vinyl, were found to be effective but short-lived, generally lasting less than one year. Exposed butyl rubber and chlorinated polyethylene (CPE) sheeting has been found to be long lasting and resists degradation for more than fifteen years if secured to the ground to increase resistance to wind damage and other mechanical damage. This material is relatively expensive, however, and its use has been limited to the more developed countries.

Gravel-Covered Plastic

Graveled plastic catchments utilize inexpensive polyethylene covered with an 0.5 to 1.0 inch (12.7 to 25.4 mm) layer of gravel (Cluff, 1971). The gravel cover effectively protects the polyethylene and holds it to the ground. Inasmuch as some precipitation is retained in the gravel cover, this method should not be used in climates where a substantial percentage of the rainfall occurs in less than 0.25 to 0.50 inch (6.4 to 12.7 mm) storms.

A Gravel Extracting Soil Sifter (GESS) has been developed to screen gravel out of the soil, lay down the sheet plastic on top of the fine material, and cover the soil with the extracted gravel.

A plastic-dispensing gravel chute attached to a dump truck as well as a modified self-propelled chip spreader has also been used to install a gravel-covered plastic catchment (Cluff, 1971; Cluff, 1974).

One of the big advantages of the gravel-covered plastic catchment is that it can be installed using hand labor if none of the above equipment is available. The water produced by a gravel covered plastic catchment is of excellent quality and can be used directly for domestic use. The life appears to be in excess of fifteen years if a gravel cover is maintained and the plastic is protected against mechanical damage. The latter would include sterilization of the underlying soil to prevent weed growth.

Asphalt-Based Catchments

Asphalt and its asphaltic derivatives have been used extensively in the construction of water harvesting catchments.

In Australia, several asphalt-concrete paved catchments for municipal supply have been installed using standard road methods (Hollick, 1974). Asphalt concrete requires a smoothed compacted subgrade of select material containing little clay. If properly installed so that cracking is minimized the runoff efficiency will be close to 100 percent. However, asphalt concrete is relatively expensive and requires specialized equipment and skilled labor.

A less expensive method of using asphalt involves a membrane formed by spraying emulsified asphalt on the soil. This method has been tested over a period of several years (National Academy of Science, 1974). Research has shown that the life of unreinforced asphalt membrane catchments is usually less than two or three years. Deterioration of the membrane is accelerated due to cracking, but this can essentially be eliminated by the use of reinforcement. Unwoven 0.75 to 1.0 oz (0.025 to 0.33 kg/m) fiberglass has been successfully utilized for several years as a reinforcing fabric (Myers et al., 1974).

A relatively new catchment construction method entitled APAC (asphalt-plastic-asphalt-chipcoated) utilizes a combination of asphalt emulsion and black polyethylene sheeting protectively covered with aggregate (Cluff, 1974; Frobel et al., 1976). Similarly, a matting material of polypropylene, burlap or fiberglass can also be used in combination with asphalt and gravel chips to provide a strong, efficient catchment. In catchment construction the asphalt emulsion (RSK cationic emulsion) is sprayed on the prepared subgrade at the rate of approximately 0.25 gallons per square yard (1.136 L/m^2) (Cluff, 1974). Polyethylene sheeting (4 mil) or one of the matting materials is then placed over the asphalt and a second coat or asphalt emulsion is applied over the reinforcement. This is immediately followed by an application of aggregate chips. The chips extend the life of the asphalt and inhibit the production of oxidation products which can significantly discolor the harvested water (Myers et al., 1967) (Figures 4 and 5).

Recently, at the University of Arizona, a 10 mil fiberglass matting has been successfully incorporated into the APAC type treatment. With the thin fiberglass it is possible to spray through the material in a single pass. Thus, a boot truck is equipped with a dispenser which rolls the fiberglass out just ahead of the asphalt distribution bar. Asphalt is sprayed through the thin fiberglass onto the soil surface beneath. The optimal rate of application has not yet been determined, but should be in the order of 0.6-0.7 gallon per square yard (2.27-3.17 L/m^2). Immediately after spraying, the surface is covered with gravel chips, which hold the matting firmly to the ground during the curing process. This method is referred to as the fiberglass asphalt chipcoated (FAC) method.

