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ESTIMATION OF RIVER SEDIMENT CONCENTRATIONS DURING HYDROLOGIC EVENT

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Analyses undertaken in this paper show that the Universal Soil Loss Equation (USLE) fails to predict the soil losses during hydrologic events, especially for arid region. The cause is due to the neglect of runoff in predicting the rainfall erosivity index. In this paper, the erosivity index in USLE is modified by relating the kinetic energy with rainfall, infiltration and runoff processes. The modified USLE model is verified to reflect the hydrological processes more accurately and to be capable of estimating event soil losses. As a new approach for modeling the event-based soil erosions in large catchments, the proposed erosion model also takes the channel erosion into account, together with sediment deposition and transport simulations; its application is broadened to model the variations of sediment concentrations during single events. Through a case study in the large arid region - Lushi River basin in China, the designed erosion model is validated to have good performances during most hydrologic events.

Key Words: *USLE, sediment concentration, hydrologic event, BTOPMC*

1. INTRODUCTION

The spatial variation in erosion is of interest to water quality research. There exist many kinds of soil erosion models, both physically based and empirical models. Because physically based models are either not well verified or require many input parameters, empirical soil loss models still play an important role in the soil conservation planning. This is especially true for large catchments, where the required extensive soil and biological data for physically based models are not readily available. Among empirical models, the Universal Soil Loss Equation (USLE) developed by Wischmeier[1)] is the most widely used soil erosion model worldwide. The USLE is intended to estimate the average soil loss over an extended period, while three major limitations of the USLE restrict its application in many modeling analyses. First, it is not intended for estimating soil loss from single events. Second, it is an erosion equation, and consequently it does not estimate deposition. Third, it does not estimate gully or channel erosion[2)]. These three limitations restrict the application of USLE to predict the soil erosions during the events and in large catchments. For large region, the channel erosion is an important soil source to the river sediment, while the USLE equation can only model the overland flow or sheet-rill erosion. Hence, the channel erosion should also be considered additional to the USLE equation. Secondly, in arid catchments, the soil losses mainly occur during several storms in one year, which needs the capability of the USLE in predicting soil losses during single events. One problem with USLE, which limit its application in single events, is that there is no direct consideration of runoff even though erosion depended on sediment discharged with flow. Although the modern understanding

Table 1 Runoff ratios and β values obtained at a number of plot locations in USA from the USLE database

Place	Arnot	Bethany	Tifton
State	New York	Missouri	Georgia
Soil type	Silt loam	Gravelly loam	Sandy loam
Number of plots	16	10	9
Data period	1935-1953	1931-1942	1951-1956
Runoff ratio	0.471	0.238	0.18
β value	2.1	4.2	5.7

of rainfall erosion processes recognizes that runoff is a primary independent factor in modeling rainfall erosion[3)] and Foster observed that lumped erosivity indices that included rainfall amount, rainfall intensity and runoff amount were better than EI_{30} index[4)], the product of storm rainfall energy and maximum rainfall rate recorded using a 30-minute time base, the runoff is still not a factor explicitly considered in the USLE.

The main purpose of this paper is to propose one erosion model which can describe the detachment, deposition and transport processes of soil particles during events for large catchments. The description of soil detachment is based on the structure that the sheet-rill erosion is modeled by the modified USLE equation and the channel erosion by concentrated flow is also taken into consideration. Additionally, possible deposition during the sediment transport is predicted by comparing the transport capacity with the river sediment load in each grid cell.

2. MODIFIED USLE MODEL

(1) Event-based modification of USLE

The USLE has been widely used for estimating the mean annual soil loss resulting from rainfall erosion from different crops and land managements. This paper improved the USLE by introducing the runoff ratio into the erosivity factor to account for the runoff effect on rainfall erosions. Despite the modified USLE is still an empirical model, the new erosivity factor in USLE was endowed with some physical meaning. The modification was undertaken under the concept that only the part of soil that was transported from the source location by runoff could be treated efficient soil loss. To calculate the surface runoff, the soil infiltration volume should be taken in consideration; thus, the modified erosivity factor is described to be related to:

(a) The total amount of rainfall for kinetic energy with effective runoff volume.

