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1 **Impacts of Raindrops Increase Particle**
2 **Sedimentation in a Sheet Flow**

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13 **Author contributions**

| | |
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| Lionel Cottenot | c, d, i |
| Pierre Courtemanche | c, d |
| Carine Lucas | a, b, c, g, h, i |
| François James | a, b, c, g, i |
| Frédéric Darboux | a, b, c, d, e, g, h, i |

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16 data etc); (f) software (its provision and development); (g) supervision; (h) writing –
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23 **Data Availability Statement**

24 Data archiving is under way at <https://data.inrae.fr>.

1 **Impacts of Raindrops Increase Particle**
2 **Sedimentation in a Sheet Flow**

3
4 **Abstract**

5 Interrill erosion is driven by raindrops and sheet flow. Raindrop impacts
6 cause sediment detachment and splash, but can also affect flow transport.
7 Even if these processes have been studied for long, the actual effect of rain-
8 drop impacts on particle settling velocities has not been experimentally as-
9 sessed. This leads to unconstrained adjustments in the soil erosion models,
10 the settling velocity of particles being a freely adjustable parameter allow-
11 ing for better fitting the particle flux measured at the outlet. To address the
12 effect of raindrop impacts on the settling of particles in sheet flow, a labora-
13 tory flume experiment was designed, using an upstream feeder of sediment
14 (100–200 μm) and simulated rainfalls. It reproduced conditions close to sheet
15 flow, while not allowing for the detachment of particles from the flume bottom.
16 Two series of experiments were run: a series with a high rainfall intensity
17 (175 mm h^{-1}) generated by an oscillating-nozzle rainfall simulator, and a se-
18 ries with lower rainfall intensities (10, 15, 25, 35, 55 mm h^{-1}) generated by a
19 drop-former rainfall simulator. When a rainfall was applied, it systematically
20 decreased the sediment concentration at the outflow compared to the no
21 rain condition, however no obvious relationship was found with the rainfall
22 intensity. This shows that raindrop impacts increase particle settling veloc-
23 ities in sheet flow. Two underlying mechanisms are suggested, related to
24 the momentum of the raindrops or to the turbulence caused by the raindrops
25 into the flow. Further studies should be carried out, using computational fluid
26 dynamics and collaboration with the fluid mechanics community.

27 **Keywords:** Rainfall, sediment flux, overland flow, interrill, settling velocity

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1 Introduction

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In interrill areas, raindrop impacts and sheet flow are the main soil erosion drivers. If their respective role and their interactions has driven many research works, it remains a subject of debate (Kinnell, 2005; Zhang, 2019). Numerous works have shown that the impacts of raindrops are a major contributor to sediment detachment for sheet flow (Moss and Green, 1983; Moss, 1988; Proffitt and Rose, 1991). While raindrop impacts detach soil particles and move them in a range of a few decimeters at most by splash (Ghadiri and Payne, 1988; Leguédouis et al., 2005), the sheet flow — a shallow and slow movement of water at the soil surface — is able to transfer them downslope (Kinnell, 1990, 2005). When sheet flow is present, raindrops can also affect flow transport, which has been termed “raindrop-induced flow transport” (or RIFT) (Kinnell, 2005). RIFT has been shown to be more efficient than splash to move particles from interrill areas to rills (Kinnell, 2005). Raindrop impacts are the most effective in detaching soil particles when water depth is between two and three raindrop diameters (Moss and Green, 1983; Kinnell, 1991). For larger flow depth, the water layer protects the soil from the raindrop impact, while, for smaller flow depth, the raindrop-induced shear stress has a shorter duration and limited spatial extend (Nouhou-Bako et al., 2019). From a physical point-of-view, Kinnell (2021) states that the distance traveled by coarse particle depends (1) on the height to which the particle are lifted, (2) on the velocity of the flow, and (3) on the settling velocity of the particles. However, the effect of raindrops on the settling velocity is not specified.

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The interactions between raindrops, sheet flow, and sediments, have fostered many studies about interrill erosion, and have allowed for the design of process-based soil erosion models. The Hairsine and Rose model (Hairsine et al., 2002) includes five processes affecting particle fate: four processes for erosion (rainfall detachment, rainfall redetachment, entrainment and reentrainment) and one process for deposition (simply termed deposition). Because the transfer of particles is based on the mass-balance between these five processes, the overall particle output of the model is very sensitive to the proper parametrization of the single deposition process. As defined by Hairsine et al. (2002), this deposition process depends on the sediment concentration (with a possible vertical gradient) and on the particle settling velocity. This means the settling velocity is a key parameter of the whole modeling effort. In the transport-distance approach of Wainwright et al. (2008), the model accounts for three detachment conditions and four transport modes. While

66 sediments are divided into size classes (to allow for selective transport) with
67 specific settling velocities, [Wainwright et al. \(2008\)](#) do not give insights about
68 the definition or measurement of these settling velocities. Similar observa-
69 tions are made for the models LISEM ([De Roo et al., 1996](#)) and EUROSEM
70 ([Morgan et al., 1998](#)).

71 Currently, no measurements are available for settling velocities in raindrop-
72 impacted flows. This questions our ability to properly parametrize the Hair-
73 sine and Rose model for such flows: Do particles in a rain-impacted flow set-
74 tle with the same velocity as in still-water? Currently, applications of Hairsine
75 and Rose model take still-water settling velocities as a reference, and can
76 adjust them to get a better fit of their calibration dataset. [Tromp-van Meerveld](#)
77 [et al. \(2008\)](#) decreased the settling velocities of particles larger than 315 μm ,
78 suggesting raindrop impacts slow down their sedimentation, but increased
79 the settling velocities of particles smaller than 315 μm , suggesting raindrop
80 impacts accelerate their sedimentation. [Jomaa et al. \(2010\)](#) increased the
81 settling velocities for the whole range of particle classes (lower than 2 μm
82 to larger than 1000 μm) for two of their experiments, suggesting raindrop
83 impacts accelerate the sedimentation for all particles. For two other exper-
84 iments, [Jomaa et al. \(2010\)](#) kept the still-water settling velocities for all par-
85 ticle sizes except for the 100–1000 μm range for which the settling velocity
86 was decreased, suggesting raindrop impacts have a selective effect on the
87 sedimentation. [Nord and Esteves \(2005\)](#) kept the settling velocities equal to
88 the still-water settling velocities, suggesting raindrop impacts have no effect
89 on sedimentation. While these discrepancies may be related to the actual
90 processes occurring in the flow, it must be noted that there is no experimental
91 data evaluating the effect of raindrops on particles transported by sheet flow.
92 Hence, settling velocity is used as an adjustable parameter.

93 While the effect of raindrop impacts on particle detachment and splash
94 has been well-documented, the actual effect of raindrop impacts on parti-
95 cle sedimentation is completely unknown. In fact, experimental studies did
96 not measure detachment and sedimentation separately: they measured the
97 mass balance of these two opposite processes at the outlet ([Moss, 1988](#);
98 [Proffitt et al., 1991](#); [Huang, 1995](#); [Römken et al., 2002](#); [Kuhn and Bryan,](#)
99 [2004](#); [Kinnell, 2011](#)). Hence, the specific effect of raindrop impacts on sedi-
100 mentation is undefined. While constraints on the settling velocities in raindrop-
101 impacted flows could be prescribed in soil erosion models, there is no avail-
102 able data.