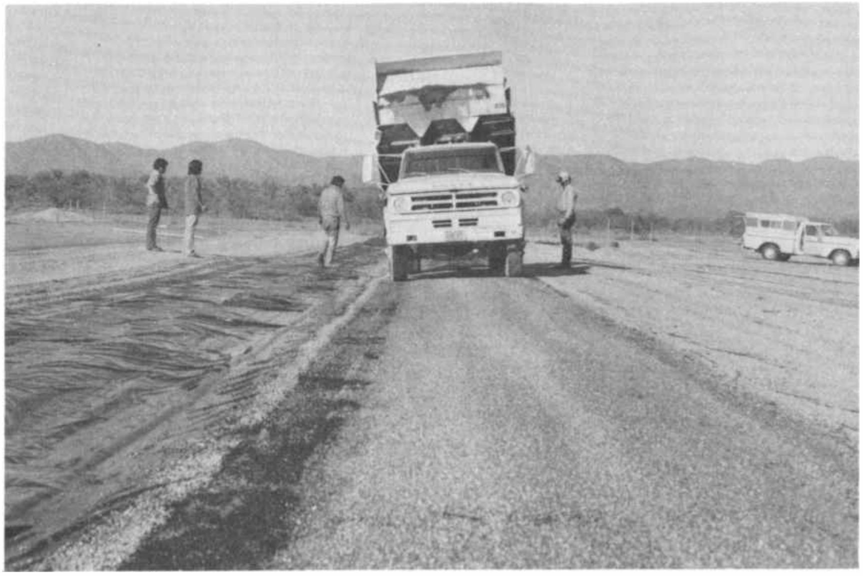


FIGURE 4. CONSTRUCTION OF APAC CATCHMENT IN PROGRESS AT SELLS, ARIZONA

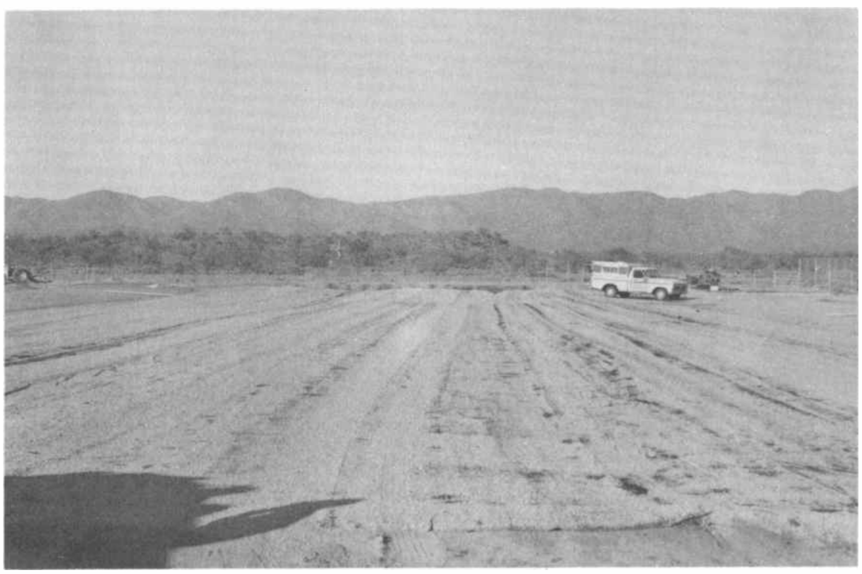


FIGURE 5. COMPLETED APAC CATCHMENT AT SELLS, ARIZONA

Both the APAC and FAC combinations can effectively deliver close to 100 percent runoff efficiency. The APAC method must be applied with special equipment such as asphalt distributor trailers or trucks, which are not always available in developing countries or remote areas. It should be possible, however, if care is exercised, to use a broom to spread the asphalt on the 10 mil fiberglass. The chips could also be added using hand labor.

Asphalt-rubber has also been tested for use in catchment construction in a recently completed research project at the University of Arizona (Frobel et al., 1977). The outer layers of rubber from used tires are shredded and added to the asphalt. Generally a 25 percent rubber mixture is used. The mixture is heated to 350^{o}F (177^{o}C) and stirred with a paddle mixer before being sprayed. The material is very viscous but can be sprayed using specially designed systems. As little as 0.5 gallon per square yard (2.66 L/m^2) is used for catchment construction. In essence, the rubber serves as a reinforcement for the asphalt.

Asphalt-rubber has been used for several years in highways. It has been observed to hold up very well against oxidation and cracking. The biggest disadvantage of this material is that it requires special equipment for application. It cannot be successfully applied by hand.

RESERVOIR CONSTRUCTION METHODS

Seepage Control

Chemical Treatments

Sodium salts such as sodium chloride, sodium carbonate, sodium silicate, and sodium polyphosphate each act similarly as dispersing agents. They are described under catchment construction methods. 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 greatly 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.

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 et al., 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 et al., 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

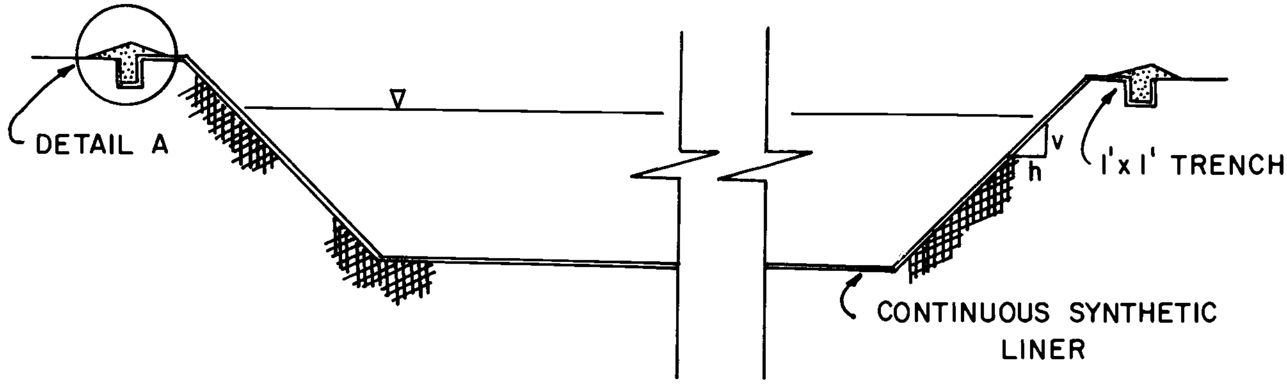
Generally, synthetic membranes such as polyethylene (PE), butyl and hypalon rubber, polyvinyl chloride (PVC), and chlorinated polyethylene (CPE) are relatively expensive in material costs but are easily installed. Their use is most appropriate in countries where construction capital is readily available and labor costs are relatively high. 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. Figure 6 shows construction details for synthetic sheet lining. Detailed construction techniques for synthetic liners may be found in the publication ASAE R340 (1970).

Concrete Linings

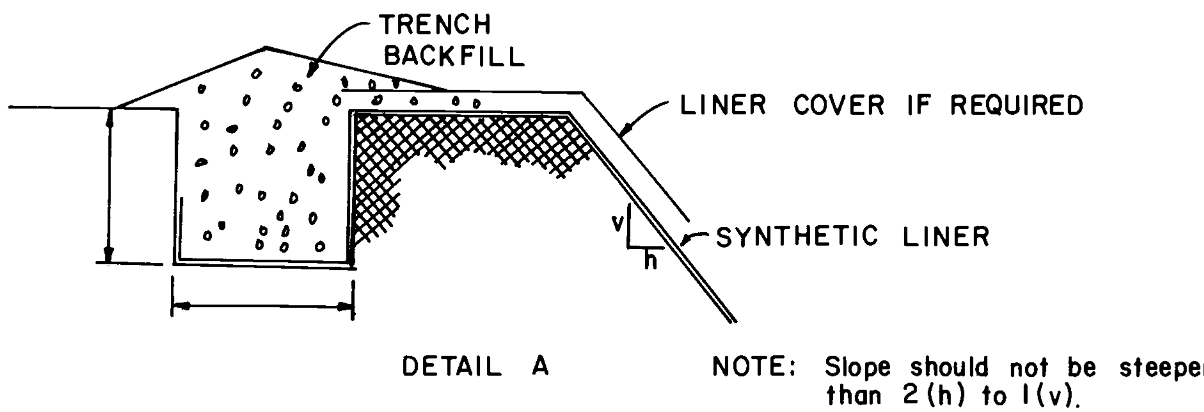
Poured concrete linings, as used in water harvesting storage projects, are generally 2 to 4 inches (51 to 102 mm) in thickness and lightly reinforced with wire mesh. A small batch plant or locally available ready-mixed concrete would be desirable in the construction of a concrete lining. A properly installed 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).

