IDENTIFICATION OF SEDIMENT SOURCE AREAS WITHIN A WATERSHED

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ABSTRACT

Two methods, one using a travel time approach and the other based on optimization techniques, were developed to identify sediment generating areas within a watershed. Both methods rely on hydrograph and sedimentograph data collected at the mouth of the watershed. Data from several events were examined over two small watersheds, and a statistical procedure was utilized to assess the erosion vulnerability of different regions within the watersheds. Results from these two independent methods showed good agreement with USLE-based observations. These methods seem viable for practical use if the number of sediment generating regions is small, and good data from several events is available to achieve statistically meaningful results.

INTRODUCTION

Sediment yield from a watershed has important implications for water quality and water resources, especially from agricultural areas. There are two important time scales associated with sediment movement and consequently with source assessment. Depending on geomorphologic properties, nature of the sediment source and size of the storm, the sediment may move from the source-region to the watershed outlet in a single event. In such instances, the time scale is fairly short and limited to the duration of surface runoff over the watershed. At this time scale, the problem of identifying the source areas of sediments based on information available at the outlet has many practical applications. However, this problem has received very little attention, as most modeling strategies have focused on the forward problem of predicting sediment concentrations given the source locations and strengths. The longer time-scale problem arises when sediment travels more slowly over the watershed. The focus of this study is on the former time scale where sediment moves to the watershed outlet in a single event.

A limited number of source assessment methods are available in the literature to estimate potential loadings from hillslopes and banks to receiving waters, for evaluating stream-storage and transport of sediments, and to estimate sediment yield from basins. The approach proposed in this study combines the strengths of using a detailed model for the flow field and incorporates the fate and transport of sediment in a way that is ideally suited for source assessment based on information gathered at the watershed outlet from the stream hydrograph and sedimentographs. The overall goal of this study is to identify sediment-generating regions within a watershed using geomorphologic information over the watershed, available rainfall data, and data on hydrographs and sedimentographs collected at the outlet of the watershed. The surface flow and sediment transport model, KINEROS (Woolhiser et al., 1990) has been utilized in this study.

STUDY WATERSHEDS

Two experimental, field scale watersheds (namely W-2 and W-3) located near Treynor, Iowa, with areas of approximately 83 and 107 acres (33 and 42 ha), respectively, were adopted for this study. Measurements of runoff, baseflow, and sediment load using weirs located at the base of each of these watersheds are available. Watersheds W-2 and W-3 are similar in characteristics with a rolling topography defined by gently sloping ridges, steep side slopes, and alluvial valleys with incised channels that normally end at an active gully head, typical of the deep loess soil in MLRA 107 (Kramer et al., 1990). Slopes usually change from 2 to 4 percent on the ridges and valleys and 12 to 16 percent on the side slopes. An average slope of about 8.4 percent is estimated for both watersheds, using first-order soil survey maps. The major soil types are well drained Typic Hapludolls, Typic Udorthents, and Cumulic Hapludolls (Marshall-Monona-Ida and Napier series), classified as fine-silty, mixed, mesics. The surface soils consist of silt loam and silty loam textures that are very prone to erosion, requiring suitable conservation practices to prevent soil loss (Chung et al., 1999). Corn has been grown continuously on W-2 since 1964, and on W-3 since 1972. The W-3 watershed was predominantly bromegrass, with small amounts of orchard grass and alfalfa from 1964 through 1971.

