332

Agricultural Water Management, 3 (1980) 125—134
Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

WATER HARVESTING BY WAX-TREATED SOIL SURFACES: PROGRESS, PROBLEMS, AND POTENTIAL

D.H. FINK*, G.W. FRASIER** and K.R. COOLEY***

**U.S. Water Conservation Laboratory, USDA-SEA-AR, 4331 East Broadway, Phoenix, AZ (U.S.A.)*

*** Southwest Watershed Research Center, USDA-SEA-AR, 442 East 7th Street, Tucson, AZ (U.S.A.)*

**** Northwest Watershed Research Center, Patti Plaza, Suite 116, 1175 South Orchard, Boise, ID (U.S.A.)*

(Accepted 3 June 1980)

ABSTRACT

Fink, D.H., Frasier, G.W. and Cooley, K.R., 1980. Water harvesting by wax-treated soil surfaces: progress, problems and potential. *Agric. Water Manage.*, 3: 125—134.

Water-harvesting techniques can increase the useable water supplies of arid and semiarid areas. A relatively new water-harvesting treatment is the application of paraffin wax to soils to create a water-repellent catchment surface. The first two such catchments were installed at the Granite Reef test site in 1972 by applying ground paraffin wax (0.7 kg/m^2 average rate) atop smoothed, rain-compacted soils. Solar energy melted the wax into the soil. The catchments are still operational after 7 years of natural weathering. Average runoff efficiency (yearly runoff/yearly rainfall) for the two catchments averaged 87% for the 7 years. Year 7 averages were 85%, i.e., only 2% less than the 7-year average. Also, the 7-year average runoff efficiency of the two catchments was only 10% less than that of a plastic membrane, but was more than four times greater than that of a simple, cleared and smoothed soil surface and nearly six times greater than that of a small untreated, natural desert watershed. Several operational wax-treated catchments have been built to supply water to livestock on arid rangeland. Ranchers are pleased with them — equating them to permanent springs. Both laboratory and field tests indicated that the wax treatment is most successful on sandy soils containing less then 20—25% clay plus fine silt.

INTRODUCTION

Population pressures are placing ever-increasing demands on marginal lands to produce life's staples of food, feed, fuel, and fiber. Each class of marginal land has its shortcomings; for arid and semiarid lands, this shortcoming is primarily water — water to drink and water for crops. Ironically, most of the limited precipitation which falls on these lands is wasted by evaporation, either directly from the soil or through the sparse vegetation.

This waste can be reduced, and needed water can be obtained by water harvesting — treating a portion of the land to increase the runoff from it so as to concentrate (store) the water for drinking or for growing crops on the remaining untreated land.

Quite a number of water-harvesting techniques have been tried (e.g., Cluff and Dutt, 1966; Evenari et al., 1971; Cooley et al., 1975; Hollick, 1975; Medina, 1976). The level of technology required varies tremendously, as does cost and runoff yield.

A relatively new water-harvesting technique is the application of wax to soil to create a water-repellent, water-shedding surface. The first two paraffin-wax-treated, water-harvesting catchments were installed at our laboratory's Granite Reef test site during the summer of 1972. Average runoff that year from the two catchments exceeded 90% of the precipitation (Fink et al., 1973). Furthermore, the quality of the collected water was excellent: (1) refined paraffin wax added no questionable organic compounds to the runoff water; (2) salt content of the runoff water was less than 50 ppm; and (3) sediment content in the runoff water was low because the wax helped to stabilize the soil.

A number of operational wax-treated catchments have been installed since then to provide water for livestock on semiarid rangeland, where drinking water rather than forage, often limits livestock production. The U.S. Bureau of Land Management (BLM) established two such systems in 1974 (Cooley et al., 1978). The immediate success of these two catchments (ranchers equated them to permanent springs) prompted the BLM to install more. As of 1979, thirteen of these wax-treated catchment systems were operating on the remote Arizona Strip region north of the Grand Canyon of the Colorado River, and the BLM is planning to build more. Additionally, the Soil Conservation Service has assisted several private ranchers in establishing their systems, and the Forest Service has several in operation.

Since the use of wax for water harvesting is increasing and since 7 years have elapsed since the first two plots were installed, evaluation of the use of wax for long-term water harvesting now seems appropriate. This paper reports on the progress made, the problems that remain, and the potential that exists for this water-harvesting technique.