103 The two goals of the present paper are (1) to ascertain that particle set-
104 tling is affected by raindrop impact in a sheet flow and (2) to quantify this

105 effect depending on rainfall intensity. A dedicated experiment, making use of
106 a laboratory flume under rainfall simulation, was carried out. One of the chal-
107 lenges was to study only one process: the interaction between the raindrop
108 impacts and the particles transported and settling in the flow. As a conse-
109 quence, an experimental setup was specifically designed to avoid (1) par-
110 ticle (re-)detachment and (2) particle-to-particle interactions (such as (dis-
111)aggregation), while keeping experimental conditions resembling sheet flow.

112 **2 Materials and Methods**

113 The experimental setup described below allowed for the assessment of
114 the effect of raindrop impacts on particle sedimentation. It makes use of a
115 flume, a particle feeder and two rainfall simulators (in two sets of runs). Rain-
116 fall simulators permitted a good control of the experimental conditions and
117 facilitate replication. Rainfall intensity, water depth, water velocity, water flux
118 were measured to assess the hydrodynamic properties. Particle concentra-
119 tion at the outlet was measured to assess the effect of raindrop impacts on
120 particle fate.

121 A first set of experiments, using an oscillating-nozzle rainfall simulator,
122 was run at a very high rainfall intensity to maximize the potential interaction
123 between raindrop impacts and flow-transported particles, and hence answer
124 the first goal. A second set of experiments made use of a drop-former rain-
125 fall simulator and was run with lower rainfall intensities to characterize the
126 particle-raindrop interaction, tackling the second goal.

127 **2.1 Flume**

128 The flume had a length of 1.9 m, a width of 50 cm and a height of 15 cm
129 (Figure 1). It was set horizontal. Conceptually, the flume consisted of four
130 sections, which were, from upstream to downstream: a water supply and
131 stabilization section (98 cm long), a particle-supply section (9 cm long), an
132 experimental section (53 cm long) and an outlet section (30 cm long).

133 Except for the outlet section, the flume had a rough bottom made with
134 glued sand grains (between 1 and 2 mm in diameter). This was designed to
135 trap sedimented particles and to avoid their subsequent detachment.

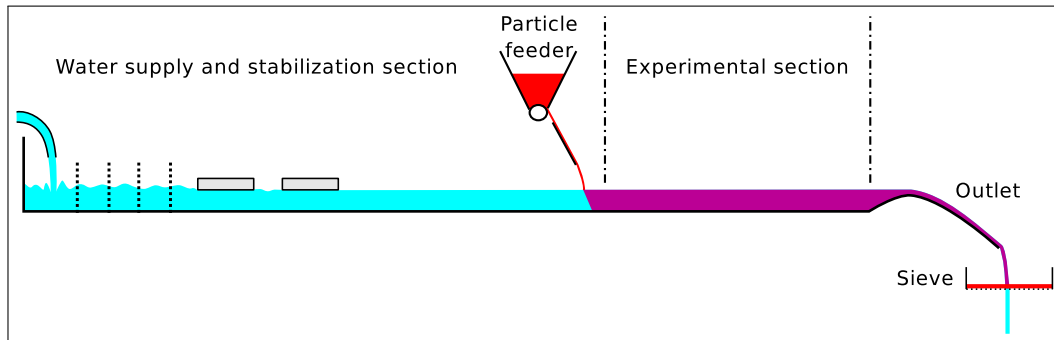


Figure 1: Scheme of the experimental setup. The water flow is supplied at the upstream end of the stabilization section. The particles are fed at the end of this section. Then follows the experimental section (only section with rainfall) and the outlet section. The particles reaching the outlet are collected in a sieve.

136 The water inflow consisted of a horizontal pipe inserted, at the upstream
 137 boundary of the flume, perpendicularly to the flow direction. The pipe con-
 138 tained holes regularly distributed over its length. The inflow rate (about
 139 73 L min^{-1}) could be adjusted with a vane. The water flow was stabilized with
 140 scouring pads, wire meshes and floats spread along the upper 50 cm of the
 141 flume. This created a sub-critical (Froude number: 0.2), laminar (Reynolds
 142 number: 2250), and homogeneous flow. In the absence of rain, no wave was
 143 visible at the water surface.

144 A particle feeder was located 9 cm upstream from the experimental area
 145 in order to protect it from water splash. It was designed to provide an homo-
 146 geneous distribution over the width of the flume. The particle feeder con-
 147 sisted of a hopper (containing the stock of particles) standing on a roller
 148 wrapped in $200 \mu\text{m}$ -particle-size emery cloth to ensure particle racking. The
 149 roller rotation was controlled by a step-by-step motor used in micro-stepping
 150 mode. The rotational speed was set to $1.36 \text{ round min}^{-1}$, giving a particle
 151 supply rate of $0.23 \pm 0.02 \text{ g min}^{-1} \text{ cm}^{-1}$ along the flume width. This rate of
 152 particle supply was chosen to get a very low particle concentration (about
 153 0.15 g L^{-1}), which should help in limiting the particle-to-particle interactions.
 154 A powder of clay brick was found appropriate in avoiding (dis)aggregation
 155 processes. The particle bulk density was 2.3 g cm^{-3} , and the particle size
 156 was between $100\text{--}200 \mu\text{m}$, leading to settling velocities of $5\text{--}16 \text{ mm s}^{-1}$ based
 157 on Cheng (1997). The particles slid on a metal sheet before reaching the
 158 water. One of the design criteria of the experiment was that no particle (re-
 159)detachment occurred. Preliminary testing confirmed this: after reaching the

160 bottom of the flume, the particles did not move further downstream for the
161 whole range of experimental conditions (water flux, rainfall intensity, etc.).

162 Rainfall was applied only in the experimental section, the other sections
163 having roofs and vertical screens. Roofs and vertical screens were covered
164 with geotextile to avoid that rain water splashed in the experimental area. The
165 outlet section was fitted with an adjustable weir that allowed for adjusting
166 the water depth. The weir geometry created a supercritical flow at the outlet,
167 preventing any upstream-moving wave to perturb the flow in the experimental
168 section of the flume.

169 2.2 Rainfall simulators

170 Two types of rainfall simulators were successively used in two separated
171 series of experimental runs.

172 The oscillating-nozzle rainfall simulator used the same design as the
173 one described in Foster et al. (1979). Two troughs were used, located 6.5 m
174 above the flume. Each trough was equipped with two nozzles (65100 Vee-
175 jet, Spraying Systems Co.), and the water pressure in the ramps was set to
176 0.8 bar, leading to a prescribed rainfall intensity of 175 mm h^{-1} . Since this
177 prescribed value may not correspond to the actual rainfall intensity, rainfall
178 intensity will be measured (see below). This extremely high rainfall intensity
179 was intended to maximize the interactions between settling particles and
180 raindrops. The mean drop diameter of the rainfall, measured with a spectro-
181 pluviometer (Laser Precipitation Monitor, Thies Clima), was 1.7 mm, with a
182 velocity of 5.8 m s^{-1} . The kinetic energy of the rainfall was $7 \text{ J m}^{-2} \text{ mm}^{-1}$. By
183 design, the rainfall was discontinuous in time: oscillating-nozzle rainfall sim-
184 ulators generate a succession of raindrop pulses. To minimize this inconve-
185 nience, the two troughs were set to oscillate alternatively at an individual rate
186 of 100 pulses per minute, leading to a pulse every 0.3 s. Since this periodic
187 sequence of rain and no-rain time intervals (even if very short) may affect the
188 particle transfer processes, supplementary experiments were carried out with
189 a drop-former rainfall simulator. This was also the opportunity to test for the
190 effect of rainfall intensity.

