Empirical Models Based on the Universal Soil Loss Equation Fail to Predict Sediment Discharges from Chesapeake Bay Catchments

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The Universal Soil Loss Equation (USLE) and its derivatives are widely used for identifying watersheds with a high potential for degrading stream water quality. We compared sediment yields estimated from regional application of the USLE, the automated revised RUSLE2, and five sediment delivery ratio algorithms to measured annual average sediment delivery in 78 catchments of the Chesapeake Bay watershed. We did the same comparisons for another 23 catchments monitored by the USGS. Predictions exceeded observed sediment yields by more than 100% and were highly correlated with USLE erosion predictions (Pearson *r* range, 0.73–0.92; $p < 0.001$). RUSLE2-erosion estimates were highly correlated with USLE estimates ($r = 0.87$; p < 001), so the method of implementing the USLE model did not change the results. In ranked comparisons between observed and predicted sediment yields, the models failed to identify catchments with higher yields (*r* range, –0.28–0.00; $p > 0.14$). In a multiple regression analysis, soil erodibility, log (stream flow), basin shape (topographic relief ratio), the square-root transformed proportion of forest, and occurrence in the Appalachian Plateau province explained 55% of the observed variance in measured suspended sediment loads, but the model performed poorly ($r^2 = 0.06$) at predicting loads in the 23 USGS watersheds not used in fitting the model. The use of USLE or multiple regression models to predict sediment yields is not advisable despite their present widespread application. Integrated watershed models based on the USLE may also be unsuitable for making management decisions.

Reduced soil fertility and sharp declines in aquatic resources have intensified worldwide efforts to limit erosion and reduce pollution in streams and rivers. In the Chesapeake Bay region, excess sediment and sediment-sorbed phosphorus have degraded shallow estuarine habitats, especially as human development has intensified during the past 50 yr (Kemp et al., 2005). Despite reduced point source contributions, sediment delivery remains high, and estuarine habitat quality remains impaired (e.g., Stankelis et al., 2003). Although these trends indicate the influence of nonpoint pollution sources (Boesch et al., 2001), identifying the most influential nonpoint sources remains difficult, especially for sediment and phosphorus (Weller et al., 2003). Empirical and simulation models provide important tools for integrating our understanding of processes controlling water and material discharges, characterizing human interactions in the landscape, and predicting discharges from ungauged basins (Carpenter, 1996).

Models derived from the Universal Soil Loss Equation (USLE) are some of the most widely applied tools for predicting sediment yield from whole catchments (Kinnell, 2004a; Yoder et al., 2004). These models are based on the original USLE developed to help farmers minimize topsoil loss on agricultural fields (Wischmeier and Smith, 1978):

$$A = R\ K\ LS\ CP$$

where A is the estimated long-term annual soil loss (Mg soil loss ha^{-1} yr^{-1}), R is a rainfall and runoff factor representing the summed erosive potential of all rainfall events in a year (MJ mm ha^{-1} h^{-1} yr^{-1}), L and S are topographic factors that describe slope length and steepness (dimensionless), K is the soil erodibility factor representing units of soil loss per unit of rainfall erosivity (Mg ha h ha^{-1} MJ^{-1} mm^{-1}), and CP characterizes land cover and conservation management practices (dimensionless).

Subsequent enhancements, notably the Revised USLE (RUSLE1 and RUSLE2), incorporate a broader set of land cover classes and attempt to capture deposition in complex terrains (Renard et al., 1997). The core USLE factors were refined by enabling users to characterize additional subfactors (Yoder et al., 2004). Process-based equations for transport capacity and deposition

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Abbreviations: CN, Curve Number; CP, USLE cover-practice management factor; K, soil erodibility; LS, USLE length-slope topographic factor; NLCD, National Land Cover Database; R, rainfall erosivity; RUSLE, revised-Universal Soil Loss Equation; SDR, sediment delivery ratio; SERC, Smithsonian Environmental Research Center; USLE, Universal Soil Loss Equation.

were incorporated to compute deposition on concave slopes, at dense vegetative strips, in terrace channels, and in sediment basins (Foster et al., 2003). The most recent release (RUSLE2) estimates annual erosion rates by summing the products of factor values for each day, rather than using annual average values, and is considered the best tool for estimating rill and interrill erosion rates for conservation planning (Foster et al., 2003).

Because the USLE and RULSE predict "edge-of-field" erosion and do not account for the interaction among adjacent field plots, catchment erosion estimates often are adjusted downward by a sediment delivery ratio (SDR). Most published SDRs are developed empirically by relating the ratio of observed sediment delivery rates and USLE predicted erosion rates to landscape characteristics such as watershed size (Vanoni, 1975), watershed shape (Maner, 1958), or the slope of the main stream channel (Williams and Berndt, 1972). More complex algorithms include distributed models that estimate SDRs from topographic variation and flow path length (Yagow et al., 1998) or additional surface characteristics including flow-path roughness and gradient, slope shape, and soil moisture, such as SEDMOD (Spatially Explicit Delivery MODel; Fraser et al., 1998). The USLE-SDR predictions remain widely used for estimating annual soil loss at the catchment scale (Trimble and Crosson, 2000a) in ungauged drainage basins (e.g., Angima et al., 2003; Martin et al., 2003; Lu et al., 2004; Boellstorff and Benito 2005; Fu et al., 2005; Onyando et al., 2005; Wang et al., 2005). A number of watershed models also rely on the USLE estimates for model parameterization. Examples include GWLF (Generalized Watershed Loading Function; Haith and Shoemaker, 1987), AGNPS (AGricultural Non-Point Source; Young et al., 1989), SWAT (Soil & Water Assessment Tool; Arnold and Allen, 1992), applications of HSPF (Hydrological Simulation Program-Fortran; Bicknell et al., 1993), and SEDD (Sediment Delivery Distributed model; Ferro and Porto, 2000).

Although the USLE framework is used extensively for catchment-scale empirical or simulation models (Kinnell, 2004a; Yoder et al., 2004), it is not well verified at that scale (Trimble and Crosson, 2000b). Watershed modelers often cite the USLE's extensive field validation based on more than 10,000 plot-years of data (Nearing et al., 2000), but that validation is for gross erosion rather than sediment transport to down-gradient areas. Previous validation efforts indicate the USLE reliably estimates erosion from individual land units (e.g., Risse et al., 1993; Ali and Sharda, 2005), and prediction of stream sediment yield has been deemed successful in small catchments where field observations of catchment geography, rather than regional spatial data, are used in the USLE calculation (e.g., Angima et al., 2003). In contrast, validation of soil erosion estimates using regional data from 98 catchments across Europe indicated the USLE-based empirical models provided poor predictions of observed stream sediment delivery (Van Rompaey et al., 2003). In addition, the study incorporated field measurements to derive basin-specific SDRs. This method limits the utility of USLE applications to monitored basins and precludes meeting the important goal of predicting loads from ungauged catchments. Although many researchers, including the developers, have cautioned against applying the plot-scale USLE at the catchment scale, (Wischmeier and Smith 1978; Risse et al., 1993; Kinnell, 2004a), widespread application continues, suggesting there is a clear need for validation at whole watershed scale.