MONITORED CATCHMENTS

The first wax-treated catchment was a small, 10-m^2 rectangular plot with a 5% south-facing slope, and the second was a 200-m^2 ridge and furrow plot with a 3% longitudinal north-facing draining channel and 10% lateral east—west-facing slopes (Table I). Soil surfaces were cleared, shaped, smoothed, and rained on several times to compact the soil and form a fine gravel desert pavement. Ground, refined paraffin wax was hand-spread atop the small and large plots in the summer of 1972 at 0.73 and 0.68 kg/m^2, respectively. The sun melted the wax into the soil, producing highly water-repellent soil surfaces.

TABLE I

Runoff efficiencies (*E*)[a] of three paraffin-treated catchments compared to three standard water-harvesting treatments

	Granite Reef catchments						Usery Pass	
		% Runoff						% Runoff
Year	Precipitation (mm)	10 m^2 wax	200 m^2 wax	200 m^2 plastic membrane	190 m^2 cleared, smoothed	640 m^2 natural watershed	Precipitation (mm)	10 m^2 wax
1972	244	92	90	95	37	24		
1973	208	88	87	98	16	14		
1974	251	94	85	92	16	15		
1975	183	96	88	100	15	13	223	92
1976	193	91	86	99	21	14	221	87
1977	116	77	80	100	20	11	189	81
1978	540	88	81	98	21	15	595	90
Yearly Average		89	85	97	21	15		88

[a] *E* = average yearly runoff efficiency = total yearly runoff/total yearly rainfall, in percent.

A third, small (10-m^2) monitored, paraffin-wax-treated catchment was installed in 1975 near Usery Pass, Arizona, as part of a runoff-farming study with jojoba (Ehrler et al., 1978). Again, ground paraffin wax was hand-spread at 1.0 kg/m^2 atop a cleared, smoothed and compacted soil.

Treatment performance of all three catchments has been monitored continuously since installation by measuring both rainfall and runoff for each storm event.

Table I shows the yearly rainfall totals and the associated average yearly runoff efficiencies, E (% runoff), for the wax-treated Granite Reef and the Usery Pass catchments, and compares their efficiencies with those of three standard water-harvesting treatments at the laboratory's Granite Reef test site. The three standard treatments are: (1) a 30-mil black polyethylene sheet bonded to the soil with asphalt emulsion; (2) a catchment cleared of vegetation, and smoothed; and (3) a small undisturbed, natural watershed.

Runoff efficiencies for 1972 (the several month period immediately following wax treatment) were 92 and 90%, respectively, for our first 10- and 200-m^2 plots. Such values approached those for the plastic membrane (95%) and were several times greater than those for either the cleared and smoothed plot or for the natural watershed. These initial results were encouraging.

Runoff efficiencies of the two Granite Reef wax plots have remained high for 7 years — all yearly E values, except one, have exceeded 80%. The E values for 1978, year 7, were only 4 and 9% less than those for the first year, and only 1 and 4% less than the 7-year averages for the 10- and 200-m^2 plots, respectively. The 7-year runoff efficiency for both plots was only about 10% less than that of the plastic membrane, but was more than four times greater than that of the cleared and smoothed plot, and nearly six times greater than that of the natural watershed. Yearly runoff efficiencies of the Usery Pass catchment have been consistently high, averaging 88% for the first 4 years.

When designing water-harvesting catchments, it is preferable that the runoff efficiency (both individual storm and composite of all storms) remains nearly constant or predictable for a long period. There are difficulties enough in such planning, trying to account for vagaries in precipitation and use patterns. Fig. 1 shows the yearly runoff efficiencies of the 200-m^2 wax-treated plot according to storm size for 7 years. Since the overall runoff efficiencies were high, we naturally expected the high runoff efficiencies for the large storms. However, even the small storms ($<$ 5 mm) averaged over 70% runoff. Since such storms constitute nearly half of the rainfall events at Granite Reef and can account for up to a third of the total yearly precipitation (Frasier, 1975), they can be an important water resource in times of critical need.

