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A REVIEW OF RAINWATER HARVESTING

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ABSTRACT

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This article reviews recent literature on rainwater harvesting and its potential application for crop production. Some 170 articles published between 1970 and 1980 were found, all of them revealing an awareness of the increasing need for rainwater harvesting and a recognition of its potential.

A definition of rainwater harvesting is presented on the basis of three characteristics common to it: arid to semi-arid climate, local water, and small-scale operation. The following elements are considered:

runoff inducement — vegetation management, surface treatment, chemical treatment;
runoff collection — Micro-Catchment Water Harvesting (MCWH) and Runoff Farming Water Harvesting (RFWH);
storage and conservation.

Design aspects of MCWH are reviewed: MC size, ratio of contributing area to collecting area, and layout. MCWH is especially suitable to non-irrigated areas. The Kinematic Wave Equation and Dynamic Equations have been used in modelling MCWH.

RFWH can be useful in improving irrigation water availability in surface reservoirs. For modelling RFWH, the Unit Hydrograph Method is suitable. More research is required to determine the potential of runoff farming without surface reservoirs.

INTRODUCTION

For thousands of years man has tried to survive in desert regions, and could only do so by skilfully managing that vital but scarce resource: water (Evenari et al., 1971; Myers, 1975; Bowden, 1977; Back, 1981). Water harvesting methods formerly developed for mere existence are nowadays receiving renewed attention because they can contribute to increased water supplies for agriculture and domestic use (Fink and Ehrler, 1978; Fink et al., 1980; Frasier, 1980; Pratt, 1980).

The first definition of water harvesting comes from Geddes, as quoted by Myers (1975): 'The collection and storage of any farm waters, either runoff or creek flow, for irrigation use.' Myers also quotes Currier's definition: 'The process of collecting natural precipitation from prepared watersheds for beneficial use.' Myers himself used the following definition: 'The practice of collecting water from an area treated to increase runoff from rainfall or snowmelt.'

These definitions show that water harvesting encompasses methods to induce, collect, and store runoff from various sources and for various purposes. The methods applied depend strongly on local conditions and include such widely differing practices as farming terraced wadi beds (Evenari et al., 1971), growing trees on micro-catchments (Nat. Acad. Sci., 1974), catching runoff from sheet metal catchments (Chiarella and Beck, 1975; Mickelson, 1975), tapping subsurface runoff (Agarwal et al., 1977; Burdass, 1975; Smith, 1978), storing runoff behind a dam (Bowler and Turner, 1977; Myhrman et al., 1978), and others (see e.g. Evans et al., 1975; Manges and Mao, 1978).

In spite of their differences, all these methods have three characteristics in common:

(1) they are applied in arid and semi-arid regions where runoff has an intermittent character. Surface runoff occurs as a discrete event and subsurface water may flow part of the year and stop during dry periods. Because of the ephemerality of flow, storage is an integral part of water harvesting (Myers, 1967);

(2) they depend upon local water such as surface runoff, creek flow, springs, and soaks (Burdass, 1975). They therefore do not include storing river water in large reservoirs or the mining of groundwater;

(3) they are relatively small-scale operations in terms of catchment area, volume of storage, and capital investment. This characteristic is a logical consequence of the other two characteristics.

The objective of this article is to review those methods of harvesting surface runoff that have a potential for application on farms in arid and semi-arid regions. For the purpose of this article therefore we define rainwater harvesting as a method to induce, collect, store, and conserve local surface runoff for agriculture in arid and semi-arid regions.

RUNOFF INDUCEMENT

The success or failure of rainwater harvesting depends to a great extent on the quantity of water that can be harvested from an area under given climatic conditions. The threshold retention of a catchment is the quantity of precipitation required to initiate runoff (Fink et al., 1979); it depends on various components such as surface storage, rainfall intensity, and infiltration capacity. The runoff efficiency of a catchment is the ratio of runoff volume to precipitation volume. Runoff efficiencies have been expressed as annual averages to discount variability due to storm size (Fink et al., 1979).

