Soil water regimes of loamy sands and sandy loams on arid rangelands in southern New Mexico

Carlton H. Herbel and Robert P. Gibbens

ABSTRACT: The matric potential of soil water is presented for five loamy sand and six sandy loam sites on arid rangelands. Gypsum-impregnated resistance blocks were placed at five soil depths to 91 cm. If caliche was encountered before the 91-cm depth, blocks were placed to that level. The average annual precipitation during the approximate 20-year study period was 237 mm, slightly above the long-term mean. At the 10-cm depth, the probability of soil matric potential ≥ - 1.5 MPa during December-April was 69 % at the 11 sites; 83 % of the probability was ≥ -0.1 MPa. During July-September, the probability of soil matric potential at the 10-cm depth was 53 %; 73 % was > -0.1 MPa. Factors affecting soil matric potential were precipitation amount, surface soil characteristics, topography, subsurface conditions, and season of the year.

AVAILABLE soil water is the major factor responsible for plant growth on arid rangeland. However, few researchers have made field measurements of soil water on arid rangelands.

In one study in central Australia, there were six significant periods of soil water recharge during a 2-year period, followed by withdrawal to an average soil water potential of -12 MPa (*17*). One MPa is the equivalent of 10 bars. Near Tucson, Arizona, the overall relationship between the amount and intensity of rainfall and the periodicity of soil water were minor; however, winter precipitation was more effective than summer precipitation in increasing soil water (*14*).

Comparison of soil water on a grassed drainage area of noncalcareous soil and on a shrubby drainage area of calcareous soil near Tombstone, Arizona, showed that water depletion at the 15-cm depth was more rapid in the grassy area. Water withdrawal from the 45-cm depth was about the same on the two areas (*9*). This indicated greater evapotranspiration from the surface layers in the grassy area.

The effects of precipitation on soil water quantity depend upon such factors as soil texture, structure, etc.; position on the landscape (runoff, runin); amount and intensity of the precipitation event; plant cover; and soil water status at the time of the precipitation event (*8*). Because information on soil water is needed to understand the ecosystems of arid rangelands, we characterized the soil matric potential of five loamy sand and six sandy loam sites on rangelands in southern New Mexico.

Study methods

Our study site was on the Jornada Experimental Range near Las Cruces, New Mexico. Most of the experimental range lies in a closed intermountain basin where topography is level to gently undulating. Average annual precipitation is 228 mm; an average of 129 mm occurs from July through September. Most summer rainfall occurs as highly variable—temporally and spatially—localized, high-intensity thunderstorms. Winter precipitation falls as low-intensity rain and occasionally snow. Spring weather is usually dry and windy. Average annual evaporation from a standard U.S. Weather Bureau pan is 2,273 mm. Average temperatures are 4°C in January and 26°C in July. The frost-free period averages 200 days/year, but the effective growing season, when both temperature and precipitation are favorable to plant growth, normally occurs during brief periods from July through September.

Soil parent materials in the basin floor are sandy sediments of the ancestral Rio Grande, the fluvial facies of the Camp Rice Formation (*3, 15*). Generally, the fluvial sediments have been moved by wind or local water erosion. Sediments of the alluvial piedmonts adjacent to the basin floor were derived from sedimentary rocks in the San Andres Mountains to the east and igneous rocks in the Dona Ana Mountains to the southwest (*11, 12*). Atmospheric additions of calcium carbonate and clay are additional important parent materials (*5*). Ground-

Carlton H. Herbel and Robert P. Gibbens are range scientists, Jornada Experimental Range, Agricultural Reserch Service, U.S. Department of Agriculture, P.O. Box 3JER, New Mexico State University, Las Cruces, 88003. This paper is published in cooperation with the Agricultural Experiment Station, New Mexico State University, Las Cruces 88003, Journal Article No. 1154.

Reprinted from the Journal of Soil and Water Conservation
November-December 1987, Volume 42, Number 6

water occurs at a depth of 90-130 m in basin-filled deposits (*10*). The soil at each study site was described in detail by the same soil scientists that prepared a generalized soil survey of the area (*2*). Horizons of silicate clay and carbonate accumulation are prominent at each study site (*8*). Morphogenetic relationships indicate that these carbonate accumulations are predominantly illuvial in origin (*4*).

