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Representing the role of soil moisture on erosion resistance in sediment models: Challenges and opportunities

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ABSTRACT

Soil's resistance to erosion or its susceptibility to resist detachment is a key parameter in the majority of soil erosion and sediment models. Although soil resistance is a function of both the intrinsic properties of soil and dynamic environmental variables (e.g., soil moisture), the influence of the latter is seldom explicitly incorporated in the definition of soil resistance. The significant and complex role of soil moisture content on erosion resistance is recognized by many studies, however, much of the emphasis regarding the role of soil moisture on sediment yield modeling has been on its impacts on runoff generation rather than on soil resistance. In this paper, we synthesize the existing state of knowledge on the processes and mechanisms by which moisture affects erosion resistance of soil, and highlight the challenges and opportunities associated with incorporating this relation in sediment yield assessment models. Through a detailed analysis of literature, we find that dry soil has the lowest resistance to erosion and thus has a high erodibility, and erosion resistance increases (erodibility decreases) with increasing antecedent moisture content until a certain threshold. After this threshold is reached, soil resistance decreases with further increase in moisture content, and soils become more susceptible to erosion. Next, the study identifies the candidate variables that may be used to quantitatively represent the soil's resistance to erosion vis-à-vis moisture, and discuss the challenges in incorporating this relation in modeling frameworks. As a way forward, through a meta-analysis of published data, we develop an exemplar relation that could be used to represent the variation in erosion resistance with soil moisture content. We find that the parameters of such a relation vary significantly across soil types, thus raising the possibility for developing a soil-type based moisture-resistance relations. Overall, this review underscores the considerable impact of antecedent soil moisture on the erosion resistance of soils, and makes a case for integrating the influence of dynamic soil moisture content on erosion resistance into predictive modeling frameworks.

1. Introduction

In the recent past, a large number of soil erosion and sediment models with varying representations of erosion, deposition, and transport processes have been developed. Their differences and consequent impact on predictions is a subject of several reviews (e.g., Aksoy and Kavvas, 2005; De Vente et al., 2013; Merritt et al., 2003; Pandey et al., 2016; Papanicolaou et al., 2008) and model intercomparison studies (e.g., Bhuyan et al., 2002; Zi et al., 2019). Irrespective of the process representation used, the majority of the sediment models account for the role of soil's resistance to erosion on sediment yield and/or erosion processes. Soil resistance, often also conversely termed as the susceptibility of soil to erosion by water, is a key physical property of the soil that indicates its ability to resist detachment by water flow or raindrop impact. Itis frequently the reason for differential rates of yield and erosion across regions with different soil types (Goudie, 2013). It is also used to explain the changes in sediment yield in time, especially due to changes in land use. Although measured at a diverse range of spatial scales, ranging from point to bench to hillslope to watershed scales, the resistance property captures the erosion rate per unit area for a given erosivity from water flow or raindrop impact. In models, this term is often obtained through calibration using measured soil erosion and other variables (Knapen et al., 2007). Although it is widely accepted that soil resistance is both a function of intrinsic properties of soil and exogenous dynamic environmental variables (Bryan, 2000; Paaswell, 1973), the influence of the latter is seldom explicitly incorporated in the

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definition of soil resistance (Knapen et al., 2007). Soil moisture is one such exogenous environment property that has been known to impact soil's resistance to erosion (Allen et al., 1999; Fell et al., 2017).

An obvious and a widely studied effect of soil moisture on sediment yield is through runoff generation. Drier soils tend to generate less runoff (Chen et al., 2015) thus have less sediment transport capacity than a wet soil where more runoff is generated and more soil will be eroded (Flanagan et al., 1988; Wei et al., 2007). The influence of moisture content on soil erosion resistance and consequently on sediment yield, although relatively understudied, can also be significant (Luk and Hamilton, 1986; Knapen et al., 2007; Shainberg et al., 1996). For example, studies have discussed the importance of moisture on the development of cohesion forces in soil (e.g. Kemper et al., 1985; Panabokke and Quirk, 1957; Shainberg et al., 1996), and have reported a differential erosional response based on differences in antecedent moisture state owing to the resistance the soil develops against erosion (e.g. Govers and Loch, 1993; Parker et al., 1995; Poesen et al., 1999). Not only the spatial variation in soil moisture, but also the temporal variation in soil moisture at the beginning, during, and between individual rain events is vital for determining erosion resistance of soil. Despite its importance, a clear elucidation of the relationship between moisture and soil's resistance to erosion for a range of soils has not yet emerged. Not surprisingly, this has resulted in non-consideration of the explicit role of antecedent moisture on soil's resistance to erosion in most sediment models.

In this paper, we synthesize the existing state of knowledge on the role of moisture on erosion resistance of soil, and highlight the opportunities and challenges associated with incorporating such a relation in sediment yield assessment models. The focus here is on the fluctuation in soil resistance to erosion at as short as event time scale, as soil moisture dynamics may vary considerably at these scales (Katul et al., 2007; Rosenbaum et al., 2012). To this end, we, (i) review the literature on the influence of soil moisture content on erosion resistance and the processes and mechanisms associated with it, (ii) highlight the need to include the moisture-erosion resistance relationship in sediment models, (iii) detail the candidate variables that may be used to quantitatively represent the soil's resistance to erosion and its relation to moisture, (iv) underscore the challenges and opportunities in incorporating the effect of soil moisture content on erosion resistance in modeling frameworks and (v) discuss future research directions.

2. Influence of soil moisture content on erosion resistance: Contrasting variations and diverse physical controls

Soil moisture affects resistance of soils to erosion through several mechanisms. Below we highlight the reported disparate relations between soil moisture and soil erosion resistance, and discuss varied mechanisms responsible for them.

2.1. Increasing soil erosion resistance with increasing moisture content

A large number of the studies agree that a completely dry soil has low resistance to erosion, and the resistance generally increases with increasing moisture (e.g. Cernuda et al., 1954; Govers, 1991; Grissinger, 1966; Kemper and Rosenau, 1984; Le Bissonnais and Singer, 1992; Lyles et al., 1974; Nachtergaele and Poesen, 2002; Shainberg et al., 1996). Below, we review studies that report an increasing (a decreasing) trend in soil's resistance with moistness (dryness), and organize them based on the disparate mechanisms explaining the trend. Table 1 provides a summarization of the assumptions and key findings of many of these studies.

2.1.1. Slaking

Slaking is often defined as the aggregate breakdown by increase in the pressure exerted by the escaping entrapped air during the rapid wetting process (Bastos, 2002; Kemper et al., 1985). Although slaking itself is not erosion, it breaks down soil aggregates and makes the soil more erodible during intense rainfall or runoff events when the soil is wetted rapidly. It has been identified as a prominent cause for high erosion rates in dry soil (Auerswald, 1993; Lim, 2006; Shainberg et al., 1996). Panabokke and Quirk (1957) and Le Bissonnais et al. (1995) noted that in certain conditions, slaking can be more efficient at breaking down dry soils and increasing detachment capacity compared to raindrop impact. In clay soils, slaking caused by differential swelling was identified as responsible for the breakdown of aggregates (Kemper and Rosenau, 1984; Panabokke and Quirk, 1957). Le Bissonnais and Singer (1992) attributed the increased aggregate stability of pre-wetted soil, as opposed to an air-dry soil, to a decrease in slaking. Diminished slaking decreases aggregate breakdown and the generation of smaller easily movable particles, thus also reducing crust formation. Le Bissonnais and Singer (1992) showed (Fig. 1a) that pre-wetted soils with high initial moisture content experienced low erosion rates compared to air-dried soils in successive rainfall events, 24 h and 7 days apart. For the pre-wetted soil, the amount of splashed material that remained was little throughout the three consecutive rainfall events, although runoff increased 10-fold. In Cernuda et al. (1954), for all fifteen soil types tested, slaking and ease of destruction with water drops decreased with increasing initial moisture content. Lyles et al. (1974) also supported the claim that much less soil was detached from field-moist soil than from air-dried clods by raindrops when other variables were kept constant (Fig. 1b). By measuring water absorption and expansion of clods, it was discovered that due to their initial larger water saturation, field-moist aggregates absorbed extra water slowly and hence resisted erosion (Kemper and Rosenau, 1984). Slower rates of wetting due to high soil moisture contents prevents entrapment of air and lowers differences in swelling, allowing a greater portion of the particles to remain cohered in the aggregates. Lim (2006) showed that the intensity of slaking (slaking slope), measured by the slaking test, increased 3 to 5 orders of magnitude for a 30% reduction in the degree of saturation (Fig. 1c). Therefore, the rate of water absorption upon wetting has been suggested to be a good measure of soil erodibility, as it indicates the intensity of the disruption occurring due to wetting (Govers and Loch, 1993; Knapen et al., 2007). A few studies suggest that slaking maybe sufficient to breakdown even the highly cohesive clay soil (Kemper and Rosenau, 1984), and this effect is predominant over any softening or solution effect of water on aggregate breakdown (Cernuda et al., 1954). Overall, slaking causes more sediment to be broken down and become available for transport by runoff, while moist soils prevent slaking and limit the ability of the soil to be disaggregated (Legates et al., 2011).

2.1.2. Microfissuration

Another mechanism for the lower erosion resistance in dry soils has been attributed to the microfissuration occurring during the rapid wetting of initially dry soil (Govers and Loch, 1993; Govers et al., 1990; Le Bissonnais et al., 1989; Poesen et al., 1999). Larionov et al. (2018) experimentally found that drying of soil samples increase their erodibility due to soil cracking that decreases the amount and strength of inter-aggregate bonds (see Fig. 1 of Larionov et al., 2018). Poesen et al. (1999) reported that concentrated flow erosion rates were 20–65% less on initially wet topsoils compared to initially air-dry topsoils. Although air-dry soil had high infiltration rates and lower sediment concentrations in the initial phase of their flume experiment, high detachability due to slaking and microcracking of dry aggregates in the intermediate and final phases contributed to high erosion rates compared to initially wet soil.

2.1.3. Cohesion from surface tension

Lower erosion from moist soil has also been attributed to surface tension forces created by the water films that increase soil cohesion (Cernuda et al., 1954; Haines, 1925; Kemper and Rosenau, 1984; Kemper et al., 1985; Panabokke and Quirk, 1957). This cohesion provides a resistance against both the raindrop impact and shearing action of the flowing water. Govers and Loch (1993) conducted a field rill

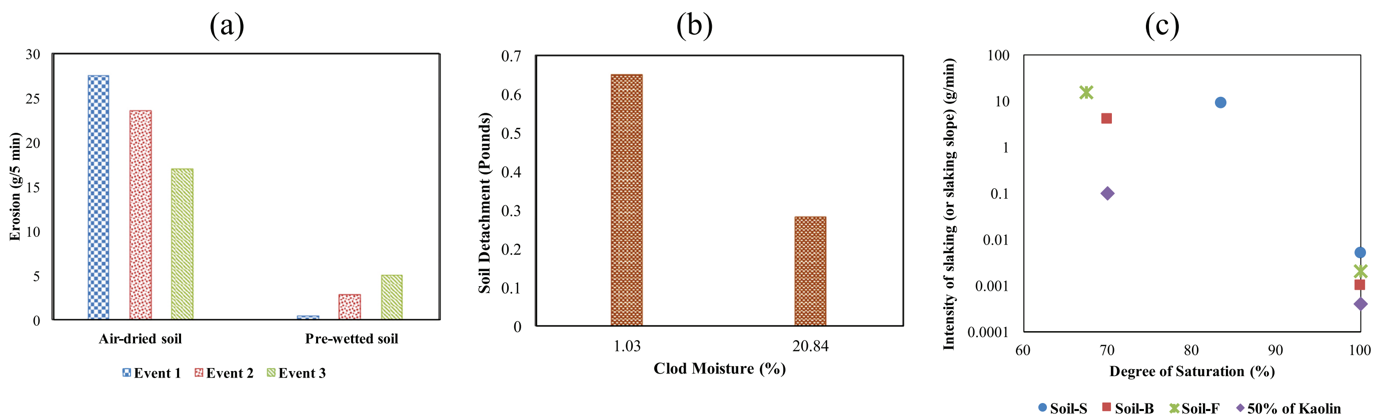

Fig. 1. (a) The change in erosion between initially air-dry and pre-wetted Solono soil for three consecutive rainfall events 24 h and 7 days apart as reported in Le Bissonnais and Singer (1992), (b) Effect of moisture on soil detachment based on Lyles et al. (1974), (c) Changes in the intensity of slaking with degree of saturation in non-dispersive soils, as reported in Lim (2006).

erosion experiment to determine the effect of the antecedent water content on the resistance of soil to erosion by overland flow in two clay soils. They found that variations in initial moisture content, which can contribute towards the development of inter-aggregate bonds, can be linked to major changes in soil erodibility. In fact, the soil strength (both shear and unconfined compressive strength) and erosion resistance were found to be higher for soils with high moisture content than air-dried soils. The effect of surface tension created by soil water on erosion resistance has been experimentally investigated in several other studies (Kemper and Rosenau, 1984; Cernuda et al., 1954; Panabokke and Quirk, 1957). Kemper and Rosenau (1984) found that cohesional forces created by water are sufficiently large to provide a significant portion of the cohesion measured in the silty loam soil they used, however, this was not true for the tested clay soil. Panabokke and Quirk (1957) tested the water stability of various soil aggregates over a range of moisture tension values and found that the aggregates were most stable at lower moisture tension values pF 2–3, i.e., at higher moisture contents, due to the capillary water films created by low tensions.