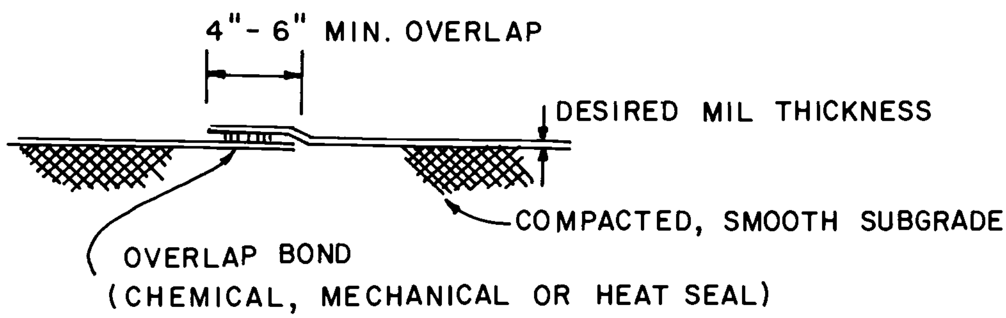
Reinforced mortar-covered plastic is another concrete lining method in which polyethylene or polyvinyl sheeting is used as the effective seepage control membrane and the wire mesh-reinforced mortar is the protective cover. The plastic must be properly sealed at the overlaps to prevent any seepage



TYPICAL RESERVOIR SECTION



ANCHOR TRENCH FOR SYNTHETIC LINERS



OVERLAP BONDING DETAIL

Figure 6. Synthetic Sheet Lining Constuction Details

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, 1974).

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-chipcoated 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 et al., 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

In water harvesting storage structures, evaporation losses often exceed the water beneficially consumed. Evaporation reduction methods should be incorporated into any efficient water harvesting system to provide a dependable water supply.

Many methods for evaporation control have been tried and discarded. In the late 1950's considerable research was done in the use of long-chain alcohols. This method, while cost effective on large reservoirs during drought conditions, is not recommended for smaller reservoirs. Wind barriers, shading of the water, floating dyes, and many types of reflective materials have been tried and discarded (Cluff, 1977a). Floating covers of heavier-than-water plastic films became flooded, due to animal-caused holes and rainwater, rendering them useless.

This section will summarize only the more promising methods of evaporation control which presently are being used.

Compartmented Reservoirs

This system of evaporation control utilizes berms to divide a conventional shallow reservoir into two or more different parts or compartments. A low-head, high-capacity pump is used to keep the water concentrated into as few compartments as possible, thus reducing the surface area with a corresponding decrease in evaporation. This systematic approach in reducing evaporation was first tried by the senior author in northwest Mexico in the fall of 1975 (Figure 7) (Cluff, 1976). It has the potential of increasing the efficiency of shallow reservoirs.

FIGURE 7. COMPARTMENTED RESERVOIR NEAR PARRUS, COAHUILA, MEXICO.

FIGURE 8. FLOATING PUMP FOR USE WITH COMPARTMENTED RESERVOIR.

If a reservoir has a depth equal to the annual evaporation rate, a conventional reservoir of such depth cannot furnish water on a constant basis. It will be dry at the end of the year without any use. However, if a reservoir is divided into three compartments and a pump is used to keep the water concentrated, it can furnish up to 50 percent of the initially stored water on a constant rate basis. Savings can be increased even more if compartments other than the receiving compartment are made deeper by increasing the height of the berms. This method of increasing the compartment depth is relatively low cost and made possible by using a pump. Low-head, high-capacity portable pumps are available which pump in excess of 25,000 gallons per minute (5,678 m^3/hour). These pumps can be operated using a tractor or vehicle equipped with a power takeoff. One pump could handle several reservoir systems, greatly reducing costs.

Alternatively, smaller low-head high-volume pumps are available that float on the water from which they are pumping. These pumps do not require suction hoses; they are lighweight, inexpensive and would be suitable for smaller systems. The floating pump shown in Figure 8 is rated by the manufacturer at 550 gallons per minute (124.9 m^3/hour) when pumping from 6.5 feet (2 m). The rate of flow from the pump drops off to 425 gallons per minute (96.6 m^3/hour) when pumping from 10.5 feet (3.2 m). The pump should not be used for lists of 16 feet (4.88 m).

If the natural slope is greater than 3 or 4 percent, a "separated" compartmented system can be used. Using this system the compartments are separated by enough distance down the slope to develop sufficient head so that the upper compartments can completely drain by use of a gravity pipeline into the lower compartments.

The cost of water from the compartmented system has been estimated to range from $22.00 per acre-foot ($17.90 per 1000 m^3) for a 97.3 acre-foot (120,000 m^3) system, to $9.74 per acre-foot (4.90 per 1000 m^3) for a 1556 acre-foot (1,920,000 m^3) reservoir system (Cluff, 1976). Larger reservoirs will produce water at even a lower cost. The cost of this water is well within the range of conventional irrigation water in the western United States.

This type of storage system has been used in conjunction with 20-hectare water harvesting agrisystem in Mexico (Cluff, 1976; Cluff, 1977c).

Sand and Rock-Filled Dams

In this type of storage, water is stored in the voids 12 inches (304 mm) or more below the surface.

Sand-filled dams have been constructed in stages across streams with steep enough gradients to be capable of carrying large quantities of sand. When the reservoir behind the first stage is filled with sand another layer is added to the dam and it too is allowed to fill.

Sand can be hauled in by truck, or rock can be developed by using rock pickers (Corey et al., 1976). This latter method was first used by the Water Resources Research Center at the University of Arizona (Cluff, 1974; Cluff, 1977a).

The biggest disadvantage of these methods is that they are limited to suitable terrains and/or the availability of suitable sand or rock. In contrast to the compartmented reservoir, these systems would be limited primarily to small storages.

Floating Covers

Materials that float on the surface and form an energy and/or vapor barrier can be used for evaporation control. In most cases, where water is scarce, they are cost effective when used for stockwater and domestic supplies or high-valued agricultural crops. For conventional agriculture they would need to be used in conjunction with the compartmented reservoir. In one simulated example using actual data, a floating cover was placed on the last compartment of a six-compartmented reservoir system. The cover was placed over only 16 percent of the area but increased the dependable water supply from the system by 50 percent (Cluff, 1977a). Inexpensive plastics, such as polyethylene or vinyl, have been anchored on the side of ponds and used as a continuous floating cover. This method has not been very successful. Since the plastic is close to the same density as water any small hole will eventually cause the cover to be submerged. It is important, therefore, that any floating cover be lighter than water. Foamed, closed-cell rubber sheeting, although more expensive, has been successfully used to form an anchored floating cover or a freely floating cover in vertical walled steel tanks (Dedrick et al., 1973). This method might be adapted for larger reservoirs through the use of a frame to form individual rafts that would resist flooding due to wave action.

