JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 13 2005

DISTRIBUTION OF RAINFALL, RUNOFF AND SOIL MOISTURE STORAGE IN THE LOW RAINFALL ZONE OF NORTHERN IRAQ

Mohammad H. Hussein[1]
Muhsen M. Awad[2]
Alae S. Abdul-Jabbar[3]

[1]Department of Soil And Water, College of Agriculture, University of Babylon, Hilla, Iraq
[2]Department of Soil and Water, Mosul University, Mosul, Iraq
[3]Center for Industrial Forests, Ministry of Industry, Baghdad, Iraq

Knowledge of the distribution of rainfall, runoff and soil moisture storage is important in dryland farming and water resources development in semiarid regions. Several natural runoff plots in fallow were established on a 6% uniform slope area to study runoff and soil moisture distribution in the low rainfall zone of northern Iraq. The soil at the site belongs to the Calciorthid suborder, which dominates in this zone. Analysis of 23 years of rainfall records at the experimental site showed that monthly rainfall distribution varied appreciably among seasons, with the monthly rainfall records following a gamma probability distribution. Monthly runoff distribution nearly follows that of rainfall in normal rainfall seasons, but may become erratic in dry rainfall seasons. Mean soil moisture storage during the season was expressed linearly in term of total seasonal rainfall infiltration. Soil moisture storage during the rainfall season follows a normal probability distribution and drops to as low as 30% of the saturation level before the start of the rainfall season in October or November.

INTRODUCTION

Shortage of water resources is evident in many regions with a semiarid climate (UNESCO, 1998). Maximum use efficiency of rainfall, runoff and soil moisture requires knowledge of their distribution during the rainfall season. The semiarid region of northern Iraq comprises a total area of more than 5 million ha of forest, grazing and dryland farming areas. The region is often divided into three rainfall zones according to the mean seasonal rainfall. The high rainfall zone receives more than 600 mm of mean seasonal rainfall. Natural oak forests are located almost exclusively within this zone. In addition, dryland farming on the gently sloping land is nearly guaranteed in this zone. The medium rainfall zone receives between 400 and 600 mm of mean seasonal rainfall. This zone is mainly used for dryland farming and grazing. The low rainfall zone receives between 300 and 400 mm of mean seasonal rainfall. Dryland farming in this zone suffers from occasional dry periods, which makes such farming uneconomical. Wheat, barley and legumes are the major crops grown in the semiarid region of northern Iraq.

Normal rainfall intensity in the region is below 20 mm/h. Hence, under such circumstances, surface runoff usually occurs when the surface crust has developed to the extent that the basic infiltration rate of the crusted layer becomes less than rainfall intensity (Awad et al., 1992). Since, in such regions, deep percolation of infiltrating water is not significant except on shallow soils (Hussein, 2001), soil moisture storage during the rainfall season is directly proportional to the difference between rainfall and runoff.

Daily and weekly distributions of rainfall and runoff are not applicable in semiarid regions due to the relatively large number of zero values during the rainfall season. Hence the more realistic monthly distribution is adopted. However, soil moisture storage can be easily expressed on a daily basis.

In the following, distribution of rainfall, runoff and soil moisture storage is analyzed for three rainfall seasons. The impact on dryland farming and water resources in the region is also discussed.

SITE AND MEASUREMENTS

Several natural runoff plots were established in March 1988 on a uniform area of 6% slope, located at Hammam Al-Alil (36° 10' N, 43° 20' E) in the northwestern part of Iraq. Plot design and installation were done according to the procedure outlined by Mutchler (1963). Access tubes for soil moisture measurement were installed on all plots.

The experimental site was used primarily as grazing land; its soil is classified as fine, mixed, thermic, calcareous, Xerrollic Calciorthid. General soil characteristics are given in Table 1. Mica and chlorite are the dominant clay minerals followed by kaolinite and montmorillinite.

The region has a semiarid climate. A wet cold winter and a dry hot summer are characteristic. The rainfall season in the region normally extends from October to May. Mean seasonal rainfall at the site is about 333 mm with a moderate season-to-season variability as shown in Table 2. Table 3 gives mean monthly values of air temperature, relative humidity and Pan A evaporation at the experimental site.