Table 1 describes the soils and the dominant plants at the 11 sample sites. Table 2 shows the textural class and soil horizon for various depths at the 11 sites. Site A occurs on a fan-piedmont that is dominated by creosotebush [*Larrea tridentata* (Sesse & Mocino ex. DC) Cov.]. It has a 2% slope and a thin vesicular layer. The vesicular layer at the surface is about 3 mm thick, gravelly, silty, and platy. This site lost about 10 cm of the A horizon due to increased erosion as it changed vegetation dominants from black grama [*Bouteloua eriopoda* (Torr.) Torr.] to creosotebush in the 1930s (*1*). This site contributes some water to the adjacent basin floor.

Sites B-K are level to gently rolling. Water movement following high-intensity rainfall is localized because the landscape is level or nearly level, and there is no runin. Sites B-E and G-I, dominated by mesa dropseed [*Sporobolus flexuousus* (Thurb.) Rydb.], had a good cover of black grama prior to the severe drought of 1951-1956 (*7*). Vegetation at Sites J and K was less affected by that drought. Site F has 2-m-high sand dunes covered with honey mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*). Honey mesquite began to dominate the area about 1900 (*1*) when some of the surface soil began to collect within the mesquite plants and form sand dunes. Measurements of soil matric potential were taken in an interdune area.

At each of the 11 locations, we placed gypsum-impregnated electrical resistance blocks at depths of 10, 25, 41, 61, and 91 cm or at the accumulation of caliche (calcium carbonate) if that occurred nearer the surface. The deepest measurements were recorded at 91 cm on sites A, B, C, D, G, H, and I; 81 cm at site E; 61 cm at site F; and 41 cm at sites J and K. We located the sampling sites within livestock exclosures. An ohmmeter recorded resistance measurements one to three times weekly when the matric potential was ≥ -1.5MPa during the summer. Measurements were recorded monthly during the remainder of the year when there were fewer changes in soil water status. We calibrated blocks in light-textured soils by determining their resistance at different pressures in a pressure plate extractor (*16*). We used only blocks with similar response curves. We replaced blocks during the study period if readings were inconsistent with other blocks at that location.

We placed thermistors at several depths at four locations to record temperatures at the same time as soil matric potentials. We corrected all resistance readings to 15.6°C. We measured precipitation at each study site with a standard U.S. Weather Bureau rain gauge modified to reduce evaporation (*6*). Precipitation is reported in terms of a crop-year, or October 1 of the preceeding year to September 30 of the year identified. For example, crop year 1961 is October 1, 1960, through September 30, 1961.

The principal forces that contribute to soil water potential are matric potential and osmotic characteristics of the soil solution (*13*). Unpublished tests by Herbel showed that the soils at the 11 study sites were nonsaline. Herein, we assumed the soil water potential to be due to the soil matric potential. We translated each resistance reading to MPa. For days when the resistance was not measured, we determined matric potential by (a) previous determinations of matric potential at that depth, (b) current precipitation, (c) matric potential at other depths at that location, and (d) previous precipitation events at that location. We grouped all the daily determinations into matric potentials of 0 to -0.1 MPa, -0.1 to -1.5 MPa, and > -1.5 MPa. Herein, we discuss soil matric potential ≥ -1.5 MPa and the percentage of matric potentials ≥ -1.5 MPa that is ≥ -0.1 MPa.

Resource availability dictated the establishment of sampling sites. We installed blocks at the 10-, 25-, and 41-cm depths at sites B-I in July 1957; at site A in July 1958; at site J in September 1960; and site K in August 1964. We installed the resistance blocks at the 61-cm and deeper depths (depending upon the soil) during July 1959. Resistance readings were terminated on December 31, 1973, at Site G and December 31, 1976, at the other sites. We did not obtain readings from August 1 through December 31, 1972, because of meter failure.

We used correlation and regression techniques to examine relationships between

Table 1. Soils and dominant vegetation at 11 sites on the Jornada Experimental Range.

Site	*Soil Classification*	*Soil Series*	*Dominant Vegetation*
A	Typic Torriorthent, coarse-loamy, mixed, thermic	Canutio	Creosotebush
B	Typic Haplargid, fine-loamy, mixed, thermic	Bucklebar	Mesa dropseed
C	Typic Haplargid, coarse-loamy, mixed, thermic	Onite	Mesa dropseed
D	Typic Haplargid, coarse-loamy, mixed, thermic	Onite	Mesa dropseed
E	Typic Haplargid, fine-loamy, mixed, thermic	Berino	Mesa dropseed
F	Typic Haplargid, fine-loamy, mixed, thermic	Berino	Mesquite
G	Typic Calciorthid, coarse-loamy, mixed, thermic	Wink	Mesa dropseed
H	Petrocalcic Paleargid, fine-loamy, mixed, thermic, shallow	Cruces	Mesa dropseed
I	Petrocalcic Paleargid, fine-loamy, mixed, thermic	Cacique	Mesa dropseed
J	Typic Paleorthid, coarse-loamy, mixed, thermic, shallow	Simona	Black grama
K	Typic Paleorthid, coarse-loamy, mixed, thermic, shallow	Simona	Black grama

Table 2. Texture (horizon) of soils at the study depths on 11 sites, Jornada Experimental Range.

