Iranian Journal of Science & Technology, Transaction B, Engineering, Vol. 30, No. B4
Printed in The Islamic Republic of Iran, 2006

PROBABILISTIC DETERMINATION OF MICROCATCHMENT AREA FOR RAIN-FED TREE CULTURES*

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Abstract– In this study a simple simulation model for the design of microcatchment water harvesting systems for rain-fed tree cultures in the Bajgah area, Fars province, I. R. of Iran, was developed. The actual daily evapotranspiration was calculated during the years 1984 to 1987. This model has been calibrated based on 34 measured volumetric soil water contents at depths of 120 cm, and soil water at depths of 0-120 cm in the study area. To calculate the daily actual evapotranspiration during these years, daily crop coefficient, the coefficient of evaporation from the soil surface, mean daily soil water stress coefficient for four years (1984-1987) and the Penman-FAO method for the calculation of reference crop potential evapotranspiration (ET_o) were used. The results indicated that the total amounts of actual evapotranspiration (ET_a) for growing seasons were 407, 346, 376 and 362 mm (mean value of 373 mm). Also, the values of yearly ET_a were 537, 472, 488 and 485 mm (mean value of 496 mm). Furthermore, a simple method based on Type III Pearson distribution and Penman-FAO ET_o was used to estimate the amount of actual evapotranspiration for different probabilities of occurrence in each month of the year. So, the total amount of actual evapotranspiration during the growing season can be obtained for different probabilities of occurrence. Moreover, by using the yearly actual evapotranspiration and yearly rainfall with different combinations of probabilities, the microcatchment areas were estimated for different probabilities of occurrence. These data were used in a simple equation for determining the microcatchment area based on the probability of annual rainfall and yearly ET_a. The results indicated that with 50 % probability of annual rainfall and yearly ET_a, the microcatchment area (sum of cropping and runoff areas) was estimated to be about 8.7 m^2 (cropping area=1.8 m^2 and runoff area=6.9 m^2). According to the indigenous knowledge of the local farmers, the microcatchment size in the study area is also 9 m^2, which is similar to the microcatchments size with a 50 % probability.

Keywords– Reference crop potential evapotranspiration (ET_o), actual evapotranspiration (ET_a), Penman-FAO method, rain-fed vineyard, microcatchment area

1. INTRODUCTION

Water harvesting can reduce the risk substantially by facilitating early planting by taking maximum advantage of the rainfall [1]. Building a microcatchment for each tree is an appropriate method to store rainwater runoff in the soil to be used efficiently by plants [2, 3]. In this system, water is collected in the catchment area and released into fields as needed to irrigate trees or crops [4]. In the Bajgah area farmers grow vine in standard vineyards without microcatchments. The most economically feasible vine cultivars in this area are Black Rishbaba and Rotabi [5]. Sepaskhah *et al*., used microcatchment water harvesting systems for vineyards, and compared the grape yield with standard vineyards (3 m × 3 m spacing with no microcatchment system) [3]. The basins were separated by ridges of 0.2-0.25 m in height on foothill

*Received by the editors September 25, 2004; final revised form January 8, 2006.
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slopes, on a gravely loam soil with an average surface slope of about 5-6 % at the Agricultural Experiment Station of Bajgah, Shiraz University. They found that the soil water content under vine, and grape yield for each vine in the microcatchment system were higher than the soil water content and grape yield without microcatchments [6]. Furthermore, Sepaskhah and Fooladmand showed that, due to the vine spacing of 3 m × 3 m for standard grape plantation in the Bajgah area, the best microcatchment area is 9 m^2 [7]. They found that the total yield per hectare increased by about 40 % compared to a standard vineyard.

Design and management of water harvesting systems can be conducted by models for soil water balance. Sepaskhah and Fooladmand [7] developed a simulation model to design a microcatchment water harvesting system for a rain-fed vineyard in the Bajgah area, Fars province, I. R. of Iran. This model was able to determine the microcatchment size and predict the grape yield. Another model was developed by Sanchez-Cohen *et al*. [8] for water harvesting strip farming systems. This model is simple and uses readily available inputs such as leaf area indices and crop stage coefficients. To determine the microcatchment area, two equations were introduced by Garduno [9] and Boers and Ben-Asher [10]. In one of them, the annual water consumption (actual evapotranspiration) of the plants and the annual rainfall were used.