The rate at which cohesion develops in disrupted soils is also slower in an air-dried soil than in a moist soil (Kemper and Rosenau, 1984; Kemper et al., 1985), and some studies have noted that moisture must be present for cohesion forces to re-form with time (Kemper et al., 1985; Shainberg et al., 1996). Kemper et al. (1985) suggested that highest rate of cohesion increase takes place when the soils are wet, but have enough tension in the water to bind the particles strongly together. The moisture content supporting the most rapid formation of bonds after disturbances was about 0.21 g/g for Portneuf silt loam soil aggregates (Kemper et al., 1985). Kemper et al. (1985) highlighted that after disruption of inter particle bonds through agricultural or construction activities, lack of time and optimal moisture content to retrieve soil's cohesion plays a key role in the greater erosion rates of the tilled or disrupted soil. Cohesion, generally, also decreases with rapid wetting, mainly owing to the loss of bonding between soil particles/aggregates caused by the action of water (Bastos, 2002).

2.1.4. *Continuity of soil air in pore spaces*

Parker et al. (1995) observed an increased erodibility of a soil composed of 87% sand, 4% silt, and 9% clay, with reducing initial soil water content between the moisture range 0.125 and 0.200 kg/kg (Fig. 2), and attributed this to the influence of continuity of soil air in pore spaces with decreasing soil water content triggering more erosion.

2.1.5. *Particle reorientation*

An experimental study by Shainberg et al. (1996) revealed that in the clayey grumusol, increased soil water facilitates the movement and reorientation of clay particles. This improves clay-to-clay connections

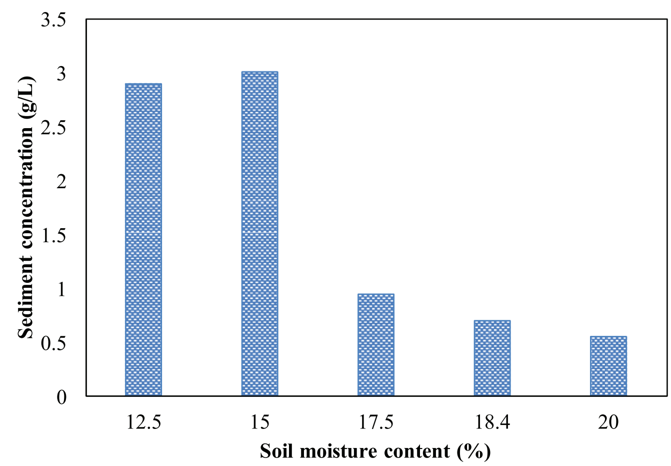

Fig. 2. Sediment concentration measured in runoff at $t = 150$ s for different initial soil moisture contents based on Parker et al. (1995).

and cementing of soil particles into a cohesive, erosion resistant structure. Therefore, rill erodibility of this clay soil decreased with increasing antecedent soil water content. Larionov et al. (2014) also suggested that water acts as a lubricant that causes uniform distribution of aggregates in soil, promoting cohesion between aggregates in their loamy soil.

2.1.6. *Runoff armoring*

The formation of a runoff water layer, which reduces the impact of raindrops and runoff on detachment and transport of sediment, was identified by Auerswald (1993) as contributing to reduction in soil loss. Also, moist soil conditions can lead to more ponding on the surface which acts as a protective water armor that reduces raindrop impact (Hairsine and Rose, 1992; Holz et al., 2015).

2.2. *A decrease or an absence of any apparent trend in soil's resistance to erosion with increasing moisture content*

In contrast to studies discussed in section 2.1, several studies have reported a decrease or absence of a defined relation in the variation of soil resistance with increasing moisture, or higher resistance in dry soil. Varied mechanisms have been noted to be responsible for it. Below we highlight these studies vis-à-vis the dominant controlling mechanism(s) in play. Table 2 provides a summary of the key findings of many of these studies.

2.2.1. Near-saturation effects

Cernuda et al. (1954) reported that soil aggregates are easily eroded when soil was completely saturated. The effect of hydraulic and surface tension forces created by water films on the stability of soil aggregates is lacking in completely saturated soils (Bastos, 2002; Christensen and Das, 1973; Hanson and Robinson, 1993). After soil disturbance, when the aggregates were close to saturation, inter-particle bonds did not reinforce with time (Kemper et al., 1985). Kemper and Rosenau (1984) mentioned that in order for moisture to cause cohesion in soils, air pressure should remain greater than the pressure of the soil water. Govers (1991), using their flume experiment with a loamy soil (17% sand, 69% silt and 14% clay), presented a parabolic equation to calculate runoff erosion resistance vis-à-vis initial moisture content for soils with 2–20% initial moisture contents. For moisture contents exceeding 20%, the erosion resistance was not dependent on moisture. Several other studies also imply that the increase in erosion resistance with antecedent moisture content is more important when the soil is drier, but when the moisture contents are closer to saturation, cohesion between aggregates and particles diminish and aggregate strength decreases resulting in high erosion rates (Bryan, 2000).

Luk and Hamilton (1986) and Coote et al. (1988) are two of the few studies that claimed that soil loss increased and aggregate stability decreased with soil moisture. Coote et al. (1988) reported that aggregate stability was negatively correlated with soil moisture content from 16.5 to 47.5%. However, Luk and Hamilton (1986) acknowledged that this observation may be true only for the data in the wetter range of the moisture scale. In the drier range, antecedent moisture may lead to an increase in soil strength and thus soil loss may decline until the moisture content corresponding to the plastic limit is reached. The plastic limit represents the soil moisture content at which the soil becomes malleable and clay begins to crack, and this reduces the shear strength of the material which increases its susceptibility to detachment (Allen et al., 1999; Holz et al., 2015). Data in Luk and Hamilton (1986) did not cover the entire moisture range to be able to investigate this effect. Atterberg consistency limits, which empirically define soil behavior as a function of changing soil moisture content, could provide some guidance to determine the optimum soil moisture content that results in greatest erosion resistance (Bryan, 2000; Lyle and Smerdon, 1965), however, the utility of this measure alone for soil erodibility prediction has been questioned (Grabowski et al., 2011; Partheniades, 2007).

2.2.2. Crust formation

Kemper and Rosenau (1984) reported faster rate of wetting in drier soil resulted in more disruption of aggregates leading to interlocking of particles to make a structure that has greater cohesion. Breakdown of aggregates from rapid wetting allows the resulting micro-aggregates and primary particles to later settle into tightly packed and well inter-leaved configurations, which would develop a greater soil strength when drying. This is also known as the surface sealing effect or crust formation. While soil crust formation could also be driven by several other biophysical and chemical mechanisms (Park et al., 2017; Williams et al., 2018), research has shown that aggregate break down and seal formation due to rapid wetting is faster in soils with <30% moisture than soils with >30% moisture (Holz et al., 2015; Le Bissonnais et al., 1989). Therefore, dry soil has a higher predisposition for surface sealing and once the crust is formed, dried crusted soil is more resistant to erosion.

2.2.3. Entrapped air preventing water entry in dry soils

Panabokke and Quirk (1957) reported that soils drier than pF 5.5 had higher aggregation due to entrapped air preventing water from entering pore spaces.

2.2.4. Limited volume of fine pores

In coarse textured soil with limited volume of fine pores required for slaking, low moisture conditions may not cause disruptive slaking during rapid wetting, thus does not cause higher erosion rates when soil is dry (Cernuda et al., 1954).

2.2.5. Mineralogical influence upstaging moisture control

Allen et al. (1999) did not find a significant relationship between moisture content and erodibility in loamy or clay soils. They suggested that when the clay content is greater than 10% in a soil, natural cohesive properties of clay becomes dominant and hinder the effect of moisture on soil cohesion. Higher soil resistance for drier soils (Billings clay soil from Colorado) was reported by Kemper and Rosenau (1984), who attributed this to the difference in the bonding mechanism of the tested clay soil that facilitates clay-to-clay bonding during drying. An increase in erodibility with increasing antecedent water was also reported for unoriented coarse kaolinitic-Greneda mixture (Grissinger, 1966). A negligible influence of soil moisture on erosion resistance was reported for dispersive soils (Lim, 2006), and loamy loess (Shainberg et al., 1996).

2.3. Moisture-erosion resistance relation shows contrasting trend beyond the optimum moisture content at which erosion resistance reaches a maximum

The two previous sections indicate that there could be an optimum moisture content beyond which the increasing trend in soil resistance with antecedent moisture may start decreasing (or at least do not show an increasing variation). Several studies have noted the existence of such an optimum moisture content (Grissinger, 1966; Larionov et al., 2014; Shainberg et al., 1996). In an experiment to test the effect of moisture content on the cohesion and erodibility of Chernozem soil samples, Larionov et al. (2014) found that the heavy loamy Chernozem samples (loess like loams) containing 22–24% water had the lowest erosion rate, and thus lowest erodibility (Fig. 3). The erosion rate increased with both increasing and decreasing antecedent water content. In Grissinger (1966), erosion rates of different types of clay soils were evaluated by subjecting molded samples of various soil mixtures to a uniform erosive force in a small flume. Erodibility decreased with increased antecedent water for the Grenada silt loam, illitic-Greneda mixture, montmorillonitic-Greneda mixture, and oriented coarse kaolinitic-Greneda mixture samples up to approximately 25% antecedent water content. After this point, erodibility increased with further increasing antecedent water (see Figs. 2 to 7 of Grissinger, 1966).

Varied reasons for the existence of optimum moisture content have been noted. Grissinger (1966), Larionov et al. (2014), and Shainberg et al. (1996) attributed it to nonlinear variations in cohesion. Development of cohesive forces is absent in air-dry soils. Also, when the soil water content is close to saturation, the rate of cohesive force development is slow and the soils are also more susceptible to erosion. Between these, there is an optimum water content that yield the highest erosion resistance. Studies also noted that a minimum moisture content is needed for the development of interparticle forces, which are strong enough to resist rill erodibility (Shainberg et al., 1996; Luk and Hamilton, 1986). In the loamy loess soil that Shainberg et al. (1996) used, the low-water-content treatment (246 g/kg) after 15 min of curing provided adequate water to support fast development of cohesive forces between soil particles that lead to low rill erodibility (see Fig. 2 of Shainberg et al., 1996). In contrast, the low-water-content treatment in the clayey grumusol (322 g/kg) was lower than the critical water content required for the fast formation of cohesion forces. Consequently, the rill erodibility was still relatively high after 15 min in the grumusol.

