A RANGELAND HYDROLOGY AND EROSION MODEL

M. A. Nearing, H. Wei, J. J. Stone, F. B. Pierson, K. E. Spaeth,
M. A. Weltz, D. C. Flanagan, M. Hernandez

ABSTRACT. *Soil loss rates on rangelands are considered one of the few quantitative indicators for assessing rangeland health and conservation practice effectiveness. An erosion model to predict soil loss specific for rangeland applications is needed because existing erosion models were developed from croplands where the hydrologic and erosion processes are different, largely due to much higher levels of heterogeneity in soil and plant properties at the plot scale and the consolidated nature of the soils. The Rangeland Hydrology and Erosion Model (RHEM) was designed to fill that need. RHEM is an event-based derivation of the WEPP model made by removing relationships developed specifically for croplands and incorporating new equations derived from rangeland data. RHEM represents erosion processes under disturbed and undisturbed rangeland conditions, it adopts a new splash erosion and thin sheet-flow transport equation developed from rangeland data, and it links the model hydrologic and erosion parameters with rangeland plant communities by providing a new system of parameter estimation equations based on 204 plots at 49 rangeland sites distributed across 15 western U.S. states. RHEM estimates runoff, erosion, and sediment delivery rates and volumes at the spatial scale of the hillslope and the temporal scale of a single rainfall event. Experiments were conducted to generate independent data for model evaluation, and the coefficients of determination (r^2) for runoff and erosion predictions were 0.87 and 0.50, respectively, which indicates the ability of RHEM to provide reasonable runoff and soil loss prediction capabilities for rangeland management and research needs.*

Keywords. *Erodibility, Erosion control, Grazing, Green-Ampt, Hydrologic modeling, Infiltration, Kinematic wave, Model validation, Parameter estimation, Runoff, Semi arid, Soil conservation, USDA, USLE, WEPP.*

A great deal of work has been undertaken to develop soil erosion prediction models, but most of the focus has been on applications to croplands. For example, in the process of developing the USLE, western rangelands in the U.S. were largely unrepresented. The focus at that time was on erosion from cropped lands, as evidenced by the locations of the 49 field research stations for collection of data. None of these stations were located on rangeland sites, and the large majority of them were located in the eastern part of the country. Correspondent development and application of empirical USLE-like models in countries outside the U.S. have also usually focused on croplands (Schwertmann et al., 1987; Larionov, 1993).

In 1981, a conference was held in Tucson, Arizona, to collectively summarize knowledge on "estimating erosion and sediment yield on rangelands" (USDA-ARS, 1982). That workshop included summaries of work on the application of the USLE to rangelands, such as the rainfall erosivity factor R (Simanton and Renard, 1982), the slope factors L and S (McCool, 1982), and the cropping and management factors C and P (Foster, 1982a). A reading of this work today illustrates the limitations of data and understanding of rangeland erosion processes at the time. The work represented in that workshop also shows a notable lack of connection with the scientific understanding at the time of rangeland science, ecology, and management. For example, the paper on the C and P factors (Foster, 1982a) makes no mention of the rangeland science concepts of that time, such as range condition or climax plant communities. The paper on the L and S factors (McCool, 1982) includes no data on slope length and steepness from *in situ* rangelands under natural rainfall because no such data existed. The effort to apply the USLE to rangelands appears to be based on a transfer of knowledge from croplands to rangelands, with sparse data from rangelands and educated guesses regarding how to adjust parameter values. Conceptually, the basis of the science was from cropland erosion. The knowledge gained from this workshop, and subsequent work inspired thereby, was largely incorporated into the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997).