Sometimes natural surfaces that can yield a good water harvest are available, e.g. sandstone rock slopes (Chiarella and Beck, 1975), slickrock hillsides (Frasier, 1975; McBride and Shiflet, 1975), or granite outcrops (Burdass, 1975) Where such natural surfaces do not exist, measures can be taken to induce runoff. Considerable research has been done on methods to reduce surface storage and lower infiltration capacity, which are the main parameters determining threshold retention and runoff efficiency. The methods can be classified as: vegetation management, surface treatments, use of chemicals. Much work has also been done with membranes (Rauzi et al., 1973; Mickelson, 1975; Fink et al., 1979), but these studies are not included in this review.

Vegetation management

A summary of studies conducted throughout the world indicates that runoff can be increased by vegetation management in areas with an annual precipitation in excess of 280 mm (Cooley et al., 1975). Runoff efficiency with this method is low and may vary greatly with storm, season, or year. The method is usually applied in combination with surface treatments (Hillel, 1967; Rands et al., 1979). The main effect of vegetation management is that it reduces the infiltration capacity.

Surface treatment

Surface treatments such as rock clearing (Evenari et al., 1971), smoothing and compacting (Frith, 1975) are usually done in combination (Anaya and Tovar, 1975; Fink and Ehrler, 1979). The runoff efficiency of catchments is difficult to generalize because it depends on such factors as antecedent soil moisture, storm intensity, storm duration, catchment size, and years after treatment (Fink et al., 1979; Frasier, 1975). For smoothed catchments, runoff efficiencies ranging from 20—35% have been reported (Fink et al., 1980; Frasier, 1980). The main effect of surface treatment is that it reduces surface storage.

Like vegetation management, surface treatment is relatively inexpensive and may last for a long time. Where the dominant factor reducing runoff efficiency is a high infiltration capacity, vegetation removal is more effective than surface treatment. Where surface storage is the dominant factor, surface treatment will be more effective.

Chemical treatment

During the past 15 years many chemicals have been tested for water harvesting. The trials cover both preliminary laboratory experiments (Fink, 1970, 1976; Hillel and Berliner, 1974; Plueddemann, 1975) and application on field scale (Fink and Cooley, 1973; Fink et al., 1973; Aldon and Springfield, 1975; Cluff, 1975).

Sodium salts, paraffin wax, and asphalt seem to offer good prospects for future application. Sodium salts cause the clay particles in the soil to disperse and partly seal the pores, while paraffin wax and asphalt clog the pores themselves. Both reactions reduce the infiltration capacity and increase the runoff.

The effect of chemical treatments on the runoff efficiency depends upon such factors as soil properties (De Jong and Wallace, 1975), rate of application of the chemical (Cooley et al., 1975; Dutt and McCreary, 1975), and years after treatment (Fink and Frasier, 1977).

Reported runoff efficiencies of salt-treated catchments vary from 25% (Rauzi et al., 1973) to 80%, and after retreatment even to 96% (Hillel, 1967). For paraffin wax, runoff efficiencies vary from 48% (Frasier et al., 1979) to 90% (Fink et al., 1979), with an average of 85% (Fink et al., 1980). Reported runoff efficiencies of asphalt treatments vary from 25% four years after treatment (Mehdizadeh et al., 1978) to over 90% (Fink et al., 1979) with an estimated average in the range of 85—95% (Frasier, 1980).

RUNOFF COLLECTION

In rainwater harvesting, many methods of collecting surface runoff have been developed (Nat. Acad. Sci., 1974). For the purpose of this article we have split them into two categories: Micro-Catchment Water Harvesting (MCWH) and Runoff Farming Water Harvesting (RFWH).

