Runoff Agriculture in the Negev Desert of Israel

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ABSTRACT

IN ANCIENT TIMES the Negev foothills and the central Negev highlands were intensively cultivated, although they were then a desert as they are today. The ancient farmers collected the runoff from watersheds 20 to 30 times larger than the cultivated area. In 1958 and 1959 two ancient farms were reconstructed and planted to a variety of fruit trees, pasture plants, field crops, and vegetables. On the reconstructed farms, runoff, floods, and rainfall were measured and their relationship was analyzed. It was shown that even with not more than 80 to 100 millimeters of yearly rainfall, enough runoff water can be collected to ensure good growth and satisfying yields of most of the cultivated plants, the majority of which proved to be quite drought-resistant.

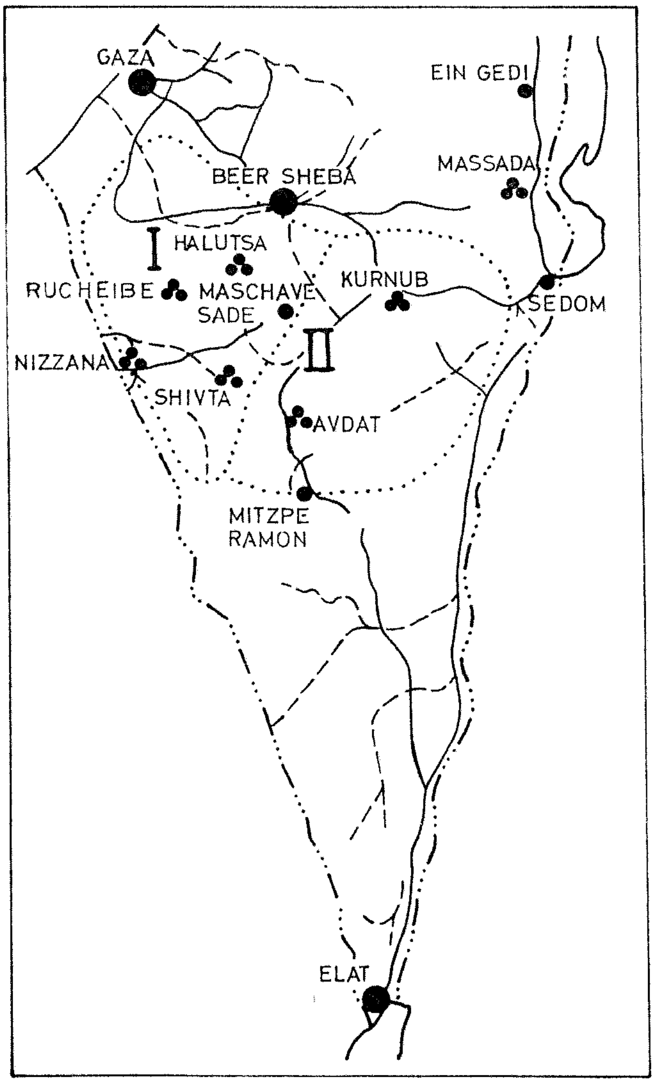
Water use of various trees and pasture plants was also studied using the neutron-moderation method. It was shown that the plants studied performed well with a relatively low water use. It is concluded that runoff agriculture without additional irrigation is feasible in vast desert areas — with climatic, edaphic, and hydrological conditions similar to Israel's Negev — where irrigation water is either not available or too expensive.

RUNOFF AGRICULTURE IN THE NEGEV DESERT OF ISRAEL

Michael Evenari, Leslie Shanan, and Naphtali H. Tadmor

THE NEGEV DESERT, which occupies about 60 percent (one million hectares) of the total area of Israel, is shaped like an irregular triangle. Its base line stretches from Gaza to Ein Gedi on the Dead Sea, and its two sides run from Gaza and from Ein Gedi to Elat on the Red Sea. It links the Sinai Peninsula in the west and the deserts of Arabia in the east. It is part of the immense desert belt stretching from the Sahara to Saudi Arabia. Physiographically, the Negev can be divided into various regions (Fig. 1). We are here concerned only with two of them: the foothills and the central highlands. Geomorphologically, the foothills consist mainly of Eocene limestone hills separating wide rolling plains with the elevation ranging from 200 to 450 meters above sea level. The hillsides carry a very shallow, gravelly, highly saline soil with an immature profile. Its surface is covered by smaller and larger stones forming a typical desert pavement. The soil of the plains and depressions, however, consists of loess, which may reach a depth of 3 meters. This loess is a fine, windblown soil which contains 70 percent silt and clay. Loess is very fertile when enough water is available.

Fig. 1. The Negev, showing (I) foothills and (II) central highlands. The dashed-and-dotted line indicates the boundary between the Negev and Jordan and Sinai. The triple dots indicate the ruins of ancient cities (together with Massada).



The highlands contain a series of parallel anticlines with an elevation of 450 to 1000 meters above sea level. They are composed of Cenomanian-Turanian limestones and cherts. The soil conditions of hillsides and plains between the high ridges are as described for the foothills.

The rain in both subregions falls during the winter months — November to March. It averages 80 to 100 millimeters (3-4 inches) annually. As typical for all deserts, the seasonal variations of rainfall are extreme (*1*, *2*). The following example illustrates this nicely: During the 1962/63 season our farm at Avdat received 25.6 millimeters of rain, and the following 1963/64 season, 152.7 millimeters! The mean yearly temperature for Shivta in the foothills region is around 20°C, for Avdat in the highlands 18°C. The two regions differ climatically also in another respect. The temperatures of the foothill region rarely fall below freezing point, whereas in the highlands the temperatures in the valleys reach minus 4 to minus 5°C, and an average of 40 to 50 nights have temperature minima below 0°C.

ANCIENT DESERT AGRICULTURE

The ruins of six large ancient cities are situated in the foothill and highlands subregions of the Negev (Fig. 1) together with innumerable remains of extensive ancient agriculture dating back to the Israelite period (about 950 to 700 B.C.) and the Nabataean and the Roman-Byzantine periods (about 300 B.C. to 630 A.D.) (*3–5*). The area, which today has no perennial streams and no underground water supply, was once intensively cultivated and supported a thriving civilization. Could it be that at those

NOTE: This chapter is adapted from a presentation at "Arid Lands in a Changing World," an international conference sponsored by the Committee on Arid Lands, American Association for the Advancement of Science, June 3–13, 1969, at the University of Arizona, Tucson, Arizona, U.S.A.