There remain data limitation problems for development of an erosion prediction tool for application on rangelands, particularly with regard to data under natural rainfall conditions. However, we know much more today about erosion on range-

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The authors are **Mark A. Nearing,** Research Leader, USDA-ARS Southwest Watershed Research Center, Tucson, Arizona; **Haiyan Wei,** Assistant Research Scientist, School of Natural Resources and the Environment, University of Arizona, Tucson, Arizona; **Jeffry J. Stone,** Research Hydrologist, USDA-ARS Southwest Watershed Research Center, Tucson, Arizona; **Frederick B. Pierson,** Research Leader, USDA-ARS Northwest Watershed Research Center, Boise, Idaho; **Kenneth E. Spaeth,** Research Rangeland Management Specialist, USDA-NRCS Central National Technology Support Center, Ft. Worth, Texas; **Mark A. Weltz,** Research Rangeland Management Specialist, USDA-ARS Exotic and Invasive Weeds Research Unit, Reno, Nevada; **Dennis C. Flanagan, ASABE Member Engineer,** Research Agricultural Engineer, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana; and **Mariano Hernandez,** Assistant Research Scientist, School of Natural Resources and the Environment, University of Arizona, Tucson, Arizona. **Corresponding author:** Mark A. Nearing, USDA-ARS Southwest Watershed Research Center, 2000 E. Allen Rd., Tucson, Arizona 85719; phone: 520-647-9063; e-mail: mark.nearing@ars.usda.gov.

lands than we did in 1981, and we have significantly more data as well. For example, a large number of experiments were conducted using a rainfall simulator in conjunction with parameterization efforts for the development of the process-based Water Erosion Prediction Project (WEPP) model (Laflen et al., 1991; Foster and Lane, 1987; Nearing et al., 1989a). Experiments were conducted in 1986 through 1988 at 24 rangeland sites in the western U.S. using a rotating boom rainfall simulator (Simanton et al., 1991). Subsequently, from 1990 through 1993, data were collected at an additional 26 rangeland sites in ten western states using a similar technique (Pierson et al., 2002). These data sets have both improved our understanding of the rangeland infiltration (Spaeth et al., 1996) and erosion (Wei et al., 2009) processes and provided a wealth of data for potential use in developing model parameter estimation equations. In addition, many other studies of rangeland runoff and erosion processes have been conducted in the past two decades (e.g., Wilcox, 1994; Parsons et al., 1996; Tongway and Ludwig, 1997; Pierson et al., 2002; Paige et al., 2003; Chartier and Rostagno, 2006; Bartley et al., 2006).

In 1985, the USDA-ARS initiated the Water Erosion Prediction Project (WEPP), and WEPP was released in 1995, representing the assemblage of state-of-the-art process-based erosion modeling technologies (Flanagan and Nearing, 1995). WEPP is based on fundamentals of infiltration, hydrology, plant science, hydraulics, and erosion mechanics (Nearing et al., 1989a). As a process-based model, WEPP has the advantages over empirical models for its capabilities to estimate spatial and temporal distributions of net soil loss and to extrapolate to a broad range of conditions (Nearing et al., 1990). During 1987 to 1988, the WEPP team collected a large set of erosion data from rangelands across the western U.S. for parameterization of erosion and hydrology factors. However, WEPP is limited in application to rangelands because many of the model concepts and erosion equations were developed from experiments on croplands. It has not been widely accepted by many rangeland managers, although it has found application in the BLM and Forest Service for rangeland application using the cropland plant growth and water balance routines.

The objective of this study was to develop an event-based runoff and water erosion model best suited for application to rangelands of the western U.S. We extracted algorithms from the process-based WEPP model, excluding relationships that were relevant only to cropland application, and incorporated relationships specific to rangelands. Rainfall simulation data collected on rangeland plots from the WEPP and IRWET (IRWET and NRST, 1998) projects were combined and analyzed, which together covered 49 rangeland sites distributed across 15 western states (fig. 1). Statistical analyses of these data form the basis of the parameter estimation equations for the primary infiltration and erodibility parameters of the model. A new splash erosion and thin sheet-flow transport equation specific for rangeland, developed based on the rangeland database (Wei et al., 2009), was incorporated. Sensitivity and uncertainty analyses were conducted for the code that was developed for the model (Wei et al., 2007; Wei et al., 2008). This article presents the overall conceptualization and structure of the RHEM model, a new system of parameter estimation equations specific to this model and based on the existing data, and results of model evaluation tests using independent measured data.

Figure 1. WEPP-IRWET data site locations.

