Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **32**, 998–1012 (2007)
Published online 5 December 2006 in Wiley InterScience
(www.interscience.wiley.com) **DOI:** 10.1002/esp.1467

DWEPP: a dynamic soil erosion model based on WEPP source terms

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Received 10 January 2006; Revised 29 September 2006; Accepted 23 October 2006

Abstract

A new rangeland overland-flow erosion model was developed based on Water Erosion Prediction Project (WEPP) sediment source and sink terms. Total sediment yield was estimated for rainfall simulation plots from the WEPP field experiments as well as for a small watershed without a well developed channel network. Both WEPP and DWEPP gave a similar level of prediction accuracy for total event soil losses measured from both rainfall simulation and small watershed experiments. Predictions for plot and hillslope scale erosion simulations were in the range of expected natural variability. Sediment yield dynamics were plotted and compared with experimental results for plots and hillslope, and the results were satisfactory. Effects of cover and canopy on the predicted sediment yields were well represented by the model. DWEPP provides a new tool for assessing erosion rates and dynamics, has physically based erosion mechanics descriptions, is sensitive to treatment differences on the experimental plots and has a well developed parameter database inherited from WEPP. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: **sediment; rangeland; hillslope; runoff; infiltration; hydrology; hydrologic models; WEPP; KINEROS2; DWEPP**

Introduction

Much research has been conducted on the development of soil erosion assessment tools. These efforts have resulted in both empirically based and process-based models. The former include the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1958) and the Revised Soil Loss Equation (RUSLE) (Renard *et al*., 1997a, 1997b), while the latter is represented by the Water Erosion Prediction Project (WEPP) model (Flanagan *et al*., 2001) and the European Soil Erosion Model (EUROSEM) (Morgan *et al*., 1998). The USLE and RUSLE models are not able to represent deposition processes or sediment pathways well, which are important issues for pollution source identification.

Process based erosion models are characterized by the presence of a governing differential equation (Nearing *et al*., 2001). The kinematic wave model (Morris and Woolhiser, 1980; Woolhiser and Liggett, 1967; Lighthill and Whitham, 1955; Woolhiser, 1973; Singh, 1996; Singh and Woolhiser, 1976), one of the more commonly applied hydrologic models, is used as the basis for runoff routing in KINEROS2 (Woolhiser *et al*., 1990). WEPP hydrology is based on an approximation of the kinematic wave equations (Stone *et al*., 1995). Erosion is represented by a steady-state equation in WEPP; i.e., it is assumed that sediment yield rates during the rainstorm event can be approximated by a steady-state solution using the proper input for peak runoff rates. Therefore, with the WEPP model, it is not possible to quantify within-storm sediment dynamics. The steady-state model does not provide information on peak sediment discharge or the sediment load pattern within a storm, both of which can be useful for assessing potential pollution loadings from sediment fluxes into water courses and identifying sediment sources for designing appropriate management alternatives that reduce sediment losses (Kalin *et al*., 2004).

On the other hand, the WEPP model uses many of the best available soil detachment and deposition concepts. One of the most important of these is shear stress partitioning (Foster, 1982), which adjusts the erosive and transport capacity influences of runoff water depending on surface residue and living plant cover (Gilley *et al*., 1990, 1991;

Gilley and Kottwitz, 1994; Weltz *et al*., 1992). This feature allows for a physically based representation of the effects of land cover on erosion rates.

It is also important that there has been an extensive effort to parameterize the WEPP model (Flanagan *et al*., 1995; Bulygin *et al*., 2002). This research has resulted in a series of estimation equations for the input parameters that require only basic field-measured values. This is a useful characteristic of the model, in that it enables application to ungaged watersheds, i.e. the calibration process can be minimized. Furthermore, quite a large number of validation studies of the runoff and erosion components of WEPP have been conducted in many parts of the world: in Austria (Klik *et al*., 1995; Savabi *et al*., 1996), Brazil (Ranieri *et al*., 1999), Italy (Santoro *et al*., 2002), USA (Savabi *et al*., 1996; Laflen *et al*., 2004; Zhang *et al*., 1996), Ethiopia (Zeleke, 1999) and the Ukraine (Nearing *et al*., 1998).

The intention of this research was to develop a dynamic version of the WEPP model based on kinematic wave routing of runoff and the WEPP source terms equations for erosion coded with a fully dynamic solution. The model was formulated, coded, tested against the steady state solutions and evaluated against measured rainfall simulator and small watershed data from rangelands.

Methods

Overall Approach

Rather than re-code the kinematic wave equations, we utilized the overland flow runoff module in KINEROS2. This offered several advantages, including savings of time and effort in re-coding what had already been accomplished, plus the added advantage that the runoff portion of KINEROS2 has been well tested and validated under a wide variety of conditions. We refer to the new model as the Dynamic Water Erosion Prediction Project (DWEPP) model.

The new model was applied for several different input conditions. The model was applied to rainfall simulation plot data in order to compare the new results with steady-state WEPP results obtained from single storm mode runs, as well as to evaluate the accuracy of the outputs within a framework of measured variability. Also, there was an opportunity to look at sedigraphs and treatment effects on the erosion rates from the plots. After this, we applied the model to a small hillslope-scale watershed with a poorly developed channel network and analyzed the output.

Model Descriptions

Sediment Continuity Equation. Hydrology in KINEROS2 is described by the 1D kinematic wave equation (Woolhiser, 1973; Woolhiser *et al*., 1990), the numerical solution of which gives water discharge at any point in time at any distance along a flow path. The 1D dynamic routing of sediment can be simulated through a numerical solution of the following differential equation (Woolhiser *et al*., 1990):

$$\frac{\partial (CA)}{\partial t} + \frac{\partial (CQ)}{\partial x} = S \tag{1}$$

where
C = sediment concentration (kg/m^3),
A = cross-sectional area of flow (m^2),
Q = flow discharge (m^3/s),
t = time (s),
x = distance downslope (m),
S = source/sink term for sediment (kg/m/s).

Equation (1), with initial and boundary conditions developed below, can be solved numerically by the finite difference method.