Fig. 2. Oblique air photograph of an area near Shivta. Many ancient runoff farms are visible, each with its terraced cultivated area surrounded by a wall and its catchment basin. The faint lines leading from the catchments to the various farms are runoff channels that led the floodwater to the cultivated area. The second farm from the bottom has a large farmhouse next to its fields.

times the Negev was not a desert as it is today, and that it had a rainfall of 400 to 500 millimeters per year, sufficient for "normal" agriculture? The arguments against a climatic change are strong.

a) The Bible describes the Negev as a desert without water (*see,* for example, Genesis 21:14–19).

b) If there had been a more humid climate in ancient times, there would have been no need to develop the ingenious ancient agriculture based on maximum water conservation which we will describe later on.

c) The most convincing argument is that working in our reconstructed farms with the same relationship of size of catchment area to size of cultivated fields as is typical for the ancient farms, we could always collect enough runoff water to sustain agricultural crops (see Agricultural Results, below).

We do not deny the existence of definite variations in the average annual rainfall. We only point out that at least since about 1000 B.C. there has occurred no major climatic change in the Negev, which then was already a desert more or less as it is today.

If there was no climatic change, how could the ancient farmers have cultivated the land under a 100-millimeter rainfall regime without any source of additional water for irrigation? It took us many years of field work to answer this question (*6-9*).

Our investigation proved, first of all, that all ancient agriculture in the Negev foothills and highlands was based on the utilization of surface runoff from small and large watersheds; hence we call the agricultural type "runoff farming." The ancient farmers used various methods for this purpose. We will describe only the most common and successful one, the "runoff farms" that received their water from relatively small watersheds. Each farm consisted of two parts (Fig. 2): the farm proper (that is, the cultivated area) and the catchment basin. Each cultivated area was situated in a narrow valley bottom on loess soil 2-3 meters deep. It was terraced by low stone walls. The farm's catchment basin (20 to 30 hectares in size) was on the surrounding slopes. When a rain occurred heavy enough to cause runoff, the runoff caused a flood (Fig. 3), and the floodwater collected in channels that led it to the various terraces of the farm proper. The terrace walls kept part of the water standing on the field, where it slowly soaked into the ground. The surplus went through drop structures in the terrace walls to the next lower terrace. The water harvest from the catchments averaged 150 to 200 cubic meters per hectare per year. Since the ratio of cultivated land to catchment area in all farm units was more or less the same (1:20 to 1:30) one hectare of cultivated land collected runoff from 20 to 30 hectares of hillside catch-

$\frac{150{,}000 \text{ L}}{10{,}000 \text{ m}^2} = 15 \frac{\text{L}}{\text{m}^2} = 15 \text{mm depth}$

ment. This means that each hectare of cultivated land received on an average about 3,000 to 6,000 cubic meters of runoff water per year. These high water yields were possible because of certain characteristics of the loess soil discussed below. One to five floods could be expected annually, producing enough runoff water to deep-wet the loess soil of the cultivated farm area. This water enabled the ancient farmers to grow successfully wheat, barley, legumes, almonds, and grapes, as reported in documents of the time found in Nizzane (*10*).

Fig. 3. A flood at the Avdat farm. In the background is a floodgate with an automatic gauge.

RECONSTRUCTED FARMS

In 1958 and 1959 we reconstructed two farms, near the ancient cities of Shivta and Avdat (*1, 11*). We superimposed on the ancient system all the instruments needed (flood and rain gauges, water meters, and so on) and a network of pipes which guaranteed an equal distribution of the floodwater inside each experimental unit. The aims of the reconstruction were: (*a*) to test experimentally whether our theories about the working of the ancient desert agriculture were correct, (*b*) to collect hydrological data typical for the area and to analyze the relationship between rainfall and floods (a vital point, since floods are the only water source for runoff agriculture), (*c*) to find out whether desert runoff agriculture is economically feasible today, and (*d*) to determine water use and drought-resistance of cultivated plants under conditions of runoff farming.

Flood Analysis

When rain starts falling, it first hits the vegetation, which prevents some rainwater from reaching the soil (interception storage). In deserts like the Negev this factor is negligible because of the scantiness of the vegetation. The first raindrops reaching the ground infiltrate the soil. Whenever the rate of rainfall is greater than the

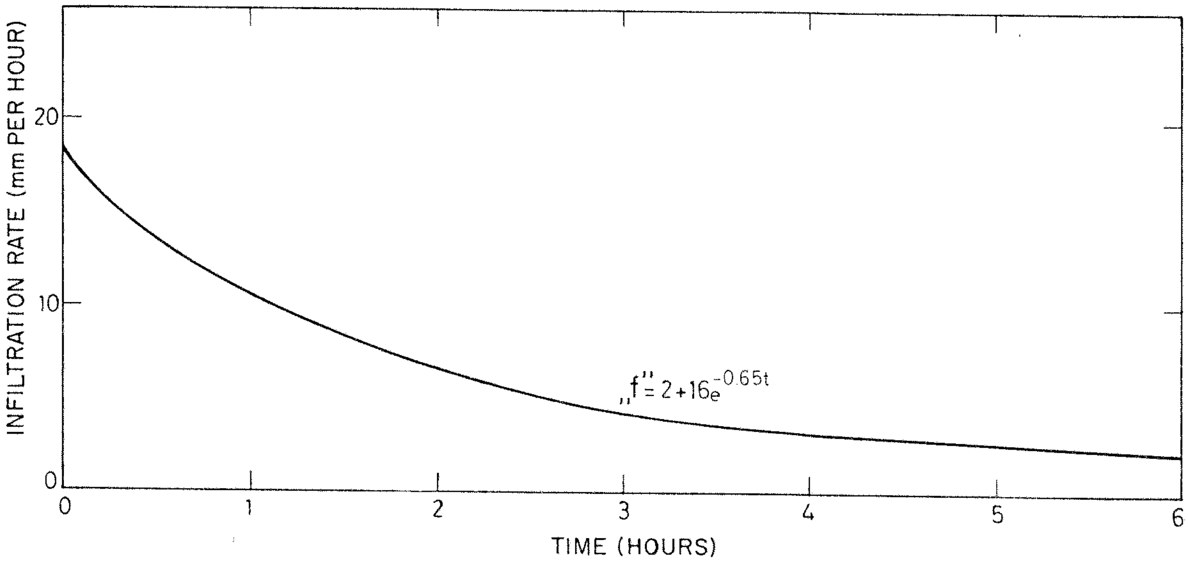


Fig. 4. Typical infiltration rate curve for Avdat watersheds. *e:* base of the naparian logarithm; *t:* time in hours.