METHODS

MODEL STRUCTURE

The infiltration equations in RHEM are taken directly from the WEPP model. Infiltration is computed using the Green-Ampt Mein-Larson model (Mein and Larson, 1973) for unsteady intermittent rainfall, as modified by Chu (1978). The rainfall excess rate is conceptualized as occurring only when the rainfall rate is greater than the infiltration rate. Equation 1 is used to calculate the average infiltration rate, f_i (m s^{-1}), for a time interval $t_i - t_{i-1}$:

$$f_i = \frac{F_i - F_{i-1}}{t_i - t_{i-1}} \tag{1}$$

where F is the cumulative infiltration depth (m) that is computed from the Green-Ampt Mein-Larson model in a Newton-Raphson iteration as:

$$K_e t = F_i - \psi\theta_d \ln\left(1 + \frac{F_i}{\psi\theta_d}\right) \tag{2}$$

where K_e is infiltration rate (m s^{-1}), t is time after time to ponding (s), ψ is average capillary potential (m), and θ_d is soil moisture deficit (m m^{-1}), which is calculated as the difference between porosity and initial soil water content. Shallow lateral subsurface flow is not considered in the model.

The runoff routing equations used in RHEM use a semi-analytical solution to the kinematic wave equation using the method of characteristics for the case where excess rainfall rate is approximated by a series of step functions, i.e., where rainfall intensity is constant within an arbitrary time interval but varies from interval to interval (Flanagan and Nearing, 1995). The empirical routing equations used in the WEPP model for the purpose of reducing computer run-time to approximate the kinematic wave solutions were not used. The rainfall excess amount at each time interval is computed when the rainfall rate exceeds the infiltration capacity:

$$\begin{aligned} V_i &= R_i - F \quad \text{when} \quad I_i > f_i \text{ and } F_i < S_p \\ V_i &= V_{i-1} \quad \text{when} \quad I_i \le f_i \text{ and } F_i < S_p \\ V_i &= R_i \quad \text{when} \quad F_i \ge S_p \end{aligned} \tag{3}$$

where V_i, R_i, and F_i are the rainfall excess amount, rainfall amount, and infiltration amount in each time interval (m); I_i is the rainfall rate (m s^{-1}); and S_p is the depression storage (m). The rainfall excess rate (v) is then calculated for each time interval:

$$v_i = \frac{V_i - V_{i-1}}{t_i - t_{i-1}} \tag{4}$$

Equation 5, the kinematic wave equation, is used to route the rainfall excess on a sloping surface:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = v \tag{5}$$

where h is depth of flow (m), q is discharge per unit width of the plane (m^3 m^{-1} s^{-1}), and x is distance from the top of the plane (m). Runoff discharge, q (m), is calculated using a depth-discharge relationship:

$$q = \alpha h^{1.5} \tag{6}$$

where α is the depth-discharge coefficient that is related to Darcy-Weisbach hydraulic friction factors.

RHEM calculates sediment load in the runoff along the hillslope as the total net detachment and deposition from rainfall splash, overland sheet flow, and concentrated flow, using a steady-state sediment continuity equation:

$$\frac{dG}{dx} = D_{ss} + D_c \tag{7}$$

where G is sediment load in the flow (kg m^{-1} s^{-1}), and D_{ss} and D_c are splash and sheet erosion and concentrated flow erosion, respectively, as discussed below. The numerical solution of equation 7 is that used in the WEPP model (Nearing et al., 1989a), with source terms (D_{ss} and D_c) based on rangeland derived parameters.

Conceptually, there are basic scale and process representations that differ for the rangeland model compared to WEPP. In croplands, erosion is often characterized as a combination of rill and interrill erosion (Meyer et al., 1975; Meyer, 1981), where rills are relatively small, actively scouring flow channels, and interrill areas are the relatively flat areas between the rills wherein soil loss is dominated by splash and thin sheet-flow erosion. Rill erosion generates a significant amount of erosion and often dominates the erosion rates from cultivated agricultural fields. However, rangeland soils are untilled and generally consolidated; hence, significant rilling does not occur readily under most undisturbed rangeland situations. In most cases, erosion in rangelands at the plot and hillslope scales is dominated by splash erosion and thin sheet-flow transport, and erosion rates in these cases can often be lower than those for cropland soils (Wei et al., 2009). Thus, in terms of scale, the D_{ss} term in equation 7 will normally represent a much larger area and slope length than generally is represented by the interrill erosion term in WEPP. This issue is discussed in more detail by Wei et al. (2009).

