HARVESTING PRECIPITATION (*)

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RÉSUMÉ

On peut trouver de nouvelles ressources en eau en recueillant les précipitations qui se perdent maintenant par une évapotranspiration inutile. La récolte des précipitations est une pratique ancienne, utilisée au désert du Negev, il y a déjà plus de quatre mille ans, mais elle n'est plus utilisée aujourd'hui qu'en de modestes proportions. La cause principale en est le coût élevé des bâtiments nécessaires pour le captage et pour l'emmagasinage des eaux pluviales et des neiges fondues. On peut en réduire, et on en réduit, le coût par la recherche et le développement de dispositifs pouvant être utilisés pour la récolte des précipitations. La recherche qui a cours indique qu'on peut développer des traitements pour imperméabiliser et pour stabiliser la surface de la terre avec un coût de deux cents le mètre carré. Un tel traitement peut capter les eaux d'une région avec une pluviosité de 200 mm avec un coût de dix cents les 1.000 litres. On peut beaucoup réduire le coût pour l'emmagasinage par de nouvelles conceptions et par l'utilisation de certains matériaux et par l'établissement des aires pour la récolte autour des réservoirs existants ou des régions pour la recharge des eaux souterraines. La récolte des précipitations peut faire concurrence à d'autres méthodes pour apporter les eaux dans beaucoup de régions, et il y a un grand nombre de ces régions où cette récolte offre la seule possibilité de procurer de nouveaux suppléments d'eau. Cette source d'eau, fondée sur des principes anciens, mais solides, mérite plus d'attention et plus de considération par les auteurs de projets et par les chercheurs de ressources en eau, qu'elle n'en a reçu jusqu'à présent.

SUMMARY

New water supplies can be developed by harvesting precipitation which is now lost to nonbeneficial evapotranspiration. Precipitation harvesting is an ancient practice, utilized over 4,000 years ago in the Negev Desert, which is little used today. The major deterrent to present use is the high cost of durable structures for collecting and storing rainfall and snowmelt. Costs can and are being reduced by research and development aimed specifically at the performance requirements for precipitation harvesting structures. These are not the same as performance requirements for conventional structures such as roads. Current research indicates that treatments can be developed to waterproof and stabilize soil surfaces for 2 cents per square meter. Such a treatment can collect water in a 200 mm rainfall zone for 10 cents per 1,000 liters. Storage costs can be greatly reduced by new concepts and materials for new construction and by building harvesting areas about existing reservoirs or groundwater recharge areas. Precipitation harvesting can be competitive with other water supply methods in many areas and there are many locations where it offers the only opportunity to develop new water supplies. This source of water, based on ancient, but sound, principles, deserves increased attention and consideration by water resource planners and investigators.

1. INTRODUCTION

Collecting or harvesting precipitation, often called water harvesting, is an ancient practice which deserves more attention by modern hydrologists and water supply engineers. Relatively little consideration is now given to possibilities for capturing a portion of the tremendous volumes of precipitation which are lost by nonbeneficial evaporation. Calculations of available water supplies in the United States, for example, have been based on streamflow, which averages about 4,500 billion (4.5×10^{12}) liters

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per day (Anon., 1960). These calculations ignore that two-thirds of the precipitation which never appears as streamflow. Some of this precipitation, averaging about 11,000 billion (11.0×10^{12}) liters per day, is transpired by useful vegetation or replenishes groundwater supplies; but much of it soaks into dry soil and then evaporates directly from the soil or from nonbeneficial vegetation. Runoff from the 668,000 square kilometer Colorado River Basin in the southwestern United States is less than 10 per cent of the precipitation. We will never wish to capture all the precipitation, but we can certainly collect more than we are getting now.

2. History

Water harvesting was practiced over 4,000 years ago in the Negev desert (Evenari, *et al.*, 1961). Farmers in that area cleared hillsides of rocks and gravel to increase rainfall runoff and constructed ditches to collect the runoff and carry it to the cultivated fields below. The amount of land a farmer could cultivate was determined by the area of hillside or rainfall-collecting surface he owned. Collection and storage of runoff from the roofs of houses has long been a common practice, although the development of central water supply systems has caused it to be abandoned and forgotten in many regions of the world. Perhaps the best known water harvesting system is on Gibraltar where the primary water supply is obtained from runoff from specially constructed areas of corrugated metal roofing, bare rock, and concrete. Catchment aprons are sometimes used at other sites, such as on the Bahama Islands, where runoff from porous soils is low despite relatively high rainfall. Water harvesting is being used at a few locations in arid regions of the United States to provide water for wildlife and livestock.