The productive rain-fed vineyards area in the I. R. of Iran is about 65000 ha, from which 39700 ha (61 %) is located in Fars province with an average yield of less than 3.0 t/ha [11]. The depth of water requirement for a rain-fed vineyard is about 350-400 mm, but Hakimi and Razavi [12] showed that in Urumia in the North West of the I. R. of Iran, with a 250 mm annual rainfall, grapevine are grown under rain-fed conditions.

The primary purpose of this study was to estimate the rain-fed vineyard actual evapotranspiration (ET_a) by using a computer model based on water balance equations in microcatchments containing grapevine in the Bajgah area, Fars province, the I. R. of Iran. The secondary purpose was to estimate the rain-fed vineyard ET_a for different probabilities of occurrence, and the third purpose was the estimation of the microcatchment area with different combinations of probabilities of occurrence for yearly ET_a and rainfall.

2. MODEL FORMULATION

Actual daily evapotranspiration during the growing and dormant seasons can be determined by the following equations, respectively [13]:

$$ET_{ai} = K_{si} \times K_c \times ET_{oi} \tag{1}$$

$$ET_{a_i} = K_e \times ET_{oi} \tag{2}$$

Where ET_{ai} is the actual crop evapotranspiration (mm), K_s is the soil water stress coefficient, K_c is the crop coefficient, K_e is the coefficient of evaporation from the soil surface that was considered equal to 0.3 [14], and ET_{oi} is the reference crop potential evapotranspiration (mm), while i stands for each day. The daily soil water stress coefficient can be obtained by the following equation [13]:

$$K_{si} = \frac{TAW - D_{r,i-1}}{TAW - RAW} \tag{3}$$

Where K_{si} is the daily soil water stress coefficient, TAW is the total available soil water in the root zone (mm), RAW is the readily available soil water in the root zone (mm), and $D_{r,i-1}$ is the total water content depletion in the root zone at the end of the previous day i-1. In this study, the grape root zone is considered equal to 140 cm, the root zone divided into seven layers each with a 20 cm thickness, and the water balance equations being used for seven layers. So, the amounts of $D_{r,i-1}$ were obtained for each day of the year. More details are reported by Sepaskhah and Fooladmand [7]. The growing season for grapes in the study area was considered from March 21 (80th day of the year) to September 22 (265th day of the years). The dormant season for grape in the study area was considered from September 23 (266th day of the year) to March 20 (79th day of the next year). Furthermore, the length of crop development stages for initial, developed, mid and late periods were 30, 60, 40 and 55 days, respectively and crop coefficient for initial, mid and end stages were selected to be 0.3, 0.7 and 0.45, respectively [13]. Daily crop coefficient was calculated by the following equations:

$$K_{ci} = K_{cini} \qquad (0 \le i \le L_1) \tag{4}$$

$$K_{ci} = K_{cini} + \left(K_{cmid} - K_{cini}\right) \times \frac{i - L_1}{L_2 - L_1} \qquad (L_1 \le i \le L_2) \tag{5}$$

$$K_{ci} = K_{cmid} \qquad (L_2 \le i \le L_3) \tag{6}$$

$$K_{ci} = K_{cmid} - \left(K_{cmid} - K_{cend}\right) \times \frac{i - L_3}{L_4 - L_3} \qquad (L_3 \le i \le L_4) \tag{7}$$

Where K_{cini} , K_{cmid} and K_{cend} are the crop coefficients for the initial, mid and end stages, respectively, L_1, L_2, L_3 and L_4 are the length of initial, developed, mid and late crop development stages, respectively (i.e. starting day = 80th, L_1 = 110th, L_2 = 170th, L_3 = 210th, and L_4 = 265th day of the year), and i is the number of each day in a year (the value of i ranges between 80 and 265). Meanwhile, Sepaskhah and Fooladmand [5] showed that the Penman-FAO [14] is the most appropriate method for calculating ET_o in the Bajgah area, which is in agreement with that reported by Sepaskhah [15]. So the Penman-FAO method was used for calculating ET_o.