RHEM adopts the new splash and sheet erosion equation developed from rangeland erosion data (Wei et al., 2009):

$$D_{ss} = K_{ss}\, I^{\,1.052}\, q^{0.592} \tag{8}$$

where D_{ss} is the rate of splash and sheet erosion for the area (kg m^{-2} s^{-1}), K_{ss} is the splash and sheet erodibility coefficient, I is rainfall intensity (m s^{-1}), and q is runoff rate (m s^{-1}). Equation 8 is the only existent splash and sheet equation developed from a broadly based rangeland dataset. The equation takes into account the dependent relationship between I and q, which was ignored by previous similar type of equations for interrill erosion. In addition, Wei et al. (2009) used large plot data (32.5 m^2) to encompass the spatial heterogeneity of rangelands, and the equation was shown to be effective in predicting erosion from splash and sheet flow in rangelands.

In rangelands, significant concentrated flow detachment causing small scour channels (rills) at the scale of the splash and sheet erosion plot (approx. 20 to 50 m^2) generally only occurs under disturbed or otherwise exceptional conditions. Under such conditions, concentrated flow erosion in RHEM is represented using an excess shear stress equation of the following form (Foster, 1982b):

$$D_c = K_c(\tau - \tau_c)\left(1 - \frac{G}{T_c}\right) \tag{9}$$

where D_c is the rate of concentrated flow erosion for the area (kg m^{-2} s^{-1}); K_c is the concentrated flow erodibility coefficient (s m^{-1}); τ is the shear stress of the concentrated flow on the soil surface (Pa); τ_c is the critical shear stress for the soil, i.e., the level of flow shear that must be exceeded before concentrated flow detachment is initiated (Pa); G is the sediment load in the flow (kg m^{-1} s^{-1}); and T_c is the sediment transport capacity of the flow (kg m^{-1} s^{-1}). Transport capacity is calculated using the Yalin equation in a manner similar to that used in the WEPP model (Finkner et al., 1989).

MODEL PARAMETERS

Parameter estimation is important in process-based erosion modeling because in order to obtain parameters directly for a specific site they must be optimized from field-measured runoff and soil loss data. The system of parameter estimation equations statistically relates inputs to measurable soil and vegetation properties, from which the required model input values for a site may be estimated.

The data we used for developing the new splash and sheet erosion equation included data previously collected by the WEPP Rangeland Field Experiment in 1987 and 1988 (Simanton et al., 1991; Laflen et al., 1991; 1997), as well as data collected by the Interagency Rangeland Water Erosion Team (IRWET) from 1990 through 1993 (IRWET and NRST, 1998; Pierson et al., 2002). The IRWET project was coordinated closely with the WEPP model development so that the experimental design and the data format were compatible with that of WEPP. The WEPP-IRWET rangeland dataset contains measurements of simulated rainfall, runoff, and sediment discharge and soil and plant properties on 204 plots from 49 rangeland sites distributed across 15 western states (fig. 1). Plot sizes were 3.06 m wide by 10.7 m long. The database covered a wide range of rangeland soil types (table 1).

RHEM's system of parameter estimation equations and procedure reflects the concept that hydrology and erosion

Table 1. WEPP-IRWET experimental sites used to develop RHEM.

