Estimation of sediment yield for geo-climatically diverse watersheds

JUI-YI HO[1], CHI-CHENG YANG[2], KWAN TUN LEE[1], YU-HAN HSU[1], SHUYOU CAO[3] & RAVINDER KAUR[4]

1 Department of River & Harbor Engineering, National Taiwan Ocean University, Keelung, Taiwan 202, R.O.C.
juiyiho@gmail.com

2 Water Resource Agency, No. 76, Sec.3 An-He Rd., Taipei, Taiwan 10651, Taiwan 202, R.O.C.

3 State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, Sichuan, China

4 Water Technology Center of Indian Agricultural Research Institute, New Delhi 110012, India

Abstract Because the route of eroded sediment is complicated, estimating watershed erosion during storms is difficult. The objective of this study is to develop a sediment transport model which can be used to simulate sedimentgraphs in geo-climatically diverse watersheds. A physically-based soil erosion simulation model was developed for sediment yield estimation. The studied watersheds are the Goodwin Creek watershed in USA and the Hsia-Yun watershed in Taiwan. The good agreement between the simulated and recorded sedimentgraphs has shown the capability of the developed erosion model for sediment yield simulation in the Goodwin Creek watershed, USA. However, because the erosion model did not consider sediment inflow due to landslides, the sediment quantity was underestimated during the peak-flow period in the Hsia-Yun watershed, Taiwan, when severe landslides occurred in the simulated typhoon events.

Key words sediment transport model; soil erosion; landslide

INTRODUCTION

Civilization and economic development of society are closely related to the ability to maximize the benefits and minimize the damage caused by global climatic change. The frequent occurrence of disastrous floods during the last twenty years, and the consequent increase in global soil erosion has raised an urgent need to develop new approaches for designing hydraulic structures and thereby mitigating extreme flood and soil loss problems under changing global climatic conditions. Approaches for estimation of sediment yield may be grouped as empirical and physically-based. From a hydraulic viewpoint, a physically-based approach can be developed without using field measurement data. Soil erosion processes can be simulated using physically-based factors such as rainfall intensity, soil type, vegetation cover, watershed topographic characteristics, and existing conservation practices. The essential feature of a lumped approach for sediment yield estimation when dealing with a particular watershed is concentrated on determining its responses to the inputs rather than on a detailed description of the soil erosion processes. Analysis of the distribution of suspended-sediment concentrations may be initiated from Johnson (1943), who first recognized the relationship between the hydrograph and sedimentgraph in certain catchments. Unit sedimentgraph methods have been reported for analysing the sediment output from watersheds. Bruce *et al.* (1975) described a sedimentgraph model based on sediment erosion and transport capacity. Renard & Laursen (1975) multiplied the runoff hydrograph by sediment concentration to yield sediment discharge. Rendon-Herrero (1978) extended the unit hydrograph method to derive a unit sedimentgraph corresponding to different storm durations. A more satisfactory sedimentgraph model is the instantaneous unit sedimentgraph (IUS). By applying the instantaneous unit hydrograph (IUH) concept, Williams (1978) derived an IUS to determine sediment discharge for ungauged watersheds. According to his definition the IUS represents the distribution of suspended sediment load from an instantaneous burst of rainfall producing one unit of runoff. The IUS is therefore the product of the IUH and the sediment concentration distribution, determined by a sediment routing function using travel time and sediment particle size. A preliminary physically-based approach (Lee & Yang, 2009, 2010) for sediment yield estimation during storms was adopted in this study. By using soil and watershed geomorphic information, analytical solutions for sediment travel time in different orders of overland areas and channels will be derived to develop a geomorphic instantaneous unit sedimentgraph (GIUS) which shows the temporal distribution of sediment discharge resulting from an instantaneous rainfall excess input. The resultant GIUS will be a function of the excess rainfall intensity and sediment delivery ratio. The linearity restriction of the unit hydrograph theory can be relaxed. The proposed model was applied to the Goodwin Creek Experimental Watershed located in Mississippi, USA, and the Hsia-Yun watershed in Taiwan to verify the applicability of the model.