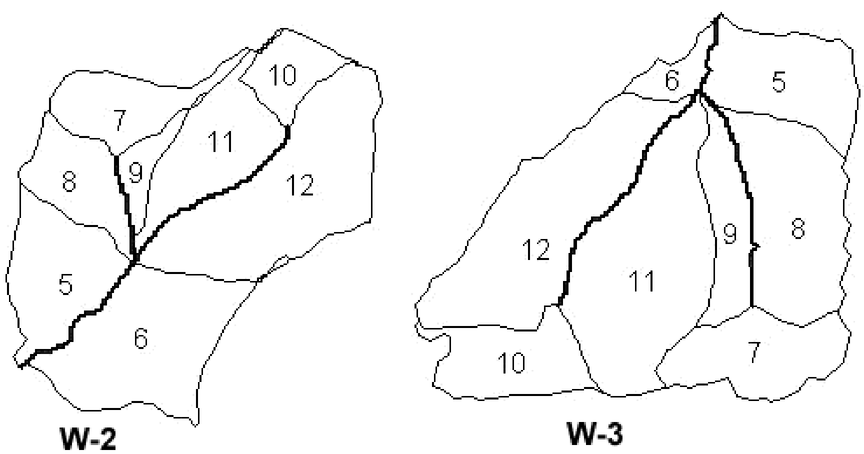


Fig. 1. Watersheds W-2 and W-3 partitioned into 8 elements used for identifying sediment sources within the watersheds. Elements 2 to 4 are channels, and element 1 is the outlet..

The regional geology is characterized by a thick layer of loess overlying glacial till that together overlay bedrock. The loess thickness ranges from 3 m in the valleys to 27 m on the ridges. These watersheds have been the subject of watershed-studies by many researchers for almost 30 years.

THE TRAVEL TIME APPRAOCH

Many studies have utilized the unit sedimentograph method for analyzing sediment output from watersheds (Singh et al., 1982; Kumar and Rastogi, 1987; Banasik and Walling, 1996). Since the goal of this paper is development of a methodology for source identification, a modified approach is described here. The watershed under consideration is partitioned into NE number of elements (k=1,2,3,…,NE). For a rainfall event (p) under consideration characterized by pulses of excess rainfall depths denoted by P_1, P_2, …, P_M each having duration of Δt, the sediment flux response of element k from that event at the basin outlet at time $t = n\Delta t$ is

$$y_k(n\Delta t) = y_{k,n} = \sum_{m=1}^{M} P_m h\left[(n - m + 1)\Delta t - s_k\right] \quad (1)$$

where $h_k(t\text{-}s_k)$ is the unit pulse response at the watershed outlet from the k^{th} element and s_k is the time when sediment from element k is first observed at the basin outlet from element k under unit amount of rainfall starting at t=0. When the response of all the elements are taken into account then the sediment discharge expected at the watershed outlet at time $t = n\Delta t$ can be estimated by

$$y(n) = \sum_{k=1}^{NE} \sum_{m=1}^{M} P_m h_{k,n-m+1} \quad (2)$$

where $h_{k,n-m+1} = h[(n\text{-}m\text{+}1)\Delta t\text{-}s_k]$. The unit pulse response function h_k is called Unit Sedimentograph (USG) of element k. The Normalized Unit Sedimentograph (NUSG) for an element k is defined as

$$NUSG_{k,t} = \frac{h_{k,t}}{\int_0^{\infty} h_{k,t}\,dt} \quad (3)$$

If λ_k is used to represent the total sediment load generated from element k due to a unit amount of rainfall, then the unit pulse response function of an element k can be written as $h_{k,t} = \lambda_k \cdot NUSG_{k,t}$. Equation (2) becomes

$$y(n) = \sum_{k=1}^{NE} \lambda_k \sum_{m=1}^{M} P_m NUSG_{k,n-m+1} \quad (4)$$

The problem reduces to finding those values of λ_k that minimize differences between observed sediment discharge and predictions from (4). A common method of achieving this is by minimization of the error expression

$$E^2 = \sum_{n=1}^{N} \left[y_n - \sum_{k=1}^{NE} \lambda_k \sum_{m=1}^{M} P_m NUSG_{k,n-m+1} \right]^2 \quad (5)$$

where y_n are the observed values with N being total number of data points. Naturally, large elements will likely be associated with large λ. If erodibility index of an element k is defined as $C_k=\lambda_k/A_k$ where A_k is the area of the element k, then source strength of different elements can be evaluated by comparing C_k values, and finally a map of the watershed showing the high and low erosion potential areas can be generated. Here C_k is defined as a measure of the erosion potential of element k.