Table 1. Soil Characteristics at the Experimental Site

Depth (m)	Particle size distribution (%): Clay	Silt	Sand	Bulk density ($Mg\ m^{-3}$)	Sat. conductivity ($mm\ h^{-1}$)
≤0.3	36	44	20	1.3	37
0.3-0.7	43	34	23	1.4	28
≥0.7	50	34	16	1.5	17

Table 2. Monthly and Seasonal Rainfall at the Experimental Site (mm)

Season	Total rainfall for the month of: Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	Season
67-68	26.5	127.1	45.3	24.5	23.3	31.9	41.3	26.9	17.2	364
68-69	10.5	35.5	85.6	144.3	23	117.7	67.4	35.9	0	520
69-70	16.6	123.3	61.4	143.1	9.7	59.6	8.7	0	0	323
70-71	0	28.6	28.6	1.9	12	1.9	130.1	1.6	0	205
71-72	1.7	41	54.6	49.5	77.1	60.3	128.9	31.9	5.2	451
72-73	5.5	31.5	49	39.8	54	17.3	19.9	27	0	244
73-74	5.1	14.2	19.2	96.6	78	161.5	35.5	6	0	416
74-75	1.5	32.8	39.7	47.5	102.9	8.8	70.2	4.1	0	308
75-76	0	20	103	52.5	78	80	43.4	16.5	0	394
76-77	11.2	0	32.5	88.7	20.7	23.2	56.6	6.1	0.3	240
77-78	7	28.4	114.9	64	104.9	27.4	4.7	0.8	2.1	355
78-79	0.2	8.3	59.6	95	60.4	46.3	2.5	4.8	0	278
79-80	15.3	40.3	85.7	12.9	112.2	72.5	54.7	3	0	382
80-81	0	71	34	54.6	45.1	97.3	19.2	5.2	0	327
81-82	20	45.9	51.2	102.7	30.2	46.5	47.5	31.2	0	376
82-83	16.2	75	46.5	41.2	32.4	24.3	11	20.6	1.4	269
83-84	1.1	25.5	18.1	9.6	10.8	31.7	83	25.3	0	206
84-85	9	178.4	52.6	33.5	48.3	129.6	8.9	0	0	452
85-86	0	19.6	55.1	19.7	44.1	29.1	30.1	0	0	198
86-87	16.6	52.5	36.8	3.7	31.4	65.2	6	0	0	213
87-88	35.3	11.2	124.9	150.4	95	95.4	44.7	11	0	568
88-89	0	6.1	84.3	9.4	21.7	126	0	8.5	0	256
89-90	0	100	39	36	57	39	28	2	0	301
90-91*	0	0	35	-	-	-	-	-	-	-
91-92*	0	37	89.1	40.4	83.7	38	13.6	8.2	0	310
Mean	8.7	44.2	57.5	57.4	51	60.5	41	11.7	1.1	332.4
St. dev.	9.8	42.3	29.2	45.9	32.3	43.1	36.6	12.2	3.7	102.5
Skew	1.2	1.9	0.9	0.8	0.5	0.8	1.2	0.8	4.1	0.6

Table 3. Mean Monthly Values of Some Meteorological Variables at the Experimental Site

Month Mean value of:	Jan	Feb	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Air temp. (^{0}C)	6.9	8.5	12.1	16.9	23.3	28.9	33.1	32.7	28	21.3	12.9	7.9
Rel. humid. (%)	82	81	75	67	46	32	30	32	42	55	70	84
Pan A evap. (mm)	33	70	100	133	272	418	542	517	340	185	77	34

Each autumn, and after rain showers had moistened the soil, the plots were tilled by spading then smoothed and left in the fallow condition throughout the rainfall season. Gramaxon was used to control weeds. After each runoff-producing rainstorm, the runoff volume in the collecting tank at each plot outlet was measured. The site was equipped with a nonrecording raingauge. A recording raingauge has been used since the 1989-1990 rainfall season. Soil moisture measurements using a neutron probe were made periodically on the plots at a 0.1 m interval throughout the experiment. The period between soil moisture measurements was between one and two weeks. All measurements were discontinued during the period from mid January 1991 to the end of the 1990-1991 rainfall season.

