Contour-based digital elevation modeling of watershed erosion and sedimentation: Erosion and sedimentation estimation tool (EROSET)

H. Sun and P. S. Cornish

Landscape and Ecosystems Management, University of Western Sydney, Sydney, New South Wales, Australia

T. M. Daniell

Department of Civil and Environmental Engineering, University of Adelaide, Adelaide, South Australia, Australia

Received 21 September 2001; revised 29 April 2002; accepted 29 April 2002; published 13 November 2002.

[1] An erosion and sedimentation model, erosion and sedimentation estimation tool (EROSET), was developed and applied to a watershed in Happy Valley, South Australia. The model simulates the dynamics of event runoff, soil detachment, and transport processes. The erosion and sedimentation model is able to predict watershed erosion and deposition for storm events at an element as well as watershed scale. The model was developed and incorporated into an existing rainfall-runoff model based on a contour-based digital elevation framework. It combines the use of the USLE data source and extended erosion and transportation modeling into a distributed and intra storm erosion and deposition analysis. This results in storm-based, time-variant, distributed erosion and deposition modeling in the watershed for both storm-based and long-term sediment estimation. The modeling can better enable land managers to identify the areas in a watershed where erosion and deposition may occur. The modeled processes and results can be related to total storm erosion estimated by MUSLE, although they operate on different temporal and spatial frames. Satisfactory modeling results were obtained with very limited calibration which compares well with other studies. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 1860 Hydrology: Runoff and streamflow; 1871 Hydrology: Surface water quality; *KEYWORDS:* erosion, sedimentation, watershed, modeling

Citation: Sun, H., P. S. Cornish, and T. M. Daniell, Contour-based digital elevation modeling of watershed erosion and sedimentation: Erosion and sedimentation estimation tool (EROSET), *Water Resour. Res.*, *38*(11), 1233, doi:10.1029/2001WR000960, 2002.

1. Introduction

[2] Approaches used to estimate erosion and sedimentation consist generally of three types, empirical modeling, physically based modeling, and methods in between the two. Empirical methods such as the rating curve method have been widely used in erosion estimation [*Olive and Rieger*, 1984; *Banasik and Walling*, 1996; *Jansson*, 1997; *Hodson et al.*, 1998; *Jansson*, 1996]. With rating curve methods, monthly or annual runoff is related to total sediment yield in the corresponding time, giving the relevant erosion magnitude of the watershed on a monthly or annual basis. Such a method, however, is open to large errors due to the highly variable relationship between flow and sediment transport [*Olive and Rieger*, 1988]. The problem is caused by the underlying assumption that each individual storm is equally accountable for sediment production on a unit volume basis, which is often not the case. Research has shown that sediment transport in Australia is dominated by individual storms, particularly the larger ones [*Edwards*, 1987; *Geary*, 1981; *Olive and Rieger*, 1984; *Sun et al.*, 2001]. Therefore a storm-based sediment estimation approach is necessary to model watershed erosion and sedimentation dynamics. Storm erosion loads can then be added to give better estimates of long-term annual sediment load [*Sun et al.*, 2001].

[3] Physically based models such as ANSWERS [*Beasley et al.*, 1980], WEPP [*Nearing et al.*, 1989], KINEROS [*Woolhiser et al.*, 1990], EUROSEM [*Morgan et al.*, 1998] and GUEST [*Misra and Rose*, 1990] have been developed to simulate sediment processes on a storm basis. Most of these and other erosion and sedimentation models can be incorporated within or linked to GIS models for watershed erosion and deposition estimation [*Mitas and Mitasova*, 1998; *Sun*, 1999]. The distributed modeling approach enables the analysis of sediment detachment and transport not only at the watershed outlet, but also inside the watershed for possible impact analysis of land use changes. A major problem with some of the traditional GIS models lies in that they make steady state estimates of erosion and sedimentation which do not account for dynamic, time-variant processes such as storm rainfall and runoff processes. They generally predict erosion *potential* based on soil, slope, land uses and other geographic properties [*De Vantier and Feldman*, 1994; *Mitas and Mitasova*, 1998].

[4] WEPP [*Nearing et al.*, 1989] models interrill and rill processes operating at field plot scale on average or steady state conditions, which requires details of rills for the plot or

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hillslope. KINEROS [*Woolhiser et al.*, 1990] operates on a subcatchment basis, modeling erosion and sedimentation through a cascade of planes and channels. EUROSEM [*Morgan et al.*, 1998] has the capacity to model gully erosion in addition to modeling within-storm processes.

[5] USLE [*Wischmeier and Smith*, 1978] can be regarded as an erosion estimation method that sits between the empirical and physically based approaches. It uses physically based parameters but does not model the detailed storm processes. The modified USLE or MUSLE [*Williams*, 1995] is similar in this respect in that it estimates storm erosion but not the processes in a storm. Over the last forty years of erosion study associated with the USLE [*Wischmeier and Smith*, 1978], there has been an enormous amount of data collected in the US as well as in other countries [*Edwards*, 1987]. However, this information has rarely been used in the development and verification of the physically based models.

[6] The erosion and sedimentation model (EROSET) developed in this study combines a contour-based digital terrain network and a rainfall-runoff model to estimate erosion and deposition on an element as well as watershed scale. It is able to model storm and within-storm erosion and deposition processes. The development of the erosion and sediment model in this study combines the valuable data sources of USLE with a storm-based, distributed hydrological model. The model, while not using MUSLE for erosion estimation, can be regarded as an extension of the approach to estimate not only the total erosion of a storm, but also within-storm runoff processes and deposition on a watershed as well as element scale.

