WATER RESOURCES BULLETIN
VOL. 29, NO. 3 AMERICAN WATER RESOURCES ASSOCIATION JUNE 1993

MODELING WATER BALANCE WITH THE ERHYM MODEL ON SOUTH TEXAS RANGELANDS[1]

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ABSTRACT: Understanding the hydrologic processes of rangeland plant communities is essential to determine if water augmentation through shrub management is feasible. Vegetation manipulation studies are costly, difficult to accurately replicate, and often require more than 10 years to determine treatment effect on the water budget. If properly applied, hydrologic simulation models are an attractive alternative for assessing vegetation manipulation practices. The ERHYM-II model was evaluated to determine if it was capable of simulating the water balance for honey mesquite shrub clusters, grass interspaces, and bare soil in south Texas. The simulated water budget was within 2 percent of the measured evapotranspiration for the shrub clusters and grass interspaces. The model underestimated the number of runoff events and overestimated runoff volume for the grass interspace and shrub clusters. Simulated runoff was overestimated by approximately twofold for the grass interspace and threefold for the shrub clusters. Although simulated runoff was substantially overestimated, observed and simulated runoff only accounted for 3 to 6 percent of annual rainfall for the grass and shrub dominated areas, respectively. Simulated evapotranspiration was underestimated by 18 percent and soil water content was overestimated by 82 percent for the bare soil. The model underestimated evapotranspiration for the bare soil as a result of restricting evaporative losses to the first soil layer. Based on our analysis, the ERHYM-II model has the potential for simulating the annual water balance for semiarid rangeland plant communities where runoff and deep drainage are limited components of the water balance.
(KEY TERMS: runoff; soil water content; drainage; leaf area index; curve number.)

INTRODUCTION

The majority of Texas' rangelands (40 million ha) are classified as arid or semiarid, generally characterized by precipitation being less than potential evapotranspiration. Under these conditions, water availability is the most important environmental factor controlling plant growth and survival (Brown, 1977). It has been estimated for western rangelands that evapotranspiration accounts for as much as 96 percent (Branson *et al.*, 1981; Lane *et al.*, 1984; Carlson *et al.*, 1990) and surface runoff accounts for less than 5 percent of annual precipitation (Gifford, 1975; Lauenroth and Sims, 1976; Wight and Neff, 1983; Carlson *et al.*, 1990).

The Texas Department of Water Resources (1984) has projected a major water shortage for the state by the year 2030. One alternative proposed to help alleviate this deficit is a comprehensive vegetation manipulation program (Rechenthin and Smith, 1964). The hypothesis is that deep-rooted woody plants have higher evapotranspiration rates than do herbaceous plants. By replacing woody plants with herbaceous plants, a substantial quantity of water would be made available as stream flow, recharge to aquifers, and additional water on-site for increased forage production.

Hydrologic response to management activities varies depending on vegetation type, percent canopy and ground cover, type of treatment, soils, and climate. Bosch and Hewlett (1982), who reviewed 94 watershed type conversions from around the world, estimated that a 10 percent decrease in shrub cover on scrub woodlands would result in water yield increase of 10 mm for areas with annual rainfall in excess of 400 mm. In Arizona, Hibbert (1983) estimated 6 mm of additional water yield could be expected for each additional 25 mm above a threshold of 384 mm precipitation after removal of woody species. A study of pinyon-juniper removal by Collings and Myrick (1966) found no significant change in water yield. Clary *et al.* (1974) reported that the possibility of increasing water yield through removal of pinyon-

[1]Paper No. 91135 of the *Water Resources Bulletin*. **Discussions are open until February 1, 1994.**
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juniper overstory was marginal. In the Edwards Plateau region of Texas, removal of oaks by root plowing decreased annual surface runoff by 32 percent over a five-year period (Richardson *et al.*, 1979). In the Blackland Prairie region of Texas, killing of mesquite trees with diesel oil increased surface runoff by 10 percent (Richardson *et al.*, 1979). No change in the water balance is expected where herbaceous vegetation increases as a result of removal of honey mesquite trees in the Rolling Plains of Texas (Carlson *et al.*, 1990; Dugas and Meyeux, 1991). There is a need for additional studies to quantify the relationships between plant community types and hydrologic response before water supply forecasts and economic analysis of shrub management can be assessed (Griffin and McCarl, 1989).

Hydrological research is expensive and time consuming. Vegetation manipulation studies often require more than 10 years to determine the treatment effect (Baker, 1984; Osborn and Simanton, 1990; Woolhiser *et al.*, 1990a). Use of hydrologic simulation models to simulate the response of vegetation to alternative management decisions has been receiving increased attention in the last decade (Wilcox *et al.*, 1990; Woolhiser *et al.*, 1990a; Osborn and Simanton, 1990). Simulation models, when properly calibrated, provide an inexpensive and rapid method of evaluating vegetation manipulation practices. Most of the hydrologic simulation models that have been used on rangelands were developed for use on croplands. Only in the last decade have hydrologic simulation models such as SPUR (Simulation of Production and Utilization of Rangelands (Wight and Skiles, 1987) and the ERHYM-II model (Ekalaka Rangeland Hydrology and Yield Model (Wight, 1987) been developed specifically for application on rangelands.

The objective of this research was to evaluate the ERHYM-II model for simulating the water budgets of honey mesquite-dominated shrub clusters, grass-dominated interspaces, and bare soil in south Texas.

ERHYM-II MODEL DESCRIPTION

ERHYM-II is a climatically-driven water balance model which functions on the plant community level. For any given time period and ignoring run on and subsurface lateral flow, the one-dimensional water balance equation to the depth of the root zone can be written as:

$$W = PPT - Q - ET - D \tag{1}$$

where W = stored soil water or moisture (mm), PPT = total precipitation (mm), Q = net runoff (mm), ET = evapotranspiration (mm), and D = drainage (mm) below the root zone. Equation (1) shows that all components of the water balance are interrelated and a function of precipitation.

The ERHYM-II model can be parameterized to represent both perennial and annual plant communities. The model simulates evaporation, transpiration, runoff, and soil water routing on a daily time step. The ERHYM-II model can utilize either long-term weather records or simulate the necessary daily air temperature and solar radiation data. Daily precipitation values must be supplied by the user.