On the other hand, Malek [16] showed that weather data in the Bajgah area is homogeneous. The calculation of ET_o by the Penman-FAO method for most synoptic weather stations in the I. R. of Iran, showed that Type III Pearson and Normal distributions are the most appropriate distributions [17]. Furthermore, they also introduced a simple method for calculating ET_o based on Type III Pearson and Normal distributions for different probabilities of occurrence [18]. The following equations can be used based on type III Pearson distribution [18]:

$$Cr = 1 + m \times CV_T{}^{a} \times \left(EL + 25\right)^{b} \tag{8}$$

$$ET_{Op} = Cr \times ET_{Om} \tag{9}$$

Where CV_T is the coefficient of the variation of mean monthly air temperature, EL is the elevation from sea level (m), ET_{op} is the monthly ET_o in each probability of occurrence, ET_{om} is the mean monthly ET_o, Cr is the ratio between ET_{op} to ET_{om}, and a, b and m are the constants which are different for various probabilities of occurrence. The values of these constants are shown in Table 1 [18].

Furthermore, for determining the microcatchment area the following equation can be used for squared microcatchments [9]:

$$A_c = A_f + \frac{\left(CU - P_m\right) \times A_f}{\eta \times P_m} \tag{10}$$

Table 1. The constant coefficients (m, a and b for Eq. (8)) for determining the ratio between monthly ET_o for different probabilities of occurrence and mean monthly ET_o (Cr) [18]

Probability (%)	m	a	b
90	0.338	0.275	-0.051
80	0.270	0.310	-0.056
70	0.188	0.363	-0.072
60	0.091	0.269	-0.075
40	0.047	0.176	-0.028
30	0.108	0.249	-0.032
20	0.226	0.289	-0.049
10	0.412	0.332	-0.057

Where A_c is the microcatchment area (m^2), A_f is the cultivated area (m^2), CU is the annual water consumption (actual evapotranspiration) of the plant (mm), P_m is the annual rainfall (mm), and η is the annual runoff coefficient. Runoff coefficient for the gravely loam soil in the study area with an average slope of 5-6 % was 0.08 as reported by Sepaskhah *et al*. [3]. The average diameter of mature vine canopy was considered as 1.5 m, so the cultivated area for each vine is 1.8 m^2. To calculate annual water consumption of the plant (CU), the following equation was used:

$$CU = \sum_{i=1}^{i=365} ET_{ai} \tag{11}$$

Where ET_{ai} is the daily actual evapotranspiration at different days of the year, i. By using the yearly ET_a and annual rainfall for different probabilities of occurrence in Eq (10), microcatchment areas were obtained for different combinations of probabilities. On the other hand, Sepaskhah and Fooladmand [7] showed that with decreasing the microcatchment area, the total yield of the Black Grape in the unit area (ha) will increase due to the higher number of trees per hectare. They obtained the following equation for the rain-fed vineyard in the study area:

$$Y = 3794.3\ A_c^{-0.58} \tag{12}$$

Where Y is the total yield (kg / ha). So, the rain-fed vineyard yield for different probabilities of yearly ET_a and annual rainfall can be estimated.

3. MATERIALS AND METHODS

Fars province is located in the southern part of the I. R. of Iran, at 50°30´ to 55°38´ longitude and 27°3´ to 31°42´ N latitude, with an arable land area of 1.32 million km^2. The mean annual precipitation for the province ranges from 50 to 1000 mm [19]. The Bajgah area is located 16 km north of Shiraz (central portion of Fars province) at 52°46´ longitude, 29°50´ N latitude, elevation is 1810 m above sea level and the mean annual rainfall is approximately 420 mm [7]. The climate of this region is semi-arid as reported by Malek [16].

Ten basins (6.7 m × 2.0 m) were separated by ridges of 0.2-0.25 m in height, on foothill slopes with an average surface slope of about 5-6 % at the Agricultural Experiment Station of Bajgah, Shiraz University. The data of runoff and soil water content obtained in these plots were used to calibrate a computer model developed to predict the microcatchment area [7]. The most typical soils on foothill areas are Bamo, Shekarbani and Koy-e-Asatid series [20]. The texture of these soils is gravely loam with high infiltrability. One neutron tube with a length of more than 1.2 m was placed in the soil under each vine canopy in 10 microcatchments, and under five vine canopies with no basins located around the experimental site. Thirty four measurements of soil water content at depths of 0-120 cm and volumetric soil water content at a depth of 120 cm were made. The computer model made by Sepaskhah and

Fooladmand [7], was used to estimate the amounts of daily ET_a. Then, Eqs. (8) and (9) were used to determine the amounts of ET_a, while the Weibull equation [21] was used to calculate the amounts of P_m for different probabilities of occurrence. This equation is as follows:

$$p = \frac{r}{n+1} \tag{13}$$

Where p is the probability of occurrence for each data point, r is the rank of each data point, and n is the total number of data. Also, Eq. (10) was used to calculate the microcatchments area for different combinations of probabilities of annual CU and P_m.