	*Texture by Depth**				
Site	*10 cm*	*25 cm*	*41 cm*	*61 cm*	*91 cm*
A	gr sa lo (B_2)	gr sa lo (B_2)	gr sa lo (C_1ca)	gr sa lo (C_1ca)	gr cl lo (II B_2t)
B	sa lo (B_1)	cl lo (B_2t)	cl lo (B_2t)	cl lo (C_1ca)	cl lo (C_1ca)
C	lo fi sa (A_{12})	lo fi sa (A_{12})	sa lo (B_{21}t)	sa lo (B_{22}t)	lo sa (C_1ca)
D	lo fi sa (A_1)	fi sa lo (B_1)	sa cl lo (B_2t)	sa cl lo (B_3ca)	sa cl lo (Cca)
E	sa lo (A_1)	sa cl lo (B_{21}t)	sa cl lo (B_{22}t)	sa cl lo (B_{22}t)	sa cl lo (B_3ca)†
F	sa lo (A_1)	sa cl lo (B_{21}t)	sa cl lo (B_{22}t)	sa cl lo (B_{22}t)	
G	lo sa (A+)	sa lo (A_1)	sa lo (B_2)	sa lo (C_1ca)	sa cl lo (C_2ca)
H	sa lo (B_{21}t)	sa lo (B_{21}t)	sa lo (B_{22}t)	ca (Ccam)	ca (Ccam)
I	lo sa (A+)	sa lo (A_1)	sa cl lo (B_{21}t)	sa cl lo (B_3ca)	ca (Ccam)
J	sa lo (B_{21})	co sa lo (Cca)	ca (Ccam)		
K	sa lo (B_{21})	co sa lo (Cca)	ca (Ccam)		

*Abbreviations used in describing soil textures: ca = caliche, cl = clay, co = cobbly, gr = gravelly, lo = loam or loamy, sa = sand or sandy, si = silt or silty.
†81-cm soil depth.

precipitation and soil matric potentials. Graphs of daily precipitation and matric potentials were prepared for visual interpretation. We examined soil matric potential during the following periods: (a) October and November typify fall when it is too cool for warm-season plants to grow but when cool-season annual plants germinate if the surface soil is wet, (b) December through April are wintry months when cool-season plants grow if soil water is available, (c) May and June are often quite dry but plants will grow if there is soil water. We examined July, August, and September individually because precipitation more likely occurs during those months than other months and because soil water during those months dissipates rapidly. We calculated probabilities by determining the percentage of days in each month at each location that had matric potentials (a) ≥ -0.1 MPa, (b) between -0.1 and -1.5 MPa, and (c) < -1.5 MPa, then averaged these percentages for the entire study period. For the probability of matric potential ≥ -1.5 MPa, we combined b and c.

Results and discussion

The average July-September precipitation for the 11 sites was 143 mm. The average crop-year precipitation for the study period was 237 mm (Table 3). Correlations between precipitation and matric potentials at the various locations were low (r ≤ 0.25). Thus, we averaged precipitation measurements for the 11 sites (Table 3).

Analysis of daily precipitation and matric potential revealed that when the matric potential was < -1.5 MPa it took at least 13 mm precipitation in a single day to change the matric potential at the 10-cm depth to ≥ -1.5 MPa. At Site G, for example, the average number of events of ≥ 13 mm daily precipitation during the study period were 1.1 each month for July through September, 0.4 each for June and October, 0.2 each for November and December, and 0.1 each month for January through May. Thus, there were an average of five events per year that could change the soil matric potential from < -1.5 MPa to ≥ -1.5 MPa at the 10-cm depth.

We also examined an array of precipitation values when daily amounts < 13 mm were omitted. For example, the precipitation for July through September ranged from 0 to 232 mm and 15 to 164 mm for the remainder of the year over the study period at site B. Correlations between precipitation and matric potentials were still low (r ≤ 0.30 when daily amounts < 13 mm were omitted.

