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16	Variability of rill detachment capacity with sediment size, water depth and soil slope
17 18	in forest soils: a flume experiment
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30	
31	Abstract
32	
33	Rill detachment is the most important erosive process in steep slopes and its comprehension
34	and prediction accuracy is important to properly develop soil conservation practices in
35	forest areas. This process is largely influenced by sediment size, soil slope and water flow
36	characteristics, but the results of the studies that have explored these influences are
37	contrasting. This study has simulated in an experimental flume the rill detachment capacity
38	(D_c) of soil with five particle sizes (0-0.25, 0.25-0.5, 0.5-1, 1-2, and 2-3 mm) at five water
39	flow rates (0.26, 0.35, 0.45, 0.56, and 0.67 L $m^{-1} s^{-1}$) and five bed slopes (3.5%, 9.1%,
40	19.2%, 29.1%, and 38.3%) on samples collected in a forestland of Northern Iran. $D_{\rm c}$ was
41	significantly higher (by 70%) for sediments size over 1 mm compared to the other soil
42	fractions and increased primarily with soil slope and secondarily with water depth. A
43	modelling approach has shown that the unit stream power is the best predictor of D_c using
44	power equations (NSE over 0.87). Linear regression models between D_c and shear stress (τ)
45	were very accurate (r^2 over 0.80 with few exceptions) in predicting both rill erodibility and
46	critical shear stress, when developed separately for each particle size class. Sediments with
47	size higher than 1 mm had lower resistance to rill erosion compared to the finer fractions.
48	Overall, the study helps to better understand particle detachment of the erosion process, on
49	which particle size is a key parameter. The modelling activity proposes to land planners

values of the rill erodibility and critical shear stress of forested areas for applications inprocess-based erosion models.

52

53 Keywords: Shear stress; Rill erodibility; Plantation; Unit stream power; Rill erosion;
54 Different sizes of sediment.

55

56 1. Introduction

57

58 Soil erosion is a severe threat for ecosystem health in many parts of the world (Rodrigo-59 Comino et al., 2018; Cerdà et al., 2021; Borrelli et al., 2021; Bezak et al., 2021). In the 60 water erosion process, overland flow is the most important agent of particle detachment 61 together with raindrop impact. Erosion in rills is dominant compared to laminar erosion in 62 steep hillslopes. Moreover, rill erosion is different between shallow or deep waters as well 63 high low and high flow rates (Zhang et al., 2002).

64 Soil detachment by shallow flow happens when the maximum force exerted by highly 65 turbulent water is greater than the resistance between soil particles. Sediment size plays an 66 important role in the soil detachment process, since the particle dimensions influence the 67 turbulence and detachability in sediment-laden flow (Liu et al., 2019). However, the 68 influence of sediment size in reducing or increasing soil detachment rates is sometimes 69 contrasting in literature, due to the different experimental conditions and the number of 70 factors influencing particle detachment (e.g., soil slope, water flow rates, sediment 71 concentration). For example, Ali et al. (2012) and Liu et al. (2019) state that rill detachment 72 is different from finer to coarser sediments. The experimental results by Ali et al. (2012) 73 showed that the flow velocity (and therefore soil detachment) decreases with increasing 74 median grain size. According to Liu et al. (2019), the sediment median size had a pronounced negative impact on the detachment rates. Similarly, Nearing et al. (1991) found 75 76 that the detachment rate of soils with coarse particles increases compared to finer soils. 77 Conversely, Merten et al. (2001) showed that detachment rate increases with decreasing 78 sediment size. Thus, more research is needed, in order to clarify these waiving results of the 79 literature studies. Rill detachment capacity may be even different in soils that, although 80 being of the same type and use, and subjected to the same management, are covered by 81 different tree species (Parhizkar et al., 2021a). The root system of plants may influence soil 82 aggregate stability and therefore soil detachment (De Baets et al., 2006). Moreover, the rill 83 detachment rates in reforested soils are significantly higher compared to the values measured in natural forests (Parhizkar et al., 2021b). Therefore, it is important to investigate the importance of sediment size on soil detachment in reforested soils. When soil is planted with trees, an accurate evaluation of the areas that are more exposed to rill erosion is essential, in order to choose the most protective species (Pollen, 2007; Vanoppen et al., 2015; 2017). Thus, the estimation of soil detachment capacity together with the factors that influence this parameter is important to assess not only whether a soil is exposed to non-tolerable erosion rates.

