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Micro-Catchment-Water-Harvesting (MCWH) for Arid Zone Development

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ABSTRACT

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A micro-catchment consists of two elements: the runoff area *A* and the infiltration basin or basin area *B*. The water balance equations for *A* and *B* are discussed, and combined in the water balance of the micro-catchment. The water balance is used as a tool to analyze the performance of the system, and to locate problems in the water harvesting process. Water balance data were collected during the rainy season 1982/1983 from an experimental field in Sede Boqer, in the Northern Negev Desert, Israel. Eight micro-catchments of 125 m^2 and four control basins of 9 m^2 were used, each providing water for a single tree. Analysis of the water balance illustrates two problems: runoff production and soil water storage. Effective Micro-Catchment-Water-Harvesting (MCWH) occurs in storms with sufficient runoff to allow infiltration deep into the profile free from evaporation. Besides evaporation at the surface of the basin area, water is lost by deep percolation. Efficiencies for runoff and storage are defined, which express the relevant processes in two numbers. For the eight micro-catchments during the rainy season 1982/1983 average runoff efficiency $e_r = 0.19$, and average storage efficiency $e_s = 0.18$. The analysis shows the usefulness of the water balance approach, and the methods used to evaluate its terms. MCWH is especially suitable for application in desert fringes with about 250 mm annual rainfall and loess soils, which form a surface crust. Micro-catchments are an effective tool to scale down engineering activities. They are easy and cheap to construct, which allows active participation of the local population.

1. INTRODUCTION

The problem of water shortage in arid zones is caused by low annual rainfall and unfavourable distribution of rainfall through the year. In arid zone development this problem is often overcome by the introduction of irrigation, if surface water or groundwater is available. In such land reclamation schemes a drainage system in addition to the irrigation system is necessary, in order to

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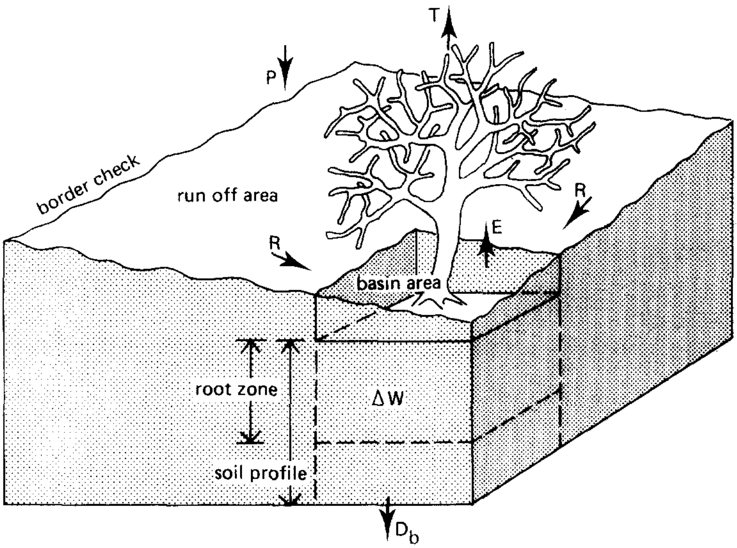


Fig. 1. Micro-catchment consisting of runoff area A and basin area B in which tree grows. Main water balance components are: P=rainfall, R=runoff, E=evaporation, T=transpiration, ΔW=increase in soil water storage and D_b=deep percolation below soil profile of basin.

maintain a favourable salt balance for crop growth. Examples of areas where agricultural production is expanded with the use of irrigation and drainage systems, are the Nile Delta of Egypt and the Indus Basin of Pakistan (see for instance Schulze and Van Staveren, 1980).

This approach is not everywhere applicable and desirable. In arid zones river water may be absent and groundwater may be saline, brackish or too costly to use. Also, intensive agriculture may be undesirable in arid zones, from an environmental point of view, or may not be the best solution, because of the cultural background of the local population. Nomads may be opposed to agriculture, because it would restrict their freedom of movement. Examples may be found in the Middle East and North Africa. Water harvesting can be an interesting alternative to arid zone reclamation by irrigation and drainage (Boers and Ben-Asher, 1980).

One method of water harvesting is called Micro-Catchment-Water-Harvesting (MCWH), which is defined as collecting surface runoff from a runoff area over a distance of less than 100 m and storing it in the rootzone of an adjacent infiltration basin to cover the crop water requirement. The runoff area A and the area of the infiltration basin B, located downstream of the runoff area, are two basic elements of a micro-catchment (Fig. 1). In the basin there may be a single tree, bush or annual crop (Boers and Ben-Asher, 1982). The aim of MCWH is to store sufficient runoff water in the rootzone below the basin during the rainy season, to cover the water requirement of the crop or tree during the growing season.

This water harvesting method has been tested in a number of countries since 1963 (National Academy of Sciences, 1974). Most research has concentrated on the runoff problem, while the storage of soil water in the basin area has received less attention (Hillel, 1967; Evenari et al., 1971; Frasier, 1975). A water balance analysis, as given in this article, shows the importance of the storage problem. A water-balance equation is usually applied to an entire catchment, or to sections of it. In a previous article Boers et al. (1986) studied and simulated the soil-water balance of the basin area. The present article deals with the water balance equations of runoff area, basin area and total micro-catchment.