We tested the ability of USLE-based models to predict whole catchment sediment discharges using two independent data sets. Observed annual average sediment yields were compared with estimates from Geographic Information System implementations of the original USLE, the RUSLE2.0, and the erosion models enhanced with sediment delivery ratios to explore whether the base model or any of its derivatives effectively predicted whole catchment discharges. Based on their widespread acceptance, we expected that some USLE-based models could provide good predictions of sediment yield from watersheds. We further expected that more recent versions that account for sediment deposition (SDRs) or include other improvements would give better predictions than earlier versions. Even if yield predictions were not quantitatively accurate, we expected all the USLE implementations to correctly separate erosion-prone watersheds from those with little erosion. That is, we expected that across many watersheds, the rank correlation of observed sediment yield with sediment yield predicted by any of the USLE-based models should be strong and statistically significant.

Materials and Methods

Study Location

The Smithsonian Environmental Research Center (SERC) established continuous monitoring stations in 78 drainage basins across the 166,000 km^2 Chesapeake Bay watershed (Jordan et al., 1997a; Liu et al., 2000). Catchment sizes ranged between 5 and 91,126 ha. The basins were arranged in clusters throughout the Chesapeake watershed (Fig. 1; Table 1), which extends over six physiographic provinces (Langland et al., 1995): the Coastal Plain (n = 45 study watersheds), Piedmont (n = 10), Mesozoic Lowland (n = 7), Appalachian Mountain (n = 9), and Appalachian Plateau (n = 7). Basins were selected with differing proportions of agricultural and nonagricultural land cover and no reservoirs or point sources to observe the effects of land cover on water quality in different physiographic provinces. Land cover ranged from 2 to 100% forest, 0 to 39% agriculture, and 0 to 82% residential and commercial development (1992 National Land Cover Database [NLCD]; Vogelmann et al., 2001). Percent impervious area ranged from 0 to 40% (Regional Earth Science Application Center [RESAC]; Goetz et al., 2003).

Data from 23 additional drainage basins in the Chesapeake Bay watershed where USGS monitoring programs provided annual mean estimates of sediment delivery were evaluated (Table 2) (Gellis et al., 2005; Langland et al., 1995). Estimates of annual average sediment yield were based on data collected daily or determined from the ESTIMATOR model (Cohn et al., 1992). Catchment sizes ranged between 101 and 90,530 ha. Land cover ranged from 5 to 100% forest, 0 to 40% agriculture, and 0 to 30% development. Catchments with reservoirs were not included in our analyses.

Water Monitoring Data

In the 78 SERC study catchments, automated samplers were used to monitor stream depth continuously and to collect flow-weighted water samples composited weekly for at least 1 yr between 1974 and 2004. This approach effectively quantified dissolved and suspended materials, including those transported episodically during storm flows (Jordan et al., 1997a). Samples were analyzed for a suite of constituents including total suspended solids (Jordan et al., 1997a). Total suspended solids in unpreserved composite samples were collected on weighed 0.45-μm membrane filters, rinsed with distilled water to remove salts, dried in a vacuum desiccator, and reweighed. Annual mean flow rates and flow-weighted mean concentrations were multiplied to estimate annual average loads and divided by catchment area to produce yield estimates (Mg ha^{-1} yr^{-1}).

Digital Data Sources

Digital spatial data sets describing topography, land cover, and soil characteristics were acquired from public websites. Watershed delineations (Baker et al., 2006a) and topographic variables, including slope and slope variation, were derived from the USGS National Elevation Database (EROS Data Center, 1999; source resolution: 27.78 m pixels). Land cover estimates were obtained from the 1992 NLCD (Vogelmann et al., 2001) (source resolution, 30 m pixels). The 21 land cover classes were consolidated into six classes: cropland, grassland, development, forest, wetland, and barren areas. Surface soil erodibility was derived from the USDA-NRCS STATSGO soils database (USDA-NRCS, 1995) (scale: 1:250,000) converted to a grid with 30-m resolution. The proportion of impervious area for each catchment was derived from the RESAC dataset (Goetz et al., 2003) (source resolution, 30 m). Physiographic province was determined from surficial geology maps (Langland et al., 1995) (scale: 1:500,000). Monthly average precipitation amounts (1971–2000) were provided by the Spatial Climate Analysis Service (2002) (scale, 1:250,000).

