# A New Splash and Sheet Erosion Equation for Rangelands

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Soil loss rates predicted from erosion models for rangelands have the potential to be important quantitative indicators for rangeland health and for assessing conservation practices. Splash and sheet erosion processes on rangelands differ from croplands, where the process is conceptualized in part as interrill erosion. Previous interrill equations were developed from cropland soils where interrill erosion was conceptualized and modeled for small plots, which are not generally large enough to encompass the relative high spatial heterogeneity of rangelands. Also, interrill erosion is usually modeled as a function of rainfall intensity ($I$) and runoff rate ($q$) such that $I$ and $q$ are independent of each other. Splash and sheet erosion is the dominant type of erosion on most undisturbed rangeland hillslopes where there is adequate vegetation, and these important erosion processes need to be addressed to develop an appropriate rangeland erosion model. In this study, we developed a new equation for calculating the combined rate of splash and sheet erosion ($D_{ss}$) using a large set of rainfall simulation data from the western United States. The equation we propose: $D_{ss} = K_{ss}I^{1.052}q^{0.592}$, where $K_{ss}$ is a splash and sheet erosion coefficient, takes into account a key interrelationship between $I$ and $q$ revealed in the data. This equation was successfully evaluated using independent sets of multiple-intensity experimental data. The new equation should enable improved estimation of water erosion on rangelands in the western United States and in other parts of the world.

Abbreviations: IRWET, Interagency Rangeland Water Erosion Team; WEPP, Water Erosion Prediction Project.

Rangelands cover nearly 50% of the Earth's land surface (Williams et al., 1968) and are characteristically located in arid and semiarid climates. Soils on arid and semiarid rangelands tend to be shallow, with low organic matter and poor structure, and often have relatively sparse vegetation coverage (Wight and Lovely, 1982). Tolerable soil loss rates for rangeland soils are often lower than those for most cultivated soils due to their shallower topsoil depth and the slow rates of soil formation that occur in dry climates.

The soil surface loss rate on rangelands is considered as one of the quantitative indicators of rangeland health (Pyke et al., 2002; Pellant et al., 2005), where rangeland health is defined as the degree to which the integrity of the soil and ecological processes of rangeland ecosystems are maintained (National Research Council, 1994). Reliable published data on measured soil loss rates from rangelands are few in comparison with data collected on croplands. The rangeland data that have been collected, such as that at El Reno, OK (Schoof, 1983; Garbrecht, 2008; Zhang, 2005), Reynolds Creek, ID (Pierson et al., 2001), Tombstone, AZ (Nearing et al., 2007), and Riesel, TX (Williams and Knisel, 1971; Jones et al., 1985) have tended to be from plots and small watersheds where total erosion rates are measured, and the results were not generally oriented toward developing process-based models.

Erosion rates on rangelands tend to be relatively low compared with those on cropland soils (USDA, 2000). Under certain conditions, however, the rates can be significant. Measurements of sediment yields from seven unit source (0.02–0.054-km$^2$) watersheds in the USDA-ARS Walnut Gulch Experimental Watershed near Tombstone, AZ, between 1995 and 2005 indicated a range between 7 and 566 g m$^{-2}$ yr$^{-1}$ (0.07 and 5.66 t ha$^{-1}$ yr$^{-1}$) (Nearing et al., 2007). Similar measurements by the USDA-ARS at the University of Arizona Santa Rita Experimental Range, located south of Tucson, have shown sediment yield values between 6 and 421 g m$^{-2}$ yr$^{-1}$ (0.06 and 4.21 t ha$^{-1}$ yr$^{-1}$) (Lane and Kidwell, 2003). Even fewer measurements of on-site erosion rates have been documented under natural rainfall conditions to quantify hillslope soil loss rates. Estimates of soil loss measured by $^{137}$Cs on hillslopes within two small watersheds located in the Walnut Gulch Experimental Watershed gave estimates of mean erosion rates in eroding areas of 560 and 320 g m$^{-2}$ yr$^{-1}$ (5.6 and 3.2 t ha$^{-1}$ yr$^{-1}$) (Ritchie et al., 2005; Nearing et al., 2005). Maximum erosion rates within the watersheds were calculated at >100 g m$^{-2}$ yr$^{-1}$ (10 t ha$^{-1}$ yr$^{-1}$). These results suggest that rangeland erosion rates can be significant under certain conditions.

Erosion models are widely used tools to predict soil loss rates. Splash and sheet erosion causes the removal of soil in thin layers and is driven by both raindrop splash and overland flow, with both contributing to detachment and transport processes. The combined processes may also be referred to as rain-impacted

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flow (Kinnell, 1991, 1993a,b). Splash and sheet erosion are important erosion processes to model because they dominate on many undisturbed rangeland hillslopes with adequate vegetation cover. In previous erosion models, such as the Water Erosion Prediction Project (WEPP), *interrill erosion* was the term used to account for splash and sheet erosion; however, interrill erosion is not an optimum concept for applications to rangelands for several reasons. For one, the data used to derive the interrill equations in the past were taken exclusively under cropland conditions (Kinnell, 1993a,b; Truman and Bradford, 1995; Zhang et al., 1998; Parsons and Stone, 2006), which are usually different from rangeland conditions in terms of both their basic characteristics (Herrick et al., 1999) and their management (Gebhardt, 1982). Second, the spatial distribution and heterogeneity of vegetation under range conditions are quite different from croplands (Bartley et al., 2006; Ludwig et al., 2007). Finally, interrill-based models have used the concept of a "baseline" condition, which is usually a freshly tilled area bare of vegetative cover (Laflen et al., 1991). Such a condition does not make sense for rangeland soils.