4. RESULTS AND DISCUSSION

Sepaskhah and Fooladmand [7] ran their model in the Bajgah area during the years from 1984 to 1987 with the Penman-FAO method for calculating ET_o, and calibrated it based on 34 measured volumetric soil water contents at depths of 120 cm, and amount of soil water at depths of 0-120 cm. The results of soil water stress coefficients (K_s) during the growing season of the years 1984-1987, and the mean values of K_s for four years are shown in Figs. 1a and 1b, respectively. The amounts of estimated daily crop coefficients during the growing season are shown in Fig. 2. Also, the results of potential and actual evapotranspiration (ET_p and ET_a) during the growing season of the years 1984-1987 are shown in Figs. 3a-3d, respectively. The results showed that the amounts of ET_a during the growing and dormant seasons of the years 1984 to 1987 were 407, 346, 376 and 362 mm (mean value of 373 mm), and 131, 126, 112 and 123 mm (mean value of 123 mm), respectively. So, the amounts of the yearly total of ET_a during these years were estimated to be 537, 472, 488 and 485 mm (mean value of 496 mm), respectively. The results indicated that the mean value of the total ET_a (496 mm) is higher than the mean annual rainfall (420 mm). The reason is due to the consideration of the water contribution from deeper soil layers (0.72 mm/d) as upward flux in Sepaskhah and Fooladmand's model [7].

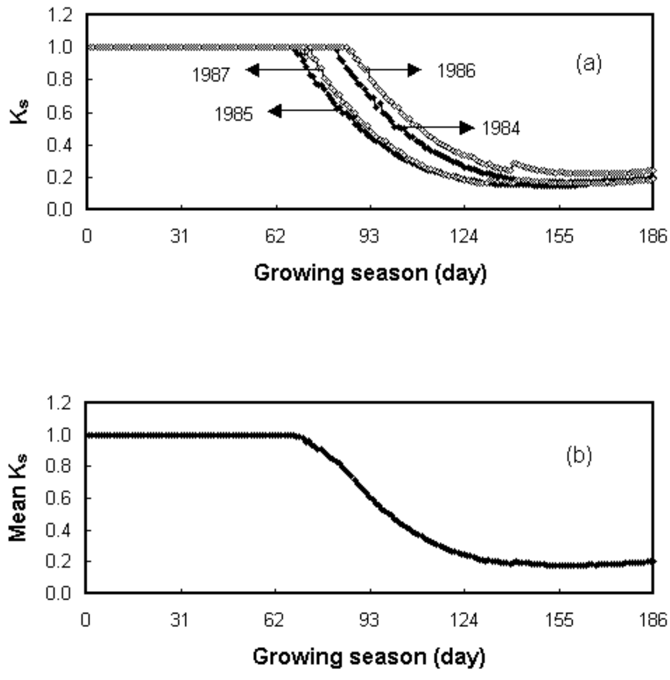

Fig. 1. Soil water stress coefficient (K_s) during the growing seasons 1984-1987 (a) and mean soil water stress coefficient (K_s) during the growing season (b)