This article is based on data from an experimental field with pistachio trees at Sede Boqer, Israel in the Northern Negev Desert, approximately 50 km south of Beer-Sheva. The prevailing climate is extremely arid with hot dry summers and cool winters. Mean annual rainfall is 91 mm, with extremes of 34 mm and 167 mm (Yair and Danin, 1980). Rainfall is limited to the winter season, which extends from October to April. The soil is a silt loam of aeolean origin, which is deposited as a loess cover of several meters thickness on a limestone bedrock of neogene conglomerate.

The objectives of this paper are: (1) to study the water balance of micro-catchments; (2) to examine practical and readily available methods of evaluating the water balance terms; and (3) to discuss prospects for application of this method in arid zone development. Water harvesting from micro-catchments can be particularly beneficial for application in developing countries. Therefore this article tries to outline a method of data collection and analysis which requires a minimum of equipment.

2. THEORY

For a system with well-defined space and time boundaries, the water-balance equation can be written in units of volume as:

$$\Delta S = I - O \tag{1}$$

where ΔS is the increase in storage during the given period of time, I is incoming components, and O outgoing components.

All inflow to the micro-catchment comes from precipitation, while the outflow consists of infiltration below the bottom of the system and water vapour losses through the upper boundary. The change of storage water occurs in the soil profile. The spatial boundaries of a micro-catchment are defined as shown in Fig. 1.

The upper boundary is formed by the soil surface. Strictly speaking, at the runoff area the lower boundary coincides with the upper boundary. Once a

TABLE 1

Main flow processes in a micro-catchment for water harvesting

	Rainy season	Growing season
Runoff area A	Production of surface runoff, R	Evaporation of shallow water, E_{a2}
Basin area B	Water storage in soil profile, ΔW	Water uptake and transpiration, T

water particle has infiltrated here, it is lost for runoff production. However, for the water balance of the whole micro-catchment, the soil profile below the runoff area has to be considered too. In the water balance, evaporation losses occur from the runoff area, which follow infiltration here.

In the horizontal direction the boundaries of the micro-catchment are formed by its borders, which prevent any lateral surface flow. Lateral soil water flow below the basin was assumed negligible. For a width of the basin of 3 m and a profile depth of 1.75 m, the width/depth ratio is 1.7. For this ratio the assumption seems justified. The results of a simulation study by Boers et al. (1986) showed that in fact some lateral flow occurred. This aspect is discussed in Section 4. (See also Fig. 9.)

For definition of the time boundaries of the water-balance equations, the hydrological year can be divided in two seasons:

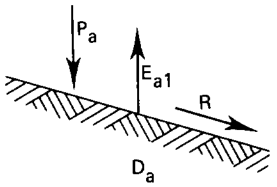
— rainy season: 1 October — 1 April
— growing season: 1 April — 1 October.

Table 1 shows the main water harvesting processes that occur in these seasons. During the rainy season the runoff area A transforms rainfall into surface runoff, and the runoff collected in the basin B infiltrates and is stored in the profile. In this season the trees are dormant and without leaves. During the growing season there is no rainfall and no runoff. On the runoff area evaporation occurs, of water which was lost by shallow infiltration during the rainy season. The main process in the basin area is the uptake of stored soil water and transpiration by the tree.

For each of the four processes in Table 1, water-balance equations can be written. Where necessary, subscripts are used: 1 and 2 refer to rainy and growing season, and a and b refer to runoff area and basin, respectively. During the rainy season the water balance for the runoff area is (Fig. 2):

$$R = P_a - E_{a1} - D_a \quad (2)$$

where R is runoff, P_a rainfall, E_{a1} evaporation of shallow infiltrated rainfall from soil surface, and D_a the increase of shallow soil water storage due to infiltration (m^3). Here shallow means in the top 25 cm. This aspect is further discussed in Sections 3 and 4.



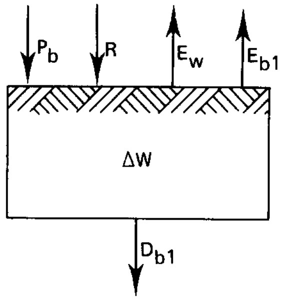


Fig. 2. Water balance components of the runoff area (subscript a) during the rainy season (subscript 1): P_a = rainfall, R = runoff, E_{a1} = evaporation from bare soil of shallow infiltrated rainfall, D_a = increase of shallow soil water storage due to infiltration.

Fig. 3. Water balance components of the basin area (subscript b) during the rainy season: P_b = rainfall on basin, R = runoff collected in basin, E_w = evaporation from water surface during infiltration, E_{b1} = evaporation from bare soil, ΔW = increase in soil water storage, D_b = deep percolation below soil profile.

