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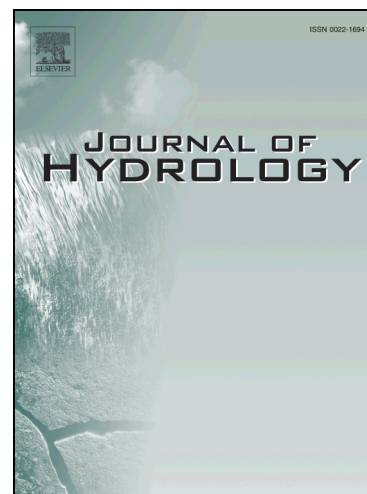
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Soil erosion model tested on experimental data of a laboratory flume with a pre-existing rill

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Abstract

Prediction of sediment discharge transported within flow is strongly needed in order to provide measures for a well-established erosion control and water quality management practice. Initiated by runoff generation and erosion processes sediment transport is influenced by microtopography over hillslopes of hydrological watersheds. Consideration of microtopography provides better accurate results. In this study, a process-based two-dimensional rainfall-runoff mathematical model is coupled with erosion and sediment transport component. Both the rainfall-runoff and

sediment transport components make simulations in rills and over interrill areas of a bare hillslope. Models at such fine resolution are rarely verified due to the complexity of rills and interrill areas. The model was applied on a data set compiled from laboratory experiments. Erosion flume was filled with granular sand to replace a bare soil. A longitudinal rill and an interrill area were pre-formed over the soil in the flume before the simulated rainfall exerted on. The flume was given both longitudinal and lateral slopes. The simulated rainfall was changed between 45 mm/h and 105 mm/h and exerted on granular uniform fine and medium sand in the erosion flume with longitudinal and lateral slopes changing from 5% to 20%. Calibration of the models shows that it is able to produce good results in terms of sedigraphs, which suggest also that the model might be considered an important step to verify and improve watershed scale erosion and sediment transport models.

Keywords: Erosion flume; Rainfall simulator; Rill; Sedigraph; Sediment transport model; Soil erosion

1 Introduction

Soil material detached from the surface of the soil matrix is subsequently transported away from the site of the detachment (Kinnell, 2005). Sediment transport is an important issue, because it creates environmental concerns as well as engineering design problems. Sediment particles may absorb pollutants over the watershed, carry them along the river, and finally deposit within a receiving water body or at another point in the watershed. It has also a potential to remove nutrients from the fertile agricultural lands. In terms of engineering design problems, the sediment load is a measure to predict the dead storage volume of the reservoir which should neither be underestimated nor overestimated. Both the underestimation and overestimation bring

unnecessary costs, in that maintenance or additional capacity would be needed in the former and construction costs would be higher than needed in the latter.

The sediment transport process is space- and time-dependent. Therefore, it cannot be modelled by a single universal equation. For the same reason, several sediment transport models have so far been available in the literature at either hillslope- or watershed-scale. In general, the hydrological or sediment transport models are categorized based on different criteria such as process description, scale, and solution technique (Singh, 1995; Singh & Woolhiser, 2002; Aksoy & Kavvas, 2004). Empirical models are limited to the conditions for which they have been developed. In conceptual models, a watershed is represented by storage systems. In the process-based model, mass conservation equation of sediment is used together with the momentum equation of the process. The USLE (Wischmeier & Smith, 1978) can be given as an example to the empirical models. The hydrological part of ANSWERS (Beasley et al., 1980) uses a conceptual process. Such models as KINEROS (Smith, 1981), WESP (Lopes, 1987), SEM (Storm et al., 1987), SHESED (Wicks, 1988), EUROSEM (Morgan et al., 1998), Erosion 3-D (Schmidt et al., 1999; Schindewolf & Schmidt, 2012; Starkloff & Stolte, 2014), STREAMS (Cerdan et al., 2001; Souchère et al., 2005; Couturier et al., 2013), MAHLERAN (Wainwright et al., 2008a, b, c); and LISEM (De Roo et al., 1996; De Roo & Jetten, 1999; Starkloff & Stolte, 2014) are popular examples of the process-based models which are all formulated by deterministic differential equations (Merritt et al., 2003; Aksoy & Kavvas, 2004; Jetten and Favis-Mortlock, 2006; Karydas et al., 2014). As a development towards the non-deterministic process-based modelling, Kavvas et al. (2004) proposed a two-dimensional rainfall-runoff model coupled with an environmental module to accommodate the erosion and sediment transport processes that consider the random behaviour of the watershed as well as the rill formation on

the soil surface (Kavvas et al., 2006). Clearly, such an analysis of erosion and sediment transport processes is not an easy task that requires simplification of the nature for which different approximations are needed.

At hillslope-scale with no rilling, Rose et al. (1983) modelled erosion due to rainfall and runoff by taking the rainfall intensity into account through an ordinary differential equation. Similarly, Hairsine and Rose (1991) studied the erosion due to rainfall solely as a function of rainfall intensity. It has been a custom to link the rainfall erosion to the rainfall intensity as used by Lopes (1987), Lopes and Lane (1988), and Proffitt et al. (1991). In a similar study (Hairsine and Rose, 1992), rilling over hillslopes is considered together with the stochastic structure of the 2-mode sediment transport: motion and no-motion. Govindaraju and Kavvas (1991) combined the surface flow model of Govindaraju et al. (1990) with the erosion model of Foster and Meyer (1972). The diffusion wave approach was used together with a sine-curve flow depth approximation in the surface flow model. An analytical solution was obtained to check the suitability of the model based on the field and laboratory experimental datasets of Kilinc and Richardson (1973) and Singer and Walker (1983). In a similar study, Laguna and Giraldez (1993) used the kinematic wave approach in the hillslope-scale erosion and sediment transport process. The kinematic wave approach has been the key element of the two-dimensional models of Tayfur (2001) and Aksoy et al. (2003).

Kavvas and Govindaraju (1992), Govindaraju and Kavvas (1992) and Govindaraju et al. (1992) dealt with the rilling over hillslopes due to its importance in the sediment transport over hillslopes. Govindaraju (1995) derived dimensionless numbers and reduced number of calibration parameters to two; one measures how erosive the flow is, another shows how resistant the soil is against erosion; i.e., how erodible it is. The stochastic structure of the two

parameters have further been investigated by Govindaraju (1998) who concluded that the former fits the exponential probability distribution while the latter could be represented by independent random numbers. The rilling structure of the topography has been considered not only at the hillslope scale but also at the watershed scale-modeling in such models as the Limburg Soil Erosion model - LISEM - (De Roo et al., 1996), Chemicals, Runoff, and Erosion from Agricultural Management System - CREAMS - (Foster et al., 1981), Water Erosion Prediction Project - WEPP - (Nearing et al., 1989), and the European Soil Erosion Model - EUROSEM - (Morgan et al., 1998) among others.

The use and development of erosion and sediment transport models still expands due to the importance of the topic. Therefore, an unsteady deterministic erosion and sediment transport model is developed based on the two-dimensional continuity equation of sediment transported within flow. The model developed in this study is the continuation of the two-dimensional unsteady deterministic rainfall-runoff model of Aksoy et al. (2016) in which only the longitudinal direction of flow is taken into account although it was derived from a two-dimensional control volume. The model is novel not only because of the reduction in the number of dimensions but also because it considers the rilling topography over a hillslope. Erosion exerted by rainfall and runoff are considered in the model. The number of parameters is reduced to the least for the sake of obtaining as parsimonious a model as possible. The parameters are calibrated and then validated with laboratory measurements. A discussion of results is provided after which concluding remarks are finally presented.

2 Sediment Transport Model

Sediment transport model detailed below is coupled with a rainfall-runoff model considering microtopography over the hillslope that accommodates rills and interrill areas

(Aksoy et al., 2016). In the microtopography over the hillslope as used in the rainfall-runoff model of Aksoy et al. (2016), the hillslope was divided into rills and interrill areas in constructing the sediment transport model of this study.