Evapotranspiration is simulated as a function of a crop coefficient (Kc), such that

$$Kc = ET / ET_h \tag{2}$$

where ET is the observed evapotranspiration (mm) with water nonlimiting. ET_h is estimated potential evapotranspiration (mm) calculated from the Jensen-Haise (1963) equation. The Kc accounts for the reduction in potential ET_h on arid and semiarid rangelands where water is limiting for plant growth. Potential evapotranspiration for rangelands (ET_r) is simulated as:

$$ET_r = ET_h \bullet Kc \tag{3}$$

Potential transpiration (Tp) is a function of the relative growth curve (RGC), transpiration coefficient (Tc) and potential ETR, and is expressed as:

$$Tp = Tc * RGC * ET_r \tag{4}$$

The unitless Tc coefficient is based on the work of Ritchie and Burnett (1971) for cotton and grain sorghum. Wight (1987) proposed that for rangelands TC could be calculated as:

$$Tc = 0.0213 + 0.0162(Y / 1.1234)^{0.5} \tag{5}$$

where Y is average above-ground biomass production (kg/ha). The RGC is used to indicate seasonal changes in standing live phytomass. The RGC is calculated with a modified Poisson density function (Wight *et al.*, 1986) as:

$$RGC = [(x-b)/(a-b)]^c \; e \; (c/d \; (1.0-[(x-b)/(a-b)]^d)) \tag{6}$$

where RGC = seasonal growth expressed as a decimal fraction of 1.0, a = Julian day peak standing crop occurs, b = Julian day growth begins, c = unitless shape parameter for left side of curve, d = unitless shape parameter for right side of curve, and x = current Julian day.

Accurate estimates of root density as a function of depth is critical for determination of transpiration. Transpiration is simulated as:

$$Ts = \sum_{i=1}^{n} Tp_i [Wa_i / Wp_i * ROOT_i * TEMP_i] \quad (7)$$

where Ts = estimated transpiration (mm), Tp = potential transpiration (mm), Wa = available soil water (mm), Wp = potentially available soil water (mm) at field capacity, ROOT = the root density expressed as a decimal fraction of 1.0, TEMP = the soil temperature (C), i = the soil layer, and n = the number of soil layers.

Root density is expressed as the percentage of roots in each soil layer in relationship to the surface layer. Root density is a means of restricting water uptake from each soil layer. Soil water extraction through transpiration proceeds one layer at a time, beginning with the surface layer. If the surface layer cannot supply the full potential ET, then the model extracts water from the second layer, and so on, until the full potential ET_r has been satisfied or until all soil layers have been sampled. Soil layers can be initialized to 0 to prevent transpiration.

Soil water evaporation (mm) is simulated as a function of potential soil water evaporation (mm) and time since the last rainfall. Soil water evaporation is limited to the surface 300 mm of the soil profile. Soil water evaporation (E) is simulated as:

$$E = Ep / t^{0.5} \quad (8)$$

where t is time in days since a precipitation event was at least 1.5 times potential soil water evaporation. Potential soil water evaporation (Ep) is simulated as:

$$Ep = ET_r - Tp \,. \quad (9)$$

ERHYM-II uses a modified curve number (CN) technology to estimate runoff. The curve number equation to predict runoff is commonly expressed as:

$$Q = (PPT - 0.2S)^2/(PPT + 0.8S) \; for\ all\ PPT > 0.2S \quad (10)$$

where Q and PPT are as defined previously and S is the potential maximum retention (mm) (SCS, 1985). The retention parameter S is a function of soil water content and is expressed as:

$$S = S_{mx} [(UL - S_m) / UL] \quad (11)$$

where S_m is stored soil water content (mm) in the root zone, UL is the upper limit of soil water storage (mm), S_{mx} is the maximum value of S (mm). The maximum S value is calculated for dry soil moisture conditions as:

$$S_{mx} = (1000 / CN_I) - 10 \quad (12)$$

where CN_I is the antecedent moisture class I CN.

Drainage is calculated as the residual of the water balance. After al soil layers are filled to field capacity and runoff and ET have been satisfied, any excess water is routed out of the soil profile as deep drainage. The model does not account for the redistribution of water in the soil profile by unsaturated flow.

STUDY AREA AND CLIMATE

The research area is located in Jim Wells County, approximately 20 km south of Alice, Texas, on the Texas Agricultural Experiment Station La Copita Research Area. Mean elevation of the 1,093 ha research area is 76 m above sea level. Normal precipitation is 704 mm, of which 493 mm (70 percent) usually falls from April through September. Annual snowfall is less than 5 mm. The heaviest one-day recorded rainfall during the past 35 years was 338 mm (Minzenmayer, 1979; Orton, 1969). Mean annual temperature is 22.4°C and the mean frost-free period is 289 days (Minzenmayer, 1979).

The research site is located on a soil closely resembling a Miguel fine sandy loam, and is classified as a fine sandy loam range site. The Miguel soil series is classified as a fine, mixed, hyperthermic, Udic Paleustalf. The Miguel soil series is in hydrologic group D. Potential plant community is an open grassland with 90 percent of the area comprised of grasses and 10 percent comprised of forbs and woody shrubs. Presently, the landscape is comprised of a matrix of shrub clusters and grassland interspaces. The shrub clusters range in size and complexity from single honey mesquite (Prosopis glandulosa var *glandulosa*) trees with an average canopy of 1.7 m^2 to dense shrub clusters with up to 15 woody species and an average canopy area of 56 m^2.

METHODS

Six dense shrub clusters and three grass-dominated interspaces were encircled within nonweighing lysimeters in the summer of 1984. The nonweighing lysimeters were constructed by trenching around the perimeter of the treatment area to a depth of 2.5 m. The inside wall of the trench was double lined with an impervious plastic and the trenches were back filled. Each lysimeter was approximately 5 m by 7 m long with the long axis parallel to the slope. Three of the shrub clusters were cleared by hand slashing and the debris removed (hereafter referred to as "bare soil"). The area was sterilized with tebuthiuron N-(5-(1,1-dimethylethyl)-1,3,4-thiadiazonal-2-yl))-N,N'-dimethylurea(0.75 kg ai/ha) to kill and prevent regrowth of herbaceous and woody vegetation. The remaining shrub clusters were left undisturbed.

Fiberglass sheets, 30 cm tall, were used to form the sides and upper end of each lysimeter. The fiberglass sheets were glued to the plastic lining and inserted 10 cm into the soil creating a 20 cm high border. A flume was constructed on the downslope side to measure surface runoff. Four neutron access tubes, each 2 m in length were placed in the lysimeters. Soil water content was monitored with a moisture depth gauge about once every two weeks. Water content was measured at 7.5, 15, 30, 60, 90, 120, 150, and 180 cm. For this study, the rooting depth of the soil profile was defined as 120 cm. Root density for the bare soil lysimeters was initialized to 0 for all soil layers to prevent transpiration. The water added to the soil below 120 cm was considered as drainage. The soil water content at the beginning of the year were used to initialize the model.