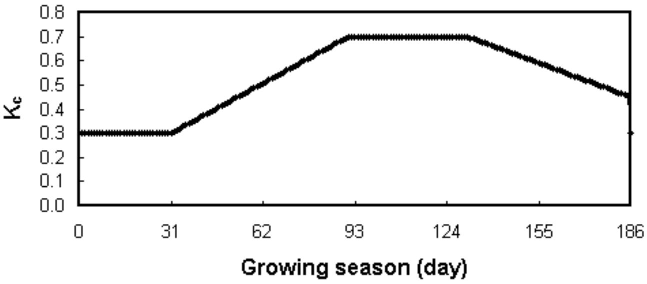

Fig. 2. Crop coefficient (K_c) for grape vine during the growing season

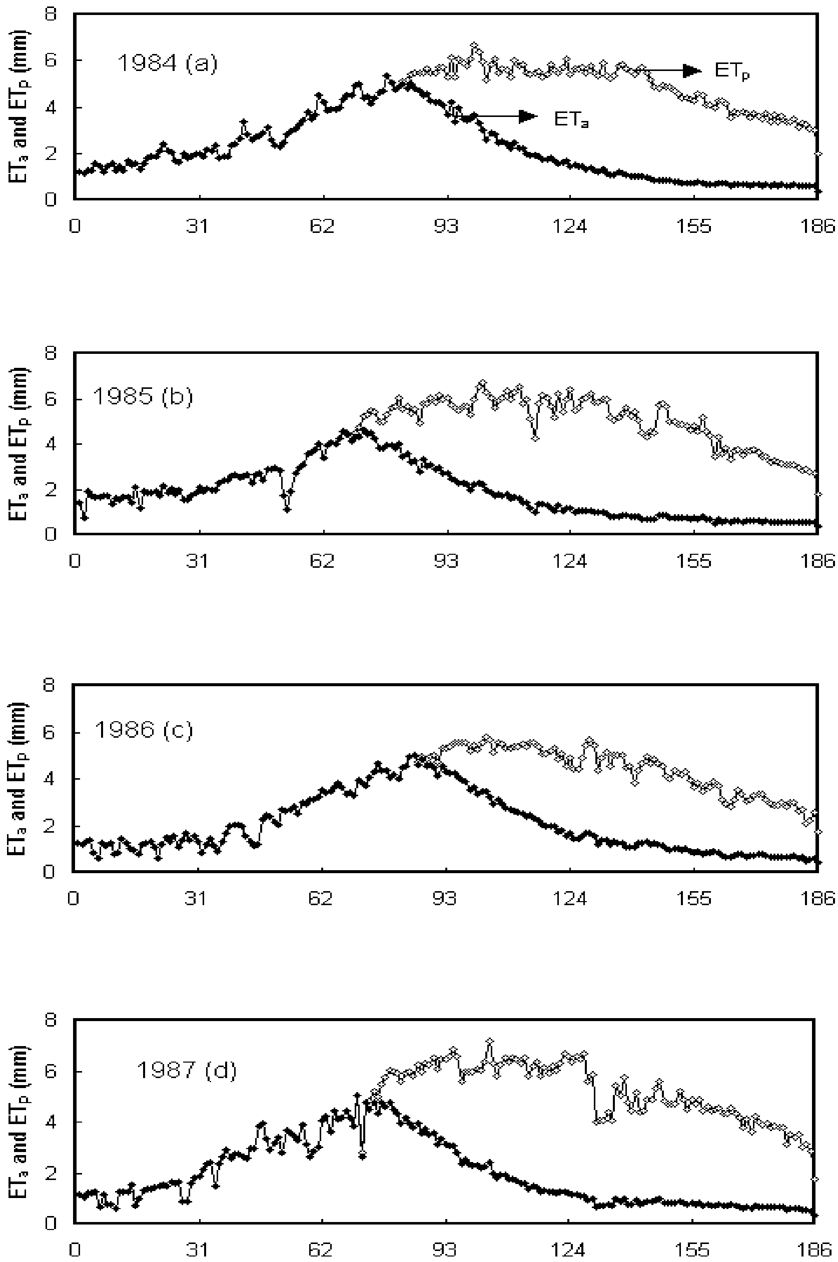

Fig. 3. Potential evapotranspiration (ET_p) under irrigated condition (◇) and actual evapotranspiration (ET_a) under rain-fed vineyard (◆) during the growing seasons of 1984-1987 (a-d).

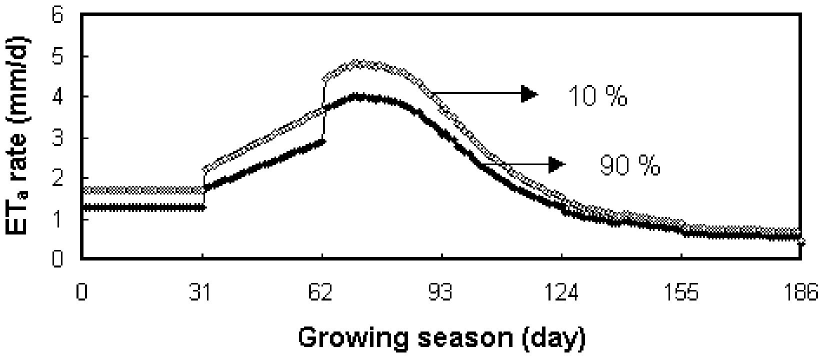

Fig. 4. Actual daily evapotranspiration rate (ET_a) of rain-fed vineyard for 90 and 10 % probabilities of occurrence