Micro-Catchment Water Harvesting (MCWH)

For the purpose of this review we define MCWH as: a method of collecting surface runoff from a Contributing Area (CA) over a flow distance of less than 100 m and storing it for consumptive use in the rootzone of an adjacent Infiltration Basin (IB).

The CA and the IB are the two basic elements of a Micro-Catchment (MC). In the IB there may be a single tree (Evenari et al., 1971), bush (Fink and Ehrler, 1979), or a row crop (Gardner, 1975). According to our definition, we regard as types of MCWH: Contour Catchment Water Harvesting (Mehdizadeh et al., 1978), Desert Strip Farming (Morin and Matlock, 1975), Contour Bench Farming (Jones and Hauser, 1975; Smith, 1978), and Runoff Based Pitcher Farming (Oswal and Singh, 1975).

It is a well-known fact that because of reduced infiltration losses the percentage of runoff increases with decreasing catchment size (Amerman and McGuinness, 1968). Small watersheds can produce runoff amounting to 10—15% of the annual rainfall (Fig. 1) and for an MC this can be even higher.

The design of an MC affects water-use efficiency, crop yield, erosion hazard, earth work, and farm operations (Gardner, 1975; Shanan and Tadmor, 1976). The first design factor to consider is the size. In experiments MC size has ranged from roughly 0.5 m^2 (Aldon and Springfield, 1975) to 1000 m^2 (Evenari et al., 1968) for trees, shrubs, and row crops; average annual rainfall ranged from 100 mm (Evenari et al., 1971) to 650 mm (Anaya and Tovar, 1975).

The key parameter in MC design is the CA/IB ratio, which depends on climate, soil conditions, and crop water requirement. In experiments the

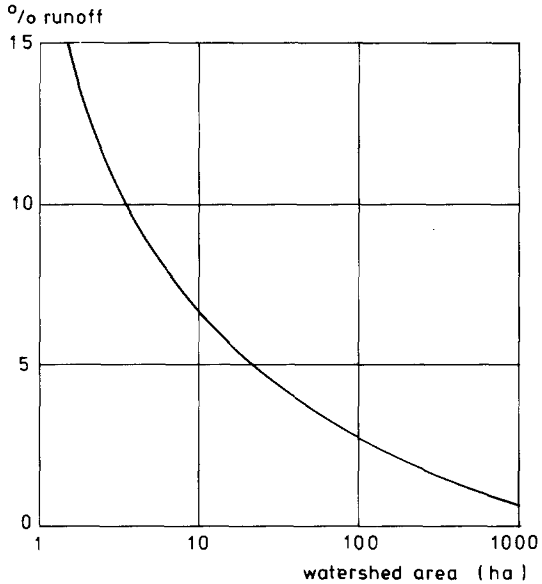

Fig. 1. Surface runoff in percentage of rainfall as a function of watershed area (Avdat, Israel).

CA/IB ratio generally varied from 1 (Luebs and Laag, 1975) to 6 (Rawitz and Hillel, 1975), but Anaya and Tovar (1975), referring to Newman (1966), mention a CA/IB ratio of 25 in a catchment used to increase yields of range plants in Australia.

A CA/IB ratio which is too large for the prevailing conditions may result in deep percolation losses (Gardner, 1975), high border checks to store runoff from large storms (Fairbourn, 1975), and crop aeration problems due to prolonged water ponding in the IB (Fangmeier, 1975). On the other hand, a relatively large CA/IB ratio promotes infiltration, which reduces direct evaporation losses (Gardner, 1975). Because of the stochastic nature of rainfall events, the optimum CA/IB ratio should be found for each set of local conditions separately.

Another important design factor for a given MC size and CA/IB ratio is the length/width ratio of CA and IB, the length coinciding with the direction of flow and the width perpendicular to it. The ratio depends on rainfall characteristics, topography, and water-spreading properties of the soil. A too large length/width ratio of CA may create problems in earth work and erosion; a too long IB may be only partially wetted (Gardner, 1975).