DERIVATION OF INSTANTANEOUS UNIT SEDIMENTGRAPH MODEL

Geomorphologic instantaneous unit hydrograph theory

Based on the Horton-Strahler stream ordering scheme, a watershed of order Ω can be divided into $2^{\Omega-1}$ states (as shown in Fig. 1). The IUH for the watershed can be derived as (Rodriguez-Iturbe & Valdes, 1979):

$$u(t)=\sum_{w\in W}\left[f_{x_{oi}}(t)*f_{x_i}(t)*f_{x_j}(t)*\cdots*f_{x_\Omega}(t)\right]_w\cdot P(w) \quad (1)$$

where $u(t)$ is the instantaneous unit hydrograph; W is the flow path space given as $W=\langle x_{oi},x_i,x_j,\cdots,x_\Omega\rangle$; $f_{x_{oi}}(t)$ is the runoff travel time probability density function in state x_{oi}; $f_{x_j}(t)$ is the runoff travel time probability density function in state x_j; * denotes a convolution integral; $P(w)$ is the probability of a drop of effective rainfall adopting path w. Figure 2 shows a conceptual runoff system for an ith-order subwatershed. In Fig. 2, the ith-order hillslope in the watershed is conceptually simplified as a V-shaped model. Consequently, the runoff travel time for the path w

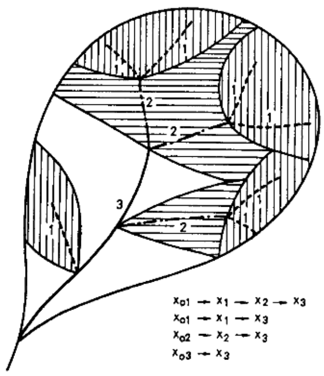


Fig. 1 Flow paths of a third-order watershed (after Lee & Yen, 1997).

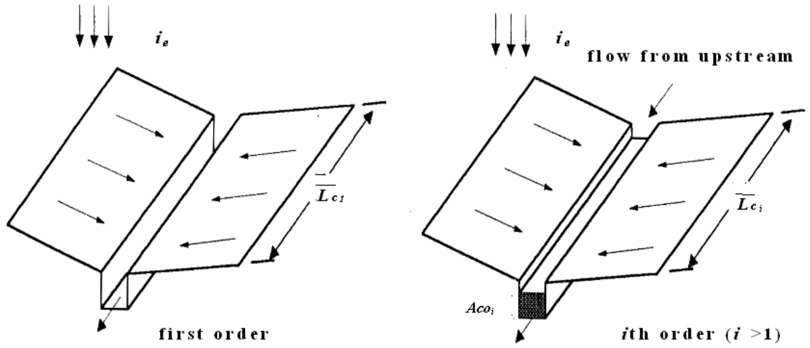


Fig. 2 V-shaped subwatershed.

is (Lee & Yen, 1997; Lee *et al*., 2008):

$$T_{x_w} = \left(\frac{n_o \overline{L}_{o_i}}{\overline{S}_{o_i}^{1/2} i_e^{m-1}} \right)^{1/m} + \sum_{i=1}^{\Omega} \frac{B_i}{2 i_e \overline{L}_{o_i}} \left[\left(h_{co_i}^m + \frac{2 i_e n_{c_i} \overline{L}_{o_i} \overline{L}_{c_i}}{B_i \overline{S}_{c_i}^{1/2}} \right)^{1/m} - h_{co_i} \right] \quad (2)$$

where i_e is the effective rainfall intensity; n_o and n_c are the roughness coefficients for overland areas and channels, respectively; $\overline{L}_{o_i}$ and $\overline{L}_{c_i}$ are the mean *i*th-order overland-flow length and channel-flow length, respectively; $\overline{S}_{o_i}$ and $\overline{S}_{c_i}$ are the mean *i*th-order overland and channel slopes, respectively; B_i is the *i*th-order channel width; *m* is a constant which can be recognized as 5/3 from Manning's equation; and h_{co_i} is the inflow depth of the *i*th-order channel due to water transported from upstream reaches.