Three replicated plots, 30x3 m in size were selected for this analysis. Soil profile depth at the lower end of these plots is 1.2 m and decreases in the upslope direction. Only soil moisture measurements at the lower end of plots are considered here.

RESULTS AND DISCUSSION

Plot to plot variability in runoff depth and soil moisture storage was not significant at the 95% probability level. Hence average values from the three replicates are considered in the following discussion.

Rainfall and runoff

Table 2 gives monthly and seasonal rainfall at the experimental site during the period 1967-1992. Excluding the month of June, the coefficient of variation for monthly rainfall data listed in Table 2 ranges from 50% for December to 112% for October. Such season to season variability in monthly rainfall is typical of rainfall in arid and semiarid regions (Maidment, 1993). Positive skewness was observed in the same data with the coefficient of skewness ranging from 0.5 for February to 1.9 for November. The pronounced right skew for the records in Table 2 is caused mainly by a few very large observed values during this short period of record. The highest variability and skewness in monthly rainfall occurred at the beginning and at the end of the rainfall season.

The gamma probability distribution function is a useful continuous distribution function for many natural events especially those occurring in arid and semiarid regions (WMO, 1966). The gamma probability distribution function is given (NIST/ SEMATECH, 2003) by:

$$f(x) = (x/\beta)^{\gamma-1} e^{-x/\beta} / [\beta \Gamma(\gamma)] x \geq 0 \gamma, \beta \succ 0 \qquad (1)$$

where γ= shape parameter, β = scale parameter, $f(x)$ = the probability density function of the random variable x and Γ is the gamma function given by:

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt \qquad (2)$$

The cumulative gamma distribution function, $F(x)$, is the integral of the probability density function:

$$F(x) = \left[\int_0^x (t/\beta)^{\gamma-1} e^{-1/\beta} dt \right] / [\beta \Gamma(\gamma)] \qquad (3)$$

Both $f(x)$ and $F(x)$ values can be obtained from computer software such as Microsoft Excel.

The monthly rainfall records in Table 2 (1967-1990) were fitted to the gamma probability distribution function (Figure 1). Using the method of moments (NIST/SEMATECH, 2003), the gamma distribution parameters were estimated from:

$$\gamma = (\bar{x} / S)^2 \qquad (4)$$

and

$$\beta = S^2 / \bar{x} \qquad (5)$$

where $\bar{x}$ and S are respectively the mean and standard deviation of the monthly rainfall records. Parameter values obtained for this analysis were γ = 1.17 and β = 36.01.

Figure 1 shows that the gamma probability distribution gives a reasonable fit, at the 95%