Soil matric potentials. Site A. There was a lower probability of soil matric potential

Table 3. Average monthly precipitation for the 1957-1976 study period at 11 sites, Jornada Experimental Range.

Month	Precipitation (mm)
October	21
November	10
December	15
January	11
February	7
March	8
April	4
May	4
June	14
July	50
August	50
September	43
Total	237

≥ -1.5 MPa at site A than at the other sites, particularly during the summer when rainfall was more intense than other times of the year. Figure 1 shows the monthly probabilities of the matric potential ≥ -1.5 MPa for all study depths at sites A-F. The annual probability for the soil matric potential ≥ -1.5 MPa for site A ranged from an average of 42% at the 10-cm depth to 8% at the 91-cm depth. The probabilities of the matric potential ≥ -1.5 MPa were highest from October through March in the B_2 horizon at the 10-cm depth, with decreasing probabilities to the 91-cm depth. During this 6-month period, highest probabilities occurred at the 10- and 25-cm depths, and probabilities were higher in the C_1ca horizon at the 41- and 61-cm depths than in the IIB_2t horizon at 91 cm. The highest probabilities for the year occurred in January-February at depths of 10, 25, and 41 cm. In April-June, there was a drying trend with the shallower depths drying out the earliest. During the summer, when average precipitation is the highest, the probability of the matric potential ≥ -1.5 MPa at the 10-cm depth was 43%, with considerably lower probabilities at deeper soil depths. This indicates that summer rainfall increased the soil matric potential primarily at the shallower depths.

Site B. The annual probability of the soil matric potential ≥ -1.5 MPa on the Haplargid at site B averaged 49, 38, 30, 19, and 12% respectively, for the five soil depths where matric potentials were determined. Probabilities of the matric potential ≥ -1.5 MPa at a depth of 10 cm in the B_1 horizon were greatest in January and February (Figure 1). At the 25-cm depth, the probability was above 60% for January-March. The highest period at the 41- and 61-cm depths was February-April. During April and May, the probability of matric potential ≥ -1.5 MPa was greater in the B_2t horizon at the 41-cm depth than at the other depths. During July-September the probability of the matric potential ≥ -1.5 MPa at the 10-cm depth was 53%, which was higher than the other depths. In the C_1ca horizon at the 91-cm depth, the average for July-September was 8%.

Site C. The probability of the soil matric potential ≥ -1.5 MPa was 78% during December-April and 57% during July-September in the A_{12} horizon at the 10-cm depth. In the C_1ca horizon at the 91-cm depth, it was 23% and 9%, respectively. The highest probabilities for each month occurred at the 10-cm depth, except during April when the 25-cm depth had a higher probabilty than the 10-cm depth and during May when all depths had a higher probability of matric potential ≥ -1.5 MPa than the 10-cm depth (Figure 1).

Site D. The annual probability of the matric potential ≥ -1.5 MPa in the A_1 horizon at the 10-cm depth was 48%, 50% in the B_1 horizon at the 25-cm depth, 36% in the B_2t horizon at the 41-cm depth, 25% in the B_3ca horizon at the 61-cm depth, and 12% in the Cca horizon at the 91-cm depth. We observed the highest monthly probabilities at the 10-cm depth in November, January, August, and September. The probability was highest at the 25-cm depth during December and March-June and similar at the two depths in October, February, and July. During May and June, the probability of the matric potential ≥ -1.5 MPa was lower at the 10-cm depth than the other depths (Figure 1).

Site E. In the A_1 horizon at the 10-cm depth, the probability of the matric potential ≥ -1.5 MPa was 69% for December-April and 54% for July-September. It was 29 and 22%, respectively, at the 81-cm depth in the B_3ca horizon. We observed the highest monthly probabilities at the 10-cm depth, except for the April-June period when the surface soil was drying (Figure 1).

Site F. The annual probability of the matric potential ≥ -1.5 MPa was 51, 50, 54 and 48% for the 10-, 25-, 41-, and 61-cm depths, respectively, for the interdune area at site F. It was 70% during December-April and 48% during July-September in the A_1 horizon at the 10-cm depth. The monthly probabilities of matric potential were more similar among depths than at other locations within the Typic Haplargids (Figure 1).

Site G. The probability of the matric potential ≥ -1.5 MPa was 66% in the A+ horizon at the 10-cm depth and 70% in the A_1 horizon at the 25-cm depth in this Typic Calciorthid during December-April. During April, it was 57% and 68% for the 10- and 25-cm depths, respectively (Figure 2). During July-September the probabilities for the two depths were 49% and 34%, respectively.