[7] The model simulates detachment in overland and channel areas, and sediment transport for distributed storm erosion and sedimentation [*Sun*, 1999]. It differs from WEPP in that it does not require the details of rills, such as rill structure, distribution and flow directions, and also from KINEROS in that it is based on a contour based one-dimensional flow network that can be delineated directly from a DEM map to form a realistic channel network with defined flow routes. It has the capacity to model erosion including gully erosion as does EUROSEM but with minimal data requirement.

2. Development of the Erosion and Sedimentation Model

[8] The erosion and sedimentation model developed in this study includes the mathematical representation of the sediment continuity equation [*Blau et al.*, 1988], soil detachment [*Foster*, 1982], sediment transport capacity [*Yang*, 1973], and sediment transport and deposition within an element. A brief review of watershed partitioning and the rainfall-runoff model is also provided below.

2.1. Watershed Partitioning and the Rainfall-Runoff Model

[9] *Onstad and Brakensiek* [1968] developed the "stream tube" concept by assuming the contour lines are equipotential lines, the orthogonal lines to the equipotential lines form the "stream tubes". Flow from an upslope element successively enters into the downslope elements to form a one dimensional flow tube. TAPES-C is a set of programs that partitions the watershed using this "stream tube" approach [*Moore and Grayson*, 1991]. A one dimensional flow network can thus be developed which is shown in Figure 1 for the studied Sauerbier Creek watershed in Happy Valley, South Australia.

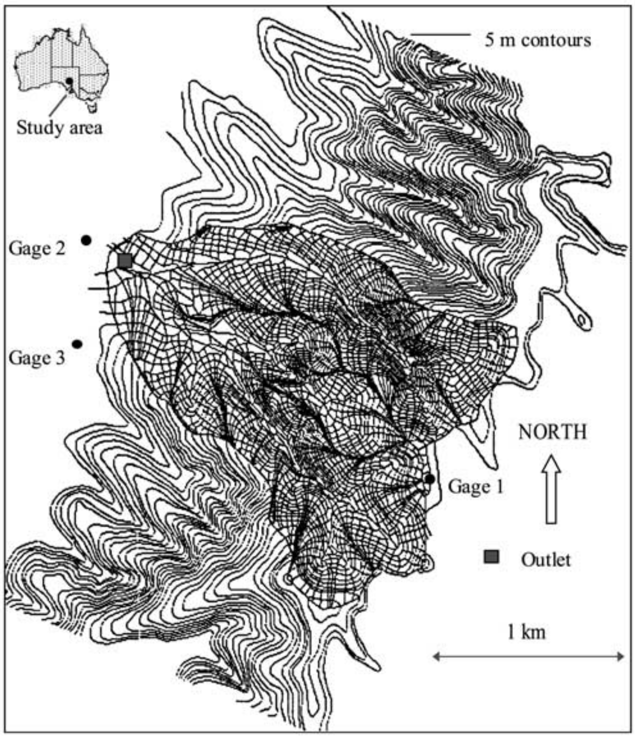

Figure 1. Sauerbier Creek watershed as partitioned into 3477 elements where darker lines are the ridges of the watershed and channels are in between the ridges.

[10] THALES is a storm rainfall-runoff model based on the element network created by TAPES-C [*Moore and Grayson*, 1991]. It is a one-dimensional model simulating kinematic overland flow and channel flow for both saturation excess and infiltration excess runoff. THALES generates flow variables on an element basis which are used by the sediment detachment and transport model developed in this study.

2.2. Erosion and Sedimentation Model

[11] The sediment continuity equation is described as

$$\frac{\partial(Ch)}{\partial t} + \frac{\partial(Cq)}{\partial x} = D_i + D_r \quad (1)$$

where C is sediment concentration (kg/m^3), q is discharge per unit width (m^2/s), h is local depth of flow or hydraulic radius (m), t and x are time and distance along the flow line respectively. D_i and D_r are interrill and rill erosion rates, respectively (kg/m^2/s). When equation 1 is used to calculate channel sediment transport, the rill erosion rate is replaced by channel erosion rate, and the interrill erosion rate is replaced by lateral sediment inflow rate per unit length of the channel. Equation 1 can be delineated into a finite difference form as [*Sun*, 1999]

$$\frac{2\Delta t}{\Delta x} qC_4q_4 + C_4h_4 = C_1h_1 + C_3h_3 - C_2h_2 + \frac{2\Delta t}{\Delta x}(1-q) \cdot (C_1q_1 - C_3q_3) + \frac{2\Delta t}{\Delta x} qC_2q_2 + 2\Delta t(D_i + D_r) \quad (2)$$

where subscripts 1, 2, 3, 4 represent the time and distance grid, representing the four corners of an element at (t, x), ($t + \Delta t$, x), (t, $x + \Delta x$) and ($t+ \Delta t$, $x+ \Delta x$) respectively. Δt and Δx are time and distance increments, respectively. This is the primary equation used for sediment transport routing in the watershed.

[12] The mass conservation and momentum equations for runoff were solved numerically using the Newton Raphson or Regula Falsi method [*Moore and Grayson*, 1991]. Once the flow variables are obtained, equation 2 can be explicitly solved for C_4, and erosion and deposition can be estimated and routed through the watershed channel network. Deposition is calculated as a constant process of erosion and deposition in an element during a runoff event, depending upon whether the sediment concentration exceeds the local sediment transport capacity calculated by the unit stream power method described in section 2.4.