Source Term. WEPP differentiates between interrill and rill erosion processes (Nearing *et al*., 1989). Interrill erosion is described as a process of soil detachment by raindrop impact, transport by shallow sheet flow and sediment delivery to rills. Rill erosion is described as a function of the flow's ability to detach sediment, the sediment transport capacity and the existing sediment load in the flow. Following this concept, A in Equation (1) represents rill cross-sectional area, Q is discharge in the rill and S can be written as $S = D_I + D_R$, where D_I is the interrill sediment delivery to the rill (kg/m/s) and D_R is the rill erosion rate (kg/m/s).

DOI: 10.1002/esp

Adopting the forms of these terms from the WEPP model for rangelands (Nearing *et al.*, 1989; Flanagan and Nearing, 2000), the interrill sediment delivery to the rill is

$$D_{\mathrm{I}} = K_{\mathrm{iadj}} I \sigma_{\mathrm{IR}} R_{\mathrm{s}} \tag{2}$$

where

$$K_{\mathrm{iadj}} = K_{\mathrm{ib}} \mathrm{e}^{-7(\mathrm{intcov}+\mathrm{canopy})} \tag{3}$$

K_{iadj} = adjusted interrill erodibility (kg s/m^4),
K_{ib} = base interrill erodibility (kg s/m^4),
intcov = covered interrill area fraction,
canopy = fraction of area covered with canopy,
I = rainfall intensity (m/s),
σ_{IR} = interrill runoff rate (m/s),
R_{s} = rill spacing (m).

The rill detachment rate is computed as

$$D_{\mathrm{R}} = \begin{cases} D_{\mathrm{c}}\left(1 - \dfrac{CQ}{wT_{\mathrm{c}}}\right)w, & CQ \le wT_{\mathrm{c}} \\ \dfrac{0{\cdot}5V_{\mathrm{f}}}{q}(wT_{\mathrm{c}} - CQ), & CQ \ge wT_{\mathrm{c}} \end{cases} \tag{4}$$

where
T_{c} = sediment transport capacity in the rill (kg/s/m),
V_{f} = particle fall velocity (m/s),
q = flow discharge per unit width, m^2/s,

and D_{c} is computed as

$$D_{\mathrm{c}} = \begin{cases} K_{\mathrm{r}}(\tau_{\mathrm{s}} - \tau_{\mathrm{c}}), & \tau_{\mathrm{s}} \ge \tau_{\mathrm{c}} \\ 0, & \tau_{\mathrm{s}} \le \tau_{\mathrm{c}} \end{cases}$$

where
K_{r} = rill erodibility (s/m),
τ_{s} = flow shear stress acting on the soil (Pa),
τ_{c} = critical shear stress (Pa).

Following WEPP, the rill width, w, is computed as a function of the discharge along the flow path (Gilley *et al.*, 1990) as

$$w = 1{\cdot}13 Q_{\mathrm{e}}^{0{\cdot}303} \tag{5}$$

where
Q_{e} = rill discharge at the end of the plane (m^3/s).

Equation (5) was developed for croplands, and therefore may be subject to improvement as additional information becomes available. However, the parameterization for the erosion routines was based on the same assumption of rill width as the model uses, hence there is an internal consistency in the modeling system. Sensitivity analyses to date have indicated that rill characteristics are not as significant as several other characteristics in determining erosion and sediment delivery from rangelands (Laflen *et al.*, 1994).

Thus, interrill erosion is proportional to rainfall intensity and interrill runoff rate, and depends on soil and cover characteristics of the interrill area. Increases in ground and canopy cover tend to decrease interrill erosion rate

DOI: 10.1002/esp

significantly. For example, the estimated interrill erosion rate would be twice as much for bare soil as compared to a 10% combined canopy and ground cover, as can be estimated from Equation (3).

The rill erosion term represents two interplaying processes (Nearing *et al*., 2001), the flow's ability to detach soil and its sediment transport capacity. If there is no transport limitation, then the controlling factor for the rill erosion rate is the detachability of the soil, which is linearly dependent on shear stress excess acting on the soil. The shear stress partitioning concept (Foster, 1982) distinguishes between total shear stress and its fraction acting on the soil, which is a driving force for detachment. As sediment is carried by the flow, a detachment limitation comes into play. That is, the more sediment that is present in the flow, the less the detachment rate becomes. Detachment rate approaches zero as sediment discharge reaches sediment transport capacity.

If the sediment load exceeds a threshold transport capacity for a given overland flow regime then deposition occurs, which is represented in the rill erosion sink term in Equation (4).

Flow Shear Stress and Transport Capacity. From Nearing *et al*. (1997), flow shear stress acting on the soil is given by

$$\tau_s = \tau_{tot}\frac{f_s}{f_{tot}} = \rho_w gSR\frac{f_s}{f_{tot}} \tag{6}$$

where
τ_{tot} = total shear stress acting on the surface (Pa),
ρ_w = water density (kg/m^3),
g = acceleration due to gravity (m/s),
S = slope (m/m),
R = hydraulic radius (m),
f_s and f_{tot} = Darcy-Weisbach friction factors for bare soil and composite surface, respectively.

Rills are assumed to be rectangular with widths that depend on flow rate. Their widths are calculated from Equation (5), while flow depths are computed iteratively using the Chezy or Manning equation, which relates discharge to depth.

There are several formulas for computing sediment transport capacity. Many of the equations were developed for stream flow, and later applied to shallow overland flow and channel flow. Alonso *et al*. (1981) and Foster and Meyer (1972) concluded that the Yalin equation (Yalin, 1963) was the most adequate for shallow flows associated with upland erosion. The Yalin transport capacity equation can be written as

$$T_c = 0{\cdot}635\mathrm{SG}d\sqrt{\rho_w\tau_s}\,\delta\left[1 - \frac{1}{\beta}\ln(1+\beta)\right] \tag{7}$$

where
SG = particle specific gravity (—),
d = particle diameter (m),

and δ and β are computed as

$$\delta = \begin{cases} \dfrac{Y}{Y_{cr}} - 1, & Y < Y_{cr} \\ 0, & Y \geq Y_{cr} \end{cases}, \tag{8}$$

$$\beta = 2{\cdot}45\mathrm{SG}^{-0{\cdot}4}Y_{cr}^{0{\cdot}5}\delta, \tag{9}$$

where

$$Y = \frac{\tau_s}{\rho_w(\mathrm{SG}-1)gd} \tag{10}$$

Y = dimensionless shear stress from the Shields diagram,
Y_{cr} = dimensionless critical shear stress from the Shields diagram.