Geomorphologic instantaneous unit sedimentgraph

While rain falls on ground, the soil particles are detached by raindrops impact and transported by surface runoff. Consequently, the IUS can be represented by integrating all the soil particles along different paths towards the watershed outlet as (Lee & Yang, 2010)

$$u_s(t) = \sum_{w \in W} \left[f_{x_{oi}}(t) * f_{x_i}(t) * f_{x_j}(t) * \cdots * f_{x_\Omega}(t) \right]_{sw} \cdot P(w) \quad (3)$$

where $u_s(t)$ is the instantaneous unit sedimentgraph. This equation indicates that IUS for a watershed can be determined from the summation of products which are calculated by convoluting sediment-travel-time probability density functions of soil particles moving in different runoff states, multiplied by the specified path probability of soil particles.

If the relationship between overland-flow discharge and sediment yield is assumed to be $q_{so_i} = a_o q_{o_i}^{b_o}$, in which q_{so_i} is the *i*th-order sediment yield per unit width from overland plane; q_{o_i} is the *i*th-order overland flow discharge per unit width; a_o and b_0 are coefficients. Thus, the sediment travel time for the *i*th-order overland plane can be derived as (Lee & Yang, 2010):

$$T_{so_i} = \frac{1}{i_e} \left[\frac{n_o}{\overline{S}_{o_i}^{1/2}} \left(\frac{D \overline{L}_{o_i}}{a_o} \right)^{1/b_o} \right]^{1/m} \quad (4)$$

where *D* is the erosion rate per unit area. In this study, a simple relationship between effective rainfall intensity and soil properties was adopted (Meyer, 1981):

$$D = K \cdot i_e^{\,p} \quad (5)$$

where K and p are coefficients. If a relationship is further proposed as $Q_{sc_i} = a_c Q_{c_i}^{b_c}$ in which Q_{sc_i} is the ith-order sediment discharge; Q_{c_i} is the *i*th-order channel-flow discharge; a_c and b_c are coefficients. Thus, the sediment travel time for the ith-order channel is (Lee& Yang, 2010)

$$T_{sc_i} = \frac{1}{2 \overline{i_e L_{o_i}}} \left\{ \left(\frac{n_{c_i} B_i^{m-1}}{\overline{S}_{c_i}^{1/2}} \right)^{1/m} \left[\left(\frac{\overline{S}_{c_i}^{1/2} h_{sco_i}^m}{n_{c_i} B_i^{m-1}} \right)^{b_c} + \frac{2 D \overline{L}_{o_i} \overline{L}_{c_i} SDR_{o_i}}{a_c} \right]^{\frac{1}{mb_c}} - h_{sco_i} \right\} \quad (6)$$

where SDR_{o_i} is the overland sediment delivery ratio (SDR) denoting the sediment reduction ratio from ith-order overland planes into channel; h_{sco_i} is sediment laden-flow depth at the entrance of the *i*th-order channel. In this study, the SDR is estimated by (Vanoni, 1975):

$$SDR_o = 0.4724 A^{-0.125} \tag{7}$$

where A is watershed area (km^2). The regression relationship was verified by using data from 300 watersheds throughout the world.

Model application

Two watersheds in different geomorphologic and climatic conditions were used to validate the model in this study, the Goodwin Creek watershed in USA and the Hsia-Yun watershed in Taiwan. Goodwin Creek Watershed, located in northern Mississippi, was used to verify the capability of the model for sediment yield prediction. Discharge and sediment are monitored by 14 gauging stations, and precipitation is measured by 31 raingauges located in or near the basin. The drainage area of the study watershed is 21.44 km^2; elevation ranges between 66 and 129 m; the average channel slope is 0.004; the stream network is fourth order and the channel width at the watershed outlet is 29.58 m. Figure 3(a) shows the channel network extracted from the 30-m resolution digital elevation data set using DEM (Lee, 1998).