Site	No. of plots	State	City	Soil Texture	Dominant Plant Form
A187	2	Arizona	Tombstone	Sandy loam	Shrub
A287	2	Arizona	Tombstone	Sandy clay loam	Bunchgrass
C187	2	Texas	Sonora	Cobbly clay	Sodgrass
D187	2	Oklahoma	Chickasha	Loam	Sodgrass/bunchgrass
D188	2	Oklahoma	Chickasha	Loam	Sodgrass/bunchgrass
D287	2	Oklahoma	Chickasha	Sandy loam	Bunchgrass
D288	2	Oklahoma	Chickasha	Sandy loam	Bunchgrass
E287	2	Oklahoma	Woodward	Loam	Bunchgrass
E288	2	Oklahoma	Woodward	Loam	Bunchgrass
E588	2	Oklahoma	Woodward	Sandy loam	Bunchgrass
F187	2	Montana	Sidney	Loam	Forb
G187	2	Colorado	Degater	Silty clay	Shrub
H187	2	South Dakota	Cottonwood	Clay	Bunchgrass
H188	2	South Dakota	Cottonwood	Clay	Bunchgrass
H287	2	South Dakota	Cottonwood	Clay	Bunchgrass
H288	2	South Dakota	Cottonwood	Clay	Bunchgrass
I187	2	New Mexico	Los Alamos	Sandy loam	Forb
J187	2	New Mexico	Cuba	Sandy loam	Sodgrass
K187	2	California	Susanville	Sandy loam	Shrub
K188	2	California	Susanville	Sandy loam	Shrub
K288	2	California	Susanville	Sandy loam	Shrub
H392	3	North Dakota	Killdeer	Sandy loam	Bunchgrass
K287	4	California	Susanville	Sandy loam	Shrub
B190	6	Nebraska	Wahoo	Loam	Sodgrass
B290	6	Nebraska	Wahoo	Loam	Sodgrass/bunchgrass
C190	6	Texas	Amarillo	Loam	Bunchgrass
C190	6	Texas	Amarillo	Loam	Sodgrass
E191	6	Kansas	Eureka	Silty clay loam	Forb
E291	6	Kansas	Eureka	Silty clay loam	Sodgrass/bunchgrass
E391	6	Kansas	Eureka	Silty clay	Sodgrass
F191	6	Colorado	Akron	Loam	Bunchgrass
F291	6	Colorado	Akron	Fine sandy loam	Bunchgrass
F391	6	Colorado	Akron	Loam	Sodgrass
G191	6	Wyoming	Newcastle	Very fine sandy loam	Bunchgrass
G291	6	Wyoming	Newcastle	Clay loam	Bunchgrass
G391	6	Wyoming	Newcastle	Very fine sandy loam	Bunchgrass
H192	6	North Dakota	Killdeer	Sandy loam	Bunchgrass
H292	6	North Dakota	Killdeer	Fine sandy loam	Bunchgrass
I192	6	Wyoming	Buffalo	Silt loam	Shrub
I292	6	Wyoming	Buffalo	Loam	Bunchgrass
J192	6	Idaho	Blackfoot	Silt loam	Shrub
J292	6	Idaho	Blackfoot	Silt loam	Bunchgrass
K192	6	Arizona	Prescott	Sandy loam	Bunchgrass
K292	6	Arizona	Prescott	Sandy loam	Bunchgrass
L193	6	California	San Luis Obispo	Clay loam	Forb
L293	6	California	San Luis Obispo	Clay loam	Annual grass
M193	6	Utah	Cedar City	Sandy loam	Shrub
M293	6	Utah	Cedar City	Sandy loam	Sodgrass

processes on rangeland are affected by plant growth forms (Pierson et al. 2002). The equations were designed to reproduce generally observed trends in hydrologic and erosion response due to differences in management, soil, and vegetation types. Management effects are represented by amounts of canopy and ground cover, soil types are based on the 12 classes of the USDA soil classification, and the vegetation types are bunchgrass, sodgrass, annual grass and forbs, and shrubs. Values of K_{es} and K_{ss} for each plot were calculated from the simulator-based, measured rainfall and runoff volumes and rates, sediment discharge rates, and corresponding equations. K_{es} in this case represents the K_e value as determined from the rainfall simulator data. Multiple linear regression was then conducted to develop equations between the logarithm of the input values for K_{es} and K_{ss} and soil and cover properties. Large plots were used because the relatively high heterogeneity of rangeland conditions requires a relatively large representative area. The small plots (0.75 m square) were not used to develop parameters.