The objective of this study was to develop a new splash and sheet erosion equation, taking into account the interaction between rainfall and runoff responses, based on a large set of representative rangeland rainfall simulation plots. A series of field-based, multiple-intensity, rainfall simulator experiments were conducted to evaluate the new relationship. Finally, a comparison of soil loss predictions from the new equation with estimations from the WEPP model was conducted to show the improved ability of the new equation in predicting soil erosion from rangeland.

## A REVIEW OF INTERRILL EQUATIONS

There have been many efforts to model interrill erosion since Nichols and Sexton (1932) found that rainfall intensity was more important than the amount of rainfall in causing erosion. Based on experiments with a series of rainfall storms at different intensities on a wide range of agricultural soils, Meyer (1981) found that the relationship between interrill soil erosion and rainfall intensity could be expressed as an exponential function:

$$E = aI^{b} \qquad [1]$$

where $E$ (t ha$^{-1}$ h$^{-1}$) is the soil loss rate, $I$ (mm min$^{-1}$) is the rainfall intensity, $b$ is an exponential coefficient, and $a$ was later defined as an erodibility factor that accounts for the soil and surface condition. From Meyer's experiments, $b$ ranged from 1.63 to 2.30, and except for soils with very high clay content, $b$ was near 2. Equation [1] was then simplified into

$$D_{\mathrm{i}} = K_{\mathrm{i}} I^{2} \qquad [2]$$

and used in the original version of the WEPP model as the interrill erosion equation, with $a$ substituted by $K_{\mathrm{i}}$ (kg s m$^{-4}$), the interrill erodibility, and $E$ substituted by $D_{\mathrm{i}}$ (kg m$^{-2}$ s$^{-1}$), the interrill erosion rate (Nearing et al., 1989).

Kinnell (1991) and others proposed that the runoff rate effect on sediment delivery should not be ignored and the interrill erosion should combine the influence of both rainfall and runoff. To account for this, Eq. [3] was adopted in the current version of the WEPP model with $q$ (m s$^{-1}$) as the interrill runoff rate (Flanagan and Nearing, 1995):

$$D_{\mathrm{i}} = K_{\mathrm{i}} I q \qquad [3]$$

Several other interrill erosion equations have been developed and evaluated (Kinnell, 1993a,b; Truman and Bradford, 1995; Zhang et al., 1998; Parsons and Stone, 2006), and they all are of a form similar to

$$D_{\mathrm{i}} = K_{\mathrm{i}} I^{\alpha} q^{\beta} \qquad [4]$$

but with different coefficients $\alpha$ and $\beta$. A common problem with all the previous interrill equations, however, is that they were all developed based on the assumption that $I$ and $q$ are independent of each other, so that $\alpha$ and $\beta$ could be optimized individually. As pointed out by Huang (1995), this is not an optimum method since there are strong interactions between rainfall and runoff response.

Also, all the previous interrill erosion equations were developed from either cropland runoff plots or laboratory pans filled with cropland-derived agricultural soils. Rangeland soils are different from agricultural soils in that they are generally consolidated, uncultivated, and shallower, and often contain lower organic matter content. On croplands, erosion tends to be dominated by a combination of rill and interrill erosion, with rills capable of generating a significant amount of erosion (Meyer et al., 1975; Dabney et al., 1993), while on rangelands, the surface water flow often tends to be tortuous and spreads as it moves across the hillslope. The vegetation hummocks and complex slopes also tend to absorb the water and sediment in transit so that less water is available to form concentrated flow, thus significant rilling does not occur readily under most undisturbed situations. On most undisturbed rangelands, rainfall splash and sheet erosion dominate erosion.

In addition, there is an issue with the representative plot size being used for modeling interrill erosion. Most interrill plots are of a size of approximately 0.6 by 1.2 m, which might be appropriate for agricultural land but is not large enough for representing rangeland conditions. Rangeland surfaces are more complex compared with surfaces with uniformly arranged crops and tilled soil. Rangeland surfaces are often rocky and covered by plant residue, evidence of animal activities, and various rangeland plants that are irregularly distributed, usually in a naturally "patchy" arrangement (Bartley et al., 2006; Ludwig et al., 2007). The high natural heterogeneity associated with rangeland surfaces requires a larger representative plot to measure and model rangeland splash and sheet erosion.

## METHODS AND DATA

Erosion data on rangelands is limited compared with that on croplands. An immense data set that exceeded 15,000 plot-years of soil erosion and runoff measurements was collected on croplands for developing the empirically based Universal Soil Loss Equation (Wischmeier and Smith, 1978). The WEPP project, which aimed to develop a process-based model, designed and conducted rainfall simulation experiments on croplands as well as on rangelands (Laflen et al., 1991), but the rangeland data were only used to optimize the erosion parameters and to develop parameter estimation equations, rather than to develop erosion equations for rangelands (Nearing et al., 1989). In WEPP, the core erosion equations developed from cropland were used for rangelands, including the empirical interrill equation (Eq. [3]).