During the rainy season, the following equation holds for the basin area (Fig. 3):

$$\Delta W = P_b + R - E_w - E_{b1} - D_{b1} \qquad (3)$$

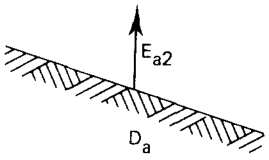
where ΔW is the increase in soil water storage P_b rainfall on basin, R runoff collected in basin, E_w evaporation from water surface during infiltration, E_{b1} evaporation from bare soil in basin, and D_{b1} deep percolation below soil profile (m^3).

The maximum depth at which soil water content could be measured with neutron meter was 1.75 m. For this practical reason, 1.75 m was taken as the depth of the soil profile in which soil water storage ΔW was calculated. Flow below 1.75 m was considered deep percolation. The trees used for the experiments were rather small, with the bulk of the roots at 1.00 m depth. It was assumed that soil water from a depth of 1.75 m could reach the roots by capillary rise during the growing season. Therefore in (3) soil water storage ΔW up to 1.75 m is assumed to be available for the trees. During the rainy season the trees are inactive and have no leaves, therefore, interception of rainfall as a parameter was neglected.

During the rainy season the water balance equation for the whole microcatchment is found by adding equations (2) and (3):

$$\Delta W = P_a + P_b - E_w - E_{a1} - E_{b1} - D_a - D_{b1} \qquad (4)$$

During the growing season, evaporation of shallow soil water, infiltrated in the runoff area during the rainy season, continues. It is assumed that all temporary shallow storage in the runoff area returns to the atmosphere. During



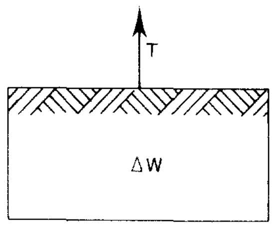


Fig. 4. Water balance components of runoff area during growing season (subscript 2): E_{a2} = evaporation from bare soil, D_a = increase in storage of shallow soil water.

Fig. 5. Water balance components of basin area during the growing season: T = transpiration by tree, ΔW = increase in soil water storage.

the growing season, the water-balance equation for the runoff area can then be written as (Fig. 4):

$$E_{a2} = D_a \tag{5}$$

where E_{a2} is the evaporation from the runoff area.

In this analysis it has been assumed that deep percolation in the basin area has ceased at the end of the rainy season. So the loss D_{b1} does not increase further during the growing season. Because at the end of the rainy season the top layer in the basin is cultivated, this layer dries out and strongly reduces further evaporation. It was therefore assumed that during the growing season no further evaporation occurs in the basin area.

During the growing season we then have for the basin (Fig. 5):

$$T = \Delta W \tag{6}$$

where T is the transpiration by the tree (m^3).

The water-balance equation for the micro-catchment during the growing season follows from equations (5) and (6):

$$T = \Delta W + D_a - E_{a2} \tag{7}$$

The annual water balance of the whole micro-catchment follows from equations (4) and (7):

$$T = P_a + P_b - E_w - E_a - E_{b1} - D_{b1} \tag{8}$$

where E_a ($= E_{a1} + E_{a2}$) is the total evaporation from the runoff area.

If we consider only the basin area, the annual water balance can be found by substituting (3) into equation (6). This is the same as the equation used by Boers et al. (1986):

$$T = P_b + R - E_w - E_{b1} - D_{b1} \tag{9}$$

Fig. 6. Part of the experimental field immediately after a runoff event. The basin areas of micro-catchments contain rainfall and runoff water, while control basin in foreground contains rain water only. Runoff areas show little storage in shallow depressions. During winter season Pistachio trees are dormant and without leaves.

3. FIELD MEASUREMENTS

For the water balance measurements of the rainy season from 01.10.1982 to 01.04.1983 we used eight micro-catchments of 125 m^2 ($A=116$ m^2, $B=9$ m^2) and four control basins (9 m^2) (see Fig. 6). A control basin received only rainfall and no runoff water. Each basin in a micro-catchment and each control basin had one pistachio tree (*Pistacia vera* L. cv. Kerman). The water balance of the eight micro-catchments was compared with that of the four control basins.

The micro-catchments were surrounded by low border checks of about 10 cm height. The sparse vegetation was cleared from the micro-catchments and at the lowest point of each micro-catchment a basin of 3m × 3m was excavated, about 25 cm deep with side slopes 1:1. Before the beginning of the rainy season the top layer of each basin was cultivated, to facilitate infiltration. At the end of the rainy season the basin top layer was cultivated again, in order to reduce soil evaporation. The control basins were treated in the same manner.