For estimating K_{es}, we used the averages of the replicated plots and found that a single equation was able to give a reasonably good fit ($r^2 = 0.67$) for bunchgrass, annuals, and forbs:

$$\log K_{es}\ (\mathrm{mm\ h^{-1}}) = 0.174 - (1.450 clay) + (2.975 gcover) + (0.923 cancov) \quad (10)$$

where *clay* is the fraction of clay content of upper 4 cm of surface soil (g g^{-1}); *gcover* is the fraction of total ground cover inside and outside of the canopy (m^2 m^{-2}) including rock and gravel >5 mm, litter in contact with the soil surface, basal area, and cryptogams; and *cancov* is the fraction of standing live and dead canopy cover (m^2 m^{-2}). Comparisons of the data showed that for similar levels of cover and soils, K_{es} was approximately 20% less for the sodgrasses compared to the bunchgrasses, forbs, and annuals, while K_{es} was approximately 20% greater for the shrubs. Hence, we suggest adjusting the K_{es} value computed by equation 10 by 1.2 and 0.8, respectively, when using the model for shrub and sodgrass communities. Furthermore, data from past experimental comparisons have indicated that the K_{es} value as derived from the rainfall simulator data must be multiplied by approximately 0.3 in order to be applicable for the same soils and site conditions when applied to natural rainfall storm conditions (Risse et al., 1995; Nearing et al., 1996), i.e., K_e (mm h^{-1}) = $0.3K_{es}$. This is discussed in more detail below.

Similar to the determination of K_e, we found no statistical difference in this dataset between the bunchgrass data and the annuals and forbs data for K_{ss}. Hence, they were treated together, producing the following equation:

$$K_{ss} = 10\text{\^{}}(3.13 - 0.506 litter - 0.201 cancov) \quad (11)$$

where *litter* is the fraction of the ground surface covered by litter (m^2 m^{-2}). The sod grass data indicated that the K_{ss} values were approximately a factor of 1.5 times the value for bunch grasses under roughly similar soil and vegetation conditions, with similar sensitivities to the cover terms. The shrubs were much different, with sensitivities of K_{ss} to surface rock cover (m^2 m^{-2} of greater than 5 mm material) and litter:

$$K_{ss} = 10\text{\^{}}(4.01 - 1.18 rokcov - 0.982 litter) \quad (12)$$

For undisturbed sites, rills are not generally active in many rangeland situations. More work is needed in order to define parameters for RHEM under situations where concentrated flow is active, and disturbed rangeland sites are not discussed in this article. However, even under undisturbed conditions, analysis has shown (Nearing et al., 1989b) a relatively small, but significant, increase in sediment loads as a function of flow rates. Thus, for undisturbed sites, we use relatively small, baseline values of K_c (0.000477 m s^{-1}) and τ_c (1.23 Pa) in this study based on average results from WEPP rangeland experiments (Laflen et al., 1991) for the purposes of model evaluation.

STATISTICS

Statistics used for model evaluation included standard linear regression and Nash-Sutcliffe model efficiency (Nash and Sutcliffe, 1970). Model efficiency is a measure of the measured vs. predicted values, where an efficiency of 1 indicates a perfect fit and a value of zero indicates that the predictive equation performs no better than using the average of measured values.

MODEL EVALUATION

A set of rainfall simulation experiments at six sites located south of Tucson, Arizona, was conducted to collect data for model evaluation (table 2). Estimation equations developed for each plant form group were used in the model evaluation. The plot sizes for evaluation were of a similar order, and the experimental procedures were similar to those of the large plots from the WEPP-IRWET database as well as for the splash and sheet erosion equation we developed for RHEM (Wei et al., 2009). The sediment load also fell within the range of the WEPP-IRWET dataset, i.e., 0 to 2.0 ton ha^{-1}.

Figure 2 shows that the regression slope was 1.0075, the coefficient of determination (r^2) was 0.87, and the Nash-Sutcliffe model efficiency (E) was 0.83, which indicates that runoff volumes from RHEM were quite close to the observed volumes. The slope of 0.81, r^2 of 0.50, and E of 0.21 in figure 3 show that the sediment prediction is overall acceptable in that it was capable of explaining 50% of the variance in the data and the model efficiency was greater than zero. The somewhat lower level of fit for erosion compared to runoff volumes was not unexpected because the accuracy of the sediment prediction is dependent on multiple factors, such as accuracy of the runoff prediction, uncertainty in the parameter estimation equations for both K_e and K_{ss}, and the sediment detachment equations. Furthermore, it has been shown that higher uncertainty is associated with lower soil loss predictions due to the natural variability within a replicated treatment (Nearing et al., 1999; Nearing, 2000). The erosion rates measured here were relatively low because the sites were undisturbed. More experiments and data collection are needed to improve RHEM and test the model

Table 2. Experimental plots used for model evaluation.