Site H. The probabilities of the matric potential ≥ -1.5 MPa were similar for the 10- and 25-cm depths during October-March in this Petrocalcic Paleargid (Figure 1). During April, the probability was 16% higher at 25 cm, but similar to other depths during May-September. The probabilities were similar at the 61- and 91-cm depths during October-February, June, July, and September. The probabilities at the 41-cm depth were intermediate to the 10- and 25-cm depths and the 61- and 91-cm depths, except for April when it was similar to the 25-cm depth, May when it was similar to the 61- and 91-cm depths, and June when it was similar to the 25-, 61-, and 91-cm depths.

Site I. The probability of the matric potential ≥ -1.5 MPa was 84, 86, 76, 69, and 53% for the 10-, 25-, 41-, 61-, and 91-cm depths, respectively, during December-April. It was 62, 55, 48, 41, and 31% for those depths, respectively, during July-September. The annual average probability of the matric potential ≥1.5MPa was higher for this Petrocalcic Paleargid site at all depths than at all other sites (Figure 1).

Site J. The probability of the matric potential ≥ -1.5 MPa in this shallow soil was 70, 73, and 64% for the B_{21}, Cca and Ccam horizons at the 10-, 25-, and 41-cm depths, respectively, during December-April. During July-September, it was 59, 47, and 37% at those depths, respectively. The highest probabilities occurred at the 10-cm depth during October, November, and July-September (Figure 1). The probabilities at the 10- and 25-cm depths were similar during December-March, while they were similar at the 25- and 41-cm depths during April-June.

Site K. At the 10-, 25-, and 41-cm depths, with the same textures and horizons as at site J, the probabilities of matric potential ≥ 1.5 MPa during December-April were lower than at site J; 66, 54, and 47%, respectively. At the above depths, probabilities were 54, 40, and 34%, respectively, for July-September. The highest probabilities of matric potential ≥ -1.5 MPa were at the 10-cm depth every month except February, March, and May when highest probabilities occurred at a depth of 25 cm (Figure 2). All of the probabilities at the 25-cm depth were higher at site J than site K.

Soil matric potential > -0.1 MPa. Table 4 shows the percentage of soil matric potential ≥ -1.5 MPa that is ≥ -0.1 MPa. A fairly high percentage of the matric potential ≥ -1.5 MPa was between -0.1 MPa and 0 at all depths during October-April. During May and June when the soil was generally in a drying trend, more of the matric potential was between -1.5 MPa and -0.1 MPa. During the summer months, most of the soil