91 Erosion models are useful tools to help land managers adopting the most effective anti-92 erosive practices (Parhizkar et al., 2021d). Many process-based erosion models use soil 93 detachment capacity as key input parameter (Nearing et al., 1989, 1999; Li et al., 2015). 94 Therefore, accurate estimations of rill detachment capacity are essential to achieve reliable 95 predictions in forest ecosystems that are prone to erosion. This study has analysed the rill 96 detachment capacity through flume experiments on soils sampled in a reforested area with 97 steep slopes of Northern Iran. More specifically, we have (i) evaluated the impact of 98 different sediment size on soil detachment rate at variable water flow rates and soil slopes, 99 and (ii) setup simple models to predict the soil detachment capacity and rill erodibility from 100 hydraulic parameters for each studied sediment size. We hypothesize that the rill 101 detachment process is significantly variable with sediment size with higher detachability of 102 coarser soil fractions and steeper soils, and the prediction models developed in this study 103 are able to take into account this variability.

104

105 **2. Materials and methods**

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108

The experiments were conducted in the laboratory of soil physics at the Guilan University (Iran) on soil samples collected in the Saqalaksar Forestland Park (37°09'24"N, 49°31'50"E, Northern Iran) (Figure 1). The park is located in Guilan province, 15 km south of Rasht city, at an elevation of about 60 m above the mean sea level. The climate conditions of the area are typically Mediterranean, Csa type (Koppen–Geiger classification, Kottek et al., 2006), with mean annual values of precipitation and temperature of 1360 mm and 16.3 °C, respectively (IRIMO, 2016).

116 The soil of the park is silty clay loamy (according to the USDA classification), on average 117 33.5% of clay, 46.8% of silt and 19.6% of sand. The mean organic matter content of soil

^{107 2.1.} Study area

118 1.42%. Moreover, the mean soil bulk density of soil is 1.2 g/cm³ (Parhizkar et al., 2021c).

119 Other soil properties are reported in Parhizkar et al. (2021a).

The vegetal biodiversity in the park is large, with a great variety of tree and shrub species, mainly *Zelkova carpinifolia*, *Quercus castaneifolia*, *Alnus glutinosa*, *Parrotia persica*, *Pinus taeda*, and *Carpinus betulus* (80% of the park area). Beside these natural species, other species were planted in this forestland and then subjected to different management operations, such as harvesting, tree planting and fires (Parhizkar et al., 2021c). Some of these management practices, targeted to rehabilitation of this forestland, have modified soil properties, including soil detachment capacity (Parhizkar et al., 2021a).

127

128 2.2. Soil sampling

129

Soil was randomly but uniformly sampled in different points of the experimental area, 130 about one samples each 2000 m² (Figure 1). After sampling, soil was transferred to the 131 132 laboratory, where each sample was separated into five sediment size classes: (i) 0-0.25 mm 133 (clay, silt, and very fine to fine sand); (ii) 0.25-0.5 mm (medium sand); (iii) 0.5-1 mm 134 (coarse sand); (iv) 1-2 mm (very coarse sand); and (v) 2-3 mm (gravel). Sieves with meshes 135 of 4, 2, 1 and less than 1 mm were used, respectively. Hereinafter, the five classes will be 136 indicated using the mean value of the range: (i) 0.125 mm for clay, silt, and very fine to fine 137 sand; (ii) 0.375 mm for medium sand; (iii) 0.75 mm for coarse sand; (iv) 1.5 mm for very 138 coarse sand; and (v) 2.5 mm for gravel.







Figure 1 - Aerial map (left), Geographical location and the sampling point (right) of the
study area (Saqalaksar Forestland Park, Northern Iran). Aerial view source: Google®
Maps®.

- 146
- 147

148 2.3. Measurement of rill detachment capacity

149

150 Rill detachment capacity (D_c , kg s⁻¹ m⁻²) of the soil samples was measured in a hydraulic

151 flume with rectangular cross section (0.2 m x 0.2 m) and length of 3.5 m (Figure 2). More

152 details about this flume and the experimental procedure for running the experiments are

153 reported in Parhizkar et al. (2020a; 2020b; 2021a; 2021b).