The method used in this study to develop a new splash and sheet erosion equation also takes an empirical approach, but used a larger data set specifically from rangeland soil measurements. 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, as well as data collected by the Interagency Rangeland

Water Erosion Team (IRWET) in 1990, 1991, and 1992 (Franks et al., 1998). The IRWET project was coordinated closely with WEPP model development so that the experimental design and the data format were compatible with that of WEPP. The WEPP-IRWET rangeland data set is a valuable erosion database that contains measurements of simulated rainfall, soil, plant properties, runoff, and sediment discharge on 204 plots from 49 rangeland sites distributed across 16 western states (Fig. 1). Plot sizes were 3.06 by 10.7 m. Table 1 shows that the database covers a wide range of rangeland soil types. For detailed information on WEPP and IRWET experiment design, see Laflen et al. (1991, 1997) and Pierson et al. (2002).

The methodology for creating the new splash and sheet erosion equation was to first evaluate the relationships from the plot data between rainfall intensity ($I$ in m s$^{-1}$), runoff rate ($q$ in m s$^{-1}$), and sediment discharge ($D_{ss}$ in kg m$^{-2}$ s$^{-1}$) under steady-state conditions, and then develop a single erosion equation. We used the very wet run measurements in the WEPP-IRWET database because they were designed for multiple rainfall intensities. The very wet run started with a rainfall intensity around 60 mm h$^{-1}$, which was increased to ~120 mm h$^{-1}$ and then returned to 60 mm h$^{-1}$. All changes in rainfall intensity were imposed only after steady-state runoff from the plots was reached. Although there were only two rainfall intensities in the experiments, the WEPP-IRWET data set covered many rangeland soils and vegetation conditions in the western United States. To analyze the relationships between rainfall intensity, runoff rate, and sediment discharge, we developed individual relationships among the three variables and derived the final equation by combining the resultant relationships. There were two replicated plots for each site in the WEPP data set, and six replicated plots for each site in the IRWET data set. Thus, there were either six (for WEPP data) or 18 (for IRWET data) sets of steady-state runoff discharge, sediment discharge, and the rainfall intensities available for examining the relationships between $I$, $q$, and $D_{ss}$.

To evaluate our equation developed based on this data set, we conducted another set of rainfall simulation experiments in 2007 using five rainfall intensities: 60, 100, 120, 160, and 180 mm h$^{-1}$. The measured soil loss, rainfall intensity, and runoff rate were used to evaluate the dependence of the erosion rate on runoff and rainfall intensity as derived from the WEPP-IRWET data set. The experiments were done on three 2- by 6-m grassland plots in a rangeland watershed located south of Tucson, AZ. The soils in all three plots were gravelly sandy loam and the vegetation type was short grass. The slopes were 14.6, 11, and 10.7%, with grass covers of 46, 30, and 38%, respectively, for Plots A, B, and C.

# RESULTS AND DISCUSSION

## Equation Development

Exponential relationships were derived between $D_{ss}$ and $I$, $D_{ss}$ and $q$, and $q$ and $I$ from the 49 sites of the WEPP-IRWET rainfall simulation data set. Figure 2, as an example, shows $D_{ss}$ vs. $q$ and $D_{ss}$ vs. $I$ for Site B190. At this site, the sediment discharge increased exponentially as the runoff rate increased ($r^2 = 0.73$) and also as the rainfall intensity increased ($r^2 = 0.53$). In Fig. 3, runoff rate was plotted against the rainfall intensity for the same site, and the $r^2$ of the exponential relationship between these two variables was 0.54. The exponential coefficient as well as the $r^2$ value of each relationship varied at different sites. Table 2 gives the average $r^2$ and the statistics on the three empirically derived exponents for the dependence of $D_{ss}$ on $I$, $D_{ss}$ on $q$, and $q$ on $I$ ($e_1$, $e_2$, and $e_3$, respectively) for all the sites. The average $r^2$ values of 0.52, 0.62, and 0.64 indicate the significance of the three relationships, and the average values of $e_1$, $e_2$, and $e_3$ were 2.162, 1.152, and 1.731, respectively, with CVs <60%. These three averaged exponent values were used as a basis for developing the splash and sheet erosion equation.

Assuming the validity of the exponential form of the relationships

**Fig. 1. Distribution of Water Erosion Prediction Project (WEPP) and Interagency Rangeland Water Erosion Team (IRWET) study sites.**

discussed above, dependencies between $D_{ss}$, $I$, and $q$ may be expressed in general form as

$$D_{ss}=c_1I^{e_1} \qquad [5]$$

$$D_{ss}=c_2q^{e_2} \qquad [6]$$

$$q=c_3I^{e_3} \qquad [7]$$

where $c_1$, $c_2$, and $c_3$ are constant coefficients. Substituting Eq. [7] into Eq. [6] results in

$$D_{ss}=c_2c_3^{e_2}I^{e_3e_2} \qquad [8]$$

which suggests that the exponent $e_1$ in Eq. [5] should be equivalent to the multiple $e_3e_2$. Using the average empirical exponents from the analyses of the data (Table 2), we found that $e_3e_2 = 1.731 \times 1.152 = 1.994$, while $e_1 = 2.162$. The difference between the values is due to expected random variation in the data, since each was derived independently.