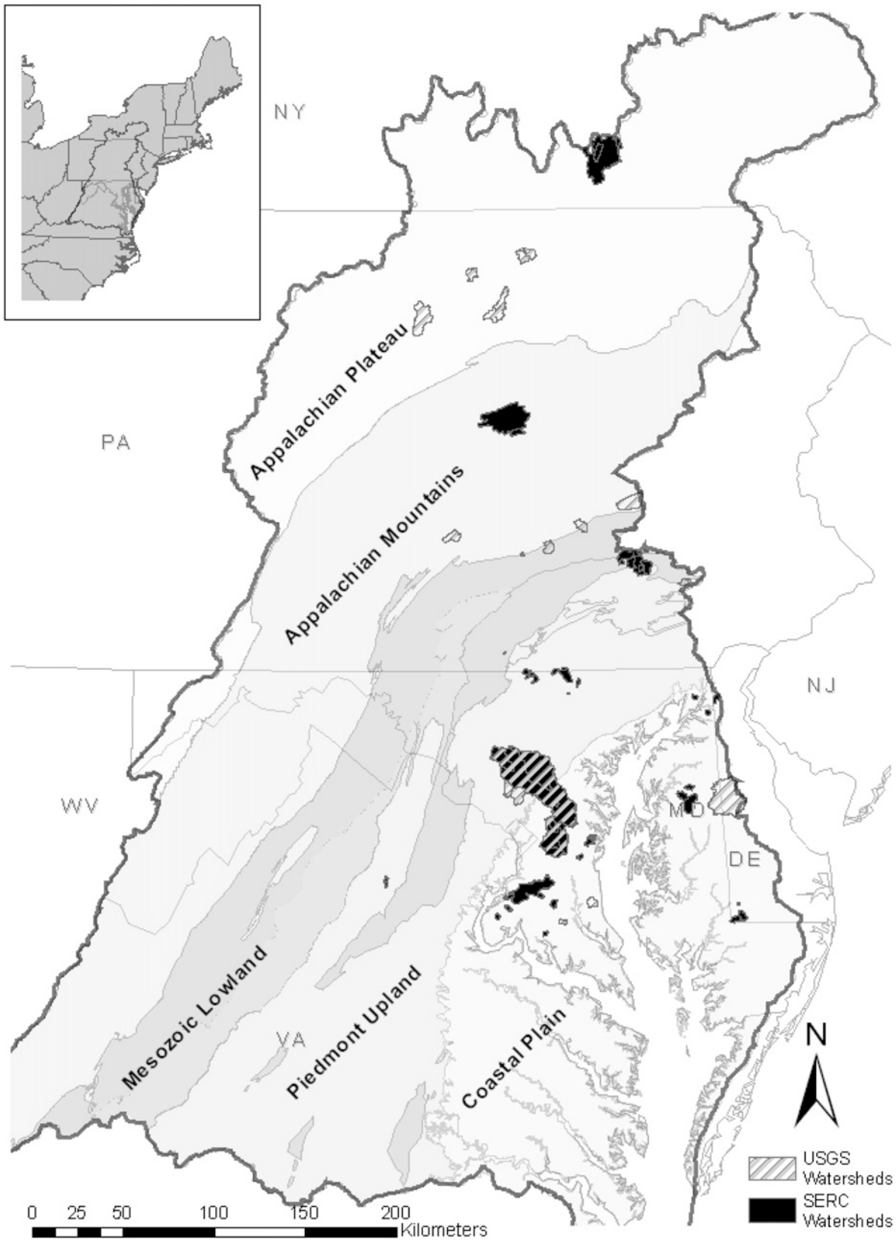

Fig. 1. Locations of study catchments within physiographic provinces of the Chesapeake Bay watershed. Black shading indicates basins monitored by the Smithsonian Environmental Research Center (SERC); striped shading indicates basins monitored daily by USGS. Inset shows the location of the Chesapeake Bay watershed in the eastern USA.

Data Analysis

Grid-based USLE Analysis

Average erosion rates for each catchment were calculated from an erosion grid (resolution, 30 m), which was a product of USLE-factor grids. Slope length (L) equaled the pixel width of the National Elevation Dataset (NED) (27.78 m). Slope steepness (S) was defined as the maximum change in elevation of the NED within a 3 × 3 grid cell neighborhood. The resulting LS grid was resampled to a 30-m resolution using cubic interpolation (ArcGIS 9.1). Rainfall erosivity (R) was derived from linear interpolation of the national iso-erodent map (Wischmeier and Smith, 1978). Cover management factors (C) were assigned based on land cover derived from the consolidated NLCD classes. We did not differentiate erosion control practices, and the support practice factor (P) was set to one. Surface soil erodibility (K) was extracted and rasterized from the STATSGO database.

Table 1. Regional landscape characteristics of drainage basins within the Chesapeake Bay watershed that were monitored by the Smithsonian Environmental Research Center (SERC).

Landscape metric/predictor†	Appalachian Plateau	Appalachian Mountain	Mesozoic Lowland	Piedmont Upland	Coastal Plain
Number of watersheds	7	9	7	10	45
Area (ha)	990–32,672	700–28,637	533–7873	45.3–3241	5.2–91,126
Mean annual R† (MJ mm ha^{-1} h^{-1} yr^{-1})	1370–1400	1885–1970	2400–2550	2550–2550	2800–3425
Mean USLE (LS) (dimensionless)	1.76–3.70	0.51–5.06	0.59–2.91	0.98–2.12	0.07–1.72
Mean K (Mg ha h ha^{-1} MJ^{-1} mm^{-1})	0.03	0.02–0.04	0.04	0.04	0.02–0.06
Mean USLE CP factor (dimensionless)	0.08–0.10	0.09–0.13	0.08–0.17	0.07–0.11	0.05–0.26
Mean A (Mg soil loss ha^{-1} yr^{-1})	6000–16,000	3300–22,000	5800–26,700	8500–25,500	400–22,500
Mean 30-m pixel difference in elevation (m)	8–12.5	3–15	3–11	5.5–9.5	0–9
Basin relief ratio	0.02–0.07	0.04–0.18	0.01–0.24	0.02–0.27	0.01–1.43
% Cropland	0–1	0–31	0–39	0–22	0–61
% Development	0–1	0–1	0–5	0–1	0–82
% Impervious area	<1	0–2	0–6	0–1	0–39
% Forest	2–98	73–95	4–99	11–92	9–100
Weighted CN	68–74	60–79	69–74	60–68	57–81
Annual runoff (cm yr^{-1})	23–32	21–46	31–38	15–30	14–52
Mean annual stream flow (cm yr^{-1})	49–80	54–80	49–82	23–46	10–104
Mean annual sediment yield (Mg ha^{-1} yr^{-1})	0.09–0.5	0.02–1.2	0.3–0.9	0.05–0.5	0.01–1.2
Mean annual total P yield (kg ha^{-1} yr^{-1})	0.3–0.8	0.1–3.0	0.6–3.5	0.2–0.8	0.0–4.6

† A, erosion rate; CN, curve number; CP, cover-practice; K, soil erodibility; LS, length-slope; R, rainfall erosivity; USLE, Universal Soil Loss Equation.

RUSLE Analysis

Gross erosion rates were estimated using the automated version of the Revised-USLE2 (Renard et al., 1997; USEPA, 2004). The application identifies potential sediment transport routes, using raster grid cumulation and maximum downhill slope methods (Van Remortal et al., 2001), and depositional zones based on significant changes (>50%) in slope (Hickey et al., 1994). Slope length is subsequently defined as the distance from the origin of an overland flow path to a point where deposition occurs or where the flow path converges with others to form a defined channel (Van Remortal et al., 2001). Cover and practice (CP) values were calculated from the RUSLE database, which incorporated a wider range of land use and land cover characteristics than our USLE application by using additional information from county-level agricultural censuses (Yoder et al., 2004). Applied CP values also incorporated climatic effects (Foster et al., 2003).