191 The drop-former rainfall simulator (Cottenot et al., 2021) was designed to
192 give a rainfall both homogeneous in space and continuous in time, at lower
193 rainfall intensities than the oscillating-nozzle simulator. It was made with
194 porous pipes of 16 mm in diameter. The pipes were aligned horizontally and

195 separated by 24 mm. They were attached on a grid every 20 mm with tie
196 straps. Drops formed preferentially at the tie straps. The pipes were sup-
197 plied in water by a manifold. A manometer, fixed on the manifold, allowed
198 to set the water pressure. A mesh with square openings of 3 mm was at-
199 tached 65 cm below the pipes to break the drops and to allow for a higher
200 spatial homogeneity. The mesh of the simulator was located at 6.6 m above
201 the flume. The frame supporting the whole simulator was slightly and contin-
202 uously moved horizontally to improve further the spatial homogeneity. The
203 spectropluviometer gave a mean raindrop diameter of 3.0 mm with a velocity
204 of 7 m s^{-1} , and a kinetic energy of about $20 \text{ J m}^{-2} \text{ mm}^{-1}$. Raindrop charac-
205 teristics were independent of the water pressure. The simulator was used
206 with pressures ranging from 0.18 to 1.4 bar, leading to prescribed intensities
207 from 10 to 55 mm h^{-1} (the actual rainfall intensity will be measured — see
208 below). The Christiansen's uniformity coefficient of the rainfall intensity was
209 always above 90 %.

210 **2.3 Measurements**

211 At the beginning of each experimental run, rainfall intensity was mea-
212 sured within the experimental section by timing the partial filling of 28 cylindri-
213 cal beakers (64 mm in diameter) and weighing their content. It was used to
214 check the proper setup of the rainfall simulator. During the actual experimen-
215 tal rain, rainfall intensity was checked using four or eight beakers.

216 In the absence of rainfall, the water depth was measured as the differ-
217 ence between the height of the water surface and the height of the flume
218 bottom using a mechanical comparator. During the rainfall application, no
219 accurate depth measurement could be done because of the strong agitation
220 of the water surface caused by raindrops.

221 The flow velocity was measured using the salt-velocity gauge of Planchon
222 et al. (2005). The device consisted of two pairs of conductivity probes, lo-
223 cated in an upstream-downstream configuration, and spaced by 3 cm. A salt
224 solution was added upstream from the first pair of electrodes and conductiv-
225 ity recordings were taken. The solution was supplemented with fluorescein
226 to ensure the proper orientation of the device. The signals from the probes
227 were used to solve a diffusion wave equation, allowing for the measurement
228 of the flow velocity. For each location, the velocity value was the mean of ten
229 readings.

230 The water depth and the flow velocity were measured at the nine same
231 points at first. Considering the good homogeneity of the measured values,
232 the number of measurement points per run was then reduced to three or four.
233 The water flux was measured at the flume outlet by timing the partial filling of
234 a tank, followed by the weighing of the tank.

235 The measurement of particle concentration was carried out at the flume
236 outlet. The particles were collected in a sieve of 50 μm . A sieve was placed
237 under the flow for one minute, and then replaced by another sieve. After
238 the experimental run, the sieve contents were dried in an oven (90 $^{\circ}\text{C}$), and
239 then weighed, allowing for the calculation of the particle flux. The particle
240 concentration (in mg L^{-1}) was calculated as the ratio of particle flux and water
241 flux.

242 During the design phase of the experiment, particle splash was measured
243 by attaching a collector to the side of the experimental section. Almost no
244 splashed material was collected. This means the particles entering the exper-
245 imental section had only two possible fates: sedimenting on the flume bottom
246 or reaching the flume outlet.

247 **2.4 Experimental runs**

248 The experimental runs consisted in two series. The first series, termed
249 “oscillating-nozzle series”, paired a no-rainfall condition with an extremely
250 high intensity condition. There was 3 replicates of such pair (plus a special
251 run — see below). The second series, termed “drop-former series”, evalu-
252 ated the effect of rainfall intensity from 0 to 55 mm h^{-1} using a total of 19 runs.

253 **2.4.1 Oscillating-nozzle series**

254 The first series of experimental runs made use of the oscillating-nozzle
255 rainfall simulator, with a prescribed rainfall intensity of 175 mm h^{-1} . The ra-
256 tionale for running this series was that its extremely high rainfall intensity
257 would increase the probability of interactions between raindrops and settling
258 particles, hence maximizing the effects of the rain on particle sedimentation.

259 At the beginning of an experimental run, water depth, velocity and flux
260 were measured. Then the no-rainfall condition was tested: the particle supply

261 was launched for 7 min, with particle concentration being measured every
262 minute at the outlet. After the end of the particle supply, water flux and parti-
263 cle concentration continued to be measured for three minutes. Subsequently,
264 sedimented particles were manually cleaned from the flume bed, and the
265 water flux measured. Then rainfall was initiated using the oscillating-nozzle
266 rainfall simulator. The measurements were identical in their sequence and
267 timing. Finally, the rainfall was stopped, and the water flux measured a last
268 time.

269 This oscillating-nozzle series consisted of three experimental runs with
270 paired condition: no-rainfall condition followed by rainfall condition, as de-
271 scribed above. A fourth run is included: the rainfall condition (5 min long) was
272 ran first and immediately followed by the no-rainfall condition (5 min long).
273 In fact, this fourth run was initially considered to be flawed: the rainfall was
274 stopped too early while the particle feeder was run for a longer duration.
275 However, upon inspection, the data showed to be of interest, and so were
276 included in the dataset.

277 **2.4.2 Drop-former series**

278 To assess the effect of rainfall intensity, a second series of experiments
279 was carried out. The experiment setup was similar to the oscillating-nozzle
280 series, except that the drop-former rainfall simulator was used, and that the
281 runs were not carried out by pairs.

282 This series of lower rainfall intensities (compared to the first series) con-
283 sisted of 19 experimental runs with a range of prescribed rainfall intensity:
284 3 runs with no rainfall (0 mm h^{-1}), and 2 runs at 10 mm h^{-1} , 3 runs at 15 mm h^{-1} ,
285 2 runs at 25 mm h^{-1} , 7 runs at 35 mm h^{-1} , and 2 runs at 55 mm h^{-1} . The runs
286 were not carried out in sequence of increasing rainfall intensity to avoid a
287 bias. Initially, 2 to 3 runs per intensity were planned. Owing to the large differ-
288 ences in sediment concentration among the 35 mm h^{-1} runs, additional runs
289 were carried out at this intensity.

290 **2.5 Data analysis**

291 At first, a qualitative assessment of tabulated values and graphs was
292 carried out. Owing to the limited number of samples (that do not allow for

293 asserting a normal distribution of residues), this primary analysis was com-
294 plemented with non-parametric tests. The Wilcoxon test was carried out to
295 compare two samples using R Core Team (2017). The Kruskal-Wallis test
296 was used to check for the existence of differences among groups (Dinno,
297 2017). A significance level alpha of 5 % was considered. It must be noted
298 that the tests are expected to have a low power, owing to the limited number
299 of samples.