The following direct measurements were taken: rainfall; water depth in the basins; open water evaporation from class-A pan; and soil water content in the basin area. From these measurements the following water balance terms were

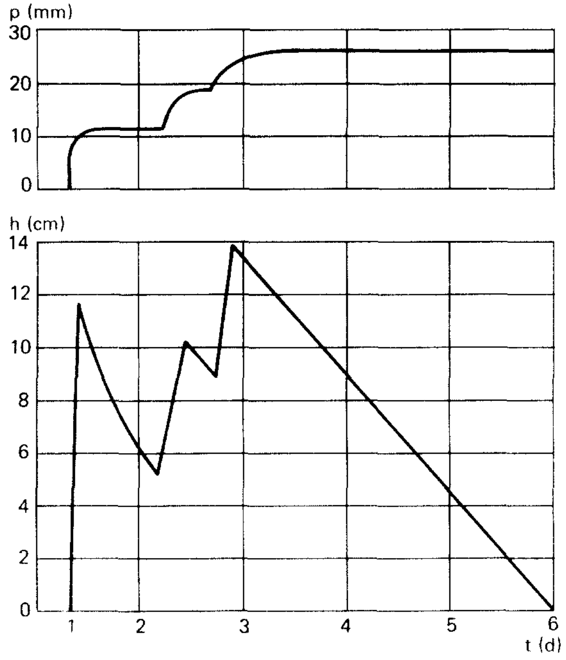


Fig. 7. Illustration of changing water depth h (cm) in basin of micro-catchment during period in which storms occurred. The curve shows the depth of water due to rainfall on the basin, inflowing runoff and infiltration into the rootzone. The upper curve shows cumulative rainfall.

calculated: P_a, P_b, R, E_w, E_{b1} and ΔW. Other water balance terms followed as the remainder: $(E_{a1}+D_a)$ from (2) and D_{b1} from equation (3). So the terms E_{a1}, D_a and D_{b1} were not measured directly. In order to check the depth of infiltration in the runoff area, gravimetric samples were taken from the runoff area of a micro-catchment at the end of the rainy season. This is discussed in Section 4.

The meteorological data, which were collected on a station close to the site, were provided by the Institute for Desert Research. Rainfall was measured with a standard rain gauge, which was read every morning at 09:00 h, and a recording rain gauge. We defined a storm as identical to a rainy day, so that storm depth is equal to standard rain gauge reading. Because balance terms were expressed in volumes, daily rainfall was calculated by multiplying storm depth with area A.

The volume of runoff R collected in the basin (equation 2) was found from measurements of water depth with a scale, on a reference level fixed at the bottom of the basin. Figure 7 illustrates the collection of runoff in the basin. The lower curve shows the water depth h in the basin during a storm period. The cumulative rainfall is indicated by the upper curve. At the end of day 1 the water depth in the basin is 12 cm, and the next portion of the curve shows

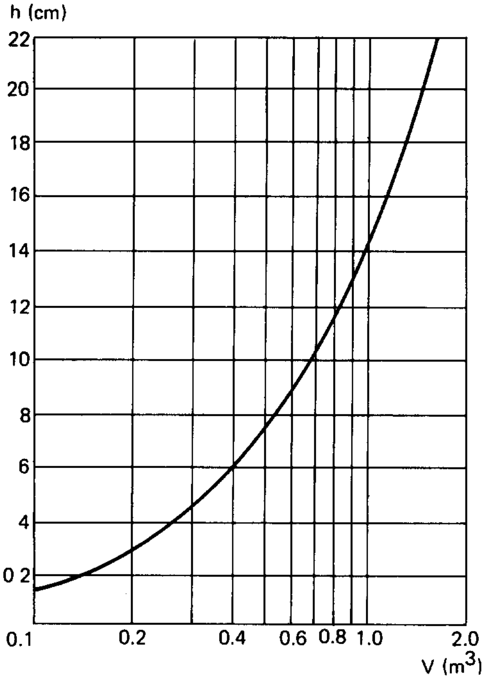


Fig. 8. Volume of water V (m^3) in infiltration basin as a function of water depth h (cm).

infiltration from the basin into the rootzone. On day 2 there are two separate showers. After collection of the runoff from the first shower, water depth is 10 cm. Runoff from the second shower brings the water depth to 14 cm. After this, 3 days of uninterrupted infiltration occur.

The volume of runoff water was determined by applying the following equation to each runoff event:

$$r = v - p_b + i$$

where r is volume of runoff water from one event, v volume of water in basin after one runoff event, p_b rainfall on basin from one shower, and i infiltration during rainfall-runoff event (m^3).

The volumes of runoff water from each event were added per storm i.e. per day, and by adding the daily volumes the total R for the rainy season was found. For the conversion of water depth to volume, the calibration curve in Fig. 8 was used.

Soil water storage W in the basin areas of the eight micro-catchments and four control basins, was calculated from measurements of soil water content. In the upper layer of the basin area (0–25 cm), θ was measured gravimetrically in duplicate, and in the lower layer (25–175 cm) with a neutron meter at 10-

TABLE 2

Water balance components (m^3) of the runoff area ($A = 116\ m^2$) for two micro-catchments during rainy season (P_a and R were measured, while $E_{a1} + D_a$ was calculated from equation 2)

	P_a	$E_{a1}+D_a$	R
Micro-catchment #1	16.3	12.1	4.2
Micro-catchment #2	16.3	13.8	2.5

cm depth increments. To monitor the storage process, the neutron meter measurements were taken weekly.