2.1 Interrill area sediment transport model

As used by Tayfur and Singh (2004) among others, the time-varying two-dimensional continuity equation for sediment transport can be given by

$$\frac{\partial h C_s}{\partial t} + \frac{\partial q_x C_s}{\partial x} + \frac{\partial q_y C_s}{\partial y} = \frac{E}{\rho_s} \quad (1)$$

where h is flow depth [L], t is time [T], q_x and q_y are, respectively, flow rates [L^2T^{-1}] through cross-sections perpendicular to the x - and y -directions, C_s is volumetric concentration of sediment within flow [L^3L^{-3}], ρ_s is mass density of sediment [ML^{-3}], and E mass of sediment eroded from unit area in unit time [$ML^{-2}T^{-1}$]. It should be noted that h , C_s and E are functions of both time and space (x, y). Taking derivatives in Equation (1) results in

$$\left(\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} \right) C_s + h \frac{\partial C_s}{\partial t} + q_x \frac{\partial C_s}{\partial x} + q_y \frac{\partial C_s}{\partial y} = \frac{E}{\rho_s} \quad (2)$$

The factor of C_s in Equation (2) can be linked to the time-varying two-dimensional continuity equation of rainfall-runoff model (Aksoy et al., 2016) which is given by

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = r - f \quad (3)$$

where, r is rainfall intensity (LT^{-1}) and f is infiltration rate (LT^{-1}). Substituting Equation (3) into Equation (2) results in

$$(r - f)C_s + h \frac{\partial C_s}{\partial t} + q_x \frac{\partial C_s}{\partial x} + q_y \frac{\partial C_s}{\partial y} = \frac{E}{q_s} \quad (4)$$

The source term of Equation (4) shows the total mass of rainfall erosion (E_r) and runoff erosion (E_f) as

$$E = E_r + E_f \quad (5)$$

Rainfall erosion is quantified usually in terms of rainfall intensity in the form of

$$E_r = \alpha r^\beta \quad (6)$$

in which α and β are calibration parameters often associated with soil or energy properties (Tayfur, 2002); α shows the detachability of the soil; the higher α is, the easier detached is the soil; whereas β is taken in between 1 and 2 (Meyer, 1971; Foster et al., 1977; Foster, 1982; Sharma et al., 1993; Tayfur, 2001). In this study, it is assumed that rainfall intensity is constant and uniformly distributed over the hillslope. The parameter α is indeed not constant. Therefore, it can be taken as a function of rainfall intensity if needed as it was in the SHESSED model (Wicks, 1988). Not only α but also β has been considered as a function of rainfall intensity by Wicks (1988) who found that the parameters decrease when rainfall intensity increases. This is understandable as runoff is generated after rainfall, and runoff erosion becomes dominant with increasing rainfall intensity.

Runoff erosion is considered a function of the excess transport capacity and expressed as (Foster 1982; Govindaraju et al., 1992; Tayfur 2007)

$$E_f = \begin{cases} \sigma(T_c - q_s) & T_c > q_s \\ 0 & T_c \leq q_s \end{cases} \quad (7)$$

where σ [L^{-1}] is model calibration parameter, T_c sediment transport capacity of flow [$ML^{-1}T^{-1}$], and q_s unit-width sediment discharge transported within flow [$ML^{-1}T^{-1}$]. Also, from its dimension, it is possible to note that E_f corresponds to erosion from the unit area of a hillslope per unit time [$ML^{-2}T^{-1}$].

Sediment particles detached from their original location are transported within flow. It is clear that the amount of sediment within flow must be less than the sediment transport capacity of flow in order to ensure the transport of the eroded sediment particles. In other words, runoff can erode sediment particles from their place and transport them downstream when the transport capacity of flow is higher than the available sediment within flow. In the opposite case; when the transport capacity is less than the amount of sediment within flow, deposition takes place. This also means that available sediment within flow already exceeds the transport capacity; and the exceedance portion of sediment is deposited. Deposition was not considered in the model development. Substituting Equations (6) and (7) into Equation (5) gives

$$E = \begin{cases} \alpha r^\beta + \sigma(T_c - q_s) & T_c > q_s \\ \alpha r^\beta & T_c \leq q_s \end{cases} \quad (8)$$

The unit width sediment discharge, q_s , in Equation (8) can be determined by (Foster 1982; Tayfur 2002)

$$q_s = \rho_s C_s q \quad (9)$$

while the transport capacity of flow is given as a function of net shear stress exerted on soil particles, which is defined as the difference between the shear stress generated by runoff and its minimum (critical) value required for the detachment and transportation of sediment particles (Govindaraju & Kavvas 1992; Tayfur & Singh, 2004):

$$T_c = \eta(\tau - \tau_c)^\varepsilon \quad (10)$$

In Equation (10), η and ε are dimensionless calibration parameters, τ and τ_c are the shear stress [$\text{ML}^{-1}\text{T}^{-2}$] exerted by flow and its critical value, respectively. The critical shear stress is a measure of resistance of sediment particles against motion. The higher the critical shear stress is, the harder to detach the soil. The critical shear stress (τ_c) in Equation (10) exists as a model parameter. However, as assumed by Lopes (1987), within flow exist sediment particles already detached by wind and similar agents. Such sediment particles do not resist against flow

This reduces Equation (10) to

$$T_c = \eta\tau^\varepsilon \quad (11)$$

However, it should be kept in mind that the critical shear stress may not always be omitted but could be taken as an extra parameter of the model.

Assuming that the hillslope behaves as a wide channel, the shear stress is calculated by

$$\tau = \rho g h S \quad (12)$$

In addition to the previously defined overland flow depth h [L], here, ρ is mass density of water [ML^{-3}], g gravitational acceleration [LT^{-2}] and S the resulting topographical slope [-] which can be given, as defined in Tayfur (2001), by

$$S = \sqrt{S_x^2 + S_y^2} \quad (13)$$

Hydraulic gradient is taken the same as the topographical slope when the kinematic wave approximation is used under the wide channel assumption. Considering Equations (6-13), Equation (5), the source term of the sediment transport model is obtained as

$$E = \alpha r^\beta + \sigma \left(\eta (\rho g h S)^\epsilon - \rho_s C_s C_z S^{1/2} h^{3/2} \right) \quad (14)$$

where, C_z is the Chezy roughness coefficient ($L^{1/2}T^{-1}$).

Returning back to the sediment transport model by considering Equation (4) together with Equation (14), and using the kinematic wave approximation, results in

$$\begin{aligned} (r - f)C_s + h \frac{\partial C_s}{\partial t} + k_x h^{3/2} \frac{\partial C_s}{\partial x} + k_y h^{3/2} \frac{\partial C_s}{\partial y} = \\ \frac{1}{\rho_s} \left(\alpha r^\beta + \sigma \left(\eta (\rho g h S)^\epsilon - \rho_s C_s C_z S^{1/2} h^{3/2} \right) \right) \end{aligned} \quad (15)$$

in which all variables are as defined previously other than k_x and k_y which are calculated by (Aksoy et al., 2016)

$$k_x = \frac{C_z S_x^{1/2}}{\left[1 + \left(\frac{S_y}{S_x} \right)^2 \right]^{1/4}} = \frac{C_z S_x}{(S_x^2 + S_y^2)^{1/4}} = C_z \frac{S_x}{S^{1/2}} \quad (16)$$

$$k_y = \frac{C_z S_y^{1/2}}{\left[1 + \left(\frac{S_x}{S_y} \right)^2 \right]^{1/4}} = \frac{C_z S_y}{(S_x^2 + S_y^2)^{1/4}} = C_z \frac{S_y}{S^{1/2}}. \quad (17)$$