300 **3 Results**

301 **3.1 Oscillating-nozzle series**

302 **3.1.1 Hydrodynamic conditions**

303 Rainfall intensity varied between 157 and 192 mm h⁻¹ (Table 1). Water
304 depth was about 2.5 cm and water velocity about 9 cm s⁻¹ (Table 1). Varia-
305 tions of water depth and water velocity were quite limited and not statistically
306 significant ($P_{\text{water depth}} = 0.82$ and $P_{\text{water velocity}} = 0.50$).

307 Water flux at the outlet was around 74 L min⁻¹ (Table 2). The water flux
308 with rain was statistically higher than the water flux with the no rain condition
309 ($P_{\text{water flux}} = 0.008$). The rainfall increased the water flux by about 0.8 L min⁻¹
310 (i.e. by about 1 % of the total flux), which is consistent with the amount of
311 water supplied by rain to the experimental section.

312 **3.1.2 Particle concentration**

313 Considering the first three runs, a similar evolution was observed with or
314 without rain (Figure 2): the particle concentration at the outlet increased from
315 the first to the second minute (i.e. from $T = 0$ to $T = 2$ min) and then reached
316 a steady state. This steady state persisted up to the cut of the sediment sup-
317 ply (at $T = 7$ min). Then the particle concentration decreased sharply dur-
318 ing the eighth minute, and became close to zero afterwards. This dynamics
319 shows that the sediment supply has a direct control on the particle flux at the
320 outlet.

Table 1: Rain intensity, water depth and water velocity for the oscillating-nozzle series.

| Measurement condition | | Rain intensity (mm h ⁻¹) (n=4) Mean ± Std dev. | Water depth (cm) (n=9) Mean ± Std dev. | Water velocity (cm s ⁻¹) (n=9) Mean ± Std dev. |
|-----------------------|---------|---|---|---|
| Run 1 | No rain | 0 | 2.49 ± 0.09 | 9.2 ± 0.3 |
| | Rain | 157 ± 2 | 2.50 ± 0.09 | 9.0 ± 0.8 |
| Run 2 | No rain | 0 | 2.55 ± 0.08 | 9.2 ± 0.7 |
| | Rain | 173 ± 5 | 2.54 ± 0.06 | 9.1 ± 0.5 |
| Run 3 | No rain | 0 | 2.54 ± 0.06 | 9.3 ± 0.4 |
| | Rain | 192 ± 21 | 2.53 ± 0.07 | 9.3 ± 0.3 |
| Run 4 | No rain | 0 | ND | ND |
| | Rain | 172 ± 2 | 2.50 ± 0.08 | 9.2 ± 0.5 |

n: number of samples

321 For a given run, there was always a clear difference in the concentration
 322 at steady-state between the rain and the no-rain conditions. And, among the
 323 runs, this difference was replicated: the particle concentration was about
 324 15 mg L⁻¹ without rain, and about 10 mg L⁻¹ with rain, i.e. a 30 % decrease in
 325 particle concentration at the outlet.

326 The same behavior was observed in run 4: with rain and without rain, it
 327 took about one minute to reach the steady-state, and the particle concentra-
 328 tion decreased after the cut of the sediment supply. During the rain applica-
 329 tion, the particle concentration at steady-state (12 mg L⁻¹) was higher than
 330 for the first three runs. After the rain was stopped, the particle concentration
 331 increased and stabilized at 15 mg L⁻¹.

332 The concentrations at steady-state are summarized in Figure 3. The con-
 333 centration for the rain condition was significantly lower than the concentration
 334 for the no-rain condition (P = 0.015).

335 As supplementary observation, no sediment was found in the lateral plu-
 336 viometers, ensuring that the particles were not splashed from the water flow
 337 into the air. Hence, all observations concur to a particle deposition hastened
 338 by the rain.

Table 2: Water flux at the outlet for the oscillating-nozzle series.

| Measurement condition | | | Water flux (L min ⁻¹) (n=6) Mean±Std dev. |
|-----------------------|-----------------------|------------------------|--|
| Run 1 | No rain | Before sediment supply | 73.8 ± 0.4 |
| | | After sediment supply | 73.7 ± 1.1 |
| | Rain | Before rain | 73.1 ± 0.9 |
| | | During rain | 74.1 ± 0.7 |
| | | After rain | 73.7 ± 0.6 |
| | Run 2 | No rain | Before sediment supply |
| After sediment supply | | | 73.7 ± 0.4 |
| Rain | | Before rain | 73.6 ± 0.4 |
| | | During rain | 74.4 ± 0.3 |
| | | After rain | 73.5 ± 0.7 |
| Run 3 | | No rain | Before sediment supply |
| | After sediment supply | | 73.0 ± 0.4 |
| | Rain | Before rain | 73.5 ± 0.4 |
| | | During rain | 74.6 ± 0.5 |
| | | After rain | 73.6 ± 0.7 |
| | Run 4 | No rain | Before sediment supply |
| After sediment supply | | | ND |
| Rain | | Before rain | 73.0 ± 0.3 |
| | | During rain | 73.6 ± 0.7 |
| | | After rain | 72.9 ± 0.5 |

ND: no data; n: number of samples

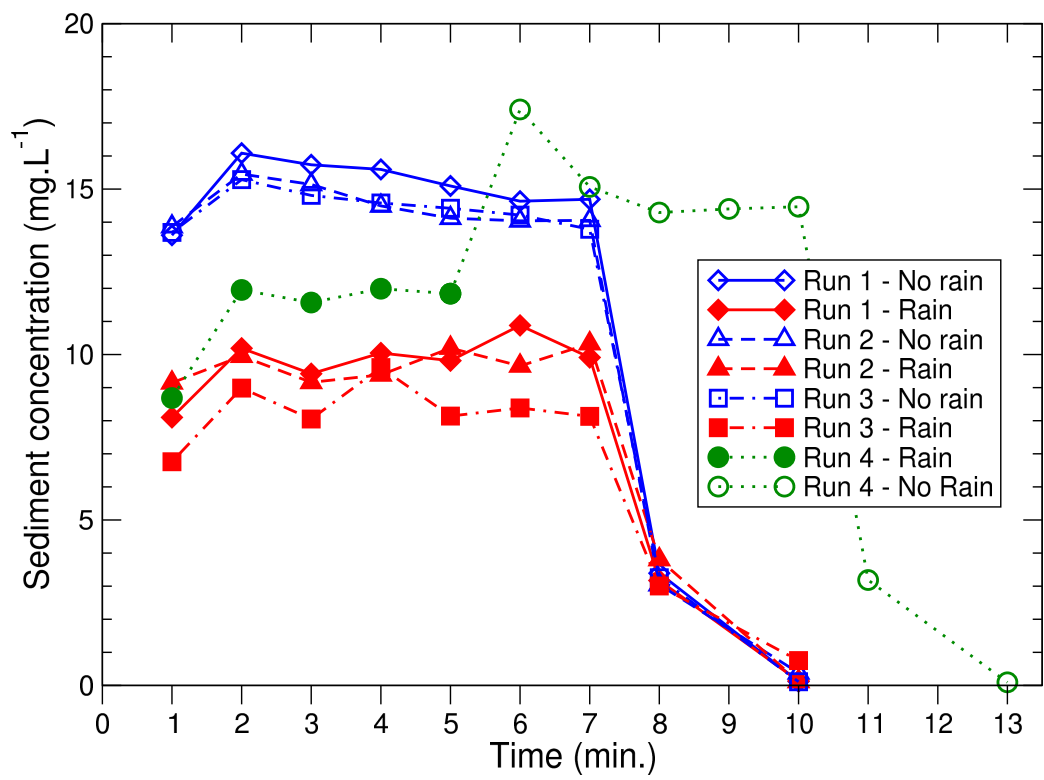


Figure 2: Time evolution of particle concentration at the outlet for the oscillating-nozzle series. A value plotted at $T = N$ min corresponds to the particle concentration measured from $T = N - 1$ min to $T = N$ min.