To balance the equation, we optimized the sets of equations by introducing a constant $x$ to reduce 2.162 and increase 1.731 and 1.152 (i.e., substituting the three numbers with $2.162/x$, $1.731x$, and $1.152x$, respectively) so as to make the equation set internally consistent. The value of $x$ was computed as 1.027 and new balanced equations were obtained so that internal consistency was obtained:

$$D_{ss}=c_1I^{2.162/1.027}=c_1I^{2.104} \qquad [9]$$

$$D_{ss}=c_2q^{(1.152)1.027}=c_2q^{1.183} \qquad [10]$$

$$q=c_3I^{(1.731)1.027}=c_3I^{1.778} \qquad [11]$$

In other words, the values of the exponents were adjusted by 2.7% to create a mathematically consistent set of equations.

The relationship between $q$ and $I$ is important when developing an equation of $D_{ss}$ from $q$ and $I$. Our data showed that there was strong interaction between runoff rate and rainfall intensity (Fig. 4). For 38 out of 49 sites, the $r^2$ of relationship $q = c_3I^{e3}$ was >0.5. To develop an erosion equation that combines the effects of rainfall intensity and runoff, we consider it to be important that such interaction between the two factors should be accounted for.

It was clear from the regression statistics that $D_{ss}$ was statistically related to both $I$ and $q$, and that the exponential form of the relationship was satisfactory. Thus, the new splash and sheet erosion equation takes the form of

$$D_{ss}=K_{ss}I^{e_4}q^{e_5} \qquad [12]$$

**Table 1. Study site descriptions.**

| Site ID† | No. of replicated plots | State | City | Soil name | Soil texture |
|---|---|---|---|---|---|
| A187 | 2 | AZ | Tombstone | Stronghold | sandy loam |
| A287 | 2 | AZ | Tombstone | Forest | sandy clay loam |
| B187 | 2 | NV | Nevada Test Site | (Durorthid) | sandy loam |
| B287 | 2 | NV | Nevada Test Site | (Durorthid) | sandy loam |
| C187 | 2 | TX | Sonora | Purves | cobbly clay |
| D187 | 2 | OK | Chickasha | Grant | loam |
| D188 | 2 | OK | Chickasha | Grant | loam |
| D287 | 2 | OK | Chickasha | Grant | sandy loam |
| D288 | 2 | OK | Chickasha | Grant | sandy loam |
| E588 | 2 | OK | Woodward | Woodward | sandy loam |
| F187 | 2 | MT | Sidney | Vida | loam |
| G187 | 2 | WY | Meeker | Degater | silty clay |
| H187 | 2 | SD | Cottonwood | Pierre | clay |
| H188 | 2 | SD | Cottonwood | Pierre | clay |
| H287 | 2 | SD | Cottonwood | Pierre | clay |
| H288 | 2 | SD | Cottonwood | Pierre | clay |
| I187 | 2 | NM | Los Alamos | Hackroy | sandy loam |
| J187 | 2 | NM | Cuba | Querencia | sandy loam |
| K187 | 2 | CA | Susanville | Jauriga | sandy loam |
| K188 | 2 | CA | Susanville | Jauriga | sandy loam |
| K288 | 2 | CA | Susanville | Jauriga | sandy loam |
| K287 | 2 | CA | Susanville | Jauriga | sandy loam |
| L188 | 2 | CA | Los Banos | Apollo | clay loam |
| B190 | 6 | NE | Wahoo | Burchard | loam |
| B290 | 6 | NE | Wahoo | Burchard | loam |
| C190 | 6 | TX | Amarillo | Olton | loam |
| C290 | 6 | TX | Amarillo | Olton | loam |
| E191 | 6 | KS | Eureka | Martin | silty clay loam |
| E291 | 6 | KS | Eureka | Martin | silty clay loam |
| E391 | 6 | KS | Eureka | Martin | silty clay |
| F191 | 6 | CO | Akron | Stoneham | loam |
| F291 | 6 | CO | Akron | Stoneham | fine sandy loam |
| F391 | 6 | CO | Akron | Stoneham | loam |
| G191 | 6 | WY | Newcastle | Kishona | very fine sandy loam |
| G291 | 6 | WY | Newcastle | Kishona | clay loam |
| G391 | 6 | WY | Newcastle | Kishona | very fine sandy loam |
| H192 | 6 | ND | Killdeer | Parshall | sandy loam |
| H292 | 6 | ND | Killdeer | Parshall | fine sandy loam |
| H392 | 6 | ND | Killdeer | Parshall | fine sandy loam |
| I192 | 6 | WY | Buffalo | Forkwood | silt loam |
| I292 | 6 | WY | Buffalo | Forkwood | loam |
| J192 | 6 | ID | Blackfoot | Robin | silt loam |
| J292 | 6 | ID | Blackfoot | Robin | silt loam |
| K192 | 6 | AZ | Prescott | Lonti | sandy loam |
| K292 | 6 | AZ | Prescott | Lonti | sandy loam |
| L193 | 6 | CA | San L Obispo | Diablo | clay loam |
| L293 | 6 | CA | San L Obispo | Diablo | clay loam |
| M193 | 6 | UT | Cedar City | Taylors Flat | sandy loam |
| M293 | 6 | UT | Cedar City | Taylors Flat | sandy loam |

† The last two digits of Site ID indicate the year of the experiment.