The gradual trend in lower runoff efficiencies for the small storms in 1977 and 1978 (Fig. 1) were caused by increased surface-water retention, which is indicative of a gradual loss of water repellency at the soil surface and of an increase in surface roughness as fines gradually erode, leaving the gravel. The high runoff efficiency in 1978 of the large storms suggested, however, that a water-repellent layer still existed within the treated zone, essentially prevent-

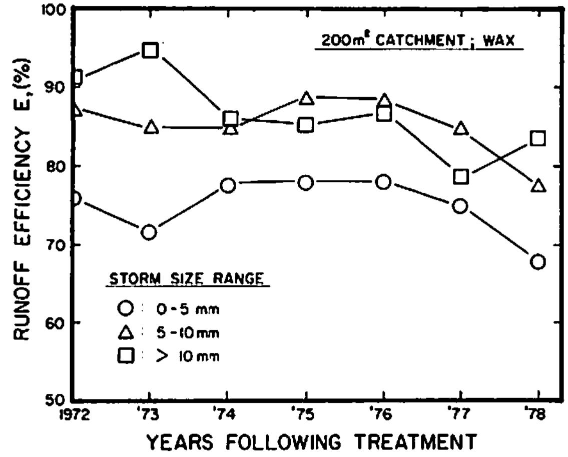

Fig. 1. Runoff efficiencies (E) for the 200-m² paraffin-treated catchment as a function of storm size for the 7 years following treatment.

ing deep percolation losses. If the wax does weather from the soil surface downward, then small topical reapplications of wax when needed should maintain high runoff efficiencies. To date, these three monitored wax-treated catchments have received no maintenance, other than clipping of weeds — primarily at plot edges where water seeps beneath the treatment. Low water retention on the catchment means soil surfaces dry too quickly for weed seeds to germinate. This near absence of soil moisture undoubtedly also protects the wax from microbial destruction.

OPERATIONAL CATCHMENTS

We also wanted to know the effectiveness of wax-treated operational catchments. Continuous monitoring of all precipitation—runoff events, as is done at the Granite Reef test site, is best, but is logistically impossible for remote, scattered locations. Occasional measurement of the water in the storage tank is helpful, but this can be a misleading indicator, particularly if use patterns and precipitation are not closely monitored. To partially overcome these difficulties, Frasier et al. (1979) developed a small portable sprinkler to estimate runoff efficiencies of operational catchments.

Catchment installation procedures varied, but generally soil surfaces were scraped smooth, treated with a sterilant to prevent weed growth, and coated with 0.9 or 1.5 kg/m² of melted, refined, paraffin wax using an asphalt distributor truck (Table II). All were designed to provide water for livestock, but were also used by wildlife. Details on the installation and costs of two of these catchments have been published (Cooley et al., 1978).

Runoff efficiencies of nine of these operational catchments were determined spring and fall each year if possible by measuring runoff from 1-m²

TABLE II

Treatments and runoff efficiencies (*B*) of paraffin-treated catchments

Catchment	Installation			Runoff efficiency		Soil texture		
Name	Size (m^2)	Rate (kg/m^2)	Date	Last test	B(%)	Clay(%)	Silt(%)	Sand(%)
Operational catchments								
Snap Point	3000	0.9	1974	Aug. 1977	70[a]	8	44	48
Slope	4000	0.9	1974	May 1979	74	12	65	23
Westwind	4000	0.9	1976			11	70	19
(retreat)		0.9	1977	May 1979	80			
Temple	4000	0.9	1976			10	69	21
(retreat)		1.5	1977	May 1979	76			
Graham	1000	0.9	1976	May 1978	100	8	28	64
Burnt Ridge	3000	1.5	1977	May 1979	95	15	57	38
Toquer	3000	1.5	1977	May 1979	86	[c]	[c]	[c]
Gubler	3000	1.5	1977	Sep. 1978	48	31	48	21
Corner	1000	0.9	1977	May 1978	99	[c]	[c]	[c]
Monitored catchments								
Granite Reef								
No. 1	10	0.73	1972	1978	100[b]	7	27	66
No. 2	200	0.68	1972	1978	87	7	27	66
Usery Pass	10	1.0	1975	1978	99	5	10	85

[a] Slope of plot of accumulated runoff vs. accumulated "rainfall" applied by sprinkler after initiation of constant rate of runoff (average of three runs).

[b] Slope of linear regression of runoff vs. rainfall amounts by storms (zero runoff data omitted).