Sediment concentration can be approximated by

$$C_s(x, y, t) = Y(y) C_s(x, t) \quad (18)$$

for which the variable Y is defined as

$$Y(y) = \sin \frac{\pi y}{2l_y} \quad (19)$$

Aksoy et al. (2016) used this approximation as proposed by Govindaraju et al. (1988a, b) previously for the overland flow depth in the rainfall-runoff model in the form of

$$h(x, y, t) = Y(y)h(x, t) \quad (20)$$

Referencing Figure 1, $Y = 1$ for $y = l_y$ where interrill area reaches the rill, and

$$C_s(x, l_y, t) = C_s(x, t) \quad (21)$$

$$h(x, l_y, t) = h(x, t) \quad (22)$$

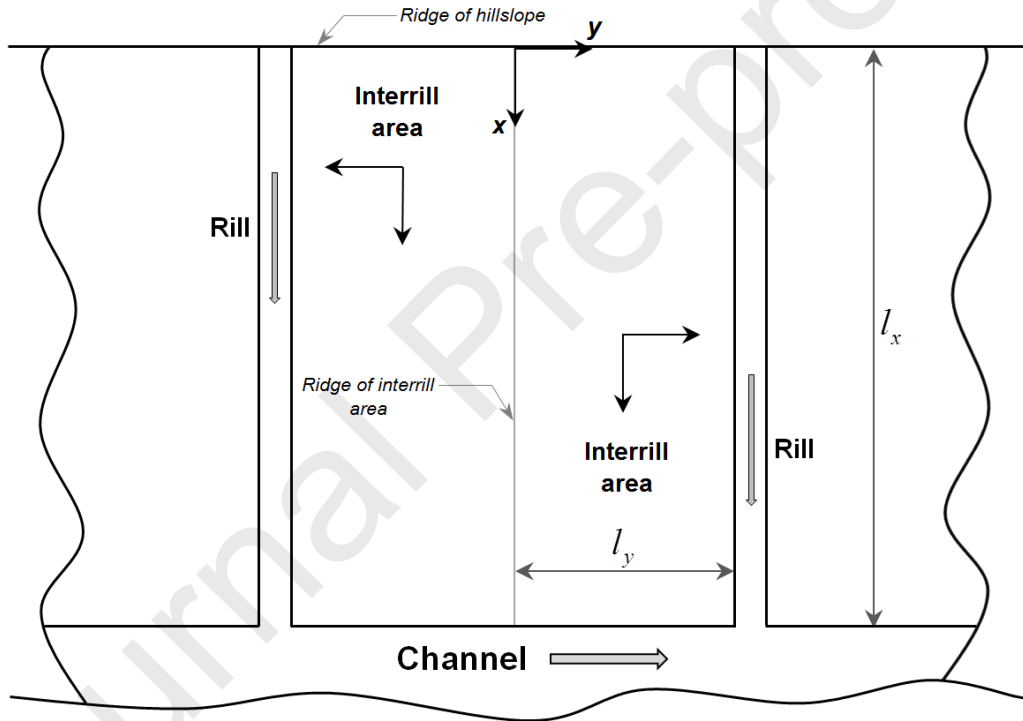


Figure 1 Microtopographical scheme (rilling structure) over the hillslope used for the 2-dimensional model

Introducing Y as in Equation (19), sediment concentration and overland flow depth become independent of the lateral distance at $l_y = y$ where the interrill area reaches the rill. The number of

independent variables of sediment concentration and overland flow depth is reduced to two from three. Equation (15) takes the form

$$\begin{aligned} h \frac{\partial C_s}{\partial t} Y^2 + k_x h^{3/2} \frac{\partial C_s}{\partial x} Y^{5/2} + \left((r-f)Y + \frac{2}{5} k_y h^{3/2} \frac{\partial Y^{5/2}}{\partial y} + \sigma C_z S^{1/2} h^{3/2} Y^{5/2} \right) C_s \\ = \frac{\alpha r^\beta}{\rho_s} + \frac{\sigma}{\rho_s} \eta (\rho g S)^\varepsilon h^\varepsilon Y^\varepsilon \end{aligned} \quad (23)$$

when approximations in Equations (18-22) are considered. Integration of Equation (23) along the hillslope length at direction y results in;

$$\begin{aligned} h \frac{\partial C_s}{\partial t} \int_0^{l_y} Y^2 dy + k_x h^{3/2} \frac{\partial C_s}{\partial x} \int_0^{l_y} Y^{5/2} dy \\ + \left((r-f) \int_0^{l_y} Y dy + \frac{2}{5} k_y h^{3/2} \int_0^{l_y} \frac{dY^{5/2}}{dy} dy + \sigma C_z S^{1/2} h^{3/2} \int_0^{l_y} Y^{5/2} dy \right) C_s \\ = \frac{\alpha r^\beta}{\rho_s} \int_0^{l_y} dy + \frac{\sigma}{\rho_s} \eta (\rho g S)^\varepsilon h^\varepsilon \int_0^{l_y} Y^\varepsilon dy \end{aligned} \quad (24)$$

The integral terms in Equation (24) are evaluated as;

$$\int_0^{l_y} Y dy = \frac{2}{\pi} l_y \quad (25a)$$

$$\int_0^{l_y} Y^2 dy = \frac{l_y}{2} \quad (25b)$$

$$\int_0^{l_y} Y^{5/2} dy = 0.45765 l_y \quad (25c)$$

$$\int_0^{l_y} dy = l_y \quad (25d)$$

$$\int_0^{l_y} Y^\varepsilon dy = \phi(\varepsilon) l_y \quad (25e)$$

$$\int_0^{l_y} \frac{\partial Y^{5/2}}{\partial y} dy = 1 \quad (25f)$$

Function $\phi(\varepsilon)$ in Equation (25e) is approximated by

$$\phi(\varepsilon) = 0.95975 - 0.492211\varepsilon + 0.21038\varepsilon^2 - 0.0412993\varepsilon^3 \quad (0.5 < \varepsilon < 1.5) \quad (25g)$$

By substituting Equations (25a-g) into Equation (24),

the final form of the model is obtained as

$$\begin{aligned} h \frac{\partial C_s}{\partial t} + (0.915312k_x h^{3/2}) \frac{\partial C_s}{\partial x} \\ + \left(1.27324(r-f) + 0.8 \frac{k_y}{l_y} h^{3/2} + 0.915312\sigma C_z S^{1/2} h^{3/2} \right) C_s \\ = 2 \frac{\alpha r^\beta}{\rho_s} + 2 \frac{\sigma}{\rho_s} \eta (\rho g S)^\varepsilon h^\varepsilon \phi(\varepsilon) \end{aligned} \quad (26)$$

It should be noticed that Equation (26) is valid for $0.5 < \varepsilon < 1.5$ on which the approximation in Equation (25g) is based.

2.2 Numerical solution of the interrill area sediment transport model

A backward finite difference scheme was used as in the hydrological component (Aksoy et al., 2016) for solving Equation (26) numerically. Considering h_i as the flow depth at point i at current time, and H_i the flow depth at point i at previous time as defined previously in the hydrological component (Aksoy et al., 2016) and similarly defining c_i as sediment concentration at point i at current time, and C_i sediment concentration at point i at previous time

$$\begin{aligned}
& h_i \frac{c_i - C_i}{\Delta t} + \left(0.915312 k_x h_i^{3/2} \right) \frac{c_i - c_{i-1}}{\Delta x} \\
& + \left(1.27324(r - f) + 0.8 \frac{k_y}{l_y} h_i^{3/2} + 0.915312 \sigma C_z S^{1/2} h_i^{3/2} \right) c_i \\
& = 2 \frac{\alpha r^\beta}{\rho_s} + 2 \frac{\sigma}{\rho_s} \eta (\rho g S)^\varepsilon h_i^\varepsilon \phi(\varepsilon)
\end{aligned} \tag{27}$$

is obtained as the finite difference form of Equation (26).

