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Raindrop-Induced Erosion and Sediment Transport Modelling in Shallow Waters: A Review

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Abstract

The rainfall-runoff events and erosion process usually begins with raindrop impact on bare or nearly bare soils with the resulting splash causing the soil particles to become detached and subsequently, overland flow transports these particles towards down slope. During the past decades, the understanding of soil splash mechanisms by raindrops and their erosivity have been actively investigated. Many significant studies and models are performed to investigate the process of raindrop-induced erosion and sediment transport in shallow waters which differ in terms of their effecting factors. This paper attempts to review the physically-based models related to the raindrop-induced process of soil particles detachment and suspended sediments transport in overland flow is pursued in detail. This review is expected to be of interest to researchers and soil and water conservation managers who are working on erosion and sediment transport phenomena in shallow waters.

Keywords

Shallow water, Raindrop impact, Erosion and sediment transport models, Physically-based models

Introduction

Soil erosion and its degradation effects on productivity of land, and water quality of rivers and other valuable water resources, such as estuaries and lakes, is one of the major concerns of watershed managers and decision makers. Erosion is a process of detachment and transportation of soil materials by erosive agents from any part of the earth's surface [1]. Affecting factors on water erosion comprises climate, topography, soil structure, vegetation and anthropogenic activities such as tillage systems and soil conservation measures [2]. Sheet and interrill erosion is considered one of the first steps of erosion in catchments which is widely observed on bare or almost bare soils on agricultural lands, pasturage, and open areas. In this type of erosion, the process begins by hitting the soil surface by rain drops, and their effect on detaching the soil structure is an important factor in particulate matter transport. Particularly in very shallow water, raindrops can provide temporary disturbances to cause static particles to move. Subsequently, the overland flow transports the sediment in a down slope direction. Generally, all particles that are detached are not transported out of the eroding area. Three types of transportation are taking place on sheet erosion; Raindrops splash, overland flow action, and the combination of overland flow and rainfall impact [3].

Due to increasing use of computer applications and computing powers in the recent decades, the exploration of soil erosion and sediment transport through the development of computer models had been rapidly increased. The key objective of this paper is to provide a source that addresses the physically-based models re-

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lated to the raindrop-induced processes of soil particles detachment and suspended sediments transport in overland flow. The review is expected to be of interest to researchers, decision-makers and water quality managers who are concerned with erosion and sediment transport phenomena in shallow waters. This paper will conclude with the major issues of introduced erosion and sediment transport models, including discussions on models complexity and accuracy, data availability and models uncertainties. This review is prepared to provide an overview of the wide range of issues related to the erosion and sediment transport processes in shallow waters. For a detailed analysis of these components the reader is required to refer to the appropriate references throughout this text prior to modelling.

Raindrop-Induced Erosion

Soil particle detachment by raindrop impact

The rainfall-runoff events and erosion process usually begins with raindrop impact on bare or nearly bare soils with the resulting splash causing the soil particles to become detached and subsequently, overland flow transports these particles towards down slope [4]. Indeed, erosion cannot occur unless first detachment of soil matrix occurs, and raindrops can provide a temporary disturbance to cause static particles to move. Various factors such as rainfall intensity, infiltration, runoff rates, soil properties and antecedent soil moisture content, roughness, slope length and steepness are important in the process of the soil detachment [5]. During the past decades, the understanding of soil splash mechanisms by raindrops and their erosivity have been actively investigated. Worthington [6], at the end of 19th century, was the first researcher who was primarily involved with the mechanism of surface tension and the splash by raindrop impact and systematically studied the deformation of a water surface hit by a raindrop. His monograph was posthumously republished decades later in 1963. Building on this research, other investigators [7-11] used photographs to correlate various aspects of drop morphology, such as crown droplet formation, crater shape, and maximum crater size and height of the recoil jet, with initial conditions such as drop size, raindrop velocity and water depth. Laws and Parsons [12] empirically showed that the raindrop momentum is correlated with rainfall intensity.