In the design of an MC layout, topography plays an important role. The following patterns have been used (Shanan and Tadmor, 1976): a square IB in one corner of the MC (Evenari et al., 1971), an IB in the centre of the MC, with radial flow direction (Aldon and Springfield, 1975; Oswal and Singh, 1975); a triangular MC with the IB in one corner (Ehrler et al., 1978); terrace with IB receiving water from CA on one side (Jones and Hauser, 1975); ridge and furrow type with IB receiving runoff from CA on two sides (Fairbourn, 1975).

The main advantage of an MC is the high specific runoff yield as compared with that obtained from small catchments (of a few km^2) and large catchments (of hundreds of km^2). The limitation of MC is the low crop yield per unit area, even when each crop is producing a high yield per m^3 of water. This is caused by the low number of crops per unit area, which also means that farm operations must cover extensive areas. In deserts, however, where these methods are applied, water and not land, is the limiting production factor. Thus, even though MCWH shows a low potential of crop production per unit area, the potential efficiency for water use by plants is high.

Runoff Farming Water Harvesting (RFWH)

For the purpose of this review we define RFWH as a method of collecting surface runoff from a Catchment Area (CA), using channels, dams, or diversion systems, and storing it in a Surface Reservoir (SR) or in the rootzone of a Farmed Area (FA) for direct consumptive use. RFWH without SR is also called Runoff Farming (Tadmor et al., 1960).

The water collected from the CA and stored in the SR (Cluff, 1975; McBride and Shiflet, 1975; Frasier, 1980) is often used for livestock drinking water. A major part of the literature covers this application (Fink and Cooley, 1973; Burdass, 1975; Frasier, 1975; Cooley et al., 1978; Frasier and Cooley, 1979; Heaton, 1979; Laing, 1975). However, in line with the above definition, we shall regard the water in the SR as being primarily a source for crop production (ICRISAT, 1978).

More water from the CA can be stored in an SR than in the soil profile; so SR enables the user to maintain a better water distribution in space and time. One of the major design problems is to determine the relative sizes of CA and SR (Frasier, 1975). The main disadvantage of RFWH with SR is the investment for construction of SR and the system to distribute the water from the SR to the cultivated area. For this reason, SRs are generally only applicable where the economy can bear this investment or where outside financial aid is available. Spiegel-Roy et al. (1977) discuss the alternative of storing the harvested water in the soil profile.

We found the literature on runoff farming rather limited compared with that on other water harvesting practices. However, several methods have been developed to store water for agriculture in the soil profile. The most simple method, which is probably also the most ancient, uses individual terraced wadis (Evenari et al., 1971). The Bedouins still use this method today. After an early flood, they sow the wetted terrace soil with barley and other crops and, considering the circumstances, the yields they obtain are fair (Boers and Ben-Asher, 1980).

Another method, commonly applied in the Negev, uses groups of terraced fields located in small tributary wadis surrounded by hills. Running down the hillsides are runoff collecting channels that carry the water to the fields. Each runoff unit includes two basic features: a farmed area at the wadi bottom and a catchment area, divided into sub-catchments by water conduits that collect the runoff water. The relative size of catchment areas and cultivated fields was calculated for 100 different runoff farms and expressed as the CA/FA ratio. It varied between 17 and 30, with an average of about 20 (Tadmor et al., 1960).

In runoff farming the problem is that few rainfall data are available for flood prediction and often there are no runoff data at all (Cooley et al., 1975). If the FA is too small compared with the size of the flood, water will be lost by deep percolation. Conversely, if FA is too large compared with the size of the flood, crops may be damaged by the lack of soil water.

Detailed design specifications cannot be given here, as these depend strongly on local conditions. For siting and system design, basic data are required on topography, soil type and depth, quantity and distribution of rainfall, and quantity and distribution of crop water requirement.