Ten 0.5 by 0.5 m plots were used to determine a monthly leaf area index (LAI) of the herbaceous vegetation inside the lysimeters and in an area of similar vegetation outside the lysimeters using the 10-point frame technique (Levy and Madden, 1933). LAI was estimated as equal to the number of hits on live vegetation divided by the total number of pins lowered on the plot. Plots inside each lysimeter were permanently marked and were evaluated at monthly intervals. After the LAI was determined on the plots outside the lysimeters, the vegetation was clipped to a 2 cm stubble height, dried at 60°C for 72 hours, and weighed. Regression analysis of LAI to standing crop from outside the lysimeter was utilized to estimate the monthly standing crop inside the lysimeters. The relative growth curve was estimated by the relationship between change in standing crop to LAI over time (Figure 1).

Peak standing crop and LAI of the dominant shrubs within the shrub clusters were determined by using dimensional and regression analysis techniques (Kirmse and Norton, 1985; Ludwig *et al.*, 1975). The dimensional analysis technique estimated total leaf biomass for a shrub at a point in time. Leaf biomass was estimated at four times during the study: May, August, and November 1985, and January 1986. Leaf area (cm^2) of the shrubs was determined by using a leaf area meter. A regression relationship was established to predict leaf area from leaf biomass. LAI for the shrub clusters was then estimated by multiplying the estimated leaf weight times the appropriate leaf area equation, summing the total leaf area and dividing by the surface area of the lysimeter. The relative growth curve of the shrub clusters was estimated from the change in the relationship between LAI and standing crop over time (Figure 1).

The curve number was estimated by the standard method outlined by the Soil Conservation Service (1985). The handbook CN values ranged from 89 to 76 depending on the hydrologic condition. Using these values, simulated surface runoff was 8 to 12 times that of observed surface runoff for the shrub clusters and grass interspaces (Table 1). Wood and Blackburn (1984) reported that, for the rangelands they evaluated, the CN method overpredicted runoff 67 percent of the time. Haily and McGill (1983) estimated that for San Diego Creek, an area of similar soils and vegetation located 18 km from the study site, the average soil-cover complex CN value was 43.2. There were 45 rainfall events in 1985; 21 of these events were greater than 12.7 mm and all produced runoff greater than 0.1 mm. Fifteen rainfall events occurred when the soil was considered dry (< 33 percent of field capacity). Five rainfall events occurred when the soil water content was intermediate (> 33 percent of field capacity < 66 percent). One rainfall event occurred when the soil was wet (> 66 percent of field capacity). The 21 rainfall events greater than 12.7 mm were used to calculate a CN value for each rainfall-runoff event. The observed CN for the grass interspaces, shrub clusters, and bare soil ranged from 25 to 97. The median observed CN value was 43, which was used to initialize the model.

The ERHYM model is currently limited to four soil horizons. The soil profile was divided into four layers, each 30 cm thick, to parameterize the model. If two genetic horizons occurred within a soil layer, the weighted average of the soil attribute was used. Soil layers 1 and 2, and soil layers 3 and 4 were combined to form two soil layers for the purpose of analysis of model performance. Model performance was evaluated using linear regression coefficients of determination of observed versus simulated data (Steel and Torrie, 1980) and the coefficient of efficiency (Nash and Sutcliff, 1970). The Nash-Sutcliff coefficient is computed as

$$E = 1 - \left[\Sigma \left(Y_{obs} - Y_{sim} \right)^2 / \Sigma \left(Y_{obs} - Y_{mean} \right)^2 \right] \tag{13}$$

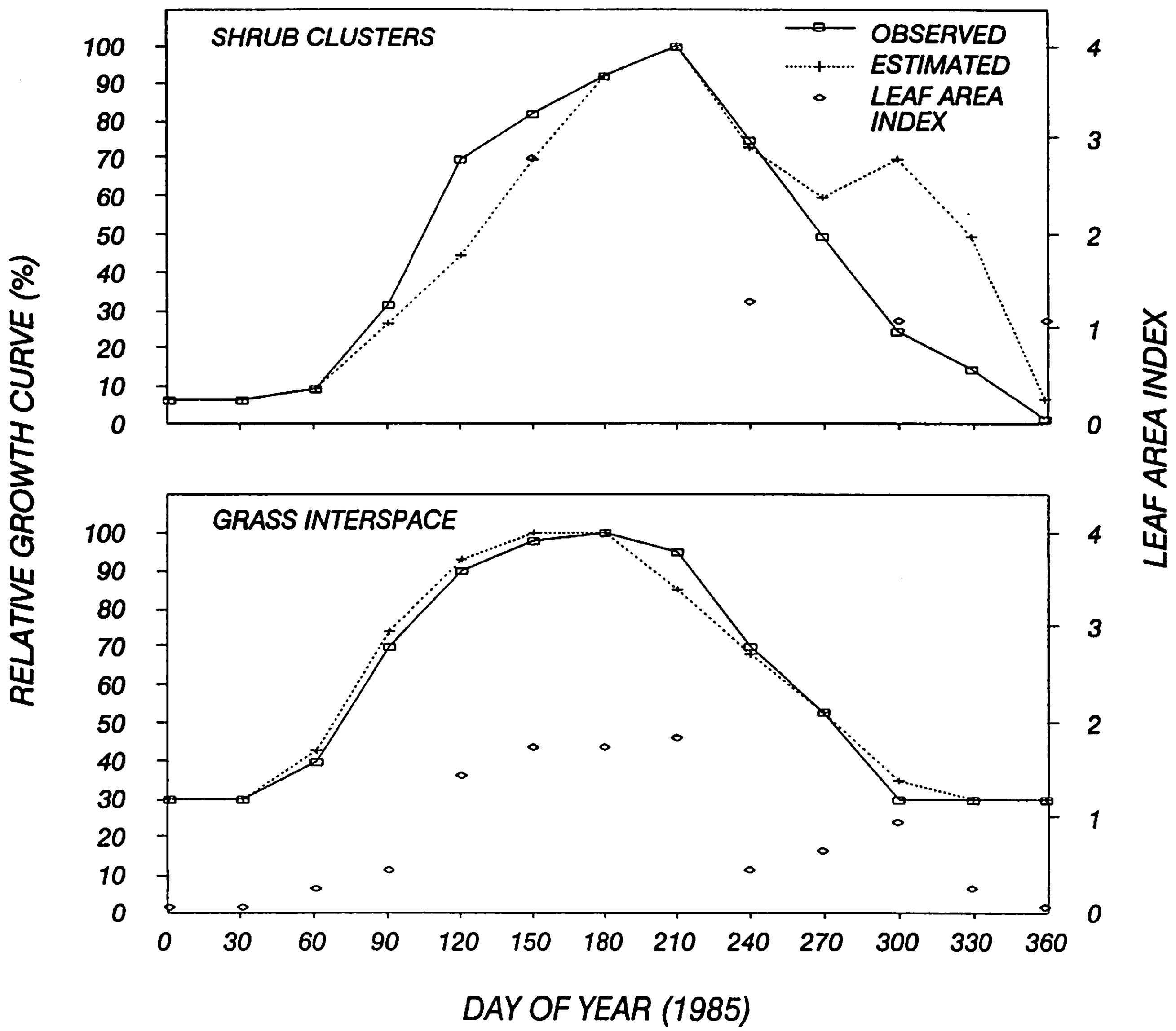

Figure 1. Observed Versus Simulated Relative Growth Curves and Leaf Area Index for Mesquite Shrub Clusters and Grass Interspace.