Smith and Wischmeier [13] were among the first researchers who noted that sheet flow and uniform erosion occurred only where the effects of rainfall impact were dominant over those of overland flow. Their groundbreaking research leaded to the development of the Universal Soil Loss Equation in 1960. Empirical models, like the universal soil loss equation (USLE) developed by Wischmeier and Smith [14], predict sheet erosion in areas where these forms occur. USLE measures the raindrop momentum or kinetic energy (KE) as the product of the total storm energy (E) multiplied by the maximum 30 min intensity which is a function of rainfall intensity (I). Kinetic energy of a rainstorm is proportional to rainfall intensity, drop sizes, velocity of drops at the moment of impact with the soil surface, and angle of incidence. Since measurement of these values is not possible for a natural rainfall, typically only two parameters, rainfall duration and intensity, are considered to calculate the rate of soil loss. Rose [15,16] assumed that the rate of rainfall detachment per unit area is non-selective for each size class and represented an equation for rainfall detachment. Young and Wiersma [17] observed that reducing the raindrop impact energy by 89% decreased soil loss by over 90%, indicating that soil detachment was primarily caused by the impacting raindrops. Ghadiri and Payne [18,19] studied the induced stress by raindrop impact and concluded that the erosive capability of a raindrop is related to the product of its diameter and the square root of its velocity.

Following these studies, Moss, et al. [3] explained the role of rain-flow transportation of particulate matters. They stated that raindrops on shallow water induce particle suspension in a manner similar to turbulence in deeper water. Poesen and Savat [20] using an experimental setup, studied the detachment and transportation of nine loose sediments by raindrop splash as a time-dependent phenomenon. They concluded that fine sandy sediments have the lowest resistance to raindrops. They also noted that the transportability of studied sediment was negatively related to grain size. Rose, et al. [21] studied the detachment of sediment by raindrop and sediment transport by overland flow on a uniform slope and in the absence of rills. In this study, soil detachment by raindrop impact was assumed to be proportional to the intensity of rainfall. Moss and Green [22] pointed out that the role of rain-flow in sediment transport by overland flow in shallow waters, where detachment of soil is augmented by rain drop impact. In laboratory studies, they added that the rain-flow reaches a maximum transport rate when the water depth is 2-3 times the diameter of the drops of water.

Nearing, et al. [23] measured the force vs. time for raindrop impact and revealed a relationship between them and Epema and Riezebos [24] also introduced the fall velocity of water at different heights as a factor influencing erosivity by simulating rain. Deletic, et al. [25] addressed a wash-off model that identified both threshold shear stress and rainfall effects. They also combined shear and rainfall effects on erosion as additive processes in their model, and achieved a reasonable fit to catchment-scale data with calibration coefficients. Sharma, et al. [26-28] represented the soil detachment by raindrops and sediment transport processes into the basic interrill erosion model by incorporating the intensity and kinetic energy of rainfall. Hairsine and Rose [29] developed an important equation to describe the rainfall detachment in the absence of overland flow. In their equation, the rate of raindrop detachment was dependent on rainfall intensity. They also found out that the subsequent deposited layer shields a portion of the surface from the action of raindrops. Govers, et al. [30] used a relationship between kinematic energy and raindrop circumference to predict the rate of soil detachment due to rain splash. This relationship gave the best statistical fit to splash detachment data sourced from the literature by Gilley and Finkner [31]. Proffitt, et al. [32] and Sander, et al. [33] both found out that when the overland flow depth is around three times greater than the raindrop diameter, rainfall detachability of both the original soil and the deposited shield layer decreases considerably. Under these conditions, raindrop splash affects the short-time behavior much more than the long-time behavior. Misra and Rose [34] modeled rainfall detachability and re-detachability with different soil erodibility parameters and reported that values of re-detachability were approximately 1000 times greater than values of detachability. This indicates that the pre-detached material can be eroded easier than uneroded surfaces. They also pointed out that both detachability and re-detachability increased as steepness increased. Morgan, et al. [35] found out that when splash erosion during a rainstorm takes place, the initial sediment concentration in the resulting runoff cannot be taken as zero.