157 Figure 2 - Flume installed at the Guilan University (Iran) and used for the experiments on 158 rill detachment capacity on soils sampled in the Saqalaksar Forestland Park (Northern Iran). 159

160

161 The experiments were carried out for each sediment size class, and D_c was measured at five water flow rates (0.26, 0.35, 0.45, 0.56, and 0.67 L m⁻¹ s⁻¹) and five gradients of the flume 162 163 bed (3.5%, 9.1%, 19.2%, 29.1%, and 38.3%). Each experiment consisted of four replicates. 164 Overall, 500 soil samples (5 sediment size classes \times 5 water flow rates \times 5 slope gradients \times 165 4 repetitions) were tested. 166 The experimental procedure consisted of the following steps. Each soil sample was packed

167 in a steel ring (diameter of 0.1 m and height of 0.05 m) and then was saturated by wetting 168 for 24 h before the flume experiment. Then, the sample was inserted in a hole of the flume 169 bed, close to the downstream outlet. After the setup of flow rate and bed gradient in the 170 flume, the experiment started pouring water from the upstream side and a stable water level 171 was waited for. The maximum duration of each experiment was 300 seconds, but sometime 172 the experimental test was ended before this limit, when a depth of 0.015 m of soil was

eroded from the steel ring. After the experiment, the wet soil sample was oven-dried andweighed.

The mean flow rate was checked by collecting and measuring five samples of water 175 176 downstream of the flume by a graduated plastic cylinder. Following Abrahams et al. 177 (1985), the average water velocity was also determined as the mean of seven 178 measurements, and this value was reduced by 0.6, 0.7, or 0.8 factors, for laminar, 179 transitional, or turbulent conditions, respectively. The mean water depth was measured by 180 averaging six measures in two cross sections of the flume using a level probe with accuracy 181 of 1 mm (Parhizkar et al., 2020a). Given the importance of water depth for the evaluation of 182 D_c, the accuracy of this measure was further checked using a self-made digital instrument. 183 In summary, this device consisted of two sections, of which the first was a printed circuit 184 board (PCB) for the detection of the water level in the flume, and the second contained a 185 junction box and a LED display.

186 D_c was calculated as the mean value of the four replicates of each experiment at a given
187 flow rate and bed gradient using equation (1).

188

$$D_c = \frac{\Delta M}{A \cdot \Delta t} \tag{1}$$

190

191 In this equation, ΔM is the dry weight of detached soil sample (in kg), Δt is the test duration 192 (in s) and A is the area of the soil sample (in m²).

In addition to the flow rate (Q, L m⁻¹ s⁻¹), depth (m) and velocity (m s⁻¹), the other hydraulic parameters measured in each experiment were the shear stress (τ , Pa), stream power (Ω , kg s⁻³), unit stream power (ω , m s⁻¹) and unit flow energy (E, m). The equations to calculate these parameters are reported in Parhizkar et al., 2020a and 2020c, while the related values measured or calculated for each experiment are reported in Table 1.

198 The rill erodibility (K_r) and critical shear stress (τ_c), which are important parameters for 199 estimating soil resistance to rill erosion (Wang et al., 2014), were calculated as the slope 200 and intercept of the following equation regressing D_c and τ :

$$202 \qquad D_c = K_r \left(\tau - \tau_c \right) \tag{2}$$

- 203
- 204

Table 1 - Hydraulic parameters measured or calculated in experiments for measuring therill detachment capacity in the Saqalaksar Forestland (Northern Iran).

Experiment	S	Q	h	V	τ	Ω	ω	E
ID	$[m m^{-1}]$	$[L m^{-1} s^{-1}]$	[m]	$[m s^{-1}]$	[Pa]	[kg s ⁻³]	$[m s^{-1}]$	[m]
1		0.26	0.005	0.17	1.70	0.29	0.006	0.007
2		0.35	0.006	0.24	1.91	0.46	0.008	0.009
3	0.035	0.46	0.007	0.36	2.15	0.78	0.013	0.013
4		0.57	0.008	0.45	2.60	1.17	0.016	0.019
5		0.69	0.009	0.56	2.89	1.62	0.020	0.025
6		0.26	0.004	0.27	3.59	0.97	0.025	0.008
7		0.35	0.005	0.38	4.49	1.71	0.035	0.013
8	0.091	0.45	0.006	0.52	5.21	2.71	0.047	0.020
9		0.56	0.007	0.61	6.07	3.70	0.056	0.026
10		0.67	0.008	0.68	6.91	4.70	0.062	0.032
11		0.26	0.003	0.33	4.77	1.57	0.063	0.008
12		0.35	0.004	0.43	6.36	2.74	0.083	0.013
13	0.192	0.45	0.005	0.55	9.47	5.21	0.106	0.021
14		0.56	0.006	0.66	11.32	7.47	0.127	0.029
15		0.67	0.007	0.74	12.96	9.59	0.142	0.035
16		0.26	0.002	0.37	5.04	1.87	0.108	0.009
17		0.35	0.003	0.47	8.57	4.03	0.137	0.014
18	0.291	0.45	0.004	0.57	11.76	6.70	0.166	0.021
19		0.56	0.005	0.71	14.61	10.37	0.207	0.031
20		0.67	0.006	0.81	17.15	13.89	0.236	0.040
21		0.26	0.001	0.39	5.18	2.02	0.149	0.009
22		0.35	0.002	0.52	8.80	4.57	0.199	0.016
23	0.383	0.45	0.003	0.61	12.34	7.53	0.234	0.022
24		0.56	0.004	0.78	15.47	12.07	0.299	0.035
25		0.67	0.005	0.89	18.89	16.81	0.341	0.045

