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, pasture, 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-
related 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 led 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 catch-
ment-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...
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.
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:

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

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

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

$$v = \alpha \cdot h^{m-1}$$  (3)

$$q = \alpha \cdot h^n$$  (4)

Overland flow can be either laminar or turbulent. There are two different equations for \(\alpha\) (the kinematic-wave resistance parameter) and the exponent \(m\). For laminar flow \(m = 3\) and \(\alpha = 8gs/K\), and for turbulent flow \(m = 5/3\) and \(\alpha = S^{1/2}/h\), where \(S\) is the soil surface slope, \(g\) is the gravitational acceleration, \(v\) is the kinematic viscosity of water, \(K\) 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:

$$h(x, 0) = 0, 0 \leq x < L$$  (5)

$$h(0, t) = 0, 0 \leq t < \infty$$  (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 rough-
ness 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]   | $\frac{\partial (qc_i)}{\partial t} + \frac{\partial (c_iD_i)}{\partial x} = e_i - r_i - d_i$ | $D$ = 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]  | $\frac{\partial (qc_i)}{\partial t} + \frac{\partial (c_iD_i)}{\partial x} = r_i + r_{ri} + r_{si} + d_i$ | $q$ = 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, $r_{si}$ = Gravity process, $d_i$ = Rate of deposition per unit area. |
| [144]  | $\frac{\partial (HC_i)}{\partial t} + \frac{\partial (HC_iC_i)}{\partial x} + \frac{\partial (HC_iC_i)}{\partial y} - \frac{\partial (D_i\frac{\partial HC_i}{\partial x})}{\partial x} - \frac{\partial (D_i\frac{\partial HC_i}{\partial y})}{\partial y} = -f_i HC + (U,V)_i$, $\gamma$ | $C(x, y, t)$ is depth averaged concentration, $\gamma$ is the deposition coefficient, $E(U,V)$ = (LP + VP) $(m^2s^{-2})$ is a function of flow velocities and the term $\lambda_i E(U,V)$ models erosion of sediment particles. The particle pick up function is parameterized as $\lambda_i E(U,V)$, where, $\lambda_i$ is the erosion coefficient, it can be related to sediment properties. |
| [84]   | $\frac{\partial Q_c}{\partial x} + \frac{\partial (Ch)}{\partial t} = D_i + F_i$ | $Q_c$ = The sediment load (kg m$^{-1}$s$^{-1}$), $h$ = The flow depth (m), $C$ = The sediment concentration in flow (kg m$^{-3}$), $D_i$ and $F_i$ 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]   | $\frac{\partial C_i}{\partial t} + u \frac{\partial C_i}{\partial x} = EC_i + GC_c \exp(-\eta h) - (Y + E)C$ | $C_i$ = The sediment transport rate or sediment discharge, $C_i$ = Sediment transport capacity of surface runoff, $u$ = The velocity of the flow, $C_c$ = The sediment discharge corresponding to $c_c$, $c_c$ = The maximum sediment concentration generated by the raindrop impact, $E$ and $Y$ are coefficients, $\eta$ = The damping rate of the water depth (h). |
| [39]   | $\frac{\partial (hq_{i,x}}{\partial t} + \frac{\partial q_{i,x}}{\partial x} = Dis \frac{\partial (hq_{i,x})}{\partial x^2} - \lambda_i q_{i,x}$ | $q_{i,x}$ = The sediment loading rate of fraction $s$ per unit width (gs$^{-1}$m$^{-1}$), $Dis$ = Dispersion coefficient (m$^{-2}$s$^{-1}$), $\lambda_i$ = The trapping efficiency for fraction $s$ per unit length (m$^{-1}$). |
| [120]  | $q \frac{\partial C_i}{\partial x} + D_i \frac{\partial C_i}{\partial t} = r_i + r_{si} - d_i = r_i - \frac{\partial M_{si}}{\partial t}$ | $Q$ = Unit flux of water (m$^3$/s), $c_i$ = Sediment concentration of class $i$ sediment (kg/m$^3$), $D_i$ = Water depth, $r_i$ = Rate of entrainment of class $i$ sediment from the soil matrix (kg/m$^3$/s), $r_{si}$ = Rate of re-entrainment of class $i$ sediment from sediment in the deposited layer (kg/m$^2$/s), $d_i$ = Rate of deposition, $M_{si}$ = Rate the mass per unit area. |
| [145]  | $\frac{d q_i}{d x} = D_i + D_i$ | $dq_i/dx$ = The sediment rate per unit width of rill channel, $D_i$ = Rate of rill and interrill net detachment, $D_i$ = Rill and interrill 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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References