DOI: 10.1002/esp

The Yalin equation as well as interrill erosion rate can be modified to consider mixtures consisting of particles of varying sizes and density (Flanagan and Nearing, 2000; Foster and Meyer, 1972). DWEPP uses up to five particle classes. This allows representation of clay, silt and sand primary particles, and small and large aggregate fractions, which are computed from equations for particle size classes in the CREAMS (Chemicals, Runoff, Erosion from Agricultural Management Systems) model (Foster *et al.*, 1985).

It should be noted that DWEPP uses the expressions given above for shear stress and transport capacity calculations, while WEPP applies approximate ones based on a polynomial function of downslope distance (Nearing *et al.*, 1989; Finkner *et al.*, 1989). This was possible in the original WEPP solutions because of the steady-state approximations and the study of Finkner *et al.* (1989) that showed the difference between the full and approximate calculations to be negligible.

Initial and Boundary Conditions. At ponding time, t_p, there is no spatial dependence of sediment, and cross-sectional flow area, A, is zero, therefore Equation (1) transforms into

$$\left.\left(C\frac{\partial A}{\partial t}\right)\right|_{t=t_p} = S \tag{11}$$

where

$$\left.\frac{\partial A}{\partial t}\right|_{t=t_p} = w\sigma \tag{12}$$

Transport capacity at time of ponding is zero, and rill width is equal to rill spacing. Hence, taking into account the chosen form of the erosion source term, initial conditions are

$$C(t_p,x) = \frac{K_i^{adj} I\sigma}{\sigma + 0{\cdot}5V_f} \tag{13}$$

Upper boundary conditions will reflect the presence of an upper plane. If there is one, then the sediment concentration at the top of current plane is set to the one at the bottom, x_b, of the upper plane, $C_{up}(t,x_b)$. It can be expressed as

$$C(t,0) = \begin{cases} C_{up}(t,x_b), \text{ there is an upper plane} \\ 0, \text{ there is no upper plane} \end{cases} \tag{14}$$

Model Evaluation Methods

A two-step validation was undertaken to evaluate model performance: (A) comparison with measured rainfall simulator data and (B) comparison with measured hillslope scale data under natural rainfall.

Observed values of erosion represent a sum of the 'true' mean value and noise. Noise can be characterized by some distribution, parameters of which (for example, standard deviations) can be heteroscedastic, i.e. can depend on 'real' value magnitude. As the intent of the model is to estimate a 'true' value, a discrepancy between observed and predicted values is expected, the acceptance of which can be estimated based on noise characteristics. Nearing *et al.* (1999) gave the estimates of noise ranges depending on erosion rate. Following the study of Nearing (2000), relative differences $\frac{P - M}{P + M}$, where P was model-derived sediment yield and M was the measured value, were calculated for plot and small watershed scale simulations. The confidence intervals for this relative difference term were calculated by Nearing (2000) based on a very large erosion data set, and these ranges were used to evaluate the differences between measured and predicted erosion rates in this study. Following the study of Nearing (2000), a model prediction was considered to be satisfactory if the model predicted values were within the 90% confidence range of natural variability found in replicated plot studies.

Also, the Nash–Sutcliffe coefficient of determination $\mathrm{NS} = 1 - \frac{\sum_i (\mathrm{Obs}_i - \mathrm{Pred}_i)^2}{\sum_i (\mathrm{Obs}_i - \overline{\mathrm{Obs}})^2}$, where Obs_i and Pred_i are measured and simulated values and $\overline{\mathrm{Obs}}$, the average of measured values, was used to characterize the results. NS = 1 indicates

DOI: 10.1002/esp

Table I. Soil series, texture, location and erosion parameters for the rainfall simulation data used for model validation

Site number	Soil series	Location	Soil surface texture	Critical shear stress, Pa	Rill erodibility, s/m	Interrill erodibility, kg s/m^4
1	Grant	OK	loam	0·7125	0·000 11	422 000
2	Grant	OK	sandy loam	1·165	0·000 15	357 000
3	Degater	CO	silty clay	4·36	0·001 62	1 195 000
4	Woodward	OK	loam	0·001	0·000 09	903 000
5	Stronghold	AZ	sandy loam	0·5025	0·000 53	285 000
6	Forrest	AZ	sandy clay loam	1·3615	0·000 35	263 000
7	Pierre	SD	clay	0·4266	0·000 2	1 030 000

that the model reproduces the observed response, while NS = 0 indicates that model predicts no better than the mean of the data (Nash and Sutcliffe, 1970).

Plot scale validation. To test the model at the plot scale, data from the WEPP rangeland rainfall simulator field experiments (Simanton *et al*., 1991) conducted by the USDA–ARS were used. In this experiment, a rotating boom rainfall simulator was used to apply water on two 3 m × 10 m plots at a time. Plot treatments included a control (natural), vegetation canopy removed (clipped) and vegetation canopy and ground cover removed (bare). Each treatment was replicated twice. Three rainfall simulations were conducted on each plot: a dry run at initial soil moisture conditions, a wet run 24 hours after the dry run and a very wet run 30 minutes after the wet run. Rainfall rates were computed using a recording rain-gage, runoff depths were measured using a pre-calibrated flume and sediment concentrations were measured from grab samples taken at various times during the simulation event. The data used to test the model were from the wet run, which had a rainfall intensity of approximately 60 mm/hr for 25 minutes. To represent a variety of different available soil types and erosion parameter ranges, we chose 35 bare and vegetated plots from seven rangeland sites (Table I).

Critical shear stresses varied from 0·001 to 4·36 Pa, rill erodibility ranged from 9×10^{-5} to 162×10^{-5} kg/s/m^4 and interrill erodibility ranged from 263×10^3 to 1195×10^3 s/m. We calibrated the model to match total runoff amount for each simulation by adjusting the soil moisture deficit in each model, which was the only parameter not listed in the database. All other parameters were taken from the database. All of the data were used in order to evaluate calculations of total erosion amounts. To evaluate the sediment yield dynamics, two plots (one bared of vegetation and one natural) with simulated peak runoff rates and total sediment yields that were approximately the same as the measured values were considered. This was done in order to best evaluate the time dependent aspect of the erosion model response with errors associated with hydrology reduced to a minimum.