Floating blocks of wax have been tested for several years on vertical-sided tanks. Paraffin wax with a low melting point has also been applied in chip form and allowed to melt in the hot summer sun to form a continuous vapor barrier. Its use would be limited to hot climates when wax can be melted on the water's surface (Cooley, 1974). This method has only been used on small vertical-sided storages.

Expanded polystyrene rafts have been used in the semi-arid climate of southern Arizona since 1970. The polystyrene is first cut into 4x4 ft (1.2 x 1.2 m) squares, 1/2 to 1-1/4 inches (12.7 to 31.7 mm) thick, and coated with various types of coatings to protect it from atmospheric degradation. Until recently, the coating squares were coupled together to form a continuous, flexible, floating cover that will move with the water level of the storage reservoir. The coupled, expanded polystyrene rafts can be adapted to virtually any climate and would require only minimal training of unskilled labor for installation and maintenance (Figure 9).

Over the past two years, wax-impregnated expanded polystyrene has been tested for evaporation control. The wax waterproofs the foam and prevents it from becoming water-logged. It also weatherizes and strengthens the foam so that it is more suitable for evaporation control. The wax will prevent weed growth which has proven to be a problem in unwaxed foam.

It will also add weight, making the foam more wind resistant.

Low-density expanded polystyrene can be completely impregnated with wax, increasing the specific density from 0.016 up to 0.224. The maximum attainable density is still much less than that of water, providing ample flotation. The impregnation greatly increases the strength properties of the foam in addition to waterproofing and weatherproofing the expanded polystyrene. This process has been patented (U.S. Patent Number 4,079,170). The material has many potential uses in the construction industry in addition to its use for evaporation control. There are various types of waxes available so that several different types of wax-impregnated expanded polystyrene can be made.

Small pieces of paraffin wax-impregnated polystyrene were exposed for a year with little effect from weathering (Figure 10). It has been noted that accelerated weathering does occur when the surface is coated with dark material such as wind-blown organic soil. If such a dust storm occurs during a period of high temperature in which the surface wax is molten the dust sticks to the surface. The higher temperatures caused by the darkened surface accelerate the weathering. Additional research is being done to test the use of waxes with higher melting points and/or precoat the surface with a lighter sand so that the excess wax is not available to trap the darker soil particles.

Cooley has been using paraffin wax blocks for several years and reports excellent weathering properties (Cooley, 1974). The wax-impregnated foam is an excellent insulation material. Thus it serves as both a vapor and energy barrier. An evaporation savings proportional to the area covered will be obtained. The temperature of a body of water partially covered with expanded polystyrene has been observed to be close to the same as an adjacent uncovered reservoir. Such is not the case when a non-insulation material, such as polyethylene film, is used to partially cover a reservoir. In that case the temperature rises, increasing the evaporation loss on the uncovered portions of the reservoir.

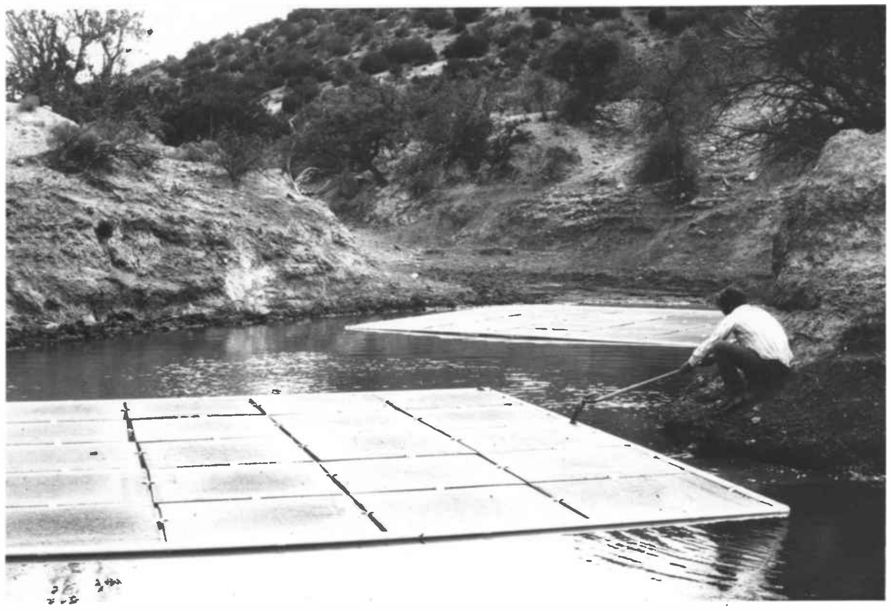


FIGURE 9. ASPHALT CHIPCOATED COUPLED EXPANDED POLYSTYRENE RAFTS ON A TYPICAL EARTH STOCK TANK.

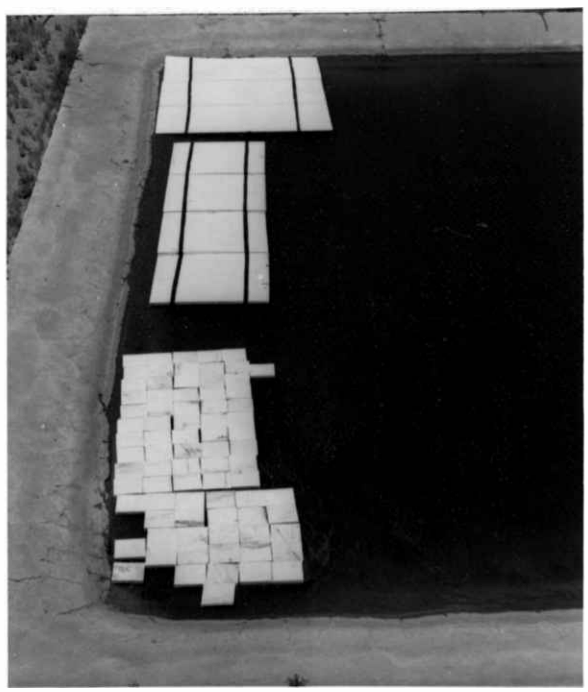


FIGURE 10. WAX IMPREGNATED EXPANDED POLYSTYRENE FLOATING COVER. (Hypalon Squares in Foreground. Rubber Banded Sheets in Background. Tested at Water Resources Research Center Field Laboratory, University of Arizona.)