We estimated the evaporation loss from the gravimetric samples taken from the 0–25-cm layer in the basin area at intervals during the drying process. The total over the rainy season, E_{b1}, was found by adding the evaporation losses after individual events. A class-A pan close to the site was used to measure daily open water evaporation E_o, and we assumed that E_o was equal to the depth of evaporation from the basin E_w during infiltration. The deep percolation D_{b1} below the soil profile (175 cm) was not measured, but followed from equation (3) as the remainder.

4. DISCUSSION OF THE WATER BALANCE DATA

During the rainy season 1982/83 total rainfall was 140.4 mm, well above the average for this location. Tables 2 and 3 present the data of two micro-catchments (#1 and #2), and the average of the four control basins.

Table 2 shows that the runoff production of catchments #1 and #2 is 4.2 m^3 and 2.5 m^3, respectively. The major part of the rainfall is lost as infiltration on the runoff area and evaporation during dry spells. This loss is caused by the distribution of the rainfall. Of the 40 storms that occurred, only 10 storms (90.6 mm) produced runoff, while the other storms (49.8 mm) were too small or had too low rainfall intensity to generate runoff. These storms without runoff caused a loss of 5.8 m^3. The remaining loss occurred during storms with runoff: before and during runoff a portion of the rainfall still infiltrated into the top layer of the runoff area and was lost.

The surface had 1–2% slope and only minor depressions, so the main cause of the losses was not depression storage but infiltration over the whole runoff area. Storm periods are usually followed by dry spells of 1, 2 or sometimes 3 weeks, during which the runoff area dries out by evaporation. In the field this can be observed, because the surface becomes lighter (see Fig. 9). After rainfall the surface is soft and muddy and cannot be walked on. After a few days of sunshine the surface is again hard enough to walk on. Part of the water evap-

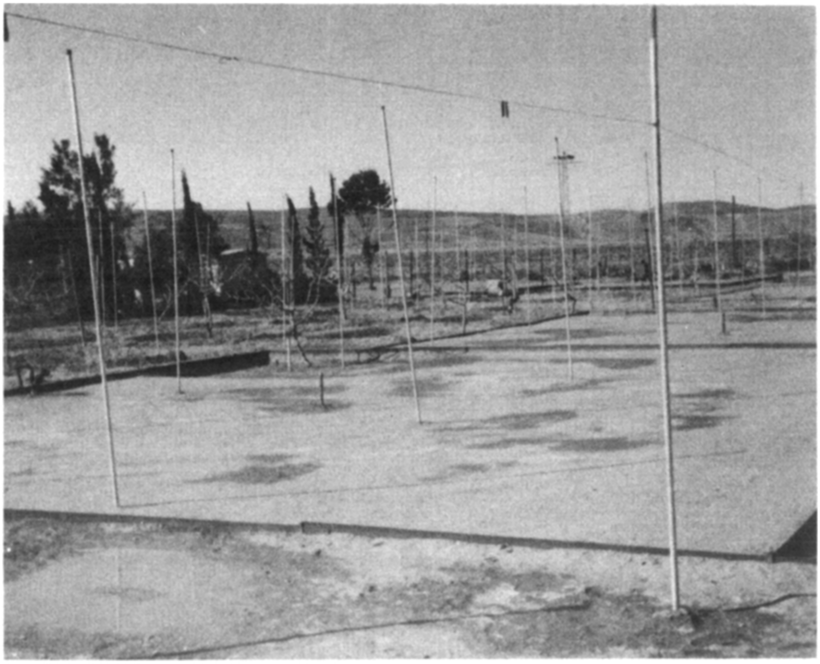


Fig. 9. Surface of runoff area dries out during dry spell after storm period. Dark spots indicate shallow depressions where more water infiltrated. A few days later dark spots have disappeared.

orates during the rainy season (E_{a1}) and another portion (D_a) remains at shallow depth in the top 25 cm, and will return to the atmosphere during the growing season (E_{a2}).

After the rainy season, some weeds started to grow on the runoff areas. A few weeks later, these weeds died because the soil water had been used up. In the annual water balance $D_a = 0$, and for the average of the eight micro-catchments $E_a = 13.2$ m^3. Although E_{a1}, E_{a2} and D_a were not measured, we checked the soil water content in the runoff area of a micro-catchment at the end of the rainy season. Samples taken from 0 to 25 cm depth and analysed gravimetrically showed low water content. This result was taken as validation of the assumption that deep percolation does not occur in the runoff area. Water which infiltrates here (D_a) returns to the atmosphere during dry spells in the rainy season (E_{a1}) or during the growing season (E_{a2}).

The performance of the micro-catchments in producing runoff can be expressed as a runoff efficiency. One way to do this is to apply the linear regression model (Diskin, 1970), to describe the relation between rainfall and runoff. This model was used by Fink et al. (1979) and has been discussed in a previous paper (Boers et al., 1986). The following definition can be used to express the runoff efficiency for the whole season in a single number:

$$e_r = \frac{R}{P_a} \tag{9}$$

where e_r is the runoff efficiency.

