One-Dimensional Hairsine-Rose Erosion Model: Parameter Consistency in the Presence of Rainfall Splash

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1. Introduction and motivation

The one-dimensional Hairsine-Rose (1D H-R) [1-3] erosion model describes time-varying suspended sediment concentrations of multiple particle sizes. The H-R model, in contrast to other process-based erosion models, considers erosion and deposition processes separately by taking account of the contributions of the individual size classes to the total sediment concentration. The H-R model has been evaluated under different experimental conditions, and has been shown to explain reliably experimental data in a consistent manner [4-5]. However, the H-R model has not been validated under conditions of significant raindrop splash even though for interrill erosion it is known that raindrop splash is an important mechanism of sediment detachment and therefore of sediment delivery [6]. The aim of this study is to test experimentally and numerically the consistency of the H-R model parameters in the presence of raindrop splash. The effect of splash is differentiated by carrying out experiments that are the same in all aspects except that different transversal widths are used within the 2 m 6 m EPFL erosion flume.

2. Objectives and methodology

The H-R model was used to fit the integrated data and to provide parameter estimates for each flume. A comparison between the experimental results and the numerical approximations provide the basis to investigate the H-R model parameter consistency for erosion situations where raindrop splash is significant.

Experiments were conducted using different configurations of the 2 m 6 m EPFL erosion flume. Vertical barriers were used to divide the flume into four smaller flumes, with widths of 1 m, 0.5 m and 2 0.25 m. Except for their width, all four flumes were otherwise identical. At the end of each flume, drainage volumes and sediment concentrations were measured in central or symmetrically located drains. In one of the smaller flumes however the drainage point was off-set to check the influence of boundary condition asymmetry on the experimental data.