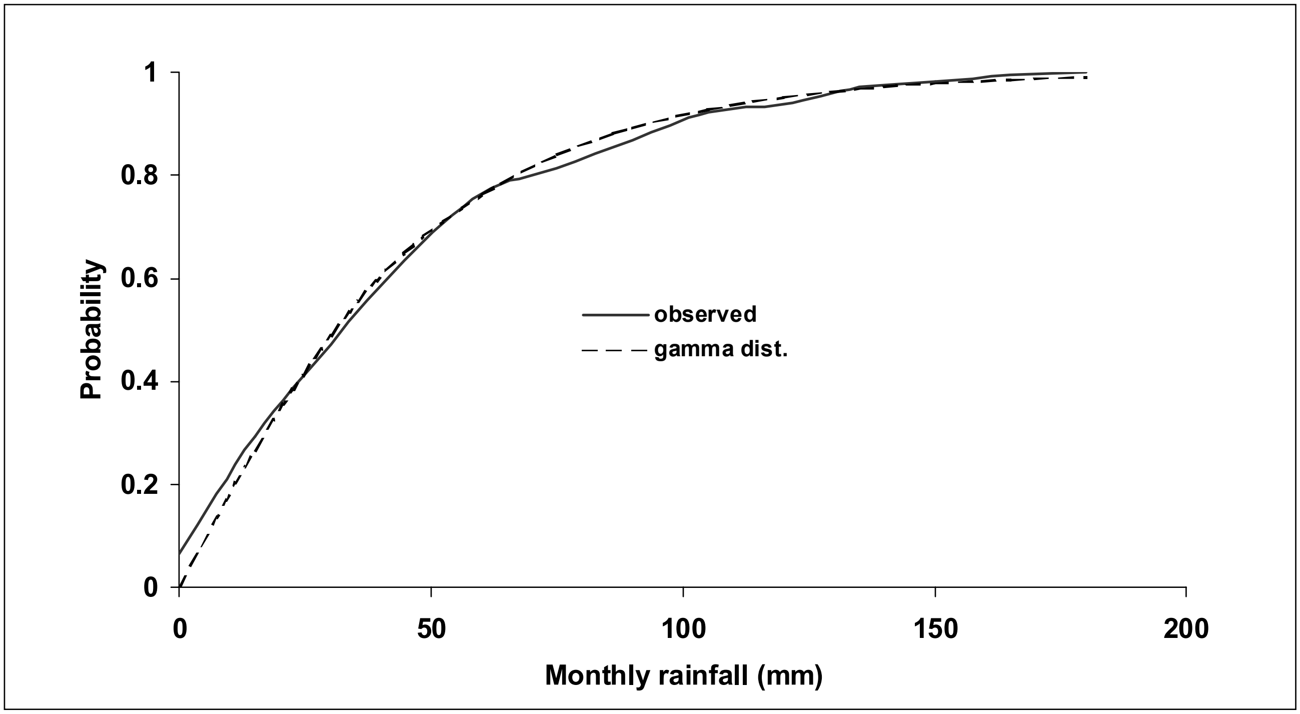

Figure 1 Cumulative probability [F(x)] for the continuous monthly rainfall records (1967-1990) listed in Table 2.

probability level, to the monthly rainfall data in Table 2. The fit was verified using the chi-square test (Chow et al., 1988). The computed chi-square value was 10.25 compared to a critical value, at the 95% level, of 16.92 (Walpole & Myers, 1978).

Figure 1 also indicates that the probability of monthly rainfall being less than 10 mm is more than 20%. On the other hand, the probability of monthly rainfall being more than 100 mm is 10%. Median monthly rainfall depth is about 35 mm. Hence dry spells are not uncommon in the region with occasional months of heavy rainfall that may cause significant runoff and erosion (Hussein, 1998).

Data of monthly runoff for the three seasons are listed in Table 4. Monthly rainfall distribution during the dry 1988-1989 season was discontinuous due to a zero total rainfall in April (Table 2). Monthly runoff distribution during this season was erratic with runoff occurring only during the months of December and March. The 1989-1990 season was normal with a continuous monthly rainfall distribution after October and a highest monthly rainfall depth in November. Monthly runoff distribution during this season nearly follows that of rainfall except in the months of November and March where some severe storms (intensity>20 mm h^{-1}) resulted in higher runoff coefficients (i.e. runoff divided by rainfall) on the plots. The 1991-1992 season was normal with a continuous monthly rainfall distribution after October and highest monthly rainfall depths in December and February. Monthly runoff distribution during this season indicates a diminishing runoff after the month of February. This may be due to the dominance of low intensity storms occurred during this season, where only 30% of the rainstorms produced runoff compared to about 60% for each of the other two seasons (Hussein, 1996).

Table 4. Recorded Monthly Runoff at the Experimental Site (mm)

Season	Total runoff for the month of:							
	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May
1988-1989	0	0	2.7	0	0	7.4	0	0
1989-1990	0	47	2.6	1.7	3.7	20	3.3	0
1991-1992	0	2.4	28.3	1.3	2.3	0.3	0	0

As indicated by Tables 2 and 4, seasonal runoff coefficient varies from 0.04 for the 1988-1989 season to 0.26 for the 1989-1990 season. Hence long term measurements are necessary to establish an acceptable value for mean seasonal runoff coefficient in the region. The mean seasonal runoff coefficient is needed in the planning, design and operation of water resources projects.

Soil moisture storage

Soil moisture storage dynamics

The relationship between mean soil moisture storage during the season and total seasonal rainfall infiltration may be expressed as:

$$\int_0^T \theta(t)dt / T = \alpha F_s + \theta_s \tag{6}$$

where $\theta(t)$ = soil moisture storage at day t (mm), T = length of soil moisture fluctuation season at the site (day), F_s = total seasonal rainfall infiltration on the plot (mm), α = factor reflecting soil-climate interaction and θ_s = soil moisture storage just before the start of rainfall season (mm).