208 Notes: S = bed gradient; Q = flow rate; h = water depth; V = mean flow velocity; τ = shear stress; Ω = stream

209 power; ω = unit stream power; E = unit flow energy.

213 Prior to the experiments, we run a 2-way ANalysis Of VAriance (ANOVA) considering the 214 rill detachment capacity as dependent variable and soil slope and flow discharge as factors 215 (independent variables, including their interaction). This allowed identifying that both soil 216 slope and flow discharge, but not their interaction, play a significant influence on D_c. Then, 217 ANOVA was applied to D_c (dependent variable) and five sediment size classes (factors). In 218 both cases, the normality of sample distribution was checked by QQ-plot tests. The 219 pairwise comparison by Tukey's test (at p < 0.05) was used to assess the statistical significance of the differences in D_c among the various sizes of sediments. 220 Moreover, non-linear models were used to evaluate possible regressions between D_c and 221 hydraulic parameters. The models are based on power equations, as suggested in the 222 223 previous studies (Parhizkar et al., 2020a; 2020c; 2021a). The Root Mean Square Error 224 (RMSE), Nash-Sutcliffe Efficiency (NSE, Nash and Sutcliffe, 1970) and the coefficient of determination (r^2) were used as evaluation criteria to verify the accuracy of these equations. 225 226 The satisfactory values of these evaluation criteria are less than 50% of observed standard deviation for RMSE, over 0.35 for NSE, and over 0.50 for r^2 . If NSE is over 0.75, the 227 228 model prediction capacity of a variable is good (Moriasi et al., 2003; Singh et al., 2008; 229 Van Liew and Garbrecht, 2003).

230 All statistical analyses were carried out using XLSTAT 9.0 software.

231

232 **3. Results**

233

3.1. Variability of rill detachment capacity with sediment size, water depth and soil slope
235

236 The preliminary ANOVA showed that both soil slope and flow rate, but not their interaction (p = 0.924), have a significant influence (p < 0.0001) on the rill detachment 237 capacity (Table 2). D_c was similar (p < 0.05) among three sediment size classes (0.125, 238 239 0.375, and 0.75). In contrast, D_c of the two coarser sediment classes (1.5 and 2.5 mm) was 240 significantly (p < 0.05) different from the finer classes. The highest D_c was measured for the coarser class (0.047 kg $m^{-2} s^{-1}$), while the finer sediments showed the lowest value 241 $(0.0263 \text{ kg m}^{-2} \text{ s}^{-1})$. Moreover, D_c of each class was highly variable around the mean value 242 of each class, as shown by the large standard deviations (Figure 3). 243

Table 2 - Two-way ANOVA of the rill detachment capacity on soil samples collected in the
Saqalaksar Forestland (Northern Iran).

248

Factors	Degree of freedom	Sum of squares	Mean squares	F-value	P-value
Soil slope	4	0.100	0.025	162.095	< 0.0001
Flow rate	4	0.003	0.001	5.548	0.000
Soil slope x flow rate	16	0.001	0.000	0.533	0.924

249

250



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Figure 3 - Box plot of variability of rill detachment capacity (D_c) among sediment size classes of forest soils sampled in Saqalaksar Forestland Park (Northern Iran) (Different letters indicate significant differences after ANOVA at p < 0.05).

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257 3.2. Relationships between rill detachment capacity and hydraulic parameters

258

The power equations between D_c and flow depth (h) at different soil slopes (S) and sediment size classesd showed high to very high correlations ($r^2 > 0.66$ with a maximum of 0.99) between these two variables, with D_c increasing with S and h. In each sediment class, the exponent of the equations increases with S, athough not monotonically (Table 3 and Figure 4).