The NUSGs were generated for each element of the two watersheds and were found to be well-represented by log-normal distributions. Further, the NUSGs could be characterized completely in terms of the average travel times of sediments from the element to the outlet of the watershed. Using the model of equation (4), sample results for some events are shown in Figs. 2a and 2b.

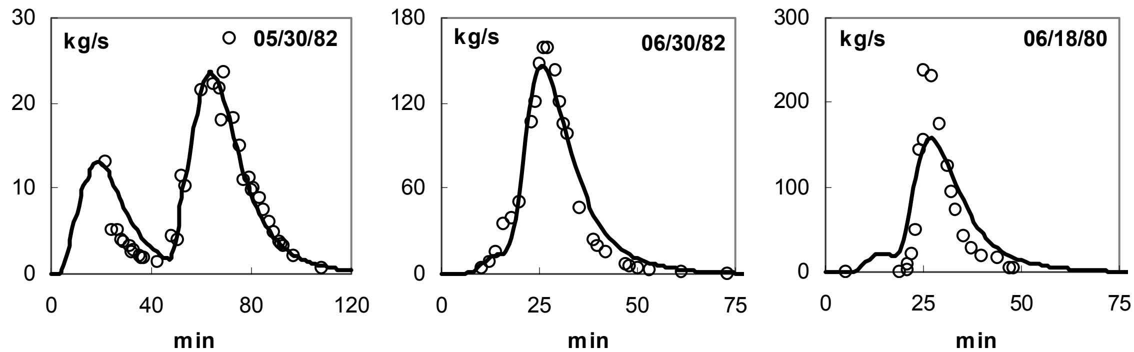


Figure 2a. Observed (hollow circles) and predicted (solid line) sediment discharges for three sample events from W-2 using travel time approach.

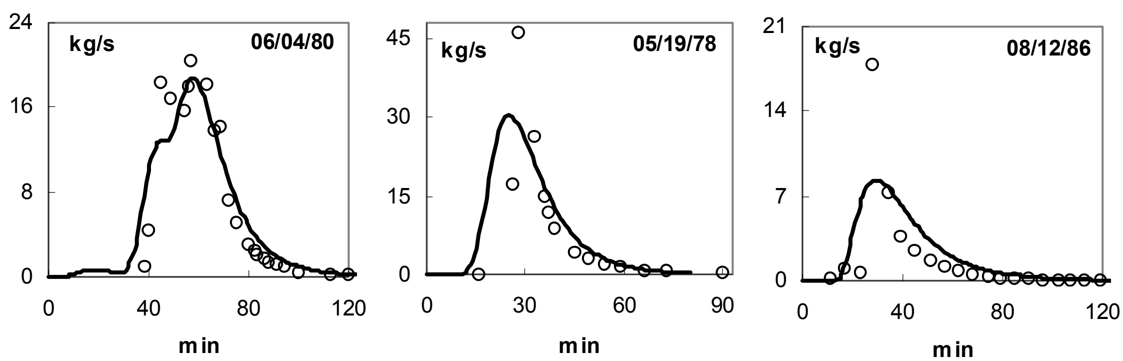


Figure 2b. Observed (hollow circles) and predicted (solid line) sediment discharges for three sample events from W-3 using travel time approach.

Data from different rainfall events yielded different C_k values. Tukey's procedure was utilized to evaluate if the erodibilities of different elements were statistically different. Table 1 summarizes the results of the statistical test for different relative C_k values for W-2.