Sediment Delivery Ratios

Five variations of SDR models were implemented, including three lumped-parameter models that estimate the SDR from watershed area (in square miles) or watershed slope:

$$\text{SDR} = 0.42 \times \text{Area}^{-0.125} \text{ (Vanoni, 1975)}$$

$$\text{SDR} = 0.417762 \times \text{Area}^{-0.134958} - 0.127097 \text{ (USDA-NRCS, 1983)}$$

$$\text{Log(SDR)} = 2.943 - 0.824 \log(L/R) \text{ (Maner, 1958)}$$

where L = maximum length of watershed, and R = watershed relief, represented by the difference between average elevation

Table 2. Regional landscape characteristics of selected drainage basins within the Chesapeake Bay watershed that were monitored by USGS.

Landscape metric/predictor	Appalachian Plateau	Appalachian Mountain	Mesozoic Lowland	Piedmont Upland	Coastal Plain
Number of watersheds	5	2	5	7	4
Area (ha)	2607–11,981	3874–8854	101–2894	1510–90,527	963–29,062
Annual R† (MJ mm ha^{-1} h^{-1} yr^{-1})	1480–1600	2090–2320	2160–2720	2710–3080	3240–3360
Mean USLE LS (dimensionless)	2.72–6.36	1.81–2.84	0.12–3.12	0.62–1.40	0.10–1.23
Mean K (Mg ha h^{1} ha^{-1} MJ^{-1} mm^{-1})	0.03	0.03	0.03–0.04	0.04	0.03–0.05
Mean USLE CP factor (dimensionless)	0.01	0.01–0.02	0.01–0.05	0.02–0.06	0.02–0.05
Mean A (Mg soil loss ha^{-1} yr^{-1})	8700–25,600	11,400–13,500	500–19,000	6400–12,900	1300–15,900
Mean 30 m pixel difference in elevation (m)	10.1–16.1	7.9–10.3	0.7–10.5	4.1–8.1	0.5–6.8
Basin relief ratio	0.16–0.51	0.09–0.13	0.06–0.19	0.07–0.30	0.03–0.05
% Cropland	0–4	5–12	0–14	1–12	3–39
% Development	0–1	0–1	1–30	1–23	1–19
% Impervious area	0–1	0–1	2–19	1–10	2–14
% Forest	48–99	48–59	6–64	30–38	28–73
Weighted CN	61–76	65–71	68–78	64–69	60–68
Annual runoff (cm yr^{-1})	18–31	20–40	32–43	21–35	17–31
Mean stream flow (cm yr^{-1})	35–70	44–59	36–55	36–45	35–42
Mean annual sediment yield (Mg ha^{-1} yr^{-1})	0.03–1.0	0.2–0.6	0.6–2.8	0.1–3.7	0.05–0.3

† A, erosion rate; CN, curve number; CP, cover-practice; K, soil erodibility; LS, length-slope; R, rainfall erosivity; USLE, Universal Soil Loss Equation.

of the watershed divide and the watershed outlet.

We also used two distributed models that calculate a SDR for each pixel and estimate the proportion of eroded sediment that is transported from each cell to the stream channel. The first model weights erosion estimates by flow path distance and by the relief of the potential sediment source above the stream:

SDR = exp(–0.4233 × flow path length [m] × slope factor)

where

slope factor = exp{–16.1 × (relief to stream/flow path length + 0.057)} – 0.6 (Yagow et al., 1998).

The second distributed model was provided by USEPA in combination with the automated RUSLE2 program (USEPA, 2004). SEDMOD provides pixel-based SDR estimates based on flow-path slope gradient and shape, vegetation surface roughness, stream proximity, and soil texture and moisture content (Fraser et al., 1998). For each catchment, five predictions of sediment delivery resulted by multiplying erosion estimates by the five SDR algorithms.

Annual Runoff

The Curve Number (CN) method (USDA Soil Conservation Service, 1986) was used to estimate runoff potential and annual runoff. STATSGO data describing hydrologic soil groups were combined with the land use data and assigned a curve number. Monthly runoff was calculated from monthly average precipitation data (Spatial Climate Analysis Service, 2002) and summed to derive annual average runoff.

Correlation and Multivariate Regression Analyses

Zonal statistics (ArcGIS 9.1) were used to derive summary values of landscape characteristics for each catchment. Spearman rank correlation coefficients were used to assess how well the observed sediment yields corresponded with predictions from the USLE-based models. Pearson correlations were used to compare results among the USLE-based models and to compare USLE-predicted erosion rates with input factors (i.e., LS, R, CP, and K). For the multiple regression analysis, additional predictor variables considered included physiographic province, watershed size, variation in terrain complexity (determined by comparing slopes in adjacent grid cells), topographic relief ratio, land cover proportions, percent impervious area, runoff potential, and annual average runoff (determined using the CN method). Continuous variables except rainfall erosivity (R), mean annual erosion, and basin topographic relief ratio were $\log_{10}$ transformed, and percentage variables were square-root transformed to improve normality and reduce heteroscedascity before analysis. We used Pearson correlation coefficients to detect and eliminate redundant variables. Univariate linear regressions were used to detect which of the independent variables best predicted annual sediment yield. Best subsets multiple regressions were subsequently used to model the relationship between sediment yield and catchment landscape features.

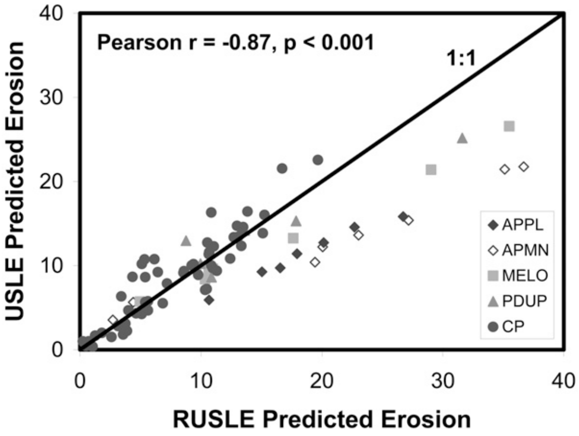

Fig. 2. Universal soil loss equation (USLE) versus revised USLE (RUSLE2) predictions of mean annual soil erosion rates (Mg ha^{-1} yr^{-1}). Symbols indicate the physiographic province in which a catchment is located. APPL, Appalachian Plateau; APMN, Appalachian Mountain; MELO, Mesozoic Lowland; PDUP, Piedmont Upland; CP, Coastal Plain.