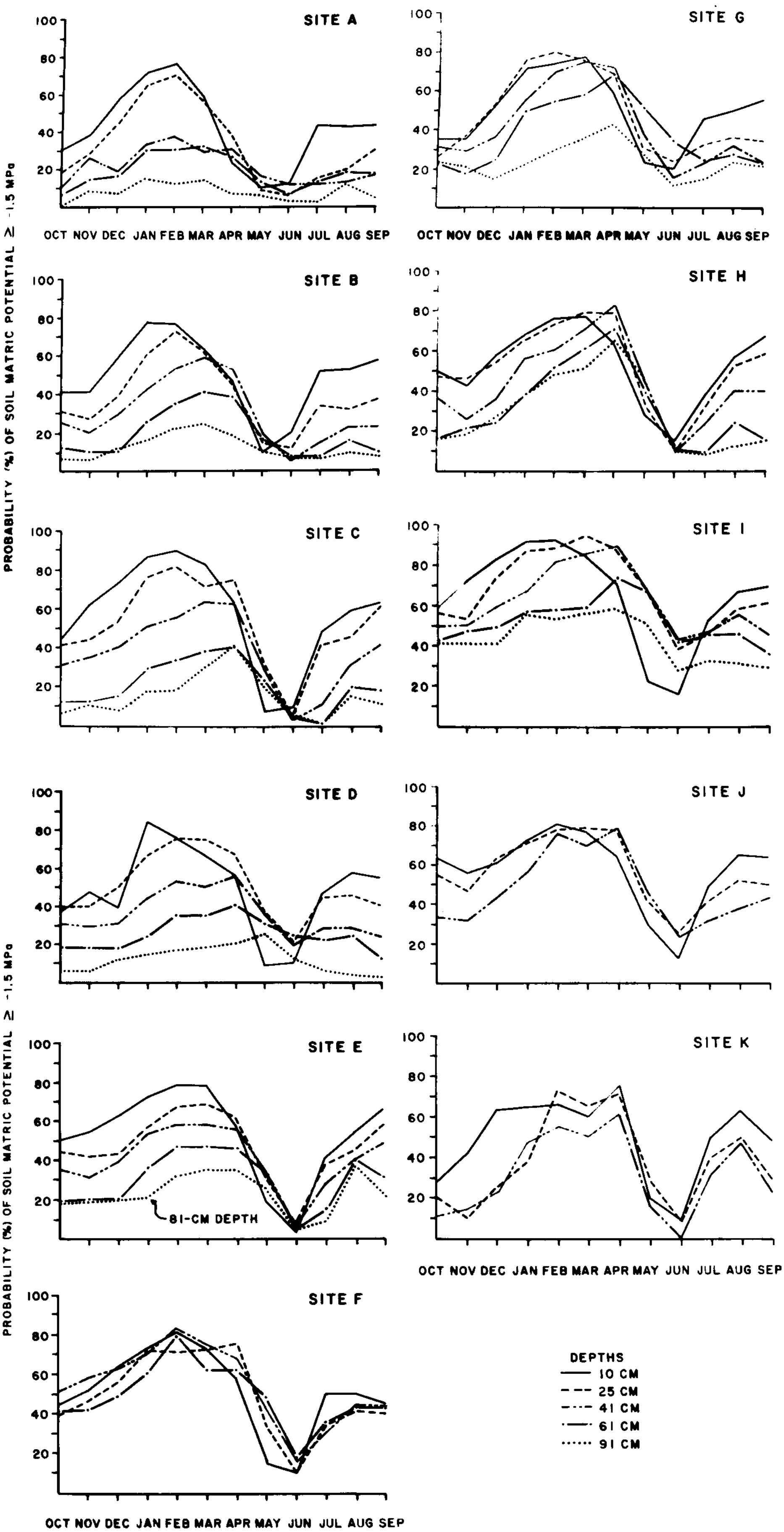

Figure 1. Monthly probability (%) of the matric potential ≥ -1.5 MPa for sites A-K.

matric potential at the shallower depths was ≥ -0.1 MPa. At the 91-cm depth, most of the matric potential ≥ -1.5 MPa was between -1.5 MPa and -0.1 MPa.

Variability among years. Figure 2 shows the percentage of days with soil matric potential ≥ -1.5 MPa and precipitation for 4 crop years at site C. These data are typical of those obtained at other locations and illustrate the variability among years.

Precipitation during crop year 1962 totaled 330 mm (average = 228 mm). Precipitation during this year may be characterized as a wet fall, dry winter and spring, and a wet summer. The precipitation during October and November was 46 mm (average = 35 mm); December-April, 28 mm (average = 45 mm); May and June, 5 mm (average = 19 mm); July, 122 mm (average = 46 mm); August, 54 mm (average = 50 mm); and September, 75 mm (average = 33 mm). Probabilities of soil matric potential ≥ -1.5 MPa were above average in October and November at the 10- to 61-cm depths, in December-April at all depths, in May-June at the 10- to 41-cm depths, and in August at the 10- to 61-cm depths (Figure 2).

Table 4. The average probabilities of soil water matric potential ≥ -0.1 MPa as a percentage of matric potential ≥ -1.5 MPa for 11 sites, Jornada Experimental Range.

Depth (cm)	October-November	December-April	May-June	July	August	September
			%			
10	76	83	44	77	69	73
25	73	81	44	65	65	63
41	70	81	41	56	55	62
61	63	75	46	49	53	54
91	72	72	44	30	21	27

Total precipitation in crop year 1964 was 157 mm. This may be classified as a droughty year, but the fall and summer had 79% and 86% of average precipitation, respectively, whereas the winter and spring had 33% and 53% of average precipitation, respectively. Soil matric potential ≥ -1.5 MPa was above average during October and November only at the 10-cm depth, very low during December-April, and none in May-June (Figure 2). In July and August, matric potential ≥ -1.5 MPa was above average only at the 10- and 25-cm depths. In September, it was above average at the 10-cm and 25-cm depths. There was no matric potential ≥ -1.5 MPa for the entire year at the 61- and 91-cm depths.