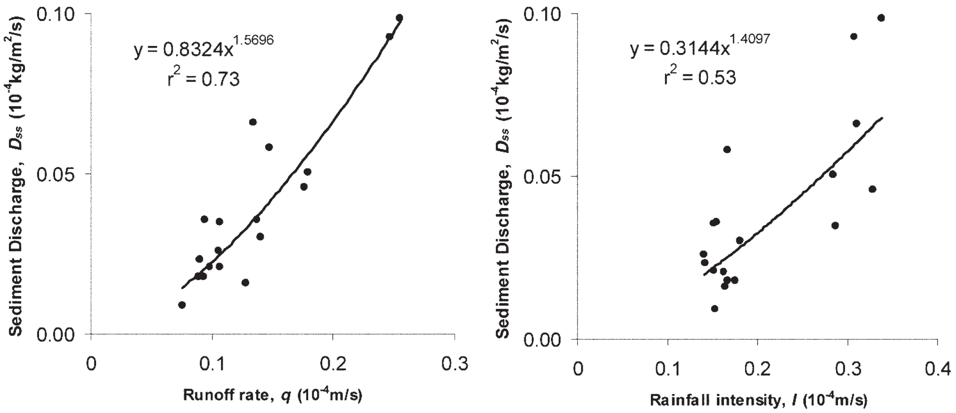

**Fig. 2. Exponential relationships between sediment discharge ($D_{ss}$) and runoff rate, and between $D_{ss}$ and rainfall intensity for Site B190 ($n$ = 18).**

where $K_{ss}$ is the splash and sheet erosion coefficient representing the effect of soil characteristics and surface conditions. In other words, one could use Eq. [9] or [10] to estimate the value of $D_{ss}$ in an erosion model. We consider the use of both $I$ and $q$ in the same equation to be superior, however, as the two terms together better account for the interdependent processes of detachment by splash and transport by rain-impacted flow (Kinnell, 1993a,b).

Assuming the utility of the form of Eq. [12], we can derive the values of $e_4$ and $e_5$. Maintaining the same weightings for the two terms in Eq. [12] as in Eq. [9–10], which were derived from the data, the ratio of $e_4/e_5$ should be equivalent to the ratio of the exponents from Eq. [9–10], the value of which is 1.778. Thus, substituting $I$ for $q$ in Eq. [11] results in $D_{ss} = K_{ss}I^{e4}q^{e5} = K_{ss}I^{1.778e5}q^{e5}$. Further substitution using either Eq. [9] or [10] resulted in a value of 1.052 for $e_4$ and 0.592 for $e_5$. Thus the final equation for rangeland splash and sheet erosion, which relates $D_{ss}$ to both $I$ and $q$, was obtained as

$$D_{ss} = K_{ss} I^{1.052} q^{0.592} \qquad [13]$$

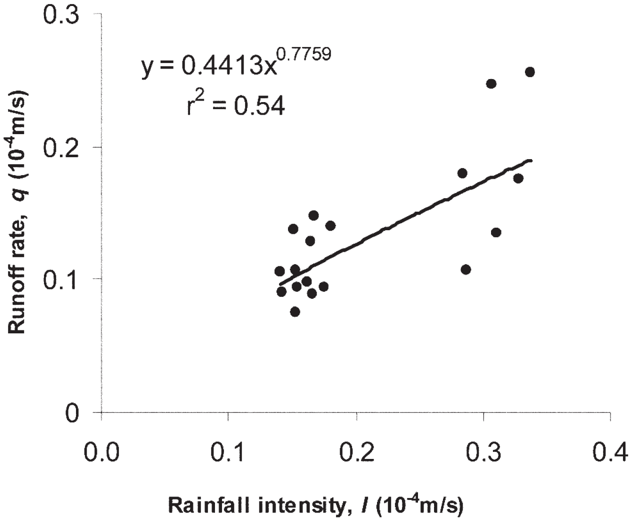

**Fig. 3. Exponential relationships between runoff rate and rainfall intensity for Site B190 ($n$ = 18).**

The values for $K_{ss}$ can be determined from the erosion data at each plot using Eq. [13]. Factors such as slope, vegetation, and soil characteristics will affect the $K_{ss}$ value.

## Model Evaluation: Comparison with Multiple-Intensity Data

The evaluation experiments were designed for evaluating the new equation using five rainfall intensity scenarios. Only splash and sheet erosion with no apparent rilling was observed during the evaluation experiments. The measured soil loss rates were plotted against the product of $I^{1.052}q^{0.592}$ for the three evaluation plots in Fig. 5. The value of $D_{ss}$ exhibited a linear relationship ($r^2$ = 0.88–0.97) with $I^{1.052}q^{0.592}$. The slope of the linear relationships indicated the value of the $K_{ss}$ coefficient, which varied due to the different slopes and cover conditions of the plots. The result from the evaluation experiments verified that our splash and sheet erosion equation worked well for multiple rainfall intensity situations.