Sediment concentration can be calculated explicitly from the numerical solution of Equation (27) as

$$c_i = \frac{\lambda_1}{\lambda_2} \tag{28}$$

where

$$\lambda_1 = 2 \frac{\alpha r^\beta}{\rho_s} + 2 \frac{\sigma}{\rho_s} \eta (\rho g S)^\varepsilon h_i^\varepsilon \phi(\varepsilon) + h_i \frac{C_i}{\Delta t} + 0.915312 k_x h_i^{3/2} \frac{c_{i-1}}{\Delta x} \tag{29a}$$

$$\lambda_2 = \left(0.915312 \frac{k_x}{\Delta x} + 0.8 \frac{k_y}{l_y} + 0.915312 \sigma C_z S^{1/2} \right) h_i^{3/2} + \frac{1}{\Delta t} h_i + 1.27324(r - f) \tag{29b}$$

2.3 Rill sediment transport model

Only erosion due to shear stress exerted by runoff being taken into-account renders the water depth in rills to prevent rainfall from eroding sediment particles. Also, the lateral contributions of sediment to rills from the interrill areas are considered (Figure 2) in which E_R is defined as rill erosion along the unit length of a rill in unit time [$\text{ML}^{-1}\text{T}^{-1}$], and $q_{S,IR}$ as incoming sediment rate from the right- and left-hand side interrill areas along the unit length of the rill [$\text{ML}^{-1}\text{T}^{-1}$]. Taking other variables as defined previously, the time-dependent one-dimensional

continuity equation of sediment transport in the rill is given by (Tayfur & Kavvas, 1994; 1998; Tayfur, 2007)

$$\frac{\partial AC_s}{\partial t} + \frac{\partial QC_s}{\partial x} = \frac{1}{\rho_s} (E_R + q_{s,IR}) \quad (30)$$

where A is rill cross-section area [L^2], t is time [T], Q is flow discharge [L^3T^{-1}], and x is longitudinal distance along the rill [L]. It should be noticed that A , C_s , Q , E_R and $q_{s,IR}$ change all with time and along the rill length.

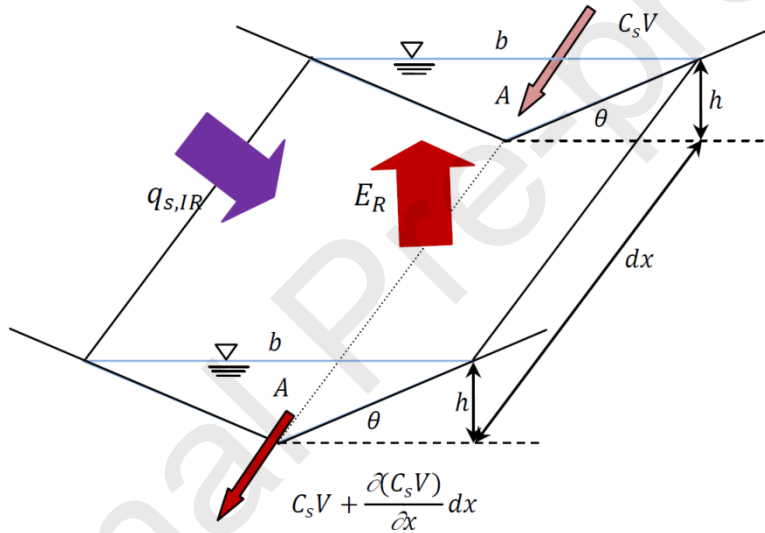


Figure 2. Control volume used for the rill sediment transport continuity equation

Taking derivatives in Equation (30) and upon rearranging yields,

$$\left(\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} \right) C_s + A \frac{\partial C_s}{\partial t} + Q \frac{\partial C_s}{\partial x} = \frac{1}{\rho_s} (E_R + q_{s,IR}) \quad (31)$$

The factor of C_s in Equation (31) can be linked to the continuity equation of one-dimensional flow in the rill, given as

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_l + q_{IR} \quad (32)$$

where q_l is excess rainfall on the rill [L^2T^{-1}] and q_{IR} is flow coming from interrill areas along a unit length of the rill [L^2T^{-1}]. Source terms in Equation (32) are defined as

$$q_l = (r - f)b \quad (33)$$

$$q_{IR} = q_y^{IR}(x, l_y, t) \quad (34)$$

in which r and f , as defined before, are rainfall intensity [LT^{-1}] and infiltration rate [LT^{-1}], respectively, and b is the width of the rill [L] (Figure 2). In Equation (34), q_y^{IR} is the unit width discharge [LT^{-1}] coming from the interrill area at the lateral distance $y = l_y$ which is the most downstream section of the interrill area where it reaches the rill. Introducing Equations (32-34) into Equation (31) yields

$$((r - f)b + q_{IR})C_s + A \frac{\partial C_s}{\partial t} + Q \frac{\partial C_s}{\partial x} = \frac{1}{\rho_s} (E_R + q_{s,IR}) \quad (35)$$

Erosion within a rill is taken only due to runoff, and is given, similar to the runoff erosion over interrill areas as in Equation (7), by

$$E_R = \begin{cases} \sigma_R (T_{cR} - Q_{sR}), & T_{cR} > Q_{sR} \\ 0, & T_{cR} \leq Q_{sR} \end{cases} \quad (36)$$

in which σ_R is the first-order reaction coefficient [L^{-1}] (Foster, 1982), T_{cR} is the sediment transport capacity of flow in the rill [MT^{-1}], and Q_{sR} is sediment load in the rill [MT^{-1}]. It should be noticed that the erosion term in Equation (36) is provided for the whole cross-section of the rill not for the unit width as it was the case in the interrill area part of the model.

Flow is not able to transport the incoming sediment when $T_{cR} < Q_{sR}$. In this case, deposition occurs. Under the limit condition when $T_{cR} = Q_{sR}$ neither erosion nor deposition is observed. This is the equilibrium case between T_{cR} and Q_{sR} where what comes from the upstream is transported to the downstream. When $T_{cR} > Q_{sR}$, the incoming sediment is transported downstream; also, erosion is observed in order to fulfill the deficit between T_{cR} and Q_{sR} . It should be emphasized that erosion would be observed as long as the source material for the energy level of the flow is available. The transport capacity of the flow in a rill is given by

$$T_{cR} = \rho_s G \quad (37)$$

where G is flow discharge through the rill cross-section [L^3T^{-1}] given by Yalin (1963) as

$$G = b V_* 0.635 D \left(\delta - \frac{1}{a} \ln(1 + a\delta) \right) \quad (38)$$

in which b is width of the rill cross-section at the water surface [L], V_* is shear velocity [LT^{-1}], and D is sediment size (diameter) [L]. In Equation (38),

$$\delta = \begin{cases} \frac{F_*}{F_{*C}} - 1, & F_* > F_{*C} \\ 0, & F_* \leq F_{*C} \end{cases} \quad (39)$$

in which F_* is the dimensionless shear stress given in Yalin (1963) as

$$F_* = \frac{\tau}{(\rho_s - \rho)gD} \quad (40)$$

to compare with the constant critical shear stress ($F_{*C} = 0$)

due to the fact that flow in the rill can be considered turbulent (Bogardi, 1974). On the other hand, Yalin (1963) defined a in Equation (38) by

$$a = 2.45 \frac{(F * c)^{0.5}}{s^{0.4}} \quad (41)$$

where s is the ratio of sediment mass density to water mass density.