2.3. Interrill, Rill, and Channel Erosion Representation

[13] Erosion in interrill areas is generally considered to be caused primarily by the splashes of raindrops. The equation for interrill detachment is expressed as a square function of rainfall intensity and can be described as [*Foster*, 1982]

$$D_{ih} = 0.0138 i^2 K(SF) C_{slr} \quad (3)$$

where D_{ih} is detachment rate per hour (kg/m^2/h), (divided by 3600 to derive D_i in kg/m^2/s); i is rainfall intensity (mm/h); the coefficient of 0.0138 was obtained by fitting i^2 to the $EI/2$ vs. i of USLE relationship; K is the soil erodability factor of the USLE for detachment by raindrop impact (kgh/N/m^2); and C_{slr} is the soil loss ratio. SF is the slope factor expressed as

$$SF = 1.05 - 0.85 EXP(-4 SIN(\theta)) \quad (4)$$

where θ is the local slope angle in degrees [*Lal*, 1990]. SF varies from 0.2 for a flat slope to 1.0 for a slope angle of 45°, to 1.05 for a slope angle of 90°.

[14] Sediment delivery from the interrill is the lower value of either the transport capacity or the available soil detachment. A roughness factor can be used to estimate the interrill sediment delivery [*Foster*, 1982]. The factor varies from 0.3 for large-scale roughness with depressions greater than 150 mm, to 1.0 for a smooth surface. A roughness factor of 1.0 is assumed in this study.

[15] Rill erosion can be described by the hydraulic processes in rills. The shear stress or the incisive force that applies on the rill surface by the flow in a rill, is the primary force for rill detachment. When this incisive force exceeds the critical shear stress of the soil, which is the force required to detach soil particles in a rill, soil particles are released and rill erosion occurs. Rill detachment is usually represented by [e.g., *Foster*, 1982]

$$D_r = a(\tau - \tau_{cr})^b \quad (5)$$

with

$$\tau = \gamma RS \quad (6)$$

where D_r is the rill erosion detachment capacity rate (kg/m^2/s); τ is the flow shear stress (N/m^2); τ_{cr} is critical shear stress (N/m^2); a and b are fitted parameters. γ is density of water (N/m^3) multiplied by the acceleration of gravity g (m/s^2); R is hydraulic radius (m) and S is slope gradient of rill bottom.

[16] Using equation 6 for rill erosion would require the defining of rill shape and density in a watershed, which is not very practical under field conditions. On the other hand, runoff or flow information can usually be obtained with greater accuracy. Consequently, rill erosion can be simplified as [*Foster*, 1982]

$$D_r = \alpha QSKC_{slr} \quad (7)$$

where α is a calibrated parameter and Q is discharge (m^3/s); other variables are described earlier. In applying equation 7 to the studied watershed, the estimated detachment is found to be too flat around the storm peak, compared to the observed [*Sun*, 1999]. Therefore a power function to the runoff factor Q is proposed in this study

$$D_r = \alpha Q^\beta SKC_{slr} \quad (8)$$

where β is a calibrated parameter. The flow rate and the slope are calculated by the model on an element basis, which enables equation 8 to be used for erosion and deposition estimation on an element basis in a watershed. For channel elements, equation 8 represents detachment in channels and the factors on the right hand side of the equation represent channel parameters.

2.4. Sediment Transport Capacity Estimation

[17] *Yang* [1972, 1973] used unit stream power, defined as the time rate of potential energy expenditure per unit weight of water in an alluvial channel, to derive a relationship between unit stream power and total sediment concentration as

$$\log C_t = I + J \log((VS - V_{cr}S)/\omega) \quad (9)$$

in which

$$I = 5.435 - 0.386 \log(\omega d/\upsilon) - 0.457 \log(U^*/\omega) \quad (10)$$

$$J = 1.799 - 0.409 \log(\omega d/\upsilon) - 0.314 \log(U^*/\omega) \quad (11)$$

where C_t is total sediment concentration, parts per million (ppm); VS is unit stream power, m/s (V is flow velocity in m/s and S is slope gradient m/m); $V_{cr}S$ is critical unit stream power (V_{cr} is critical flow velocity) required at the incipient motion (m/s); ($VS - V_{cr}S$) is effective unit stream power; ω is the sediment terminal fall velocity in water (m/s); d is the median particle size of the bed material (mm); υ is the kinematic viscosity of the water (m^2/s). U^* is the average shear velocity (m/s), and $U^* = (gDS)^{0.5}$; D is water depth (m); and g is acceleration of gravity (m/s^2). Equation 9 can be applied for noncohesive natural beds with particle sizes between 0.062 mm and 2 mm, a specific gravity of 2.65 g/cm^3, and a shape factor of 0.7.

[18] For most cases, the term $V_{cr}S$ can be assumed zero when C_t is equal to or greater than 100 ppm [*Yang*, 1973]. *Moore and Burch* [1986] found that Yang's equation, which was originally applicable to natural channels, could also be extended to overland sediment flow prediction.

[19] Using unit stream power and Manning's equation, and assuming that the flow is uniform, turbulent and kinematic sheet flow, the unit stream power equation for overland sheet flow sedimentation, can be derived as [*Moore and Burch*, 1986]

$$VS = (Q/w)^{0.4} S^{1.3}/n^{0.6} \quad (12)$$

where Q is discharge (m^3/s), w is the width of an element (m), and n is Manning's roughness coefficient. For flow in a channel

$$VS = Q^{0.25} S^{1.375} R^{0.5}/A^{0.25} n^{0.75} \quad (13)$$

where R is hydraulic radius (m) and A is cross-sectional area (m^2), other items were described earlier.