Results

Correlation of Observed Sediment Yields with USLE-based Predictions

The USLE and RUSLE erosion estimates were strongly correlated and not statistically different for SERC drainage basins (Pearson $r = 0.87$; $p < 0.001$) (Fig. 2) or USGS drainage basins (Pearson $r = 0.95$; $p < 0.001$). Variation between USLE and RUSLE predictions differed by physiographic province; RUSLE estimates were consistently higher than USLE for catchments in the Appalachian Plateau and Appalachian Mountain regions and lower for catchments in the Coastal Plain and Piedmont regions. Differences between the two models were larger in basins predicted to have higher erosion rates by both models. Because of the strong correlation between the USLE and RUSLE predictions, we focus on the USLE results for subsequent analyses, including implementation of the SDR equations and the statistical analyses.

When erosion predictions were compared with measured sediment yields from the SERC or the USGS monitoring sites, rank correlations were numerically low (Spearman r range, –0.22 to –0.02) and not statistically significant (p range, 0.21–0.69). Many of the highest observed sediment yields occurred in the Coastal Plain where low erosion rates were predicted.

Adjusting predicted erosion rates with SDR equations did not improve the rank correlations between observed and predicted sediment yield across the region or within physiographic provinces of the Chesapeake Bay watershed (Table 3). Sediment delivery ratio predictions were strongly correlated with the unadjusted USLE predictions (r range, 0.73–0.92; $p < 0.001$), and correlations between observed and SDR-predicted sediment yield were numerically low for both SERC drainage basins (Spearman r range, –0.17 to –0.08; p range, 0.14–0.50) and USGS drainage basins (Spearman r range, –0.28 to 0.00; p range, 0.20–0.99). The Yagow algorithm was not implemented for USGS-monitored drainage basins because of the similarity in all other results and the extensive effort required for calculating flow path dis-

Table 3. Summary of Spearman rank correlations of Universal Soil Loss Equation–based predictions and annual average sediment yields observed by the Smithsonian Environmental Research Center (SERC) and USGS.

	SERC observed sediment yield (n = 78)		USGS observed sediment yield (n = 23)	
Model	*r*	*p*	*r*	*p*
Erosion model†				
USLE	−0.02	0.69	−0.22	0.32
RUSLE2	−0.12	0.21	−0.01	0.96
Sediment delivery model				
Vanoni, 1975	−0.11	0.34	−0.07	0.72
USDA Soil Conservation Service, 1986	−0.10	0.36	−0.02	0.94
Maner, 1958	−0.08	0.50	−0.28	0.20
Yagow, 1998	−0.13	0.28	na‡	na
Fraser, 1998 (RUSLE2)	−0.17	0.14	0.00	0.99

† RUSLE, revised Universal Soil Loss Equation; SCS, Soil Conservation Service; USLE, Universal Soil Loss Equation.

‡ This correlation was not assessed.

tance and flow path relief across each drainage basin. Estimates from RUSLE applications yielded similar negative correlations between observed and predicted sediment yields (Fig. 3).

We examined which of the component USLE factors most strongly influenced SERC and USGS basin erosion estimates and found that these corresponded primarily with the average LS factor (Table 4). The importance of the LS factor was emphasized by the significant but negative correlations of erosion estimates with other USLE input factors known to promote erosion. For example, higher annual rainfall erosivity (R) counterintuitively corresponded with lower estimated erosion rates due to the predominant influence of topography on rainfall distribution (Pearson $r = -0.79$; $p < 0.001$). Land cover patterns were also associated with differences in basin topography. Land cover classes presumed to be more susceptible to erosion, including developed land and cropland, occupied a greater proportion of area in drainage basins with lower mean LS factors (Pearson $r = -0.30$; $p = 0.002$ for LS and developed land and $r = -0.45$; $p < 0.001$ for LS and cropland), whereas forest land cover predominated in catchments with steeper slopes ($r = 0.56$; $p < 0.001$ for LS and forest). As a result, there was significant negative correlation between the CP factor and the LS factor ($r = -0.56$; $p < 0.001$). Lower C values, presumed to represent land uses that promote soil stability and limit erosion, were also counterintuitively associated with higher erosion rates ($r = -0.45$; $p < 0.001$).

Relating Sediment Discharges to Geographic Factors

Using data from all 78 SERC catchments, correlation analyses of annual sediment yield with the independent variables indicated seven significant univariate relationships between observed stream water quality and catchment characteristics (Table 5). Before the best subsets multiple regression analysis, estimates for percent impervious and cropland areas were removed because of significant covariance with urban and forest areas, respectively. The best univariate predictors of sediment delivery included the USLE input factors K and CP, percent development, percent forest cover, annual average runoff, and mean observed stream flow. The multiple regression analysis identified a set of six variables that together explained 55% of the observed variance in annual sediment yield (F[5,72] = 17.31; $p < 0.001$) (Table 6). The six variables chosen were soil erodibility (K), log(stream flow), basin shape (log basin topographic relief ratio), square-root–transformed values of percent forest, and occurrence in the Appalachian Plateau. However, the best subsets multiple regression model performed poorly when the USGS observations of sediment yield were used as a verification data set (Pearson $r = -0.01$; $p = 0.95$) (Fig. 4). Sediment delivery generally was underpredicted.