OPTIMIZATION APPROACH

Details of the governing flow and erosion equations can be found in Woolhiser et al. (1990) and are not repeated here. The Bagnold/Kilinc (Kilinc and Richardson, 1973) formula is used for the estimation of the equilibrium concentration C_{mx}, which states

$$C_{mx} = \frac{C_0[u(\tau - \tau_c)]^{1.67}}{h\gamma_w u} \qquad \tau > \tau_c \tag{6}$$

where $\tau = \gamma_w hs$ with γ_w being specific weight of water, h as flow depth and s as the slope, τ_c is Shields critical tractive force, u is velocity of water and C_0 is a scaling parameter and a measure of soil erodibility. Then, for a large rainfall event p, the following relationship applies from the linearity of sediment transport equation

$$Q^{(p)}(t) = \sum_{i=1}^{NE} C_{0,i}^{(p)} \cdot f_i^{(p)}(t) \tag{7}$$

Table 1. Grouping of elements for W-2 according to Tukey's procedure with varying α levels using travel times approach.

Element	mean	α = 0.10	α = 0.20	α = 0.30
12	0.00	A	A	A
11	0.18	A	A	A
6	1.13	A	A	A
8	4.19	A B	A	A B
7	9.02	A B C	A B	A B C
5	23.89	A B C	A B C	B C D
9	28.26	B C	B C	C D
10	33.33	C	C	D

In (7), $Q^{(p)}(t)$ represents the sedimentograph resulting from rainfall event p. $C_{0,i}^{(p)}$ is the value of the C_0 parameter for element i during rainfall event p and $f_i^{(p)}(t)$ is the unit sedimentograph resulting from rainfall event p under the condition

$$C_{0,k} = \delta_{i,k} \tag{8}$$

where $\delta_{i,k} = 1$ for i=k and zero otherwise. Note that $f_i^{(p)}(t)$, i=1,..,m can be computed from KINEROS for any rainfall event. The goal now is to estimate the values of $C_{0,i}^{(p)}$ in an optimization framework. If the error between observed ($Q_o^{(p)}(t_n)$) and computed sediment discharge ($Q(t_n)$) at n^{th} observation time t_n is defined as

$$\varepsilon_n^{(p)} = Q_o^p(t_n) - \sum_{i=1}^{NE} C_{0,i}^{(p)} \cdot f_i^{(p)}(t_n) \tag{9}$$

then the objective function to be minimized is

$$F = \sum_{n=1}^{N} \left(\varepsilon_n^p\right)^2 \qquad (10)$$

where N is total number of data points in the observed sedimentograph. Since erodibilities cannot be negative, the constraint $C_{0,i}^{(p)} \geq 0$ has to be imposed during optimization. Model results from equation (7) are shown in Figs. 3a and 3b for the two watersheds, and statistical analysis results in Table 2.

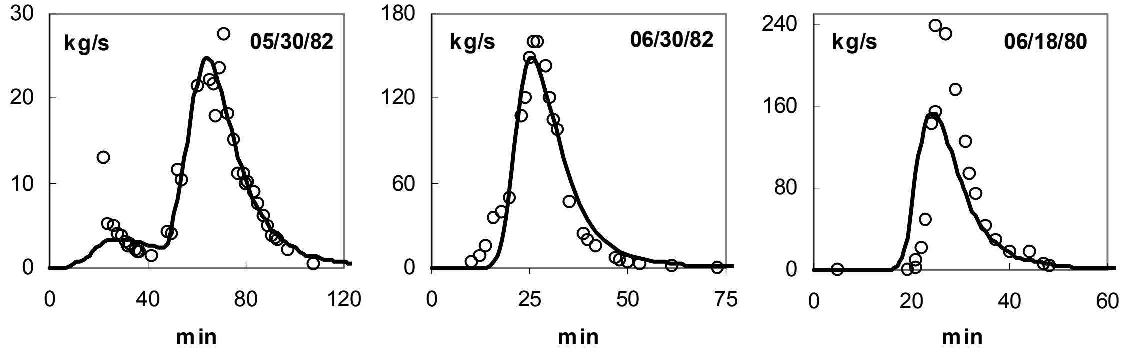


Figure 3a. Observed (hollow circles) and predicted (solid line) sediment discharges for three sample events from W-2 using an optimization approach.