infiltration rate, part of the rainwater will fill the surface depressions (depression storage). Our measurements have shown that in our region this factor amounts to very little. When the depression storage has been filled, runoff starts. Therefore the amount of runoff under our desert conditions is mainly determined by the rate of rainfall on the one hand and the infiltration rate on the other.

The infiltration rate depends much on physicochemical qualities of the soil. After being wetted, loess, because of its composition, forms on its surface a very thin crust nearly impermeable to water (7). This quality explains why its initially high infiltration rate drops rapidly during the first half hour of wetting and reaches a steady rate of 2.5-3.5 millimeters per hour (Fig. 4). It is interesting that the infiltration rates we measured in various catchment areas in Avdat were more-or-less similar, even though these catchments differ in their soils and physiographical structure.

Though the rainfall rate is an exceedingly variable quantity, the average annual rainfall rate can be calcu-

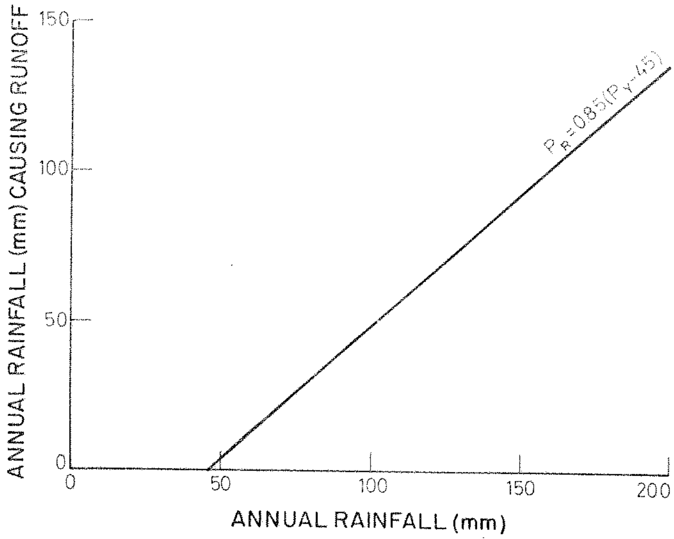


Fig. 5. Relationship between annual rainfall (P_y) and annual rainfall causing runoff (P_R).

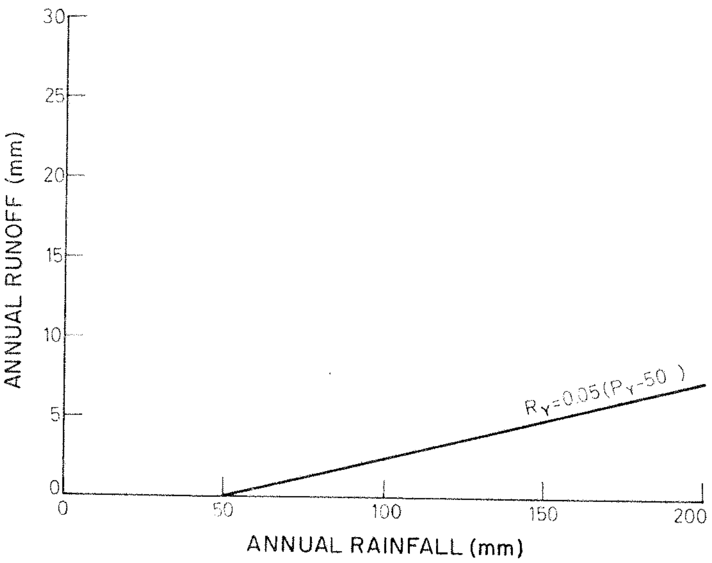


Fig. 6. Relationship between annual rainfall (P_y) and annual runoff (R_y) from a large catchment (350 hectares).

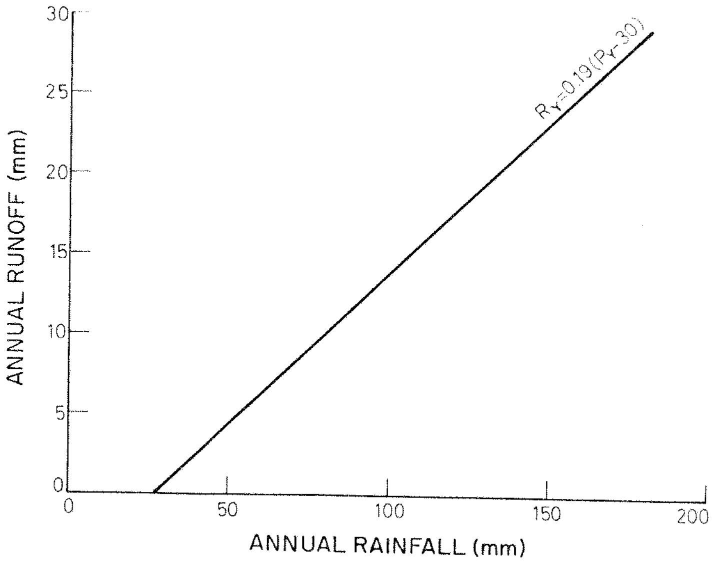


Fig. 7. Relationship between annual rainfall (P_y) and annual runoff (R_y) from a smaller catchment (10 hectares).