## Model Evaluation: Comparison with the WEPP model

To further evaluate the effectiveness of the new equation, we calculated the predicted soil loss rates for 15 randomly selected rainfall simulation events with observed soil loss rates ranging from 0.001 to 0.03 kg m$^{-2}$ s$^{-1}$ using the $K_{ss}$ values obtained for each site. We then compared these results to the corresponding predictions from the WEPP model using the optimized erodibility values for the same sites, following the procedures outlined in the WEPP model user summary and documentation (Flanagan and Nearing, 1995). The predicted soil loss from WEPP combined the interrill erosion and rill erosion, with interrill erodibility obtained from small bare plots and adjusted for cover conditions, and rill erodibility factors optimized from large plot measurements.

Figure 6 shows the predicted and observed soil loss rates from the new equation and the WEPP model. Predicted soil losses from the new equation were closer to the observed soil loss rates than those from the WEPP model and more outliers were present in the WEPP predictions (Fig. 6). This evaluation shows that the new equation improved the predictive ability.

**Table 2. Statistics of the three exponents in the relationships between sediment discharge ($D_{ss}$), rainfall intensity ($I$), and runoff rate ($q$) for 49 sites; $e_1$, $e_2$, and $e_3$ and $c_1$, $c_2$, and $c_3$ are the corresponding exponentials and constant coefficients, respectively.**

| Statistic | $e_1$ in $D_{ss} = c_1 I^{e_1}$ | $e_2$ in $D_{ss} = c_2 q^{e_2}$ | $e_3$ in $q = c_3 I^{e_3}$ |
|---|---|---|---|
| Avg. | 2.162 | 1.152 | 1.731 |
| Min. | 0.720 | 0.261 | 0.219 |
| Max. | 6.03 | 2.52 | 6.21 |
| SD | 1.04 | 0.393 | 1.01 |
| CV, % | 47.9 | 34.1 | 58.4 |
| Avg. $r^2$ | 0.52 | 0.62 | 0.64 |

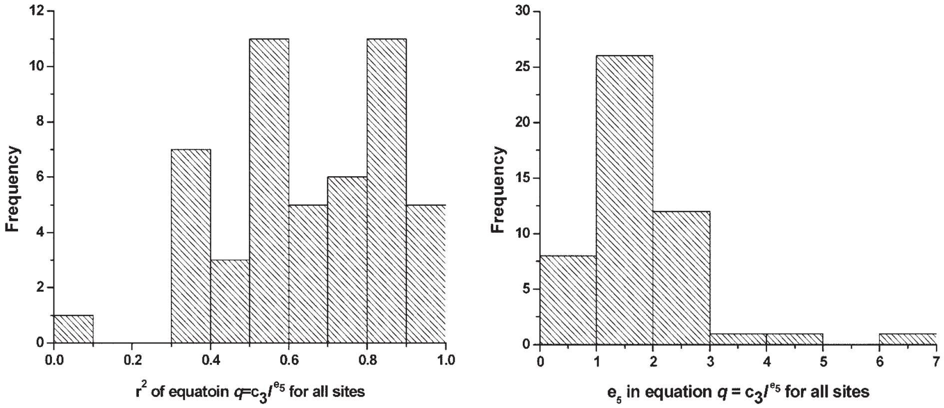

**Fig. 4. The $r^2$ and the exponential coefficient ($e_5$) of the relationship between runoff rate ($q$) and rainfall intensity ($I$); $c_3$ is a constant coefficient.**

## CONCLUSIONS

A new splash and sheet erosion equation, $D_{ss} = K_{ss}I^{1.052}q^{0.592}$, was developed based on the WEPP-IRWET data set, which included rangeland rainfall simulation experimental data collected at 49 sites across the western United States. The new equation relates $D_{ss}$ to both $I$ and $q$ exponentially in a single equation, and implicitly includes the interaction between $I$ and $q$. Such interaction is not only physically sound but also statistically tested from our data set, thus we feel that its inclusion improves the robustness of the new splash and sheet erosion equation. Large plots (3.06 by 10.7 m) were used to develop the new equation to help encompass the greater level of spatial heterogeneity typically found in the rangeland environment. In an independent set of rainfall simulation experiments using five rainfall intensities, the linear relationship between $D_{ss}$ and $I^{1.052}q^{0.592}$ with $r^2 > 0.87$ indicated the validity of our equation for multiple-intensity scenarios. To evaluate the effectiveness of the new equation, we also compared the predicted soil loss from the new equation with that from the WEPP model based on the same input information. Compared with the WEPP predictions, our new equation increased the $r^2$ approximately threefold (0.76 compared with 0.23) and had fewer outliers.

## REFERENCES

Bartley, R., C.H. Roth, J.A. Ludwig, D. McJannet, A.C. Liedloff, J.P. Corfield, A.A. Hawdon, and B.N. Abbott. 2006. Runoff and erosion from Australia's tropical semi-arid rangelands: Influence of ground cover for differing space and time scales. Hydrol. Processes 20:3317–3333.