2.5. Erosion and Deposition on an Element

[20] The rainfall-runoff model calculates the flow rate and velocity at a fixed time interval (one minute in modeling) in each element of the watershed. These flow variables were then used for estimating the sediment concentration at the inlet and outlet of the element during the time interval. The erosion/deposition rate was then estimated by calculating the sediment fluxes entering and exiting the element. For an element, assuming the upslope inlet flow rate and sediment concentration are Q_u and C_u respectively, and the downslope outlet flow rate and sediment concentration are Q_d and C_d respectively, the net sediment flux Y_d (mL/s/m^2) at time t within an element area of A_e, is

$$Y_d = (Q_u C_u - Q_d C_d)/A_e \quad (14)$$

Assuming the specific gravity of the soil is 2.65, the erosion/deposition per unit area (g/m^2) during the time interval Δt is

$$Y_r = 2.65 Y_d \Delta t \quad (15)$$

And the erosion/deposition per unit area (g/m^2) during an event time T is

$$Y_e = \sum_{t=0}^{T} Y_r \quad (16)$$

Equation 16 was used for sediment erosion and deposition calculation for each element during a storm runoff event. Annual erosion or deposition on an element scale can be estimated based on all the storm events of the year

$$T_{as} = \sum_{e=1}^{L} Y_e \quad (17)$$

where T_{as} is the total annual sediment (erosion/deposition) per unit area (g/m^2) for the element, Y_e is the event erosion/deposition per unit area (g/m^2) for the element, and L is the number of storm events during the year.

3. Watershed Data Collection and Parameter Estimation

[21] The Sauerbier Creek watershed has an area of 2.87 km^2, a high and low elevation of 370 m and 180 m respectively, and has three small creeks contributing to the main channel where a weir was constructed at the outlet of the watershed to measure and record storm flow. An automatic sampler was installed approximately 100 meters upslope from the weir. Three pluviometers were installed in or bordering the watershed (Figure 1). The long-term annual average rainfall for the watershed is 650 mm. The watershed is fairly steep with an average slope of around 10%. The lower part of the watershed (5%) is urbanized, while the upper part is predominantly pasture for sheep and cattle grazing. The amount of forested watershed is negligible, while areas with no vegetation are rare except in limited housing development areas. The creek beds and sides were mostly covered by grass, or boulders and pebbles except in the lower part of the watershed where channel incision has cut approximately 1 × 1 m^2 cross section to the bed and sides. This suggests that channel erosion occurred in the lower part of the creek when the soil surface was not covered by a protective layer of grass or pebbles. The watershed was partitioned into 3477 elements as shown in Figure 1 with an average element area of 825 m^2. Element properties including element number, area, length, width and slope of element are calculated during the partitioning process.

[22] Individual elements with an upslope contributing area equal to or greater than two hectares were assumed to be channel elements. This partitions the watershed elements into overland and channel elements. The resultant channel network corresponds well with the channel configuration in detailed topographical maps. The upslope contributing area that separates channel and overland elements in a watershed is a parameter determined by the user, according to the catchment size and topographical features. Since there is no apparent or widespread rilling in the watershed, rill modeling is not performed in this study, which leaves overland and channel modeling only for the watershed. Detachment in an overland element is described by equation 3; while detachment in a channel element is estimated mostly by equation 8, with overland detachment contribution estimated by equation 3 and added as lateral detachment to the channel element.

[23] Fourteen soil samples were collected from distributed sites throughout the watershed using borehole drilling equipment. These samples were processed in the laboratory to acquire soil moisture content at saturation, soil depth to the clay layer, soil bulk density and particle size analysis for runoff modeling [*Sun*, 1999]. Although these samples were taken from distributed sites of the watershed, it was not sufficiently detailed to distribute the derived parameters for each element across the watershed. Instead, averaged parameter values were used in modeling. Three storms that occurred in 1993 were used for runoff calibration. Saturation excess flow was assumed in the watershed, which resulted in good predictive capacity of the rainfall-runoff model [*Sun*, 1999]. The median diameter of the soil particles was calculated to be 0.203 mm from soil sampling, which is within the range for application of Yang's equations (0.062–2 mm). Figure 2 shows the saturated areas of the catchment under wet conditions using a wetness index w_t (w_t = ln (a_u/tan θ), where a_u is the upslope contributing area drained over per unit width of cross section, and θ is the

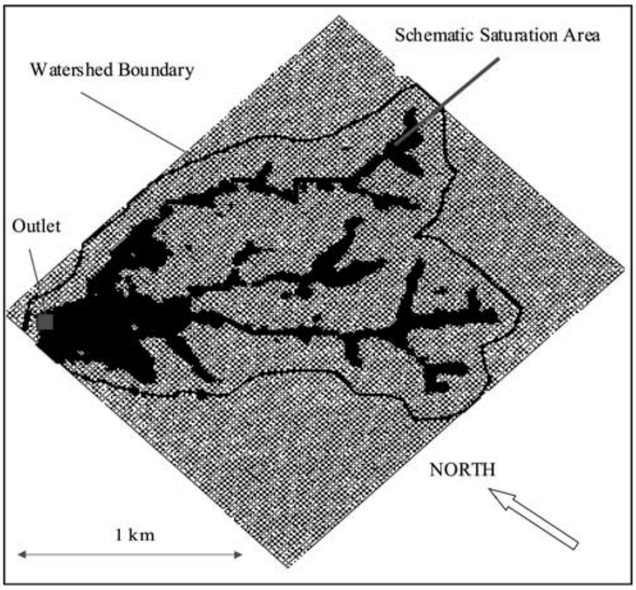

Figure 2. Defined channel network and flatter area in the lower part of the studied watershed using a wetness index.

local slope angle). The saturated areas are estimated by calibrating runoff events and developing a relationship between wetness index and antecedent base flow in the watershed [*Sun*, 1999]. Thus a certain area of the watershed (elements with larger wetness index values) were assumed to be saturated depending on the base flow prior to a storm. Figure 2 displays the contributing areas of saturation excess flow in wet seasons, comprising primarily of channel elements and the lower and flatter part of the watershed. Eleven storm events with sediment sampling data were recorded in the watershed in 1996. Water samples were collected at a time interval of between 5 to 20 min for each storm, which were processed in the laboratory immediately after sample collection. Details of the rainfall, runoff and sediment data collection program are given by *Sun* [1999].