The previously high cost of water harvesting structures is undoubtedly the major reason this source of water has received so little attention from hydrologists and engineers. Initial expenditures for durable catchment aprons built from conventional materials in the U.S.A. have ranged from \$2.00 to \$5.00 per square meter, with an average annual cost exceeding 10 cents per square meter. Water from this source would cost at least 30 cents per 1,000 liters at a location with an annual precipitation of 300 mm. This high price has prohibited consideration of water harvesting as a source of water supply in arid regions except under unusual circumstances. Recent developments indicate that this cost can be greatly reduced.

3. Harvesting structures

Conventional materials which have been used for water harvesting structures have included Portland Cement concrete, asphaltic concrete, soil cement, corrugated sheet metal, and asphalt impregnated fiber planking. These materials are intended to provide considerable structural integrity as well as an impermeable surface. Such materials were not developed for water harvesting but for other uses such as road building and reservoir lining. Most of them require the use of heavy construction equipment or large amounts of hand labor. Those which may not require heavy construction equipment require transportation of all materials from a source of supply to the construction site. Costs and performance of completed structures have varied widely because of variations in design and in transportation and labor requirements. The lowest costs have been too high for durable structures made of conventional materials.

Lower costs for water harvesting structures can be obtained only by developing new materials and construction procedures which reduce requirements for materials, equipment, and labor. This can be done by research and development aimed specifically at the performance requirements for water harvesting structures. These are not the same as performance requirements for road building and reservoir lining. Some of the desirable characteristics of materials for catchment aprons are as follows:

1. Runoff from the structure must be nontoxic to man and animals.
2. The surface of the structure should be smooth and impermeable to water.
3. The structure should have high resistance to weathering damage and should not deteriorate because of internal chemical or physical processes such as crystallization.
4. The structure need not have great mechanical strength but should be able to resist damage by hail or intense rainfall, wind, occasional animal traffic, moderate flow of water, plant growth, insects, birds, and burrowing animals.
5. The material used should be inexpensive, on an annual cost basis, and should permit minimum site preparation and construction costs.
6. Maintenance procedures should be simple and inexpensive.

All of these characteristics may not be obtained with any one material, and the best structure may often be obtained by using a combination of materials.

The simplest artificial water harvesting structure is a smoothed soil surface. Runoff data for such a surface are presented in table 1, together with measured precipitation

TABLE 1

Runoff from Plots at the Granite Reef Test Site near Phoenix, Arizona, USA.

Date	Rain Gage Data				Runoff			
	Precipitation	Intensity	Butyl Rubber		Smoothed Soil		Desert Pavement	
	mm	mm/hr	mm	%	mm	%	mm	%
26-01-62	4.6	4.6	4.9	107	0.5	11	0.0	0
28-07-62	7.9	30.5	8.2	104	3.4	43	1.3	16
17-10-62	5.3	50.8	5.9	111	1.7	32	0.4	8
15-11-62	2.0	1.0	2.6	130	0.0	0	0.0	0
03-12-62	3.0	5.9	3.9	126	0.0	0	0.0	0
18-12-62	8.4	6.4	10.2	122	2.4	29	0.0	0
03-01-63	20.3	3.3	21.6	103	6.0	30	1.3	6
Total	51.5		57.3	111	14.0	27	3.0	6

and runoff from a natural desert pavement surface. Data are presened only for dates when reliable measurements were obtained from all plots. The soil is a sandy loam with 51.4 per cent sand, 34.3 percent silt, and 9.3 per cent clay. The smoothed plot is about 230 square meters, leveled to a 5 per cent slope with a road grader and a small amount of handwork, and sprayed with a soil sterilant. The runoff is compared to an undisturbed plot of about 4,000 square meters having a variable slope averaging about 10 per cent and a natural desert pavement surface of fine gravel with occasional small shrubs. The gravel particles do not completely cover the soil, but the coarse surface causes considerable retention of water. Total precipitation for the dates listed in table 1 was 51.5 mm. Runoff was 27 per cent for the smoothed plot and 6 per cent for the desert pavement. These results indicate that considerable increase in runoff can be obtained by eliminating the fine gravel cover. Some erosion must be expected but this has been essentially eliminated, for this site, by reducing the slope. Annual costs for this type of treatment can be less than 1 cent per square meter. When site conditions are favorable, additional water supplies can be obtained at low cost by smoothing naturally rough soil surfaces to increase runoff.