TABLE 1. Observed Versus ERHYM-II Model Simulated Water Balance (mm) for Grass Interspaces, Shrub Clusters, and Bare Soil on Sandy Loam Soils, La Copita Research Area, Alice, Texas.

Source	PPT	ET	Drainage	Runoff	Change in Soil Water (mm) 0-60	Change in Soil Water (mm) 60-120
Grass Interspace						
Observed	890	834	24	28	−3	+7
Simulated	890	818	3	55	−19	+33
Shrub Clusters						
Observed	890	887	0	19	−15	−1
Simulated	890	890	0	56	−14	−42
Bare Soil						
Observed	890	643	144	84	−11	+30
Simulated	890	529	177	84	+15	+85

where Y_{obs} is the observed value; Y_{sim} is the model simulated value; and Y_{mean} is the mean observed value. The Nash-Sutcliff coefficient is the proportion of the variance of the observed values accounted for by the simulation model. Its values can range from 1 to – infinity. A negative value indicates that the observed mean does better predicting the observed value than the simulation model.

RESULTS AND DISCUSSION

Precipitation

Annual rainfall for 1985 was 27 percent above the long-term normal rainfall (Figure 2). Rainfall from January 10 through June was 230 percent greater than normal. Only 19 percent of normal rainfall was recorded during July and August. From September through December, rainfall was 27 percent less than normal. The bimodal rainfall distribution provided the opportunity to determine the effect of potential ET_r on observed ET from the lysimeters, and the model simulated ET during periods of above normal rainfall (January-June), during drought conditions (July and August), and below normal rainfall (September-December) within one year.

Evapotranspiration

Crop coefficients have been used most often in simulating ET from irrigated croplands, and are difficult to define for rangelands where water is almost always limiting for plant growth (Wight and Hanson, 1990). Kc values for grass pastures have been estimated between 0.75 and 1.0 (Jensen, 1974; Soil Conservation Service, 1967). Wight and Hanson (1990) reported that KC for rangelands were between 0.79 and 0.85, and could be determined by using the median KC value for periods immediately following rainfall

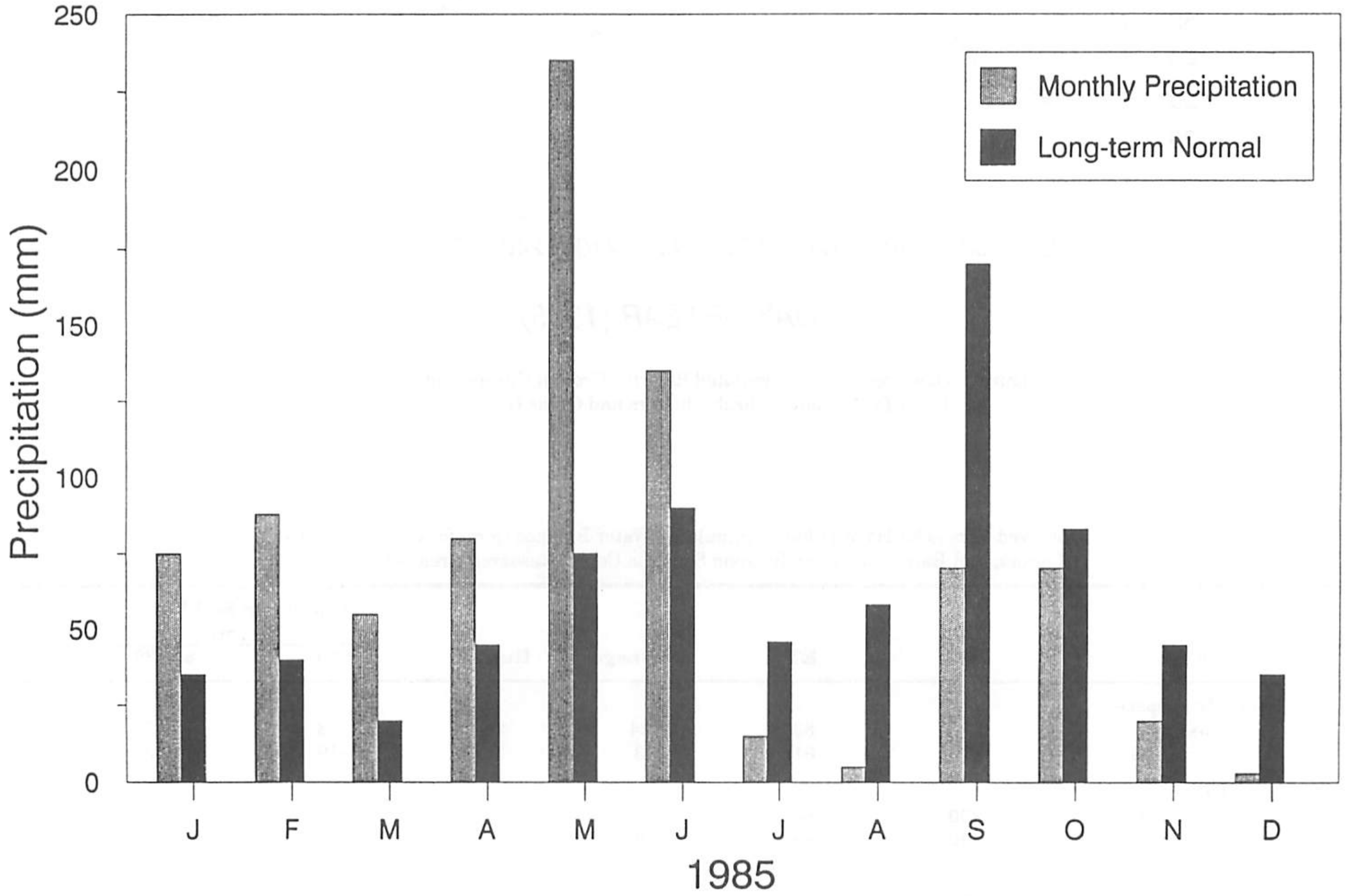

Figure 2. Long-Term Normal and Observed Monthly Precipitation During the Study Period.