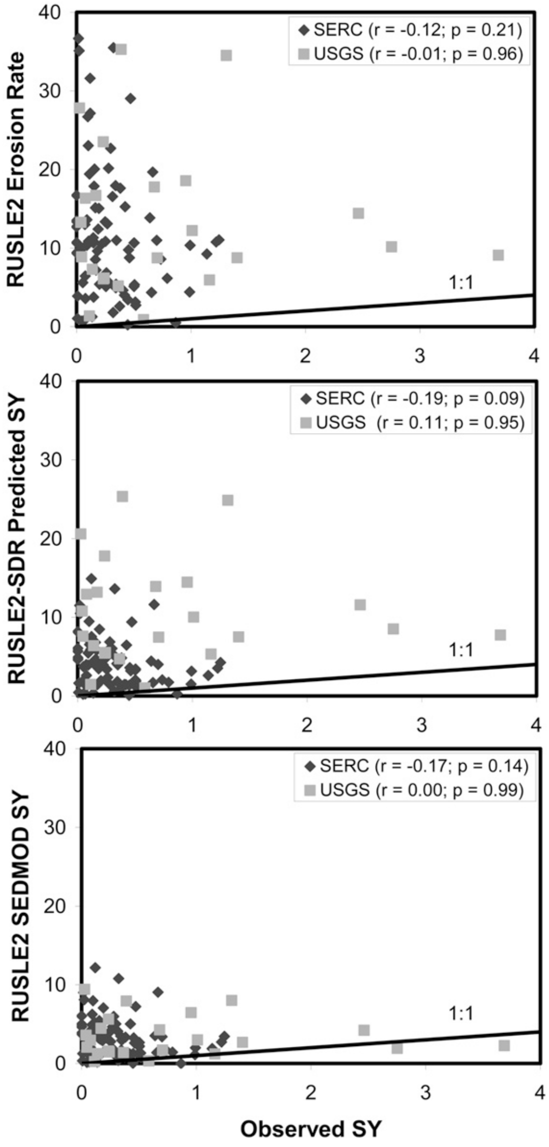

Fig. 3. Revised Universal Soil Loss Equation (RUSLE2)-based predicted erosion, RUSLE2 area-based sediment yield (SY) (Vanoni, 1975), and SEDMOD (Fraser et al., 1998) flowpath-based SY versus observed SY in basins monitored by the Smithsonian Environmental Research Center (SERC) and USGS. Spearman rank correlation coefficients between the observed sediment yields and predicted estimates are indicated for each dataset.

Table 4. Pearson correlation coefficients between mean basin Universal Soil Loss Equation (USLE) input factors and mean basin USLE erosion estimates.

	USLE-based erosion estimate			
	SERC basins (*n* = 78)		USGS basins (*n* = 23)	
USLE input factor	***r***	***p***	***r***	***p***
Topographic length-slope	0.66	<0.001	0.85	<0.001
Rainfall erosivity	−0.27	0.01	−0.47	0.02
Surface soil erodibility	−0.04	0.71	−0.40	0.05
Land use cover-practice	−0.43	<0.001	−0.55	0.01

Table 6. Percentages of variance explained for multiple regression models relating average annual sediment yield to geographic variables. Each percentage of variance explained is for a model including the term on the line and all terms on previous lines.

	Log(Sediment Yield in kg ha^{-1} yr^{-1})	
Factor	**Coefficient**	**% Variance explained**
Constant	−0.09	
Soil erodibility	30.71**	19
Log (stream flow in cm yr^{-1})	0.86**	32
Basin topographic relief ratio	−0.23*	42
Sqrt (% forest)	−0.68**	52
Appalachian Plateau Province	0.33*	55

* Significant at the 0.05 probability level.

** Significant at the 0.001 probability level.

Discussion

Results from this study demonstrate the limitations of USLE-based predictions for whole catchments and reinforce previous arguments against using these models for watershed management (Kinnell, 2004a; Trimble and Crosson, 2000b). The USLE and RULSE2-based predictions, used in conjunction with SDRs, did not adequately predict observed sediment yield or the rankings of yields from whole catchments as measured in two independent datasets collected by SERC and by the USGS (Gellis et al., 2005; Jordan et al., 1997a; Jordan et al., 1997b; Langland et al., 1995). Instead, estimates from the SDR applications were strongly correlated with the unmodified USLE estimates of edge-of-field erosion. These results demonstrate the inadequacy of extrapolating USLE erosion estimates to the whole catchment by incorporating current algorithms to account for hillslope or catchment transport processes. The lack of correlation of USLE-based predictions with measured sediment yields also suggests that integrated hydrologic models that rely on USLE-SDR estimates as valid input or calibration data and treat the estimates as observed data (Chen and Mackay, 2004; Kinnell 2004a) may also be poor tools for predicting sediment yields. Such models include HSPF applications (e.g., Donigian and Bicknell, 2006), GWLF (Haith and Shoemaker, 1987), and SWAT (Arnold and Allen, 1992).

One of the difficulties in assuming that the plot-scale erosion model can be applied at the regional scale is that it is not possible to incorporate the plot-scale complexities and details prescribed for each of the USLE factors. For example, plot-based applications require users to assign cover management (C) values based on detailed characterizations of crop coverage (including crop rotation schedule, crop type, density of fine roots, density of ground cover, soil roughness, soil consolidation potential, and antecedent moisture conditions). Assigning plot-scale management factors (P) has similar complexities. In contrast, catchment-scale assignments of C and P factors are necessarily much less detailed. For example, as in other reported analyses, we aggregated land use classes into five categories and did not distinguish different forms of agriculture or different housing densities (e.g., Ali and Sharda, 2005; Boellstorff and Benito, 2005), nor could we incorporate the effects of different conservation practices (i.e., we set the P factor to one across the entire drainage basin). Using broad land cover classes disregards the significant effects that spatial heterogeneity in agricultural practices

Table 5. Summary of univariate regression analyses relating log-transformed observed annual sediment yield (kg ha^{-1} yr^{-1}) to catchment landscape features.

Landscape metric/predictor†	**Chesapeake Bay watershed (*n* = 78)**	**Appalachian Plateau (7)**	**Appalachian Mountain (9)**	**Mesozoic Lowland (7)**	**Piedmont Upland (10)**	**Coastal Plain (45)**
Area (ha)	0.01	0.16	0.16	0.25	0.00	0.02
R MJ mm ha^{-1} h^{-1} yr^{-1}	0.00	0.00	0.84***	0.08	0.02	0.04
USLE LS factor (dimensionless)	0.00	0.48	0.69**	0.04	0.01	0.11*
K Mg ha h ha^{-1} MJ^{-1} mm^{-1}	0.19***	na‡	0.97***	na	na	0.21**
USLE CP factor (dimensionless)	0.09**	na	0.59*	0.10	0.02	0.06
Annual A (Mg soil loss ha^{-1} yr^{-1})	0.00	0.46	0.82***	0.09	0.01	0.15**
Variation in terrain complexity	0.00	0.11	0.06	0.04	0.10	0.01
Basin topographic relief ratio	0.05	0.00	0.15	0.00	0.01	0.21**
% Cropland	0.02	0.00	0.87***	0.04	0.02	0.00
% Development	0.13***	0.05	0.12	0.39	0.51*	0.15**
% Impervious area	0.08**	0.17	0.86***	0.10	0.08	0.06
% Forest	0.14***	0.20	0.70**	0.03	0.01	0.15**
Weighted CN	0.04	0.02	0.15	0.04	0.02	0.01
Annual runoff (cm yr^{-1})	0.18***	0.00	0.62**	0.21	0.01	0.10*
Mean stream flow (cm yr^{-1})	0.13***	0.02	0.07	0.04	0.09	0.36***

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 level.

† A, erosion rate; CN, curve number; CP, cover-practice; K, soil erodibility; LS, length-slope; R, rainfall erosivity; USLE, Universal Soil Loss Equation.