A pressurized system that will saturate 4 x 8 ft (1.2 x 2.4 m) sheets of expanded polystyrene has been successfully completed at the Water Resources Research Center at the University of Arizona. Preliminary tests indicate that it has the capability of wax saturating 2000 to 4000 square feet (185 to 370 m^2) of one inch (2.5 cm) thick foam per hour. Untreated foam has a density of one pound per cubic foot (15.9 Kg/m^3). Pressure impregnation to a density of 6-8 pounds per cubic foot (95.4-127.2 Kg/m^3) will approximately double the cost per unit area of foam. However, it should be possible to use thinner sheets than would be needed with non-impregnated foam since the waxed material is much stronger. The sheets can either be clamped together using sections of PVC pipe, described earlier, or connected with straps of butyl or hypalon rubber (Figure 10). Use of the straps will make it possible to accordian-fold the waxed sheets so they can be quickly deployed in times of drought or be easily stored during periods of excess rainfall. Both types of connectors can be used on larger reservoirs provided some type of wave energy dissipation is used to protect the outer perimeter of the system.

Suspended Covers

A suspended cover suitable for remote villages consists of a cover made of locally available materials suspended over the water surface by steel wires. An example would be the mud-polyethylene tank at Radisele School, Botswana, South Central Africa (Intermediate Technology Development Group, Ltd., 1969). This tank is covered with sorghum stalks tied together in bundles and supported by high-tensive wire as indicated in Figure 11. Reinforced butyl rubber has been successfully suspended by plastic hose-covered cable. The cable is tied down by buried reinforced concrete anchors. The edge of the rubber is buried in a trench along the edge of the tank (Cluff, 1971; Cluff, 1977a). These methods are suitable for narrow reservoirs of relatively small volume.

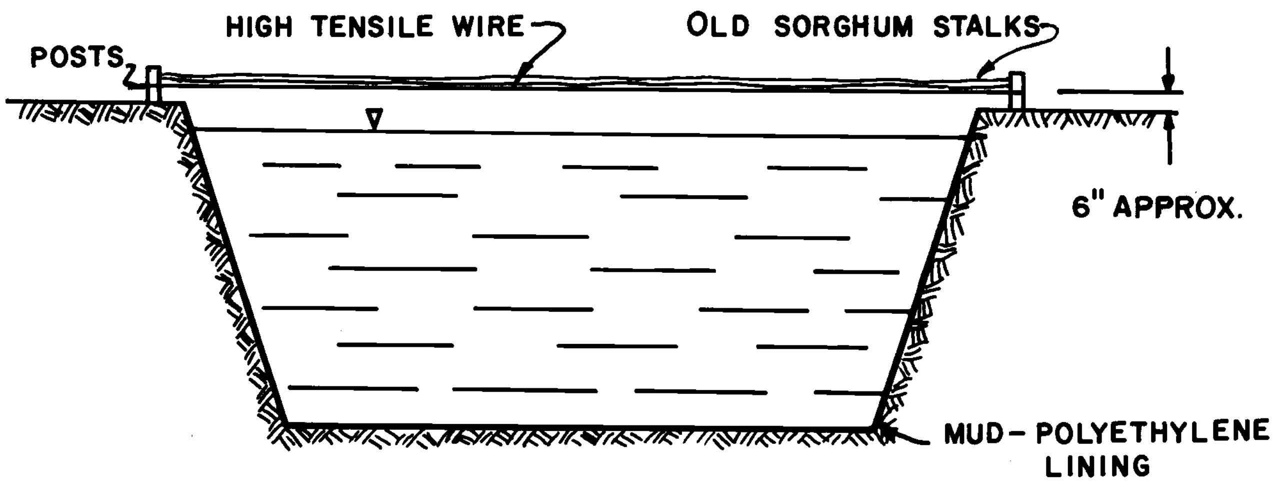


Figure 11. Mud-Polyethylene Tank Covered with Native Materials for Evaporation Control.

Roof Structures

Rigid roof structures made of steel or concrete are considered permanent evaporation suppression devices but are limited to countries that are economically independent and have an abundance of skilled labor. Rigid roof structures can be shipped to a site as a pre-fab package but require skilled labor and suitable tools for erection. Desirable local materials for evaporation control may not always be found in arid or semi-arid climates, however. An economic analysis should be made before the more expensive methods of evaporation control are used. Rather than provide an evaporation cover it may be more economical to do any one or more of the following: (1) build a larger catchment to counter-balance evaporation, (2) build a deeper reservoir with a smaller surface area, or (3) build a compartmented reservoir.

The use of a floating cover on the "last" compartment of a compartmented reservoir system appears to be very cost effective and should be considered when an efficient system is needed.

The health hazards of open domestic water supply reservoirs should be considered, too. A covered reservoir will reduce the risks of pollution and maintain a high quality of water while preventing the accumulation of algae and breeding of disease-carrying insects such as mosquitoes. A continuous floating or continuous suspended cover should, therefore, be considered for potable water supplies.

COST ESTIMATING

Tables I through V provide an approximate economic analysis and effectiveness criteria for various methods and materials available for use in water harvesting systems. Three distinct phases in constructing a water harvesting system are represented in the tables--catchment construction, water storage seepage control, and evaporation control. Although there are other methods or materials available, the one presented in the tables are considered the most common or have been proven through actual field use.

TABLE I. COMPARISON OF CATCHMENT CONSTRUCTION METHODS

Catchment Treatment	Estimated Capital Cost[a] ($/m²)	Estimated Life (Years)	Estimated Annual Maintenance Costs[b] (Percent)	Estimated Retreatment Costs ($/m²)	Estimated Average Amortized Costs $/m² (20 years)[c]	Estimated Runoff Efficiency (percent)[d]
I Earth Structures						
Land Clearing	0.03	5–10	15	0.01	0.006	20–30
Roaded Catchments	0.10	10–15	10	0.03	0.013	15–45
II Chemical						
Sodium Chloride	0.14	8–10	5	0.07	0.025	50–70
Sodium Carbonate	0.18	6–8	5	0.11	0.044	50–70
Wax (paraffin)	0.42	5–10	5	0.32	0.206	60–90
III Asphalt						
Fiberglass Asphalt-Chipcoated (FAC)	0.50	10–15	1	0.30	0.081	90–100
Asphalt-Plastic-Asphalt-Chipcoated (APAC)	0.75	10–15	1	0.30	0.107	90–100
Asphalt Rubber	0.80	10–15	1	0.65	0.143	90–100
Asphalt-Concrete (4 in.)	3.35	15–20	0.1	3.35	0.426	90–100
IV Synthetic Membranes						
Graveled Polyethylene Plastic	0.60	15–25	1	0.60	0.086	60–80
Reinforced Mortar-Coated Polyethylene Plastic	2.10	20–25	0.1	2.10	0.214	95–100
Chlorinated Polyethylene	3.50	10–15	1	3.40	0.703	95–100
Sheet Metal	3.50	20–25	0.2	3.40	0.356	95–100
Artificial Rubber	4.50	10–15	0.2	4.40	0.906	95–100

[a] Capital costs include estimated labor, equipment and material at 1976 U.S. prices for systems under approximately two hectares in size. To convert to $/yd² multiply by 0.836.