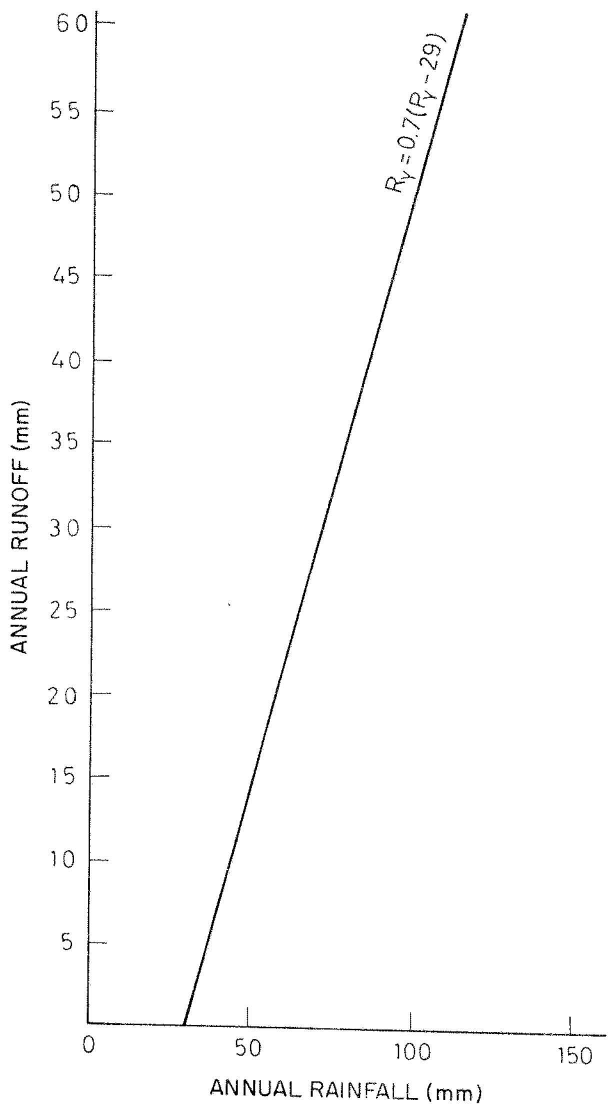


Fig. 8. Relationship between annual rainfall (P_y) and annual runoff (R_y) from a microcatchment.

Fig. 9. Runoff plots at Avdat. To the right, one stone-covered control plot; to its left, a bare plot; further left, a plot with stones raked together into mounds. The runoff from each plot is collected in the barrels visible in the foreground.

TABLE 1

Total Annual Runoff (in Millimeters) Measured on Twenty Runoff Plots in Avdat During the Periods 1965/66 and 1966/67

Treatment	*Slope (%)*	*1965/66 runoff (mm) (90.7 mm rainfall)*	*1966/67 runoff (mm) (69.3 mm rainfall)*	*Runoff increase (%) of treatment over control plots (2-year average)*
Control	10.0	23.64	9.46	. .
	13.5	21.23	8.03	. .
	17.5	17.88	7.41	. .
	20.0	13.61	4.67	. .
Mounds	10.0	26.02	11.85	13
	13.5	26.22	11.35	29
	17.5	20.70	8.77	17
	20.0	17.60	8.26	43
Bare	10.0	30.26	13.82	32
	13.5	21.83	9.53	8
	17.5	21.02	9.19	20
	20.0	16.91	8.15	32
Mounds, wet rolled	10.0	31.46	14.86	40
	13.5	27.59	12.24	36
	17.5	20.75	9.56	21
	20.0	20.08	9.23	61
Bare, wet rolled	10.0	31.46	15.29	41
	13.5	24.54	10.37	23
	17.5	25.27	11.67	45
	20.0	17.22	9.17	36

lated from existing rainfall records. The rainfall depth-time equation has the approximated form of $R = 5\sqrt{t}$, where R is the depth of rain in millimeters and t the period of the rainstorm in hours. This means that a half-hour rain will produce about 3.5 millimeters, an hour rain 5 millimeters, a 10-hour rain 16 millimeters, and so on. This is naturally only an approximation, and there are rainfalls of one hour duration which produce more than 50 millimeters, but they are comparatively rare phenomena.

The next step in our analysis is to look at the relationship between rainfall causing runoff and annual rainfall, and between annual rainfall and annual runoff, from our various catchment areas in Avdat. These calculations are based on our observations during the seven-year period 1960/61 - 1966/67 made on 8 catchment areas of various sizes and 20 runoff plots.

Figure 5 indicates the amount of rain that will cause runoff out of a given annual rainfall. It shows that about 30 millimeters of an annual rainfall of 80 millimeters will cause runoff, 50 millimeters of an annual rainfall of 100 millimeters, about 90 millimeters of an annual rainfall of 150 millimeters, and so on. Figure 5 does not tell us how much actual runoff we will get in each case. Figures 6 through 8 show actual runoff for three catchments of different size. The largest catchment (350 hectares) produces only about 2.5 millimeters of runoff with an annual rainfall of 100 millimeters, a smaller catchment (10 hectares) produces about 13 millimeters for the same rainfall, and a very small catchment of 0.1 hectares (a "microcatchment") produces about 50 millimeters runoff with the same rainfall.

The import of the figures is that the smaller the catchment the larger the percentage of rainwater which appears as runoff. Or, in other words, the smaller the catchment the larger the amount of runoff per unit surface. Naturally this does *not* mean that the smaller catchments produce the most runoff in absolute terms. There is an additional advantage of the microcatchments. Rains which are ineffective, that is, do not cause runoff on the large catchments, are effective on the microcatchments. During the 1967/68 rainy season, for example, we had one large flood on the 350-hectare catchment area and 11 on the microcatchments.

It is obvious that topography and nature of the surface of a catchment affect the runoff. We studied this experimentally in 20 small runoff plots of equal size (80 square meters) (Fig. 9). We arranged the plots in 4 replicates, each with 5 different surface treatments. Each replicate had a different slope ranging from 10 to 20 percent. The different treatments were: (*a*) stones of the desert pavement removed and soil bare, (*b*) the same, but soil once gone over with a roller when first wet ("rolled"), (*c*) stones removed but piled into heaps on the runoff plot, (*d*) the same, but bare soil between stone heaps rolled, and (e) untreated control.