- 265
- 266 Table 3 Power equations correlating the rill detachment capacity (D_c , kg m⁻² s⁻¹) with the
- 267 water depth (h, m) and coefficients of determination (r^2) for different sediment size classes
- 268 of the soil sampled in Saqalaksar Forestland Park (Northern Iran).
- 269

Sediment size class	Soil slope	Faustion	r^2
(mm)	(%)	Equation	I
	3.5	$D_c = 0.646 h^{1.184}$	0.99
	9.1	$D_c = 0.347 h^{0.772}$	0.94
0.125	19.2	$D_c = 1.542 h^{0.882}$	0.93
	29.1	$D_c = 0.551 h^{0.471}$	0.99
	38.3	$D_c = 0.221 h^{0.208}$	0.86
	3.5	$D_c = 0.497 h^{1.057}$	0.95
	9.1	$D_c = 0.334 h^{0.761}$	0.94
0.375	19.2	$D_c = 1.618 h^{0.892}$	0.89
	29.1	$D_c = 0.733 h^{0.518}$	0.97
	38.3	$D_c = 0.226 h^{0.211}$	0.73
	3.5	$D_c = 0.215 h^{0.668}$	0.94
	9.1	$D_c = 0.259 h^{0.916}$	0.95
0.75	19.2	$D_c = 3.328 h^{1.008}$	0.93
	29.1	$D_c = 0.422 h^{0.409}$	0.99
	38.3	$D_c = 0.214 h^{0.196}$	0.72
	3.5	$D_c = 0.178 h^{0.721}$	0.95
	9.1	$D_c = 4.468 h^{1.185}$	0.66
1.5	19.2	$D_c = 1.077 h^{0.606}$	0.97
	29.1	$D_c = 0.454 h^{0.343}$	0.94
	38.3	$D_c = 0.231 h^{0.147}$	0.96
2.5	3.5	$D_c = 0.127 h^{0.639}$	0.93
	9.1	$D_c = 26.238 h^{1.507}$	0.80
	19.2	$D_c = 0.858 h^{0.550}$	0.99

29.1	$D_c = 0.452 h^{0.333}$	0.95
38.3	$D_c = 0.231 h^{0.147}$	0.96



Figure 4 - Linear regressions between the rill detachment capacity and water depth for different soil slopes and sediment size classes of the soil
sampled in Saqalaksar Forestland Park (Northern Iran).

For all sediment classes, D_c was predicted with very high accuracy by power equations (1) based on the unit stream power (ω). This good prediction capacity is confirmed by the very high evaluation criteria, which were all very high (Table 4). Conversely, the equations using the stream power (Ω) and shear stress (τ) as input showed a lower, but satisfactory, prediction capacity of D_c . The mean flow velocity (V) and unit flow energy were poor predictors of D_c (Table 4).

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282

Table 4 - Power equations predicting the rill detachment capacity (D_c , kg m⁻² s⁻¹) from hydraulic parameters and evaluation criteria for different sediment size classes of the soil sampled in Saqalaksar Forestland Park (Northern Iran).

	Sediment size	Equation	2	NCE	DMCE
Variable	class (mm)	Equation	r	NSE	KMSE
	0.125	$D_c = 0.061 \text{ V}^{2.007}$	0.37	0.26	0.02
	0.375	$D_c = 0.061 \text{ V}^{-1.991}$	0.38	0.26	0.02
V	0.75	$D_c = 0.063 V^{1.961}$	0.37	0.26	0.02
	1.5	$D_c = 0.099 V^{1.835}$	0.38	0.27	0.03
	2.5	$D_c = 0.109 V^{1.841}$	0.40	0.31	0.03
	0.125	$D_c = 0.0008 \tau^{1.535}$	0.60	0.58	0.02
	0.375	$D_{c} = 0.0009 \tau^{1.523}$	0.61	0.60	0.02
τ	0.75	$D_c = 0.0009 \tau^{1.519}$	0.61	0.59	0.02
	1.5	$D_c = 0.002 \tau^{1.461}$	0.65	0.50	0.02
	2.5	$D_c = 0.002 \tau^{1.451}$	0.66	0.59	0.02
	0.125	$D_c = 0.005 \ \Omega^{0.955}$	0.55	0.53	0.02
	0.375	$D_c = 0.005 \ \Omega^{0.948}$	0.56	0.53	0.02
Ω	0.75	$D_c = 0.005 \ \Omega^{0.942}$	0.56	0.51	0.02
	1.5	$D_c = 0.009 \ \Omega^{0.899}$	0.58	0.52	0.02
	2.5	$D_c = 0.010 \ \Omega^{0.895}$	0.60	0.55	0.02
ω	0.125	$D_c = 0.220 \omega^{1.035}$	0.91	0.87	0.01
	0.375	$D_c = 0.218 \omega^{1.025}$	0.91	0.87	0.01