The soil moisture fluctuation season at the site extends for the period from October to October of the next year (Hussein et al., 1993). However, soil moisture measurements in this study were carried out during the period from late October to early July. This period is considered as the effective soil moisture fluctuation season at the site (Figure 2).

Equation 6 may be written as:

$$\left\{\sum_{i=1}^{n}\left[(\theta_i\theta_{i1})/2\right](\Delta t)_i\right\} / \sum_{i=1}^{n}(\Delta t)_i = \alpha\left[(Vr)_s - (Vu)_s - R_s\right] + \theta_s \tag{7}$$

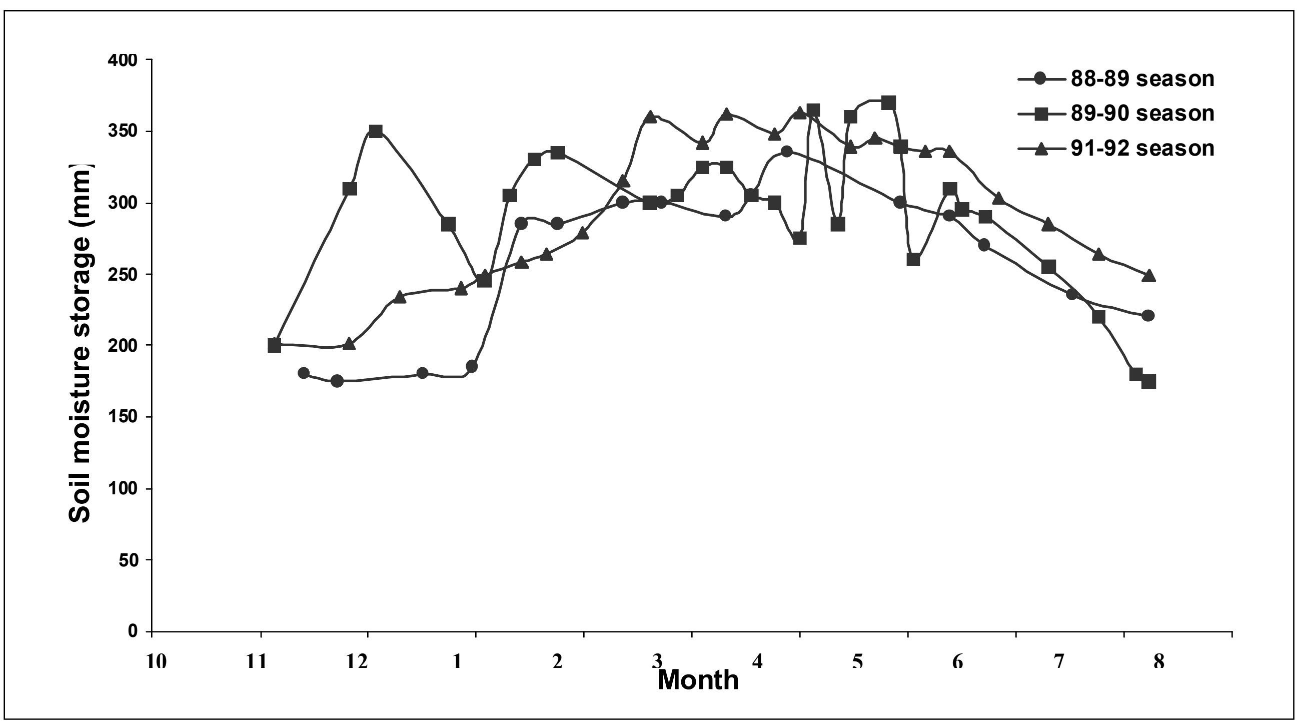

Figure 2. Observed time series of soil moisture storage (Soil profile depth = 1.2 m).

where θ_i, θ_{i+1} are two consecutive soil moisture storage measurements separated by a time period of $(\Delta t)_i$, $(Vr)_s$ = total seasonal rainfall (mm), $(Vu)_s$ = total seasonal runoff (mm), R_s = deep percolation during the rainfall season (mm) given by Hussein (2001), and n = number of soil moisture storage measurements during the season.