The results of two typical rainy seasons given in Table 1 show that the steeper the slope the smaller the amount of runoff. This is true for all treatments, including the control. The other important point is that in all treatments in which the stones were partly or completely removed, the runoff yields are increased in comparison with the controls. The highest runoffs were obtained on the rolled plots. This obvious effect of the stone-clearing has an interesting implication. It had already been found by Palmer (*8*), the first investigator to detect and study the ancient agricultural systems in the Negev, that the catchments surrounding the ancient fields were covered by innumerable stone mounds and strips (Fig. 10), and

Fig. 10. Oblique air photograph of stone mounds and strips on the catchment basin of an ancient farm.

all the later investigators speculated about the function of these strange man-made structures (*3*) and agreed only on one point: they must have had something to do with agriculture. Our runoff experiment has now shown that the structures apparently were made by the ancient farmers in order to increase the water harvest from their catchment areas. The device is simple, ingenious, and efficient.

It is interesting to note that the yearly average of soil washed down from the stone-cleared slopes by the runoff waters amounts to not more than 0.1 - 0.2 millimeters. This means that if we take the ratio of cultivated land to catchment area as 1:20, the loess in the bottomlands receives yearly only an additional 2-4 millimeters of soil from the stone-cleared slopes.

All our experience concerning the relationship between runoff and rainfall is schematically summed up in a nomogram (Fig. 11). It shows that with an annual rainfall of 100 millimeters, for example, one can expect, from a 100-hectare catchment area with a 5 to 10 percent slope and an untreated surface, about 70 cubic meters of runoff per hectare. The same area when cleared of stones will produce about 130 cubic meters per hectare. A microcatchment, however, will produce under the same conditions about 160 cubic meters and 210 cubic meters per hectare respectively. If we assume that the ratio size of cultivated fields to size of catchment area is 1:30 (as mentioned above), under the conditions stated above a field of one hectare will receive 2,100 cubic meters (equivalent to 210 millimeters of rain), 3,900 cubic meters (=390 millimeters), 4,800 cubic meters (=480 millimeters), and 6,300 cubic meters (=630 millimeters) respectively.

Agricultural Results: Fruit Trees

After the reconstruction of the farms, fruit trees were planted there in 1960 and 1961 (Fig. 12). They were olives, carobs, figs, pomegranates, peaches, apricots, almonds, apples, grapevines, cherries, and loganberries. Various varieties of each tree species were tried out, and different combinations of root stock and scion (*1*). The trees received a small amount of water at planting time and from thereon lived exclusively on runoff water. The most successful were almonds, apricots, grapes, and figs. A promising species is the pistachio; it is too early to pass final judgment because the pistachios, which grow very slowly, were planted only in 1963. All the trees grow well (Fig. 12), and the yields of the most successful species are satisfying (Table 2). Most of the trees proved to be astonishingly drought-resistant, if we take this term in its most simple meaning — the ability to survive prolonged periods of drought without damage. (Plant physiologists have tried to define "drought-resistant" in terms of physiological mechanisms making plants resistant to water stress. We are unable to do this, since in our case we lack the necessary information.)

TABLE 2

Yields of Various Fruit Trees Over a Two-year Period (tons per hectare)

Fruit	*Yield*
Peaches	8-12
Apricots	5- 8
Grapes	12-15
Figs	6- 8
Almonds (dry shelled)	0.43-0.93

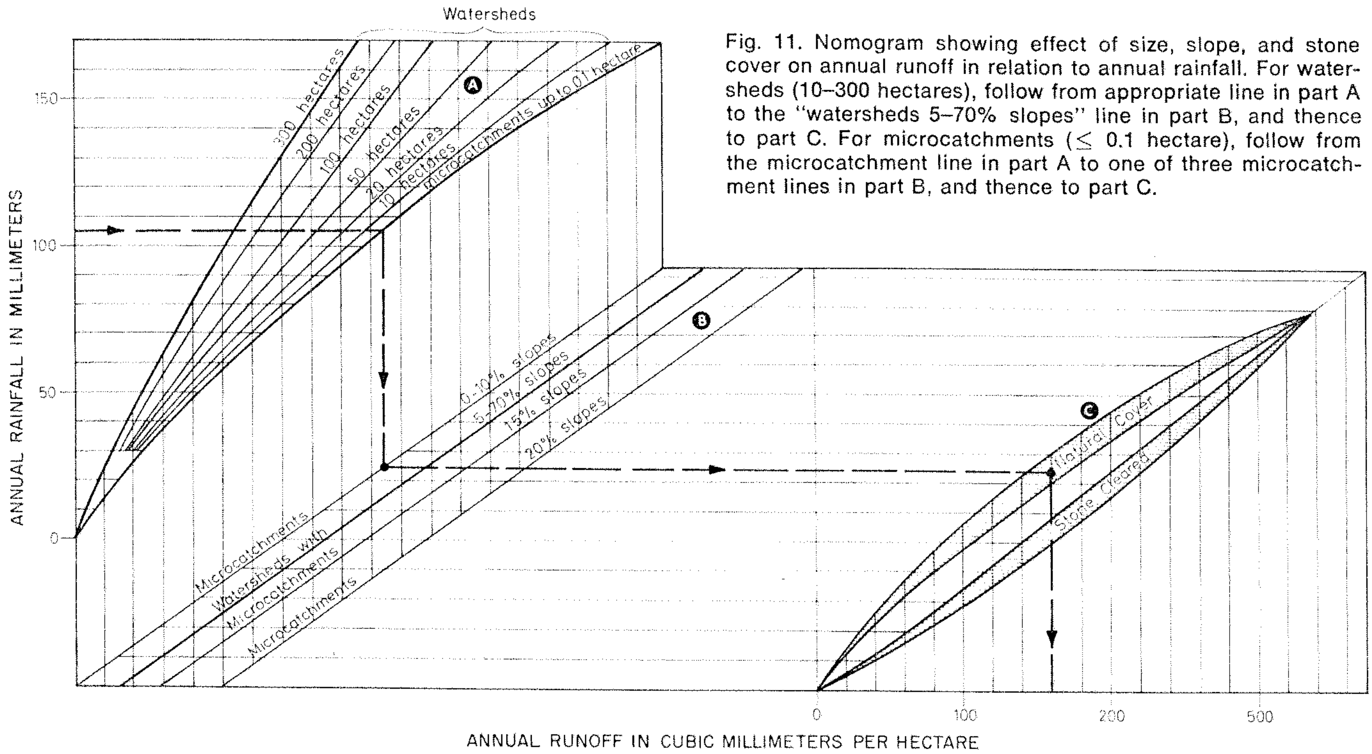


Fig. 11. Nomogram showing effect of size, slope, and stone cover on annual runoff in relation to annual rainfall. For watersheds (10–300 hectares), follow from appropriate line in part A to the "watersheds 5–70% slopes" line in part B, and thence to part C. For microcatchments (≤ 0.1 hectare), follow from the microcatchment line in part A to one of three microcatchment lines in part B, and thence to part C.