events. Using this technique, the Kc value for the grass interspaces and shrub clusters ranged from 0.63 to 1.68 when soil water was nonlimiting. Kc values of > 1 indicated that observed ET exceeded simulated potential ET_r. One reason for overestimating simulated ET was partially attributed to the model not accounting for interception. Although there was no direct measurement of canopy interception during the study, the interception rates of the shrub clusters is estimated to be approximately 15 percent of annual rainfall based on work in other shrub dominated plant communities. Thurow *et al.* (1987), working in central Texas, estimated that for oak mottes, midgrass, and shortgrass dominated areas canopy interception of annual rainfall was 25 percent, 18 percent, and 11 percent, respectively. Interception of rainfall for California chaparral dominated shrub communities was estimated to be 8 percent of annual rainfall (Rowe, 1948; Hamilton and Rowe, 1949). A second limitation is that, by using maximum daily temperature, the model will overestimate ET on days with afternoon clouds or rainstorms. The median KC value (0.85) was used to initialize the model for both the grass interspaces and shrub clusters. No kc value adequately simulated ET for bare soil. For the bare soil simulations the Kc was initialized to 1.0.

Herbaceous production in South Texas followed a slightly bimodal growth pattern during 1985 (Figure 1). Several woody species within the lysimeters are drought deciduous and their growth followed a bimodal distribution pattern. However, the contribution of these drought deciduous shrubs to total leaf biomass of the shrub clusters were minimal and were masked by the leaf biomass of the evergreen lime prickly ash (*Zanthoxylum fagara*). The inability of the model to accommodate bimodal growth did not result in a significant difference between simulated ET and observed ET for the grass interspaces and shrub clusters (Figure 3). Where soil water content is nonlimiting and a bimodal growing season exists, the water budget for each portion of the growing season should be modeled independently, or the model needs to be modified to account for bimodal growing seasons.

The ET and surface runoff components of the model are relatively insensitive to changes in root density as a function of depth. The effect of changes in root density on simulated ET is nonlinear. A 10 percent change in root density in the second or third layer had minimal effect (1 percent) on simulated ET. When root density in the fourth layer was reduced from 10 percent to 0 percent, simulated ET was reduced by 5 percent and surface runoff by < 1 percent. A 10 percent increase in roots in the fourth soil layer increased simulated ET by 7 percent and decreased surface runoff by < 1 percent. Simulated ET will decrease and drainage and soil water will increase if root density is underestimated in the lower soil layers. Changes in root density in the lower soil layers had a relatively large effect on drainage (changing by 11-17 percent) and soil water content (20 percent), but minimal effect on surface runoff (< 1 percent).

Simulated annual potential ET_r was 1,760 mm, close to the average predicted pan evaporation (1,840 mm using a pan coefficient of 0.80), Penman (2,100 mm), and the Priestly-Taylor (1,700 mm) estimates. Annual simulated ET for the grass interspaces and shrub clusters were within ± 2 percent of observed ET (Table 1). The simulated ET for the bare soil lysimeters was underestimated by 18 percent. Wight *et al.* (1986) reported that ERHYM-II estimates of potential ET_r were highly correlated with observed ET for a sagebrush-grass plant community in southwest Idaho. Simulated ET for the grass interspaces and the shrub clusters were will correlated with observed ET (Figure 3) and model performance was considered very good (positive Nash-Sutcliff coefficients) (Table 2). The simulated ET of the bare soil was poorly correlated with observed ET. The poor model performance in simulating ET from the bare soil is indicated by the low Nash-Sutcliff coefficient. The model underestimated evaporation from the bare soil because it limited evaporation to the surface 300 mm of the soil profile. A substantial quantity of water was evaporated from the 300-600 mm portion of the soil profile during the entire year from the bare soil lysimeters. Other researchers have also reported that evaporation from undisturbed rangeland soils exceeded the surface 300 mm of the soil profile (Johnson, 1970; Carlson *et al.*, 1990).

The model showed some difficulty in simulating ET over short time steps. The reason for the model's poor performance was partially attributed to the model not accounting for interception losses. A second limitation is that, by using maximum and minimum temperatures, the model overestimates ET on days with afternoon clouds and rain storms and will underestimate ET for days with low relative humidity and strong winds. When different time periods of simulation were evaluated, the model overpredicted sometimes and underpredicted other times. This resulted in good annual prediction of accumulative ET, but poor within season predictions. During the period of relatively high rainfall (January through June 1985), the average daily simulated ET of the shrub clusters and grass interspaces were similar and were within 4 percent of observed ET (Table 3). Dugas and Meyeux (1991), also working in Texas, reported that ET was similar between grass dominated landscapes and mesquite dominated landscapes when soil water availability was high. For the bare soil, the model underestimated daily observed ET by 13 percent.