Site	No. of Plots	Average Slope (%)	Soil Texture	Dominant Plant Form
ER2	4	12.9	Sandy loam	Bunch grass
ER3	4	13.6	Sandy loam	Bunch grass
ER4	4	4.3	Sandy loam	Bunch grass
Kreen	4	10.8	Sandy loam	Bunch grass
LH	4	15.8	Sandy loam	Shrub
Tank	4	22.0	Clay loam	Bunch grass

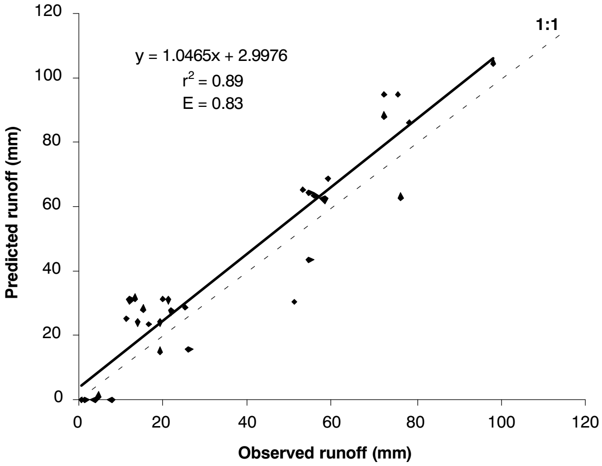

Figure 2. Runoff volume predicted from RHEM vs. observed values from the evaluation data sets (r^2 is the coefficient of determination, and E is the Nash-Sutcliffe efficiency coefficient).

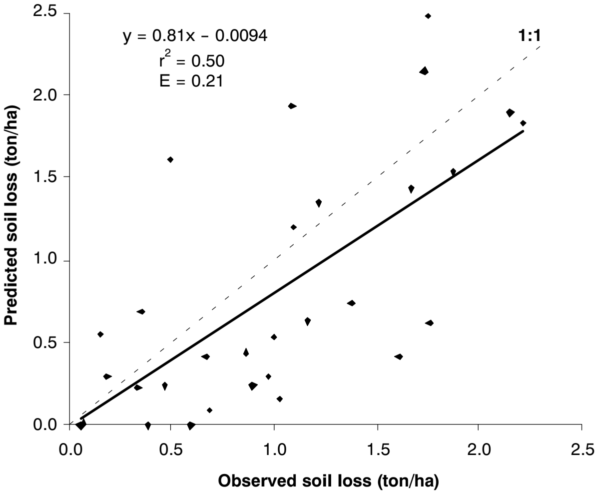

Figure 3. Soil loss values predicted from RHEM vs. observed soil loss from the evaluation data sets (r^2 is the coefficient of determination, and E is the Nash-Sutcliffe efficiency coefficient).

prediction on other vegetation types and for larger soil loss events.

DISCUSSION

Our scientific understanding of soil erosion processes on rangelands, as well as the inherently different management questions asked in regard to rangelands, suggests the need for the development and use of erosion models for rangeland management and assessment that are different from models developed for croplands. Toward that end, this study was undertaken to develop a Rangeland Hydrology and Erosion Model (RHEM) that incorporates the up-to-date scientific understanding of hydrology and erosion processes on rangelands. This article reports a first step in that process.

The research problems associated with building an erosion model appropriate for rangeland applications include how to correctly characterize the rangeland hydrology and erosion processes, how to structure model concepts and model equations to represent these processes, and how to address management effects specific to rangelands. In addition, the model should maintain a balance between being complete enough to represent the important and complex processes of nature and being user-friendly so as to be easily applied. For a model to be useful for prediction purposes requires that sufficient amounts of data are available and used to develop the parameter estimation equations needed to apply the model at unmeasured sites with some level of confidence.