Furthermore, the values of coefficient of variation for mean monthly air temperature and mean monthly ET_o rate (mm/d) based on 19 years of data (1984-2002) are shown in Table 2. The results of ET_o in each probability of occurrence in each month of the year, based on the Penman-FAO method, are shown in Table 3. Then, according to the daily crop coefficients (Fig. 2) and mean daily soil water stress coefficients, K_s (Fig. 1b), ET_a for each probability of occurrence in each month of the year were calculated. The amounts of ET_a during the growing season, dormant season and the whole year, and the amounts of annual rainfall for 90, 80, 70, 60, 50, 40, 30, 20 and 10 % probabilities of occurrence are shown in Table 4. Also, the amounts of daily ET_a during the growing season for 90 and 10 % probabilities of occurrence are shown in Fig. 4.

The results of the model showed that the amounts of ET_a during the growing season and the yearly ET_a of the years 1984-1987 varied between the ranges occurring for probabilities of 90 and 10 %. Then, by using the amounts of yearly ET_a and annual rainfall for different probabilities of occurrence in Eq. (10), the microcatchment areas were estimated. The size of the microcatchment area based on different probabilities of yearly ET_a and annual rainfall are shown in Table 5. In this table, empty places showed that the amount of P_m is greater than CU, therefore, according to the Eq. (10) the microcatchment area for this probability level of yearly ET_a and annual rainfall could not be estimated. On the other hand, due to the spacing of 3 m × 3 m for vines in the study area, the microcatchment size can not be smaller than 9 m^2.

Table 2. The values of coefficient of variation of mean monthly air temperature (CV_T) and the value of mean monthly ET_o rate

Month	CV_T	ET_o(mm/d)
January	0.364	2.21
February	0.333	2.69
March	0.127	3.66
April	0.128	4.95
May	0.089	6.46
June	0.039	7.94
July	0.033	8.22
August	.037	7.75
September	0.041	6.83
October	0.059	5.13
November	0.068	3.59
December	0.168	2.53

Table 3. Monthly ET_o rate (mm) for different probabilities of occurrence

Month	Probability (%)								
	90	80	70	60	50*	40	30	20	10
January	1.82	1.92	2.04	2.12	2.21	2.28	2.36	2.47	2.36
February	2.23	2.35	2.49	2.59	2.69	2.77	2.86	3.00	3.19
March	3.19	3.36	3.47	3.56	3.66	3.76	3.85	3.98	4.16
April	4.30	4.52	4.69	4.81	4.95	5.08	5.20	5.38	5.62
May	5.70	5.96	6.17	6.30	6.46	6.62	6.76	6.96	7.24
June	7.19	7.43	7.67	7.78	7.94	8.11	8.24	8.42	8.66
July	7.48	7.71	7.96	8.06	8.22	8.39	8.52	8.70	8.93
August	7.03	7.25	7.49	7.60	7.75	7.91	8.03	8.21	8.44
September	6.18	6.39	6.60	6.70	6.83	6.98	7.10	7.26	7.47
October	4.58	4.75	4.92	5.01	5.13	5.24	5.34	5.48	5.66
November	3.19	3.31	3.44	3.50	3.59	3.67	3.74	3.85	3.98
December	2.17	2.27	2.38	2.45	2.53	2.60	2.66	2.76	2.90

*Mean monthly ET_o

Table 4. Actual evapotranspiration (ET_a) in growing season, dormant season and whole year and annual rainfall for different probabilities of occurrence

Probability (%)	ET_a(mm)			Rainfall (mm)
	Growing season	Dormant season	Total year	
90	337	105	442	224
80	350	110	460	257
70	361	115	476	299
60	368	119	487	335
50	376	123	499	382
40	384	126	510	436
30	391	129	520	487
20	401	134	535	517
10	414	141	555	589