Overall, preceding studies highlight the existence of optimum moisture content at which soil's resistance to erosion (soil erodibility) is maximum (minimum), with resistance decreasing with both increase or decrease in antecedent moisture. Notably, the optimum moisture content appears to be different for different soils. Larionov et al. (2014) and Grissinger (1966) both suggested that the influence of antecedent water content on erodibility varied among soils, depending upon the clay minerals in the mixture, clay particle orientation, bulk density of the sample, and particle size. In addition, aggregation characteristics such as

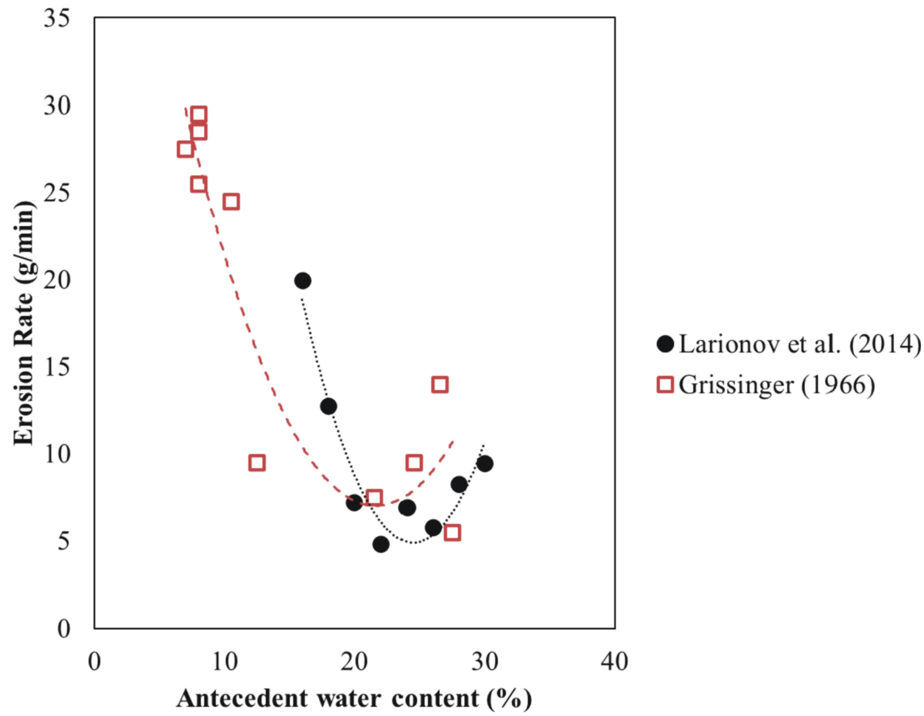

Fig. 3. Erosion rate of the soil sample as a function of water content as reported in Larionov et al., 2014 and Grissinger (1966).

aggregate size and shape which influence pore space geometry were also suggested to determine moisture-erodibility relationship (Bryan, 2000).

2.4. Ancillary dynamic factors that influence the moisture-erosion resistance relation

Aforementioned studies highlight the role of soil moisture content on soil resistance to erosion. However, several studies have noted that in addition to the magnitude of the antecedent moisture in the soil, moisture-erosion resistance relation is also influenced by factors such as (i) the curing or aging time, and (ii) moisture at the time of compaction. Curing, also known as aging of soil, refers to the time for which the soil is left undisturbed, during which stable linkages develop. Kemper and Rosenau (1984) found that cohesive strength increases due to curing, after reaching a desired water content. Shainberg et al. (1996) found that aging of soil samples reduced rill erodibility due to the development of cohesion forces with time, and that soil must be wet for these cohesion forces to develop. The rill erodibility values obtained by Shainberg et al. (1996) after 24 h of curing were similar at all moisture contents. Thus, after reaching a critical moisture content, the effect of aging time on rill erodibility was more pronounced than that of soil water content.

Moisture content at the time of compaction also has an effect on erosion resistance of soil. Compaction may be experienced during anthropogenic interventions related to agricultural and engineering activities. The erosion resistance increases as the compaction moisture content increases with the exception when soil is saturated (Christensen and Das, 1973; Hanson and Robinson, 1993; Wan and Fell, 2004). This increase in resistance was attributed to the influence of moisture on smoothening of the surface of the clay (Christensen and Das, 1973), reduced swelling during compaction (Hanson and Robinson, 1993), and an overallfacilitation of the orientation of clay particles to a high cohesion low energy state (Grissinger, 1966).

2.5. Soil moisture's influence on erosion resistance at field or larger scales

Beyond the laboratory scale experiments where studies have demonstrated a strong control of soil moisture on soil erosion resistance (see previous subsections for numerous examples), field scale studies have also noted the differences in sediment yield from wet and dry soils. Antecedent soil moisture at the start of a rain event is shown to be particularly important for soil erosion in field settings, due to its influence on soil's resistance (Govers et al., 1990; Grissinger, 1966; Rauws and Auzet, 1989). The effect of initial moisture content alone can cause a few orders of magnitude change in runoff erosion resistance of loamy soils (Govers, 1991). Moderate to high intensity rainfall events occurring on dry, bare soil can lead to greater erosion, whereas initially moist soil can be relatively hard to break down by the impact of raindrops or overland flow. This can lead to a range of sediment concentrations at the outlet for the same runoff/discharge values depending on high and low initial soil moisture conditions (Battista et al., 2020). Nachtergaele and Poesen (2002) showed that morphological differences in gullies formed in winter and summer under similar erosive power were due to different initial soil moisture contents. Wide and shallow gullies in the summer were attributed to intense rain that hit an air-dry top soil, whereas small winter gullies were formed when soil is at or near field capacity. In contrast to decreasing the runoff erosion resistance of soils, low initial moisture contents are also known to increase the infiltration capacity of the soil and decrease runoff generation, which can lead to a reduction in erosion (Sun et al., 2018). In an attempt to assess the relative significance of these two countering factors, Govers et al. (1990) found that a given rainfall event may lead to more erosion and sediment when the soil is initially dry, regardless of their higher infiltration capacity. The greater sediment yields in arid and semiarid zones (Collins and Bras, 2008; Istanbulluoglu and Bras, 2006) may also be because of the higher runoff detachability of dry soil, in addition to the reduced contribution of vegetation cover to provide protection against erosion (Govers et al., 1990). In arid and semiarid areas, the likelihood of precipitation events occurring on a dry soil is greater than in temperate or tropical settings (Pilgrim et al., 1988). Overall, reductions in soil erosion/sediment generation due to enhanced infiltration capacity and reduced runoff in dry soil can be potentially offset by high erosion rates of dry soil due to their low erosion resistance specially during intense rainfall events (Fig. 4). Therefore, the influence of initial soil moisture content on erosion resistance may provide an explanation to the runoff-sediment

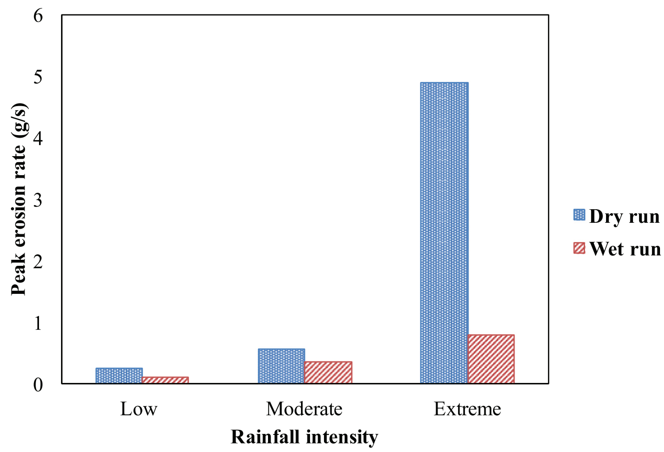

Fig. 4. Peak erosion rate under rainfalls of low intensity long duration, moderate intensity and duration, and extreme intensity short duration, for soils in dry state (blue) and wet state (red), based on Ran et al. (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relationships observed at continental and global scales (Govers et al., 1990).

3. A need to define moisture-erosion resistance relationship in sediment modeling

Aforementioned studies (discussed in section 2) emphasize that soil erosion models, especially those that perform predictions at seasonal, event, or finer temporal resolutions, should incorporate the effects of antecedent soil moisture content on soil loss predictions not only via runoff generation but also soil's resistance (Luk and Hamilton, 1986; Poesen et al., 1999). It is also important to recognize and incorporate the spatial and temporal dimensions of this relation as well (Nachtergaele and Poesen, 2002). Spataully, local rainfall patterns and the fraction of runoff occuring on initially wet soil need to be considered when simulating soil loss (Govers and Loch, 1993), because the relative contribution of the amount of sediment produced in various areas of a catchment may highly depend on the spatial distribution of antecedent moisture content of the soil (Kim et al., 2016; Zi et al., 2019). Given the fact that antecedent moisture can cause several orders of magnitude change in erosion (Govers, 1991), accounting for its spatial distribution may help reduce errors in sediment simulations. Temporally, the variation in moisture content on sediment response during a single rainfall event as well as a series of events needs to be considered. When a series of rainfall events occur after a dry period, sediment production may be largest in the first storm, and erosion resistance will increase in subsequent events due to soil becoming moist and also due to surface sealing effect (Govers, 1991). As one of the few studies that considered the time series of soil loss, Luk and Hamilton (1986) recognized the complexity that is added to the erosion resistance-soil moisture relationship by the variation in soil moisture content over time during a single rainfall event. During a single event, for dry soil, the variability in sediment concentration can be higher, and peak sediment concentration can occur towards the beginning of the event as more dry, easily removable materials are available (Fig. 3 of Ran et al., 2012), whereas on moist soil, sediment concentrations can be largely constant in time (Govers, 1991). Although antecedent soil moisture content during and between individual storm events is most vital for determining erosional response, erodibility is also influenced by soil moisture regime over longer time periods (Bryan, 2000). Many studies have shown that recurring wetting–drying cycles can result in a decline of aggregate stability (Bryan, 2000; Shiel et al., 1988), while there can be complex responses with both increased and decreased stability considering disturbed and undisturbed soils (Utomo and Dexter, 1982). At longer time scales (e.g., annual to interdecadal) as well, changes in moisture regimes due to variations or changes in climate may result in variations in soil erosion resistance. In summary, spatially and temporally dynamic relationships of soil resistance needs to be incorporated in sediment models for both short- and long-term predictions.

All the evidence presented here suggest that the use of a single value for erodibility can cause serious errors in trends and magnitudes of predicted erosion, especially for event scale simulations. It is important that the variation in soil erosion resistance through time and space vis-à-vis the influence of initial soil moisture contents be considered in erosion resistance variables (Nachtergaele and Poesen, 2002).

4. Candidate variables for quantifying the soil's resistance to erosion vis-à-vis antecedent moisture

To account for the role of moisture on soil erosion resistance, several candidate variables exist. These include soil cohesion (Haines, 1925; Kemper and Rosenau, 1984), aggregate stability (Cernuda et al., 1954; Kemper and Rosenau, 1984; Panabokke and Quirk, 1957), erodibility (Allen et al., 1999; Grissinger, 1966; Larionov et al., 2014; Parker et al., 1995; Shainberg et al., 1996), soil loss/rate of erosion (Govers et al., 1990; Le Bissonnais and Singer, 1992; Lim, 2006; Luk and Hamilton, 1986; Lyles et al., 1974), intensity of slaking (Lim, 2006), critical shear stress (Allen et al., 1999; Gilley et al., 1993; Nachtergaele and Poesen, 2002), and shear strength (Govers and Loch, 1993; Yokoi, 1968). More details regarding each variable vis-à-vis the soil resistance property they encapsulate are listed below.

4.1. Erodibility

Erodibility is a widely used lumped parameter that captures the average annual soil erosion from a standard plot. It is used in a range of models, including the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) and modified USLE, ANSWERS (Beasley et al., 1980), GUESS (Carroll et al., 1986), and SWAT (Arnold et al., 2012). Erodibility (or *K-factor*) is used to indicate the resistance that soils have against the effect of raindrops on the soil surface and the shearing action of runoff between soil clods (FAO, 2019). It is quantified as the average rate of soil loss per unit rainfall erosivity from a cultivated continuous fallow plot with 9% slope and 22.1 m length. Since direct measurement of the *K-factor* for each soil configuration is implausible, data from long-term erosion measurements at standard field plots has been used to generate a soil erodibility nomograph, which relates erodibility to inherent properties of the soil. Specifically, a soil erodibility nomograph relates the *K-factor* to soil parameters such as percentage of silt, percentage of sand, percentage of organic matter, and structure and permeability classes (Wischmeier et al., 1971). Since it was first developed, the nomograph has formed the basis for soil erosion prediction in many parts of the world. Later, a sixth variable, namely rock fragment cover, was added by Wischmeier and Smith (1978). In summary, erodibility is often parameterized as a constant value for a given soil type (Bryan, 2000; Nachtergaele and Poesen, 2002).