For catchments #1 and #2 the values of e_r are 0.26 and 0.15, respectively. The average value of e_r for eight micro-catchments was 0.19. This value is considerably higher than the value of 0.03–0.05 often found for large catchment areas. These numbers illustrate the advantage of micro-catchments for water harvesting. The runoff efficiency of micro-catchments can be increased by making the runoff area more impervious, thus reducing infiltration losses. Several treatments have been tried to this end (see e.g. Boers and Ben-Asher, 1982). In the present study we limited our experiments to runoff from natural soil surfaces.

Evanari et al. (1971) reported the runoff efficiencies for 80-m^2 plots with 10% slope in Avdat, 20 km south of Sede Boqer. During the very wet year 1963/64 (169.2 mm), 13 runoff events occurred, with $e_r = 0.27$. The following year 1964/65 was also very wet (159.8 mm), and produced 17 runoff events on the same plots, with $e_r = 0.30$. The order of magnitude of e_r is the same as found in the present experiments. The Avdat values are higher because more runoff events occurred (cf. 10 in Sede Boqer, 1982/83). Besides, rain depth and intensity may have been higher. Also, the combination of smaller plots and steeper slopes may have reduced infiltration losses.

Table 3 shows the water-balance terms (m^3) of the basin area during the rainy season (equation 3) for catchments #1 and #2 and the average data of the control basins. All terms were measured as discussed earlier, except for D_{b1}, which followed as the remainder in equation (3). The quantities coming into the basin differ because of difference in R. At the beginning of the rainy season (1 October) total stored soil water in the basin areas was measured, which amounted to about 2.0 m^3. The last column shows the increase in storage during the rainy season. Because of the evaporation and deep percolation losses,

TABLE 3

Water balance components (m^3) of the basin area ($B = 9$ m^2) for two micro-catchments, and control basin (9 m^2) during the rainy season (all components were measured except for D_{b1}, which was calculated from equation 3)

	P_b	R	E_w	E_{b1}	D_{b1}	ΔW
Micro-catchment #1	1.3	4.2	0.1	1.2	3.2	1.0
Micro-catchment #2	1.3	2.5	0.1	1.2	1.3	1.2
Control basin	1.3	0.0	0.0	1.25	0.0	0.05

only a relatively small portion ΔW of the total inflow is available for the tree at the beginning of the growing season (1 April).

Evaporation from the water surface E_w is of minor importance, compared with the evaporation from the soil surface E_{b1}. The difference between catchments #1 and #2 shows that more inflow results in more percolation. The difference in R between catchment #1 and #2 is 1.7 m^3, and the difference in D_{b1} is of the same order: 1.9 m^3. Apparently the maximum quantity of soil water has already been stored in catchment #1 and additional water must percolate.

The large deep-percolation loss $D_{b1}=3.2$ m^3 in micro-catchment #1, 356 mm over 9 m^2, may need some explanation. The bulk soil volume for which storage is calculated is $3\times3\times1.75$ m^3 $=15.75$ m^3. At the beginning of the rainy season on 1 October storage is roughly 2 m^3, which equals an average soil water content of 12.7% by volume. On 1 April total storage in micro-catchment #1 is 3 m^3, or 19.1% soil water by volume. This value seems low for this type of soil. A higher value would mean more storage capacity and less deep percolation. In fact we found higher values of soil water content after heavy showers, and the following factors should be taken into consideration:

(1) the profile contains two gravel bands (one at 50 cm and one at 100 cm depth), which reduces the storage capacity of the profile;

(2) April 1 having been taken as the end of the rainy season, it was assumed that trees became active on this date. In fact during the preceeding weeks the trees emerged from their dormant stage, and probably the roots started already to take up water, thereby lowering the quantity of stored soil water;

(3) field capacity in this study is defined as the soil water content 24 h after a heavy shower, and there have indeed been measured values of soil water content higher than 19.1% after heavy rainfall; but at the end of the rainy season there are several weeks of low rainfall, during which soil water content reduces due to unsaturated downward flow, so the value of 19.1% does not represent field capacity of this soil profile.

The present data deal with a wet year. During an average or dry year deep percolation will be reduced sharply. These effects have been calculated in the simulation study (Boers et al., 1986). The last row of Table 3 shows that for the control basins, where rainfall is the only inflowing component, almost all this water is lost through evaporation. The increase in storage is only 50 l. The high value of E_{b1} can be understood from the shallow infiltration that occurs here. The major portion of the water stays in the top 25-cm layer and never reaches a depth in the profile where it is prevented from evaporating. In comparison, the runoff water in the micro-catchments causes a larger inflow, which reaches greater depth into the profile, where it is protected against evaporation.

The advantage of micro-catchments over control basins can be illustrated by comparing the control basins with catchment #2. Rainfall is 1.3 m^3, and in both cases almost all this water is lost by evaporation E_{b1}. In catchment #2 an additional quantity of 2.5 m^3 is available from runoff. Of this water 1.2 m^3 is stored (ΔW) and the remaining portion percolates below the profile (D_{b1}).