‡ The relationship was not analyzed because there was no variation in the landscape characteristic throughout the physiographic province.

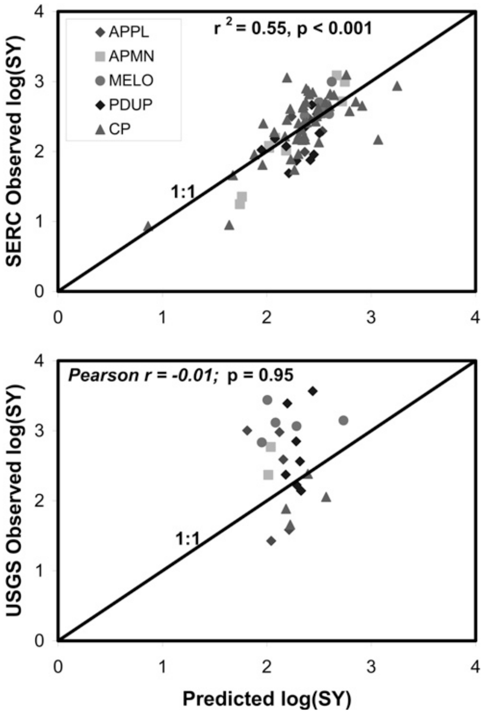

Fig. 4. Observed annual average sediment yield (SY in kg ha^{-1} yr^{-1}) versus sediment yield predicted by linear regression on log- or square-root transformed landscape factors. Plot A depicts calibration with SERC data; Plot B depicts attempted validation with USGS data. Points along the diagonal 1:1 line indicate perfect agreement between predictions and measurements. Symbols indicate the physiographic province in which a catchment is located: Appalachian Plateau (APPL); Appalachian Mountain (APMN); Mesozoic Lowland (MELO); Piedmont Upland (PDUP); or Coastal Plain (CP).

and residential and livestock densities can have on nutrient loading and export (Johnes, 1996). In addition, land cover constants assigned for the USLE calculations ignore interactions with other geographic factors, such as variations in climatic patterns and plant growth along latitudinal gradients (Risse et al., 1993). Discrepancies in the model scale also affect the reliability of characterizing soil erodibility (K). At the plot scale, the K factor is determined from field measurements of soil texture, structure, organic matter content, and permeability (Wischmeier and Smith, 1978), but these properties become more variable and difficult to parameterize with increasing scale (Zeleke and Si, 2005). Regional analyses rely on generalized parameter estimates from broad-scale soil maps such as STATSGO (USDA-NRCS, 1995).

Additionally, the USLE-based sediment delivery models do not account for complexities at the landscape level that influence sediment transport and delivery. Predictions are based on plot-scale mechanisms, namely the effects of rainfall energy on soil detachment given the plot's surface characteristics. When the scale is increased from a plot to a hillslope or catchment, additional processes such as overland flow and infiltration hydraulics become increasingly important to controlling sediment transport and delivery (Slaymaker, 2006; Yoder et al., 2004). We tried to capture some of the landscape-level effects by implementing SDR algorithms that incorporate watershed flow path characteristics (e.g, Fraser et al., 1998; Yagow et al., 1998). Despite the strong potential for improving predictive capability by accounting for flow path characteristics (Baker et al., 2006b), this approach did not improve the reliability of the USLE-based predictions. Because USLE estimates at the plot scale are well verified (Risse et al., 1993), our results suggest that the effects of sediment transport processes are predominantly more important than the plot-scale erosion rates, which is counter to the assumptions underlying the USLE-SDR approach.

Hydrologic processes that control sediment transport and delivery at the catchment scale are at best crudely accounted for in various USLE-SDR models (Slaymaker, 2006). One of the key processes affecting sediment delivery is catchment runoff generation (Sheridan and Hubbard, 1987; Smith et al., 2005), suggesting the potential utility of combining USLE erosion estimates with runoff calculations, such as the CN method (e.g., Haith and Shoemaker, 1987). We tested whether incorporating annual average runoff estimates improved our ability to predict sediment discharge. We expected that runoff estimates would be an adequate proxy for the effects of catchment relief and development and that observed sediment yield would increase with estimated annual runoff. The logic and approach is similar to the MUSLE (Modified USLE; Williams, 1975), which transforms the USLE into an event-based model by replacing the long-term annual rainfall erosivity with runoff estimates for each storm. Incorporating hydrologic characteristics at an annual timescale showed some promise, but results were variable, as demonstrated by the significant correlation between estimated runoff and observed sediment yields from the SERC study watersheds and the lack of a similar correlation for the USGS watersheds. This inconsistency also may reflect limitations of the CN method (Garen and Moore, 2005).

The importance of hydrologic processes to sediment transport processes, which are driven by precipitation events, suggests that the timescale of the USLE model may be inappropriate for predicting catchment sediment discharge. The USLE predicts long-term (>20 yr) annual average soil erosion rates, a much longer time than the brief extreme events that often dominate sediment discharge events (e.g., Jordan et al., 1997a). Although the MUSLE is event based, our results indicate potential limitations with this approach because it assumes the landscape factors (i.e., soil erodibility, length-slope, cover, and management) remain relatively static on a year-to-year basis, representing an unchanging erosion potential. We found weak correlations between any of the USLE factors and the observed sediment yields. Results likely reflect interactive effects of weather patterns on USLE input factors, resulting in erosion and sediment delivery rates that vary inconsistently with the amount and intensity of rainfall events (e.g., Lenzi et al., 2003; Kinnell, 2004b). Successful empirical models will require a focus on short-term precipitation data and more time relevant land use and cover data and incorporating nonlinear relationships between sediment production and rainfall erosivity.

Perhaps the most significant limitation of using USLE-based watershed models is that they do not account for sediment generation by processes other than the effects of overland flow on interrill and rill erosion. In particular, gully erosion (Prosser et al., 2001) and in-stream processes, especially bank erosion and resuspension of sediment materials, can contribute significantly to observed sediment loads (Trimble, 1997). Stream bank ero-

Table 7. Summary of published statistical models relating observed stream sediment yield (SY) or total suspended solids (TSS) to catchment landscape characteristics.