Plastic and artificial rubber sheets have been used as ground covers for water harvesting. Vinyl and polyethylene plastic sheeting have proved unsatisfactory from an annual cost standpoint. Two to three years appear to be the maximum life of 10-mil sheeting, and 2-mil sheeting has deteriorated in less than 6 months. Thirty-mil butyl rubber has proved to be an excellent material. Work by C.W. Lauritzen (1960) has indicated an expected life of over 10 years for this material. Installation costs are low because the ground surface does not have to be completely smoothed. The only disadvantage of butyl sheeting is the initial cost of approximately $1.60 per square meter for 30-mil material. Current developments promise to reduce this cost.

We have recently constructed a low-cost ground cover from 1-mil aluminum foil bonded to the soil surface with cationic asphalt emulsion. The foil is unrolled from a spindle mounted just ahead of a foam rubber roller which presses the metal sheet against the soil. Asphalt emulsion is sprayed on the soil surface immediately ahead of the unrolling foil which is laid down in overlapping 4-foot wide strips. This process is readily adaptable to machine laying. Fiberglass reinforcing can be easily included in the treatment if desired, but the bonded foil alone has appreciable resistance to mechanical damage. The foil treatment has been installed on a 230 square meter plot for over one year at Granite Reef with no sign of deterioration. Resistance to severe winter weather and high winds is now under test on operational catchments in northern Arizona. Cost of the installed foil is about 25 cents per square meter, including soil sterilant, asphalt, and application costs, but not including site preparation. Clearing, smoothing, and light rolling to prepare the small test site added about 5 cents per square meter on a rough, gravelly, and gullied hillside. Construction of larger areas would reduce all these expenses. The suitability of this treatment will depend upon the durability of the foil-asphalt-soil bond.

Water harvesting areas can be constructed by spraying soil with a material which will waterproof it and protect it against erosion. Asphalt offers considerable promise for this purpose since it is relatively inexpensive and can be compounded to provide good resistance to weathering. Application costs are low. We have been using a 7.5-meter spray boom which will treat over 115 square meters per minute. The sprayed surface does not have to be completely smoothed and site preparation costs can be low. We have tested a number of formulations which would have an annual cost of less than 5 cents per square meter. A treatment is now under development which should have an annual cost of 3 cents per square meter or less. Asphalt plots have one major disadvantage at the present time, and that is slight discoloration of the first runoff water obtained after a period of weathering. Cattle do not object to the color, but some humans would. Improved compounding of protective top sprays should solve this problem. Asphalt catchments are presently feasible and satisfactory for obtaining stock water supplies, but additional development is required before such structures are used to obtain water for human consumption.

Site selection will often be a major factor in determining the cost and performance of a catchment structure. Leveling and smoothing requirements will obviously be less for a naturally smooth site than for a rough site. In this regard, it should be remembered that a catchment does not have to be rectangular, and preparation expenditures can often be greatly reduced by using an irregular shape which fits the natural topography. The size of the catchment structure required to produce a given amount of water may be reduced by considering local orographic influences. Consistent differences in quantitative precipitation may occur within relatively short distances at a given locality. Other site factors such as soil type, depth of soil, vegetation, and animal activity should also be carefully considered to insure the selection of a site which will permit the construction of a satisfactory catchment structure at minimum cost.

4. Water storage

Storage must be provided in conjunction with any water harvesting system. This can be done with enclosed tanks, open surface reservoirs, or subsurface groundwater reservoirs. The determination of necessary storage volume will depend upon many factors including miniumum daily water requirements and the anticipated quantitative distribution of precipitation in time. Determination of precipitation patterns will be the most difficult problem since the long-term precipitation data required for probability analysis are not available in many regions of the world. Average precipitation data are usually misleading and probability analysis must be used for water harvesting design. For example, average annual precipitation for Phoenix, Arizona, is 198 mm, but less precipitation than this has occurred during 60 percent of the 80 years of record. Many other factors will influence the determination of storage capacity, such as the existence of a limited groundwater supply which can be used as an emergency source of water.

The use of natural underground reservoirs should not be overlooked as a means of water harvesting storage. Groundwater recharge is often attempted at unfavorable sites, such as the lower areas of depleted former artesian basins, because that is where surplus surface waters presently accumulate. Good recharge sites are usually found near the upper slopes of such basins where there is little or no water for recharge. A scheme can readily be conceived wherein good recharge sites will be located and prepared, wherever they may be, and water harvesting structures will be built above them. Such a system can be used as a primary means of storage or can be used in conjunction with surface storage.