[c] Not available.

areas of the catchments using simulated rainfall produced by the sprinkler. "Rainfall" was applied at a constant, known rate (45—50 mm/h) using one low-pressure, wide-angle, full square nozzle, placed 152 cm above the treatment surface. Accumulated runoff was plotted vs. accumulated "rainfall". The slope of the plot at constant runoff rate (usually attained within 10—15 min following start-up for wax-treated catchments) is the *B* runoff efficiency. Table II lists the *B* efficiencies of the operational catchments obtained on the last test prior to publication.

This *B* efficiency represents the resistance of the treated soil to water infiltration (e.g., no infiltration if $B = 100\%$, but 25% infiltration if $B = 75\%$), and is comparable in meaning to the slope term (*B*) of a linear regression of runoff vs. rainfall totals of individual storms by years (zero runoff data omitted) of monitored catchments. Table II also lists the *B* efficiencies of the three monitored catchments as determined by linear regression of the storm data for 1978. Characteristically, the *B* efficiency values for highly efficient water-harvesting treatments such as wax are 5—10% greater than their associated *E* efficiency values (compare 1978 *B* and *E* values of the

Granite Reef and Usery Pass sites in Tables I and II). The simplistic explanation of this difference is that *B* efficiencies disregard the threshold rainfall (amount needed to initiate runoff), while *E* efficiencies are the average of all data from all rainfall events.

Table II lists average *B* values obtained using the sprinkler on the nine operational wax-treated catchments. Values range from 100% for the Graham catchment to only 48% for the Gubler catchment; all others were 70% or greater. Runoff efficiencies of less than 75% are low for repellent-treated soil catchments; yet, slight overdesign of catchments, as was done for all the operational catchments listed in Table II, assures adequate water supplies.

All the operational catchments installed since 1974, except Gubler, are exceeding expectations and are providing adequate water for the cattle allotment assigned to the area. For example, the Slope catchment provided water for 70 head of cattle for 270 days the first year following installation, and 100 head for 150 days each of the next 2 years. Furthermore, the 300 000-l storage tank overflowed each year and some water was hauled away to cattle elsewhere (Cooley et al., 1978). Ranchers like the systems because now for the first time water is not a limiting factor in utilizing the range, and the government agencies which manage the land like the systems because now rotational grazing systems can be based on carrying capacity rather than on water availability.

Several factors when in combination may account for the low runoff efficiency of the Gubler catchment: (1) high clay content (31%); (2) high incidence of freeze—thaw cycling (Herschfield, 1974); (3) winter storms; and (4) a steep slope (10—20%). Singly, the factors may not necessarily be destructive, e.g., all the other operational sites listed are subject to freeze—thaw cycling and winter rain — yet have maintained high runoff efficiencies.

The first operational wax-treated catchment (Seneca — 1973) failed completely within only 6 months. Initially the failure was thought to be due to the low application of wax (0.5 kg/m^2). Subsequent investigations, however, showed that the soil was essentially untreatable because of the large amount of swelling clay percent (49%), which would swell and crack when flooded and subsequently dried (Fink and Mitchell, 1975).

Some of the problems with structural failures of wax-treated soils may be solved by increasing the wax application rate. The BLM now applies 1.5—2 kg/m^2 of paraffin wax to partly compensate for the destructive effects of excessive clay and freeze—thaw cycling. They also slightly overdesign the catchment size to compensate for loss of runoff efficiency as the treatments weather. Both these practices are economically justifiable because the wax costs only 15—20% of the total water-harvesting unit (Cooley et al., 1978).

These sprinkler test evaluations of operational catchments will be continued to (1) assess treatment longevity, (2) schedule maintenance, and (3) better relate such sporadically obtained data with those obtained from continuously monitored plots and from laboratory studies.

LABORATORY ANALYSES

Laboratory research has continued concurrently with field studies. Laboratory procedures have been developed to quickly and easily evaluate the response of numerous, potential water-repellent soil treatments to the most damaging of the natural weathering elements, i.e., freeze—thaw cycling, UV radiation, and prolonged hydration (Fink and Mitchell, 1975; Fink, 1976). Results have shown that treatments fail either by a loss (or lack) of repellency, or loss of soil structural stability. Repellency was found to be primarily a function of the type of organic coating material, while structural stability relates primarily to soil physical—chemical properties, e.g., type and amount of soil, clay, and cations on the exchange complex, and only secondarily to the properties of the repellent.