Bertuzzi, et al., Cogo, et al., Darboux and Huang, Deletic, Farres, Gómez and Nearing, Helming, et al., Johnson, et al., Le Bissonnais, et al., Moldenhauer and Kemper, van Wesemael, et al., [36-46] have indicated that surface roughness increases the resistance of soil to detachment by raindrop impact. Hairsine, et al., Huang, Bradford and Onstad [47-49] in their studies concluded that surface roughness also increases the surface storage capacity of rain and reduces the flow velocity and thus, the erosive power of runoff. van Dijk, et al. and Leguédois, et al. [50,51] in their studies focused on the splash-induced distribution of various soil size particles and found that the average splash distance was in the range of 4 to 23 cm and was independent of the soil type. In addition, they found that the greatest splash-induced displacements were in mid-size fractions (100-200 lm). Kinnell [52] reviewed the previous research in the field of raindrop-impact-induced erosion (RIIE) processes. He introduced four different transport processes for generated detached soil particles, and described some mathematical equations as a result of his investigations. Kinnell [53] pointed out that in rain impacted flows; The dissipation of raindrop kinetic energy has an effect on the detachment and transport processes. By increasing the flow depth, the dissipation of raindrop energy increases which can lead to a decrease in sediment concentration. Shaw, et al. [54] found that the rate of particles ejection due to raindrop impact was proportional to rain intensity and the spatial density of particles on the surface. They also determined that the ejection rate was proportional to spatial density for low particle spatial densities, but independent of spatial density for high spatial densities. Deng, et al. [55] developed a one-dimensional mathematical model, termed sediment transport rate-based model, to determine the rainfall-induced soil erosion and sediment transport. They approximated the rate of soil erosion caused by raindrop impact or rain splash based on the detachment equation for rainfall adopted in EUROSEM.

The presence of rock fragments on the soil surface reduces the cross-sectional area available for overland flow; Thus, in circumstances of uniform rainfall, the addition of rock fragments leads to an increase in overland flow depth [56].

Other researchers [57-70] reported the effects of rock fragments existence in the soil surface and determined that rock fragments can preserve the original soil structure by absorbing and dissipating the kinetic energy of raindrops, resulting in the reduction of soil detachment due to raindrop splash. This also results in the increased depth of water on the soil surface and increases the infiltration rate, which leads to soil erosion reduction [18,71-74]. The more commonly used algorithms describing the soil detachment by raindrop impact are summarized in Table 1.

Soil particle detachment by shallow overland flow

Overland flow can also play an important role as an erosive agent in soil particle detachment, depending on certain characteristics of soils, such as cohesion and inter-particle friction forces. The influence of overland flow on the sediment detachment rate is extensively reported by many researchers in both laboratory and field experiments, and in different environmental conditions. Different hydraulic parameters such as flow depth, flow regime, discharge, velocity, slope gradient, sediment concentration and friction force have been considered in their studies [75-96]. Hydrodynamic lift and drag forces of overland flow can detach and transport soil particles. When the tractive force or shear stress of steady flowing water is equal to or greater than the gravitational force and the critical shear stress in the flow direction, drag force power of flow can detach the soil particles and entrain them to a particular distance depending on their

Table 1: Commonly used algorithms describing the soil detachment by raindrop impact.