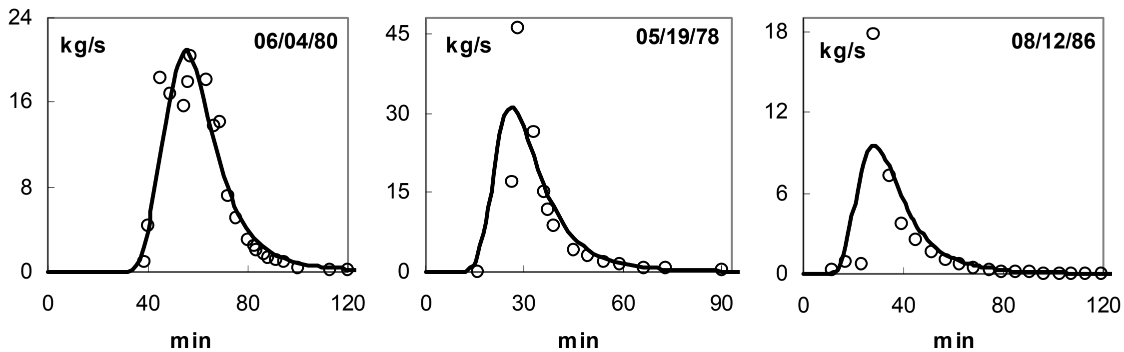
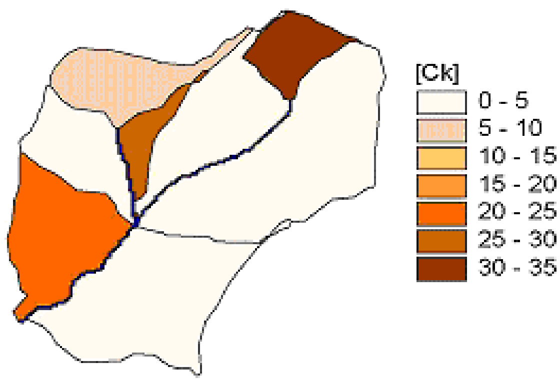


Figure 3b. Observed (hollow circles) and predicted (solid line) sediment discharges for three sample events from W-3 using an optimization approach.

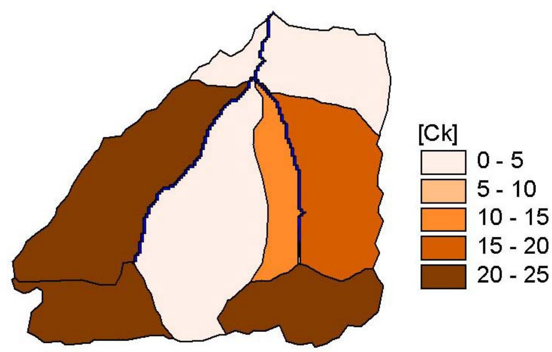
Figure 4 shows spatial maps of erosion potential areas for W-2 and W-3 using the two methods. For comparison with physical properties of the watershed, erosion vulnerability was also studied using parameters of the USLE, and the results are shown in Fig. 4e and 4f.

Table 2. Grouping of elements for W-2 according to Tukey's procedure with varying α levels using the optimization procedure.