[24] Four parameters, C_{slr}, K, α and β, need to be determined before applying the erosion and sedimentation equations for sediment modeling. The first two are USLE parameters, and the last two were calibrated. Both the interrill and channel detachment equations use the cover and management factor or soil loss ratio C_{slr} of USLE to represent the ratio of soil loss from an area with specified cover and management to that from an identical area in a standard tilled continuous fallow condition. The soil loss ratio C_{slr} reflects the vegetation cover of the watershed surface and the channel bed and banks. The USLE table [*Wischmeier and Smith*, 1978] gives the C_{slr} value of 0.003 for greater than 95% grass cover. In Australia, *Edwards* [1987] reported values of C_{slr} from pasture plots ranging from 0.000 to 0.012, with most values less than or equal to 0.002 for New South Wales (NSW) soil tests. As a result, the C_{slr} value was assumed to be 0.002 for Sauerbier Creek watershed, which is predominantly covered by pasture.

[25] The soil erodability factor K used in the English soil erodability nomograph range from 0.05 to 0.60. This should be multiplied by 0.1317 to give a metric K having units of kilograms per Newton times hour per square meter (kgh/N/m^2) [*Foster*, 1982]. The NSW soil tests [*Edwards*, 1987] at seven soil research centers showed that the metric K value ranged from 0.02 to 0.058 with a mean of 0.035. This average value was used for detachment estimation in the Sauerbier Creek watershed. The same C_{slr} and K values are used for both overland elements and the channel elements.

[26] The α and β values in equation 8 were calibrated against one storm event in 1996. When β is close to 2 and α equals 4300, the simulation of the storm erosion at the outlet of the watershed gave the best fit with the observed. Therefore, these values were used for sediment prediction of the other 10 storm events occurring in 1996, without further calibration.

4. Modeling Results

[27] Two of the modeled storm runoff events are shown in Figures 3 and 4. The predicted runoff, sediment concentration and sediment discharge were compared with the observed in each figure. A total of 11 storms with sediment data were used for sediment prediction. A summary of all

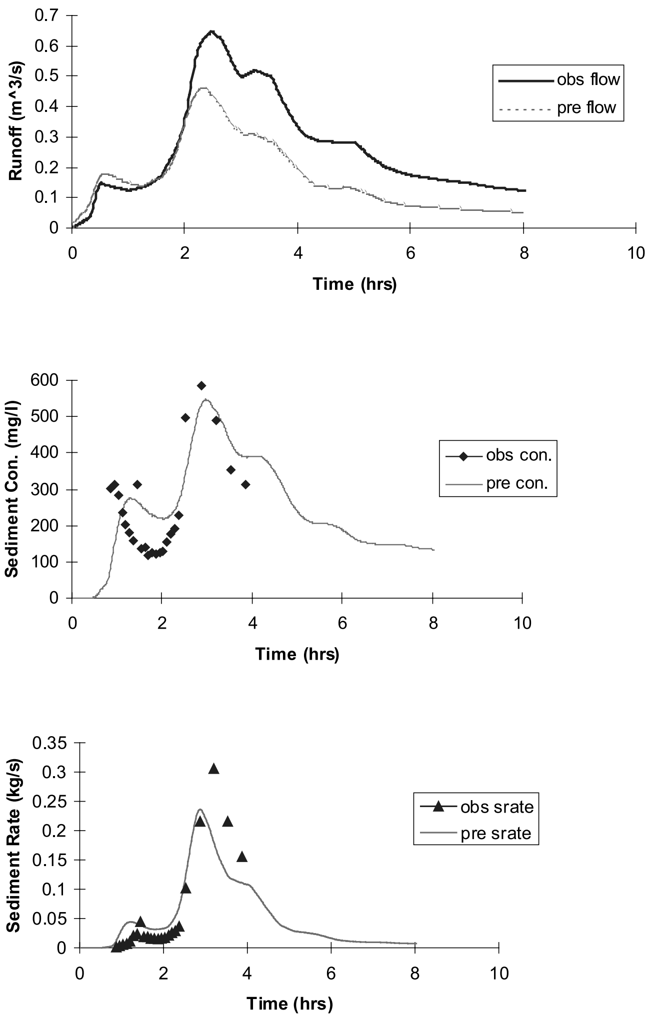

Figure 3. Prediction of the 31 July 1996 runoff event, sediment concentration, and sediment discharge.