	0.75	$D_c = 0.229 \omega^{1.023}$	0.91	0.87	0.01
	1.5	$D_c = 0.354 \omega^{0.980}$	0.91	0.91	0.01
	2.5	$D_c = 0.374 \omega^{0.971}$	0.92	0.92	0.01
	0.125	$D_c = 0.826 E^{-1.008}$	0.22	0.05	0.02
	0.375	$D_c = 0.837 E^{1.006}$	0.11	-0.01	0.02
Е	0.75	$D_c = 0.805 E^{0.984}$	0.22	0.05	0.02
	1.5	$D_c = 0.963 E^{0.892}$	0.22	0.05	0.03
	2.5	$D_c = 1.092 E^{0.903}$	0.23	0.07	0.04

Notes: V = mean flow velocity (m s⁻¹); τ = shear stress (Pa); Ω = stream power (kg s⁻³); ω = unit stream 288 power (m s⁻¹); E = unit flow energy (m); r^2 = coefficient of determination; NSE = coefficient of Nash and 289 Sutcliffe; RMSE = Root Mean Square Error.

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291

292 Grouping all the studied sediment size classes of soil, equation (2), applied to couples of D_c vs. shear stress (τ), showed good, although not very high coefficients of determination (0.61 293 \leq r^2 \leq 0.70) (data not shown). When D_c was regressed against τ separately for each 294 295 sediment class, the coefficients of determination increased up to values over 0.80 (with two 296 exceptions, soil slopes of 9.1% and sediment classes of 1.5 mm) (Table 5 and Figure 5).

297 Rill erodibility (K_r) and critical shear stress (τ_c) were clearly different for sediments of variable class and soil slopes. Kr generally increased with the mean diameter of the 298 299 sediments, although this increase was not always uniform (Figure 6). In addition, τ_c 300 increased with sediment diameter and soil slope (also in this case not uniformly) (Figure 7).

301

302

Table 5 – Regression equations between the rill detachment capacity ($D_{c.} \text{ kg m}^{-2} \text{ s}^{-1}$) and 303 shear stress (τ), and coefficients of determination (r^2) at different soil slopes and for 304 different sediment size classes of the soil sampled in Saqalaksar Forestland Park (Northern 305 306 Iran).

Soil slope	Sediment size	Equation	r ²	
(%)	class (mm)	Equation	7	
3.5	0.125	$D_c = 0.0014 \tau - 0.0005$	0.99	
	0.375	$D_c = 0.0014 \tau - 0.0004$	0.94	

	0.75	$D_c = 0.0013 \ \tau - 0.0001$	0.96
	1.5	$D_c = 0.0018 \ \tau + 0.0010$	0.95
	2.5	$D_c = 0.0017 \ \tau + 0.0016$	0.93
	0.125	$D_c = 0.0010 \ \tau + 0.0015$	0.94
	0.375	$D_c = 0.0010 \ \tau + 0.0016$	0.94
9.1	0.75	$D_c = 0.0009 \ \tau + 0.0023$	0.94
	1.5	$D_c = 0.0034 \ \tau - 0.0064$	0.65
	2.5	$D_c = 0.0047 \ \tau - 0.0116$	0.78
	0.125	$D_c = 0.0016 \tau - 0.0003$	0.93
	0.375	$D_c = 0.0017 \ \tau - 0.0009$	0.88
19.2	0.75	$D_c = 0.0021 \ \tau - 0.0023$	0.93
	1.5	$D_c = 0.0031 \ \tau + 0.0152$	0.98
	2.5	$D_c = 0.0031 \ \tau + 0.0182$	0.99
	0.125	$D_c = 0.0019 \ \tau + 0.0197$	0.97
	0.375	$D_c = 0.0020 \ \tau + 0.0190$	0.94
29.1	0.75	$D_c = 0.0018 \ \tau + 0.0235$	0.99
	1.5	$D_c = 0.0025 \ \tau + 0.0400$	0.99
	2.5	$D_c = 0.0025 \ \tau + 0.0432$	0.99
	0.125	$D_c = 0.0014 \ \tau + 0.0492$	0.93
	0.375	$D_c = 0.0015 \ \tau + 0.0483$	0.83
38.3	0.75	$D_c = 0.0015 \ \tau + 0.0515$	0.80
	1.5	$D_c = 0.0010 \ \tau + 0.0806$	0.93
	2.5	$D_c = 0.0014 \ \tau + 0.0814$	0.99



Figure 5 - Linear regressions between the rill detachment capacity and shear stress at different soil slopes and for different sediment size classes of
 the soil sampled in Saqalaksar Forestland Park (Northern Iran).