After all these are considered, Equation (35) can be written as

$$((r-f)b + q_{IR} + \sigma_R Q)C_s + A \frac{\partial C_s}{\partial t} + Q \frac{\partial C_s}{\partial x} = \frac{1}{\rho_s} (\sigma_R T_c + q_{s,IR}) \quad (42)$$

2.4 Numerical solution of rill sediment transport model

The backward finite difference scheme is used for the numerical solution of Equation (42). Based on the previous definitions of h_i as flow depth at point i at current time, H_i as flow depth at point i at previous time in the hydrological component; and c_i as sediment concentration at point i at current time, and C_i as sediment concentration at point i at previous time,

$$((r-f)b + q_{IR} + \sigma_R Q)c_i + A \frac{c_i - C_i}{\Delta t} + Q \frac{c_i - c_{i-1}}{\Delta x} = \frac{1}{\rho_s} (\sigma_R T_c + q_{s,IR}) \quad (43)$$

is written as the numerical form of Equation (42).

Sediment concentration within flow in a rill can simply be calculated from the numerical solution of Equation (43) as

$$c_i = \frac{\lambda_3}{\lambda_4} \quad (44)$$

where

$$\lambda_3 = \frac{\sigma_R}{\rho_s} T_c + \frac{1}{\rho_s} q_{s,IR} + \frac{A}{\Delta t} C_i + \frac{Q}{\Delta x} c_{i-1} \quad (45a)$$

$$\lambda_4 = (r - f)b + q_{IR} + \sigma_R Q + \frac{A}{\Delta t} + \frac{Q}{\Delta x} \quad (45b)$$

3 Model Parameters

Parameters of the sediment transport model are listed in Table 1. They were calibrated by using experimental data of an indoor laboratory rainfall simulator with an erosion flume (Aksoy et al., 2012, 2013; Arguelles et al., 2013). In order for keeping the calibration simple, two of the parameters (β and ε) were fixed as frequently applied in the literature (Singh & Regl, 1983; Lopes & Lane, 1988; Laguna & Giraldez, 1993; Franchini, 1994; Govindaraju, 1995) while the other four; the rainfall erosion parameter (α), and the runoff erosion parameters (σ and η) over the interrill area and (σ_R) in the rill are adjusted. It should be noticed that additional parameters exist for the rainfall-runoff part of the model (Aksoy et al., 2016). Parameters existing in the literature are listed in Table 2 from which it is seen that they change within orders of magnitude. For example; $\sigma = 0.30 \text{ m}^{-1}$ in Singh and Regl (1983) while it is 10 m^{-1} in Govindaraju (1995). Tayfur (2001) followed Foster (1982) and proposed using the range of $3\text{-}33 \text{ m}^{-1}$ for this particular parameter.

Table 1. Model parameters

Parameter	Dimension [M ^x L ^y T ^z]	Definition	Remarks
α	$\text{ML}^{-(\beta+2)}\text{T}^{\beta+1}$	Erodibility factor of soil under rainfall effect	Dimension depends on β (ML^{-3} for $\beta = 1$)
β	-	Exponent	Fixed at $\beta = 1$
σ	L^{-1}	Erosion coefficient in interrill area	
σ_R	L^{-1}	Erosion coefficient in rill	
η	$\text{M}^{1-\varepsilon}\text{L}^{\varepsilon-1}\text{T}^{2\varepsilon+1}$	Detachability factor of soil under flow effect	Dimension depends on ε (T for $\varepsilon = 1$)

ε

-

Exponent

Fixed at $\varepsilon = 1$

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Table 2. Sediment transport model parameters existing in the literature

α (Dimension/unit changes with β)	β	σ (m^{-1})	σ_R (m^{-1})	η (Dimension/unit changes with ε)	ε	Reference
			3-33			Foster (1982)
	2	0.30	0.03		1.5	Singh & Regl (1983)
	2				1.5	Lopes & Lane (1988)
				0.001-0.5 $\text{kg}^{-1/2}\text{m}^{1/2}\text{s}^2$	1.5	Kavvas & Govindaraju (1992)
	1				1.5	Laguna & Giraldez (1993)
	2	0.10	0.01-1			Franchini (1994)
		10			1	Govindaraju (1995)
104-106 $\text{kgm}^{-4}\text{s}^{-1}$ (for $\beta = 2$)	1-2	0.36				Sharma (1998)
0.0006-0.0086 $\text{kgm}^{-2}\text{mm}^{-1}$ (for $\beta = 1$)	1-2	3-33				Tayfur (2001)
1 $\text{kgm}^{-4}\text{s}^{-1}$	2	1.3		0.06 s	1	Aksoy et al. (2003)

4 Experimental Setup and Measurements

The experimental setup is composed of an indoor laboratory rainfall simulator with an erosion flume (Figure 3). The erosion flume is 6.50 m-long, 1.36 m-wide, and 17 cm-deep. The flume has adjustable longitudinal and lateral slopes. It is filled with bare sand in advance before each experiment starts. In the first series of the experiments, the flume was filled with medium sand of median diameter $d_{50} = 0.45$ mm while the fine sand with median diameter $d_{50} = 0.15$ mm was used as the soil in the second series. Microtopography (the rilling) was considered in the experiments. Before the rainfall was applied in each experiment, the sand-filled flume was given an initial topography of a triangular cross-section rill, 2 cm-deep and 26 cm-wide, longitudinally pre-formed in the right-hand side of the flume (see the plan view of the erosion flume in the right panel of Figure 4). However, the effect of vegetation, macro pore, and small-scale heterogeneity in the soil is not considered in the experiments as the surface of the sand is kept bare.

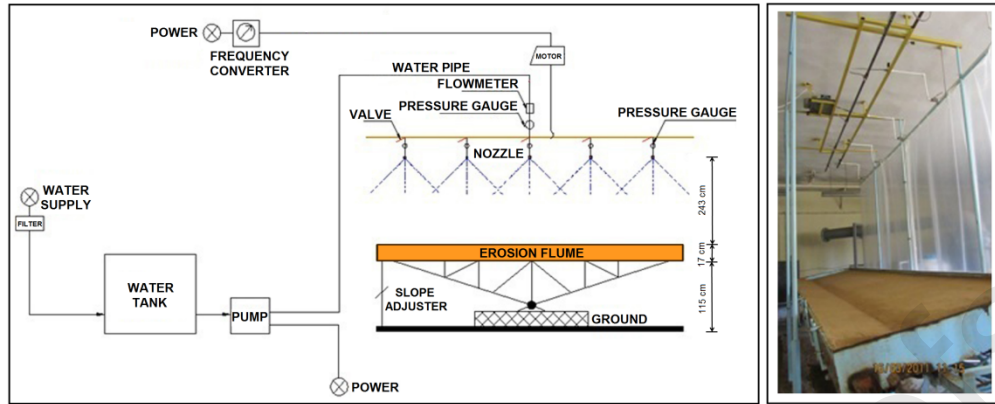


Figure 3. Sketch of the indoor laboratory rainfall simulator and erosion flume (Aksoy et al., 2012)