The left hand side of Equation 7 approaches the mean value of soil moisture storage measurements during the season (Table 5) if the measurements were taken at a regular time interval.

Table 5. Statistical Summary of Soil Moisture Storage Data

Season	Mean (mm)	Standard deviation (mm)	Coefficient of skewness	Recorded maximum (mm)	Recorded minimum (mm)	Median (mm)
1988-1989	258	54	-0.56	335	175	285
1989-1990	293	52	-0.80	370	175	302.5
1991-1992	296	53	-0.34	363	201	303

The soil-climate interaction factor (α) is likely related to the soil depth effectively supplied by rainfall (i.e. active soil depth) and to seasonal evaporation from the soil surface. Active soil depth in this study was considered 1.2 m (i.e. the entire soil profile) (Hussein et al., 1993). Furthermore, total seasonal evaporation is assumed equal to total seasonal infiltration (F_s), since soil moisture storage nearly returns to its original level just before the start of the rainfall season at the start of the next rainfall season. Hence we expect α to be approximately constant at this particular site.

Calculated α values were 0.36 for the 1988-1989 season (R_s=24 mm, θ_s=180 mm), 0.45 for the 1989-1990 season (R_s=9.7 mm, θ_s=200 mm) and 0.37 for the 1991-1992 season (R_s=34.9 mm, θ_s=201 mm). The increase in α during the 1989-1990 season is due to several severe storms that occurred in late November 1989 and mid March 1990. These storms increased seasonal runoff (Table 4). This means that the value $[(Vr)_s-(Vu)_s-R_s]$ decreased during this season. In the mean time, the left hand side of Equation 7 decreased to a lesser degree due to the relatively low potential evaporation rate in November and March (Table 3 and Figure 2).

Figure 2 shows the time series of soil moisture storage during the three seasons. The three time series curves are approximately similar in shape. Table 5 gives a statistical summary of the data used to plot Figure 2. The slight to moderate left skew indicated by Table 5 is due to the low soil moisture storage values that occurred at the beginning and/or at the end of seasons (Figure 2). The maximum skew was in the data of the 1989-1990 season. The relatively large number of measurements during this season (Figure 2) gave a better representation of soil moisture variability during the season. The minimum skew was in the data of the 1991-1992 season, which were the most uniformly distributed. The reason may be related to the dominantly low intensity storms that occurred during this season. For such storms, most rainwater infiltrates into the soil surface. Soil moisture storage values during the dry 1988-1989 season were generally lower than the other two seasons, especially at the beginning and at the end of the season.

Figure 2 also shows that soil moisture storage starts to increase in November or December to a reach a maximum during the period from February through April then drops effectively after the month of May due to the lack of rainfall and increased evaporation (Tables 2 and 3). Soil water content after the saturated soil has drained under gravity to equilibrium is called field capacity. Field measurements during this study indicated a mean field capacity in the soil profile of 0.3 V_w/V_t, where V_w = volume of water and V_t = total soil volume. This corresponds to 360 mm of soil moisture storage for the 1.2 m soil profile depth. Soil moisture storage remained below the field capacity level during the dry 1988-1989 season, but reached this level in November and April during the 1889-1990 season and in February, March and April during the 1991-1992 season.

It is useful to have some idea about the probability distribution of soil moisture storage at the site. As indicated by Figure 2, a sufficient number of data points are available from the 1989-1990 soil moisture measurements. This allows for a reasonable plot of probability density function of soil moisture storage at the site (Figure 3a). Figure 3a clearly shows the left skew indicated by Table 5. It also shows a drop in probability between soil moisture storage levels of 185 and 250 mm respectively. Measurements corresponding to this range of soil moisture storage levels took place mostly after the end of the rainfall season in May. Hence it is desirable to consider only soil moisture storage measurements during the rainfall season, which in this case extends from November to May (Table 2).