New concepts, materials and methods must be developed to reduce the costs of storage facilities for water harvesting and to reduce the loss of water from such storage facilities. Groundwater recharge offers one possibility. The expense of surface storage can be reduced by the use of films and chemical sealants to line open earthwork reservoirs. Good progress is being made in developing materials for this purpose. Additional attention should be given to the problem of reducing evaporation from such reservoirs. Floating films of high-strength, durable materials can be developed to provide protection against evaporation and contamination. None of the problems involved are insurmountable and they will be solved as they begin to receive adequate consideration by scientists and engineers.

5. Cost of water

The cost of water obtained from a precipitation harvesting structure will depend upon the cost of the structure and the amount of precipitation runoff obtained during the period in question. Precipitation data are ordinarily reported for a calendar year and cost estimates can be on the same basis. Costs of harvesting structures should ordinarily be considered in terms of annual costs, including interest on invested capital, rather than initial cost. The interest factor will serve to limit initial costs. Figure 1 has been prepared to show the relationships among cost of water, runoff, and cost of catchment area per square meter.

Water harvesting structures can presently be built for an annual cost of 5 cents per square meter. Figure 1 shows that with 200 mm runoff, water from this source would cost 25 cents per 1,000 liters at the structure. This is comparable with many estimates of anticipated sea water conversion costs. Representative precipitation data

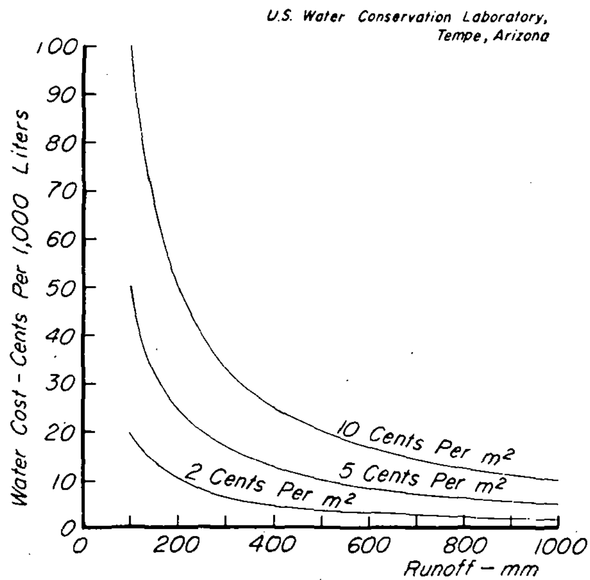

Fig. 1 — Cost of water from precipitation harvesting structures for various amounts of runoff and structural costs.

are listed in table 2. Runoff of 300 mm, which is the average precipitation for Alice Springs, Australia, would lower the cost to 17 cents per 1000 liters. We can anticipate that within the next few years annual costs for structures will be lowered to 2 cents per square meter. This would result in average annual costs per 1,000 liters of 16 cents at Baghdad, 10 cents at Alexandria, and 5 cents at Oran.

Runoff from a water harvesting structure depends upon the roughness and porosity of the surface as well as the quantity and intensity of precipitation. Impervious, smooth surfaces at the Granite Reef test site have caught 100 per cent or more of the precipitation measured by a standard U.S. Weather Bureau recording raingage, including the lightest recorded showers. This is shown for butyl sheeting in table 1. These data indicate that raingage data may represent a minimum runoff quantity for smooth impervious surface. Precipitation data must be adjusted for rough or permeable surfaces by multiplying by an average runoff percentage determined from field testing.

The annual precipitation amount to be used for estimating costs may be determined by standard probability analysis, but it is important to recognize the fact that the design precipitation may not be the precipitation at the point of use. Average annual precipitation for Phoenix, Arizona, USA, is 198 mm. With an annual structures cost of 2 cents per square meter a water cost of 10 cents per 1,000 liters would be indicated. However, the average precipitation only 40 kilometers from Phoenix is 500 mm and water obtained at this location could be transported by gravity to Phoenix in existing natural and artificial conveyance systems (Sellers, 1960). This means that the cost could easily be reduced to 4 cents per 1,000 liters.