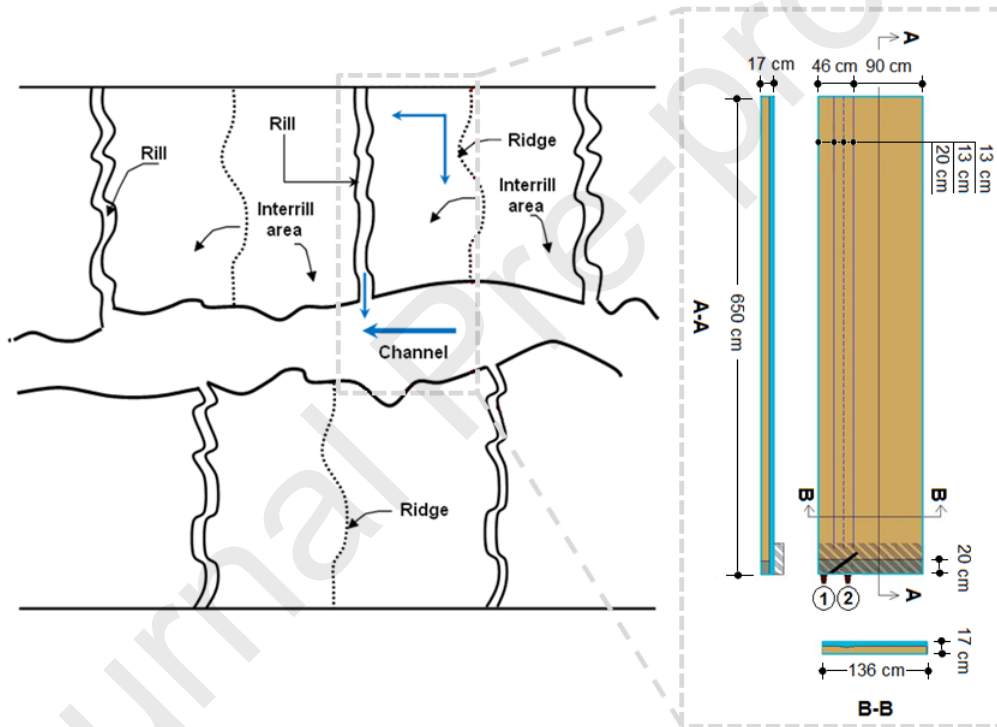


Figure 4. Schematic description of the microtopography in a watershed and plan view of the corresponding laboratory erosion flume (Aksoy et al., 2012)

The rainfall simulator is equipped with four or five VeeJet nozzles spaced at 125-145 cm, depending on the intensity of the simulated rainfall. In the experiments, four rainfall intensities (45, 65, 85, and 105 mmh^{-1}) were applied subsequently. Four VeeJet 8030 and 8050 nozzles spaced 125 cm-distance from each other were used for rainfall intensities of 45 and 65 mmh^{-1} ,

respectively, while the number of nozzles was increased to five VeeJet 8060 and 8070 with 100 cm-distance for 85 and 105 mmh⁻¹, respectively. Rainfall intensity was changed by using the proper number and size of VeeJet nozzles. For each rainfall intensity, 10 experiments were performed; 40 experiments in total, considering combinations of lateral and longitudinal slopes (5, 10, 15, 20%) conditional that longitudinal slope of the flume is not milder than its lateral slope for which 10 combinations exist. When the 10 combinations of the longitudinal and lateral slopes were completed under four rainfall intensities, a new series of experiments was performed by filling the erosion flume with another type of soil and performing experiments for the 10 combinations of longitudinal and lateral slopes under four rainfall intensities.

In each experiment, a while after the rainfall was applied, soil was saturated and surface flow was observed in the rill. Flow was not measured until surface flow reached the outlet of the flume after which rainfall was applied for 15 minutes. Flow was measured from the flume by means of measurement cups every 1 minute or at as short time intervals as 10-15 seconds depending on how fast the cups were filled. Measurements continue to be taken for 10 more minutes after the rainfall ended, the total time period for the measurement in each experiment was set at 25 minutes. Then the ascension curve, the steady-state period when it exists, and the recession curve of hydrographs were constructed from the observations of the total volume collected at the two outlets of the flume.

More details on the experimental setup including the rainfall simulator, observations, measurements, and the use of experimental data can be obtained from a series of publications by Aksoy et al. (2012, 2013, 2016), Arguelles et al. (2013, 2014) and Mallari et al. (2015a, b).

5 Model Calibration

Model parameters were calibrated by the least square method to minimize the difference between the observed and calculated sediment discharges. Using m data pairs of $(x_1, y_1), (x_2, y_2), \dots, (x_m, y_m)$ from the experiments,

$$y = f(x, \beta) \quad (46)$$

can be written in which y is the model output as a function of x , the model input, and $\beta = (\beta_1, \beta_2, \dots, \beta_n)$, the parameter vector, where $m \geq n$. Residual (error) between the observation and the model is calculated by

$$r_i = y_i - f(x_i, \beta), \quad i = 1, 2, \dots, m \quad (47)$$

The summation of the squared residuals is a vector computed as

$$S = \sum_{i=1}^m r_i^2, \quad i = 1, 2, \dots, m \quad (48)$$

It is minimized for the best approximation of the model to the observation. Minimization is satisfied when the derivative of S with respect to each independent variable is zero:

$$\frac{\partial S}{\partial \beta_j} = 2 \sum_i r_i \frac{\partial r_i}{\partial \beta_j} = 0, \quad j = 1, \dots, n \quad (49)$$

Derivatives in Equation (49) are functions of both independent variables and the parameters. Therefore, an explicit solution is not achieved; instead, as an iterative solution

$$\beta_j \approx \beta_j^{k+1} = \beta_j^k + \Delta \beta_j \quad (50)$$

is proposed by selecting initial values, in which k is the iteration number, and $\Delta\beta$ is the numerical step selected for the parameter vector.

Using the above methodology, model calibration was carried out in two steps: First; 32 sedigraphs out of 40 were used for the calibration; that is, a single set of calibrated parameters was determined for each sedigraph. From the calibrated parameters a new single set was obtained as the representative set of all sedigraphs. This was performed by simply taking the average of two of the parameters and linking the other two to the rainfall intensity and resulting slope by a multiple linear regression optimized with genetic algorithm. While performing the calibration, not only the total mass of sediment was conserved but also the time-varying structure of the sedigraph was taken into consideration. That is, the ascension and recession curves of the sedigraphs were paid particular attention. Each of 32 sedigraphs was fitted by the calibrated parameters listed in Table 3. It is seen from Table 3 that the calibrated model parameters vary within wide ranges as the parameters existing in the literature listed in Table 2 change within orders of magnitude. Therefore, the calibrated parameters in Table 3 were considered consistent with the parameters existing in the literature.

Figure 5 provides fitted simulations of sedigraphs at the calibration stage together with the corresponding hydrographs of the rainfall-runoff model. Although sedigraphs are not as perfect as the hydrographs, they are considerably well. However, in some cases, significant discrepancies are observed between the experimental data and the fitted model. The calibration can be considered satisfactory particularly when compared to the calibration studies reported in the literature such as SHESED (Wicks, 1988; Wicks et al., 1992; Bathurst et al., 1995), MULTSED (Wicks et al., 1988), and WESP (Lopes, 1987; Lopes & Lane, 1988).

Table 3. Calibrated parameters of the sediment transport model

r (mm h ⁻¹)	S_y (%)	S_x (%)	S (%)	α (kg m ⁻³)	σ (m ⁻¹)	σ_R (m ⁻¹)	η (s)
45	5	5	7.07	16.0	2.88	3.51	0.190
45	5	10	11.18	16.0	3.50	3.72	0.200
45	5	20	20.62	35.0	3.99	4.44	0.234
45	10	10	14.14	17.0	3.31	3.62	0.210
45	10	15	18.03	21.0	3.80	4.25	0.220
45	15	15	21.21	28.0	4.04	4.20	0.220
45	15	20	25.00	60.0	5.00	4.62	0.160
45	20	20	28.28	53.0	8.92	9.52	0.261
65	5	5	7.07	16.0	3.13	4.11	0.192
65	5	10	11.18	17.0	4.29	4.25	0.200
65	5	20	20.62	38.0	0.30	7.90	0.220
65	10	10	14.14	9.0	8.59	4.29	0.207
65	10	15	18.03	13.0	0.40	5.20	0.220
65	15	15	21.21	72.0	0.07	0.28	0.222
65	15	20	25.00	81.0	3.32	15.54	0.230
65	20	20	28.28	84.0	3.47	13.60	0.240
85	5	5	7.07	32.0	3.00	3.60	0.193
85	5	10	11.18	42.0	4.55	3.17	0.197
85	5	20	20.62	78.0	3.20	3.70	0.225
85	10	10	14.14	37.0	0.15	3.46	0.210
85	10	15	18.03	40.0	0.10	2.80	0.220
85	15	15	21.21	47.0	0.01	9.00	0.230
85	15	20	25.00	117.0	0.11	8.43	0.240
85	20	20	28.28	114.0	0.07	9.87	0.250
105	5	5	7.07	5.0	2.91	3.67	0.190
105	5	10	11.18	45.0	0.04	0.17	0.210
105	5	20	20.62	56.0	0.01	0.98	0.240
105	10	10	14.14	48.0	0.05	0.22	0.220
105	10	15	18.03	58.0	0.06	0.10	0.230
105	15	15	21.21	73.0	2.54	14.70	0.250
105	15	20	25.00	157.0	11.20	1.72	0.260
105	20	20	28.28	172.0	10.00	1.30	0.270