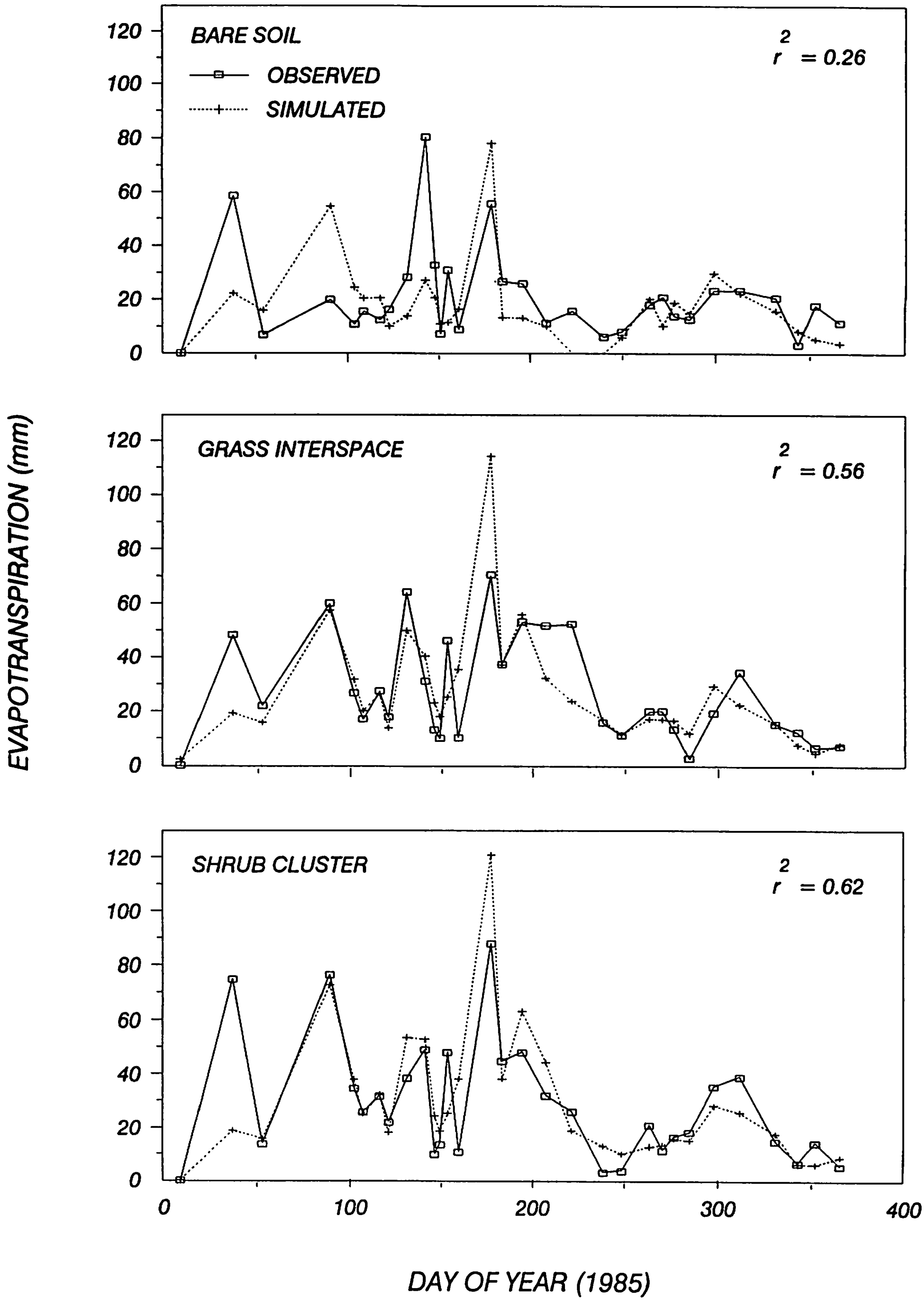

Figure 3. Observed Versus Simulated Daily Evapotranspiration (mm) for Mesquite Shrub Clusters, Grass Interspace, and Bare Soil.

During the dry period (July and August), the average daily simulated ET of the grass interspaces was overestimated and the shrub clusters were underestimated by 25 percent. The average daily simulated ET of the bare soil was underestimated by 72 percent. From September 1985 through January 7, 1986 (a period of below normal rainfall), the simulated ET closely approximated the observed ET for the grass interspace. The model underestimated the daily observed ET for the shrub clusters and the bare soil by 21 and 10 percent, respectively.

TABLE 2. Nash-Sutcliff Coefficient of Efficiency Values for Observed Versus ERHYM-II Model Simulated Components of the Water Balance for Grass Interspaces, Shrub Clusters, and Bare Soil on Sandy Loam Soils, La Copita Research Area, Alice, Texas.

Source	ET	Drainage	Runoff	Change in Soil Water (mm) 0-60	60-120
Grass Interspace	0.48	0.1	–0.21	0.53	–0.44
Shrub Clusters	0.54	NA*	–2.32	0.14	–2.42
Bare Soil	0.07	–1.92	0.83	0.01	–15.15

*NA = Not appropriate because no drainage was observed.

Drainage

After all soil layers are filled to field capacity and runoff and ET have been satisfied, any excess water is routed out of the soil profile as deep drainage. The model does not account for the redistribution of water in the soil profile by unsaturated flow. Once the model simulated that the soil profile from 300 to 1200 mm became saturated within the bare soil treatment, any subsequent water entering the soil profile below 300 mm was routed as deep drainage. The observed lowermost soil profiles of all three treatments (600-1200 mm) never attained field capacity. The observed drainage from the bare soil and grass interspace treatments was a function of unsaturated flow. The model overpredicted drainage from the bare soil by 8 percent and underestimated drainage from the grass interspaces by 87 percent (Table 1). The lowermost subsurface layer beneath the shrub clusters (900 to 1200 mm) for both the observed and the model simulation never attained field capacity. The simulated and observed drainage were the same (0 mm).

Runoff

Simulated runoff and observed runoff from the bare soil were the same (Table 1). The simulated annual runoff from the grass interspaces and shrub clusters was two to three times greater than measured amounts from the grass interspaces and shrub clusters. The negative Nash-Sutcliff coefficient for runoff for both the grass interspace and the shrub clusters indicates that the observed mean runoff is a better estimate of annual runoff than the model (Table 2). Wilcox *et al.* (1990) reported that the CN technique was a poor estimator of both monthly and annual runoff for shrub dominated watersheds in central Idaho.

Although observed and simulated annual runoff for the bare soil were the same, the CN technique consistently underestimated runoff from small rainfall events (< 25 mm) and overestimated runoff from large rainfall events (> 25 mm). Twenty-six runoff events from the bare soil were recorded in 1985, but the model simulated runoff from approximately one-half of the rainfall events. The shrub clusters and the grass interspaces had 21 and 20 measured runoff

TABLE 3. Observed Versus ERHYM-II Model Simulated Daily Evapotranspiration (mm/day) for Grass Interspaces, Shrub Clusters, and Bare Soil for 1985 on Sandy Clay Loam Soils, La Copita Research Area, Alice, Texas.

Source	Annual	Seasonal Evapotranspiration (mm/day) January-June	July-August	September-December
Grass Interspace				
Observed	2.30	2.87	2.82	1.38
Simulated	2.25	2.99	2.10	1.40
Shrub Clusters				
Observed	2.40	3.35	1.74	1.70
Simulated	2.45	3.38	2.29	1.34
Bare Soil				
Observed	1.80	2.36	1.02	1.53
Simulated	1.45	2.06	0.29	1.38

events, respectively. However, as with the bare soil, the model only simulated runoff from one-half of the rainfall events. Seventy-five percent of the annual surface runoff for the grass interspaces and 65 percent of the runoff for shrub clusters and bare soil was the result of three rainfall events. The proportion of model simulated runoff was similar to the observed runoff for the three rainfall events. The overprediction of surface runoff from the shrub clusters resulted in a 4 percent increase in soil water deficit.

Soil Water

Simulated soil water contents of the first two layers (0 to 600 mm) were well correlated with the observed soil water content and the Nash-Sutcliff coefficients were positive for the shrub clusters and grass interspaces (Table 2, Figure 4). However, simulated and observed soil water contents for the bare soil was poorly correlated and the Nash-Sutcliff coefficient was close to zero. There was no correlation between simulated and observed soil water content in the lower two soil layers (600 to 1200 mm) in the bare soil (Figure 5). The Nash-Sutcliff coefficients for all three vegetation treatments were negative for soil water content for the two lower soil layers (Table 2). This indicates poor correspondence between the simulated soil water content and observed values for all three treatments at the lower soil profile depths.