315 Figure 6 - Variability of rill erodibility for different soil slopes sediment size classes of the

0.75

Sediment size class (mm)

1.5

2.5

0.375

316 soil sampled in Saqalaksar Forestland Park (Northern Iran).

0.125



318

Figure 7 - Variability of critical shear stress for different soil slopes and sediment size
classes of the soil sampled in Saqalaksar Forestland Park (Northern Iran).

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- 322

323 **4. Discussion**

324

The influence of sediment size on soil detachment has been widely investigated, but the contrasting results of the studies have suggested an analysis in hillslopes with variable steepness in reforested areas of Northern Iran. The experimental study at the laboratory 328 scale has confirmed that rill detachment, which is the dominant erosion agent in slopes with 329 the highest gradients, is different from finer to coarser sediments (Ali et al., 2012; Liu et al., 330 2019). In more detail, under the same flow rate, the variations in rill detachment capacity 331 among the five sediment size classes under investigation were noticeable, with significantly 332 higher rill detachment capacity for sediments size higher than 1 mm and lower compared to 333 size smaller than 1 mm. This result could be explained by four reasons. First, the flow 334 energy is mainly spent to detach the sediments of higher size, which leads to a lower 335 detachment rate for finer classes. This is in accordance with Liu et al. (2019), who stated 336 that the flow energy consumed to maintain coarser particles in motion for transport is not 337 available to detachment the finer fractions of soil. Second, the coarser sediments are looser 338 compared to finer particles (which include also silty and clayey fractions), and the lack of 339 resisting forces between particles, as indicated by the tensile strength, contributes to 340 increase the detachment rate for medium to coarser sandy particles. Third, the unit surface 341 of the finer particles (that is, the area per unit weight or volume) of soil is higher compared 342 to the fractions of higher size, and, therefore, the drag force act on higher surface of 343 sediment, decreasing shear stress. Therefore, lower shear stress results in lower soil 344 detachment. This is again consistent with the literature, which shows that, in shallow 345 surface flow, the tensile strength and the bursting force of particles can affect the 346 detachment rates (e.g., Nearing et al., 1991). Four, also flow turbulence plays an important 347 role in driving soil detachment. Coarser particles are subject to lower turbulence (e.g., Liu 348 et al., 2019), and this reduction hinders the ability of sediments of higher size to be lifted 349 and flushed downstream by the water flow.

350 The rill detachment capacity measured in the experimental flume increased with water 351 depth for all sediment classes, and this can be explained by the increasing flow rates. This 352 is in accordance with other works (Nearing et al., 1991; Zhang et al., 2002), who stated that 353 soil detachment rates are a function of flow depth, since particle detachment is more intense 354 with increased flow rate and depth (Zhang et al., 2002). Moreover, the higher the bed slope, 355 the higher is the rill detachment rate for all sediment classes, and therefore also the soil 356 slope plays an important role in driving the rill detachment rate. However, the equations of 357 Table 3 show that the effect of water depth on rill detachment capacity is lower at milder 358 soil gradients compared to steeper soil at all sediment sizes, as shown by the equation 359 slopes (increasing with bed slope). Presumably, higher slopes increases the dragging forces 360 on the soil particles exerted by the overland flow compared to soils with lower slopes, 361 which, in contrast, are less erodible. In other words, rill detachment is generally less