During the rainy season 1962/63, the Avdat farm received only 27.7 millimeters of rain, and only two small floods occurred. Because the last small flood of 1962/63 came in February 1963 and the first one of the 1963/64 season occurred in December 1963, the trees did not receive a drop of water for 9 months and survived well with little available water.

TABLE 3

Moisture Depletion (millimeters) of the Soil Volume in Which Apricot and Peach Trees Are Rooted

Period	*Apricots*	*Peaches*
Dec 26/63-Dec 3/64	306.2	242.7
Jan 2/65-Sept 22/65	288.1	308.0
Oct 15/65-Oct 10/66	223.9	262.2
Nov 22/66-Aug 3/67	133.8	142.0

In 1963 we began to measure the water use of apricot and peach trees by the neutron-moderation method (*1, 14*). Table 3 shows the moisture depletion of the whole soil volume in which the trees are rooted. In order to know what the real water use of the trees is, we have to know how much water evaporates from the soil and how much is lost by internal drainage. Evaporation from the soil is 8 to 11 millimeters per year. This is an astonishingly low figure for an area with a very high potential evaporation; it is explained by the formation of the crust immediately after the loess is wetted by the floods. The internal drainage could not be measured exactly. However, the main point here is that the fruit trees can grow and yield well with comparatively little water. Since irrigated orchards in the vicinity of our farms are watered with about 1,000 millimeters of water, it becomes obvious that our figures point the way to a much more rational water use and the possibility of decreasing water wastage.

Agricultural Results: Pasture Plants

In 1961 we started in Avdat an experiment to test 127 different species and cultivars of perennial and annual pasture plants for drought resistance, yields, and water use under conditions of runoff agriculture (*1, 15*). Table 4 shows as an example the performance of the best species for two periods. The yields in 1964/65 were high, as this was a relatively good year with 140.7 millimeters of rain and six floods. In 1965/66, in spite of 84.3 millimeters of rain and one good flood, the pasture plants received little water, because the pipe distributing the flood water to the pasture plant plots was accidentally blocked. The yields therefore were low, but the main point is that after 14 months without any appreciable amount of water the plants did not die; they survived until the next flood, showing a high degree of drought-resistance. The most efficient water user was the annual *Avena sterilis*, which produced 2.6 and 2.9 kilograms of dry matter for each cubic meter of water used.

Fig. 12. Almond trees of the Avdat orchard. Some access tubes for the neutron probe are visible.

After we knew what the most promising pasture plants were, we used them in an experiment with simulated floods given at different times of the year with different frequencies and with different amounts of water (*11*). We conducted this experiment because the effect on yield and performance of a natural flood occurring in October is very different from one occurring in April. The same is true for different numbers of floods per season and for floods of different depths. We also tested the effect of a

TABLE 4

Yields, Water Use, and Water Requirements of One Annnual (*Avena*) and Four Perennial Pasture Plants in Avdat

	1964/65 season			*1965/66 season*		
Species	*Yield (dry weight, kg/ha)*	*Water use (m^3/ha)*	*Water requirement (kg of dry matter/ m^3 water)*	*Yield (dry weight, kg/ha)*	*Water use (m^3/ha)*	*Water requirement (kg of dry matter/ m^3 water)*
Agropyrum elongatum	7,800	5,660	1.40	870	1,650	0.53
Medicago sativa *	8,080	6,000	1.35	1,630	1,500	1.10
Oryzopsis miliacea	8,400	5,500	1.50	1,560	1,570	1.00
Phalaris tuberosa	8,240	5,800	1.42	660	1,570	0.42
Avena sterilis	10,660	4,000	2.65	9,650	3,320	2.90

* *Medicago* also produced 590 kilograms per hectare of seed in addition to herbage.

TABLE 5

Harvesting Yields of Alfalfa (*Medicago sativa*) in 1967/68 Under Various Simulated Flood Regimes With Triple, Double, and Single Harvesting Programs

Flood regime (cubic meters per hectare)	*Fresh weight (tons per hectare)*			*Dry weight (tons per hectare)*		
	Triple	*Double*	*Single*	*Triple*	*Double*	*Single*
5,520	26.6	22.8	16.4	6.4	6.0	4.1
4,400	24.9	21.0	10.7	5.5	5.3	3.3
3,900	23.3	17.8	9.8	5.2	3.9	2.7
2,680	16.7	11.3	5.4	4.6	3.4	1.6
1,940	12.5	4.5	5.0	3.5	1.7	. .
1,440	3.5	4.4	5.0	1.7	1.3	. .

single, double, and triple harvest on yields. Table 5 shows some of the results for alfalfa (*Medicago sativa*). A triple harvest gives the highest yields. This is most pronounced for the lowest flood regimes. The yields again prove (as was already shown in Table 4 for natural floods) that runoff agriculture produces satisfying yields even with as little water as 3,000 to 4,000 cubic meters per hectare. Alfalfa irrigated with 13,000 cubic meters of water (usual in Israel) produces considerably higher yields, but in the light of our experience the question arises as to whether this practice is worthwhile, taking into account the scarcity and high price of water in Israel. This point is accentuated when we calculate the optimal water use, that is, the highest amount of dry matter produced per one cubic meter of water applied. Alfalfa (triple harvest) reaches this point (1.8 kilograms of dry matter per 1 cubic meter of water) at an annual water use of about 2,000 cubic meters per hectare (Fig. 13). With higher amounts of water the efficiency of water use decreases, although the yields increase (Fig. 13), but this increase is very low.