The model's capability in predicting the effects of cover on erosion was assessed using the data from the seven sites listed in Table I using a general linear model (a GLM was used rather than ANOVA because the data were not balanced). A Duncan comparison test was used to determine whether the model was able to differentiate site treatment differences in a manner consistent with the measured data.

Small watershed scale validation. Since the change made in the DWEPP sediment routine involved only overland flow erosion (i.e., not channel erosion), we chose a gaged watershed that was small enough that it had no incised channel network. The Lucky Hills 105 subwatershed located in Walnut Gulch Experimental Watershed, Tombstone, AZ, meets these requirements. The runoff and total sediment yield data for 32 events for 1982–1985 and 1992 were taken from the USDA–ARS archive.

This catchment has an area of 1821 m^2 (0·18 ha). Its soil series is Stronghold, erosion parameters from the WEPP database are K_i = 285 000 kg/sec/m^4, K_r = 0·000 53 s/m, τ_c = 0·5025 Pa. These parameter values were based on rainfall simulation experiments conducted on this soil series near this watershed (Simanton *et al*., 1991). The geometry can be represented by a single plane with length equal to the average overland flow path (64 m) and slope set to the average slope along the flow paths (6%). Saturated conductivity of 15 mm/hr and its coefficient of variation of 0·7 were used by DWEPP. This estimate was obtained from the previous site parameter calibration done by the ARS research group at Tucson (Hernandez, personal communication). An effective hydraulic conductivity for WEPP of 11 mm/hr was calibrated using least squares for total runoff amount for four dry events (five previous days cumulative precipitation depth was less than 12 mm). Canopy and interrill cover values used were 32 and 23% correspondingly.

For each runoff event, DWEPP and WEPP were calibrated for runoff amount by adjusting the initial soil moisture deficit. In order to calibrate for peak runoff, the Chezy hydraulic roughness coefficient (DWEPP) and interrill friction factor (WEPP) were adjusted using five randomly chosen events (one from each year of data). Also, modeled total

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sediment yield was matched with observed for these same five events by adjusting the rill friction factor term (DWEPP and WEPP), which is related to the shear stress adjustment factor. These events had sediment yields ranging from 78 to 649 kg/ha. All calibration was done by using mean square error as a measure of fit.

It was assumed that rill and interrill roughness, canopy, interrill cover, effective hydraulic conductivity, rill and interrill erodibilities and critical shear stress were constant from one event to another. This was a reasonable assumption because all the events occurred during the same summer rainy period, which is the usual time for thunderstorms that lead to runoff in this region.

Because of measuring instrument specifics, only suspended sediment discharge rate records were available during the storm event. However, total sediment yield could be calculated by adding the total amount of trapped sediment from the flume to the total suspended sediment discharge integrated over the entire storm period. To estimate the sedigraph for the total sediment load, the existing suspended load data were multiplied by the ratio of total storm sediment yield (both suspended and trapped load) to the integrated suspended sediment yield. All of the events were used to evaluate total sediment yields. Three events were used to evaluate sediment discharge rates during the storm as predicted by DWEPP and WEPP models.

Results

Model response on plot dataset

Peak discharges from the rainfall simulation plots for both models (steady state and dynamic) were similar, with a coefficient of determination, r^2, between values predicted by the two models of 0·995, a regression intercept not statistically different from zero and a slope of the regression line of 1·024 ± 0·012. Results for sediment yield (Figure 1) were characterized by $r^2 = 0·99$, a statistically insignificant intercept and slope for the WEPP versus DWEPP regression line of 0·956 ± 0·006.

Figure 2 shows the graphs of measured sediment yield versus DWEPP predicted and Figure 3 shows the relative differences between measured and DWEPP predicted sediment yield as well as the 90% confidence interval based on the recommendations of Nearing (2000) for evaluating model results in the presence of experimental variability. The Nash–Sutcliffe (NS) (Nash and Sutcliffe, 1970) coefficient for plot sediment yield was 0·77, while the NS coefficient for corresponding peak runoff was 0·91. All of the predictions fell within the expected confidence ranges for the measured data values, and were thus considered to be acceptable predictions.

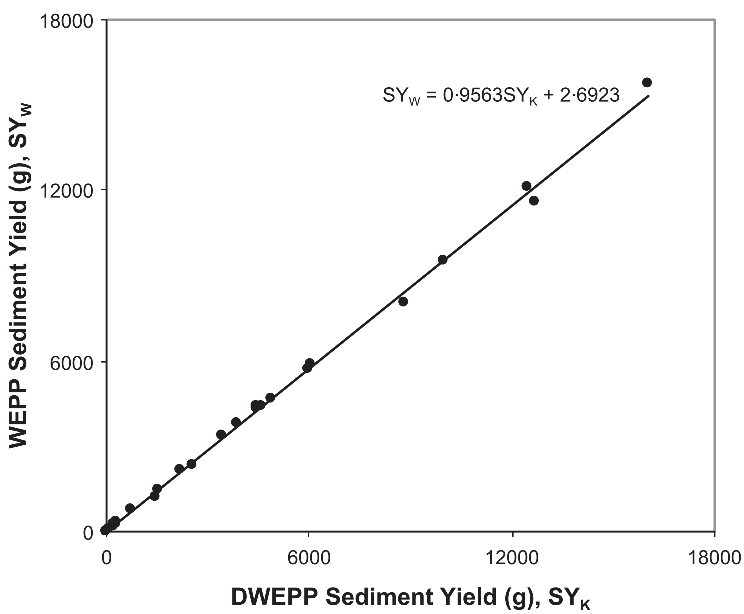

Figure 1. Predicted sediment yield comparison between the WEPP and DWEPP models for results of simulations on the rainfall simulation plot data.