(b) Effect of rainfall intensity which could be accounted for by I_{30}, the maximum 30-minute rainfall intensity.

In USLE, the event soil loss A is represented by six factors, that is, the rainfall erosivity factor R, soil erodibility factor K, soil length factor L, slope steepness factor S, landcover management factor C and supporting practices factor P.

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{1}$$

in which, the rainfall erosivity factor R is the primary factor. Under stepwise rainfall intensities, the value of R factor during one event can be stated as one function of the maximum 30-minute rainfall intensity I_{30} and the summation of the rainfall energy e_t during each time step t in the event. In USLE, the erosivity index reveals that the amount of soil loss is only determined by rainfall; however, the real sediment carrier is runoff, which is neglected in the erosivity factor. If the soil has a high infiltration capacity, especially for the arid regions, the infiltrated water shares an appreciable amount of rainfall that is going to generate the erodibility energy, thus, the actual infiltration rates $f^*(t)$ should also be considered in the calculation of R factor, the equation is modified into the form as:

$$R = \sum_{t=1}^{T} e_t \cdot Q_t \cdot I_{30} \tag{2}$$

where T is the total time steps during the event, Q_t is the runoff ratio and can be derived from:

$$Q_t = (I(t) - f^*(t)) / I(t) \tag{3}$$

$I(t)$ is the rainfall intensity during the time step t. In practice, the event continuous infiltration rates were calculated by using an improved infiltration model developed from the concept of coupling the Philip's equation with the time compression approximation method[5)]. The Philip's equation takes the form as:

$$f(t) = 0.5S \cdot t^{-0.5} + 0.67K_S \tag{4}$$

where S is the soil sorptivity, which depends on the soil water potential, K_s (mm/h) is the saturated hydraulic conductivity. Under the concept of the time compression approximation (TCA), the infiltration rates during one event depend only on the cumulative infiltration till that time and initial soil properties. Therefore, with the same initial soil conditions, the cumulative infiltrations derived from the potential infiltration rate $f(t)$ at the compression time t_c and from the actual infiltration rate $f^*(t)$ at the ponding time t_p have the same values. Accordingly, the actual infiltration rate can be expressed as:

$$f^*(t) = I(t) \qquad for \quad t < t_p \tag{5a}$$

$$f^*(t) = f(t - (t_p - t_c)) \quad for \quad t \geq t_p \tag{5b}$$

By describing the effects of surface water and infiltrated water on erosion respectively, the modified R factor can reflect the soil hydraulic characteristics more accurately. However, the USLE uses empirically derived parameters, changing the calculation of erosivity factor leads to one concern

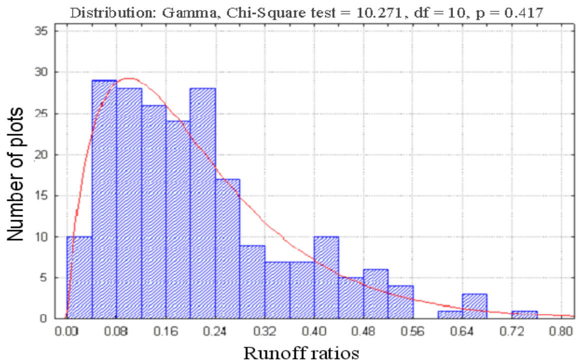

Fig.1 Map for numerical distribution of runoff ratios

about the changes of parameter values for other USLE factors. Although, redefining the values for K and C factors can keep the same equation form, a coefficient β calculated as the reciprocal of the runoff ratio from USLE database is preferred. The modified R factor, which includes the β, can differentiate the event infiltration rates in Lushi basin from those recorded in the USLE database.

$$R = \sum_{t=1}^{T} e_t \cdot Q_t \cdot \beta \cdot I_{30} \tag{6}$$

As a correction coefficient, β values were converted from the runoff ratios for different soil types, which were calculated by using the historic rainfall and runoff data from the USLE database. The data were selected from plots in several cities as shown in **Table 1**. The general distribution of the runoff ratios shown in **Fig. 1** was plotted by the gamma equation.

$$f(x,k,\theta) = x^{k-1} \cdot \frac{e^{-x/\theta}}{\theta^k \cdot \Gamma(k)} \text{ for } x > 0 \tag{7}$$

where x is the time series, k is the shape factor, θ is scale factor and $\Gamma(k)$ is the gamma value of k. The normalized distribution of the runoff ratios shows that even for different soil types, most values concentrate within a narrow scale about 0.08 to 0.2, accordingly, for the unlisted soil types in the USLE database, the runoff ratio can be approximated from the recommended value scale.