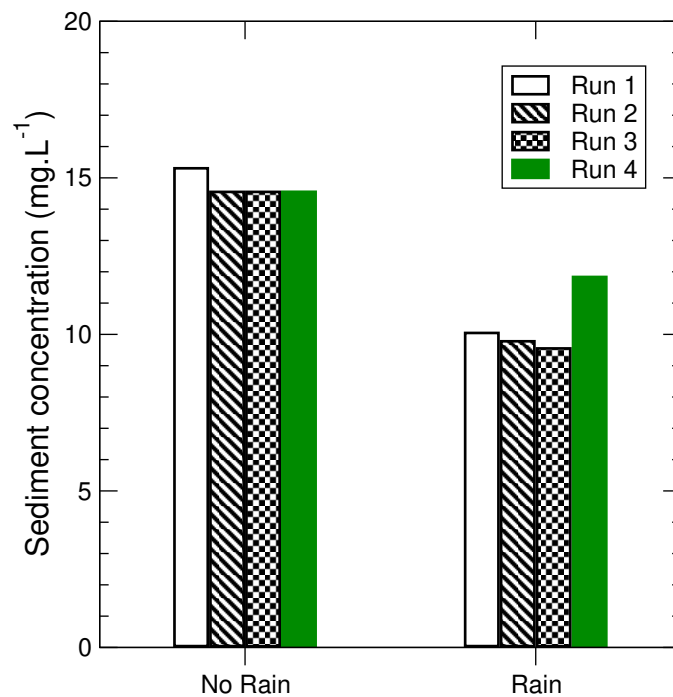


Figure 3: Mean particle concentration at steady-state at the outlet for the oscillating-nozzle series. For the first three runs, values are considered for the range 2–7 min. For the fourth run, values are considered for the ranges 2–5 min (i.e. with rain) and 8–10 min (i.e. without rain).

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3.2 Drop-former series

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3.2.1 Hydrodynamic conditions

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Actual rainfall intensities were generally close to the prescribed values (Table 3). As in the oscillating-nozzle series, water depths, velocities and fluxes had limited variations (Tables 3 and 4). Differences were not statistically significant ($P_{\text{water depth}} = 0.17$, $P_{\text{water velocity}} = 0.42$, and $P_{\text{water flux}} = 0.88$). The case “0 mm h⁻¹ – run 2” had the highest mean velocity (9.7 m s⁻¹), but its water depth and flux were in the regular range. The lowest water flux was measured for the case “35 mm h⁻¹ – run 1” (66 L min⁻¹), without obvious relation with its water depth and velocity.

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For this drop-former series, the rainfall did not contribute significantly to the increase in the water flux at the outlet ($P_{\text{water flux}} = 0.39$). Indeed, at the maximal prescribed value of 55 mm h⁻¹, the contribution of the rainfall is expected to be of 0.2 L min⁻¹, which is three times lower than the average standard deviation (0.7 L min⁻¹) and 0.3 % of the total flux only.

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3.2.2 Particle concentration

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The flux of particles at the outlet (Figure 4) had a behavior similar to the one of the oscillating-nozzle series: an initial increase in the particle concentration from the first to the second minute, then a steady state, and, finally, a sharp decrease after the sediment supply was cut. For two runs (one at 0 mm h⁻¹, one at 60 mm h⁻¹), the sediment supply was continued for three extra minutes (because an operator forgot to stop the sediment feeder at the prescribed duration of 7 min). Except for their longer duration, these runs did not show a specific behavior.

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Considering the steady states, the runs at 0 mm h⁻¹ had the highest concentration. For the other rainfall intensities, the curves seemed intermingled. The runs at 35 mm h⁻¹ had the largest range in concentration, especially with run 7 which showed the lowest concentration and a large shift between 3 and 4 min. For the runs at 10, 15, 25 and 55 mm h⁻¹, the range of variation was limited.

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Summarizing the steady-state concentration with their mean values (Figure 5) gives a better view of the change in concentration with the rainfall

Table 3: Rain intensity, water depth and water velocity for the drop-former series.

| Prescribed rain condition (mm h ⁻¹) | | Rain intensity (mm h ⁻¹) | Water depth (cm) | Water velocity (cm s ⁻¹) |
|--|-------|---|---------------------|---|
| | | Mean ± Std dev. | Mean ± Std dev. | Mean ± Std dev. |
| 0 | Run 1 | 0 | 2.81 ± 0.04 n=4 | 8.2 ± 0.2 n=4 |
| | Run 2 | 0 | 2.60 ± 0.02 n=3 | 9.7 ± 0.6 n=3 |
| | Run 3 | 0 | 2.63 ± 0.04 n=3 | 8.2 ± 0.8 n=3 |
| 10 | Run 1 | 9 ± 1 n=28 | 2.72 ± 0.12 n=9 | 8.2 ± 0.2 n=3 |
| | Run 2 | 9 ± 1 n=28 | 2.72 ± 0.08 n=9 | 8.2 ± 0.2 n=3 |
| 15 | Run 1 | 16 ± 2 n=28 | 2.69 ± 0.08 n=4 | 8.3 ± 0.1 n=4 |
| | Run 2 | 16 ± 2 n=28 | 2.71 ± 0.04 n=4 | 8.2 ± 0.1 n=4 |
| | Run 3 | 14 ± 2 n=28 | 2.52 ± 0.08 n=9 | 9.4 ± 0.1 n=3 |
| 25 | Run 1 | 25 ± 3 n=27 | 2.64 ± 0.15 n=3 | 8.5 ± 0.4 n=3 |
| | Run 2 | 26 ± 3 n=28 | 2.57 ± 0.41 n=9 | 8.5 ± 0.3 n=3 |
| 35 | Run 1 | 37 ± 4 n=28 | 2.64 ± 0.08 n=9 | 8.6 ± 0.4 n=3 |
| | Run 2 | 32 ± 3 n=28 | 2.68 ± 0.08 n=9 | 9.1 ± 1.7 n=3 |
| | Run 3 | 35 ± 4 n=28 | 2.74 ± 0.11 n=4 | 8.2 ± 0.1 n=4 |
| | Run 4 | 33 ± 7 n=8 | 2.71 ± 0.05 n=4 | 8.3 ± 0.2 n=4 |
| | Run 5 | 34 ± 4 n=28 | 2.73 ± 0.07 n=4 | 8.1 ± 0.2 n=4 |
| | Run 6 | 32 ± 4 n=28 | 2.81 ± 0.09 n=4 | 8.2 ± 0.2 n=4 |
| | Run 7 | 35 ± 7 n=8 | 2.60 ± 0.02 n=3 | 9.1 ± 0.1 n=3 |
| 55 | Run 1 | 52 ± 9 n=8 | 2.58 ± 0.04 n=9 | 9.3 ± 0.1 n=9 |
| | Run 2 | 53 ± 12 n=8 | 2.51 ± 0.03 n=3 | 9.3 ± 0.1 n=3 |

n: number of samples.