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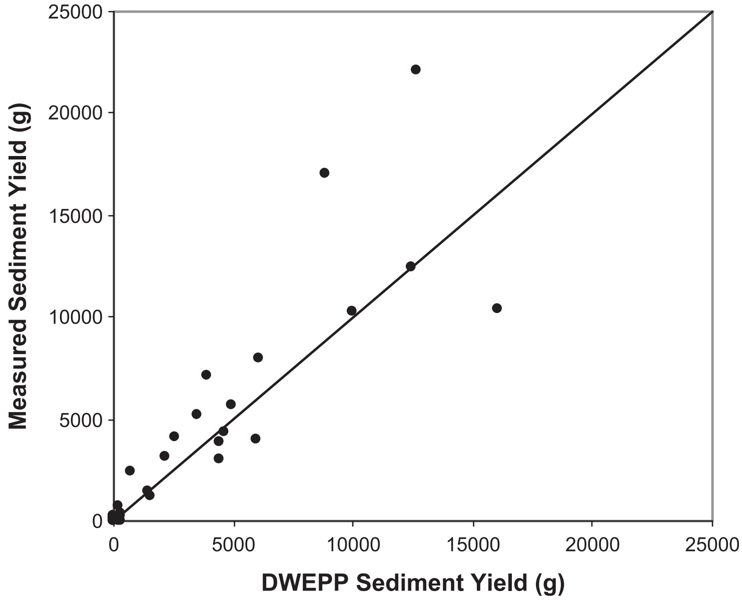

Figure 2. Measured sediment yield versus that estimated by DWEPP with 1:1 line plotted.

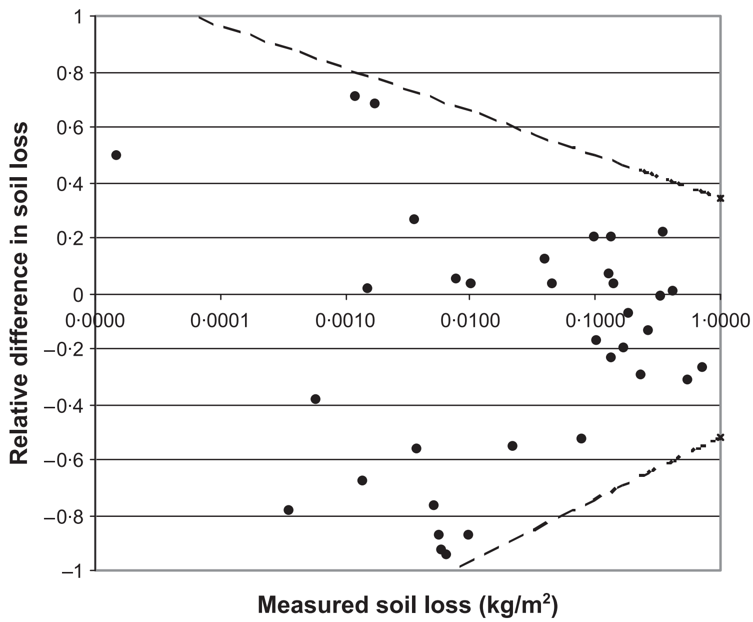

Figure 3. Relative differences between measured and predicted soil loss (using DWEPP) and the confidence interval for measured plot data (after Nearing, 2000).

In order to assess the sediment yield rates with time, data from two rainfall simulator plots were assessed in detail: a bare plot with loamy Grant soil from Oklahoma and a natural plot with sandy clay loam Forrest soil from Arizona. The bare plot had all ground cover and canopy removed, while for the natural plot interrill cover and canopy were 7 and 19%, respectively. Table II lists runoff peaks and total sediment yields, and Figures 4 and 5 represent measured and predicted hydrographs and sedigraphs for these experimental plots.

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Table II. Runoff peaks and total sediment yields for the plots used in the assessment of the dynamic response of DWEPP

	Measurement	DWEPP
Bare plot (total runoff = 19·45 mm)		
Peak runoff (mm/hr)	51·71	51·85
Total sediment yield (g)	4348	4597
Natural plot (total runoff = 12·8 mm)		
Peak runoff (mm/hr)	38·89	38·09
Total sediment yield (g)	234	260

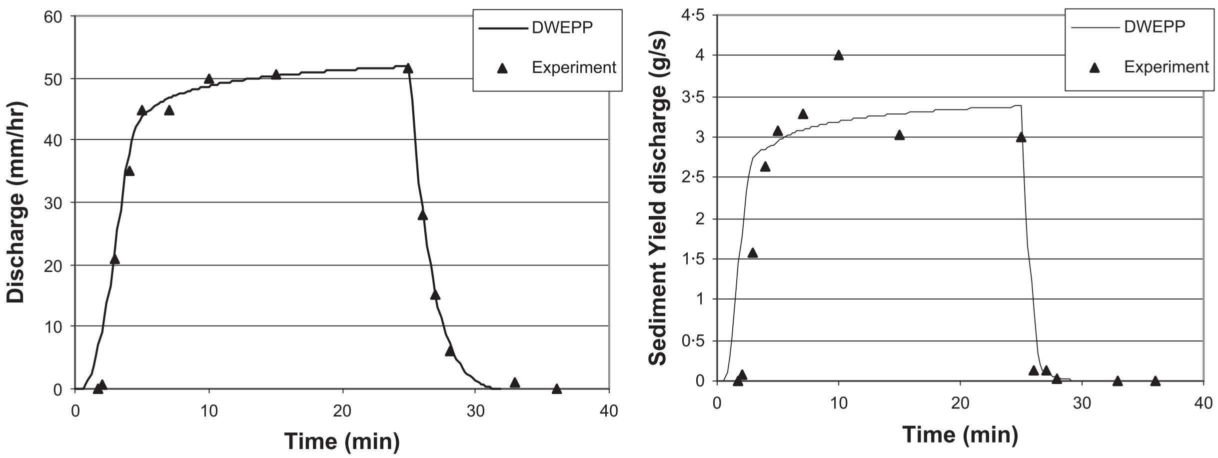

Figure 4. Measured and predicted hydrograph and sedigraph for the bare plot on loamy Grant soil from Oklahoma.