362 sensitive to changes in flow depth than in slope gradient. Our results agree with Zhang et al. 363 (2002), who highlighted the large influence of soil slope on the particle, particularly at the 364 higher gradients, using a similar flume under the same soil slopes; moreover, the effect of 365 flow depth on soil detachment rate is also dependent on slope gradient (Zhang et al., 2002). 366 The combined effect of water depth and bed slope on soil detachment capacity is 367 analytically expressed by the shear stress, which is proportional to the bed slope multiplied 368 by the hydraulic radius (which is in turn dependent on the flow depth). About the modelling 369 approach of this study, several hydraulic parameters of overland flow are descriptors of 370 water properties and this can be used to predict soil detachment capacity (Nearing et al., 1991). Several studies have tried to develop mathematical relations between hydraulic 371 372 parameters and rill detachment capacity by overland flow (Zhang et al., 2003; Xiao et al., 373 2017; Li et al., 2019; Wu et al., 2019), also in forest areas (Parhizkar et al., 2020c; 2021b). 374 This study has confirmed that, also in planted forestland, the stream power and its unit 375 value are better descriptors of rill detachment capacity compared to the other flow variables 376 tested in the flume experiments (mean velocity and energy) and ω shows the best prediction 377 capacity of rill detachment at all the investigated sediment size classes, and particularly for 378 the coarser size (mean diameter higher than 1.5 mm). This is close accordance with the 379 collection of power regression models developed in the previous study by Parhizkar et al. 380 (2021a), which was carried out in the same forestland, but without exploring the model 381 accuracy for sediments of different size. The very good prediction capacity of power 382 equations based on unit stream power derives from the fact that this hydraulic parameter 383 considers the flow velocity and soil slope at the same time, and both the latter variables 384 affect soil detachability due to the overland flow (Parhizkar et al., 2020a). In addition, 385 Wang et al. (2018) showed that the unit stream power as input of power functions is a 386 reliable prediction of soil detachment capacity, while Zhang et al. (2002) proposed other 387 hydraulic parameters to model soil detachment process.

388 Soil resistance to rill erosion can be estimated from the rill erodibility (K_r) and critical shear 389 stress (τ_c) (Nearing et al., 1989). Wang et al. (2016) and Parhizkar et al. (2020a; 2021a) 390 have highlighted the linkage of these parameters to the rill detachment capacity. Compared 391 to previous literature, this study has focused the impacts of the sediment size classes on 392 these two parameters in forestlands. In this context, the linear regressions between D_c and τ 393 must be individually developed for each sediment size class rather than for the whole soil 394 samples, and this specific modelling approach is consistent with the variability of rill 395 detachment with sediment size that has been previously analyzed. More equations with

396 regression coefficients varying with slope and sediment size simulate better reflects the 397 different effects that the drivers of rill detachment process previously identified (i.e., flow 398 energy, sediment size, unit surface of particles, and flow turbulence) play on soil erodibility 399 due to concentrated flow. In any case, the high to extremely high coefficients of 400 determination of the developed regression models show the high accuracy of these 401 equations in predicting the rill erodibility and critical shear stress. This result is consistent 402 with the conclusions of Zhang et al. (2008) and Parhizkar et al. (2020a), who reported the 403 high accuracy in linear equations regressing D_c and τ . Considering that K_r and τ_c are two of 404 the most important parameters reflecting soil resistance to rill erosion (Nearing et al., 1989), 405 the values of these variables proposed in this study can help modellers for accurate 406 predictions of rill erosion in process-based models that are very sensitive to reliable input 407 (Geng et al., 2017; Wang et al., 2016; Knapen et al., 2008). This study has shown that also 408 K_r and τ_c are highly variable with sediment size and slope of soil, both increasing from finer 409 to coarser classes and from milder to steeper profiles. The increase in these parameters in 410 sediment classes with size larger than 1 mm confirms the higher detachability of coarser 411 soil fractions and, of course, high-slope soils, and again shows less resisting force between 412 soil particles in these classes.

413

414 **5.** Conclusions

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416 This study has evaluated the influence of sediment size on rill detachment capacity of a 417 reforested soil using an experimental flume at variable flow rates and bed slopes. Rill 418 detachment capacity was significantly higher for sediments size over 1 mm compared to the 419 other soil fractions. This result has been explained by the combined effects of flow energy 420 and turbulence as well as of particle size and unit surface. Moreover, rill detachment capacity was more influenced by bed slope compared to water depth. Therefore, the first 421 422 working hypothesis of the current study (significant variations of rill detachment capacity 423 with sediment size) can be confirmed.

Power regression models were developed to assess the rill detachment capacity by hydraulic parameters for each sediment size class. The unit stream power as input parameter of power equations is the best predictor of rill detachment at all the investigated particle size classes. Linear regression models between rill detachment capacity and shear stress were very accurate in predicting both rill erodibility and critical shear stress, provided that these models are developed and calibrated separately for different sediment size classes

430	of soil. Therefore, also the second hypothesis of the current study (need to consider the rill
431	detachment variability with particle size) can be confirmed. The modelling approach of the
432	study has again confirmed that soil particles with size higher than 1 mm have a lower
433	resistance to rill erosion compared to the finer fractions.
434	Overall, the study is a contribution to a better understanding of a key process of soil
435	erosion, such as particle detachment, on which particle size plays a high influence.
436	Furthermore, the results of the modelling activity propose values of the rill erodibility and
437	critical shear stress to be used by land planners in process-based erosion models.
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