Notably, erodibility does not explicitly account for the impact of soil moisture on soil resistance. Given that standard erosion plots with identical soils in two different hydroclimatological settings can yield different sediment amounts, erodibility estimate is after all not agnostic of local hydroclimatology (and associated hydrologic states such as the soil moisture regime) at the measurement plot (Coote et al., 1988; Govers and Loch, 1993; Grissinger, 1966). Hence, its estimate based on data from experimental plots may be affected by moisture regime of the setting where the observations were made (Bryan, 2000). This limitation is being increasingly recognized and attempts are being made to address this concern. For example, Dangler and El-Swaify (1976) calculated K values for wet and dry soil conditions, and Hosoyamada (1986) calculated cold and warm K values. Seasonal effects on the USLE K, intended to capture the effect of freezing and thawing processes and other factors influencing the temporal variations in soil erodibility including antecedent soil water (Alewell et al., 2019; Mutchler and Carter, 1983), are also being considered. However, these do not and are not intended to exclusively represent the full effects of the soil moisture content on erosion resistance. Govers et al. (1990) conducted experiments in a 20 m flume to evaluate the changes in the erosion resistance of a loamy soil due to compaction and initial moisture content. The constant k_1 (measured in kg/(m h (m^3/h)$^{5/3}$), which is proportional to the total soil loss, was found to be reasonably well predicted using a parabolic equation with percent initial gravimetric moisture content (GMC_i) being one of the independent variables:

$$k_1 = 2005.63 - 157.47 GMC_i + 3.23\, GMC_i^2 \tag{1}$$

Allen et al. (1999) conducted field experiments using a submerged jet apparatus to calculate the erodibility coefficients in alluvial soils along stream channels. Increasing moisture contents yielded lower erodibility coefficients for moisture content range ~ 6 to 21% for sand/silt textured alluvial soil along stream channels. Using multiple regression analysis on different soil parameters, erodibility coefficient, K, (measured in cm/h/Pa) was derived for soils with less than 10% clay,

$$Jet\ Index = -0.0272 + 0.000459 Sand - 0.0004752 Moisture \tag{2}$$

$$K = 0.003 e^{385 Jet\ Index} \tag{3}$$

This equation indicates that, for soils with less than 10% clay, antecedent moisture content is important in determining soil erodibility measured by the submerged jet test, and the erodibility increases with decreasing moisture content. Preetha and Al-Hamdan (2019) developed a method to dynamically predict the modified USLE erodibility factor or K factor for a selected watershed and identified it to be affected by five variables one of which is soil moisture content. The robust correlation between the K value (measured in ton ha hr/ha MJ mm) estimated from the multiple linear regression model and the measured K indicated that the using soil moisture content as a predictor variable ($R^2 = 0.84$, $p < 0.05$) provides a better estimate of soil erodibility in areas with notable temporal variability in land cover. Two regression equations were developed,

$$K = -0.059 + 0.161 AWC + 0.134 BD - 0.000062 P; \qquad R^2 = 0.898 \tag{4}$$

$$K = -0.064 + 0.173 AWC + 0.122 BD - 0.000044 P + 7.699 LS + 0.0081 C; \qquad R^2 = 0.903 \tag{5}$$

where, AWC is antecedent soil moisture content (%), BD is bulk density (g/cm^3), P is soil permeability (mm/h), LS is USLE slope length and steepness (m), and C is USLE crop management factor. Studies such as these are promising. However, a relation defining the variation in erodibility with moisture for a range of soil types still remains unidentified.

4.2. Soil cohesion

Soil cohesion is another variable that is used to represent the resistance of soils to erosion. Kemper and Rosenau (1984) presented equations to calculate the cohesion forces due to hydraulic pressure and surface tension. Using the results of their study, they suggested that pressure difference between air and water i.e., ($P_a - P_w$), and the soil volume occupied by water, θ, (m^3 m^{-3}) could provide an estimate of the cohesion in bulk soils due to hydraulic pressure, F_{hs}, (N/m^2) as follows:

$$F_{hs} = \theta(P_a - P_w) \tag{6}$$

The cohesion associated with surface tension forces was calculated by assuming spherical pores with an air water interface around their perimeter that applies a surface tension. Therefore, a given pore of radius r_i, produces a cohesion of, $2\sigma\pi r_i$ in the soil. σ is the surface tension of the air-water interface measured in N/m. The cohesional force due to surface tension in the soil, F_{ss}, was estimated using,

$$F_{ss} = \sum_{i=1}^{n} \frac{\theta_i}{\pi r_i^2} 2\pi r_i \sigma = 2\sigma \sum_{i=1}^{n} \frac{\theta_i}{r_i} \tag{7}$$

The summation of cohesional forces created by water phase hydraulic pressure and surface tension were sufficient to explain the measured soil cohesion for these soils. In spite of these quantitative theoretical developments, a review performed by Jain and Kothyari (2009) showed that quantitative relations between the effect of cohesion and erosion/sediment transport processes have not been established yet.

A few efforts have been made to incorporate the influence of soil moisture conditions on cohesion. Zi et al. (2016) incorporated the dependency of soil cohesion on soil moisture in the spatially-explicit, sediment erosion, deposition and transport module they developed for the GEOtop distributed hydrological model. They used soil cohesion to represent the soil's resistance to erosion and calculate rainfall splash detachment D_R (kg m^{-2} s^{-1}) using,

$$D_R = \left(0.1033 \frac{K_e}{\zeta} e^{-1.48h} + 3.58\right) {}^{*}I \tag{8}$$

where ζ is soil cohesion (kPa), K_e is rainfall kinetic energy (J/m^2 mm), h is depth of overland flow (m), and I is the precipitation intensity (mm/h). This cohesion term is a combination of the effect of soil moisture and root tensile strength on cohesion (ζ).

$$\zeta_s = \left(\frac{\theta}{\theta_s}\right)^2 \zeta_{ss} \tag{9}$$

$$\zeta = \zeta_{add} + \zeta_s \tag{10}$$

where ζ_s, ζ_{ss}, ζ_{add} are bare soil cohesion, saturated bare soil cohesion and cohesion added by roots respectively, θ and θ_s are the moisture content and the saturated moisture content of the soil respectively.

Although cohesion seems to be the right parameter to represent the resistive forces of soils against water erosion, its magnitude as measured by a torvane under saturated conditions, is not very appropriate for studying the spatial and temporal variability in soil erosion resistance (Govers et al., 1990; Knapen et al., 2007). This is because, all the soil and environmental properties affecting the soil's erosion resistance (e.g. tillage effects, roots, rock fragments etc.) cannot be represented by variations in cohesion. Notably, even if a nomograph connecting the easily observable soil properties to cohesion under saturated conditions were available, a need to incorporate the influence of soil moisture conditions on cohesion for a wide range of soils still remain.

4.3. Aggregate stability

Aggregate stability is another variable used to define soil resistance to erosion. Grissinger (1966) related erosion contribution from aggregate instability to the rate of sample wetting. This empirical relationship is given by (Paaswell, 1973),

$$ER = b^{*} p \left(\frac{\Delta \text{water}}{\text{time}}\right) \tag{11}$$

where, ER is erosion rate, b is regression constant, and p is sample porosity. Auerswald (1993) presented the following equation that explained 81% of the variation in soil loss (SL) in t/ha using only two variables; antecedent soil moisture (ASM) in % wt., and time since tillage (TsT) in days. They attributed the increased stabilization of soil against erosion with increasing moisture between 10 and 31%, to two processes that reduced aggregate breakdown; reduced slaking, and the development of a protective water mulch that reduced splash.

$$SL = \frac{1}{-0.027 + 0.0022*ASM + 0.006*ASM*TsT} \quad (12)$$

Le Bissonnais (1996) proposed a unified framework to measure aggregate stability that can be used to effectively measure soil's susceptibility to erosion. However, Le Bissonnais (1996) and Le Bissonnais and Singer (1992) both noted that aggregate stability tests will not provide a comprehensive assessment of crusting and erodibility. A quantitative relation between aggregate stability and soil moisture remains undetermined.

4.4. Flow shear stress and soil shear strength parameters

Flow shear stress and soil shear strength parameters have also often been used to evaluate erosion-related soil properties (Briaud et al., 2001; Nearing and West, 1988; Nearing et al., 1988; Shainberg et al., 1996). Nachtergaele and Poesen (2002) demonstrated that detachment rate (D_r) in kg m^{-2} s^{-1} for a given loamy soil horizon, could be predicted using only flow shear stress and initial gravimetric moisture content:

$$D_r = \left(nw_g^2 - mw_g + p\right)\tau + b \quad (13)$$

where, w_g is initial gravimetric soil moisture content (kg/kg), τ is flow shear stress (Pa) and n, m, p and b are constants. They derived these coefficients as well as the lower and the upper limit of the initial gravimetric moisture content that is applicable. Values of τ which represents the force of the moving water flow against the soil bed was calculated using water density, acceleration due to gravity, width of the experimental channel, flow velocity, flow discharge, and slope gradient. Detachment calculated using this equation resulted in a R^2 of 0.83 for the top soil layer with observed values. However, some researchers have reported little or no correlation between critical flow shear stress and soil erodibility (Knapen et al., 2007; Laflen et al., 1991; Mamo and Bubenzer, 2001), and erodibility and soil shear strength (Ansari et al., 2003; Knapen et al., 2007; Parker et al., 1995). They reported that factors or processes that affect critical flow shear stress or shear strength of soils do not necessarily affect erodibility and vice versa.

The above review indicates that while some promising advances have been made in regards to quantifying the soil's resistance to erosion and estimating the influence of soil moisture content, they have mostly been performed for specific catchments, soil categories, and resistance variables. Challenges associated with measuring or estimating resistance variables across a range of soil types and properties remain.

5. Synthesis

Based on the review presented above, next we discuss the potential challenges and opportunities in incorporating the effect of soil moisture content on erosion resistance.

5.1. Challenges

A multitude of challenges exist towards representing the influence of soil moisture on soil erosion resistance. These include:

i) There are a number of parameters used to represent the soil's resistance to erosion. Each parameter, be it erodibility, cohesion, shear stress, or aggregate stability, includes various erosional processes and any single parameter does not capture all the processes involved in erosion or all the factors that influence soil erosion resistance. Also, the way these variables are measured are different, and many a times the same variable is measured differently. Most importantly, the implementation of these parameters lacks explicit representation of the dynamic nature of soil and environmental factors that govern erosion resistance. This poses a major challenge in incorporating the relationship between soil moisture content and erosion resistance in soil erosion and sediment models.

ii) Studies report various factors affecting the control of soil moisture on erosion resistance, including the type and percentage of clay minerals in the mixture (Grissinger, 1966; Larionov et al., 2014), clay particle orientation (Grissinger, 1966), curing/aging time (Kemper and Rosenau, 1984; Kemper et al., 1985; Le Bissonnais and Singer, 1992; Shainberg et al., 1996), bulk density of the sample (Grissinger, 1966), organic matter content (Cernuda et al., 1954), soil type (Shainberg et al., 1996), and texture/particle size (Allen et al., 1999; Grissinger, 1966; Kemper and Rosenau, 1984; Larionov et al., 2014). In general, there are no clear guidelines as to how prominent soil moisture influence will be on soil erosion resistance under a certain combination of soil physical conditions. Moreover, contradictory results are often reported for some parameters. For example, when the influence of texture is concerned, Allen et al. (1999) found that antecedent moisture content is important in determining soil erodibility for soils with less than 10% clay, but no significant relationship when clay content is higher. However, in many other studies, discussed above, water content in soils of diverse textural classes, including fine grained soils, has been found to have an influence on erosion resistance and this effect also shows conflicting results for some soil types (Kemper and Rosenau, 1984). No standardized relations have been derived (for different soils) that can help parameterize models easily.

iii) Most of the studies have been conducted under controlled settings. Notably, the standard laboratory tests often use small disturbed samples (Holz et al., 2015). Although these data are useful to assess the behavior of agricultural soils, most of the time they neglect the natural structure and macroporosity of the soil. In the context of fluvial geomorphology and hydrology, it is essential to consider the behavior of soil in natural undisturbed settings. Unfortunately, our understanding of the behavior of natural soils, especially in complex topographic or forested conditions, where structural characteristics of soil are usually different from agricultural soils (Chaer et al., 2009), is greatly lacking. Therefore, more appropriate tests that use much larger blocks that mimic natural soil conditions or soil in natural state are needed in order to understand the effect of dynamic soil properties on erosion resistance (Bryan, 2000).

iv) It is clear that soil resistance variables such as erodibility are not a single constant value for a given soil type, but they are strongly influenced by spatially and temporally dynamic intrinsic soil properties and extrinsic environmental conditions. The USLE erodibility or K-factor is purely a lumped, empirical parameter and intended to provide a practical tool to aid in agricultural decision making. It is not intended to apply for complex soils and topographical conditions which are typically of interest in sediment modeling. Also, it was designed to capture long-term response patterns and was not envisioned to provide the spatial and temporal variability necessary for event-based predictive modeling. In the long term, researchers propose that a standardized erosion resistance parameter that can integrate dynamic properties such as soil moisture need to be introduced, for use in dynamic sediment modeling (Bryan, 2000; Knapen et al., 2007).