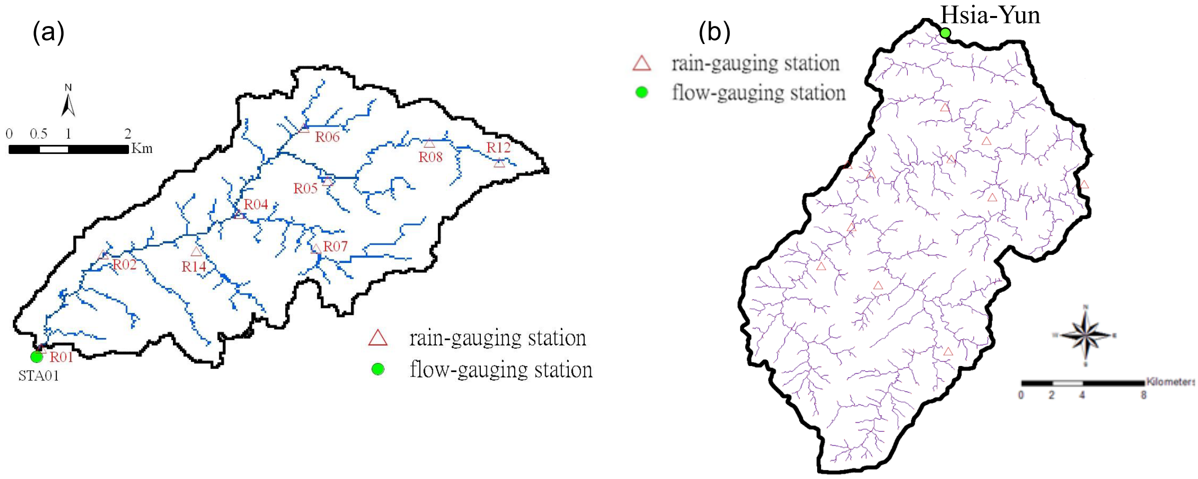
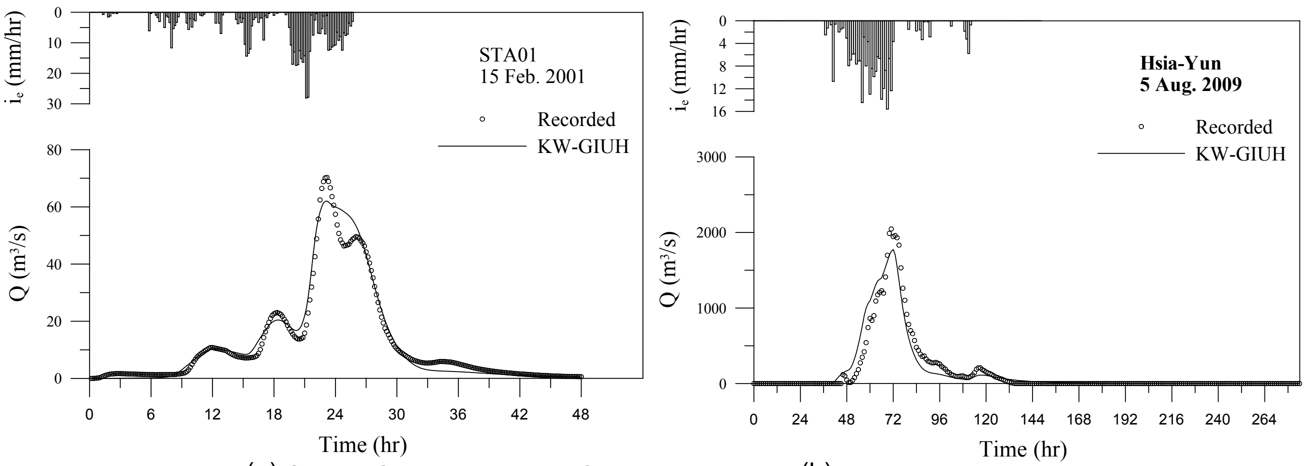


Fig. 3 Maps of studied watersheds: (a) Goodwin Creek watershed in USA, (b) Hsia-Yun watershed in Taiwan.