Laboratory studies confirm the field observations of difficulty in treating fine-textured soils with wax. In several closely related experiments, 11 different soils were compacted wet into 9-cm diameter petri dishes, air dried, and treated with paraffin wax at rates ranging from 0.5 to 2 kg/m^2. The wax was melted into the soil with heat lamps. A large 2—3-cm diameter water drop was placed atop the center of each sample to check for water repellency (repellency being defined as some remnant of the drop remaining atop the soil after 4 h).

Samples were then placed in a freeze—thaw chamber which cycled between ± 20°C. A 2—3-cm diameter water drop was maintained on the soil surface. Cycling continued until stability was destroyed (Fink, 1976).

Fig. 2 shows the number of freeze—thaw cycles the treated soils could withstand before losing structural stability, and plots this as a function of the <20 μm soil fraction. Clearly, soils containing more than 20—25% of

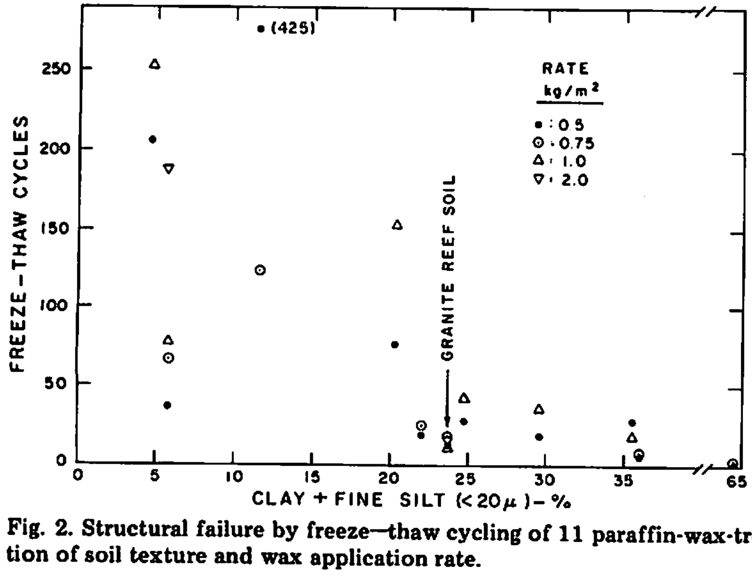

Fig. 2. Structural failure by freeze—thaw cycling of 11 paraffin-wax-treated soils as a function of soil texture and wax application rate.

clay plus silt (< 20 μm) fraction do not withstand many freeze—thaw cycles. Increasing the wax rate improves resistance some, but primarily for coarse-textured soils. Treated soils failed only under that portion covered by water, never under the dry peripheral portions. The implications for care in smoothing the soil of field sites vulnerable to freeze—thaw cycling before treating with wax are obvious. Maintaining surface dryness has undoubtedly been the salvation for most of the successful operational catchments listed in Table II.

Interestingly, the Granite Reef soil (location of our first two wax field plots) is very vulnerable to freeze—thaw cycling when water is present. Soils at the Granite Reef site rarely freeze, however, which helps account for the longevity of these two wax plots. These and already published studies (Fink and Mitchell, 1975) all show that it is better to locate wax-treated, water-harvesting systems on coarser-textured soils. Of course, the scatter in the data of Fig. 2 indicates that factors other than soil texture influence wax treatment performance.

Recent laboratory studies (Fink, 1980) suggest that certain soil stabilizers and antistripping agents added to the wax markedly improve weathering resistance, reduce both the amount and grade of wax required to treat the soil, and may permit the treatment of finer textured soils. These materials are now being field tested.

POTENTIAL

Arid and semiarid areas, which account for about a third of the world's total land, are particularly well suited for water-harvesting techniques. For much of these areas it is the only practical available source of water. Water harvesting could supply water for most uses; however, economic factors will restrict the type of systems installed and the uses to which they will be put. The wax treatment for water harvesting is gradually being accepted by others and its use is being expanded. Utilization for livestock watering has already been discussed. Several researchers have utilized wax for runoff-farming studies: (1) Aldon and Springfield (1975) for watering shrubs for reclamation of disturbed lands; (2) Sauer (Anonymous, 1979) for growing crops between spoil banks; (3) Cluff (1978) and Ehrler et al. (1978) for growing jojoba; and (4) Schreiber and Frasier (1978) for establishing rangeland grasses.