5.2. Opportunities

Equations provided by various studies that are discussed in section 4 provide the basis for incorporating moisture's influence on soil erosion resistance in sediment yield predictions. Specially equations proposed by Preetha and Al-Hamdan (2019) and Zi et al. (2016) can be important starting points. However, generic equations that can be easily parameterized based on soil properties, as is done using nomographs for soil erodibility (Wischmeier et al., 1971), will likely be more useful for future soil erosion and sediment modeling efforts.

Given the fact that there is some coherence in the relation between soil resistance to erosion vis-a-vis soil moisture reported in literature, we compared the experimental observations reported for 13 soil samples from 6 different studies after transforming the reported erosion values into erosion rates per unit surface area (Fig. 5). These studies report experimentally determined soil erosion values for different antecedent soil moisture contents. All studies that reported soil moisture data along with soil erosion values that were either in (or could be converted to) erosion rate per unit surface area, were included in this meta-analysis. It is to be noted that these studies have significant differences in methodologies as well as experimental conditions. These differences are in the definition of erosion, choice of erosion measurement device, slope, soil compaction, rainfall duration and characteristics etc. Despite these differences, and the fact that erosion rates span over several orders of magnitude, all the relationships presented here show a fairly consistent trend where erosion rate decreases as initial moisture content increases, and for some, beyond a threshold moisture content, erosion rate starts increasing again. Overall, these variations can be represented by a generic quadratic equation of the form,

$$Ln\left(\frac{E}{E_d}\right) = \sigma\theta^2 - b\theta \tag{14}$$

where, E is the erosion rate per unit area of the soil (g/s/m^2) at a given moisture content, E_d is dry soil erosion rate (erosion rate at 8% moisture), θ is soil moisture content (%), and σ and b are constants. Eq. 14 was fitted to the data obtained from meta-analysis of literature. Derived parameter values of this relation for each soil type are summarized in Table 3. Table 3 and Fig. 5 highlight that parameters (in eq. 14) for silt/loam, clay, and sand are quite distinct. If E_d can be measured for a given soil, equations such as this may allow for the estimation of E at a particular soil moisture content. Although here the relation has been derived between $(\frac{E}{E_d})$ and θ, ratio of other soil resistance variables can be considered in place of $(\frac{E}{E_d})$. The ‘optimum moisture content’ at which moisture vs. cohesion relation changes trend, in other words the moisture content at which the erosion resistance is maximum, appears to be in the range of 19%–26% soil moisture depending on the soil type, given that they are cured for at least 4 h. This range was derived based on seven soil types including sandy, silty and clayey soils as reported by 5 studies reviewed in this paper (Govers, 1991; Grissinger, 1966; Larionov et al., 2014; Nachtergaele and Poesen, 2002; Shainberg et al., 1996). However, this range may differ for other soil configurations depending on the types and fraction of clay minerals present, organic matter content, and other soil conditions. More confidence in the model structure and the magnitude of optimum moisture content may be established by collecting data from a large number of soil samples with different soil types and configurations.

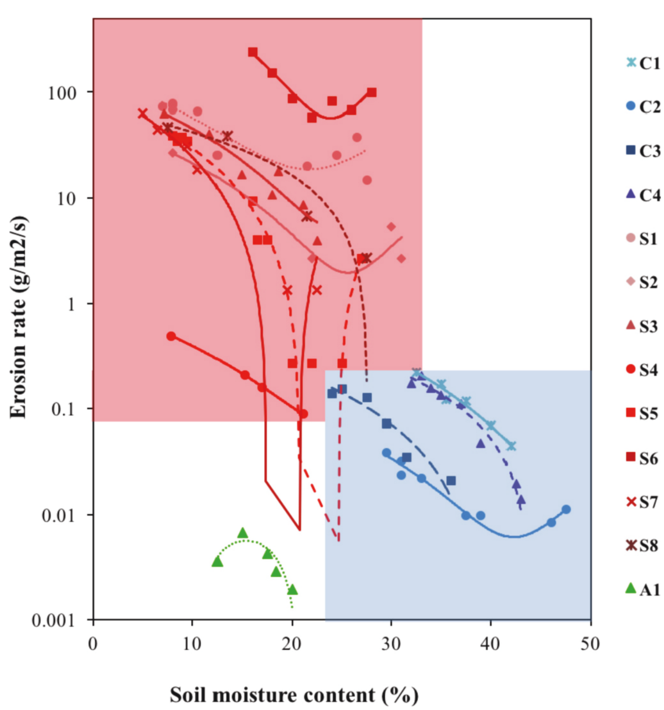

Fig. 5. Variation of soil moisture content and soil erosion rates presented by various studies. Blue, red, and green colors indicate clay, loamy, and sandy soils, respectively. Soil types and their data sources corresponding to the legend entries are provided in Table 3. The unit erosion rate (calculated in g/m^2/s) is log-stretched to aid visualization. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Parameters of eq. 14 for each soil type, as derived in Fig. 5.

Soil type	Soil name	Regression coefficients		R^2	Reference
		σ	b		
Silt/loam					
S1	10% Natural silt - Grenada silt loam	0.2838	12.287	0.853	Grissinger (1966)
S2	10% Illite - Grenada silt loam	0.0795	4.0714	0.985	Grissinger (1966)
S3	Caen silt loam with 8.5% sand, 76.2% silt and 15.3% clay	0.1948	9.4951	0.962	Govers et al. (1990)
S4	Loamy soil with 17% sand, 69% silt and 14% clay	0.0014	0.0709	0.999	Govers (1991)
S5	5% Ca montmorillonite - Grenada silt loam	0.1891	8.5869	0.989	Grissinger (1966)
S6	Heavy loamy Chernozem samples	2.8119	134.22	0.959	Larionov et al. (2014)
S7	Grenada silt loam with 20% clay, 74% silt, 6% fine sand	0.3075	11.732	0.984	Grissinger (1966)
S8	5% Illite - Grenada silt loam	0.0238	3.2816	0.939	Grissinger (1966)
Clay					
C1	Kaolinite-sand mixture	0.0010	0.0902	0.958	Christensen and Das (1973)
C2	Grundite clay	0.0002	0.0156	0.945	Christensen and Das (1973)
C3	Grundite-sand mixture	0.0004	0.0361	0.908	Christensen and Das (1973)
C4	Kaolinite clay	0.0004	0.0438	0.949	Christensen and Das (1973)
Sandy					
A1	Loamy sand soil with 87% sand, 4% silt, and 9% clay	−0.0002	0.0062	0.775	Parker et al. (1995)

6. Future research directions

Deriving robust quantitative relations that capture the influence of antecedent soil moisture on erosion resistance of soils, and methods (preferably resembling a nomograph) for easy parameterization of such relations, remain a high priority for fluvial geomorphology research. Based on the above review, several short-term and long-term future research needs can be identified.

Future short-term research need to be directed towards a better understanding of how antecedent moisture content in soils affect erosion resistance under rainfall events of different intensities and soil types. This should include experiments designed to understand the role of rain

Table 1
Summary of studies that found an increase in soil resistance to erosion with increasing moisture.

Reference	Indicator of erosion resistance	Test method	Soil type	Assumptions/conditions/ dependencies	Key findings
Allen et al. (1999)	Erodibility coefficient K	Submerged jet test	Alluvial soil with <10% clay		For soils tested with <10% clay, antecedent moisture content is important in determining soil erodibility and erodibility increases with decreasing moisture content.
Auerswald (1993)	Soil loss	Filed erosion experiment using a rainfall simulator with plot size 1.8 m by 4.7 m.	Loessial Dystric Eutrochrept top horizon (24% clay 61% silt, 4% very fine sand and 15% sand)	Rainfall over a period of 10 days, 1 h first run, and a 0.5 h second run after a break of 0.5 h. Average rain intensity 55 mm/h with a kinetic energy of 19 J/(m^2 mm)	81% of the variation in soil loss explained by only moisture and time since tillage. Increased stabilization of soil against erosion with increasing moisture between 10 and 31%, owing to reduced aggregate breakdown due to reduced slaking, and the development of a water mulch that reduced splash.
Bastos (2002)	Erodibility by Inderbitzen test, shear stress represented by cohesion	Inderbitzen test, conventional and suction-controlled direct shear tests	B (lateritic) and C (saprolitic) horizons of four residual soils found in Southern Brazil		Soils where total cohesion decreased significantly with rapid moisture increase (due to the action of superficial flow) were those more susceptible to erosion. Rapid wetting causes a significant decrease in soil shear strength related to pore pressure, the destruction of bonding between soil particles/aggregates triggered by the force of erosion flow, and slaking.
Cernuda et al. (1954)	Aggregate stability	Slaking and resistance to falling water drops	15 types of soils from Puerto Rico		Low tensions created by capillary water films can increase the stability of soil aggregates. Slaking and the ease of destruction was greatest for dry soil.
Govers and Loch (1993)	Sediment concentration	Field erosion experiment	Irving clay soil (66% clay 18% silt and 12% fine sand) and Moola clay soil (44% clay 18% silt 32% fine sand and 6% coarse sand) of Queensland	Sites with wet soils were kept for 4–5 days after wetting Discharges of 0.15, 0.4, and 1.2 L/s.	Erosion resistance was greater for soils with initially high water content than air dried soil due to the development of inter-aggregate bonds and disruption of the soil aggregates by slaking and microfissuration during rapid wetting of initially dry soil.
Govers et al. (1990)	Sediment concentration and soil loss.	Flume study on a 20 m long flume with a 0.07 slope using a rainfall simulator	Caen silt loam with 8.5% sand, 76.2% silt and 15.3% clay.	For wet runs, moisture was regulated for at least 24 h before the experiment. Experiment duration was 1 h 30 m and rainfall intensity was 100 mm/h.	Runoff erosion by high- intensity events of medium duration may lead to more erosion and sediment when the soil is initially dry, regardless of their higher infiltration capacity. Micro-cracking caused by differential expansion of the swelling clay components of soil contribute to soil shear strength reduction.
Govers (1991)	Sediment concentration	Flume experiment	Loamy soil (17% sand, 69% silt and 14% clay)		Variations in the initial soil moisture content is an important factor in explaining spatial and temporal variations in sediment yield. The relationship between moisture and soil resistance can be expressed by a simple parabolic equation. Erosion resistance increases with increasing initial moisture content.
Grissinger (1966)	Rate of erosion	Flume test	Grenada silt loam mixtures with various clay minerals	Erosion resistance-moisture relationship depends on the type and amount of clay minerals in the mixture, clay mineral orientation, bulk density, aging time after pre-wetting, water temperature, particle size.	Erodibility decreased with increased antecedent water up to 25% antecedent water content.
Kemper and Rosenau (1984)	Cohesion measured by aggregate stability and moduli of rupture	Wet sieving (aggregate stability) and soil cylinders (moduli of rupture)	Portneuf silty loam from Idaho (wind deposited over 60% silt and < 20% clay) and Billings clay soil from Colorado (alluvial)		The rate of cohesion increase after disruption was slower in an air-dry soil than a moist soil. Slower wetting allows more particles to remain coherent in the aggregates, due to reduced slaking. A

(continued on next page)

Table 1 (*continued*)