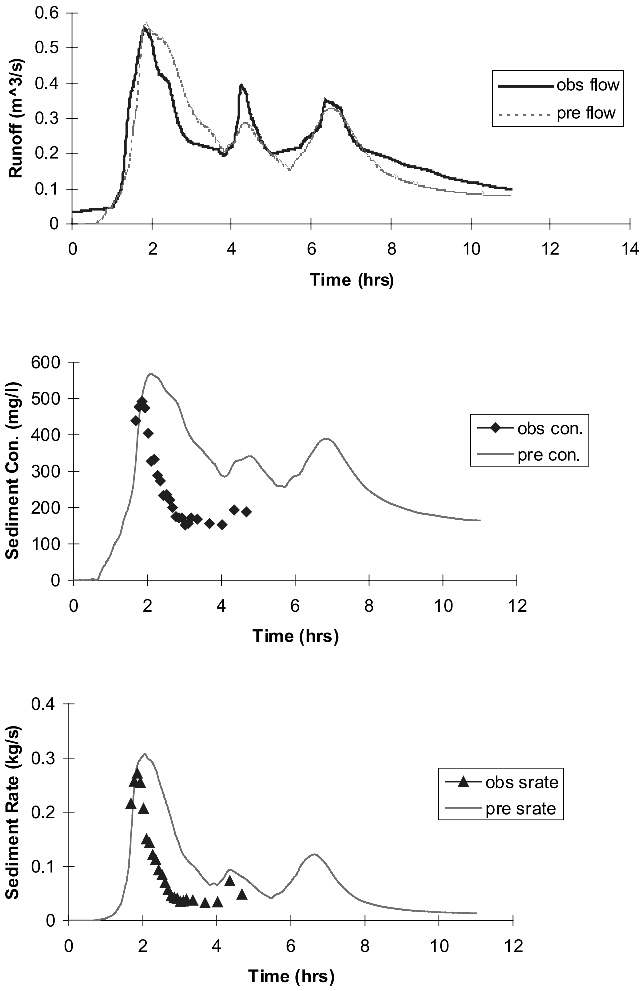

Figure 4. Prediction of the 29 September 1996 runoff event, sediment concentration and sediment discharge.

these storm events, as well as the prediction results, is given in Table 1. All the runoff results presented here are predicted runoff results reported by *Sun* [1999]. Other than the storm of 28 June 1996 that was used for model calibration, all other sediment results are predicted results based on the predicted runoff hydrographs. The predicted runoff peak, sediment concentration and load are compared with the observed, and the average or total values are given in the last row of the table. The errors for storm sediment load estimation are shown in the last column of Table 1. Table 2 shows a comparison of this study with ten earlier studies using the U statistic, the root mean square error (RMSE), the coefficient of determination (R^2), or the correlation coefficient [*Sun*, 1999].

[28] It can be seen from Table 2 that some of the earlier studies [*Van Liew and Saxton*, 1984; *Smith*, 1977; *Foster et al.*, 1977] returned excellent results with very low U statistics and high R^2. This is chiefly because these studies were done on well established small experimental watersheds in the US, where complete data sets were collected for each and every slope in the watersheds, and the number of parameters was generally large and well calibrated with significant amounts of data before prediction. For example, *Van Liew and Saxton* [1984] used eight calibrated parameters (excluding USLE parameters) for detachment description that are extensively calibrated before prediction. Other than these studies, our study with lower U and RMSE values, compares favorably with other studies, adding to the advantages of the physically based distributed approach, enabling erosion and deposition estimation of within-storm processes.

[29] In addition to modeling erosion at the watershed scale, erosion and deposition within the watershed can be estimated on an element basis for individual storm events. Figure 5 displays sediment erosion/deposition distribution in the watershed for the event of 29 September 1996. No deposition was found in any element for the event, suggesting a detachment-limited sediment transport scenario in the watershed. As a result, Figure 5 demonstrates the erosion areas of the watershed for the event. The primarily erosion scenario in the watershed was likely caused by the small size of the watershed and the high slopes of watershed at an average of 10% , which results in high sediment transport capacity. Much of the erosion source area identified is in channel elements, and erosion in the overland areas is not significant for the storm. Figure 5 shows greater erosion at

Table 1. Summary of Erosion Modeling Results for Runoff Events in Sauerbier Creek Watershed

Event		Peak Runoff Rate, m^3/s			Peak Sediment Concentration, mg/L			Sediment Load, kg		
Date Month/Day/Year	Rainfall, mm	Obs.	Pre.	Diff., %	Obs.	Pre.	Diff., %	Obs.	Pre.	Diff., %
1/24/96	2.6	0.153	0.104	−32	229	192	−16	64.2	58.2	−10
6/17/96	2.6	0.077	0.127	65	259	216	−17	35.4	79.2	124
6/22/96	7.0	0.187	0.171	−37	242	272	12	22.8	10.2	−56
6/28/96	8.0	0.194	0.198	2	294	290[a]	1	199	306	54
7/4/96	31.8	0.526	0.410	−22	353	263	−25	212	431	104
7/24/96	2.6	0.119	0.121	2	485	215	−56	109	94.2	−14
7/31/96	19.6	0.646	0.376	−42	585	547	−6	1218	1062	−13
8/2/96	2.8	0.118	0.165	40	195	262	34	25.2	95.4	279
8/26/96	15.8	0.400	0.280	−30	313	391	25	233.4	306	32
9/12/96	3.6	0.374	0.233	−33	978	390	−60	276	167	−40
9/29/96	7.8	0.557	0.568	2	492	568	15	792	1698	115
Total/day	9.47[b]	0.304[b]	0.25[b]	−18[b]	402[b]	327[b]	−19[b]	3187[c]	4307[c]	36[d]

[a] Calibrated value.
[b] Averaged values.
[c] Total.
[d] Difference of total values (%).