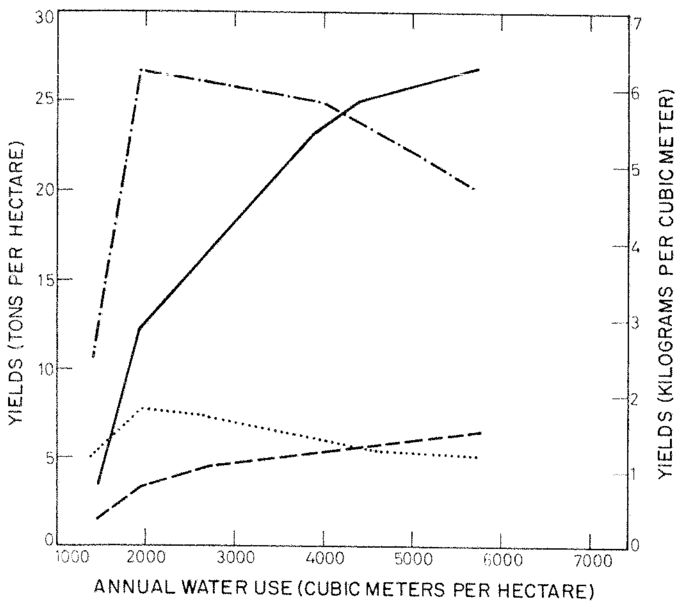


Fig. 13. Relationship between annual water use and yield of alfalfa (triple harvesting) under various simulated flood regimes. The solid line indicates fresh weight (tons/hectare); broken line, dry weight (tons/hectare); dash-dot line, fresh weight (kg/m³ water used); dotted line, dry weight (kg/m³ water used).

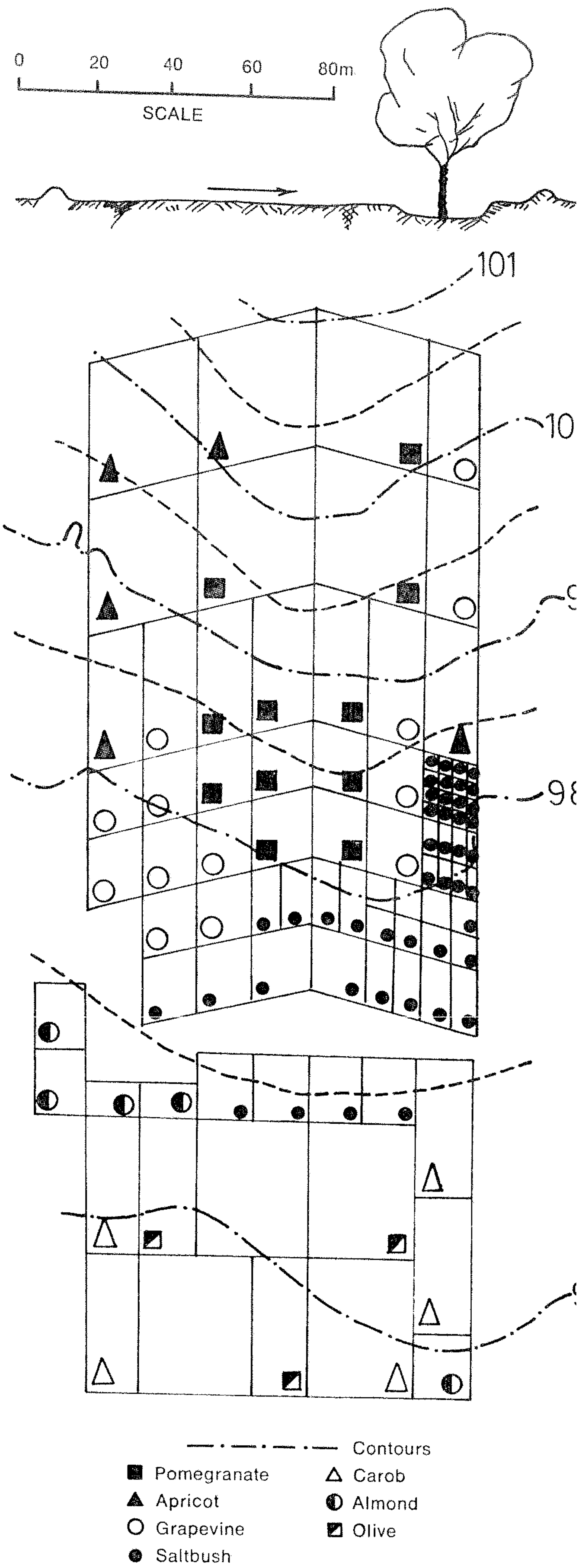


Fig. 14. Layout and typical cross section of microcatchments.

Agricultural Results: Field Crops and Vegetables

Barley, wheat, peas (seeds), sunflowers (seeds), and onions (seeds) were the most successful field crops we raised over the years (Table 6). The best vegetable was asparagus, which seems to be well adapted to the conditions of runoff farming.

TABLE 6
Yields of Various Field Crops
(tons per hectare)

Crop	*Yield*
Barley	1.2 -5
Wheat	1.1 -4.5
Peas	5 -6
Sunflowers	2.2 -5.5
Onions (seeds)	0.52-0.65

Fig. 15. Negarin with a three-year-old pomegranate tree in the foreground.

MICROCATCHMENTS (NEGARIN)

After we had found that the amount of runoff per unit surface increased as size of catchment area decreased, we decided to plant trees, each in its own small catchment, instead of having a whole farm with a comparatively large catchment. We chose as the experimental area a barren loessial plain of high salinity (0.9 to 1.2 percent total soluble salts). An area of 1.8 hectares of this plain with a natural slope of 1.5 percent was artificially divided by small border checks into 92 microcatchments (or negarin, after a Hebrew word) ranging in size from 16 to 1,000 square meters. At the lowest point of each microcatchment, a square basin was dug to collect the runoff water and to plant the trees (Fig. 14). In 44 of the microcatchments, ranging in size from 250 to 1,000 square meters, fruit trees were planted. In 48 of the negarin (16 to 250 square meters in size), seedlings of the salt bush (*Atriplex halimus*) were installed. The various plants were placed in different-sized microcatchments because we had to find the catchment size optimal for each species.