The efficiency of the process of soil water storage in the basin area can be defined as:

$$e_s = \frac{\Delta W}{P_b + R} \qquad (10)$$

where e_s is the storage efficiency.

For catchments #1 and #2 the values of e_s are 0.18 and 0.32, respectively. In an average or dry year, these values will be higher. Efficiencies can further be increased by enlarging the storage capacity of the basin area. This could be done by increasing the basin area. However, this would cause the water in the basin to spread over a larger area, where more shallow infiltration and a larger loss by evaporation from the soil E_{b1} would result.

To achieve deeper infiltration, more runoff water per event would be required, for which a higher runoff efficiency would be needed. Applying the method under less extremely arid conditions, would mean more rainfall, which would result in more runoff (see also Boers et al., 1986). The average e_s value for the control basins is 0.04, which is very low and could not be increased easily. In an average or dry year ΔW for the control basins may be even zero.

Figure 10 shows the average water balance data (in m^3) of the whole experimental field: eight micro-catchments and four control basins. The average efficiencies of the micro-catchments are $e_r = 0.19$ and $e_s = 0.18$. For the control basins $e_s = 0.04$.

For the micro-catchments the efficiency of the complete water harvesting process can be defined as:

$$e_{mc} = \frac{\Delta W}{P} \qquad (11)$$

where e_{mc} is the micro-catchment efficiency, and $P = P_a + P_b$ (m^3).

For the data in Fig. 10, $e_{mc} = 0.05$. This is a low value, and it illustrates the problem of using MCWH under such extremely arid conditions. Since rainfall varies greatly from year to year losses cannot be eliminated. In wet years water is lost by deep percolation, in dry years water shortage occurs. These aspects have been discussed in the simulation study (Boers et al., 1986).

The model in the simulation study was calibrated with catchment #2. A basin area of 11 m^2 was used, instead of the actual 9-m^2 basin, in order to correct for lateral flow. This is illustrated in Fig. 11. If this correction were applied to the present data, the values for E_{b1} and ΔW in Table 3 should be multiplied by a factor $11.0/9.0 = 1.22$. The result would be: $E_b = 1.5$ m^3, $\Delta W = 1.5$ m^3, and this would result in $D_{b1} = 0.7$ m^3. This would mean higher efficiency values: $e_s = 1.5/3.8 = 0.39$, and $e_{mc} = 1.5/17.6 = 0.09$.

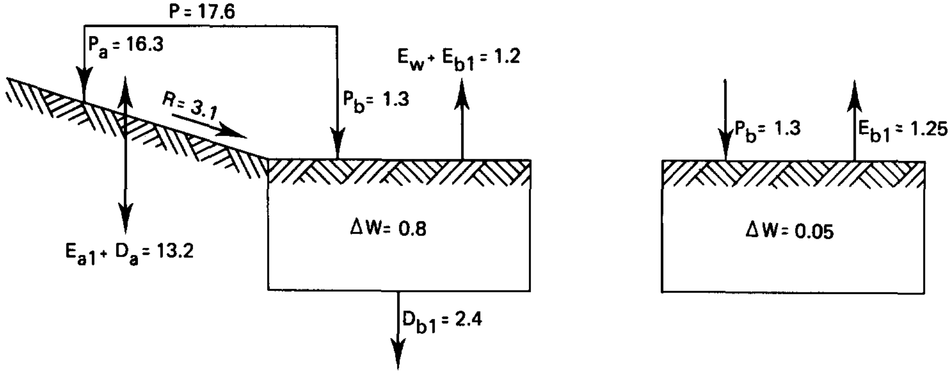


Fig. 10. Diagram showing average water balance components (m^3) of eight micro-catchments and four control basins during the rainy season.

5. APPLICATION TO ARID-ZONE DEVELOPMENT

When discussing the application of water harvesting it is important to formulate what we mean in this respect by arid-zone development. Land reclamation based on irrigation and drainage implies complete control over the water, which allows high agricultural potential. From a water control point of view, MCWH is on the other side of the scale. This method is completely dependent on rainfall and cannot be more reliable than the weather. This means that in arid zones, where rainfall is erratic, it is a marginal activity. In semi-arid zones water harvesting can be a more reliable method (see for instance ICRISAT, 1980), but that is beyond the scope of this article.

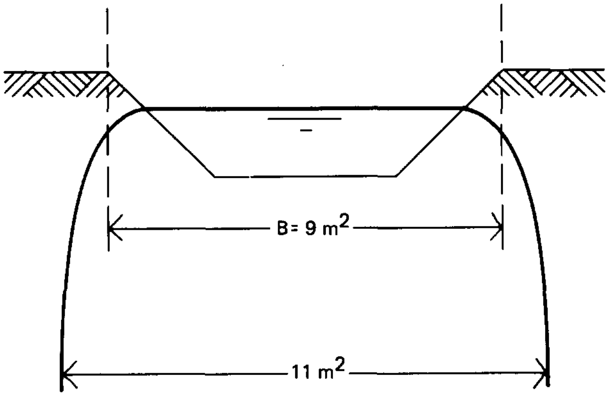


Fig. 11. Diagram of basin from which water infiltrates into the soil. In the present paper we assumed storage of water in a soil volume with horizontal cross section equal to basin area $B = 9$ m^2. In a simulation study, Boers et al. (1986a) applied a cross section of 11 m^2 for calibration of the model.