Table 2. Comparison of Watershed Sediment Load Estimation in Various Studies

Number of Studies	Type of Model Used	Catchment Type	Catchment Size, (km^2)	Number of Storms Modeled	Correlation Coefficient or R^2 of Pre and Obs	RMSE and U Statistic	Reference
This study	physical	mainly pasture	2.87	11	0.895	U = 0.396 RMSE = 0.081	*Sun* [1999]
1	MUSLE	agriculture	0.33 and 0.006	11	0.642	U = 1.25	*Onstad and Foster* [1975]
2	modified SEDLAB	agriculture experiment	0.3 and 0.335	28	0.993	U = 0.029	*Van Liew and Saxton* [1984]
3	physical	rangeland	0.012	7	0.999	U = 0.345	*Smith* [1977]
4	USLE	agriculture experiment	0.302	12	0.979	U = 0.049	*Foster et al.* [1977]
5	5 different rating curves	Field plot overland	90 m long slope	30	0.601	U = 0.456	*Morgan* [1980]
					0.594	U = 0.448	
					0.602	U = 0.444	
					0.591	U = 0.491	
					0.498	U = 0.511	
6	4 rating curves	agriculture	46	39	R^2 = 0.847	N/A	*Banasik and Walling* [1996]
					R^2 = 0.810		
					R^2 = 0.855		
					R^2 = 0.865		
7	13 rating curves	normal	Large flow up to 1000 m^3/s	N/A	2 with $R^2 > 0.8$	RMSE = 0.263	*Jansson* [1997]
					4 with $R^2 < 0.5$		
					7 with $0.5 < R^2 < 0.8$		
8	17 rating curves	normal	11.7 and 5.3	N/A	2 with $R^2 > 0.7$	N/A	*Hodson et al.* [1998]
					4 with $0.6 < R^2 < 0.7$		
					3 with $0.5 < R^2 < 0.6$		
					9 with $R^2 < 0.5$		
9	rating curve	normal	371	N/A	R^2 = 0.66	RMSE = 0.25	*Jansson* [1996]
10	rating curve	normal	N/A	25	N/A	RMSE = 0.657	*Crawford* [1991]

the lower part of the channel network, which matched our observation in the field. On average, a meter depth by a meter wide gully had been cut through the bed and sides of the creek in these areas.

5. Discussion

[30] Since the USLE is developed for long term erosion estimation, and even the modified USLE or MUSLE [*Williams*, 1995] does not consider the processes within a runoff event, it is not possible to use the USLE parameters for intra storm sediment estimation without some calibration or modification of parameters, e.g. the calibration of α and β. However, we have limited the calibration to just one storm event and applied the calibration to the remaining ten storm runoff events. Modeling results showed that the parameters performed well for erosion prediction as compared to most other studies.

[31] In MUSLE, storm erosion from a watershed (*Sed*, in metric tons) is directly proportional to a power function of

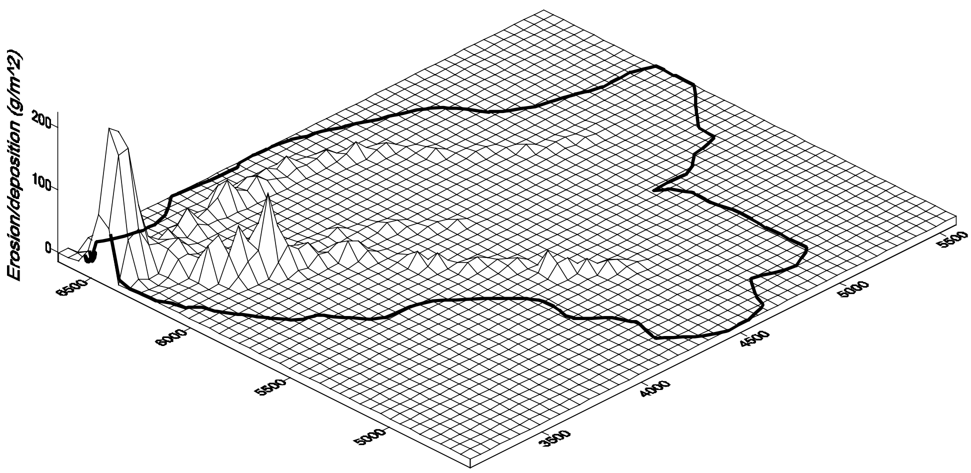

Figure 5. Erosion distribution in watershed for the 29 September 1996 event, greater erosion is predicted at the lower part of the channel network.

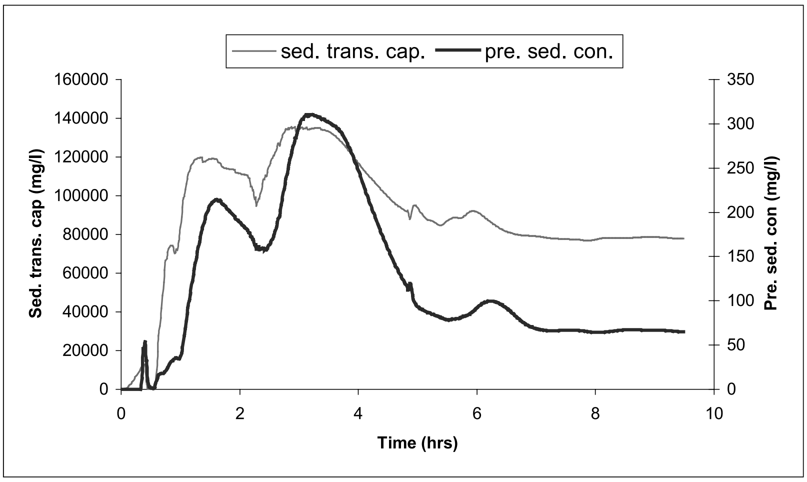

Figure 6. Comparison of predicted sediment concentration and the estimated sediment concentration at transport capacity for 2 August 1996 event.