Simulated soil water content of the bare soil profile at 600 to 1200 mm depth was greater than observed water content for the entire year. Simulated soil water content was greater than observed for the shrub clusters during the first six months of the year. The model underpredicted the observed soil water content for the last six months for the shrub clusters. The simulated soil water content was greater than observed for the grass interspace from late February through the end of the evaluation period. The reason for the model's poor performance in simulating soil water content in the lower two layers for the shrub clusters and grass interspaces was attributed to the model's overpredicting runoff. The reason for the model's poor performance in simulating soil water content for the bare soil was attributed to limiting ET to the surface 300 mm and not accounting for drainage by unsaturated flow.

SUMMARY AND CONCLUSIONS

The ERHYM-II model should perform well on arid and semiarid rangelands where runoff and deep drainage are a small percentage of the water balance. The model closely approximated the annual water balance for shrub clusters and grass interspaces in south Texas. However, the model performed poorly on the bare soil areas. The model is currently limited to use on shallow and moderately deep soils. Parameters which need further definition for rangeland are the CN, crop coefficient, and the root density distribution.

The model is very sensitive to variations in CN. The published CN values overestimated runoff 8 to 12 fold for all vegetation conditions. This resulted in an underestimation of drainage and evapotranspiration. The difference between simulated runoff and observed runoff were minimized after the CN values were reduced for the grass interspaces and the shrub clusters. Observed runoff accounted for 2 and 3 percent of annual rainfall for the shrub clusters and grass interspaces, respectively. The simulated runoff accounted for 6 percent of annual rainfall.

If more accurate estimates of surface runoff are required, then physically based models like Kineros (Woolhiser *et al.*, 1990b) or IRS (Stone *et al.*, 1992) needs to be substituted for the CN technology. The disadvantage of this approach is the increase in the number of parameters required. Many of these parameters are difficult to define or unavailable for rangelands (Chezy or Manning hydraulic roughness coefficient, effective porosity of the soil, and cumulative infiltration) and would make the model unsuitable for many applications.

Evapotranspiration in ERHYM-II is a function of available stored soil water, potentially available stored water capacity, crop coefficient, root density, and soil temperature. The ET component of the model is relatively insensitive to the root density parameters. The soil water and drainage components of the model are sensitive to the density of roots in the lowest soil horizon. The ET component of the model is sensitive to variations in crop coefficient. Work by Wight and Hanson (1990) and results of this study indicate that a crop coefficient of 0.85 is appropriate for converting the Jensen-Haise potential ET_h to a rangeland potential ET_r for shrub and grass plant communities in south Texas. No crop coefficient was found that adequately simulated ET for the bare soil. The simulated annual ET was similar to the observed ET of the shrub clusters and the grass interspaces. The model significantly underestimated annual ET for the bare soil mainly because it restricts evaporative losses to the surface 300 mm of the soil profile. There are problems with the methodology used to calculated deep percolation. A subroutine to calculate drainage as a function of unsaturated hydrologic conductivity should correct the problem of maintaining the soil profile beneath the bared soil lysimeters at field capacity. This problem will occur whenever

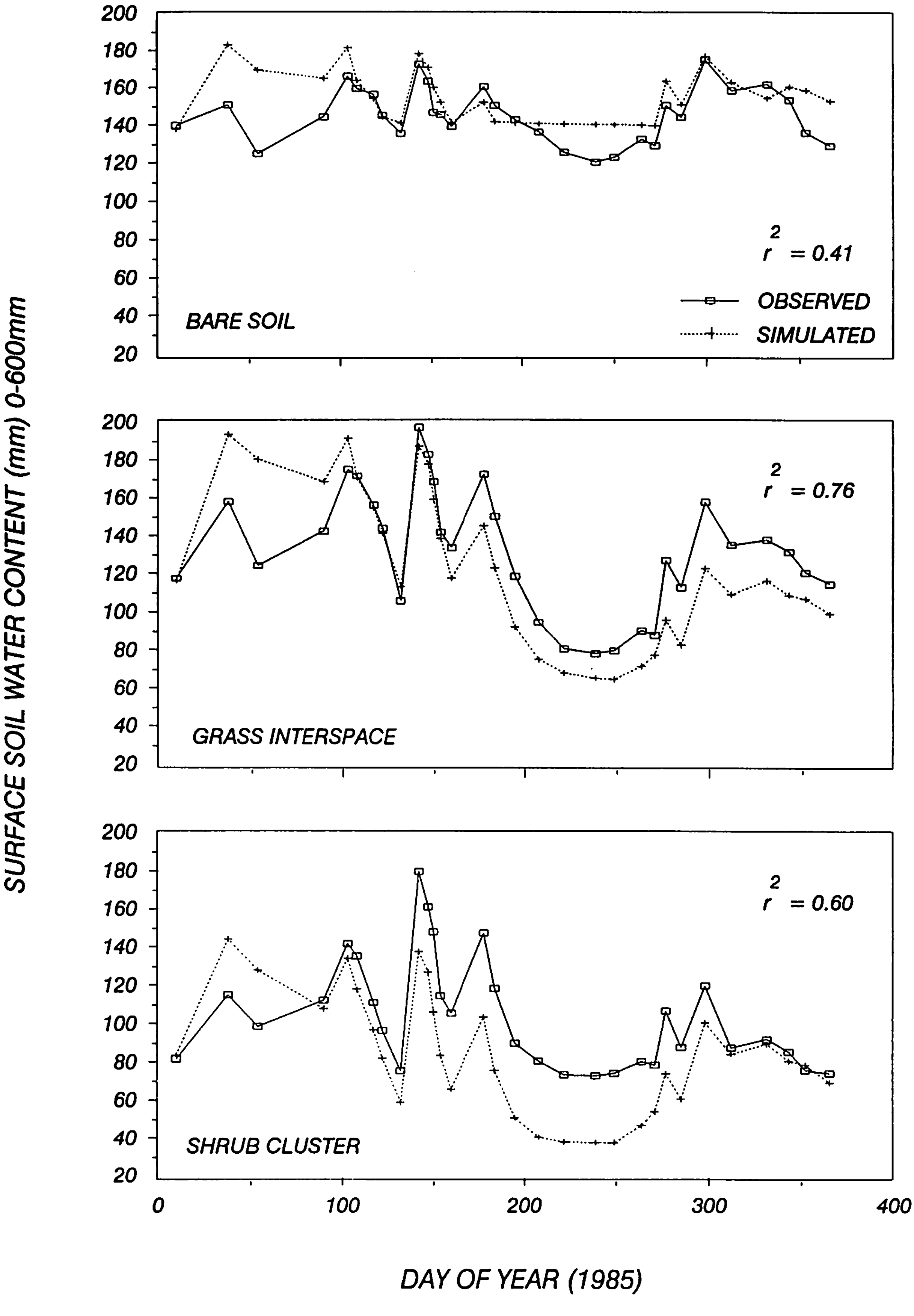

Figure 4. Observed Versus Simulated Daily Surface Soil Water Content (mm) for Mesquite Shrub Clusters, Grass Interspace, and Bare Soil.