Reference	Indicator of erosion resistance	Test method	Soil type	Assumptions/conditions/ dependencies	Key findings
					substantial portion of the cohesion in Portneuf soil is created by water phase tension and surface tension related to the air-water interface.
Larionov et al. (2014)	Erodibility calculated as $k = \frac{W}{\rho_0 u^3}$ Where k is soil erodibility, W is erosion rate, ρ_0 is the water density, u is jet velocity.	Vertical jet test	Heavy loamy Chernozem soil samples	Soil samples of density 1.4 g/cm^3, at a constant jet velocity of 1.42–1.43 m/s. After wetting, the samples were exposed in weighing cups for 10–12 h.	Maximum erosion stability was achieved at 22% initial water content, due to gaining the maximum cohesion between aggregates. The erosion rate increases with both increasing and decreasing initial water content. Water acts as a lubricant that causes uniform distribution of aggregates in soil, promoting cohesion between aggregates
Larionov et al. (2018)	Erosion rate and erodibility calculated as Larionov et al. (2014)	Flume experiment	Light-clay leached chernozem (Luvic Cherno- zem (Pachic))	Water temperature of 18–20 °C, a mean flow velocity of 0.98–1.03 m/s, and a flow depth of 1 cm.	Minimum erodibility detected at a moisture content of 30%. Under drying, the soil begins to crack, inter-aggregate bonds diminish, and the erodibility increases for soil water content from 30 to 9%.
Le Bissonnais and Singer (1992)	Sediment production rate	Plot experiment with simulated rainfall	Capay silty clay loam (fine, montmorillonitic, thermic Typic Chromoxerert) and Solano silt loam (fine-loamy, mixed, thermic Typic Natrixeralf)	Soil was packed to a depth of 10 cm over a 10 cm layer of sand at a bulk density of 1.2 mg/m^3 Slope 9% rainfall rate 40 mm/h.	Higher initial soil water content decreases aggregate breakdown and crust formation, thereby reducing erosion due to decreased runoff and detachment. Erosion remained considerably lower in all the three rainfall events in pre-wetted soil than air dried soil.
Le Bissonnais et al. (1989)	Aggregate breakdown	Plot experiment with simulated rainfall	Orthic luvisol (a cultivated silty soil) from France (19.6 clay, 72.6 silt, 7.8 sand).	Aggregates were pre-wetted under vacuum, so no air-trapping (and hence slaking) in pre-wetted aggregates.	Aggregate breakdown is determined by the way of wetting and initial soil water content. Air-dry aggregates experience micro-cracking during wetting, whereas pre-wetted aggregates do not and hence aggregate breakdown is very slow.
Lim (2006)	Shear stress (critical and threshold), Erosion rate, Slaking intesity (slaking slope)/ slaking rate	Rotating cylinder test, the hole erosion test, and the slaking test	Non-dispersive soils consisting of 4 natural clays and 3 commercial clay mixtures (30%, 50% and 70% kaolin mixed with fine sand)		The degree of saturation is important determining the erosion behavior of non-dispersive unsaturated soils. The intensity of slaking increased 3 to 5 times for a 30% reduction in saturation. Lower erodibility with increasing saturation. A little change in the erosion rate for clay soils of >90% saturation.
Lyles et al. (1974)	Soil detachment by weight	Raintower wind tunnel	Silty clay loam (sand 8.8%, silt 60%, clay 31.2%)	Bulk density of 1.45 g/cm^3, test clods 12.7 to 38.0 mm in diameter, mulch-covered soil clods exposed for 45 min to wind-driven rainfall with an intensity of 1.76 in/h.	Substantially less soil was removed from field-moist clods than from air-dry clods by raindrops due to slower absorption of additional water owing to the initial degree of saturation. Field-moist aggregates lose their resistance to breakdown well in advance to becoming air-dry.
Nachtergaele and Poesen (2002)	Soil detachment rate	Flume experiment	Loess-derived soils in Belgium		Spatial and temporal variability in soil erosion is affected by soil moisture. From the range of gravimetric soil moisture contents, spatial and temporal variations in detachability over an area can be estimated using the relationships developed. Erodibility decreases with increasing soil moisture.
Panabokke and Quirk (1957)	Water stability of soil aggregates	Wet sieving and shaking end-over-end in a cylinder of water	Soil from South Australia Urrbrae loam (red brown earth) A and B horizons – cultivated and uncultivated Riverina clay (Grey soil of heavy texture) Black clay (Hydromorphic black earth)		The aggregate stability had a major effect from the tension of the soil water. A decrease in stability with decreasing water content, was associated with rapid wetting of the aggregates and the diminishing of cohesion. In clay soils, slaking caused by differential swelling is identified as responsible for the breakdown of aggregates.
		Flume test			

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Table 1 (*continued*)

Reference	Indicator of erosion resistance	Test method	Soil type	Assumptions/conditions/ dependencies	Key findings
Parker et al. (1995)	Sediment concentration		A silty sand soil composed of 87% sand, 4% silt, and 9% clay	Bulk density of 1.52 Mg/m^3 flow rate of 0.38 m^3/(m min), flow depth 15 mm, flume slope 0.005 m/m.	Erodibility increased with decreasing initial water content between moisture contents of 0.200 and 0.125 kg/kg, due to continuity of soil air in pore spaces with decreasing soil water content triggering more erosion.
Poesen et al. (1999)	Sediment concentration	Flume experiment	Silt loam from central Belgium containing 2% sand, 81% silt, 17% clay and 1.3% OM		Concentrated flow erosion rates were 20–65% less on initially wet topsoils compared to initially air-dry topsoils, depending on rock fragment cover. Rock fragment cover is less efficient in decreasing erosion rates when it is air-dry at the beginning than when it is moist. Dry soils are more detachable due to slaking and microcracking.
Shainberg et al. (1996)	Rill erodibility	Small hydraulic flume	Grumusol clay soil (Typic Chromoxerert)	0.5-m-long, 0.046-m-wide, and 0.12-m- deep flume placed at a 5% slope, under flow rates of 0.04, 0.08, 0.12, 0.16, 0.2, 0.24, 0.28, and 0.32 L/min	Rill erodibility decreases with increasing water content. No cohesive force development when the soil is air-dry. The rate of cohesive force development increases with water content above a critical water content. The formed forces are sufficiently strong to resist rill erodibility. The critical water content depends on soil type. The effect of soil moisture content greater than a critical level on rill erodibility was less pronounced after 24 h of aging.

intermittency and duration. Much of the work, so far, has been conducted under controlled laboratory conditions involving a limited number of samples. Transfering small lab-scale experimental results to large-scale systems could face challenges associated with representativeness of the samples and tranferrability of derived relations. Field research in natural settings and laboratory experiments involving large undisturbed soil blocks can be useful in this regard, as it can provide a more comprehensive picture for realistic settings and thus potentially broaden the applicability of results.

As noted in this study, soil moisture's impact on soil's resistance to erosion is generally contradictory to its effects on runoff generation and consequent sediment erosion. For example, higher soil moisture generally increases the soil's erosion resistance, but leads to higher runoff. It is important to conduct research to understand how and when these countering factors overwhelm the other under different soil, environmental, and rainfall conditions.

One potential strategy to isolate the influence of moisture content on soil resistance to erosion is to study the sediment yield variations between events with identical runoff, and then evaluating these relations over a range of runoff magnitudes. The derived relations using data from training-years may then be used in test-years to assess the improvement in explanability of sediment dynamics, when moisture's influence on soil resistance is explicitly accounted for. To limit the challenges posted by heterogeneity of soil types, initial explorations may focus on hillslopes or watersheds with homogeneous soil distribution. Follow-up studies may assess the applicability of these relations across different soils, and over larger settings with significant soil moisture heterogeneity arising from spatial variations in topography, soil types, and other physiographic attributes (Wilson et al., 2004).

Although factors such as type and percentage of clay minerals, clay particle orientation, curing/aging time, bulk density of the sample, organic matter content, soil type, and texture/particle size have been identified to have an influence on moisture vs. erosion resistance relation, no clear understanding exists as to how prominent this effect might be or how to quantitatively incorporate the influence of these factors. Data of sediment yield from diverse sources over the landscape, which can be aided by methods such as sediment fingerprinting (Smith and Blake, 2014), and from multiple, well-instrumented watersheds such as the critical zone networks (Anderson et al., 2008) may serve useful. Overall, the aforementioned proposed explorations will likely lead to improvement in the understanding and prediction of soil erosion resistance dynamics over large spatial and temporal scales, and will especially help capture the impacts of extreme events on sediment yield better as the system transition from dry to wet conditions.

In the long-term, in agreement with Bryan (2000) and Knapen et al. (2007), we propose that soil erosion and sediment prediction research needs to define a standardized erosion resistance parameter that can integrate dynamic controls such as soil moisture. In addition, as discussed in the previous sections of this study, the resistance property being measured for quantification of this parameter should be standardized as well. Differences in measurement method and the resistance property across applications pose a major challenge for incorporating the dynamic influence of moisture on erosion resistance. Future research focused on evaluation of this dynamic resistance parameter and its ability to capture sediment yield dynamics, over a manifold of soil composition, hydroclimatic conditions, and moisture conditions, could allow for benchmarking and intercomparison with existing parameter representations.

7. Conclusion

In this study, we performed a comprehensive review of the influence of antecedent soil moisture content on erosion resistance of soils. The goals were to assess the influence of soil moisture on soil's erosion resistance, identify the various mechanisms in play, pinpoint the challenges associated with representing the influence of moisture on soil erosion resistance in sediment models, and finally to come up with a few recommendations towards developing a general parameterization that can be used in soil erosion and sediment models. We found that while several studies have highlighted a significant role of antecedent

Table 2
Summary of studies that found a decrease (or no significant change) in soil erosion resistance with increasing moisture.

Reference	Indicator of erosion resistance	Test method	Soil type	Assumptions/conditions/ dependencies	Key findings
Allen et al. (1999)	Erodibility coefficient K	Submerged jet test	Alluvial soils with >10% clay (loamy and clay soils).		There is no significant relationship between moisture content and erodibility in loamy or clay soils. When clay content is >10% in a soil, natural cohesive properties of clay becomes dominant and hinder the effect of moisture on soil cohesion.
Bastos (2002)	Erodibility by Inderbitzen test, shear stress represented by cohesion	Inderbitzen test, conventional and suction-controlled direct shear tests	B (lateritic) and C (saprolitic) horizons of four residual soils found in Southern Brazil		Hydraulic and surface tension forces created by water films on the stability of soil aggregates is lacking in completely saturated soils.
Cernuda et al. (1954)	Aggregate stability	Slaking and resistance to falling water drops	15 types of soils from Puerto Rico		Slaking was not completely destructive when fine pores were limited/absent. Completely saturated soil lacks the stability associated with hydraulic and surface tension forces.
Christensen and Das (1973)	Hydraulic tractive force (shear stress)	Maintaining a steady water flow through clay linings inside a brass tube	kaolinite and grundite as basic clay minerals and Ottawa sand as an additive	Water temperature 13–14 °C, Shear stress of the flow 0.00496–0.00571 g/cm^2	A sharp decrease in erosion with increasing compaction moisture content, with the exception when soil is saturated. Moisture influences a decrease in surface roughness that reduces erosion.
Coote et al. (1988)	Aggregate stabilty, shear strength	Water-stable aggregates by wet sieving, vane shear strength using a hand-held torvane.	Guelph Sandy Loam, Colwood Silt Loam, Fox Silt Loam, Haldimand Silt Clay, Fox Sand	Seasonal variation and freeze thaw conditions	Aggregate stability and shear strength are negatively correlated with soil water content from 16.5 to 47.5%.
Govers (1991)	Sediment concentration	Flume experiment	Loamy soil (17% sand, 69% silt and 14% clay)		For soil moisture contents exceeding 20%, the erosion resistance was not dependent on moisture.
Grissinger (1966)	Rate of erosion	Flume test	Grenada silt loam mixtures with various clay minerals	Erosion resistance-moisture relationship depends on the type and amount of clay minerals in the mixture, clay mineral orientation, bulk density, aging time after pre-wetting, water temperature, particle size.	Erodibility increased with increased antecedent water for unoriented coarse kaolinitic-Greneda mixture.
Hanson and Robinson (1993)	Erodibility using a jet index	Submerged jet test		Water supply under a constant head of 0.91 m with a nozzle velocity of 4.2 m/s.	The erosion resistance increases as the compaction moisture content increases. Resistance decreased for the saturated sample.
Kemper and Rosenau (1984)	Cohesion measured by aggregate stability and moduli of rupture	Wet sieving (aggregate stability) and soil cylinders (moduli of rupture)	Portneuf silty loam from Idaho (wind deposited over 60% silt and < 20% clay) and Billings clay soil from Colorado (alluvial)		Disintegration of the aggregates with rapid wetting allows crust formation with greater cohesion, when drying. The more cohesive Billings soil had higher cohesion at low moisture, due to the influence of other factors. If air pressure is less than the pressure of the soil water, moisture does not cause cohesion in soils.
Le Bissonnais and Singer (1992)	Sediment production rate	Plot experiment with simulated rainfall	Capay silty clay loam (fine, montmorillonitic, thermic Typic Chromoxerert) and Solano silt loam (fine-loamy, mixed, thermic Typic Natrixeralf)	Soil packed to a depth of 10 cm over a 10 cm layer of sand at a bulk density of 1.2 mg/m^3 Slope 9%. Rainfall rate 40 mm/h.	Soil detachability decreased for the initially air-dried soil, during the three consecutive rain falls due to crust formation.
Le Bissonnais et al. (1989)	Aggregate breakdown	Plot experiment with simulated rainfall	Orthic luvisol (a cultivated silty soil) from France (19.6 clay, 72.6 silt, 7.8 sand).	Aggregates were pre-wetted under vacuum, so no air-trapping (and hence slaking) in pre-wetted aggregates.	Aggregate break down and seal formation due to rapid wetting is faster in an air-dry soils than prewetted soils.
Lim (2006)	Shear stress (critical and threshold), Erosion rate, Slaking intesity (slaking slope)/ slaking rate	Rotating cylinder test, the hole erosion test, and the slaking test	Dispersive clays consisting of 4 natural clays and 2 commercial clay mixtures (30% and 50% bentonite mixed with fine sand)		The variations in saturation had negligible influence on the erosion behavior of dispersive soils.
	Soil loss, Soil shear strength	Field plot experiment with artificial rainfall		Artificial rainfall at 50 mm/h. Experimental plots of 7.8 m^2	Soil loss is mainly associated with moisture content. If the full range