Source	Algorithm	Parameters
[15,16]	$e_i = a.P/I$	e_i = Rainfall detachment rate, a = Rainfall detachability, P = Rainfall intensity, I = Number of sediment settling velocity classes.
[29]	$E_I = \alpha.r^{\beta}$	E_I = Rainfall detachment, r = Rainfall intensity, α = Soil detachability, β = An exponent.
[29]	$e_i = a.P/I\ [I - H(x, t)]$	e_i = Rainfall detachment rate, a = Rainfall detachability, P = Rainfall intensity, I = Number of sediment settling velocity classes, H = Shield layer.
[29]	$e_{di} = a_d P\ (M_{di}/M_{dт})H$	e_{di} = Re-detachment of deposited particles, a_d = Detachability of the deposited layer, P = Rainfall intensity, M_{di} = The mass per unit area of the sediment of class i in the deposited layer, $M_{dт}$ = The total mass of the sediment in the layer, H = Shield layer.
[118]	$e = a.p.M_g$	a = Detachability constant, P = Rainfall intensity, M_g = Particle mass on the surface.
[55]	$e_r = c_0\ (I^2/W_s)\ exp(-\eta h)$	e_r = Ejected particles by rain splash, c_0 = Maximum sediment concentration generated by the raindrop impact in the overlying water, I = Rainfall intensity, W_s = Settling velocity of sediment particles, η = The damping rate of the water depth, h = Water depth.
[131]	$SS = 7.50\ i^{0.41}\ e_k^{\ 1.14}\ c^{\ -0.52}$	SS = Soil splash, e_k = kinetic energy, i = Rainfall intensity, c = Clay percent.
[33]	$a = c_e(40)/C(40P/D)$	a = Rainfall detachment rate, $c_e(40)$ = Experimental sediment concentration at t = 40, C = Theoretical sediment concentration, P = Rainfall intensity, D = Flow depth.
[132]	$E_I = \alpha r^2$	E_I = Detachment by raindrop impact, α = A coefficient to be calibrated, r = Uniform rainfall intensity.
[31]	$D_{k(c)} = K_{k(c)}\ .\ R_{k(c)}$ $R_{k(c)} = 1.030\ \rho\ cos^2\ \theta\ \Sigma\ a_i\ d_i^4\ V_i^2$	$D_{k(c)}$ = Soil detachment by raindrops, $R_{k(c)}$ = Kinematic energy times unit of drop circumference, ρ = Density of water, θ = Surface slope, a_i = Number of drops in the class i, d_i = Mean drop diameter in class i, V_i = Velocity of drops with diameter d_i.
[133]	$D_s = K_d KE^b$	D_s = Rate of soil detached by raindrop impact, K_d = Soil-dependent detachability coefficient, KE = Kinetic energy of the rain, b = Dimensionless exponent varying between 0.9 for sandy soils and 1.8 for clays.
[134]	$D_s = K_I I^c$	D_s = Splash detachment, K_I = Detachability of soil, I = Rain intensity, c = An exponent that takes values in the range 1.1 [13] to 2 [134].
[135]	$D_s = K_M M^d$	D_s = Rate of soil detachment per unit area, K_M = Detachability of soil, M = Momentum, d = An exponent that takes values in the range 1.0 [15] to 2 [136].
[137]	$D_i = K_i I^2$	D_i = Interrill detachment rate, K_i = Interrill erodibility constant, I = Rain intensity.
[27]	$D_r = K_d I(E - E_0)$	D_r = Rainfall detachment rate, K_d = Detachability of rain, I = Rainfall intensity, E = Unit kinetic energy of rainstorm, E_0 = Unit threshold kinetic energy needed to initiate soil detachment.

size and settling velocity. Concepts developed by Foster and Meyer [80] are the basis of most of the existing models involved with the estimation of sediment detachment rate of overland flows. Based on their study, the detachment rate of overland flow is calculated by the difference of the sediment transport capacity and actual sediment load. Sediment transport capacity and hence, the detachment rate of overland flow at the upstream is greater, as the entering water is more clear, and decreases with distance towards down slope. Truman, et al. [97] also noted that rainfall detachment decreases when initial water content increases. Lei, et al. and Merten, et al. [98,99] pointed out that the required flow energy to detach soil particles decreases with the increase of sediment concentration. Therefore, it can be concluded that the deposition rate increases towards down slope and after traversing a specified distance, equilibrium is attained between sediment detachment and deposition.

Resistance of the top soils to erodibility controls the overland flow erosion process [100], which is mainly related to soil properties and the percentage of protected area by vegetation. As previously mentioned, soil detachability depends on several soil characteristics, such as aggregate stability, cohesion, clay content, organic matter content, infiltration rate, antecedent soil moisture content, and other physicochemical properties of soils. Therefore, changes in soil properties, due to tillage and agricultural activities or other natural and manmade disturbances, will have a direct effect on soil detachment by overland flow [35,101-108]. Detachment and deposition processes usually occur simultaneously and as it is difficult to differentiate these two, deposition may cause serious errors during experimental studies [109-111]. This can be eradicated by using a long enough flume during experimentation; this results in obtaining a constant sediment load which enables the transport capacity to be dominant. In situations that no deposition and sediment load occur, the overall process would be essentially dominated by flow detachment [112]. Different algorithms have been developed by researchers where various parameters, like flow rate, soil erodibility, slope, flow velocity, shear stress, stream power, rainfall intensity and land cover have been considered in their studies. The more well-known algorithms describing the soil detachment by shallow overland flow are summarized in Table 2.

Table 2, commonly used algorithms describing the soil detachment by shallow overland flow.

Table 2: Commonly used algorithms describing the soil detachment by shallow overland flow.