An important result of our experiment was that after one or two rainy seasons the salt of the planting basins of all the microcatchments was almost completely leached out. So far the best trees are pomegranates (Fig. 15), almonds, olives, and grapevines, but it is too early to arrive at a final judgment, as the trees are still too young. The optimal catchment size for pomegranates, olives, and almonds is apparently 250 square meters. The optimal catchment size for the saltbush is 32 square meters (Fig. 16). Such a saltbush plantation produces a yearly average of 650 kilograms per hectare fresh weight and 400 kilograms per hectare dry weight.

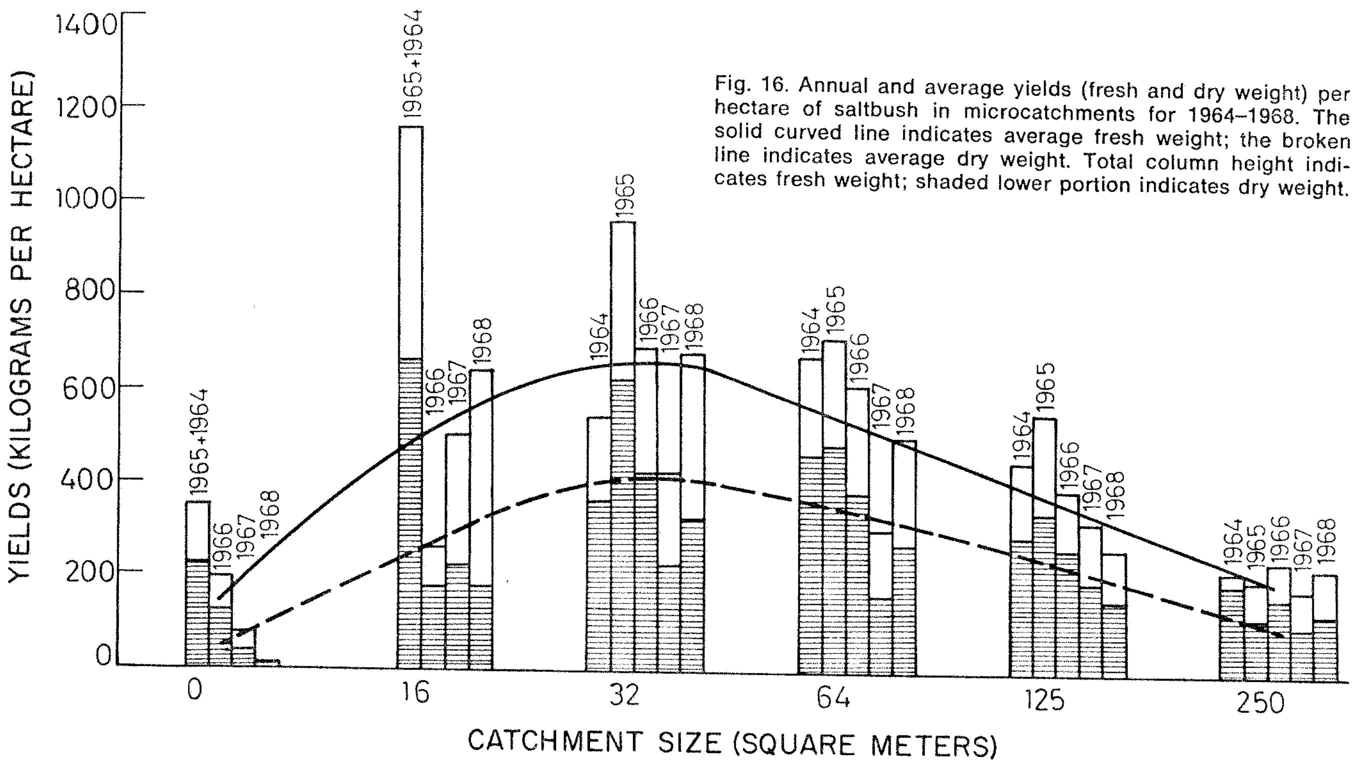


Fig. 16. Annual and average yields (fresh and dry weight) per hectare of saltbush in microcatchments for 1964–1968. The solid curved line indicates average fresh weight; the broken line indicates average dry weight. Total column height indicates fresh weight; shaded lower portion indicates dry weight.

APPLICABILITY OF RESULTS

Our experiments have shown that runoff agriculture as practiced by the ancient farmers in the Negev highlands functions properly today as it did 2,000 to 3,000 years ago (*17*). It enables man to turn wasteland into an agriculturally productive area without any additional irrigation. We think that it is also economically feasible. The microcatchments are the most promising method. We take the saltbush as an example. Using modern machinery, the cost of construction of microcatchments is between $5 and $20 per hectare, depending on the microcatchment size. If planted to saltbush, one hectare will produce 160-170 Scandinavian feed units, which is equivalent to 30 kilograms of protein per hectare. Since the area in its natural state produces only 5 to 10 feed units per hectare, this means a fifteen- to thirtyfold increase of productivity.

Since in Israel today a feed unit costs 2 to 3 cents, it is certain that the barren desert loessial plains can be turned into well-producing rangelands. It is equally certain that the same system can be adapted to other range plants such as alfalfa and *Oryzopsis miliacea*, and that with these plants the rentability could be increased. One can envisage a grass-legume-saltbush pasture as the best range under our conditions. It will also be possible to increase the efficiency of the microcatchment system by soil treatments which will increase the water yields and by other means. Fruit-tree plantations, especially of almonds and probably pistachios, are also of potential practical value, but in this respect our data are not yet complete enough to be sure.

The labor needed for the maintenance of the large catchments is negligible. Our experience shows that 5 man-days were enough in 10 years to maintain 40-hectare watersheds in proper order. The labor needed to maintain the microcatchments is even less. If nomads should use the runoff agriculture system they could set these up and visit them only once or twice a year.

The practical possibilities of extensive runoff agriculture are not limited to the Negev of Israel. Similar rainfall, climatic, and soil conditions are found outside of Israel in large desert areas of the world, where runoff agriculture appears most promising as the best and cheapest way of land use.

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17. The very generous help of the Ford Foundation (archaeological field survey), and of the Rockefeller Foundation, the Edmond and James de Rothschild Memorial Group, and Israel's Prime Minister's Office (restoration of farms and agricultural research) enabled us to carry out our work.

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Editors:

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PATRICIA PAYLORE

THE UNIVERSITY OF ARIZONA PRESS
Tucson, Arizona

1971