STORAGE AND CONSERVATION OF HARVESTED WATER

Storage is an integral part of water harvesting (Myers, 1975). The decision on which way to store water depends in the first place upon how the water is to be used. SR is generally applied if the water is required for livestock (see above), with volumes ranging from 20—350 m^3 (Frasier, 1980).

For crop production SR has been used or proposed in a few cases (Smith, 1978; Cluff, 1979) but soil water storage is far more common. Fig. 2 shows the variables that determine the quantities of runoff R and storage S, while Table I shows relevant variables for storage in rootzone or SR. In general, reservoirs are used when R is large compared with soil water storage capacity S; otherwise, soil water storage is less expensive.

Conservation of harvested water by minimizing losses mainly involves reducing direct evaporation and deep percolation. Much research has been done to reduce such losses in SR (Nat. Acad. Sci., 1974; Cluff, 1975, 1979; Cooley,

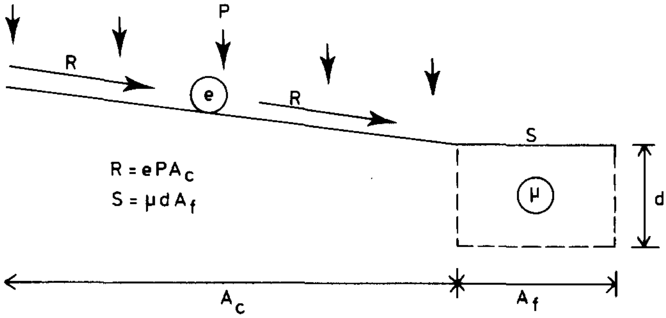

Fig. 2. Diagram showing factors determining surface runoff from catchment area and storage of harvested water. A_c, size of contributing area (m^2); A_f, size of collecting area (m^2); P, depth of rainfall (m); d, depth of storage (m); e, runoff efficiency; μ, storage coefficient; R, volume of runoff (m^3); S, volume of storage (m^3).

TABLE I

Factors relevant to water storage in MCWH and RFWH: storage in rootzone of infiltration basin (IB) or of farmed area (FA), or in surface reservoir (SR)

Water harvesting system	MCWH		RFWH
Collecting area	IB	FA	SR
Size (m^2)	A_f		A
Storage	Rootzone		Reservoir
Depth (m)	d		d
Storage coefficient	$0 < \mu < 1$		$\mu = 1$[a]
Storage volume (m^3)	$S = \mu dA_f$		$S = \mu dA$

[a]If a rock-filled storage reservoir is used, $0 < \mu < 1$ (McBride and Shiflet, 1975)

1975; Dedrick, 1975; Laing, 1975; McBride and Shiflet, 1975). Methods have been developed to reduce direct evaporation losses from soil water (Fairbourn, 1975; Gardner, 1975; Hoover, 1975). When runoff R causes a water layer of h mm to stand on IB or FA, this quantity of water can be stored in the rootzone if $h \leqslant \mu d$. If, however, $h > \mu d$, deep percolation losses will occur, due either to rainy years (Rawitz and Hillel, 1975) or to a coarse-textured profile with small μ (Cohen et al., 1968; Ehrler et al., 1978).

MODEL DEVELOPMENT

Few research efforts have been expended on the more fundamental physical and hydrological aspects of water harvesting. From this point of view, water harvesting belongs on the one hand to the classic surface hydrology and on the other to the wide field of soil physics. Two approaches have been followed in developing storm water models: the deterministic approach, which is based upon physical laws, and the statistical approach. An example of the deterministic approach is the Stanford Watershed Model (Linsley et al., 1958; Linsley and Crawford, 1960). The parameters of the model are determined by fitting the model to hydrological data.