The Hsia-Yun watershed, one of the sub-basins in Tai-Shui River basin, in northern Taiwan, was also selected to investigate the applicability of the proposed model in this study. The stream network of the study watershed is fifth order; the size of the watershed is 608.99 km^2; elevation ranges between 260 and 3700 m; the average slope gradient is 0.442. Figure 3(b) shows the channel network extracted from the 40-m resolution digital elevation data set using DEM (Lee, 1998).

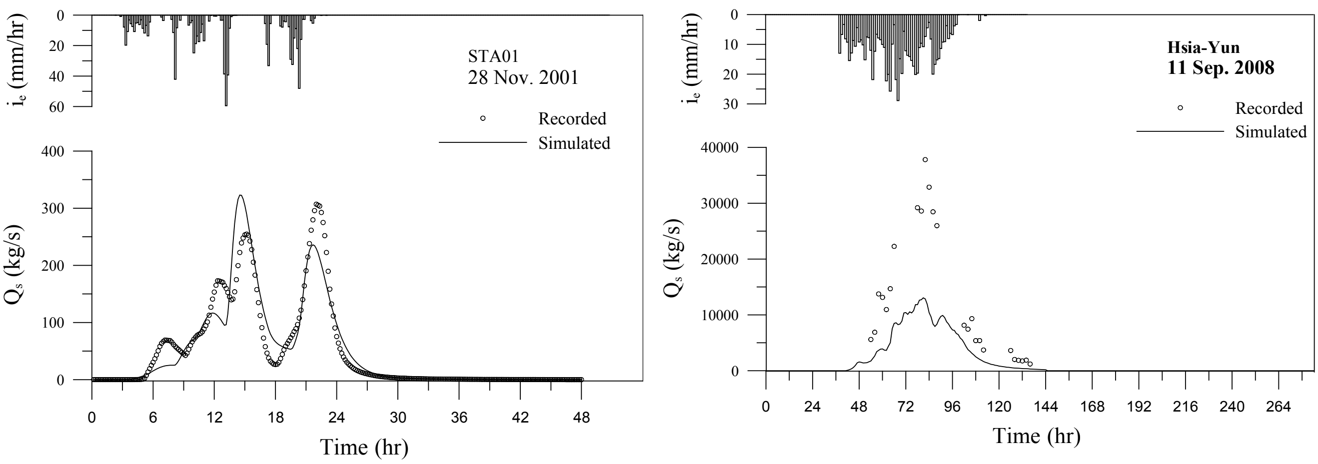
Storm events in Goodwin Creek watershed and Hsia-Yun watershed were selected for parameter calibration and model verification. Spatial average rainfall is estimated by the Thiessen polygon method. Rainfall runoff simulation was routed by the KW-GIUH model using the effective rainfall hyetograph as model input to generate direct runoff. Figure 4(a) and (b) shows the simulated hydrographs. The rising and recession limbs of the simulated hydrograph are in good agreement with the records. The foregoing results demonstrated that the KW-GIUH model displayed good performance on rainfall–runoff simulations.

The IUS for the watershed outlet is determined using equation (3), in which the sediment travel times for overland areas and channels are estimated using equations (4) and (6), respectively. The sediment yield for the watershed can be obtained by convoluting the erosion rate and the IUS. Figure 5(a) shows the sediment yield simulations for two storms in Goodwin Creek watershed. In performing the IUS, the model parameters were set as $a_o = 20$, $b_o = 2.0$, $a_c = 0.0003$, $b_c = 1.5$, and $SDR_o = 0.32$ (Lee & Yang, 2009). As shown in Fig. 6, the simulated and recorded sedimentgraphs show good agreement. The coefficient of efficiency for these simulations is above



(a) Goodwin Creek watershed in USA. (b) Hsia-Yun watershed in Taiwan

Fig. 4 Storm hydrograph simulations.