1. Committee AT (1970) Sediment sources and sediment yields. Am Soc Civil Eng Hydraul Div J 7337: 1283-1329.
2. Kuznetsov MS, Gendugov VM, Khalilov MS, et al. (1998) An equation of soil detachment by flow. Soil and Tillage Research 46: 97-102.
3. Moss AJ, Walker PH, Hultka J (1979) Raindrop-stimulated transportation in shallow water flows: An experimental study. Sediment Geol 22: 165-184.
4. Mutchler CK, Murphree CE, McGregor KC (1994) Laboratory and field plots for erosion research. Soil Eros Res Methods 11-37.
5. Kinnell PIA (1999) The effect of slope length on sediment concentrations associated with side-slope erosion. Soil Sci Soc Am J 64: 1004-1008.
6. Worthington AM (1882) On impact with a liquid surface. Proc R Soc London 34: 217-230.
7. Hobbs PV, Kezweeney AJ (1967) Splashing of a water drop. Science 155: 1112-1114.
8. Hobbs PV, Osheroff T (1967) Splashing of drops on shallow liquids. Science 158: 1184-1186.
9. Macklin WC, Hobbs PV (1969) Subsurface phenomena and the splashing of drops on shallow liquids. Science 166: 107-108.
10. Macklin WC, Metaxas GJ (1976) Splashing of drops on liquid layers. J Appl Phys 47: 3963.
11. Mitchel CK, Hansen LM (1970) Splash of a waterdrop at terminal velocity. Science 169: 1311-1312.
12. Laws JO, Parsons DA (1943) The relation of raindrop-size to intensity. Eos Trans Aagu 24: 452-460.
13. Smith DD, Wischmeier WH (1957) Factors affecting sheet and rill erosion. Trans Am Geophys Union 38: 889-896.
14. Wischmeier WH, Smith DD (1960) A universal soil-loss equation to guide conservation farm planning. Trans 7th Int Congr Soil Sci 1: 418-425.
15. Rose CW (1960) Soil detachment caused by rainfall. Soil Sci 89: 28-35.
16. Rose CW (1961) Rainfall and soil structure. Soil Sci 91: 49-54.
17. Young RA, Wiersma JL (1973) The role of rainfall impact in soil detachment and transport. Water Resour Res 9: 1629-1636.
18. Ghadiri H, Payne D (1977) Raindrop impact stress and the breakdown of soil crumbs. J Soil Sci 28: 247-258.
19. Ghadiri H, Payne D (1981) Raindrop impact stress. J Soil Sci 32: 41-49.
20. Poens J, Savat J (1981) Detachment and transportation of loose sediments by raindrop splash: Part II detachability and transport ability measurements. CATENA 8: 19-41.
21. Rose CW, Williams JR, Sander GC, et al. (1983) A mathematical model of soil erosion and deposition processes: I. Theory for a plane land element. Soil Sci Soc Am J 47: 991-995.
22. Moss AJ, Green P (1983) Movement of solids in air and water by raindrop impact. Effects of drop-size and water-depth variations. Aust J Soil Res 21: 257-269.
23. Nearing MA, Bradford JM, Holtz RD (1986) Measurement of force vs. Time relations for waterdrop impact. Soil Sci Soc Am J 50: 1532-1536.
24. Epema GF, Riezebos HT (1987) Fall velocity of waterdrops at different heights as a factor influencing erosivity of simulated rain.
25. Deletic A, Maksimovic Cbreve edo, Ivetic M (1997) Modelling of storm wash-off of suspended solids from impervious surfaces. J Hydraul Res 35: 99-118.
26. Sharma PP, Gupta SC, Rawls WJ (1991) Soil detachment by single raindrops of varying kinetic energy. Soil Sci Soc Am J 55: 301-307.
27. Sharma PP, Gupta SC, Foster GR (1993) Predicting soil detachment by raindrops. Soil Sci Soc Am J 57: 674-680.
28. Sharma PP, Gupta SC, Foster GR (1995) Raindrop-induced soil detachment and sediment transport from interrill areas. Soil Sci Soc Am J 59: 727-734.