The advantage of MCWH in arid zones is that the method is completely adaptable to the local environment. MCWH can provide production at subsistence level, and it is in this sense that MCWH can support arid-zone development. It is complementary to rather than a substitute for irrigation- and drainage-based agriculture. Some areas are suitable for high potential production, such as the Nile Delta, and in other areas MCWH can help the local population to live in equilibrium with the environment.

When planning to apply MCWH the two main factors to consider are climate and soil. Rainfall should at least be around 250 mm per year, and the soil should be suitable for runoff production. Soils that produce a surface crust under the influence of the raindrops, for instance loess soils, are suitable for water harvesting (Boers et al., 1986). From these two factors it appears that, especially in the desert fringes, MCWH can be applied successfully in Africa, the Middle East, South Asia and China.

In these desert fringes the problems of desertification and desert encroachment occur. Many studies on these subjects have appeared — see for instance Glantz (1977) and Kassas (1977). Examples of measures that have been taken to combat desertification can be found in the Indian Desert (Mann, 1980) and in China (Walls, 1982). Two applications of MCWH are: (1) runoff-based reafforestation; and (2) collection of cattle water.

(1) Trees may be planted in micro-catchments and receive only runoff water. These trees may provide fruit, fodder, fire wood, or may be planted as windbreaks or green spots in the desert to give shadow and shelter. While producing water for the trees, the micro-catchments also reduce soil erosion and flood hazard. When micro-catchments cover a large part of a catchment area they can have, as an additional advantage, a positive effect on the water balance. The deep percolation, which is inevitable in wet years, is lost for the roots, but this percolating water recharges the groundwater. In this way can micro-catchments help to redress disequilibria of regional water balances.

(2) Micro-catchments can also provide cattle water, either as runoff from a natural soil surface, or from a small plastic-covered runoff area. The runoff water can be collected and conserved in dug-in plastic storage bags. This practice would have a great advantage over the use of water pumped from wells. First of all the groundwater would be saved for dry years when there is no runoff water. Further, and more importantly, the micro-catchments can be used to design watering places at proper distances, so that the human and animal population is spread in accordance with the carrying capacity of the arid zones; this would prevent disastrous concentrations around wells. Spacing between these watering points and volumes of water can be designed in accordance with walking distances and sizes of herds.

The two above-mentioned applications illustrate the usefulness of MCWH in arid zones. Micro-catchments can be regarded as an effective tool to scale down engineering activities. The following features make this technology so appropriate:

(1) Micro-catchments are easy and cheap to construct by hand, and their functioning is easy to understand. Because of this they are ideally suited for self-help schemes of local populations, either as community activities or on individual bases.

(2) The design can be adapted and improved by the local populations according to their wishes and needs. For example the layout may be as indicated in Fig. 1, and on a large scale this would give a chess board pattern, much like the Chinese dune fixation methods (Walls, 1982). Another possible layout is the use of desert strips (Morin and Matlock, 1975). In this case the strips follow the contour lines in the area. Next to each cultivated strip with trees, lies a bare strip which produces runoff. In this way an area is covered with alternating planted and bare strips.

6. CONCLUDING REMARKS

In this paper we have reported on experiments to test the use of micro-catchments for water harvesting. We have chosen a straightforward approach that can be applied with minimum data; data collection could be less than reported here. Measurement of rainfall is necessary, at least with a standard rain gauge, but preferably also with a recording rain gauge. Runoff could be measured in the same way as discussed in Section 3. Soil water content in the basin area can be measured gravimetrically with two replicates, and measurements at two points in time, before and after the rainy season, would be enough. This was for instance done by Sharma et al. (1982). Weekly monitoring with a neutron meter, as we have done to follow soil water storage in the basin area, is not required.

The water balance approach we have followed in this study has shown that the storage of soil water in the basin area is as important as the runoff production on the runoff area. Our data show that evaporation of soil water in the basin area is an important problem which needs further study. Instead of very detailed and accurate measurements of runoff, using weirs and recorders, we chose less-accurate runoff measurement, compensating for errors by increasing the number of micro-catchments under investigation. This approach gives a good general picture over an area.

In the simulation study (Boers et al., 1986) it was shown how a preliminary design for micro-catchments can be made. Such a design can be used for an experimental field, which should then have micro-catchments of different size. The procedure used in the present study could then be used to evaluate the performance of the micro-catchments: ΔW and the efficiencies. The important information to find from such an experimental field is whether the micro-catchments can cover the water requirement of the trees or crops for which they are designed.

For arid-zone development MCWH can be particularly beneficial in the desert fringes where annual rainfall is about 250 mm and where loess soils are present. In these regions MCWH can help to support the local population and at the same time combat desertification.

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