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Table 2 (*continued*)

Reference	Indicator of erosion resistance	Test method	Soil type	Assumptions/conditions/ dependencies	Key findings
Luk and Hamilton (1986)		using a hand-held picton torvane (field) and mechanized torvane (lab)	Two Grey- Brown Luvisol soils in southern Ontario, the Font loam and the Guelph silt loam		of soil moisture is considered, soil loss may vary by as much as 800 times. Soil loss increased and aggregate stability decreased with soil moisture.
Panabokke and Quirk (1957)	Water stability of soil aggregates	Wet sieving and shaking end-over-end in a cylinder of water	Soil from South Australia Urrbrae loam (red brown earth) A and B horizons – cultivated and uncultivated Riverina clay (Grey soil of heavy texture) Black clay (Hydromorphic black earth)		For soils drier than pF 5.5, had higher aggregation due to entrapped air preventing water from entering pore spaces.
Shainberg et al. (1996)	Rill erodibility	Small hydraulic flume	A loamy loess (Calcic Haploxeralf), and a loamy sand hamra (Typic Rhodoxeralf)	0.5-m-long, 0.046-m-wide, and 0.12-m- deep flume placed at a 5% slope, under flow rates of 0.04, 0.08, 0.12, 0.16, 0.2, 0.24, 0.28, and 0.32 L/min	In the loamy sand hamra, an increase in water content increases rill erodibility of the soil. Negligible influence of water content on rill erodibility in the loamy loess erodibility was less pronounced after 24 h of aging.
Wan and Fell (2004)	Rate of erosion, critical shear stress	Slot erosion test and the hole erosion test	13 soil types		The erosion resistance of a soil is strongly determined by the saturation at soil compaction. Saturated soils do not have an influence on erosion resistance.

moisture content on soil erosion resistance, reported covariation of the two variables were very distinct depending on the antecedent wetness of the soil. Dry soils exhibited the lowest resistance to erosion, and thereby showed high erodibility, compared to their moist counterparts. This is mainly attributed to a range of factors including slaking caused by increase in the pressure and expansion of the entrapped air due to rapid wetting, microfissuration, lack of cohesional forces provided by soil moisture, increased continuity of soil air in pore spaces, restricted soil particle reorientation to a position with low energy and high cohesion, and lack of armoring provided by the runoff water film. Soil's resistance to erosion generally increases with increasing moisture. However, after the moisture content exceeds a threshold, soil resistance was observed to decrease with further increasing soil moisture content, and soils become more susceptible to erosion. This optimum water content that yields the highest erosion resistance is highly dependent on soil type.

Soil erosion and sediment yield models, especially event-based and seasonal, should incorporate the effects of antecedent soil moisture content on soil loss prediction via not only runoff generation but also soil's resistance. The use of a single soil resistance value in this regard, say in form of a constant erodibility variable, may lead to considerable biases in trends and magnitudes of predicted erosion. Consideration of dynamic influence of initial soil moisture content will therefore result in more robust predictions. However, development of a unifying equation to predict erosion resistance based on dynamic sediment properties such as soil moisture remains challenging due to (i) disparate definitions of soil's resistance to erosion (e.g. erodibility, cohesion, shear stress, aggregate stability, etc.), and the differences in measurement methods, (ii) use of a single constant value for soil erosion resistance that does not allow to consider spatially and temporally dynamic soil properties and environmental conditions, (iii) lack of a comprehensive understanding and quantification of the factors on which the moisture-erosion resistance relationship depends on e.g. type and percentage of clay minerals, clay particle orientation, curing/aging time, bulk density, organic matter content, soil type and texture/particle size, and (iv) lack of understanding about the behavior of soil in natural undisturbed settings. Despite these challenges, synthesis of erstwhile studies point to latent opportunities towards developing a moisture-explicit erosion resistance relation arising from (i) the coherent trend in the relation between soil resistance to erosion vis-a-vis soil moisture reported in literature, (ii) equations developed by various studies to quantify the relationship, and (iii) observed trends in watershed, continental and global scales that show dry, bare soil may lead to greater erosion during intense rainfall events, whereas initially moist soil produce less sediment. Data from previous studies indicate a quadratic relation between the logarithm of normalized soil resistance variable vs. soil saturation. Notably, parameters for such a relation were observed to be significantly different for silt/loam, clay, and sand. Thus a general parameter set for each of these soil types may be used. However, robust parametarization of moisture-driven soil resistance, still needs to be derived for each soil type/ composition. Development of such a relation across soil types could be facilitated by standardization of the definition of soil resistance term and its measurement methodology. Irrespective of the functional form used to capture the moisture-erosion resistance relation, it is high time to start considering the influence of moisture on soil erosion resistance in sediment models, especially in light of climate change that is anticipated to affect soil moisture regimes and hence soil erosion trends.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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References

Aksoy, H., Kavvas, M.L., 2005. A review of hillslope and watershed scale erosion and sediment transport models. Catena 64 (2–3), 247–271.
Alewell, C., Borrelli, P., Meusburger, K., Panagos, P., 2019. Using the USLE: Chances, challenges and limitations of soil erosion modelling. Int. Soil Water Conserv. Res. 7 (3), 203–225.
Allen, P.M., Arnold, J., Jakubowski, E., 1999. Prediction of stream channel erosion potential. Environ. Eng. Geosci. 3, 339–351.