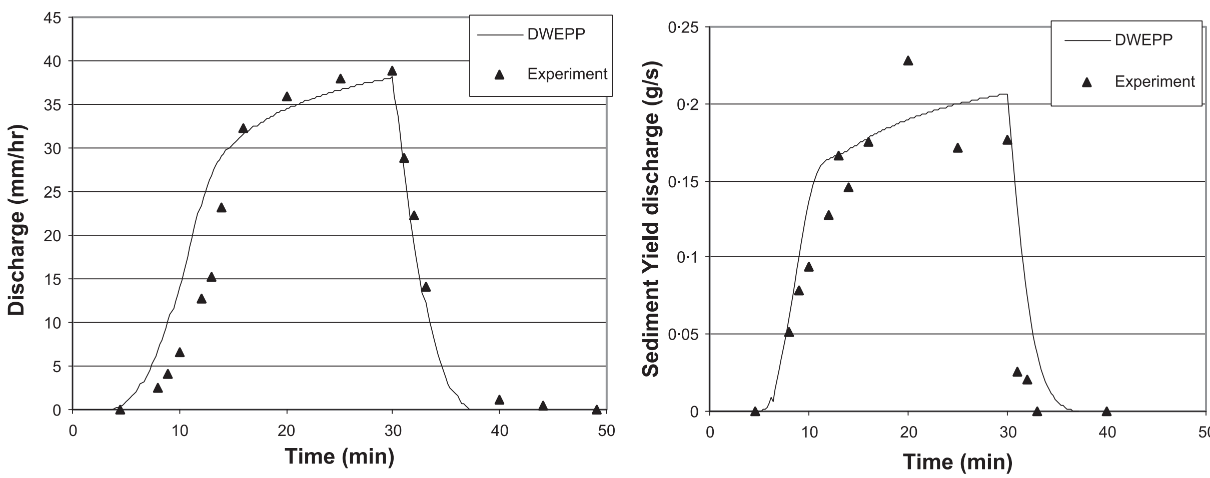

Figure 5. Measured and predicted hydrograph and sedigraph for the natural plot on sandy clay loam Forrest soil from Arizona.

The general linear model of erosion as a function of site, vegetative state (natural or bare) and source of erosion estimate (measured or predicted) showed that the erosion rate was highly dependent upon both site and cover condition (α = 0·001), but independent of whether the estimate was measured or predicted. Table III lists the averages of measured and predicted erosion for the seven sites and two cover conditions, along with results of the Duncan multiple means comparison tests. These tests showed that there were no statistically significant differences in the relative rankings of the seven sites by the measured data as compared to the predicted data.

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Table III. Average values of measured and predicted erosion for the seven sites and two cover conditions

Soil	Bare soil conditions			Natural vegetated		
	Measured erosion g	Predicted erosion g	*n*	Measured erosion g	Predicted erosion g	*n*
Grant (loam)	6 180[bc*]	4 500[bc]	4	96·6[b]	3·8[b]	4
Grant (sandy loam)	3 429[bc]	4 436[bc]	4	61·3[b]	182·4[ab]	4
Degater	6 912[bc]	6 954[abc]	2	1541·0[a]	465·5[a]	2
Woodward	3 999[bc]	5 984[abc]	1	203·3[b]	25·5[b]	2
Stronghold	19 573[a]	10 754[ab]	2	18·0[b]	8·0[b]	2
Forrest	2 668[c]	2 046[c]	2	270·5[b]	293·0[ab]	2
Pierre	10 340[ab]	13 000[a]	2	162·7[b]	15·8[b]	2

* Values within a column with the same letter are not significantly different at $\alpha = 0{\cdot}05$ (using Duncan means comparison test).

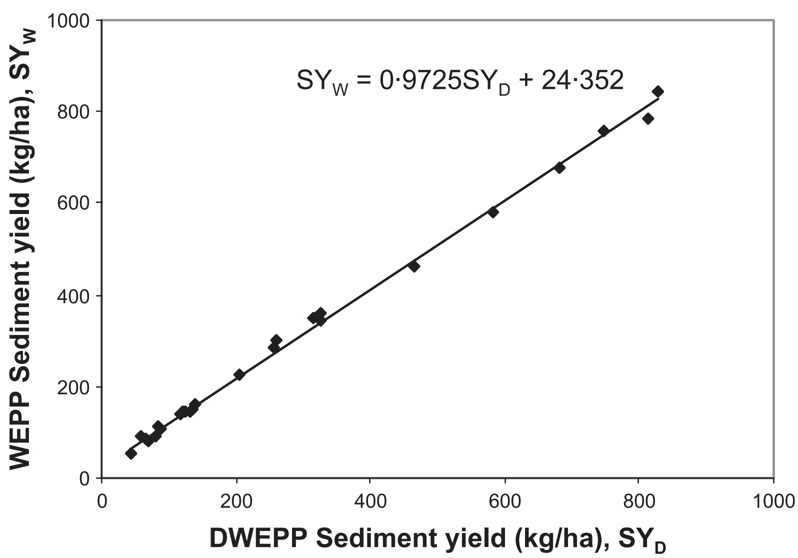

Figure 6. Predicted sediment yield comparison between the WEPP and DWEPP models for Lucky Hills 105 watershed.

Hillslope scale application of DWEPP

Results for total sediment yields (kg/ha) for DWEPP and WEPP models (Figure 6) were similar, with $r^2 = 0{\cdot}998$, a statistically significant intercept of $24{\cdot}35 \pm 3{\cdot}47$ and a slope of $0{\cdot}9725 \pm 0{\cdot}0094$.

DWEPP application to Lucky Hills 105 (LH 105) watershed resulted in total sediment yields shown in Figure 7.

The Nash–Sutcliffe (NS) coefficients for peak discharge and sediment yield prediction with DWEPP were calculated as 0·96 and 0·8, respectively; while WEPP gave 0·87 and 0·79, respectively. Relative differences between measured and DWEPP predicted, and the 90% confidence interval, are shown in Figure 8. All points were within the interval bounds.

Table IV compares measured and predicted runoff, peak runoff and sediment yield values for three events on LH 105, while Figures 9–11 show hydrographs and sedigraphs for the events that occurred on 20 September 1983, 14 July 1985 and 29 July 1992.