29. Hairsine PB, Rose CW (1991) Rainfall detachment and deposition: Sediment transport in the absence of flow-driven processes. Soil Sci Soc Am J 55: 320-324.
30. Govers G, Everaert W, Poens J, et al. (1990) A long flume study of the dynamic factors affecting the resistance of a loamy soil to concentrated flow erosion. Earth Surf Process Landforms 15: 313-328.
31. Gilley J, Finkner S (1985) Estimating soil detachment caused by raindrop impact. Transactions of the ASAE 28: 140-146.
32. Proffitt ABP, Rose CW, Hairsine PB (1991) Rainfall detachment and deposition: Experiments with low slopes and significant water depths. Soil Science Society of America Journal 55: 325-332.
33. Sander GC, Hairsine PB, Rose CW, et al. (1996) Unsteady soil erosion model, analytical solutions and comparison with experimental results. Journal of Hydrology 178: 351-367.
34. Misra RK, Rose CW (1995) An examination of the relationship between erodibility parameters and soil strength. Australian Journal of Soil Research 33: 715-732.
35. Morgan RPC, Quinton JN, Smith RE, et al. (1998) The European soil erosion model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. Earth Surface Processes and Landforms 23: 527-544.
36. Bertuzzi P, Rauws G, Courault D (1990) Testing roughness indices to estimate soil surface roughness changes due to simulated rainfall. Soil and Tillage Research 17: 87-99.
37. Cogo NP, Moldenhauer WC, Foster GR (1983) Effect of crop residue, tillage-induced roughness, and runoff velocity on size distribution of eroded soil aggregates. Soil Science Society of America Journal 47: 1005-1008.
38. Darboux F, Huang C (2005) Does soil surface roughness increase or decrease water and particle transfers? Soil Sci Soc Am J 69: 748-756.
39. Deletic A (2001) Modelling of water and sediment transport over grassed areas. Journal of Hydrology 248: 168-182.
40. Farres P (1978) The role of time and aggregate size in the crusting process. Earth Surface Processes and Landforms 3: 243-254.
41. Gómez JA, Nearing MA (1979) Influence of surface roughness and clod size and stability on soil and water losses. Soil Science Society of America Journal 35: 772-777.
42. Le Bissonnais Y, Cerdan O, Lecomte V, et al. (2005) Variability of soil surface characteristics influencing runoff and interrill erosion. CATENA 62: 111-124.
43. Johnson CB, Mannering JV, Moldenhauer WC (1979) Influence of surface roughness and clod size and stability on soil and water losses. Soil Science Society of America Journal 35: 772-777.
44. Le Bissonnais Y, Cerdan O, Lecomte V, et al. (2005) Variability of soil surface characteristics influencing runoff and interrill erosion. CATENA 62: 111-124.
45. Seberg L, Cerdan O, Lecomte V, et al. (2005) Variability of soil surface characteristics influencing runoff and interrill erosion. CATENA 62: 111-124.
46. Van Wesemael B, Poesen J, De Figueiredo T (1995) Effects of rock fragments on physical degradation of cultivated soils by rainfall. Soil and Tillage Research 33: 229-250.
47. Hairsine PB, Moran CJ, Rose CW (1992) Recent development regarding the influence of soil surface characteristics on overland-flow and erosion. Australian Journal of Soil Research 30: 249-264.
57. Abrahams AD, Gao P, Aebly FA (2000) Relation of sediment transport capacity to stone cover and size in rain-impacted interrill flow. Earth Surface Processes and Landforms 25: 497-504.