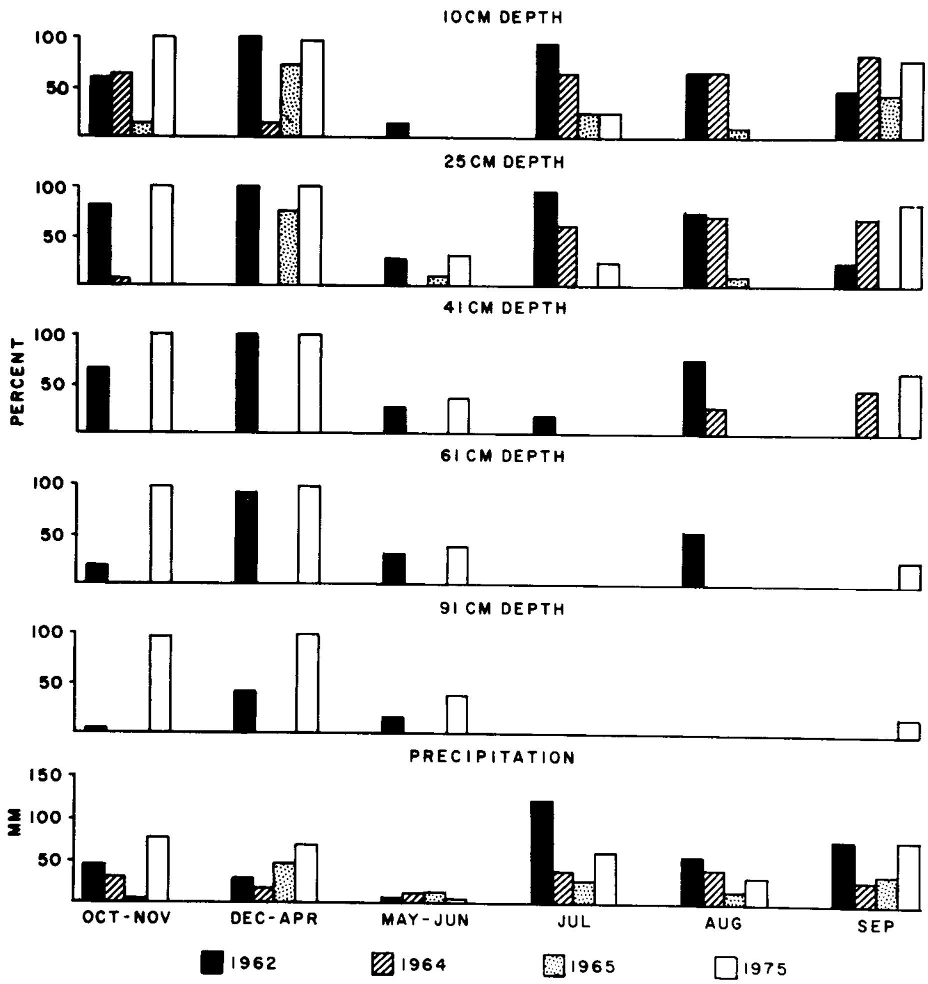

Figure 2. Percentage of days with soil matric potential ≥ -1.5 MPa and precipitation (mm) for 4 crop years at Site C.

Total precipitation for crop year 1965 was 141 mm. This was a droughty year, but December-April and September precipitation was above average. The only above-average soil matric potential ≥ -1.5 MPa occurred at the 10- and 25-cm depths during the winter. The matric potential ≥ -1.5 MPa was below average at the other soil depths and/or periods (Figure 2).

Precipitation during crop year 1975 was 314 mm. Above-average precipitation occurred during October-April, July, and September (Figure 2). Soil matric potential ≥ -1.5 MPa was considerably above average at all depths during October-April. There was a carryover of soil water at the 25- through 91-cm depths during May and June. Soil matric potential ≥ -1.5 MPa was considerably below average in July and August at all depths, while it was above average in September.

Management implications

At all sites the probability of soil matric potential ≥ -1.5 MPa was greater in winter than during other seasons of the year. The winter moisture lasted until April in most years, particularly at depths below 10 cm. Thus, in years favorable for the germination of winter annuals, these plants can develop and provide green forage in early spring when nutrients for animals are in short supply.

The dry winds of spring remove some of the soil water by evaporation; plant transpiration removes the remainder. This means that the growth of the warm-season annuals and perennial grasses and forbs, which supply most of the forage, depends largely upon soil water supplied by summer rainfall. Our study showed that daily precipitation < 13 mm did not contribute to soil water depths > 10 cm. Also, correlations between precipitation, either amounts > 0 or > 13 mm, and soil matric potentials were low, indicating that precipitation alone is not a good predictor of the water available to plants. It is the high variability and unpredictibility of both rainfall and soil water that makes management of desert rangelands difficult.