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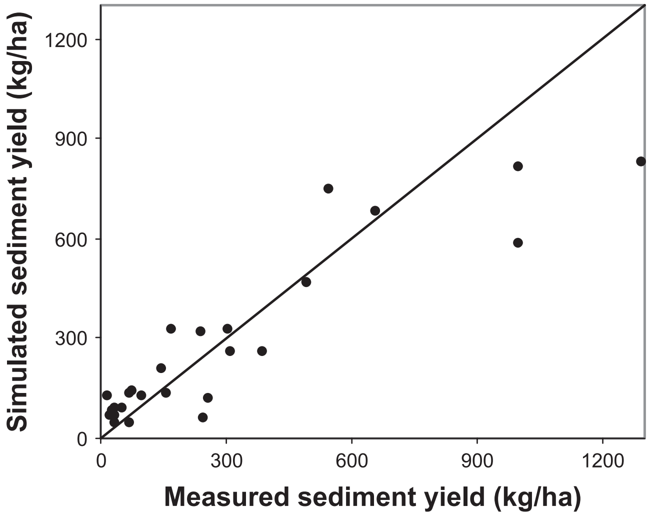

Figure 7. Total sediment yields measured and predicted by DWEPP for Lucky Hills 105 watershed with 1:1 lines.

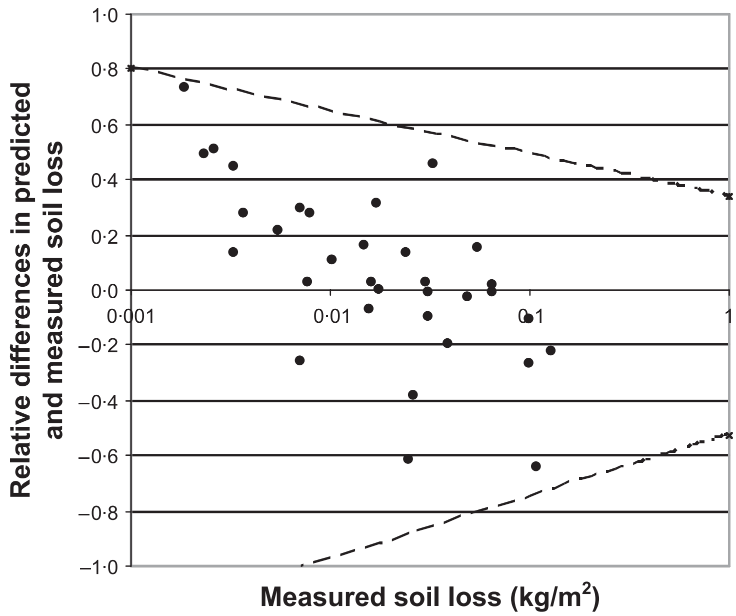

Figure 8. Relative difference in soil loss and its confidence interval for the Lucky Hills 105 watershed.

Table IV. Runoff peaks and total sediment yields for the events used in the assessment of the dynamic response of DWEPP

	Measured	DWEPP predicted
20/9/83 event (runoff = 3·22 mm)		
Peak runoff rates (mm/hr)	8·0/18·9	5·5/20·1
Total sediment yield (kg/ha)	387·9	258·3
14/7/85 event (total runoff = 3 mm)		
Peak runoff rates (mm/hr)	5·1/17·6	12·9/8·1
Total sediment yield (kg/ha)	311·4	256·9
29/7/92 event (total runoff = 9·9 mm)		
Peak runoff rates (mm/hr)	63·7	63·7
Total sediment yield (kg/ha)	998·2	812·1

DOI: 10.1002/esp

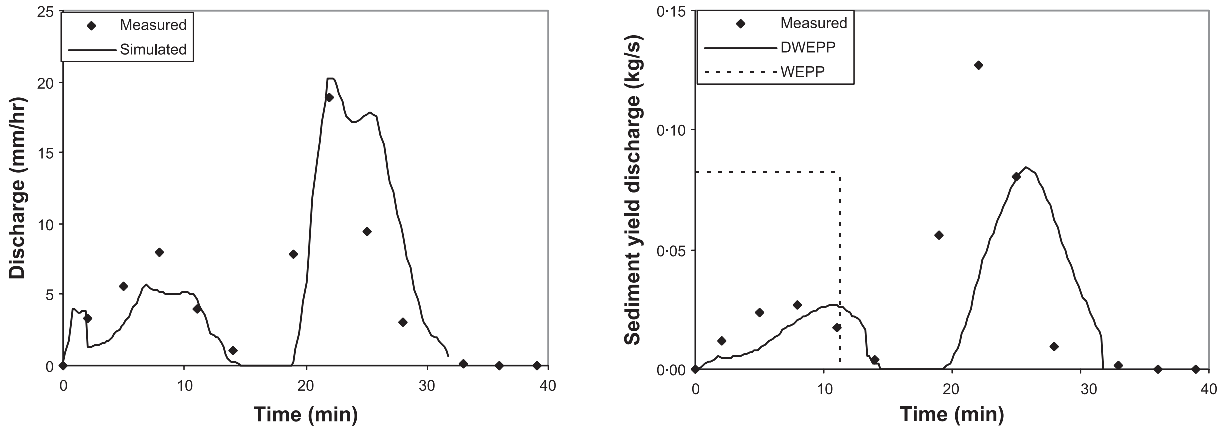

Figure 9. Measured and predicted hydrograph and sedigraph for the 20 September 1983 event on Lucky Hills 105.

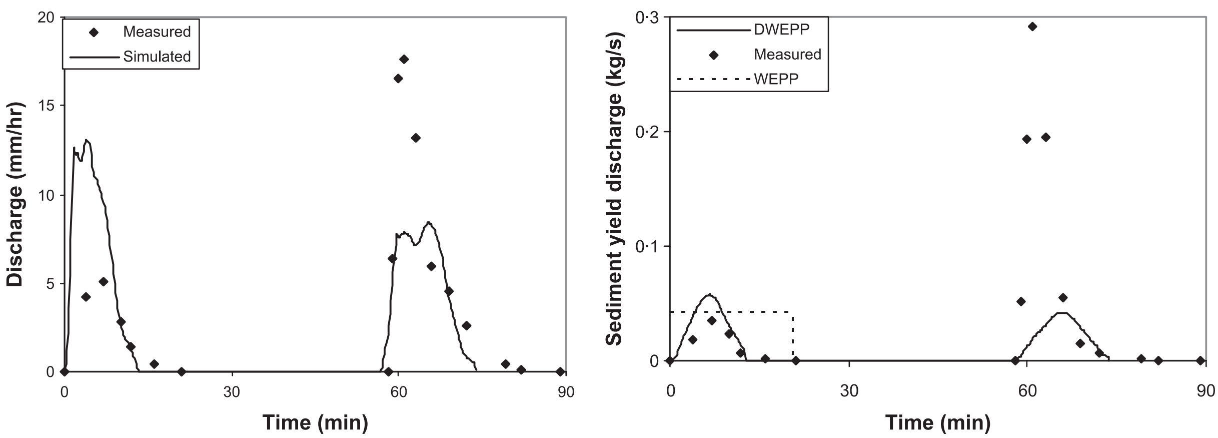

Figure 10. Measured and predicted hydrograph and sedigraph for the 14 July 1985 event on Lucky Hills 105.