58. Adams JE (1966) Influence of mulches on runoff, erosion, and soil moisture depletion. Soil Science Society of America Journal 30: 110-114.

59. Bunte K, Poensgen J (1994) Effects of rock fragment size and cover on overland-flow hydraulics, local turbulence and sediment yield on an erodible soil surface. Earth Surface Processes and Landforms 19: 115-135.

60. Guo T, Wang Q, Li D, et al. (2010) Effect of surface stone cover on sediment and solute transport on the slope of a fallow land in the semi-arid loess region of northwest China. Journal of Soils and Sediments 10: 1200-1208.

61. Hung KC, Kosugi K, Lee TH, et al. (2007) The effects of rock fragments on hydrologic and hydraulic responses along a slope. Hydrological Processes 21: 1354-1362.

62. Jomaa S, Barry DA, Brovelli A, et al. (2010) Effect of raindrop splash and transversal width on soil erosion. Laboratory flume experiments and analysis with the Haarsine-Rose model. J Hydrol 395: 117-132.

63. Katra I, Levee H, Sarah P (2008) The effect of rock fragment size and position on topsoil moisture on arid and semi-arid hillslopes. CATENA 72: 49-54.

64. Levee H, Poensgen J (1991) Overland flow generation and continuity on stone-covered soil surfaces. Hydrological Processes 5: 345-360.

65. Li XY (2003) Gravel-sand mulch for soil and water conservation in the semiarid loess region of northwest China. CATENA 52: 105-127.

66. Martinez-Zavala L, Jordán A (2008) Effect of rock fragment cover on interrill soil erosion from bare soils in western Andalusia, Spain. Soil Use Manag 24: 108-117.

67. Poensgen J, De Luna E, Franca A, et al. (1999) Concentrated flow erosion rates as affected by rock fragment cover and initial soil moisture content. CATENA 36: 315-329.

68. Poensgen J, Ingelmo-Sanchez F, Mucher H (1990) The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer. Earth Surf Process and Landforms 15: 653-671.

69. Poensgen JW, Van Wesemael B, Bunte K, et al. (1998) Variation of rock fragment cover and size along semiarid hillslopes: A case-study from southeast Spain. Geomorphology 23: 323-335.

70. Rieke-Zapp D, Poensgen J, Nearing MA (2007) Effects of rock fragments incorporated in the soil matrix on concentrated flow hydraulics and erosion. Earth Surf Process and Landforms 32: 1063-1076.

71. Barry DA, Parlane J-Y, Haverkamp R, et al. (1995) Infiltration under ponded conditions: 4. An explicit predictive infiltration formula. Soil Sci 160: 8-17.

72. Barry DA, Parlane JY, Sander GC, et al. (1993) A class of exact solutions for Richards' equation. J Hydrol 142: 29-46.

73. Parlane J, Barry DA, Parlane MB, et al. (1992) Note on the sorptivity for mixed saturated? unsaturated flow. Water Resour Res 28: 2529-2531.

74. Sojka RE, Westermann DT, Brown MJ, et al. (1993) Zone-subsoiling effects on infiltration, runoff, erosion, and yields of furrow-irrigated potatoes. Soil Tillage Res 35: 351-368.