Sites J and K had soil matric potential probabilities similar to other sites, but the shallowness of the soil to indurated caliche in these Paleorthids resulted in less drought damage to the vegetation during the severe drought of the 1950s than at sites B-E and G-I (*7*). These shallow soil sites should be managed as reserve forage sites whenever possible.

The type of vegetation, grasses, or shrubs did not appear to influence soil matric potentials. However, there is ample evidence from the steady encroachment of shrubs onto former grasslands (*1*) that shrubs can use the limited soil water supplies better than grasses. Thus, shrub suppression is an essential component of management.

The extreme variability in soil water, both within and between seasons, results in a highly variable forage resource. Such variability can only be accommodated by highly flexible management strategies.

REFERENCES CITED

1. Buffington, L. C., and C. H. Herbel. 1965. *Vegetational changes on a semidesert grassland range from 1858 to 1963*. Ecol. Monogr. 35:139-164.
2. Bulloch, H. E., Jr., and R. E. Neher. 1980. *Soil survey of Dona Ana County area of New Mexico*. Soil Cons. Serv., Washington, D.C. 177 pp.
3. El Paso Geological Society. 1970. *Cenozoic stratigraphy of the Rio Grande Valley area of Dona Ana County, New Mexico*. Dept. Geol., Univ. Tex., El Paso, 49 pp.
4. Gile, L. H., F. F. Peterson and R. B. Grossman. 1966. *Morphological and genetic sequence of carbonate accumulation in desert soils*. Soil Sci. 101:347-360.
5. Gile, L. H., J. W. Hawley, and R. B. Grossman. 1970. *Distribution and genesis of soils and geomorphic surfaces in a region of southern New Mexico*. Guidebook, Soil-Geomorph. Field Conf. Soil Sci. Soc. Am., Las Cruces, N. Mex.
6. Gomm, F. B. 1961. *A modification of the standard Weather Bureau rain gauge for summer and winter use*. Bull., Am. Meteorol. Soc. 42:311-313.
7. Herbel, C. H., F. N. Ares, and R. A. Wright. 1972. *Drought effects on a semidesert range*. Ecology 53:1084-1093.
8. Herbel, C. H., and L. H. Gile. 1973. *Field moisture regimes and morphology of some arid-land soils in New Mexico. In Field Soil Water Regime*. Soil Sci. Soc. Am., Madison, Wisc. pp. 119-152.
9. Kincaid, D. R., J. L. Gardner, and H. A. Schreiber. 1964. *Soil and vegetation parameters affecting infiltration under semiarid conditions*. In *Land Erosion, Precipitation, Hydrometry, Soil Moisture*. Publ. 65. Int. Assoc. Sci. Hydrol., pp. 440-453.
10. King, W. E., J. W. Hawley, A. M. Taylor, and R.P. Wilson. 1971. *Geology and ground water resources of central and western Dona Ana County, New Mexico*. Hydrol. Rpt. 1. N. Mex. Bur. Mines, Mineral Resources, Las Cruces. 64 pp.
11. Kottlowski, F. E. 1960. *Reconnaissance geologic map of Las Cruces 30-minute quadrangle*. Geol. Map 14. N. Mex. Bur. Mines, Mineral Resources, Las Cruces.
12. Kottlowski, F. E., R. H. Flower, M. L. Thompson, and R. W. Foster. 1956. *Statigraphic studies of the San Andres Mountains, New Mexico*. Memoir I. N. Mex. Bur. Mines, Mineral Resources, Las Cruces. 132 pp.
13. Kramer, P. J. 1983. *Water relations of plants*. Academic Press, New York, N.Y. 489 pp.
14. Shreve, F. 1934. *Rainfall, runoff and soil moisture under desert conditions*. Ann., Assoc. Am. Geogr. 24:131-156.
15. Strain, W. S. 1966. *Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas*. Bull. 10. Texas Memorial Museum, Austin. 55 pp.
16. Taylor, S. A., D. D. Evans, and W. D. Kemper. 1961. *Evaluating soil water*. Bull. 426. Utah Agr. Exp. Sta., Logan. 67pp.
17. Winkworth, R. E. 1970. *The water regime of an arid grassland* (Eragrostis eriopoda *Benth.) community in central Australia*. Agr. Meteorol. 7:387-399. □