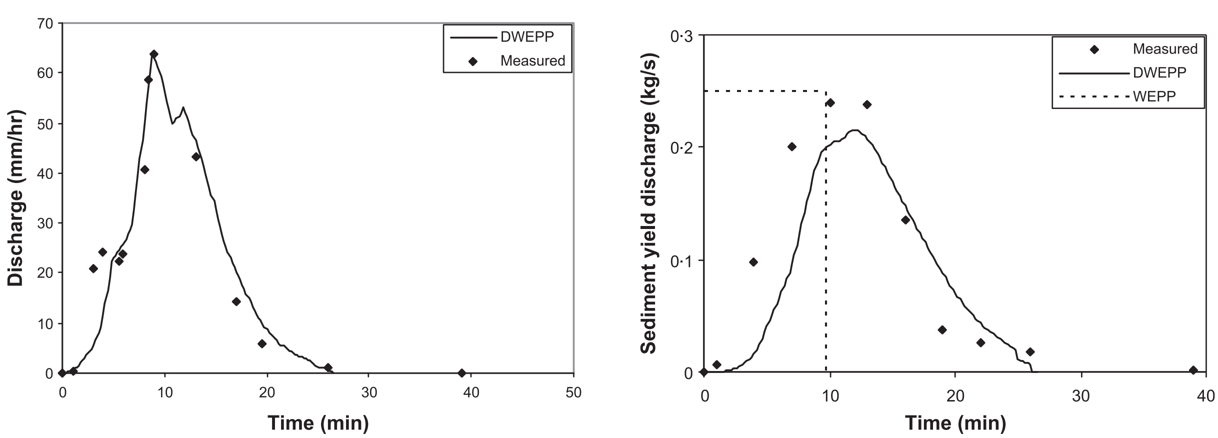

Figure 11. Measured and predicted hydrograph and sedigraph for the 29 July 1992 event on Lucky Hills 105.

DOI: 10.1002/esp

Discussion

Hydrology and erosion predicted by DWEPP and WEPP at the plot scale were similar when we used constant intensity rainfall over a long enough time period for the system to reach a state close to steady (Figure 1). However, DWEPP predicted slightly larger sediment yield values than WEPP. This can be attributed in part to the different methods of shear stress and transport capacity calculations in two models. The WEPP model uses a simplified equation polynomial equation for estimating shear distribution along the hillslope profile as described earlier, whereas DWEPP uses a direct calculation of Yalin transport at each point and time increment. From this comparison it can be concluded that for practical purposes the WEPP parameter database can be inherited by DWEPP as though it were built for this new model.

Sediment yield prediction goodness-of-fit for DWEPP was characterized by the NS coefficient of 0·77 for the rainfall simulator plot data, and all the points were in the 90% confidence interval that accounts for natural erosion and measurement variability (Nearing, 2000). We thus conclude that DWEPP gave reasonable and accurate results when validated with the rainfall simulation data.

Data from Table III showed the importance of cover and canopy for controlling erosion rates at the plot scale. Data for sediment yield were highly sensitive to the presence of cover for both the measured and simulated data. The fact that the general linear model (GLM) showed that the erosion rate was highly dependent upon both site and cover condition ($\alpha = 0{\cdot}001$) would indicate that the data was responsive to both site differences and vegetation differences. The fact that the model showed independence of whether the estimate was measured or predicted would indicate that there was no bias in the predictions relative to the measured data that could be picked up by the GLM. The Duncan multiple means comparison tests showed that the model was effective in ranking the relative differences between the seven sites for both the natural conditions and the bare conditions, as would be expected, since the model was calibrated to the data from those seven sites.

The hillslope application using data from Lucky Hills 105 showed a trend reported previously by Nearing (1998) to overestimate the erosion rate for small sediment yield events and underestimate for large ones. Nonetheless, relative differences between measured and predicted sediment yields for the events studied were within acceptable experimental ranges at the 90% confidence level (Nearing, 2000).

Sediment yield prediction by DWEPP and WEPP gave similar results. The estimated values were very nearly the same for the two models (Figure 6) for conditions of approximate steady state, as would be expected. Also, the Nash–Sutcliffe coefficients for prediction quality relative to the measured data were very nearly the same for the two models: 0·8 and 0·79, respectively.

Figures 9 and 10 represent sedigraphs for double-peaked erosion events, while Figure 11 shows a sedigraph for a single-peaked event. Sediment yield dynamics showed high dependence on the accuracy of the peak runoff estimation (Figure 10). The second peak runoff rate of the event was underestimated for unknown reasons, which caused a great underestimation of the sediment load during that peak.

For comparison, the WEPP estimated erosion rate is illustrated in Figures 9–11. WEPP does not specify a sediment discharge start time, and there is no time dependence of erosion rate from the steady-state model. This last deficiency is more pronounced in the case of double-peaked events (Figures 9 and 10). Obviously, the steady-state tool is not useful for assessing intra-storm dynamics.

The erosion validation of DWEPP showed sufficient accuracy relative to the measured data in terms of erosion response. DWEPP and WEPP gave a similar level of prediction accuracy for the total soil losses measured from both rainfall simulation and small watershed experiments. DWEPP represented the effects of vegetation satisfactorily compared with the rainfall simulator plot data. DWEPP allowed also for quantification of the intra-storm dynamics of erosion, while WEPP, which was not designed for this purpose, was unable to provide any useful information in this regard.

Acknowledgements

The authors would like to thank the USDA–ARS, Southwest Watershed Research Center work group, particularly Dr. Mariano Hernandez for helpful suggestions and information concerning watershed Lucky Hills 105 and Carl Unkrich for KINEROS2 assistance.

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