Dabney, S., C. Murphree, and D. Meyer. 1993. Tillage, row spacing, and cultivation affect erosion from soybean cropland. Trans. ASAE 36:87–94.

Flanagan, D.C., and M.A. Nearing (ed.). 1995. USDA-Water Erosion Prediction Project: Hillslope profile and watershed model documentation. NSERL Rep. 10. Natl. Soil Erosion Res. Lab., West Lafayette, IN.

Franks, C.D., F.B. Pierson, A.G. Mendenhall, K.J.E. Spaeth, and M.A. Weltz. 1998. Interagency Rangeland Water Erosion Project report and state data summaries. NWRC 98-1. USDA-ARS Northwest Watershed Res. Ctr., Boise, ID.

Garbrecht, J.D. 2008. Multi-year precipitation variations and watershed sediment yield in a CEAP benchmark watershed. J. Soil Water Conserv. 63:70–76.

Gebhardt, K.A. 1982. Use of erosion model on western rangelands. p. 39–45. *In* Proc. Worksh. on Estimating Erosion and Sediment Yield on Rangelands, Tucson, AZ. 7–9 Mar. 1981. USDA ARM-W-26. USDA-ARS, Oakland, CA.

Herrick, J.E., M.A. Weltz, J.D. Reeder, G.E. Schuman, and J.R. Simanton. 1999. Rangeland soil erosion and soil quality: Role of soil resistance, resilience, and disturbance regime. p. 209–233. *In* R. Lal (ed.) Soil quality and soil erosion. Soil Water Conserv. Soc., Ankeny, IA.

Huang, C. 1995. Empirical analysis of slope and runoff for sediment delivery from interrill areas. Soil Sci. Soc. Am. J. 59:982–990.

Jones, O.R., H.V. Eck, S.J. Smith, G.A. Coleman, and V.L. Hauser. 1985. Runoff, soil, and nutrient losses from rangeland and dry-farmed cropland in the southern High Plains. J. Soil Water Conserv. 40:161–164.

Kinnell, P. 1991. The effect of flow depth on sediment transport induced by raindrops impacting shallow flows. Trans. ASAE 34:161–168.

Kinnell, P. 1993a. Runoff as a factor influencing experimentally determined interrill erodibilities. Aust. J. Soil Res. 31:333–342.

Kinnell, P. 1993b. Interrill erodibilities based on the rainfall intensity flow discharge erosivity factor. Aust. J. Soil Res. 31:319–332.

Laflen, J.M., W.J. Elliot, D.C. Flanagan, C.R. Meyer, and M.A. Nearing. 1997. WEPP: Predicting water erosion using a process-based model. J. Soil Water Conserv. 52:96–102.

Laflen, J.M., W.J. Elliot, J.R. Simanton, C.S. Holzhey, and K.D. Kohl. 1991. WEPP: Soil erodibility experiments for rangeland and cropland soils. J.

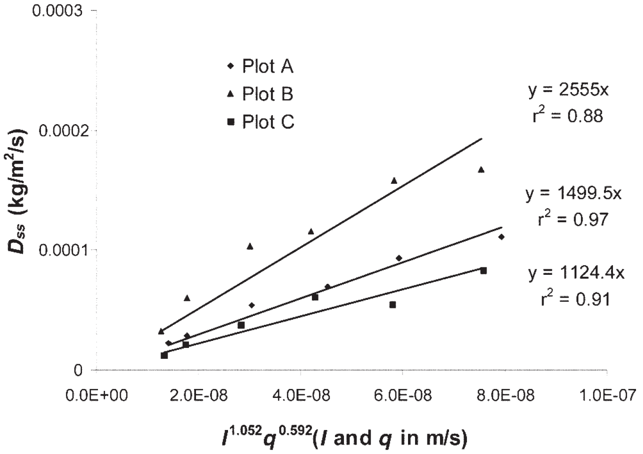

**Fig. 5. Relationships between soil loss ($D_{ss}$) and rainfall intensity/runoff rate ($I^{1.052}q^{0.592}$), as in Eq. [13], using data from a rainfall simulation on a 2- by 6-m grassland rangeland plot in Arizona.**

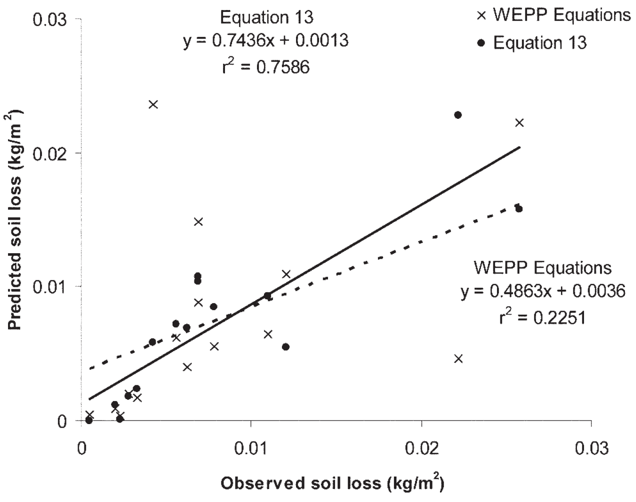

**Fig. 6. Comparison of soil loss predictions from the new splash and sheet erosion equation and those from the Water Erosion Prediction Project (WEPP) model based on rainfall simulation plot data ($n$ = 15), suggesting that the new equation provided better predictions.**

Soil Water Conserv. 46:39–44.