Source	Algorithm	Parameters
[138]	$D_i = K_i i^2$	D_i = Interrill detachment rate, K_i = Interrill erodibility factor, i = Rainfall intensity.
[139]	$D_f = D_c[1-(G/T_c)]$ $D_c = K_r.(\tau_f - \tau_{cr})$	D_f = The net detachment rate by flowing water, D_c = The detachment capacity of the flow, G = The percentage of sediment load into the passing flow, T_c = The transport capacity of flow, τ_f = Flow shear stress, τ_{cr} = Critical shear strength, and K_r = A constant.
[140]	$D_i = K_i.I^2.S_f$	D_i = Interrill detachment rate, K_i = Interrill soil erodibility factor, I = Rainfall intensity, and S_f = Soil slope factor.
[140]	$D_{f,i} = K_i\, I_e\, Q_i\, C_c\, C_g\, C_s\, (R_s/w)\, SDR$	$D_{f,i}$ = Interrill detachment rate, K_i = Interrill erodibility, I_e = Effective rainfall intensity, Q_i = Interrill runoff rate, C_c = Canopy cover, C_g = Ground cover, C_s = Interrill slope adjustment factor, R_s = Spacing of rills, w = Width of rills, and SDR = Sediment delivery ratio.
[141]	$D_c = 130.41q^{0.89}S^{1.02}$ $D_c = 0.344V^{3.18}$ $D_c = 0.0017\,\tau^{1.53}$ $D_c = 0.0088\omega^{1.07}$	D_c = Detachment rate, q = Flow rate, and S = The tangent value of slope degree, V = Mean flow velocity, τ = Shear stress, and ω = The stream power.
[142]	$D_i = K_i\, I\, q$	D_i = The interrill detachment rate, K_i = The interrill erodibility coefficient, I = The rainfall intensity, and q = The interrill runoff rate.
[143]	$e = K.C.P.h^{0.5}.S^{1.5}$	e = Detachment by shallow surface flow, K = Linear coefficient between h and S, and average mass of soil detached per failure event (M), P = Probability that the shear stress of the burst-event exceeds the local resistance to detachment and induces tensile failure, C = Chezy coefficient, h = Flow depth, S = Bed slope.

Shallow overland flow and sediment transport equations

Since shallow overland flow involves the transport of suspended sediment, development of erosion and sediment transport equations in shallow waters first begins with determination and development of appropriate shallow flow equations. The governing equation is obtained from the conservation of both mass and momentum.

Shallow water equations

The kinematic-wave approximation of the shallow-water equation (also called Saint Venant equations in its one-dimensional form) is the most widely used equation in the physically-based approach of modelling to describe the mass balance equation of overland flow along a uniform slope [54,62,84,113-122]. This equation expresses the laws of conservation of mass and momentum of the water flowing longitudinally and infiltrating vertically [123,124] and is published as:

$$\frac{\partial h}{\partial t} + \frac{\partial (q)}{\partial x} = f(t) - i(x, t) \tag{1}$$

$$\frac{\partial h}{\partial t} + \frac{\partial (vh)}{\partial x} = f(t) - i(x, t) \tag{2}$$

where h is the overland flow depth (L), t is time (T), v is the flow velocity ($L.T^{-1}$), x is the axis along the slope and flow direction (L), $f(t)$ stands for the rainfall intensity ($L.T^{-1}$), and $i\ (x, t)$ is the infiltration rate of soil ($L.T^{-1}$). The flow velocity (u), and q is unit flow discharge in slope direction (L^2T^{-1}) are calculated as:

$$v = \alpha.h^{m-1} \tag{3}$$

$$q = \alpha.h^{m} \tag{4}$$

Overland flow can be either laminar or turbulent. There are two different equations for α (the kinematic-wave resistance parameter) and the exponent m. For laminar flow $m = 3$ and $\alpha = 8\ gs/K_r v$ and for turbulent flow $m = 5/3$ and $\alpha = S^{1/2}/n$, where S is the soil surface slope, g is the gravitational acceleration, v is the kinematic viscosity of water, K_r is soil surface roughness parameter in laminar flow, and n is Manning's roughness coefficient for turbulent flow. Due to the scarcity of laminar flow in natural conditions, in the majority of studies, overland flow is considered as turbulent flow. Initial and upstream boundary conditions are required for the solution of the kinematic-wave equation [125]. Hence, equation (1) is subject to underneath initial and boundary conditions:

$$h\ (x, 0) = 0,\ 0 \le x < L \tag{5}$$

$$h\ (0, t) = 0,\ 0 \le t < \infty \tag{6}$$

As the above equations illustrate, the kinematic wave equation is sensitive to both slope and Manning's roughness coefficient. Moss, et al. [3] demonstrated that the rain-flow transportation, effective on slopes at least as low as 0.001, can operate in flows less than a millimeter deep. This type of transportation can be seen in both supercritical and subcritical flows and is able to move quartz particles up to about 3 mm in diameter. On low slopes, raindrops impacting shallow water can prevent the formation of rills to promote sheet flow.