Anderson, S.P., Bales, R.C., Duffy, C.J., 2008. Critical zone observatories: building a network to advance interdisciplinary study of Earth surface processes. Mineral. Mag. 72 (1), 7–10.
Ansari, S.A., Kothyari, U.C., Ranga Raju, K.G., 2003. Influence of cohesion on scour under submerged circular vertical jets. J. Hydraul. Eng. 129 (12), 1014–1019. https://doi.org/10.1061/(ASCE)0733-9429(2003)129:12(1014).
Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W., Kannan, N., 2012. SWAT: Model use, calibration, and validation. Trans. ASABE 55 (4), 1491–1508.
Auerswald, K., 1993. Influence of initial moisture and time since tillage on surface structure breakdown and erosion of s loessial soil. Catena Suppl. 24, 93–101.
Bastos, C.A.B., 2002. The relationship between erodibility and geomechanical properties of unsaturated resdual soils. In: Jucá, J.F.T., De Campos, T.M., Marinho, F.A. (Eds.), Unsaturated Soils: Proceedings of the Third International Conference on Unsaturated Soils, UNSAT 2002, 10–13 March 2002, Recife, Brazil, vol. 2. CRC Press.
Battista, G., Molnar, P., Burlando, P., 2020. Modelling impacts of spatially variable erosion drivers on suspended sediment dynamics. Earth Surf. Dynam. 8 (3), 619–635.
Beasley, D.B., Huggins, L.F., Monke, A., 1980. ANSWERS: a model for watershed planning. Trans. ASAE 23 (4), 938–0944.
Bhuyan, S.J., Kalita, P.K., Janssen, K.A., Barnes, P.L., 2002. Soil loss predictions with three erosion simulation models. Environ. Model. Softw. 17 (2), 135–144.
Briaud, J., Ting, F.C.K., Chen, H.C., Cao, Y., Han, S.W., Kwak, K.W., 2001. Erosion Function Apparatus For Scour Rate Predictions 5 (February), 105–113.
Bryan, R.B., 2000. Soil erodibility and processes of water erosion on hillslope. Geomorphology 32 (3–4), 385–415.
Carroll, C., Rose, C.W., Crawford, S.J., 1986. GUESS-Theory Manual. Report for National Soil Conservation Project, School of Environemental Studies. Griffith Univ, Brisbane.
Cernuda, C.F., Smith, R.M., Vicente-Chandler, J., 1954. Influence of initial soil moisture condition on resistance of macroaggregates to slaking and to water-drop impact. Soil Sci. 77 (1), 19–28.
Chaer, G., Fernandes, M., Myrold, D., Bottomley, P., 2009. Comparative resistance and resilience of soil microbial communities and enzyme activities in adjacent native forest and agricultural soils. Microb. Ecol. 58 (2), 414–424.
Chen, X., Kumar, M., McGlynn, B.L., 2015. Variations in streamflow response to large hurricane-season storms in a southeastern US watershed. J. Hydrometeorol. 16 (1), 55–69.
Christensen, R.W., Das, B.M., 1973. Hydraulic erosion of remolded cohesive soils. Highway Research Board Special Report 135.
Collins, D.B.G., Bras, R.L., 2008. Climatic control of sediment yield in dry lands following climate and land cover change. Water Resour. Res. 44 (10).
Coote, D.R., Malcolm-McGovern, C.A., Wall, G.J., Dickinson, W.T., Rudra, R.P., 1988. Seasonal variation of erodibility indices based on shear strength and aggregate stability in some Ontario soils. Can. J. Soil Sci. 68 (2), 405–416.
Dangler, E.W., El-Swaify, S.A., 1976. Erosion of selected Hawaii soils by simulated rainfall. Soil Sci. Soc. Am. J. 40 (5), 769–773.
De Vente, J., Poesen, J., Verstraeten, G., Govers, G., Vanmaercke, M., Van Rompaey, A., Arabkhedri, M., Boix-Fayos, C., 2013. Predicting soil erosion and sediment yield at regional scales: where do we stand? Earth Sci. Rev. 127, 16–29.
FAO, 2019. Soil Erodibility. Retrieved from. http://www.fao.org/3/t1765e/t1765e0f.htm (11/28/2019).
Fell, R., Hanson, G.J., Herrier, G., Marot, D., Wahl, T., 2017. Relationship Between the Erosion Properties of soils and Other Parameters.
Flanagan, D.C., Foster, G.R., Moldenhauer, W.C., 1988. Storm pattern effect on infiltration, runoff, and erosion. Trans. ASAE 31 (2), 414–0420.
Gilley, J.E., Elliot, W.J., Laflen, J.M., Simanton, J.R., 1993. Critical shear stress and critical flow rates for initiation of rilling. J. Hydrol. 142 (1–4), 251–271.
Goudie, A., 2013. Encyclopedia of Geomorphology. Routledge.
Govers, G., 1991. Time-dependency of runoff velocity and erosion the effect of the initial soil moisture profile. Earth Surf. Process. Landf. 16 (8), 713–729.
Govers, G., Loch, R.J., 1993. Effects of initial water content and soil mechanical strength on the runoff erosion resistance of clay soils. Aust. J. Soil Res. 31 (5), 549–566. https://doi.org/10.1071/SR9930549.
Govers, G., Everaert, W., Poesen, J., Rauws, G., De Ploey, J., Lautridou, J.P., 1990. A long flume study of the dynamic factors affecting the resistance of a loamy soil to concentrated flow erosion. Earth Surf. Process. Landf. 15 (4), 313–328. https://doi.org/10.1002/esp.3290150403.
Grabowski, R.C., Droppo, I.G., Wharton, G., 2011. Erodibility of cohesive sediment: the importance of sediment properties. Earth Sci. Rev. 105 (3–4), 101–120. https://doi.org/10.1016/j.earscirev.2011.01.008.
Grissinger, E.H., 1966. Resistance of selected clay systems to erosion by water. Water Resour. Res. 2 (1), 131–138. https://doi.org/10.1029/WR002i001p00131.
Haines, W.B., 1925. Studies in the physical properties of soils: II. A note on the cohesion developed by capillary forces in an ideal soil. J. Agric. Sci. 15 (4), 529–535.
Hairsine, P.B., Rose, C.W., 1992. Modeling water erosion due to overland flow using physical principles: 1. Sheet flow. Water Resour. Res. 28 (1), 237–243.
Hanson, G.J., Robinson, K.M., 1993. The influence of soil moisture and compaction on spillway erosion. Trans. ASAE 36 (5), 1349–1352.
Holz, D.J., Williard, K.W., Edwards, P.J., Schoonover, J.E., 2015. Soil erosion in humid regions: a review. J. Contemp. Water Res. Educat. 154 (1), 48–59.
Hosoyamada, K., 1986. The effects of rainfall and soil properties on farmland conservation. J. Irrig. Eng. Rural. Plan. 1986 (9), 5–14.
Istanbulluoglu, E., Bras, R.L., 2006. On the dynamics of soil moisture, vegetation, and erosion: Implications of climate variability and change. Water Resour. Res. 42 (6).
Jain, R.K., Kothyari, U.C., 2009. Cohesion influences on erosion and bed load transport. Water Resour. Res. 45 (6).
Katul, G.G., Porporato, A., Daly, E., Oishi, A.C., Kim, H.S., Stoy, P.C., Juang, J.Y., Siqueira, M.B., 2007. On the spectrum of soil moisture from hourly to interannual scales. Water Resour. Res. 43 (5).
Kemper, W.D., Rosenau, R.C., 1984. Soil cohesion as affected by time and water content. Soil Sci. Soc. Am. J. 48 (5), 1001–1006. https://doi.org/10.2136/sssaj1988.03615995005200030031x.
Kemper, W.D., Trout, T.J., Brown, M.J., Rosenau, R.C., 1985. Furrow erosion and water and soil management. Trans. Am. Soc. Agric. Eng. 28 (5), 1564–1572. https://doi.org/10.13031/2013.32478.
Kim, J., Dwelle, M.C., Kampf, S.K., Fatichi, S., Ivanov, V.Y., 2016. On the non-uniqueness of the hydro-geomorphic responses in a zero-order catchment with respect to soil moisture. Adv. Water Resour. 92, 73–89.
Knapen, A., Poesen, J., Govers, G., Gyssels, G., Nachtergaele, J., 2007. Resistance of soils to concentrated flow erosion: a review. Earth Sci. Rev. 80 (1–2), 75–109. https://doi.org/10.1016/j.earscirev.2006.08.001.
Laflen, J.M., Elliot, W.J., Simanton, J.R., Holzhey, C.S., Kohl, K.D., 1991. WEPP: Soil erodibility experiments for rangeland and cropland soils. J. Soil Water Conserv. 46 (1), 39–44.
Larionov, G.A., Bushueva, O.G., Dobrovolskaya, N.G., Kiryukhina, Z.P., Krasnov, S.F., Litvin, L.F., 2014. Effect of the water temperature and soil moisture on the erodibility of chernozem samples: a model experiment. Eurasian Soil Sci. 47 (7), 734–739. https://doi.org/10.1134/S1064229314070096.
Larionov, G.A., Bushueva, O.G., Gorobets, A.V., Dobrovolskaya, N.G., Kiryukhina, Z.P., Krasnov, S.F., Litvin, L.F., Maksimova, I.A., Sudnitsyn, I.I., 2018. Experimental study of factors affecting soil erodibility. Eurasian Soil Sci. 51 (3), 336–344.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437. https://doi.org/10.1111/ejss.4_12311.
Le Bissonnais, Y.L., Singer, M.J., 1992. Crusting, runoff, and erosion response to soil water content and successive rainfalls. Soil Sci. Soc. Am. J. 56 (6), 1898–1903.
Le Bissonnais, Y., Bruand, A., Jamagne, M., 1989. Laboratory experimental study of soil crusting: Relation between aggregate breakdown mechanisms and crust structure. Catena 16 (4–5), 377–392.
Le Bissonnais, Y., Renaux, B., Delouche, H., 1995. Interactions between soil properties and moisture content in crust formation, runoff and interrill erosion from tilled loess soils. Catena 25 (1-4), 33–46.
Legates, D.R., Mahmood, R., Levia, D.F., DeLiberty, T.L., Quiring, S.M., Houser, C., Nelson, F.E., 2011. Soil moisture: A central and unifying theme in physical geography. Prog. Phys. Geogr. *35* (1), 65–86.
Lim, S.S., 2006. Experimental investigation of erosion in variably saturated clay soils. PhD Thesis. University of New South Wales.
Luk, S.H., Hamilton, H., 1986. Experimental effects of antecedent moisture and soil strength on rainwash erosion of two luvisols, Ontario. Geoderma 37 (1), 29–43.
Lyle, W.M., Smerdon, E.T., 1965. Relation of compaction and other soil properties to erosion resistance of soils. Trans. ASAE 8 (3), 419–0422.
Lyles, L., Dickerson, J.D., Schmeidler, N.F., 1974. Soil detachment from clods by rainfall: effects of wind, mulch cover, and initial soil moisture. Trans. Am. Soc. Agric. Eng. 17 (4), 697–700.
Mamo, M., Bubenzer, G.D., 2001. Detachment rate, soil erodibility, and soil strength as influenced by living plant roots part II: field study. Trans. ASAE 44 (5), 1175.
Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models. Environ. Model. Softw. 18 (8–9), 761–799.
Mutchler, C.K., Carter, C.E., 1983. Soil erodibility variation during the year. Trans. ASAE 26 (4), 1102–1104.
Nachtergaele, J., Poesen, J., 2002. Spatial and temporal variations in resistance of loess-derived soils to ephemeral gully erosion. Eur. J. Soil Sci. 53 (3), 449–463.
Nearing, M.A., West, L.T., 1988. Soil strength indices as indicators of consolidation. Trans. ASAE 31 (2), 471–0476.
Nearing, M.A., West, L.T., Brown, L.C., 1988. A consolidation model for estimating changes in rill erodibility. Trans. ASAE 31 (3), 696–0700.
Paaswell, R.E., 1973. Causes and mechanisms of cohesive soil erosion: the state of the art. Special report 135, 52–74.
Panabokke, C.R., Quirk, J.P., 1957. Effect of initial water content on stability of soil aggregates in water. Soil Sci. 83 (3), 185–196.
Pandey, A., Himanshu, S.K., Mishra, S.K., Singh, V.P., 2016. Physically based soil erosion and sediment yield models revisited. Catena 147, 595–620.
Papanicolaou, A.T.N., Elhakeem, M., Krallis, G., Prakash, S., Edinger, J., 2008. Sediment transport modeling review—current and future developments. J. Hydraul. Eng. 134 (1), 1–14.
Park, C.H., Li, X.R., Jia, R.L., Hur, J.S., 2017. Combined application of cyanobacteria with soil fixing chemicals for rapid induction of biological soil crust formation. Arid Land Res. Manag. 31 (1), 81–93.
Parker, D.B., Michel, T.G., Smith, J.L., 1995. Compaction and water velocity effects on soil erosion in shallow flow. J. Irrig. Drain. Eng. 121 (2), 170–178. https://doi.org/10.1061/(ASCE)0733-9437(1995)121:2(170).
Partheniades, E., 2007. Engineering Properties and Hydraulic Behavior of Cohesive Sediments. CRC, Boca Raton, 338pp.
Pilgrim, D.H., Chapman, T.G., Doran, D.G., 1988. Problems of rainfall-runoff modelling in arid and semiarid regions. Hydrol. Sci. J. 33 (4), 379–400.
Poesen, J., De Luna, E., Franca, A., Nachtergaele, J., Govers, G., 1999. Concentrated flow erosion rates as affected by rock fragment cover and initial soil moisture content. Catena 36 (4), 315–329.
Preetha, P.P., Al-Hamdan, A.Z., 2019. Multi-level pedotransfer modification functions of the USLE-K factor for annual soil erodibility estimation of mixed landscapes. Model. Earth Syst. Environ. 5 (3), 767–779.

Ran, Q., Su, D., Li, P., He, Z., 2012. Experimental study of the impact of rainfall characteristics on runoff generation and soil erosion. J. Hydrol. 424, 99–111.
Rauws, G., Auzet, A.V., 1989. Laboratory experiments on the effects of simulated tractor wheelings on linear soil erosion. Soil Tillage Res. 13 (1), 75–81.
Rosenbaum, U., Bogena, H.R., Herbst, M., Huisman, J.A., Peterson, T.J., Weuthen, A., Western, A.W., Vereecken, H., 2012. Seasonal and event dynamics of spatial soil moisture patterns at the small catchment scale. Water Resour. Res. 48 (10).
Shainberg, I., Goldstein, D., Levy, G.J., 1996. Rill erosion dependence on soil water content, aging, and temperature. Soil Sci. Soc. Am. J. 60 (3), 916–922.
Shiel, R.S., Adey, M.A., Lodder, M., 1988. The effect of successive wet/dry cycles on aggregate size distribution in a clay texture soil. J. Soil Sci. 39 (1), 71–80.
Smith, H.G., Blake, W.H., 2014. Sediment fingerprinting in agricultural catchments: a critical re-examination of source discrimination and data corrections. Geomorphology 204, 177–191.
Sun, D., Yang, H., Guan, D., Yang, M., Wu, J., Yuan, F., Jin, C., Wang, A., Zhang, Y., 2018. The effects of land use change on soil infiltration capacity in China: a meta-analysis. Sci. Total Environ. 626, 1394–1401.
Utomo, W.H., Dexter, A.R., 1982. Changes in soil aggregate water stability induced by wetting and drying cycles in non-saturated soil. J. Soil Sci. 33 (4), 623–637.
Wan, C.F., Fell, R., 2004. Investigation of rate of erosion of soils in embankment dams. J. Geotech. Geoenviron. 130 (4), 373–380.
Wei, L., Zhang, B., Wang, M., 2007. Effects of antecedent soil moisture on runoff and soil erosion in alley cropping systems. Agric. Water Manag. 94 (1–3), 54–62.
Williams, A.J., Pagliai, M., Stoops, G., 2018. Physical and biological surface crusts and seals. In: Interpretation of Micromorphological Features of Soils and Regoliths. Elsevier, pp. 539–574.
Wilson, D.J., Western, A.W., Grayson, R.B., 2004. Identifying and quantifying sources of variability in temporal and spatial soil moisture observations. Water Resour. Res. 40 (2).
Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses: A Guide to Conservation Planning, No. 537. Department of Agriculture, Science and Education Administration.
Wischmeier, W.H., Johnson, C.B., Cross, B.V., 1971. A Soil erodibility nomograph for farmland and construction sites. Jour. Soils and Water Cons. 26, 189–193.
Yokoi, H., 1968. Relationship between soil cohesion and shear strength. Soil Sci. Plant Nutr. 14 (3), 89–93.
Zi, T., Kumar, M., Kiely, G., Lewis, C., Albertson, J., 2016. Simulating the spatio-temporal dynamics of soil erosion, deposition, and yield using a coupled sediment dynamics and 3D distributed hydrologic model. Environ. Model. Softw. 83, 310–325.
Zi, T., Kumar, M., Albertson, J., 2019. Intercomparing varied erosion, deposition and transport process representations for simulating sediment yield. Sci. Rep. 9 (1), 1–13.