the storm volume V_o (m^3) and the peak discharge rate Q_p (m^3/s) of a runoff event

$$Sed \propto (V_o Q_P)^{0.56} \tag{18}$$

The runoff volume V_t (m^3) during a time step Δt (s), can be calculated using the discharge rate Q_t (m^3/s) at time t of the runoff event as

$$V_t = Q_t \Delta t \tag{19}$$

Substituting V_o in relationship 18 with equation 19 and changing Q_p to Q_t to represent an instantaneous time t during a storm event, we have

$$Sed \propto Q_t^{1.12} \tag{20}$$

The exponent in relationship 20 lies between equation 7 ($\beta = 1$) and the calibration ($\beta = 2$) in this study for channel detachment at any time within a runoff event. In obtaining relationship 20, we have changed the time frame from a runoff event to a modeling time step within an event, and the spatial frame from a watershed to an element. Therefore, certain calibration in parameter values (α and β) are needed to apply equation 8 for an element based watershed storm sediment modeling. This underlines the empirical nature of the MUSLE and equation 8. However, it is possible that a MUSLE style empirical relationship with defined parameter values can be developed with further application of this model and other similar ones in more watersheds.

[32] The study demonstrated that there was little deposition in the watershed, which conforms to observation in field trips and field investigations. Comparing the observed or estimated sediment to the transport capacity using Yang's equation, the predicted watershed sediment concentration is usually 1% or less of that of the transport capacity. For example, the peak sediment transport capacity is around 130,000 mg/L for the 02/8/96 event, while the estimated peak sediment concentration for the event is approximately 300 mg/L. Figure 6 compares the predicted sediment concentration and the sediment transport capacity for the 02/8/96 event, with the left y-axis representing the sediment transport capacity and the right one representing the predicted sediment concentration. It can be seen that sediment transport capacity is generally several hundred times larger than the actual sediment transported. These results reflect that sediment transport in the Sauerbier Creek watershed is detachment limited or source limited. Observation in the creeks showed that erosion can be very serious where the channel is disturbed and without a protective layer of grass or gravel, and this may continue until some equilibrium is reached or a resistant layer of grass or gravel developed.

[33] The site where sediment deposition is most likely to occur is the pond formed by the weir constructed for flow monitoring at the watershed outlet. Using sedimentation pads in the pond over an extended period found that less than 6% of the annual sediment load is deposited in the pond [*Sun*, 1999]. The deposition is primarily of bed load, not suspended load as modeled. This further confirms the modeling results of detachment-limited erosion, and high delivery ratio of suspended sediment in the watershed.

6. Summary

[34] *Foster* [1982] suggested using existing sediment estimation tools in developing new erosion and sedimentation models, and changing them if needed rather than starting anew. We have followed this approach in our model development and obtained satisfactory modeling results by developing a simple erosion and sedimentation model (EROSET), and interfacing it with a contour-based digital terrain rainfall-runoff model. The model requires only two calibrated parameters and very limited calibration for prediction. Gully erosion can also be estimated by changing these parameters. The model can be used for within-storm, storm and annual sediment load estimation in a watershed as well as at an element scale. It combines the use of parameters in USLE for more physically based, distributed watershed erosion and sedimentation estimation. The mathematical form developed for channel detachment is closely

related to MUSLE, although it works in a much more defined frame of time and space.

[35] The study employs the topographical features of the watershed for erosion and sedimentation estimation on an element basis. The calibration at the watershed outlet implies that major parameters derived are watershed-wide averages rather than element specific parameters. The modeling results are therefore to be interpreted as watershed averages. It is likely that heterogeneity and data needs at element scale can be enormous if we are to model them in a truly distributed manner.

[36] This study provides a framework for further studies that may lead to monitoring and verifying models at an element level within a watershed. Multiple monitoring sites along the main channels and overland or hillslope plots with similar sizes of the partitioned elements need to be set up to test that the modeled results match the observed result at both the element and watershed level. Such an approach would allow better identification of the major erosion and sedimentation processes and the parameters estimated. The parameters derived are likely to provide an improved physical basis for models similar to EROSET, leading to better understanding and modeling of erosion and sedimentation processes at a range of spatial scales. Furthermore, historical data obtained at plot scale in many USLE studies may possibly be incorporated into watershed modeling, providing a substantial physical basis for spatially and temporally refined watershed studies. The integration of studies at different scales incorporating historical data appears to be a sound way to advance the future of erosion and sedimentation study. This study may be regarded as the first step in that direction.

Appendix A

[37] The root mean square error (RMSE) is expressed as

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2}$$

Where y_i is the observed sediment load and x_i the estimated sediment load. The U statistic is a measure of scaled root mean squared error expressed as

$$U = \sqrt{\frac{\sum_i (y_i - x_i)^2}{\sum_i y_i^2}}$$

The U statistic value is better than the standard error or root mean square error because it is scaled and can be evaluated with data sets having different units. It is also not bounded by 0 and 1, a large value of U indicates a poor forecasting performance.

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P. S. Cornish and H. Sun, Landscape and Ecosystems Management, University of Western Sydney, Sydney, New South Wales, Australia. (h.sun@uws.edu.au)

T. M. Daniell, Department of Civil and Environmental Engineering, University of Adelaide, Adelaide, South Australia, Australia.