(a) Goodwin Creek watershed in USA. (b) Hsia-Yun watershed in Taiwan

Fig. 5 Storm sedimentgraph simulations.

0.90. The error of the peak sedimentgraph is around ±15%. It demonstrates that the proposed IUS model is applicable to predict sediment yield in watersheds. Figure 5(b) shows the sediment yield simulation for the storm in Hsia-Yun watershed of Taiwan. The simulated sedimentgraphs is inconsistent with recorded sedimentgraphs. Since the proposed erosion model did not consider sediment inflow due to landslide, the predicted sediment quantity was underestimated during the peak-flow period because severe landslides occurred in the simulated typhoon events.

CONCLUSIONS

In this study, an instantaneous unit sedimentgraph (IUS) is derived for estimating sediment yield. The IUS is represented by the combination of a series of sediment-travel-time probability density functions for different orders of overland areas and channels. The sediment travel times are solved analytically by using the kinematic-wave approximation. Since the sediment travel time is a function of rainfall intensity, there is a set of IUSs corresponding to different values of temporally varying rainfall intensity. The peak of the IUS increases with increasing rainfall excess intensity while the time to peak decreases. The proposed model is promising to be a simple and convenient approach for sediment yield estimation during storms in gauged and/or ungauged watersheds.

However, because the sediment-yield simulation model developed in this year-long project did not consider sediment inflow due to landslides, underestimation of the sedimentgraph in the peak-flow period was found for the Taiwan catchment, because many of landslides occurred during storm events. Inclusion of a landslide sediment-yield concept to combine with the soil erosion model to obtain a better sediment-yield simulation during storm events is under consideration.

Acknowledgements Financial support provided to the present study by the State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, China, under Grant 1001, and the National Science Council, Taiwan, under Grants 99-2923-E-019-001-MY3 and 100-2218-E-006-013, are gratefully acknowledged.

REFERENCES

Blackmarr, W. A. (1995) Documentation of hydrologic, geomorphic, and sediment transport measurements on the Goodwin Creek Experimental Watershed, Northern Mississippi, for the period 1982–1993, Preliminary release, *USDA-ARS National Sedimentation Laboratory*, Oxford, Mississippi, USA.

Bruce, R. R., Harper, L. A., Leonard, R. A., Snyder, W. M. & Thomas, A. W. (1975) A model for runoff of pesticides from small upland watershed. *J. Environ. Qual*. 4(4), 541–548.

Johnson, J. W. (1943) Distribution graphs of suspended-matter concentration. *Trans. ASCE* 33(1), 100–104.

Lee, K. T. & Yen, B. C. (1997) Geomorphology and kinematic-wave-based hydrograph derivation. *J. Hydr. Engng ASCE,* 123(1), 73–80.

Lee, K. T. & Yang, C. C. (2009) Derivation of instantaneous unit sedimentgraph based on soil and watershed geomorphology characteristics. In: *An International Perspective on Environmental and Water Resources Conference* (Bangkok, Thailand), 148–149.

Lee, K. T. & Yang, C. C. (2010) Estimation of sediment yield during storms based on soil and water geomorphology characteristics. *J. Hydrol.* 382, 145–153.

Meyer, L. D. (1981) How rain intensity affects interrill erosion. *Trans. ASAE* 24(6), 1472–1475.

Renard, K. G., & Laursen, E. M. (1975). Dynamic behavior model of ephemeral stream. *J. Hydraul. Div.*, *ASCE* 100(HY7), 835–848.

Rendon-Herrero, O. (1978) Unit sediment graph. *Water Resour. Res.* 14(5), 889–901.

Rodriguez-Iturbe, I. & Valdes, J. B. (1979) The geomorphologic structure of hydrologic response. *Water Resour. Res.* 15(6), 1409–1420.

Vanoni, V. A. (1975) *Sedimentation Engineering.* ASCE, New York.

Williams, J. R. (1978) A sediment graph model based on an instantaneous unit sediment graph. *Water Resour. Res*. 14(4), 659–664.