In order to determine efficiencies of the modified USLE, a logarithmic form of Nash-Sutcliffe model[6] is adopted, which is given by:

$$Z_{\ln} = 1 - \frac{\sum_{e=1}^{n} (\ln(A_{eo}) - \ln(A_{ep}))^2}{\sum_{e=1}^{n} (\ln(A_{eo}) - A_{\ln m})^2} \tag{8}$$

where A_{eo} is the observed soil loss for event e, A_{ep} is the predicted soil loss and A_{lnm} is the mean value of $\ln(A_{eo})$ for all the events selected.

The USLE equation and the modified version are compared through the event soil loss estimations in Lushi River basin. Among all recorded event data, 44 valid events were selected over 30 years. The estimated event soil loss results from both models are plotted with the observed data using logarithmic scales respectively as shown in **Fig. 2**. The Nash efficiencies for the USLE and its modified equation reach 10.4%, 86.1% respectively. The comparison shows the improvements of the USLE through the modification, which validates predictable capacity of the modified USLE for event soil loss.

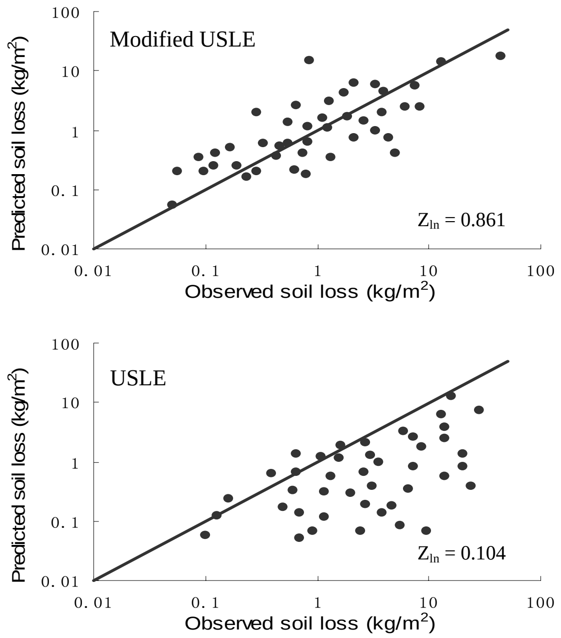

Fig.2 Scatter plots of observed and predicted unit soil loss (kg/m^2) for 44 events in Lushi River basin from the modified USLE and the USLE. The lines in the plots represent the 1:1 relationship between observed and predicted event soil loss.

Process-based models, like WEPP[7], consider the soil loss from several possible erosion types; while the huge input data limit their applications in large basins. For this purpose, the modified erosion model needs to consider all possible erosion types in the given study area while keeping the low data needs.

The USLE has already lumped interrill (sheet) erosion and rill erosion together through the regression equation of L factor. The slope length factor L has often been expressed as the normalized equation of slope length λ to the length 22.13 meters of the unit plot in USLE as[2, 8]:

$$L = (\lambda / 22.13)^{\kappa/(1+\kappa)} \tag{9}$$

in which, κ is the ratio of rill erosion to interrill erosion, which depends on the slope steepness. The USLE considers only overland flow erosion, while in most large basins; the channels are also important source for soil detachment.