TABLE 2

Annual Precipitation in Liters per Square Meter for Selected Locations

Location	Av. Precip.	Max. Precip.		Min. Precip.		Period of Record	Source of Data
	l/m²	l/m²	year	l/m²	year	years	
Argentina							
Cipolletti	148	271	1945	82	1947	1941-50	*
Sarmiento	183	295	1946	99	1947	1941-50	*
Algeria							
Oran	366	633	1943	168	1944	1941-50	*
Australia							
Adelaide	510	645	1942	408	1950	1941-50	*
Alice Springs	312	487	1947	246	1942	1941-50	*
Kalgoorlie	234	390	1948	129	1950	1941-50	*
Chile							
Arica	0.6	3	1942	0	5 years	1941-50	*
Egypt							
Alexandria	207	316	1948	109	1947	1945-50	*
Helwan	39	80	1945	13	1947	1941-50	*
Gibraltar	677	1060	1942	455	1950	1941-50	*
Iran							
Jask	118	234	1943	38	1941	1941-50	*
Iraq							
Baghdad	121	172	1949	82	1942	1941-50	*
Israel							
Jerusalem	550	862	1949	304	1947	1941-50	*
Libya							
Idris	310	422	1945	160	1947	1944-50	*
Mexico							
Chihuahua	368	428	1943	221	1944	1942-44 1950	*
Saudi Arabia							
Bahrain	60	100	1947	22	1950	1941-50	*
U.S.A.							
Flagstaff	514	876	1905	252	1942	1898-1950	**
Phoenix	198	500	1905	71	1953	1877-1959	**
Reno Ranger Station	475	860	1931	193	1956	***	**

Total cost of water obtained from precipitation harvesting must include the expense of storage and delivery. These are so variable that no meaningful estimate can be made. Storage costs could be very high if conventional design and construction

(*) Anon., World Weather Records 1941-50, U.S. Govt. Printing Office, Washington, D.C., 1959.
(**) Sellers, William D., Arizona Climate, The University of Arizona Press, Tucson, Arizona, 1960.
(***) Intermittent records 1916-43, complete records 1944-59.

methods are used at a location where periods of high rainfall are interspersed with years of low rainfall. On the other hand, existing storage and distribution facilities may sometimes be used so that there will be no additional storage and distribution costs. We can safely assume that strict water conservation measures will be enforced in conjunction with the development of a water supply from precipitation harvesting. Under these conditions the quantities and costs of relatively long-term storage should be reduced to an acceptable value. Storage costs can be decreased by increasing the size and cost of the water harvesting structure. The optimum relationship between size of catchment and volume of storage must be determined for each site. We must recognize that there will always be some sites such as Arica, Chile, with an average annual rainfall of 0.6 mm, where water harvesting may never be feasible.

Water is worth whatever it costs if the need is sufficiently great. The feasibility of water harvesting must be determined by a comparison of the cost of alternate water sources and by the cost water users can afford to pay. A recent study has indicated that the food and kindred products industries in the San Juan Basin, New Mexico, USA, could pay 9.5 cents per 1,000 liters for water used and still obtain a 10 per cent profit on invested capital (Wollman, *et al.*, 1962). Ranchers in the USA have paid over 90 cents per 1,000 liters to transport water for use by livestock (Criddle, *et al.*, 1962). Many residents of a number of cities in the USA pay about $60.00 per 1,000 liters for bottled drinking water which is of better flavor than the inexpensive water obtained from the standard city water supply. There are many situations throughout the world where high quality water can be obtained from precipitation harvesting structures at prices lower than those now being paid.

6. Future

Wide-scale application of water harvesting principles seems certain to develop within the next decade. Research on water harvesting has only recently begun and has received only a modest amount of attention. Despite the relatively small amount of time and effort devoted to this research, in comparison to research on some other water supply methods, excellent progress has been made in reducing the cost of catchment structures and in demonstrating the potential value of water harvesting.

New construction methods and materials have been developed to reduce the annual cost of water harvesting structures to less than 5 cents per square metre, and newer materials promise to reduce this to 2 cents. This means that water can be produced at the catchment site for costs less than those now being paid at many locations. Such situations will increase throughout the world as populations increase and groundwater supplies are depleted.

Storage of water from precipitation catchments can sometimes be accomplished with existing facilities, but new concepts and methods will often be required. Construction of catchments above good groundwater recharge sites is a storage technique which should be considered. More extensive and reliable information concerning the time and space distribution of precipitation is required for the design of storage systems and the location of catchment structures. There is some evidence to indicate that existing precipitation records represent minimum quantities and that these quantities can often be materially increased by locating catchment structures at some reasonable distance from the present point of measurement. The required information will be obtained and the problems will be solved as interest in water harvesting increases.

The maximum water supply which can be developed in a given area should not be based on streamflow but should be based on precipitation, which in arid regions is usually many times the streamflow. All the precipitation lost to nonbeneficial evaporation cannot be captured, but a portion of it can. The amount to be captured will depend on the need. Water harvesting is not a universal cure for water supply problems and will not be feasible in some areas, however, the cost of water supplies developed by capturing precipitation will be competitive with other sources available to many arid and semiarid regions. There are many locations where water harvesting offers the only opportunity to develop new water supplies. This source of water, based on ancient, but sound, principles, deserves increased attention and consideration by water resource planners and investigators.

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