Paraffin wax treatments are already economically competitive with many established systems of obtaining water: e.g., deep bores, piping, hauling, and certain water-harvesting treatments, such as butyl rubber, sheet metal, concrete, and asphalt. Presently, laboratory and field research efforts are being directed at (1) reducing the amount of wax required, (2) using cheaper, residual, surplus grade waxes (Fink, 1977), and (3) extending the range of treatable soils and climates. Fruition of these efforts should lead to less expensive water-harvesting systems that are easier to apply, have a high runoff efficiency, are more durable, can be applied to a wide variety of soils in a wide climate range, and provide high-quality water for a variety of uses.

REFERENCES

Aldon, E.F. and Springfield, H.W., 1975. Using paraffin and polyethylene to harvest water for growing shrubs. In: G.W. Frasier (Editor), Proc. Water Harvesting Symp. USDA, ARS-W-22, pp. 251—257.

Anonymous, 1979. New plan uses spoil banks to funnel rain to crops. Crops Soils Mag., 31: 21.

Cluff, C.B., 1978. Jojoba water-harvesting agrisystem experiment, Papago Indian Reservation, Sells, Arizona. Jojoba Happenings, 24: 3—10.

Cluff, C.B. and Dutt, G.R., 1966. Using salt to increase irrigation water. Prog. Agric. Ariz., 18: 12—13.

Cooley, K.R., Dedrick, A.R. and Frasier, G.W., 1975. Water harvesting: state of the art. Watershed Management Symp. ASCE Irrigation and Drainage Div., pp. 1—20.

Cooley, K.R., Frasier, G.W. and Drew, K.R., 1978. Water harvesting: an aid to range management. First Int. Rangeland Congr. Proc., pp. 292—294.

Ehrler, W.L., Fink, D.H. and Mitchell, S.T., 1978. Growth and yield of jojoba plants in native stands using runoff-collecting microcatchments. Agron. J., 70: 1005—1009.

Evenari. M., Shanan, L. and Tadmor, N., 1971. The Negev. The Challenge of a Desert. Harvard University Press, Cambridge, MA, 345 pp.

Fink, D.H., 1976. Laboratory testing of water-repellent soil treatments for water harvesting. Soil Sci. Soc. Am. J., 40: 562—566.

Fink, D.H., 1977. Residual waxes for water harvesting. Hydrol. Water Resour. Ariz. Southwest, 7: 199—205.

Fink, D.H., 1980. Wax water-harvesting treatment improved with antistripping agent and soil stabilizer. Hydrol. Water Resour. Ariz. Southwest, in press.

Fink, D.H. and Mitchell, S.T., 1975. Freeze—thaw effects on soils treated for water repellency. Hydrol. Water Resour. Ariz. Southwest, 5: 79—85.

Fink, D.H., Cooley, K.R. and Frasier, G.W., 1973. Wax-treated soils for harvesting water. J. Range Manage., 26: 396—398.

Frasier, G.W., 1975. Water harvesting for livestock, wildlife, and domestic use. In: G.W. Frasier (Editor), Proc., Water Harvesting Symposium. USDA, ARS W-22, pp. 40—49.

Frasier, G.W., Cooley, K.R. and Griggs, J.R., 1979. Performance evaluation of water harvesting catchments. J. Range Manage., 32: 453—456.

Hershfield, D.M., 1974. The frequency of freeze—thaw cycles. J. Appl. Meteorol., 13: 348—354.

Hollick, M., 1975. The design of roaded catchments for maximum runoff. In: G.W. Frasier (Editor), Proc., Water Harvesting Symposium. USDA, ARS W-22, pp. 201—220.

Medina, J., 1976. Harvesting surface runoff and ephemeral streamflow in arid zones. In: Conservation in Arid and semi-arid Zones. Conservation Guide No. 3, FAO, Rome, pp. 61—72.

Schreiber, H.A. and Frasier, G.W., 1978. Increasing rangeland forage production by water harvesting. J. Range Manage., 31: 37—40.