Equation (4) calculates unit flow discharge (q) using Manning's equation, which is highly sensitive to roughness coefficient. Different types of land covers can produce various mass of flow depending on the roughness of surfaces. Thus, more precision should be taken into consideration in determining the value of Manning's roughness coefficient. In general, due to spatial and temporal variability of rainfall intensity and infiltration rate in both *x* and *t* dimensions, the Saint Venant equations are required to be solved numerically. In cases where rainfall intensity and infiltration rates are uniform and the temporal variation in them is described by a series of step functions, these equations can also be solved analytically.

The physics-based equations of overland flow sediment transport in shallow waters

Many physics-based algorithms have been developed recently to describe the processes of detachment and sediment transport by shallow overland flow. These algorithms commonly have been inspired by the state sediment flux equation [118], the fundamental energy transport equation [126] and the steady state continuity equation for rill and interill detachment and/or deposition [127]. Sediment transport capacity concepts and relationships, which initially are developed for channels and alluvial rivers, are adopted for use in shallow water flows, and different complexities are widely used in these algorithms. Indeed, most of the mathematical models of soil erosion in shallow waters are borrowed from the field of fluvial sediment transport [128]. There are significant differences between shallow overland flow and deeper channel flow [84]. However, knowledge of the shallow overland flow hydraulics and soil erosion mechanics have been increasing recently, but little research has been published explaining the physical mechanisms of particulate matter wash-off in shallow flow.

Table 3: Some of the recent physically-based algorithms for sediment transport in shallow waters.

Source	Algorithm	Parameters
[29]	$\frac{\partial(qc_i)}{\partial x}+\frac{\partial(c_iD)}{\partial t}=e_i-r_i-d_i$	D = Water depth, c_i = The suspended sediment concentration of class size i in the overland flow, q = The volumetric water flux per unit width of slope, e_i = The rates of ejection of original soil, r_i = Rate of re-ejection of deposited material, d_i = Rate of deposition.
[117]	$\frac{\partial(qc_i)}{\partial x}+\frac{\partial(c_iD)}{\partial t}=r_i+r_{ri}+r_{gi}+d_i$	q = Unit width flow, D = Depth of flow, c_i = Mass of sediment per unit volume of solution, r_i = Rate of entrainment, r_{ri} = Rate of re-entrainment, r_{gi} = Gravity process, d_i = Rate of deposition per unit area.
[144] Eulerian sediment transport model	$\frac{\partial(HC)}{\partial t}+\frac{\partial(HUC)}{\partial x}+\frac{\partial(HvC)}{\partial y}-\frac{\partial}{\partial x}(D\frac{\partial HC}{\partial x})-\frac{\partial}{\partial y}(D\frac{\partial HC}{\partial y})$ $=-\gamma HC+\left(U,V\right)_{\cdot\gamma s}$	$C(x, y, t)$ is depth averaged concentration, γ is the deposition coefficient, $\mathcal{E}(U,V) = (U^2 + V^2)(m^2s^{-2})$ is a function of flow velocities and the term $\lambda_s\cdot\mathcal{E}(U,V)$ models erosion of sediment particles. The particle pick up function is parameterized as $\lambda_s\cdot\mathcal{E}(U,V)$, where, λ_s is the erosion coefficient, it can be related to sediment properties.
[84]	$\frac{\partial Q_s}{\partial x}+\frac{\partial(Ch)}{\partial t}=D_r+F_r$	Q_s = The sediment load (kg $m^{-1}s^{-1}$), h = The flow depth (m), C = The sediment concentration in flow (kg m^{-3}), D_r and F_r are, respectively, the rainfall detachment rate and overland flow entrainment rate (kg $m^{-2}s^{-1}$), x is the distance down slope (m) and t is the time (s).
[55]	$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}=EC_*+GC_0\exp\left(-\eta h\right)-\left(Y+E\right)C$	C = The sediment transport rate or sediment discharge, C_* = Sediment transport capacity of surface runoff, u = The velocity of the flow, C_0 = The sediment discharge corresponding tso c_0, c_0 = The maximum sediment concentration generated by the raindrop impact, E and Y are coefficients, η = The damping rate of the water depth (h).
[39]	$\frac{\partial(\frac{hq_{s,s}}{q})}{\partial t}+\frac{\partial q_{s,s}}{\partial x}=Dis\frac{\partial^2(\frac{hq_{s,s}}{q})}{\partial x^2}-\lambda_s q_{s,s}$	$q_{s,s}$ = The sediment loading rate of fraction s per unit width ($gs^{-1}m^{-1}$), Dis = Dispersion coefficient (m^2s), λ_s = The trapping efficiency for fraction s per unit length (m^{-1}).
[120]	$q\frac{\partial c_i}{\partial x}+D\frac{\partial c_i}{\partial t}=r_i+r_{ri}-d_i=r_i-\frac{\partial M_{di}}{\partial t}$	Q = Unit flux of water (m^2/s), c_i = Sediment concentration of class i sediment (kg/m^3), D = Water depth, r_i = Rate of entrainment of class i sediment from the soil matrix ($kg/m^2/s$), r_{ri} = Rate of re-entrainment of class i sediment from sediment in the deposited layer ($kg/m^2/s$), d_i = Rate of deposition, M_{di} = Rate the mass per unit area.
[145]	$\frac{dq_s}{dx}=D_r+D_i$	dq_s/dx = The sediment rate per unit width of rill channel, D_r = Rate of rill and interill net detachment, D_i = Rill and interill net deposition rate.