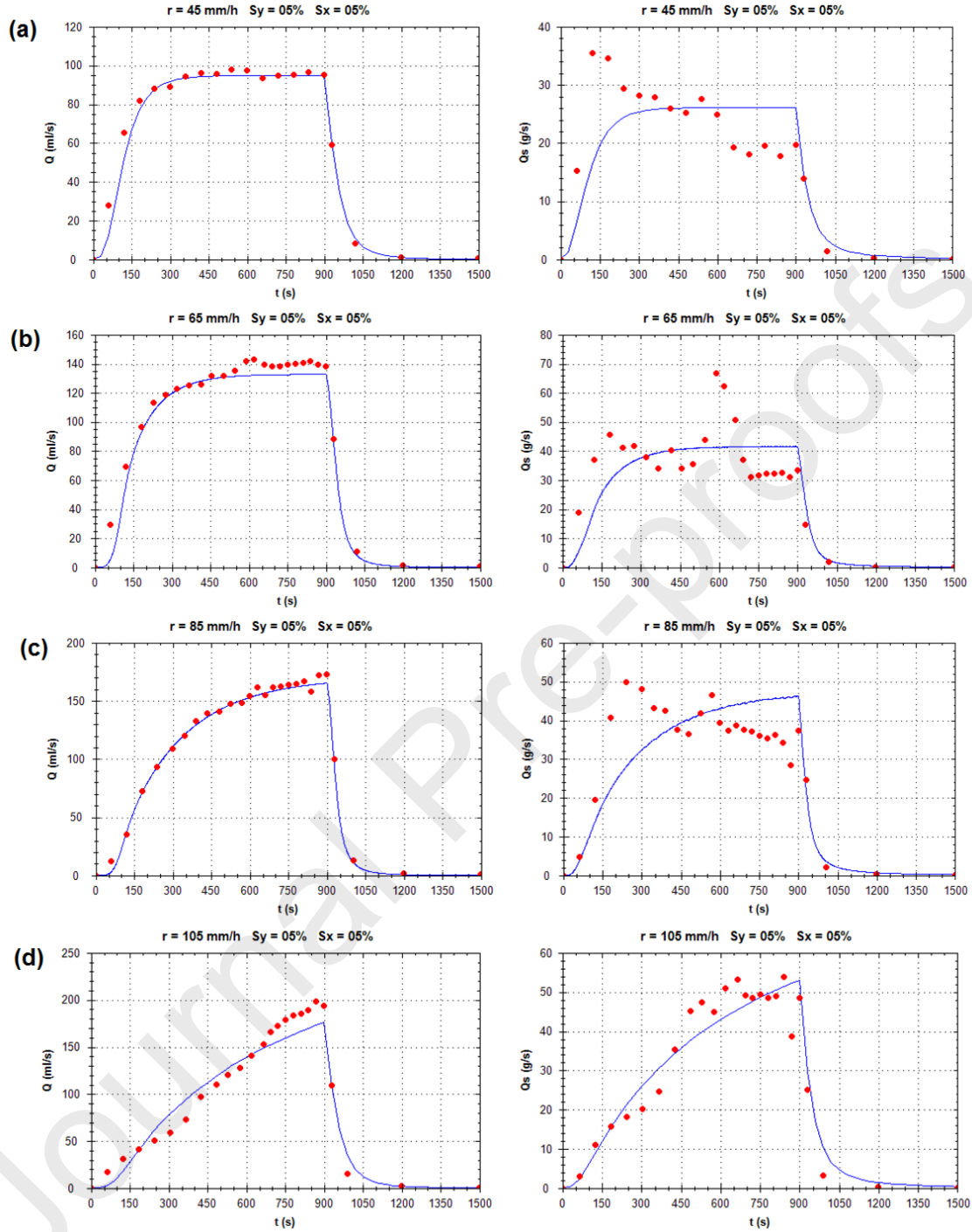


Figure 5. Calibrated hydrographs (left panel) and sedigraphs (right panel) against the measured counterparts for (a) $r = 45 \text{ mmh}^{-1}$, $S_y = 5\%$, $S_x = 5\%$; (b) $r = 65 \text{ mmh}^{-1}$, $S_y = 5\%$, $S_x = 5\%$; (c) $r = 85 \text{ mmh}^{-1}$, $S_y = 5\%$, $S_x = 5\%$; (d) $r = 105 \text{ mmh}^{-1}$, $S_y = 5\%$, $S_x = 5\%$ (Parameters used for each experiment are as in Table 3)

6 Model Validation

As pointed out above and seen in Table 3, calibrated parameters vary within wide ranges. However, a proper calibration should provide one single set of representative parameters for all experimental runs. It is hard to calibrate and then validate models with high number of parameters. Therefore, in this study, following the literature (Meyer, 1971; Foster et al., 1977; Foster, 1982; Sharma et al., 1993; Tayfur, 2001), two parameters were taken constant at unity ($\beta = 1$ and $\varepsilon = 1$) to make the model as parsimonious as possible. Another two parameters (σ and σ_R) were calibrated for each of the experimental data set after which their averages were taken for the validation stage; they were fixed at the average values of 3.03 m^{-1} and 5.00 m^{-1} , respectively, obtained from the calibration set of experimental data (Table 3). Finally, another two parameters (α and η) were linked to the rainfall intensity and slope with the multi-variable linear regression by the use of genetic algorithm, a nonlinear search and optimization technique (Goldberg, 1989; Tayfur, 2012) for which 100 chromosomes and 3000 iterations were performed in this study. The parameters, α and η , were expressed as linear regression functions of rainfall intensity and slope as

$$\alpha = 0.6471 r + 3.7692 S - 65.92 \quad (51)$$

$$\eta = 0.000098 r + 0.002872 S + 0.16222 \quad (52)$$

Table 4. Experimental characteristics and parameters used for the validation of the model

R (mm h ⁻¹)	S_y (%)	S_x (%)	S (%)	α (kg m ⁻³)	σ (m ⁻¹)	σ_R (m ⁻¹)	η (s)
45	5	15	15.81	18.6	3.03	5.00	0.206
45	10	20	22.36	47.3	3.03	5.00	0.223
65	5	15	15.81	34.6	3.03	5.00	0.214
65	10	20	22.36	63.3	3.03	5.00	0.231
85	5	15	15.81	50.6	3.03	5.00	0.222
85	10	20	22.36	79.3	3.03	5.00	0.239
105	5	15	15.81	66.6	3.03	5.00	0.230
105	10	20	22.36	95.3	3.03	5.00	0.247

Validated sedigraphs are given in Figure 6 together with their corresponding hydrographs. It is seen from Figure 6 that the model has a relatively satisfactory performance. In the ascension curve as well as during the steady-state part of the sedigraph (when exists), flow is not under stable conditions which allow sediment to fluctuate randomly in a wide range with a general trace followed. Sediment concentration within flow is less predictive than the flow discharge because of this fluctuating behaviour. Compared to the rainfall erosion, runoff erosion is more dominant, therefore it provides substantial volume of sediment for transport within flow. This is why sediment concentration shows sudden increases as pulses when runoff erosion starts by the end of the ascension curve or at the beginning of or during the steady-state part of the sedigraph.