[b] Expressed as a percentage of initial capital costs.

[c] Amortization calculated on minimum life at an annual interest rate of 8%. Inflation rates were also assumed to be 8% per annum on the retreatment costs.

[d] Percent efficiency is the percentage of annual precipitation that is collected as runoff.

TABLE II. WATER HARVESTING CATCHMENT CONSTRUCTION: WATER COSTS[a] (IN DOLLARS) PER THOUSANDS OF LITERS OF RUNOFF FOR VARYING ANNUAL PRECIPITATION RATES

CATCHMENT TREATMENT	Range (mm)	100-200	200-300	300-450	400-600	400-850	600-900	600-1200	800-1200
	Average (mm)	(150)	(250)	(375)	(500)	(625)	(750)	(900)	(1000)
I EARTH STRUCTURES									
Land Clearing		0.28	0.17	0.11	0.08	0.07	0.06	0.05	0.04
Roaded Catchments		0.51	0.31	0.20	0.15	0.12	0.10	0.09	0.08
II CHEMICAL									
Sodium Chloride		0.36	0.21	0.14	0.11	0.08	0.07	0.06	0.05
Sodium Carbonate		0.59	0.35	0.24	0.18	0.14	0.12	0.10	0.09
Wax (Paraffin)		2.02	1.21	0.81	0.61	0.48	0.40	0.35	0.30
III ASPHALT									
Fiberglass Asphalt Chipcoated (FAC)		0.60	0.35	0.24	0.18	0.14	0.12	0.10	0.09
Asphalt-Plastic-Asphalt-Chipcoated (APAC)		0.80	0.48	0.32	0.24	0.19	0.16	0.14	0.12
Asphalt-Rubber		1.06	0.64	0.42	0.32	0.25	0.21	0.18	0.16
Asphalt-Concrete		3.01	1.81	1.21	0.90	0.72	0.60	0.52	0.45
IV SYNTHETIC MEMBRANES									
Graveled Polyethylene Plastic		0.88	0.53	0.35	0.26	0.21	0.17	0.15	0.13
Reinforced Mortar-Covered Polyethylene Plastic		1.65	0.99	0.66	0.50	0.40	0.33	0.28	0.24
Sheet Metal		2.48	1.48	0.99	0.74	0.59	0.49	0.32	0.37
Chlorinated Polyethylene (CPE)		5.04	3.03	2.02	1.51	1.21	1.01	0.86	0.76
Artificial Rubber		6.26	3.75	2.50	1.88	1.50	1.25	1.07	0.94

[a]Water costs are based on capital cost, average catchment efficiency, annual maintenance and average 20 year annual amortization at 8% interest rate - see Table 1. Water costs do not consider storage losses. To convert to costs per 1000 gallons multiply by 3.785.

TABLE III. COMPARISON OF VARIOUS SEEPAGE CONTROL METHODS

COMMON SEEPAGE CONTROL METHODS	ESTIMATED CAPITAL COST[a] ($/m^2)	ESTIMATED LIFE (Years)	ANNUAL MAINTENANCE COSTS (% of initial Capital Costs)	AVERAGE 20-YEAR AMORTIZED COST[b] ($/m^2)	PERCENT EFFECTIVNESS[c]
I CHEMICAL					
Sodium Chloride	0.31	5-10[d]	5	0.126	50-90
Sodium Carbonate	0.39	5-10[d]	5	0.159	50-90
Polymeric Sealants	1.45	5-10[d]	5	0.370	70-90
II WYOMING BENTONITE					
Pure Blanket (surface)	1.95	4-5[d]	2	0.883	60-90
Mixed Blanket	2.00	8-12[d]	1	0.407	60-90
III EARTH STRUCTURES					
Compacted Earth	0.25	10-20	5	0.050	20-50
Soil Cement (4 in.)	1.85	10-20	2	0.377	40-95
IV ASPHALT					
Asphalt Fiberglass	1.00	15-20	1	0.136	90-100
Asphalt Plastic Asphalt Chipcoated (APAC)	1.20	10-20	1	0.244	90-100
Asphalt Rubber	1.60	15-20	1	0.217	90-100
Buried Asphalt Membrane	1.95	>15	0.1	0.265	80-90
Asphalt Concrete (6 in.)	5.00	20-25	1	0.509	90-100
V CONCRETE					
Portland Cement Concrete (6 in.)	5.70	>20	0.5	0.580	80-90
VI SYNTHETIC MEMBRANES					
Soil Covered Polyethylene Plastic	0.60	>20	0.1	0.061	90-100
Soil Covered Polyvinyl Chloride	1.30	>20	0.1	0.132	90-100
Reinforced Mortar-Covered Polyethylene Plastic	2.10	20	1	0.214	90-100
Chlorinated Polyethylene (CPE)	3.50	10-15	1	0.713	90-100
Artificial Rubber	4.50	10-15	0.1	0.916	90-100

[a]Capital costs include estimated labor, equipment and materials at 1976 U.S. prices for small reservoirs less than one hectare in size. To convert to \$/yd^2 multiply by \$0.836.

[b]Amortization calculated on minimum life at an annual interest rate of 8%. Retreatment costs were assumed to be the same as initial costs except for an 8% per annum inflation rate.

[c]Percent effectiveness is based on percent of water entering the reservoir that is available for beneficial use.

[d]The life is dependent on quality of water stored in the reservoir.