As mentioned, sediment transport capacity is a major concept to determine the rates of detachment and deposition in physic-based erosion and sediment transport models. The transportability of sediment by overland flow depends on the sediment concentration. During severe rainfall events or high intensity rainfall, sediment concentration is higher compared to lower rainfall intensity. This is due to the greater power of rainfall in triggering the detachment of soil particles. On the other hand, by increasing the flow depth, sediment concentration decreases and causes the transport capacity to be increased again. Proffitt, et al. [32] expressed that the detachability or re-detachability and thereby, the amounts of soil loss, is expected to decrease when the overland flow depth is increased. Many laboratory experiments have provided the necessary knowledge to establish better relationships between different hydraulic parameters and sediment transport capacity in shallow waters. This information is the initial component for any physics-based erosion and sediment transport models. For more complex problems involved with concurrent processes of erosion and sediment transport in non-uniform flows on varying topography or other situations that provide unsteady flows, numerical solutions are required in these models. In situations with simpler scenarios and when assumptions are made, the model can be analytically solved.

Reviewing the literature, there has been no emphasis on comparing the results of published models with field cases. Therefore, evaluation and recommendation of represented models was not feasible in this study. Some of the recently published physically-based algorithms for sediment transport in shallow waters are summarized in Table 3.

Conclusions and Recommendations

Soil erosion caused by water as a natural phenomenon appears in different types and has direct and indirect effects on the environment and human life. It reduces the productivity of lands and decreases the useful storage volume of rivers, reservoirs and service life of many hydraulic structures, like dams, by deposition of sediments. Physically-based soil erosion models in shallow waters are mostly inspired from the Hairsine and Rose model developed in 1992. The Hairsine and Rose model considers erosion and deposition processes separately, as well as re-entrainment and multiple sediment classes and takes into account the development of a deposited layer. These considerations have made their model the most integrated compared to others available. Previous studies using this model have approved its precision and accuracy simulation of soil erosion and sediment transport under different circumstances. In most of the cases, the Hairsine and Rose model coupled with the St. Venant equations were solved numerically. Many advanced solvers can be found in literature for the shallow water models which involve numerical approximations for the coupled erosion model. The finite difference method, due to its robustness and simplicity, was primarily used by many researchers to simulate overland flow and erosion and sediment transport. The concept behind the finite difference method is substitution of the partial derivatives of one parameter by its difference quotient approximations, and then solving explicitly or implicitly the resulting system of algebraic equations. Based on the reviewed literature, MacCormack's finite difference method is proposed to solve the wave equations for the overland flow routing and sediment transport equations. MacCormack's scheme [129,130] is more reliable and accurate when applied to overland flow simulation in comparison to the other different finite difference schemes which have been developed recently. The advantage of numerically deriving solutions is that this technique does not make many assumptions in comparison to analytical solutions. In addition, the excess rainfall parameter can vary in space and time. However, one major disadvantage of the numerical solution is that its mathematics requires calculations of sensitivity analysis, which are typically approximations of the real solutions.

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