Figure 3b shows the probability density function of soil moisture storage during the 1989-1990 rainfall season. The 295 mm soil moisture storage is the most probable. On the other hand, soil

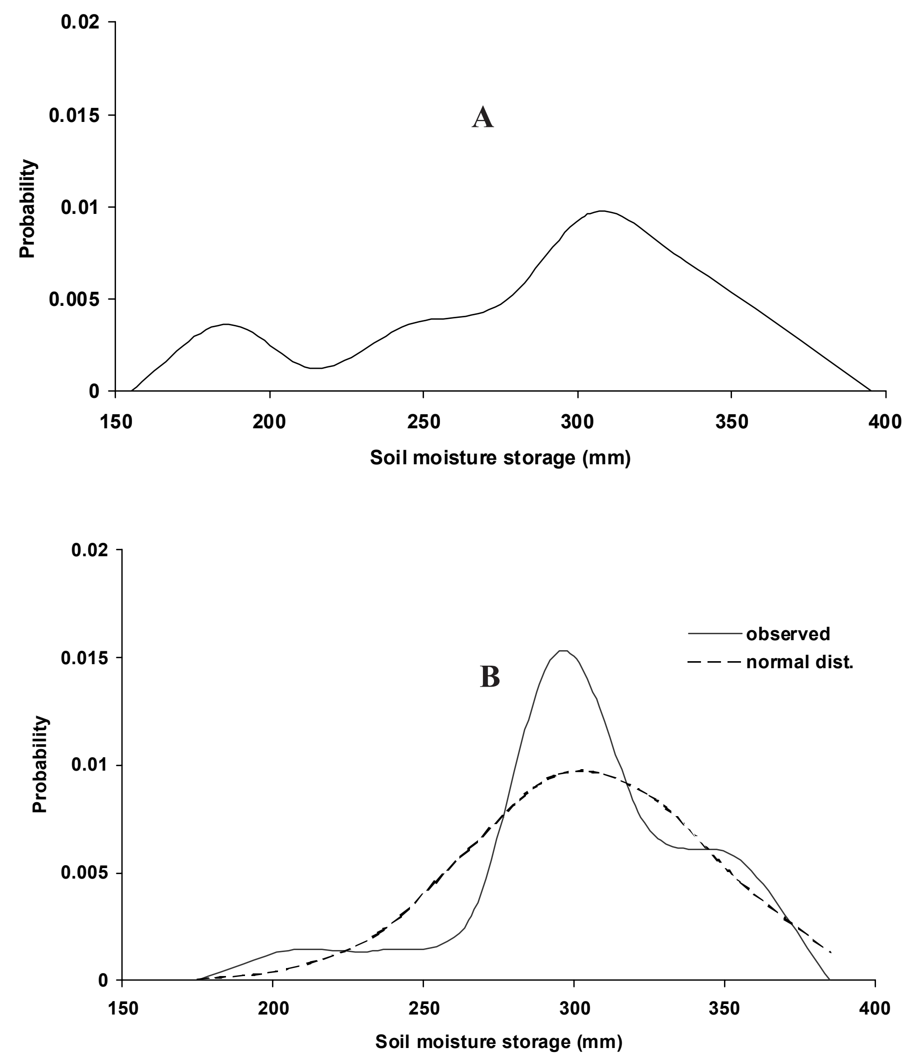

Figure 3. Probability density function [f(x)] for the 1989-1990 season soil moisture storage measurements: (A) All measurements; (B) Measurements during the rainfall season only.

moisture storages below 200 mm and above 350 mm are the least probable. The information supplied by Figure 3b is substantiated in Figure 2.

Using the method of moments, a chi-square test showed that the data in Figure 3b fit a normal distribution. The calculated chi-square value was 5.27 compared to a critical value, at the 95% level, of 7.82. The fit may be improved if daily soil moisture measurements during a normal rainfall season were used. This is because the process of soil-climate interaction becomes a more simple natural process in the absence of vegetation effects.

Effect of soil moisture fluctuation

Soil moisture deficit (SMD) is the amount of water required to restore the soil to field capacity. There is a maximum SMD for each plant type at a ‘permanent wilting point’ from which the vegetation cannot recover and dies. Local wheat varieties in the region (e.g. Saber Beg) are surface rooted; permanent wilting points for such wheat varieties were found to be at 0.09 V_w/V_t and $0.15V_w/V_t$ for seedling and maturing stages respectively. Figure 2 indicates that for a successful dryland farming in the region, such crops may be planted in November and harvested before the month of June. December planting, however, may require freezing resistant crop varieties. Furthermore, Figure 3b indicates a good chance for dryland farming success during normal rainfall seasons.