Table 4: Water flux at the outlet for the drop-former series.

| Prescribed rain (mm h ⁻¹) | Measurement condition | | Water flux (L min ⁻¹) |
|--|-----------------------|------------------------|--------------------------------------|
| | | | Mean ± Std dev. |
| 0 | Run 1 | Before sediment supply | 73.2 ± 0.6 n=6 |
| | | After sediment supply | 73.2 ± 0.5 n=6 |
| | Run 2 | Before sediment supply | 73.8 ± 0.6 n=6 |
| | | After sediment supply | 73.9 ± 1.0 n=6 |
| | Run 3 | Before sediment supply | 71.1 ± 0.5 n=6 |
| | | After sediment supply | 70.7 ± 0.4 n=6 |
| 10 | Run 1 | Before rain | 72.9 ± 0.7 n=6 |
| | | During rain | 72.7 ± 0.5 n=6 |
| | | After rain | 73.4 ± 0.4 n=6 |
| | Run 2 | Before rain | 72.7 ± 0.4 n=6 |
| | | During rain | 72.7 ± 0.7 n=6 |
| | | After rain | 72.4 ± 1.2 n=6 |
| 15 | Run 1 | Before rain | 72.2 ± 0.6 n=6 |
| | | During rain | 71.8 ± 0.5 n=6 |
| | | After rain | 72.6 ± 0.6 n=6 |
| | Run 2 | Before rain | 73.0 ± 0.5 n=6 |
| | | During rain | 73.1 ± 0.5 n=6 |
| | | After rain | 73.2 ± 0.7 n=6 |
| Run 3 | Before rain | 71.3 ± 0.6 n=6 | |
| | During rain | 71.4 ± 0.3 n=6 | |
| | After rain | 71.3 ± 0.3 n=6 | |
| 25 | Run 1 | Before rain | 73.4 ± 0.5 n=6 |
| | | During rain | 73.7 ± 0.5 n=6 |
| | | After rain | 73.4 ± 0.4 n=6 |
| | Run 2 | Before rain | 73.1 ± 0.7 n=6 |
| | | During rain | 72.9 ± 1.1 n=5 |
| | | After rain | 72.9 ± 0.5 n=6 |
| 35 | Run 1 | Before rain | 65.6 ± 0.9 n=6 |
| | | During rain | 66.4 ± 1.1 n=6 |
| | | After rain | 65.9 ± 0.6 n=6 |
| | Run 2 | Before rain | 73.0 ± 1.0 n=6 |
| | | During rain | 73.2 ± 0.7 n=6 |
| | | After rain | 73.0 ± 1.1 n=6 |
| Run 3 | Before rain | 73.6 ± 0.7 n=6 | |
| | During rain | 74.0 ± 1.1 n=6 | |
| | After rain | 73.2 ± 0.4 n=6 | |
| 55 | Run 4 | Before rain | 73.5 ± 0.6 n=6 |
| | | During rain | 73.6 ± 0.7 n=5 |
| | | After rain | 73.5 ± 0.8 n=6 |
| | Run 5 | Before rain | 71.5 ± 0.8 n=6 |
| | | During rain | 71.4 ± 0.9 n=6 |
| | | After rain | 71.7 ± 0.5 n=6 |
| Run 6 | Before rain | 71.8 ± 0.4 n=6 | |
| | During rain | 71.7 ± 1.1 n=6 | |
| | After rain | 71.7 ± 0.7 n=6 | |
| Run 7 | Before rain | 71.4 ± 0.5 n=6 | |
| | During rain | 73.5 ± 0.6 n=6 | |
| | After rain | 73.8 ± 0.5 n=6 | |
| 55 | Run 1 | Before rain | 73.2 ± 0.5 n=6 |
| | | During rain | 73.3 ± 0.8 n=6 |
| | | After rain | 73.4 ± 0.4 n=5 |
| | Run 2 | Before rain | 70.0 ± 3.6 n=6 |
| | | During rain | 71.5 ± 0.8 n=6 |
| | | After rain | 71.3 ± 0.6 n=6 |

n: number of samples.

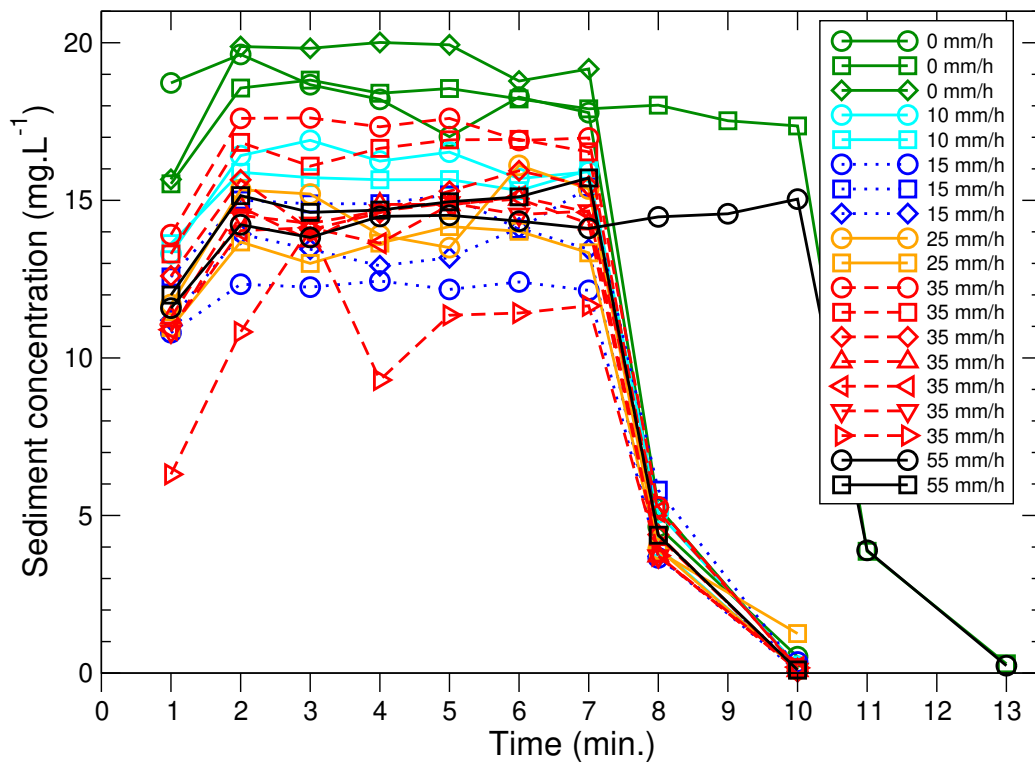


Figure 4: Time evolution of particle concentration at the outlet for the drop-former series.

The order of the cases in the legend is the same as in Tables 3 and 4.