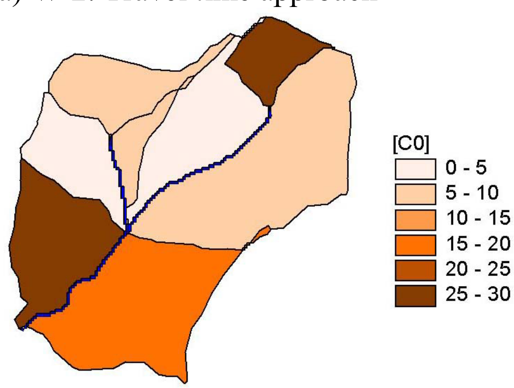
element	mean	α = 0.10	α = 0.20	α = 0.30
11	0.00	A	A	A
8	0.55	A	A	A
9	7.28	A B	A	A
12	9.38	A B	A B	A B
7	9.46	A B	A B	A B
6	10.52	A B	A B	A B
10	30.76	B	B	B C
5	32.06	B	B	C



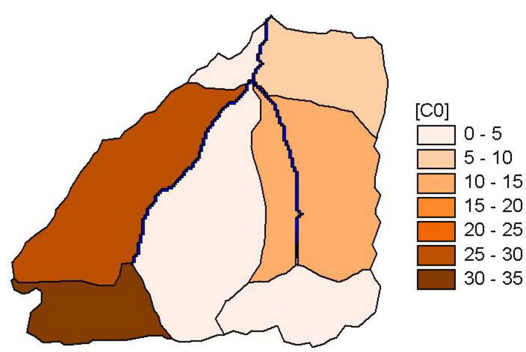
(a) W-2. Travel time approach



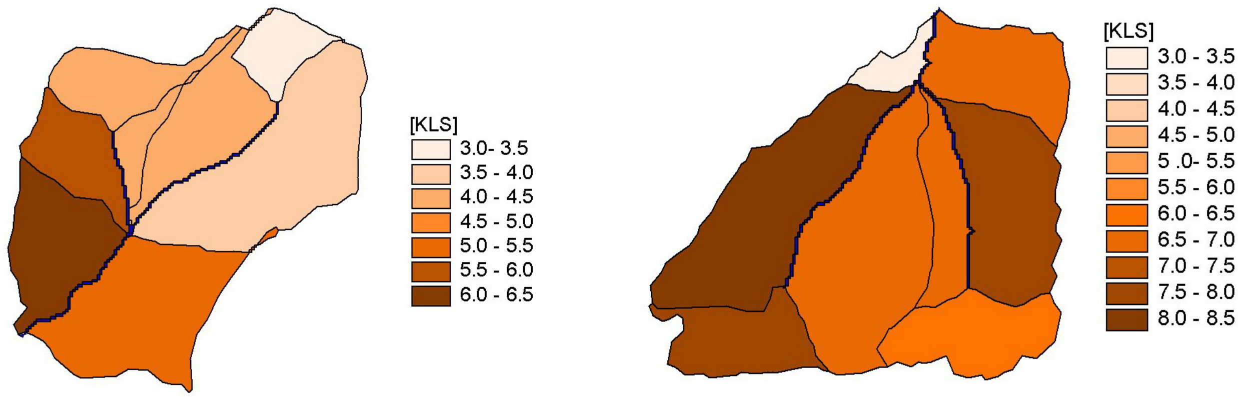
(b) W-3. Travel time approach



(c). W-2. Optimization approach



(d). W-3. Optimization approach



(e) W-2. USLE parameters

(f) W-3. USLE parameters

Fig. 4. Maps showing erosion vulnerability for the two watersheds by different methods. [KLS] represents erodibility with USLE parameters.

SUMMARY AND CONCLUSIONS

A modified unit sedimentograph method in terms of a travel time approach, along with an optimization method was implemented to rank sediment generating areas of W-2 and W-3 watersheds based on their erodibilities. The ensemble average of normalized erodibility indices over several events were compared statistically by employing Tukey's approach at different levels of statistical significance. The estimated relative erodibilities were more consistent in W-3 than the relative erodibilities in W-2 with major differences in elements having low erodibilities. Both methods estimated the same areas as the high erosion potential areas. Outcomes from the two methodologies were also compared to erosion potentials maps generated using the USLE equation. In general, results from all three methods were comparable. The only inconsistency was with the element 10 of the W-2 watershed.

ACKNOWLEDGEMENT

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