In the deterministic approach, the first major component is the rainfall. To be taken into account when trying to predict runoff production are the amounts of rainfall (Chow, 1964; Freeze, 1974) and their intensity, duration, and distribution (Morin and Benyamini, 1977; Morin and Jarosch, 1977; Zaslavsky and Sinai, 1981). It is well known that infiltration is not a purely one-dimensional vertical flow process, because it depends upon the slope (Shanan, 1975) and the heterogeneity of the soil surface. Hence spatial variability of the surface characteristics must be taken into account when one is investigating the effect of soilwater properties on runoff (Rogowski, 1972; Cassel and Bauer, 1975; Biggar and Nielsen, 1976; Carvello et al., 1976).

The runoff phenomena can be modelled in two ways, depending upon the water harvesting method. For RFWH, under conventional desert hydrograph conditions, the unit hydrograph method (Chow, 1964; Diskin et al., 1971) can be used. In MCWH, water flow has been described by the kinematic wave equation (Henderson and Wooding, 1964; Overton and Meadows, 1976; Singh, 1976; Hillel and Hornberger, 1979) and by dynamic equations (Ben-Zvi, 1974). The modelling approach should be pragmatic because the models are intended to help select desert areas that are fit for RFWH and MCWH. Such models and approaches are expected to be general enough for application to water harvesting in many countries, the only proviso being that data on rainfall and on infiltration characteristics are available.

PROSPECTS FOR WATER HARVESTING

During the past 25 years, water harvesting has been receiving renewed attention. We found roughly 170 articles, abstracts, references, and titles which had appeared on the subject between 1970 and 1980: about three-quarters of them originated from the U.S.A. Considering the total area in the world where water could be harvested and the consequent vast potential for water harvesting, an average of 17 articles a year must be regarded as low, especially in view of the large research effort taking place in the south-western part of the U.S.A. If we make a comparison with trickle irrigation, which was also developed over the past 25 years, we find that in 1980 alone, more than 400 articles on this subject were published (IIIC, 1980); in one year, 2.5 times as many as on water harvesting in a decade!

Outside the U.S.A. and Australia, water harvesting is practised in many countries although on a limited scale: throughout the Middle East (Evenari et al., 1971; Hardan, 1975; Agarwal, 1977); on the Indian subcontinent (Ryan et al., 1979; Murthy et al., 1980), in Mexico (Anaya and Tovar, 1975; Smith, 1978; Cluff, 1979), and in Africa, south of the Sahara (National Academy of Sciences, 1974). There is a growing awareness of the increased need for water harvesting and of its potential (Shrivastava and Verma, 1975; Singh et al., 1975; Banerji and Lal, 1977; Zaslavsky, 1977; Deshmukh, 1979; Verma et al., 1979; Boers and Ben-Asher, 1980; Fink et al., 1980; Frasier, 1980; Murthy and Kalla, 1980).

MCWH offers good prospects, especially in areas where traditional irrigation is not practised. It could be started on suitable natural surfaces, but the use of relatively cheap runoff inducement methods should not be excluded. Such experiments have already been performed (Rawitz and Hillel, 1975; Mehdizadeh et al., 1978; Singh et al., 1979; Yadav et al., 1979; Murthy et al., 1980).

RFWH with SR offers good prospects especially in areas where irrigation is practised, but where rainfall distribution poses a problem for crop production. Water harvesting can provide a more equitable water distribution (Singh et al., 1975; Krishna and Hill, 1979) by increasing the runoff to existing reservoirs or to irrigation canals via diversion dams (Kring, 1979), or by supplying runoff to new reservoirs for carry-over in dry years. Prospects are also good in areas where small-scale irrigation could be introduced on the basis of harvested water stored in SR.

For runoff farming as practised in Advat. Israel, i.e. RFWH without SR (Evenari et al., 1971), the prospects of its application in other areas have to be examined. Before conclusions can be drawn on the suitability of this method, more research is required on such items as: if an alternative source of water, e.g. a deep well, is available for use in a dry year, how does the quality of this water affect soils and crops? More specifically, if the farmed area receives alternate flooding with fresh runoff water and pumped brackish or saline groundwater, how do soils and crops respond to this changing water quality?

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