371 intensity. The case 0 mm h^{-1} had the highest mean concentration (19 mg L^{-1})
372 and the case 15 mm h^{-1} had the lowest one (14 mg L^{-1}). When considering
373 the experiments with rain compared to the experiments without rain, the
374 Wilcoxon test showed that concentrations were significantly larger without
375 rain ($P = 0.004$). However, the Kruskal-Wallis test did not show a significant
376 difference in concentration among the rainfall intensities ($P = 0.07$).

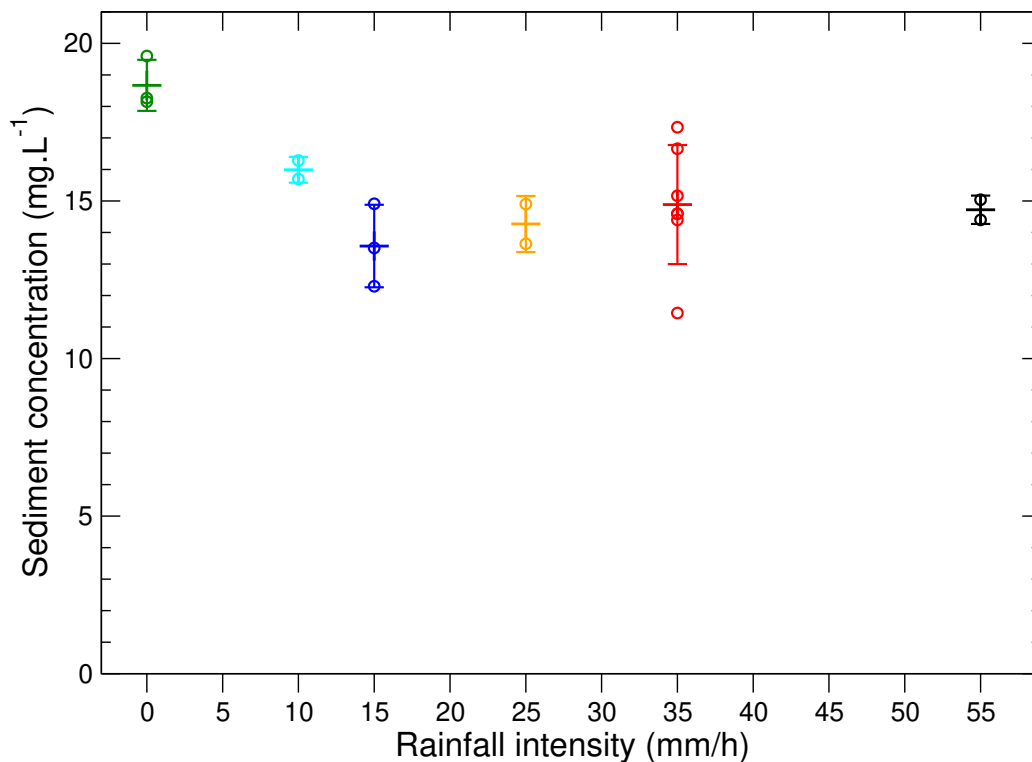


Figure 5: Particle concentration at steady-state at the outlet for the drop-former series.

Circles: mean concentration for each run. Bars: mean concentration and standard deviation for each rainfall intensity. For most of runs, the sediment concentration was calculated as the mean over the range 2–7 min. For the two longer runs, the range 2–10 min were used.

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4 Discussion

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4.1 Assessment of the experimental conditions

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The experiments were carried out in a laboratory flume. They were designed to identify the effect of raindrops on particle sedimentation in sheet flow. Even if the experiments could look far from natural conditions, their features resemble sheet flow in interrill conditions: the water depth was only a few centimeters and the water velocity around one decimeter per second. While a smaller depth may have better mimic a typical sheet flow, the 2.5 cm depth was required to ensure that sedimented particles were not detached by the raindrop impacts. The conditions could be maintained through the whole experiment. The particle concentration was kept low to limit the interactions between particles. There was no significant particle splash, and, by design, particles were not detached after reaching the flume bottom. Hence, once delivered to the flow, the particles could have two fates only: being deposited at the bottom or reaching the outlet.

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The highest rainfall intensity was around 175 mm h^{-1} . It was deemed to exacerbate the potential interactions between raindrops and particles. Such an intensity, while quite high, is not out of the natural range. Indeed, while these experiments supplied 30 mm of rainfall over a duration of about 10 min, the same amount of rainfall was observed over a single minute (WMO, 2020). However, we agree with Dunkerley (2020) that such high and constant rainfall intensity is quite unlike natural rainfall. Since this is the first study on the interaction between raindrops and settling particles, we believe that the use of rainfalls with such intensity is legitimate. Once this interaction characterized and understood, it will be necessary to investigate rainfalls with lower intensities and with time-varying intensities.

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The contrast in concentration between the rain and no-rain conditions was larger for the first experimental series than for the second one. This could be related to the larger rainfall intensity of the first series (175 mm h^{-1}) compared to the second series (which as a maximum intensity of 55 mm h^{-1}). However, at this stage, and considering the insufficient understanding of the underlying processes and determinants, it would be preliminary to elaborate more on this: the contrast could be due not to differences in rainfall intensities but to differences in other rainfall properties — such as the raindrop sizes or the raindrop kinetic energies. While the first series had a higher rainfall intensity, it had a lower mean raindrop diameter (1.7 mm vs 3.0 mm), a lower

413 specific kinetic energy ($7 \text{ J m}^{-2} \text{ mm}^{-1}$ vs $20 \text{ J m}^{-2} \text{ mm}^{-1}$), and was noticeably
414 discontinuous. To reach a detailed explanation about the contrast between
415 the two series will require a new experimental plan designed to separate the
416 effect of the various rainfall properties.

417 **4.2 Raindrop impacts foster particle sedimentation in sheet** 418 **flow**

419 For both the oscillating-nozzle and drop-former series, the particle con-
420 centration at the outlet was always the lowest when rainfall was applied.

421 This decrease in concentration could be due to the dilution of the particles
422 by the supplementary water coming from the rain. However, while the rainfall
423 increased the water flux at the outlet by up to one percent (in the oscillating-
424 nozzle series), simultaneously, the particle concentration dropped by up to
425 30%. This means that, overall, rainfall application decreased the particle
426 flux to the outlet (from 1.1 g min^{-1} to 0.75 g min^{-1}), leading to the conclusion
427 that the supplementary water flux by the rainfall was not responsible for the
428 observed results. So, the results indicate that the raindrop impacts fostered
429 the particle sedimentation to the bottom of the flume. This conclusion was
430 counter-intuitive to the authors of the experiments. Our initial rationale was
431 that, by mixing and shaking the water flow (and this shaking was visually
432 quite strong), the raindrop impacts would tend to prevent the sedimentation
433 of particles, in a same way that mixing a bucket of muddy water slows down
434 the particle settling. However, results were the exact opposite: raindrop im-
435 pacts increased particle settling.

436 Of course, this conclusion is strictly valid for our experimental setup only,
437 and this was the first experiment considering particle settling in sheet flow
438 without detachment after sedimentation. Moreover, a limited range of condi-
439 tions were tested. Rainfall intensity was the only variable; water depth, water
440 velocity, water flux, particle size, particle density and particle flux were kept
441 constant. Apart from the clear rain-no rain effect, there was no obvious re-
442 lationship between rainfall intensity and particle concentration (drop-former
443 series).