75. Agassi M, Bradford JM (1999) Methodologies for interrill soil erosion studies. Soil Tillage Res 49: 277-287.

76. Chaplot VA, Le Bissonnais Y (2003) Runoff features for interrill erosion at different rainfall intensities, slope lengths, and gradients in an agricultural loessial hillslope. Soil Sci Soc Am J 67: 844-851.

77. Cochrane TA, Flanagan DC (1995) Detachment in a simulated rill. Trans ASAE 40: 111-119.

78. De Baets S, Poensgen J, Knapen A, et al. (2007) Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. Earth Surf Process and Landforms 32: 1323-1345.

79. De Baets S, Poensgen J, Gyssele G, et al. (2006) Effects of grass roots on the erodibility of top soils during concentrated flow. Geomorphology 76: 54-67.

80. Foster GR, Meyer LD (1972) Transport of soil particles by shallow flow. Trans Am Soc Agric Eng 15: 99-102.

81. Foster GR (1982) Modeling the erosion process. Hydrological Model Small Watersheds 297-380.

82. Fristensky AJ, Grismer ME (2009) Evaluation of ultrasonic attenuation in soil to estimate infiltration under ponded conditions: 4. An explicit predictive infiltration formula. Soil Sci 160: 8-17.

83. Fristensky AJ, Grismer ME (2009) Evaluation of ultrasonic aggregate stability and rainfall erosion resistance of disturbed and amended soils in the lake tahoe basin, USA. CATENA 79: 93-102.

84. Jayawardena AW, Buiyuan RR (1999) Evaluation of an interrill soil erosion model using laboratory catchment data. Hydrological Processes 13: 89-100.
85. Liebenow AM, Elliot WJ, Laflen JM, et al. (1990) Interrill erodibility - collection and analysis of data from cropland soils. Trans ASAE 33: 1892-1898.

86. Mamo M, Bubenzer GD (2001) Detachment rate, soil erodibility, and soil strength as influenced by living plant roots part I: Laboratory study. Trans ASAE 44: 1167-1174.

87. Mamo M, Bubenzer GD (2001) Detachment rate, soil erodibility, and soil strength as influenced by living plant roots part II: Field study. Trans ASAE 44: 1175-1181.

88. McCool DK, Brown LC, Foster GR, et al. (1987) Revised slope steepness factor for the universal soil loss equation. Trans Am Soc Agric Eng 30: 1387-1396.

89. Moore ID, Burch GJ (1986) Physical basis of the length-dwelling time - collection and analysis of data from cropland soils. Trans ASAE 33: 1882-1888.

90. Nearing MA, Parker SC (1990) Soil detachment by flow - collection and analysis of data from cropland soils. Trans ASAE 33: 1896-1900.

91. Nearing MA, Simanton JR, Norton LD, et al. (1999) Soil erosion by surface water flow on a stony, semiarid hillslope. Earth Surf Process Landforms 24: 677-686.

92. Nearing MA, Bradford JM, Parker SC (1990) Soil detachment by shallow flow at low slopes. Soil Sci Soc Am J 55: 339-344.

93. Owoputi LO, Stolte WJ (1995) Soil detachment in the physically-based soil-erosion process - a review. Trans ASAE 38: 1099-1110.

94. Poensen J, Nachtergaele J, Verstraeten G, et al. (2003) Gully erosion and environmental change: Importance and research needs. CATENA 50: 91-133.

95. Wang B, Zhang GH, Shi YY, et al. (2014) Soil detachment by overland flow under different vegetation restoration models in the loess plateau of china. CATENA 116: 51-59.

96. Zhou ZC, Shangguan ZP (2005) Soil anti-scouribility enhanced by plant roots. J Integr Plant Biol 47: 676-682.

97. Truman CC, Bradford JM, Ferris JE (1990) Antecedent water content and rainfall energy influence on soil aggregate breakdown. Soil Sci Soc Am J 54: 1385-1392.