During the spring, when potential evaporation begins to exceed rainfall (Tables 2 and 3), soil moisture deficit begins first in the surface soil layers and then moves downwards into the lower layers as water in the soil is used up, and until in the summer months there could be soil moisture deficits in all the rooting zones of the soil. When rainfall totals begin to exceed potential evaporation in the late autumn (Tables 2 and 3), soil moisture storage is gradually replenished from the top soil layer downwards, until all the soil layers reach or approach the field capacity level, normally during the period between mid winter and mid spring (Figure 2).

Daily soil moisture storage on fallow plots during the rainfall season can be related to rainfall, runoff, infiltration and evaporation in a simulation model (Hussein et al., 1993). Such models can help in water resources development and in dryland farming planning in the region.

CONCLUSIONS

Monthly rainfall distribution during the rainfall season varied significantly among seasons indicating the high variability in rainfall of the semiarid regions. The gamma probability distribution function fits the monthly rainfall data reasonably well.

On a bare soil, monthly runoff distribution approximately follows that of rainfall in normal rainfall seasons.

On a bare soil, soil moisture storage during the rainfall season approximately follows a normal distribution and its mean is directly proportional to total seasonal rainfall infiltration.

Maximum soil moisture storage during the rainfall season occurs during the period from February through April in which soil moisture storage approaches the field capacity level.

ACKNOWLEDGMENTS

Thanks go to Professor Abd-Allah Al-Ani and Dr. Laith K. Ismail for a critical review of the manuscript.

REFERENCES

Awad, M.M., M.H. Hussein, and A.S. Abdul-Jabbar. 1992. Crust development under natural rainfall in northern Iraq. Mesopot. J. Agric. 24(2), 31-36.

Chow, V.T., D.R. Maidment, and L.W. Mays. 1988. Applied Hydrology. McGraw-Hill, N.Y., USA.

Hussein, M.H. 1996. An analysis of rainfall, runoff and erosion in the low rainfallzone of northern Iraq. J. Hydrol. 181, 105-126.

Hussein, M.H. 1998. Water erosion assessment and control in northern Iraq. Soil & Tillage Res. 45, 161-173.

Hussein, M.H. 2001. Direct groundwater recharge by rainfall in a region with a semiarid Mediterranean type climate. In: Impact of Human Activity on Groundwater Dynamics (ed. by Geherls H, Peters NE, Hoehn E, Karsten J, Leibundgut C, Griffioen J, Webb B and Zaadnoordijk, W J), 99-105. International Association of Hydrological Sciences Publ. no. 269, Wallingford, UK.

Hussein, M.H., M.M. Awad, and A.S. Abdul-Jabbar. 1993. Soil moisture fluctuationon an Aridisol in northern Iraq. Mesopot. J. Agric. 25(4), 29-49.

Maidment, D.R. 1993. Handbook of Hydrology. McGraw-Hill, N.Y., USA.

Mutchler, C.K. 1963. Runoff plot design and installation for soil erosion studies. Report no. ARS-41-79, US Dept. of Agriculture, Agricultural Research Service.

NIST/SEMATECH (2003) e-Handbook of Statistical Methods. http://www.itl.nist.gov/div 898/handbook/ ,[accessed 4 October 2003].

Shaw, E.M. 1994. Hydrology in Practice, 3rd ed. Chapman & Hall, London, UK.

UNESCO (1998) Summary and recommendations of the International ConferenceOn World Water Resources at the Beginning of the 21st Century, “Water: a looming crisis?” UNESCO, Paris, France.

Walpole, R.E., and R.H. Myers. 1978. Probability and Statistics for Engineers andScientists, 2nd ed., Macmillan Publishing Co., N.Y., USA.

WMO (World Meteorological Organization) (1966) Climate change. Tech. note no. 79, WMO no. 195, TP 200, 1-20. WMO, Geneva, Switzerland.

ADDRESS FOR CORRESPONDENCE
Mohammad H. Hussein
Department of Soil And Water
College of Agriculture,
University of Babylon
Hilla, Iraq

Email: husseinmohammad@yahoo.com