444 Being the first experiment to tackle the interaction between settling par-
445 ticles and raindrop in sheet flow, there is an obvious need for replication at-
446 tempts. By underlining our lack of knowledge on the interactions between

447 raindrops and particles in a flow, this calls for a broader evaluation of the
448 effect of raindrop impacts on particle sedimentation.

449 Finally, the conclusion questions our current capability to consider set-
450 tling velocities of particles in soil erosion models (De Roo et al., 1996; Mor-
451 gan et al., 1998; Hairsine et al., 2002; Wainwright et al., 2008), especially
452 when settling velocities are adjusted to better fit measurements at the outlet
453 (Tromp-van Meerveld et al., 2008; Jomaa et al., 2010). It is recognized that
454 the calibration of numerous parameters leads to equifinality, limiting the con-
455 fidence in the simulation outputs (Beven, 2008). Adding more constraints on
456 model parameters will decrease the degree of freedom of the models, and
457 help in enhancing confidence in modeling efforts (Kirstetter et al., 2016).

458 **4.3 Mechanisms that could increase the settling velocity**

459 The conclusion that raindrop impacts increase settling velocity raises
460 questions about the underlying mechanisms. If, obviously, it was not the re-
461 sult of a simple mixing as in a muddy bucket, two other potential mechanisms
462 are proposed.

463 Raindrops impacting a sheet flow do not only cause a shaking of the flow
464 and a supplementary water flux. They also add a vertical momentum. Con-
465 ceptually, the vertical movement of particles can be separated into gravity-
466 induced settling (i.e. the settling observed in still water) and an additional mo-
467 tion caused by the raindrop impacts. Individual raindrops might be pushing
468 downward the volume of water underneath, and the incorporated particles.
469 Of course, this finally gets balanced with upward movements, and goes along
470 with lateral movements of both water and particles. It is hypothesized that
471 raindrops do not cause a simple mixing/shaking as done by hand in a muddy
472 bucket, but that a more complex interaction occurs.

473 Because the probability of a raindrop-particle interaction increases with
474 the number of raindrops (Nouhou Bako et al., 2017), such an interaction
475 should depend on the rainfall intensity. Since no such a dependency was
476 observed in the presented results, it could be argued that this mechanism
477 should be discarded. It could also be argued that it is compensated by an-
478 other (and unknown) phenomenon. However, considering the huge lack of
479 knowledge on this subject, we will refrain from further consideration. We
480 simply call for further investigations. These investigations could advanta-
481 geously make use of the recent advances in computational fluid dynamics

482 (Nouhou Bako et al., 2016; Nouhou-Bako et al., 2019).

483 The experiments without rainfall had a Reynolds number of 2250. When
484 considering that the transition between laminar and turbulent regimes are at
485 a Reynolds number of 2500, it could be argued that the application of rainfall
486 caused the flow to go from laminar to turbulent. If the turbulent regime was
487 already in place at the lowest rainfall intensity (10 mm h^{-1}), its effect would
488 also be present at higher rainfall intensities (i.e. from 15 mm h^{-1} to 55 mm h^{-1}).
489 This could explain that the sediment concentration kept statistically the same
490 for the 10 mm h^{-1} to 55 mm h^{-1} intensities.

491 Many authors have made experimental and numerical studies about how
492 the settling velocity of a particle is modified in the turbulent regime (Gore and
493 Crowe, 1990; Mei et al., 1991; Wang and Maxey, 1993; Warnica et al., 1995;
494 Brucato et al., 1998; Bagchi and Balachandar, 2003). These studies ana-
495 lyzed the modification of the particle drag coefficient when the flow regime
496 changed from laminar to turbulent, and their results are reviewed in Bagchi
497 and Balachandar (2003). In summary, these results can be classified into
498 three categories:

- 499 1. Some studies have observed a decrease of the settling velocity when
500 the regime goes from laminar to turbulent (Uhlherr and Sinclair, 1970;
501 Zarin and Nicholls, 1971; Brucato et al., 1998). This decrease may
502 be due to the non-linear dependency of the drag coefficient with the
503 settling velocity. When the turbulence intensity increases, the drag coef-
504 ficient also increases, leading to a decrease of the settling velocity. This
505 effect is significant for particles having sizes larger than the Kolmogorov
506 scale, the turbulent energy being dissipated by small vortex structures.
- 507 2. Other studies like Rudloff and Bachalo (1988) and Gore and Crowe
508 (1990) have observed an increase of the settling velocity in the turbu-
509 lent regime. These authors explain the augmentation of the settling
510 velocity by the fact that particles have preferential trajectories in tur-
511 bulent flow. Particles “prefer” regions of downward flow compared to
512 regions of upward flow. This effect is dominant for particles smaller or
513 of the order of the Kolmogorov scale.
- 514 3. For some studies like Warnica et al. (1995) and Bagchi and Balachan-
515 dar (2003), the turbulence has no significant effect on the settling veloc-
516 ity of particles. This velocity remains the same regardless the nature of
517 the flow.

518 Our results are in agreement with the observations of the second category of
519 studies: their results and those presented in this article show an increase of

520 the settling velocity of particles when moving to a turbulent regime.

521 During the experiments, no turbulence measurement was carried out, and
522 so, the Kolmogorov scale could not be estimated. Indeed, turbulence mea-
523 surements as well as the Kolmogorov scale are unheard in soil erosion stud-
524 ies. The cited studies come from the fluid mechanics community. There is a
525 large stretch between our knowledge and practices in water soil erosion and
526 the knowledge and practices in fluid mechanics. The experimental conditions
527 and setup of the cited studies are quite different from what we are used to,
528 and sheet flow is not even a concept in fluid mechanics. Hence, the present
529 study calls for a collaboration with the fluid mechanics community. We be-
530 lieve that bridging the gap between our communities could foster knowledge
531 development about the settling of particles in sheet flow, and, more generally
532 about soil erosion processes by water.

533 **5 Conclusions**

534 A laboratory flume experiment under simulated rainfall was specifically
535 designed to address the effect of raindrop impacts on the settling of particles
536 in sheet flow. Depth and velocity were close to conditions observed in sheet
537 flow. The flow was supplied with 100–200 μm particles which concentration
538 was measured at the outlet.

539 A first set of experiments, using an oscillating-nozzle rainfall simula-
540 tor, compared a no rainfall condition with a high rainfall intensity condition
541 (175 mm h^{-1}). It showed that the raindrop impacts decreased the particle
542 concentration at the outlet by about 30 percent. Using a drop-former rainfall
543 simulator, this effect was confirmed by a second set of lower rainfall inten-
544 sity experiments (0, 10, 15, 25, 35, 55 mm h^{-1}), also no obvious relationship
545 was found with the rainfall intensity. The study concluded that the raindrop
546 impacts increase particle sedimentation in sheet flow. This questions the
547 current practice of adjusting the particle settling velocities to better fit model
548 outputs at the outlet.

549 While the underlying mechanism could not be determined, it could be
550 related to the momentum of the raindrops, to the turbulence caused by the
551 raindrops into the flow, or to the combination of both. Further studies need
552 to be carried out, including replication attempts. The use of computational
553 fluid dynamics and collaboration with the fluid mechanics community are
554 encouraged.

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