Table 5. Microcatchment areas for different probabilities of yearly ET_a (CU) and annual rainfall (P_m)

Probability of P_m(%)	Probability of CU (%)								
	90	80	70	60	50*	40	30	20	10
90	23.7	25.5	27.1	28.2	29.4	30.5	31.5	33.0	35.0
80	18.1	19.7	21.1	22.1	23.2	24.1	25.0	26.3	28.1
70	12.6	13.9	15.1	15.9	16.8	17.7	18.4	19.6	21.1
60	9.0	10.2	11.3	12.0	12.8	13.6	14.2	15.2	16.6
50	5.3	6.4	7.3	8.0	8.7	9.3	9.9	10.8	12.0
40	2.1	3.0	3.9	4.4	5.1	5.6	6.1	6.9	7.9
30				1.8	2.4	2.9	3.3	4.0	4.9
20							1.9	2.6	3.5
10									

Furthermore, by using the Eq. (12), the rain-fed Black Grape yields were estimated for different probabilities of yearly ET_a and annual rainfall (P_m). The ranked results for yields are shown in Table 6. The results indicated that the maximum yield can be obtained in 90 % probability of CU (ET_a) and 60 % probability of annual rainfall, and the minimum yield can be obtained in 10 % probability of CU (ET_a) and 90 % probability of annual rainfall. On the other hand, Sepaskhah and Fooladmand [7] showed that according to the Penman-FAO method for calculating ET_o the microcatchment area was estimated to be 29 m^2, which is similar to the microcatchment area with a 50 % probability of CU (ET_a) and 90 % probability of annual rainfall (Table 5). Furthermore, a simple equation was obtained by multiple regression analysis between the microcatchment area (A_c, m^2) and probabilities of CU and P_m (as %) as follows:

$$A_c = -7.328 - 0.105(\%CU) + 0.443(\%P_m)$$
$$(R^2 = 0.973,\ n = 63,\ SE = 1.365,\ p < 0.001) \quad (14)$$

Table 6. Estimated rain-fed black grape yields for different probabilities of yearly ET_a (CU) and annual rainfall (P_m)

Probability (%)		Yield (kg/ha)	Probability (%)		Yield (kg/ha)
CU	P_m		CU	P_m	
90	60	1061	30	70	701
40	50	1041	20	70	675
30	50	1004	80	80	674
80	60	987	70	80	647
20	50	954	10	70	647
70	60	930	60	80	630
60	60	898	50	80	613
10	50	898	90	90	605
90	70	873	40	80	599
50	60	865	30	80	587
40	60	835	80	90	580
80	70	824	20	80	570
30	60	814	70	90	560
70	70	786	10	80	548
20	60	783	60	90	547
60	70	763	50	90	534
10	60	744	40	90	523
50	70	739	30	90	513
40	70	717	20	90	499
90	80	707	10	90	483

Sepaskhah and Fooladmand [7] showed that the best microcatchment area for a rain-fed vineyard in the study area is 9 m^2. The results of this study indicated that with 50 % probability of CU and P_m, the microcatchment area is about 8.7 m^2 (Table 5), which is almost equal to 9 m^2. So, the most appropriate microcatchment area for vineyards for the study area, as used by local farmers, is built by 50 % probability of CU and P_m.

5. CONCLUSIONS

By using a computer model based on a water balance equation in microcatchments containing grapevine in the Bajgah area, Fars province, I. R. of Iran, the rain-fed vineyard actual evapotranspirations (ET_a) for growing season, dormant season and whole year were estimated. To calculate reference crop potential evapotranspiration (ET_o), the Penman-FAO method was used. The results showed that the mean growing season and yearly ET_a for four years were 373 and 496 mm, respectively. Also, by using a simple method, ET_o for different probabilities of occurrence was estimated. Then, the amounts of ET_a for different probabilities of occurrence were obtained, and the results showed that the amounts of ET_a during the growing season and whole year of the years 1984-1987 varied between the ranges determined for probabilities of occurrence of 90 to 10 %. Furthermore, the microcatchment area was estimated by using the different probabilities of occurrence for yearly ET_a and annual rainfall. The results showed that using 50 % probability of yearly ET_a and annual rainfall is the most appropriate situation for building squared microcatchments, which is in agreement with the vine spacing (3 m × 3 m) that local farmers use in the Bajgah area.

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