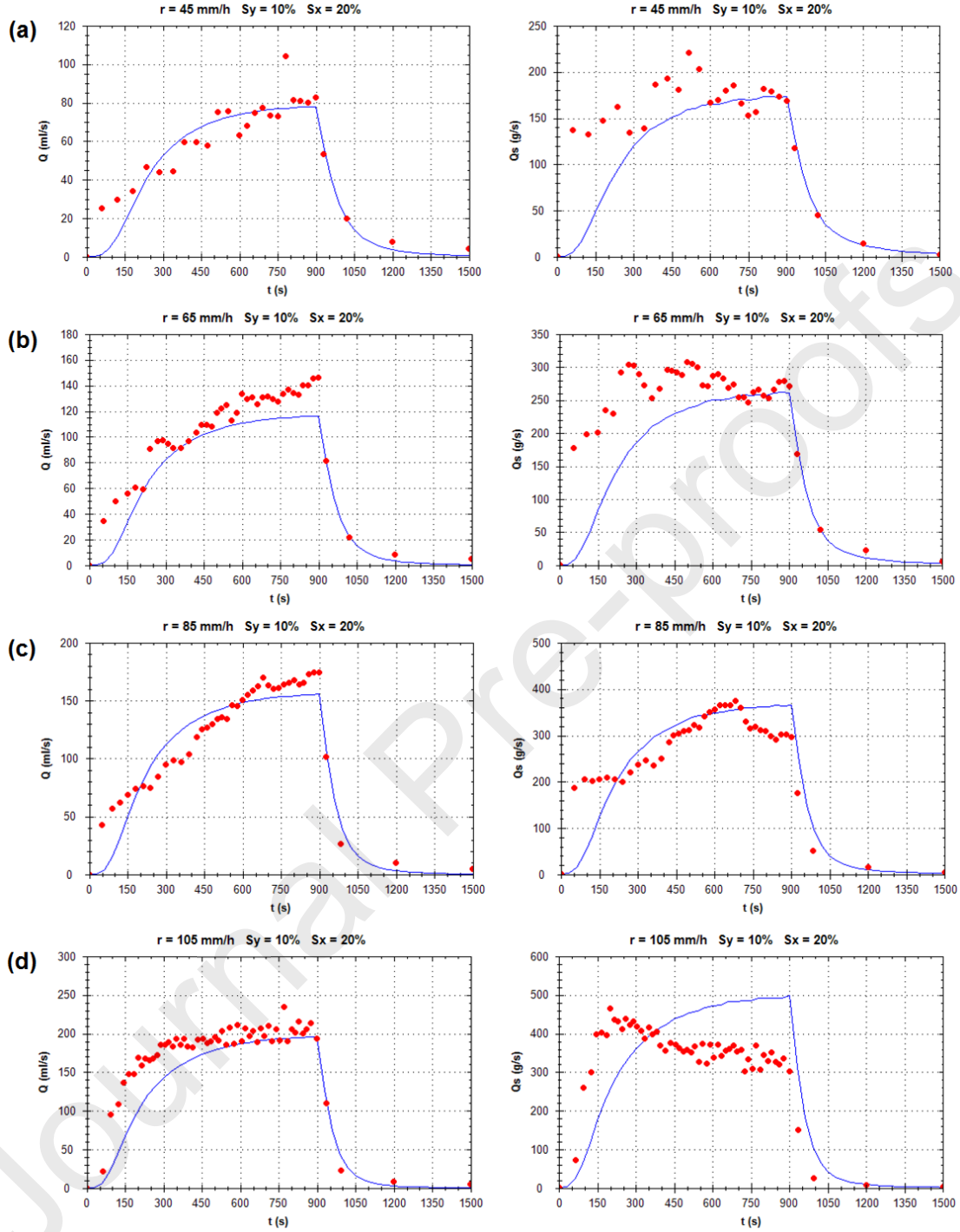


Figure 6. Validated hydrographs (left panel) and sedigraphs (right panel) against the measured counterparts for (a) $r = 45 \text{ mmh}^{-1}$, $S_y = 10\%$, $S_x = 20\%$; (b) $r = 65 \text{ mmh}^{-1}$, $S_y = 10\%$, $S_x = 20\%$; (c) $r = 85 \text{ mmh}^{-1}$, $S_y = 10\%$, $S_x = 20\%$; (d) $r = 105 \text{ mmh}^{-1}$, $S_y = 10\%$, $S_x = 20\%$ (Parameters used for each experiment are as in Table 4)

Sediment is detached from its original place only when some prerequisite conditions are satisfied. It happens, for example, after sediment becomes saturated such that the resistance of sediment is overcome by the weight of the saturated sediment. Under the limit conditions of saturation, rainfall or runoff processes may trigger sediment to be transported in bulk volumes within flow. This creates a sudden increase in the concentration to be noticed as a pulse in the sedigraph when the sediment is measured at the outlet of the erosion flume. Therefore, measured sedigraphs fluctuate around a general behaviour of the sedigraph with ascension and recession curves between which a steady-state part may be recorded. The performance of the model is satisfactory as the model aims to replicate the general behavior of the process rather than capturing all measured points. However, it is quite noticeable that the measured recession curves of all runs are closely followed by the model. The reason for this could be the post-rainfall flow during recession within which sediment particles in motion are deposited as the rainfall ceases. This shows the performance of the model in tracing the measured sediment discharge. When the validation is evaluated under the light of this discussion, it may be stated that the performance of the model is satisfactory. If the discussion is extended to the rainfall-runoff module to which the sediment module is coupled, it should be stated that the model is calibrated first in terms of its rainfall-runoff component to preserve the hydrograph, then in terms of sediment component to preserve the sedigraph. Hydrographs are much better preserved (Aksoy et al., 2016) because of the above explained less fluctuating behaviour of flow, and more fluctuating behaviour of sediment concentration. Similar to the technique applied in the hydrological part (Aksoy et al., 2016), model parameters are either fixed at their average or are regressed on rainfall intensity and slope. With this practice, the model becomes parsimonious.

7 Conclusions

A two-dimensional deterministic unsteady process-based mathematical model is developed for the simulation of the rainfall- and runoff-induced erosion and sediment transport generated in rills and on interrill areas over a hillslope. The model is calibrated and validated using a comprehensive dataset gathered from an indoor rainfall simulator and erosion flume where one can set specified lateral and longitudinal slopes changing from 5% to 20%. The flume is exposed to rainfall simulated at intensities between 45 mmh⁻¹ and 105 mmh⁻¹. The number of erosion-linked parameters is kept at minimum (six in total) for the sake of a parsimonious model. Two dimensionless exponent-form parameters are fixed at unity as frequently applied in the literature. Two erosion coefficients, one applied in the rill and another in the interrill areas, are averaged over the calibration dataset; while another two, the erodibility factor of the soil under rainfall and the detachability factor of the soil under flow, were regressed on rainfall intensity and topographical slope by the genetic algorithm. The proposed model is considered novel because (i) microtopography is introduced in the rainfall-runoff-erosion and sediment transport mechanisms over a hillslope, (ii) the longitudinal and the lateral topographical slopes are used in the model development, (iii) two out of four calibration parameters in the sediment transport model are set at constant values while another two are adjusted using equations regressed on rainfall intensity and slope. Validated sedigraphs show that the erosion and sediment transport model is capable of simulating the total sediment outflow of interrill areas and rills over hillslopes. The model is potentially useful in the prediction of hillslope-scale sediment transport process and can be taken as a well-established background for a possible watershed-scale erosion and sediment transport model.

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Highlights

- A strong need exists for the prediction of sediment transport to provide measures for erosion control and water quality management.
- Rainfall simulators equipped with erosion flume are important tools for the calibration and validation of models.
- Rilling should be considered as it highly influences runoff generation and erosion processes over hillslopes.