98. Lei T, Nearing MA, Haghighi K, et al. (1998) Rill erosion and morphological evolution: A simulation model. Water Resour Res 34: 3157-3168.

99. Merten GH, Nearing MA, Borges ALO (2000) Effect of sediment load on soil detachment and deposition in rills. Soil Sci Soc Am J 65: 861-868.

100. Knapan A, Poensen J, Govers G, et al. (2007) Resistance of soils to concentrated flow erosion: A review. Earth Science Rev 80: 75-109.

101. Abrahams AD, Parsons AJ, Wainwright J (1994) Resistance to overland flow on semiarid grassland and shrubland hillslopes, walnut gulch, southern arizona. J Hydrol 156: 431-446.

102. Ghebreiyessus YT, Gantzer CJ, Alberts EE, et al. (1994) Soil erosion by concentrated flow: Shear stress and bulk density. Trans ASAE 37: 1791-1797.

103. Khanbilvardi RM, Rogowski AS (1986) Modeling soil erosion, transport and deposition. Ecol Model 33: 255-268.

104. Knapan A, Poensen J, Govers G, et al. (2008) The effect of conservation tillage on runoff erosivity and soil erodibility during concentrated flow. Hydrol Process 22: 1497-1508.

105. Kocher MF, Summers JD (1988) A consolidation model for estimating changes in rill erodibility. Trans ASAE 31: 696-700.

106. Parsons AJ, Abrahams AD, Wainwright J (1996) Responses of interrill runoff and erosion rates to vegetation change in southern Arizona. Geomorphology 14: 311-317.

107. Wainwright J, Parsons AJ, Abrahams AD (2000) Plot-scale studies of vegetation, overland flow and erosion interactions: Case studies from arizona and new mexico. Hydrol Process 14: 2921-2943.

108. Zheng F, Huang C, Norton LD (1998) Vertical hydraulic gradient and run-on water and sediment effects on erosion processes and sediment regimes. Soil Sci Soc Am J 64: 4-11.

109. Dietrich WE (1982) Settling velocity of natural particles. Water Resour Res 18: 1615-1626.

110. Haan CT, Barfield BJ, Hayes JC (1994) Design hydrology and sedimentology for small catchments. Elsevier.

111. Lovell CJ, Rose CW (1988) Measurement of soil aggregate settling velocities. 1. A modified bottom withdrawal tube method. Soil Res 26: 55-71.

112. Torri D, Ciampalini R, Gil PA (1998) The role of soil aggregates in soil erosion processes, In: modelling soil erosion by water. Springer Berlin Heidelberg 247-257.

113. Beuselinck L, Govers G, Hairsine PB, et al. (2002) The influence of rainfall on sediment transport by overland flow over areas of net deposition. J Hydrol 257: 145-163.

114. Castro Díaz MJ, Fernández-Nieto ED, Ferreiro AM (2008) A physically based rainfall-runoff-erosion model over steep slopes. J Hydrol 339-344.

115. Gao B, Walter MT, Steenhuis TS, et al. (2003) Investigating ponding depth and soil detachability for a mechanistic erosion model using a simple experiment. J Hydrol 277: 116-124.

116. Govindaraju RS (1995) Non-dimensional analysis of a physically based rainfall-runoff-erosion model over steep slopes. J Hydrol 173: 327-341.

117. Hairsine PB, Sander GC, Rose CW, et al. (1999) Unsteady soil erosion due to rainfall impact: A model of sediment sorting on the hillslope. J Hydrol 220: 115-128.

118. Hairsine PB, Rose CW (1992) Modeling water erosion due to overland flow using physical principles: 1. Sheet flow. Water Resour Res 28: 237-243.