TABLE IV. COMPARISON OF METHODS FOR WATER STORAGE EVAPORATION CONTROL

EVAPORATION CONTROL METHOD	Estimated[a] Capital Cost ($\$/m^2$ of water surface covered)	Estimated Life (Years)	Annual Maintenance Costs (% of Initial Capital Costs)	20-year Average Amortized Cost[b] ($\$/m^2$)	Percent Effectiveness[c]	Comment
I STRUCTURAL METHODS						
Compartmented Reservoir	Site Dependent	30–40	Minimal[d]	0.008–0.020[e]	30–80	Recommended for shallow reservoirs of moderate to large size.
Sand and Rock Filled Dams	Site Dependent	Indefinite	Minimal	-	80–90	Limited to suitable locations.
II FLOATING COVERS						
Polyethylene 10 mil Sheeting	0.40	1–2	5	0.43	95–100	Easily damaged by wind, frequent replacement. Danger of submergence.
Wax (paraffin)	1.25	5–10	0.5	0.51	80–90	Has been used only on tanks with vertical sides.
Wax-impregnated Polystyrene Foam Slabs	1.75	6–8	2	0.59	85–95	Can be cut into small squares - does not waterlog.
Asphalt Chipcoated Polystyrene Foam Slabs	2.00	3–4	5	1.36	80–90	Loses strength through waterlogging after 2 to 3 hears.
Foamed Rubber Sheeting	3.40	10–15	0.5	0.69	85–95	Used for tanks with vertical sides.
Lightweight Concrete Slabs	4.00	5–10	1	1.63	70–80	Slabs are permeable and should be waterproofed.
III RIGID ROOF STRUCTURES						
Wood	64.	25–50	0.2	6.51	95–100	Used for municipal water storage.
Concrete	86.	30–60	0.1	7.70	95–100	
Aluminum	107.	25–50	0.1	8.52	95–100	

[a]Capital costs include estimated labor, equipment and materials at 1976 U.S. prices on small reservoirs less than one hectare.

[b]Amortization factor is based on the minimum estimated life with an annual interest rate of 8%. Retreatment costs were assumed to be the same as initial costs except for an 8% per annum inflation rate.

[c]Percent effectiveness is based on a complete cover, compared with evaporation loss with no treatment.

[d]Maintenance costs are minimal.

[e]This cost is the estimated cost of construction and pumping per 1000 liters saved in a 1910mm evaporation area for a 2,000,000m^3 down to a 120,000m^3 capacity system (9).

TABLE V. WATER COSTS[a] (IN DOLLARS) PER THOUSANDS OF LITERS SAVED USING EVAPORATION CONTROL ON SMALL RESERVOIRS FOR VARYING ANNUAL EVAPORATION RATES.

	ANNUAL EVAPORATION RATE							
EVAPORATION CONTROL METHOD	2200mm	2000mm	1800mm	1650mm	1500mm	1300mm	1150mm	1000mm
Compartmented Reservoirs	0.012	0.013	0.014	0.015	0.017	0.020	0.022	0.025
Polyethylene Sheeting	0.21	0.23	0.26	0.28	0.31	0.36	0.40	0.46
Wax (paraffin)	0.28	0.30	0.34	0.37	0.40	0.47	0.53	0.61
Wax-Impregnated Polystyrene	0.32	0.35	0.39	0.42	0.46	0.53	0.60	0.69
Foamed Rubber Sheeting	0.36	0.39	0.44	0.47	0.52	0.60	0.68	0.79
Asphalt Chipcoated Polystyrene Rafts	0.78	0.86	0.95	1.04	1.14	1.32	1.49	1.72
Lightweight Concrete Slabs	0.99	1.09	1.21	1.32	1.45	1.68	1.89	2.18
Rigid Roof Structures								
Wood	2.96	3.26	3.62	3.94	4.34	5.01	5.66	6.51
Concrete	3.50	3.85	4.20	4.67	5.13	5.92	6.69	7.70
Aluminum	3.92	4.31	4.79	5.23	5.75	6.64	7.50	8.62

[a]To convert to costs per 1000 gallons multiply by 3.785.

Labor and material costs can vary greatly throughout the world; the costs represented herein are based on costs in the United States for labor, materials and equipment, assuming good site conditions. The costs listed are for small projects of less than 2.5 acres (1 hectare). Costs for larger project should be determined independently. For instance, the cost per ton of sodium chloride for a 40 acre (16 hectare) area was found to be less than half of that for a 2.5 acre (one hectare) project. costs for smaller projects can be reduced if several are constructed at the same time.

Table I compares various catchment construction methods as to their relative costs and runoff efficiency. Runoff efficiency, as defined here, is the percentage of total annual precipitation that is actually collected as runoff during an average year from a particular catchment treatment.

Table II details the amortized catchment construction costs for various annual precipitation rates. The costs represented are per 1000 liters of collected runoff. Note that the amortized water costs are based on an initial capital cost, catchment efficiency, life expectancy and an annual eight percent inflation and interest rate. The capital and maintenance costs, life expectancy and percent runoff figures for different treatments have been estimated from the authors' experience and/or the literature. Replacement costs and capital costs were combined as needed to reflect a 20-year life. This combination was made easier by the assumption of the same interest and inflation rate. Reduction of costs to a standard 20-year repayment period seems to be the most realistic approach in comparing different systems. These combined costs were reduced to an annual amortized cost using standard amortization procedures.

Common seepage control methods are compared in Table III. Table IV compares the most used evaporation control methods. Table V gives amortized evaporation control costs per 1000 liters saved for these methods for varying annual rates of evaporation.

The method of storage should be selected before the appropriate catchment size can be determined. Following a selection of the seepage and evaporation methods, the reservoir can be sized according to the following empirical relationship:

$$V_R = N\ K\ \frac{R}{E_C E_S E_E}\ (10)^6 \qquad (1)$$

where V_R = Volume of reservoir in cubic meters.

N = Water demand frequency factor (= 1 if the demand is constant)

K = Rainfall frequency factor (= 1 in southern Arizona)

R = Average water requirement in cubic meters.

$E_C E_S E_E$ = Efficiencies of catchment, seepage control and evaporation control, respectively, in percent.

This approach recognizes the interrelationship of catchment, seepage and evaporation efficiencies, as well as rainfall frequency, in sizing a reservoir to match a given catchment. The approach has been shown to provide sufficient storage to meet the annual water demand more than 95 percent of the time. The validation was accomplished using daily rainfall data in a computer runoff model. The daily runoff data were then combined in a weekly array using the model and the operation of the system simulated. Catchment efficiencies ranging from 50 to 95 percent and seepage and evaporation efficiencies above 80 percent were used in the validation. For other climates and type of demand, different N and K values will be needed. The form of Equation (1) may have to be modified if climatic conditions and efficiencies differ greatly from those used in the calibration. If possible, a complete hydrologic study should be used instead of Equation (1) for sizing the reservoir.

Following the sizing of the reservoir its dimensions can be determined. If the reservoir is constructed in the ground, the most economical shape is in the form of an inverted truncated pyramid. This avoids the necessity of constructing vertical walls which are generally expensive.

The average cross-sectional area of a truncated pyramid, A_R, is given by:

$$A_R = V_R/D \tag{2}$$

where V_R = The volume of the reservoir in cubic meters.

D = Depth in meters.