A key concept of RHEM is that splash erosion and thin sheet-flow transport act as the dominant set of processes on undisturbed rangeland sites. For purposes of representing and parameterizing the sheet and splash erosion model, the area of consideration is of the order of a minimum of 12 to 50 m^2 in size, which is large enough to encompass some of the higher levels of heterogeneity found on rangeland hillslopes as compared to cropland slopes. The size of the rainfall simulator plots used as a basis for the RHEM parameter equations (32.7 m^2) falls in the appropriate scale range.

Dominant erosion processes vary with rangeland conditions. As an example, Tongway and Ludwig (1997) compared the water flow on good-condition grassland vs. degraded grassland. Tortuous and uniformly distributed flow form on dense grassland, and long straight fetches, often representing areas of concentrated flow, were found on the degraded grasslands with few tussocks. After disturbances such as fire, long-term severe drought, and severe overgrazing, degraded rangeland sites also show different dominant erosion processes. Disturbances can reduce the protective vegetation cover on rangeland soil surfaces and change the soil structure and topography such that the dominant erosion process may shift from splash and sheet erosion to rill erosion. Pierson et al. (2002) examined the fire impacts with simulated rainfall on sagebrush-dominated foothills near Boise, Idaho, and found high concentrations of rills and significant increases in soil loss rates on the burned slopes. To represent erosion on sites with significant disturbances, and where concentrated flow erosion plays a significant role, the RHEM model has the capacity to combine splash and sheet erosion with concentrated flow erosion based on the degree of the system disturbance. For purposes of model application, a "disturbed site" is simply one that exhibits appreciable erosion by concentrated flow, which is a condition that can be induced by disturbances such as fire, rain on snow and thawing soil, mechanical disturbance, or an unusual amount of cover removal for any reason. The data used for this study did not include disturbed sites. Work is underway to improve the model for use in disturbed conditions.

Two previous studies have compared Green-Ampt model infiltration parameters derived from rainfall simulation experiments to those derived from natural rainfall events on hillslopes. Nearing et al. (1996) and Risse et al., (1995) reported simulator-measured Green-Ampt conductivities on data from 30 soils compared to Green-Ampt parameters optimized using the WEPP model and natural runoff data from the same soils. In general, the simulator K_e values were greater, most of them by a factor ranging from 2 to 4 times. All of these soils were in humid climates and used for crop production rather than animal grazing. Burns (2010) reported results from application of the KINEROS2 model (Goodrich et al., 2006) to simulator plots and hillslopes under natural rainfall in southern Arizona rangelands. KINEROS2 uses the Smith-Parlange (Smith et al., 1995) model for infiltration, which is an extension and conceptual improvement of the Green-Ampt model. Burns (2010) reported that the hillslope infiltration value from the simulator data ranged from 3 to 6 times greater than the value calibrated for the hillslopes. As mentioned above, for RHEM, we recommend that the values of K_{es} reported in this article be reduced by a factor of 0.3 when applied to natural rainfall conditions.

IMPLICATIONS, CONCLUSIONS, AND FUTURE DIRECTIONS

A Rangeland Hydrology and Erosion Model (RHEM) was developed in order to fill the need for a process-based rangeland erosion model that can function as a practical tool for quantifying runoff and erosion rates specific to western U.S. rangelands in order to provide reasonable runoff and soil loss prediction capabilities for rangeland management and research. It was designed for government agencies, land managers, and conservationists who need sound, science-based technology to model and predict erosion processes on rangelands and assess rangeland conservation practices effects.

RHEM represents a modified and improved (for rangeland application) version of the WEPP model code specific for rangeland application and based on fundamentals of infiltration, hydrology, plant science, hydraulics, and erosion mechanics. When linked with appropriate data, plant information, and management models, RHEM should be capable of capturing the mechanics of how plant species, disturbances (such as fire), climate change, and management practices affect erosion rates on rangelands.

Individual evaluation experimental data indicated the ability of RHEM to predict runoff and sediment from undisturbed rangeland surfaces. More work is in progress on collecting more data, describing and quantifying disturbed rangelands, and testing the model efficiency in predicting larger soil loss events. Work is also underway to produce a working continuous simulation model specific to rangeland plants and soils.

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