(2) Prediction of channel erosion

In USLE, the channel erosion and sediment deposition can not be simulated, which usually leads to miscalculation of event soil loss. In a large basin, runoff leaving a field generally concentrates in a few major channels, the profiles of which are often concave, channel erosion can occur along the upper reach of a channel and deposition occur in the lower reaches of the channel. The channel erosion can be as extensive as sheet-rill erosion; thus, the channel/gully erosion and sediment deposition were also modeled without considering local topographic changes. In this study, the modification of USLE is based on grid cells, which takes account of the local topographic features in simulating the basin-scale soil erosions. According to the plots experiments[2], surface runoff will usually concentrate in less than 100-150 meters, for the grid based simulation in large catchments, the grid sizes are usually larger than this distance, so the channel element is assumed to exist in each grid cell. Under this assumption, each grid cell contains overland flow, rill flow and concentrated channel flow, the soil detached by overland flow and rill flow will be estimated together by using the USLE equation. As to the channel detachment, additional channel erosion model is included to account for the possible detachment occurred in channels. The erosion rate in the channel is represented as[2]:

$$E_{ch} = W_{eq} \cdot K_{ch}(1.35\bar{\tau} - \tau_{cr})^{1.05} \qquad (10)$$

where E_{ch} is the soil loss per unit channel length, K_{ch} is soil erodibility for channel erosion, $\bar{\tau}$ is average shear stress for the cross section, τ_{cr} is the critical shear stress in a function of soil properties and W_{eq} is equilibrium channel width. Shear stress distribution around a channel varies depending on channel shape and aspect ratio of width to depth. A channel is assumed to reach an equilibrium shape if allowed to erode over a long period with steady flow and with no restricting subsurface layer. The equilibrium channel width is adopted for calculating the channel erosion rate, which is derived from[2]:

$$W_{eq} = (Q \cdot n \cdot s^{0.5})^{3/8} \cdot W_* / R_*^{5/8} \qquad (11)$$

in which, Q is the discharge, n is the Manning's roughness coefficient, s is the slope steepness, W_* = channel width/ wetted perimeter and R_* = hydraulic radius/ wetter perimeter. During long-term channel erosion and deposition, the river bed shape may be changed, while for erosion occurred during single events; the change is little enough to be neglected.

3. CHANNEL SEDIMENT TRANSPORT

The eroded soil from the upstream of catchments will concentrate in rills and then be transported to the final outlet through channels. Except being an important erosion source, channels also dominate the sediment transport; sediment from the overland flow erosion and lateral sediment inflow will gather in the channel in each grid cell, if the channel flow has enough transport capacity, all the sediment will be transported to the neighboring grid cell.

(1) Sediment transport capacity

Channel flow transports most of the detached soil particles downslope, while under certain situations; the sediment load in flow can also be limited by the flow's transport capacity. If sediment load exceeds the transport capacity, deposition occurs. In general, transport capacity is a function of the flow's hydraulic forces and the transportability of the sediment. Sediment transport occurs in two related forms: bedload and suspended load. A decrease in transport capacity causes immediate deposition of excess bedload. While suspended load is more uniformly distributed throughout the flow depth, a decrease in transport capacity will not result in the immediate deposition of suspended load. To describe the suspended load transport, a suspension parameter (Z) which expresses the influence of upward turbulent fluid forces and downward gravitational forces, was defined as:

$$Z = \frac{\omega_s}{\phi \cdot k \cdot u*} \qquad (12)$$

in which ω_s is the particle fall velocity, ϕ is the coefficient related to diffusion of sediment particles, k is constant of Von Karman and $u*$ is overall bed-shear velocity. If the flow velocity reaches or exceeds the critical bed-shear velocity, then $Z \leqslant 1$, the sediment particles will remain in suspension; if the flow velocity is less than the critical bed-shear velocity, then $Z > 1$, the particle will deposit. Under this method, in order to simplify the modeling process, the soil particles deposited in the channel need the same energy to be detached as the original channel bed particles.

The sediment transport capacity is calculated using a modified form of Yalin's equation[9], which is an expression for the bedload transport of uniform, cohesionless grains over a moveable bed for steady, uniform flow of a viscous fluid. The model was derived using dimensional analysis and the average grain motion for uniform turbulent flow with a laminar sublayer that does not exceed the bed roughness. Alonso[10] reduced Yalin's equations into a simplified form as:

$$T_c = 635000 \frac{S_g \cdot dU_*}{v \cdot h} \cdot s \cdot [1 - \frac{\ln(1 + a \cdot s)}{a \cdot s}] \qquad (13)$$

where S_g is sediment specific gravity, U_* is bed shear velocity, v is average velocity, h is flow depth.