The upper and bottom dimensions are given by:

$$L_u = (A_R)^{\frac{1}{2}}+2D/S \tag{3}$$

$$L_b = (A_R)^{\frac{1}{2}}-2D/S \tag{4}$$

where L_u = Length of upper side in meters.

L_b = Length of bottom in meters,

and S = Slope of sides in ratio of depth to width (dimensionless).

The area to be lined in the reservoir is given by:

$$A_S = 2(L_u+L_b)\ (D^2+(D/S)^2)^{\frac{1}{2}}+L_b{}^2 \tag{5}$$

The required catchment area is determined using equations (6) and (7):

$$A_C = \frac{(R+S_L)\ 10^5}{PE_C} \tag{6}$$

$$S_L = R(100-E_S)\ (10)^{-2} + (100-E_E)EA_R(10)^{-5} \tag{7}$$

where A_C = Required catchment area in square meters.

R = Average annual water requirement in cubic meters.

S_L = Storage losses due to seepage and evaporation, in cubic meters (from equation (7)).

P = Average annual precipitation in mm.

E = Evaporation loss in mm.

E_C = Efficiency of the catchment in percent.

E_S = Efficiency of seepage liner in percent.

E_E = Efficiency of evaporation cover in percent.

A_R = Average surface area of the reservoir in square meters.

This catchment area is needed to determine the total project design. However, the amortized costs per 1000 liters of water collected from the catchment can be obtained from Table II and ajusted, using equation (8), to reflect the increase in size due to storage losses.

$$C_c = \frac{U_c}{R/R+S_L} \tag{8}$$

where C_c = Adjusted costs in dollars per 1000 liters.

U_c = Unadjusted costs in dollar per 1000 liters.

This equation adjusts the added cost of the catchment due to anticipated storage losses.

Table III gives storage costs in terms of costs per square meters. These costs are expressed as costs per 1000 liters of water beneficially consumed through equation (9).

$$C_s = A_S \frac{(U_S+M)}{R} \tag{9}$$

where C_S = Cost of storage per square meter.

A_S = Surface of reservoir to be lined.

U_S = Amortized cost per square meter.

M = Annual maintenance cost per square meter.

R = Water delivered in cubic meters.

Table V expresses evaporation control costs in terms of cost per 1000 liters of water saved. In order to obtain the total cost of producing water these must also be expressed in terms of cost per 1000 liters of water beneficially consumed using equation (1).

$$C_E = \frac{U_E\ E\ A_R\ (10)^{-3}}{R} \tag{10}$$

where C_E = Evaporation control costs per 1000 liters of water beneficially used.

U_E = Cost per 1000 liters of water saved.

E = Annual evaporation loss in mm.

A_R = Average area of the reservoir.

R = Water delivered in cubic meters.

In order to find the total cost of water per 1000 liters (C_T), one must add the catchment, seepage and evaporation control costs as shown in equation (11).

$$C_T = C_C + C_S + C_E \tag{11}$$

These costs can be converted to dollars per 1000 gallons by multiplying by 3.785.

The use of this design and cost estimating procedure is illustrated in the example given in Table VI.

In actual practice, this procedure would probably have to be rerun for several combinations before a near optimum design could be determined. The use of a small programmable calculator would reduce the time needed for this repeated design procedure.

TABLE VI
COMPUTATION EXAMPLE

GIVEN: Annual Water Requirement: R = 1,500,000 liters = 1500 m^3

Location: Near Tucson, where
Average Precip. (P) = 375 mm
Average Evap. (E) = 1830 mm

Reservoir:
Average Depth (D) = 4 m
Slope of Side Banks = 2:1; hence S=2
Seepage Control: APAC Treatment
Evaporation Control: Wax-Impregnated Foam

Catchment: Use APAC Treatment

DETERMINE: Size of systems and costs per 1000 liters of delivered water.

1. Required storage volume in cubic meters is found using equation (1).

$$V_R = NK \frac{R}{E_C E_S E_E}(10)^6 \qquad (1)$$

where N = 1 $\quad E_C = 95\%$

K = 1 $\quad E_S = 95\%$

R = 1,500 m^3 $\quad E_E = 90\%$

hence $V_R = 1847\ m^3$

therefore $A_R = V_R/D \qquad (2)$

$= 462\ m^2$

$$L_u = (A_R)^{\frac{1}{2}} + 2D/S \qquad (3)$$

$= 25.5$ m

$$L_b = (A_R)^{\frac{1}{2}} - 2D/S \qquad (4)$$

$= 17.5$ m

$$A_S = 2\ (L_u+L_b)\ (D^2+(D/S)^2)^{\frac{1}{2}}+(L_b)^2 \qquad (5)$$

$= 691\ m^3$

2. Required catchment area is determined using equations (6) and (7).

$$A_C = \frac{(R+S_L)10^5}{P\ E_C} \quad (6)$$

$$S_L = R(100-E_S)\ (10)^{-2}+(100-E_E)\ (E)\ (A_R)\ (10)^{-5} \quad (7)$$

where $P = 375$ mm
$E = 1830$ mm
$R = 1500\ m^3$
$A_R = 461\ m^2$
$E_C = 95\%$
$E_S = 95\%$
$E_E = 90\%$
$S_L = 159\ m^3$
$A_C = 4656\ m^2$

3. From Table II obtain catchment water costs for APAC treatment U_C = \$0.32/1000 liters.

4. Adjust costs to reflect increased area due to storage losses.

$$C_C = \frac{U_C}{R/R+S_L} \quad (8)$$

where U_C = \$0.32/1000 liters
$R = 1500\ m^3$
$S_L = 159\ m^3$
C_C = \$0.354/1000 liters (\$1.34/1000 gal)

5. Using Equation (4) and values from Table III obtain seepage costs per 1000 liters.

$$C_S = \frac{A_S(U_S+M)}{R} \quad (9)$$

where $U_S = \$0.244/m^2$
$A_S = 691\ m^2$, from equation (7)
$R = 1500\ m^3$
$M = (0.01)\ (1.20) = \$0.12$
C_S = \$0.118/1000 liters (\$0.45/1000 gal)

6. Obtain evaporation costs from Table V and adjust per 1000 liters delivered.

$$C_E = \frac{U_E E\ A_R}{R} (10)^{-3} \qquad (10)$$

where U_E = \$0.39

E = 1830 mm

A_R = 461 m^2

R = 1500 m^3

C_E = \$0.219/1000 liters (\$0.83/1000 gal)

7. Obtain total cost of water.

$C_T = C_C + C_S + C_E$

= 0.354 + 0.118 + 0.219 = \$0.691/1000 liters (\$2.62/1000 gal).

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