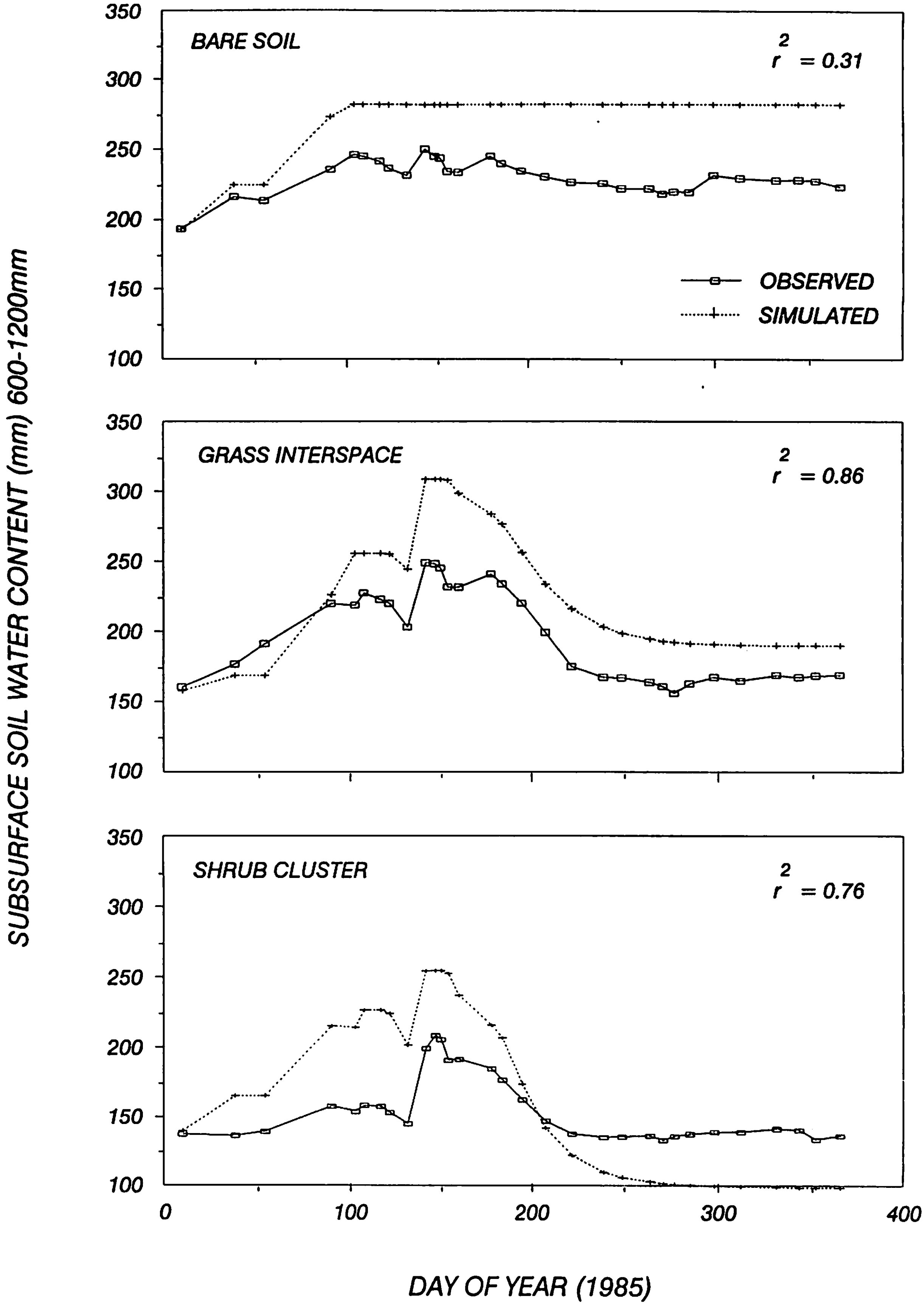

Figure 5. Observed Versus Simulated Daily Subsurface Soil Water Content (mm) for Mesquite Shrub Clusters, Grass Interspace, and Bare Soil.

soil water is added to a soil layer below active root growth.

Shrub clusters responded quicker to available soil water than did the grass interspaces. The shrub cluster transpiration rate was greater than the unsaturated flow rate, thus precluding any substantial downward movement of water into the lower soil profile. Soil water was extracted first from the surface soil horizons regardless of the vegetative cover. Evapotranspiration and runoff were essentially the same for the grass interspaces and shrub clusters. These results indicate that no net change in ET and runoff would occur if shrub clusters are replaced with deep rooted perennial grasses in south Texas. Increasing water yield in south Texas through vegetation manipulation is marginal and limited to years when rainfall exceeds potential evapotranspiration.

INTERPRETIVE SUMMARY

Understanding of the water balance for rangeland plant communities is essential if accurate estimates of the effect of vegetation manipulation on runoff and aquifer recharge is to be predicted. Field studies are costly, difficult to replicate, and often require numerous years to determine treatment effect on the water budget. If properly applied, hydrologic simulation models are a rapid alternative for assessing management practices. In this study, the ERHYM-II model was evaluated to determine if it was capable of simulating the water balance for mesquite, annual grass, and bare soil dominated areas in south Texas. The simulated water budget was within 2 percent of the measured evapotranspiration for the mesquite and grass dominated areas. The ERHYM-II model underestimated evapotranspiration (18 percent) and overestimated soil water content (82 percent) for bare soil. The model underestimated evapotranspiration for the bare soil as a result of restricting evaporative losses to the first soil layer. The model underestimated the number of runoff events and overestimated the volume of runoff by twofold for the mesquite and grass dominated areas. Although this difference seems large, observed runoff accounted for 2 to 3 percent of annual rainfall. Simulated runoff accounted for 6 percent of annual runoff. Based on our analysis, the ERHYM-II model has the potential for simulating the annual water balance for vegetated rangeland plant communities.

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