119. Lisie IG, Rose CW, Hogarth WL, et al. (1998) Stochastic sediment transport in soil erosion. J Hydrol 204: 217-230.

120. Parlangue JY, Hogarth WL, Rose CW, et al. (1999) Addendum to unsteady soil erosion model. J Hydrol 217: 149-156.

121. Rose CW, Yu B, Gadhir H, et al. (2007) Dynamic erosion of soil in steady sheet flow. J Hydrol 333: 449-458.

122. Wallach R, Grigorin G, Rivlin J (2001) A comprehensive mathematical model for transport of soil-dissolved chemicals by overland flow. J Hydrol 247: 85-99.
123. Martin JL, McCutcheon SC (1998) Hydrodynamics and transport for water quality modeling. CRC Press.

124. Woolhiser DA (1975) Simulation of unsteady overland flow. Unsteady Flow Open Channels 2: 485-508.

125. Van der Molen WH, Torfs PJF, De Lima JLM (1995) Water depths at the upper boundary for overland flow on small gradients. J Hydro 171: 93-102.

126. Engelund F, Hansen E (1967) A monograph on sediment transport in alluvial streams. Teknisk Forlag.

127. Merritt WS, Letcher RA, Jakeman AJ (2003) A review of erosion and sediment transport models. Environ Model Softw 18: 761-799.

128. Guy BT, Dickenson WT, Sohrabi TM, et al. (2009) Development of an empirical model for calculating sediment-transport capacity in shallow overland flows: Model calibration. Biosyst Eng 103: 245-255.

129. MacCormack R (2003) The effect of viscosity in hypervelocity impact cratering. J Spacecr Rockets 40: 757-763.

130. MacCormack RW (1969) The effect of viscosity in hypervelocity impact cratering. AIAA Pap 69-354.

131. Bubenzern GD, Jones BA Jr (1971) Drop size and impact velocity effects on the detachment of soils under simulated rainfall. Trans ASAE 14: 625-628.

132. Lopez-Garcia MJ, Caselles V (1987) Use of thematic mapper data to assess water quality in albufera lagoon of valencia (spain). Adv Digit Image Process 510-519.

133. Free GR (1960) Erosion characteristics of rainfall. Agric Engng 41: 447-449.

134. Nearing MA, Foster GR, Lane LJ, et al. (1989) A process-based soil erosion model for USDA-water erosion prediction project technology. Trans ASAE 32: 1587-1593.

135. Park SW, Mitchell JK, Bubenzern GD (1983) Rainfall characteristics and their relation to splash erosion. Trans ASAE 26: 795-804.

136. Styczen M, Hoeegh-Schmidt K (1988) A new description of splash erosion in relation to rain drop sizes and vegetation.

137. Lane LJ, Foster GR, Nicks AD (1987) Use of fundamental erosion mechanics in erosion prediction. Am Soc Agric Eng Microfiche Collect.

138. Meyer LD, Wischmeier WH (1969) Mathematical simulation of the process of soil erosion by water. Trans ASAE 12: 754-758.

139. Foster GR, Flanagan DC, Nearing MA, et al. (1995) Hillslope erosion component in USDA water erosion prediction project: Hillslope profile and watershed model documentation. NSERL Report.

140. Flanagan DC, Nearing MA (1995) United states department of agriculture-usda: Water erosion prediction project. West Lafayette, Natl Soil Eros Res Lab.

141. Zhang G, Liu B, Liu G, et al. (2003) Detachment of undisturbed soil by shallow flow. Soil Sci Soc Am J 67: 713-719.

142. Lafren JM, Lane LJ, Foster GR (1991) WEPP: A new generation of erosion prediction technology. J Soil Water Conserv.

143. Nearing MA (1991) A probabilistic model of soil detachment by shallow turbulent flow. Trans ASAE 34: 81-85.

144. Van Rijn LC (1993) Principles of sediment transport in rivers, estuaries and coastal seas. Aqua Publications Amsterdam.

145. Foster GR, Meyer LD, Onstad CA (1977) An erosion equation derived from basic erosion principles. Trans ASAE 20: 678-682.