The other two terms were defined by Yalin as:

$$a = 2.45 Y_{cr}^{0.5} \cdot S_g^{-0.4} \quad (14)$$

where Y_{cr} is the critical mobility factor derived from Shield's diagram and s was defined as:

$$s = Y / Y_{cr} - 1 \quad (15)$$

in which Y is a mobility number defined by

$$Y = \rho_w \cdot U_*^2 / (\gamma_s \cdot d) \quad (16)$$

where ρ_w is mass density of fluid γ_s is specific weight of sediment and d is sediment particle size. To find the critical mobility factor, Shield's diagram was used to find the value for critical shear velocity corresponding to a given Reynold's number. The calculation of sediment transport capacity leads to the generation of sediment deposition in downslope area and limit the sediment volume transported to the outlet. Generally, the amounts of the sediment transported to the outlet cover 23%-76% of the total sediment yields during several selected events.

(2) One-dimensional sediment routing

Sediment transport modeling is usually more complicated because before the sediment movement can be modeled, there must be detailed information concerning the sediment yield and the movement of water. So the in-channel sediment routing model is operated in conjunction with a sediment yield model and a distributed hydrological model for any basin of appreciable size. Since sediment routing and flow are so interrelated, it is necessary to select a proper hydrological model for simulating the flow in a large basin. The distributed hydrological model of BTOPMC was applied in this study. In BTOPMC, the discharge from each grid cell will be routed to the final outlet using Muskingum-Cunge method. For sediment transported in the flow, if the particle belongs to the wash load or can be verified to be suspended in the flow by the suspension parameter, it will be routed to the neighboring grid using the one-dimensional advection-diffusion equation.

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(QC)}{\partial x} = \frac{\partial}{\partial x}\left(AE\frac{\partial C}{\partial x}\right) + I_{ch} + I_L \quad (17)$$

where x is the distance in the flow direction, t is time, C is cross-sectional average sediment concentration, A is wetted cross-sectional area of the channel, Q is river discharge, E is the coefficient of longitudinal dispersion, I_{ch} is the erosion rate or deposition rate from the channel boundary per unit channel length, and I_L is the lateral inflow rate of sediment per unit length of channel. Fisher proposed a simple approximation equation for the longitudinal dispersion coefficient based on the laboratory data and evaluations for various shear flows as[11)]:

$$E = 0.011 w^2 \cdot v^2 / (h \cdot u*) \quad (18)$$

where w is the channel width.

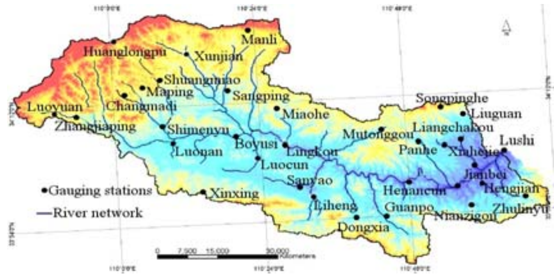

Fig.3 Map of rainfall gauging stations in Lushi River basin

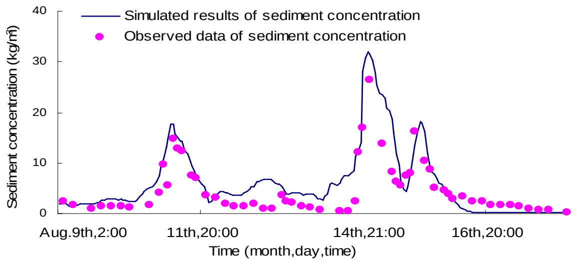

Fig.4 Event sediment concentration observation and prediction at Lushi station in 1988