Model	R^2 (%)
This study (78 catchments in the Chesapeake Bay watershed, USA): log(SY in kg ha^{-1} yr^{-1}) = 30.71 (mean soil erodibility)† + 0.86 log[stream flow in cm yr^{-1}]) – 0.23 (basin relief ratio) – 0.68 (sqrt[% forest area]) + 0.33(Appalachian Plateau)	55
(Restrepo et al., 2006) (32 catchments in the Magdalena River watershed, Colombian Andes in South America): log(SY in Mg km^{-2} yr^{-1}) = −0.8838 + 0.8140 log(runoff in mm yr^{-1}) – 0.3906 log(average maximum discharge in m^3 s^{-1})‡	58
(Weller et al., 2003) (23 catchments in the Patuxent River watershed, MD): TSS (mg L^{-1}) = 1.0(%cropland) + 0.6(% development) + 0.7 (Coastal Plain) + 11.5(Week)§ + 17.2(% cropland × week) + 7.8 (% development × week) + 11.8 (Coastal Plain × week) + 6.9(% cropland × Coastal Plain × week)	58
(Verstraeten and Poesen, 2001) (26 catchments in Central Belgium): log(SY in Mg ha^{-1} yr^{-1}) = 3.72 – 0.72 log (area in ha) – 0.84 log (hypsometric integral)¶ + 0.11 log (drainage length in m)	76
(Jones et al., 2001) (17 catchments in the Chesapeake Bay watershed): log(SY in kg ha^{-1} yr^{-1}) = 8.472 + 0.079(% development) – 0.116(% wetlands) – 0.038(riparian forest)#	79
(Basnyat et al., 1999) (21 catchments in the Fish River watershed, Al, USA): log(TSS in mg L^{-1}) = 3.7(% forest) + 17.33(% development) – 20.7(% orchard) + 11.47(% cropland) + 17.66(% pasture)	76

† Universal Soil Loss Equation parameter (Mg hr MJ^{-1} mm^{-1}).

‡ Long-term (1975–1995) average maximum water discharge.

§ Because of the week factor, model is specific to the time period monitored (August 1997–August 1999).

¶ The difference in the mean and minimum catchment elevations relative to the difference in the maximum and minimum catchment elevations.

Percent of watershed with forest land cover adjacent to stream edge, defined by land cover in adjacent 30-m pixels.

sion could be predominantly important to the sediment budget where stratified and unconsolidated deposits enhance the potential for stream incisement (Campo and Desloges, 1994; Nagle et al., 2007), as in the Coastal Plain physiographic province of the Chesapeake Bay watershed (Markewich et al., 1990). Human alterations to stream networks, such as the construction and subsequent failure of mill dams (Downward and Skinner, 2005) or enhanced peak flow due to land use change (Poff et al., 2006), also can enhance the impact of in-stream processes.

Disparities between the predicted and observed sediment yields might arise from data and computational limitations, particularly measurement error and model implementation. For example, significant differences in the LS factor can arise from variation in spatial analysis methods, including selection of the input data, variable definition, and implementation of GIS routines. User-selected GIS procedures also can influence predictions significantly. For example, simple USLE calculations summarize LS values across an entire catchment, whereas more sophisticated applications incorporate flow direction and exclude areas with steep slope declines where deposition is more likely than erosion (Hickey et al., 1994). The choice of GIS algorithms used for slope calculations (Dunn and Hickey, 1998), drainage basin delineations (Baker et al., 2006a), and flow routing (Desmet and Govers, 1996) also might alter the results. The strong correspondence between predictions from the automated RUSLE2 (USEPA, 2004) and our own USLE calculations (Fig. 2), however, suggests that computational differences in the implementation may have minor effects, so that the failure to correctly predict catchment discharges is more likely due to the more fundamental conceptual problems.

Because the USLE-based models did not work well for whole catchments, we explored the utility of the input factors, together with additional landscape features, to improve sediment yield predictions in a multiple regression model. Soil erodibility (K), stream flow, topographic relief ratio, percent forest cover, and physiographic province together explained over half of the variability in sediment yield among SERC watersheds, but a large portion of the variance (45%) remained unexplained. Previous empirical studies, which included catchment land cover and physical characteristics as potential predictors, have reported similarly significant findings, but the importance of landscape versus physiographic features was inconsistent among the efforts (Table 7). For example, some studies identified land cover features as the most significant factors (Jones et al., 2001; Basnyat et al., 1999), whereas others identified physical catchment features, such as physiographic province or drainage area, as more important (Verstraeten and Poesen, 2001; Restrepo et al., 2006). We also found that an empirical model calibrated with sediment yield data from the SERC watersheds did not perform well in a validation test with yield data from the USGS watersheds. This suggests that it may be dangerous to rely on other empirical models completed without the benefit of validation with an independent dataset. Variation among the empirical models (Table 7) could reflect the difficulty of using annual average observations to model elevated sediment loads, which occur mainly in response to short-term weather events (Jordan et al., 1997a). In addition, static models like these do not capture dynamic interactions among the input factors, which change in response to short-term and interannual weather fluctuations (Lenzi et al., 2003). These trends collectively suggest that scientists and managers have not captured the linkages between the catchment landscape setting and the physical mechanisms that regulate erosion and sediment transport processes.

Conclusions

We implemented seven variations of USLE-based models to estimate erosion and sediment delivery, but none provided a reliable tool for assessing sediment discharge from 101 catchments where stream water quality was monitored continuously for at least 1 yr. Our results reinforce previous arguments that USLE-based sediment delivery models provide an inadequate framework for managing land and water resources at the catchment scale (Kinnell, 2004a; Trimble and Crosson, 2000a, b). The USLE was not intended to predict effects on stream water quality, yet the models continue to be widely applied at the catchment scale by scientists (e.g., Boellstorff and Benito, 2005; Fu et al., 2005; Kim et al., 2005; Onyando et al., 2005; Wang et al., 2005), policymakers (e.g., Donigian and Bicknell, 2006; USEPA, 2005), and watershed modelers.

Our review of published statistical models and the poor performance of our own empirical model in a validation attempt with independent sediment yield data also suggest that many other non-USLE empirical models developed to predict annual sediment yield (Table 7) may be unreliable. First, a comparison of published statistical models revealed contradictions in the attribution of sediment delivery to land cover versus physiographic factors. Second, the disappointing performance of our model in the validation with independent data highlights the danger of relying on empirical models that have not been tested with a validation dataset.

Our findings also suggest some directions for future research on predicting sediment discharge in ungauged drainage basins: (i) Identify potential predictor variables that conceptually link landscape and stream characteristics to flow velocity, stream power, and the ability to transport sediment; (ii) incorporate metrics to indicate potential sediment sources within streams, including bank erosion and legacy sediments; and (iii) develop predictions for temporal scales finer than the long-term annual average time frame. Consistent and verifiable results from additional empirical studies will also help reduce the uncertainty in the predictions of process-based, integrated simulation models.

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