Lane, L.J., and M.R. Kidwell. 2003. Hydrology and soil erosion. p. 92–100. *In* Santa Rita Experimental Range: 100 Years (1903 to 2003) of Accomplishments and Contributions, Conf. Proc., Tucson, AZ. 30 Oct.–1 Nov. 2003. RMRS-P-30. U.S. For. Serv. Rocky Mtn. Res. Stn., Fort Collins, CO.

Ludwig, J.A., R. Bartley, A.A. Hawdon, B.N. Abbott, and D. McJannet. 2007. Patch configuration non-linearly affects sediment loss across scales in a grazed catchment in north-east Australia. Ecosystems 10:839–845.

Meyer, L.D. 1981. How rain intensity affects interrill erosion. Trans. ASAE 24:1472–1475.

Meyer, L.D., G.R. Foster, and S. Nikolov. 1975. Effect of flow rate and canopy on rill erosion. Trans. ASAE 18:905–911.

National Research Council. 1994. Rangeland heath: New methods to classify, inventory, and monitor rangelands. Natl. Acad. Press, Washington, DC.

Nearing, M., G. Foster, L. Lane, and S.C. Finkner. 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. Trans. ASAE 32:1587–1593.

Nearing, M.A., A. Kimoto, M.H. Nichols, and J.C. Ritchie. 2005. Spatial patterns of soil erosion and deposition in two small, semiarid watersheds. J. Geophys. Res. Earth Surf. 110:F04020, doi:10.1029/2005JF000290.

Nearing, M.A., M.H. Nichols, J.J. Stone, K.G. Renard, and J.R. Simanton. 2007. Sediment yields from unit-source semi-arid watersheds at Walnut Gulch. Water Resour. Res. 43:W06426, doi:10.1029/2006WR005692.

Nichols, M.L., and J.D. Sexton. 1932. A method of studying soil erosion. Agric. Eng. 13:101–103.

Parsons, A., and P. Stone. 2006. Effects of intra-storm variations in rainfall intensity on interrill runoff and erosion. Catena 67:68–78.

Pellant, M., P. Shaver, D.A. Pyke, and J.E. Herrick. 2005. Interpreting indicators of rangeland health, version 4. Tech. Ref. 1734–6. BLM/WO/ST-00/001+1734/REV05. Bur. of Land Manage., Denver CO.

Pierson, F.B., C.W. Slaughter, and Z.K. Cram. 2001. Long-term stream discharge and suspended-sediment database, Reynolds Creek Experimental Watershed, Idaho, United States. Water Resour. Res. 37:2857–2861.

Pierson, F.B., K.E. Spaeth, M.A. Weltz, and D.H. Carlson. 2002. Hydrologic response of diverse western rangelands. J. Range Manage. 55:558–570.

Pyke, D.A., J.E. Herrick, P. Shaver, and M. Pellant. 2002. Rangeland health attributes and indicators for qualitative assessment. J. Range Manage. 55:584–597.

Ritchie, J.C., M.A. Nearing, M.H. Nichols, and C.A. Ritchie. 2005. Patterns of soil erosion and redeposition on Lucky Hills watershed, Walnut Gulch Experimental Watershed, Arizona. Catena 61:122–130.

Schoof, R.R. 1983. Hydrology, erosion, and water quality studies in the Southern Great Plains Research Watershed, southwestern Oklahoma 1961–78. USDA-ARS ARM NS-29. U.S. Gov. Print. Office, Washington, DC.

Truman, C., and J.M. Bradford. 1995. Laboratory determination of interrill soil erodibility. Soil Sci. Soc. Am. J. 59:519–526.

USDA. 2000. Summary report: 1997 National Resources Inventory (revised December 2000). USDA, Washington, DC.

Wight, R.J., and C.J. Lovely. 1982. Application of soil loss tolerance concept to rangelands. p. 199–200. *In* Proc. Worksh. on Estimating Erosion and Sediment Yield on Rangelands, Tucson, AZ. 7–9 Mar. 1981. USDA ARM-W-26. USDA-ARS, Oakland, CA.

Williams, J.R., and W.G. Knisel. 1971. Sediment yield from rangeland watersheds in the Edwards Plateau of Texas. USDA-ARS 41-185. U.S. Gov. Print. Office, Washington, DC.

Williams, R.E., B.E. Allred, R.M. Denio, and H.A. Paulsen. 1968. Conservation, development, and use of the world's rangeland. J. Range Manage. 21:355–360.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses: A guide to conservation planning. Agric. Handbk. 537. U.S. Gov. Print. Office, Washington, DC.

Zhang, X.C. 2005. Spatial downscaling of global climate model output for site-specific assessment of crop production and soil erosion. Agric. For. Meteorol. 135:215–229.

Zhang, X.C., M.A. Nearing, W.P. Miller, L.D. Norton, and L.T. West. 1998. Modeling interrill sediment delivery. Soil Sci. Soc. Am. J. 62:438–444.