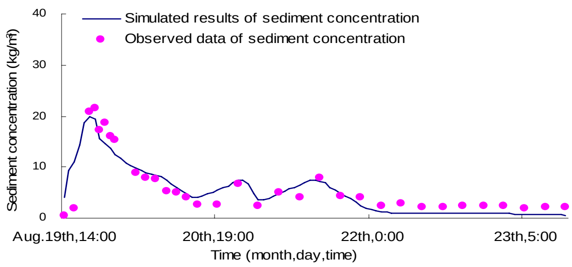

Fig.5 Event sediment concentration observation and prediction at Lushi station in 1989

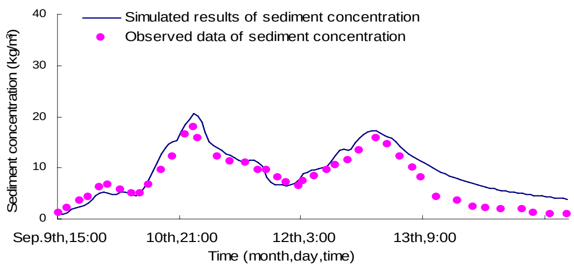

Fig.6 Event sediment concentration observation and prediction at Lushi station in 1992

The method is applicable for in-channel sediment transport, although under certain flow conditions, the equation needs to be modified to consider variations in the cross-sectional shapes. The method differs from the conservation mass equation by accounting for dispersion of the sediment while it is suspended in the flow. Also for suspended sediment it cannot necessarily be assumed that the transport velocity of the suspended sediment is the same as the longitudinal flow velocity.

Table 2 Values for several parameters involved in the model

Parameters	K_S	n	γ_s	ϕ	κ
Values	0.5 - 0.6	0.001 – 0.1	2.65	1	1 – 1.7

4. VALIDATION

In order to validate its performance, the erosion model is applied in an arid basin in China – Lushi basin. Lushi basin is a gauged basin (**Fig. 3**), where sandy loam and silt loam are the dominant soil types in the region. The basin has an area about 4623km^2, the large scale makes it difficult to obtain data from plot experiment; instead, the observed event rainfall, runoff and sediment concentration data from 1960 to 1997 were used for the sediment simulations. The validation results calculated from the events in 1988, 1989 and 1992 are shown in **Fig. 4**, **Fig. 5** and **Fig.6**. Generally, the recorded events were relatively concentrated, which sustained only several hours and had the peak rainfall intensities ranging from 10 mm/h to 30 mm/h. The involved parameters are evaluated with the values as shown in **Table 2**. On the whole, the estimated sediment concentrations are in accordance with the observed data. The Nash efficiencies for the three events are 60.8%, 84.1% and 81.7% respectively.

5. CONCLUSIONS

Soil erosion is a threat for both the river water quality and agriculture in large arid basin, where the soil erosions mainly occur during events and several erosion types coexist. The deposition also becomes an unneglected process because of the large scale, which may occur alternately along the stream according to the topographic characteristics. The paper introduced the approaches to reduce the limitations of the USLE in dealing with the event erosion and the model structure for predicting the event-based river sediment concentrations. The reasons that make the model succeed in this purpose are several improvement approaches to the USLE and the erosion model, that is:

(a) The USLE is modified towards the event soil loss estimation by relating the erosivity factor with rainfall, runoff and infiltration. The runoff and soil loss are calculated for each time step and then summed up to form the event runoff and soil loss. Since the USLE has a reasonable data need, it is selected for the sheet-rill erosion estimation, rather than simulating both erosion types independently.

(b) Channel erosion is included to account for the incapability of the USLE equation in predicting the erosion by concentrated flow. The USLE was developed from the plot experiments, where the concentrate flow was not available. While in large catchments, the concentrated flow widely exists in the channel networks, accordingly, the channel erosion should also be considered additional to the sheet-rill erosion.

(c) Additional to the soil losses, the river sediment concentrations can also be important aspect to the water environment management planning for an arid region, such as the Yellow River basin, where the high sediment concentrations decrease the river water quality.

The validation results show that the proposed model is capable of being used in predicting the event-based sediment concentrations in large-scale basins, especially in some arid regions, where such approach is needed to support the land management.

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