3. Design of experiment

Fig. 1. Overview of The EPFL erosion flume

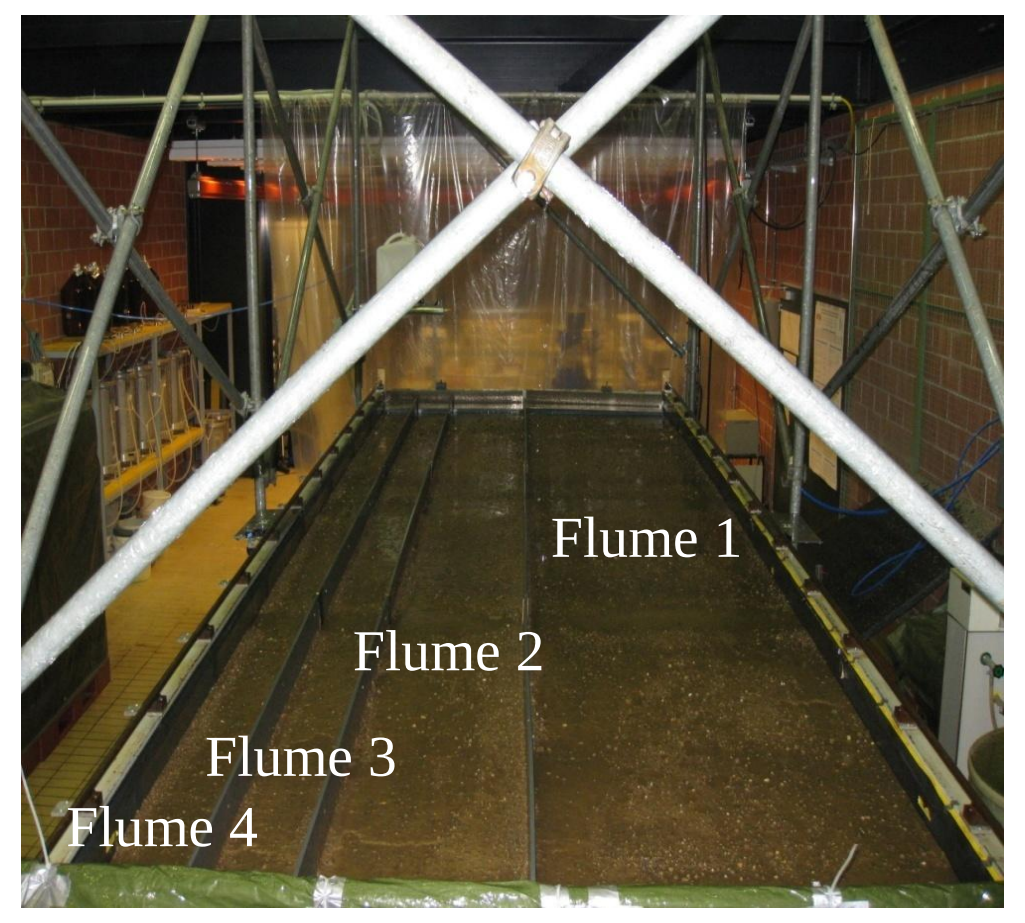


Fig. 2. The EPFL erosion flume divided into 4 smaller flumes

Fig. 3. Raindrop splash

4. Model

The 1D fixed-bed H-R model coupled with the shallow water equations, which have developed by [4], is:

$$\frac{\partial}{\partial t}\begin{bmatrix}\eta\\ hu\\ hc_1\\ \vdots\\ hc_I\end{bmatrix}+\frac{\partial}{\partial x}\begin{bmatrix}hu\\ hu^2\\ huc_1\\ \vdots\\ hcu_I\end{bmatrix}=\begin{bmatrix}P\\ -gh\left(\frac{\partial\eta}{\partial x}+S_f\right)-Pu\\ e_1+r_1+e_{r1}+r_{r1}-d_1\\ \vdots\\ e_I+r_I+e_{rI}+r_{rI}-d_I\end{bmatrix}.$$

As a function of time the protective layer of Deposited sediment develops according to:

$$\frac{\partial}{\partial t}\begin{bmatrix}m_1\\ \vdots\\ m_I\end{bmatrix}=\begin{bmatrix}d_1-e_{r1}-r_{r1}\\ \vdots\\ d_I-e_{rI}-r_{rI}\end{bmatrix}.$$

The effective settling velocity for each size class, which takes into consideration the effect of the raindrop splash on the deposition force of the particles, is:

$$V_{effective_i}=\frac{V_i}{1+\alpha D_{Splash}\frac{V_i}{q}}$$

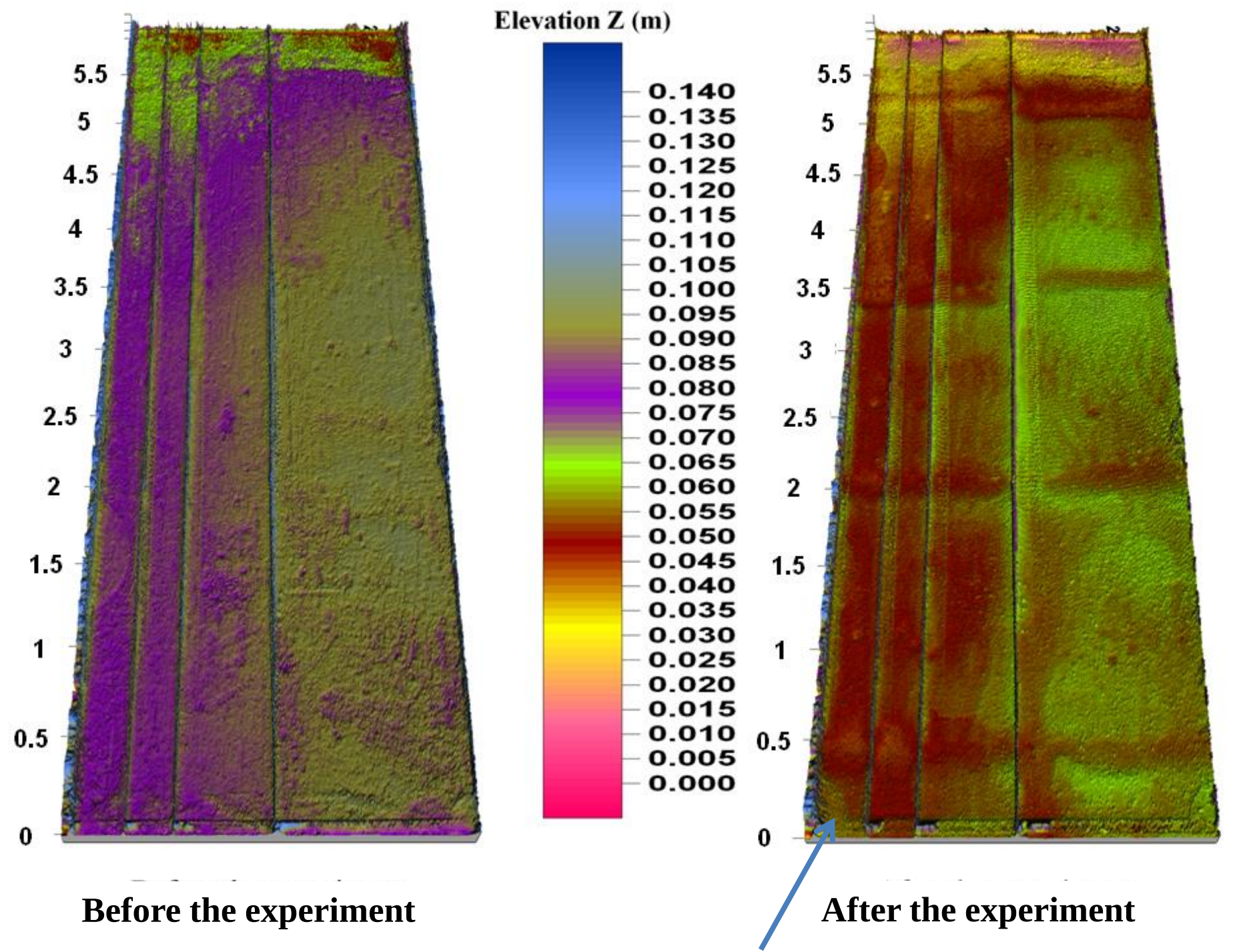
where:

α = the proportion of raindrops that generate the splash process (1/10)
D_{splash} = the average splash length ranged from 4 to 23 cm, here taken as 10 cm;
V_i = the settling velocity of each size class (m/s);
q = the overland flow per unit width (m^2/s).

Notation

η = water surface level (m)
h = water depth (m)
P = rainfall intensity (m/s)
S_f = friction slope
c_i = class i sediment concentration (kg/m^3)
e_i = rainfall detachment (kg/m^2/s)
e_{ri} = rainfall re-detachment (kg/m^2/s)
r_i = runoff entrainment (kg/m^2/s)
r_{ri} = runoff re-entrainment (kg/m^2/s)
d_i = deposition (kg/m^2/s)
m_i = mass of deposited class i sediment per unit area (kg/m^2)
I = the total number of size classes
a = the detachability of the original bare soil (kg/m^3)
a_d = the detachability of the deposited layer (kg/m^3)
m_{dt}^* = mass per unit area needed for the complete shield layer (kg/m^2)

5. DTM investigation



Additional amount of deposited sediment in the corner generated by the collector's location.

Fig. 4. Digital Terrain models (DTM) of the flumes before and after the experiment were generated using a high resolution laser scanner. The longitudinal lines within the images are the vertical (to a height of 10 cm above the initial soil surface) barriers that define the individual flumes. An additional amount of deposited sediment in the corner of the flume 4 (see left-hand bottom corner of the "After" DTM, showing the deposition of material to a distance of about 0.3 m from the drainage surface) was generated by the collector's location.

According to manual observations taken during and after the experiment, as well as the finely resolved DTM data have shown that:

- ❑ The sediment transport process alternates between 1D and 2D. In flume 1 (1m width), it is clear that the 2D behavior was dominant during the erosion event. In the flume 2 (0.5 m width) the sediment transport behavior was more 2D than 1D but less significant than in flume 1. In flumes 3 and 4 (0.25 m width) the soil erosion effect was homogenous and concentrated in the mid-line of the flumes.
- ❑ The post-experiment highlighted the presence of the 4 transversal-parallel lines of depression at distances 0.5, 2, 3.5, and 5 m from the top of the flume due to the overlap of the sprinklers.
- ❑ In the smaller flumes the sediment was stuck to the barriers (10 cm) due of splash ejection.

6. Experimental results and numerical approximations

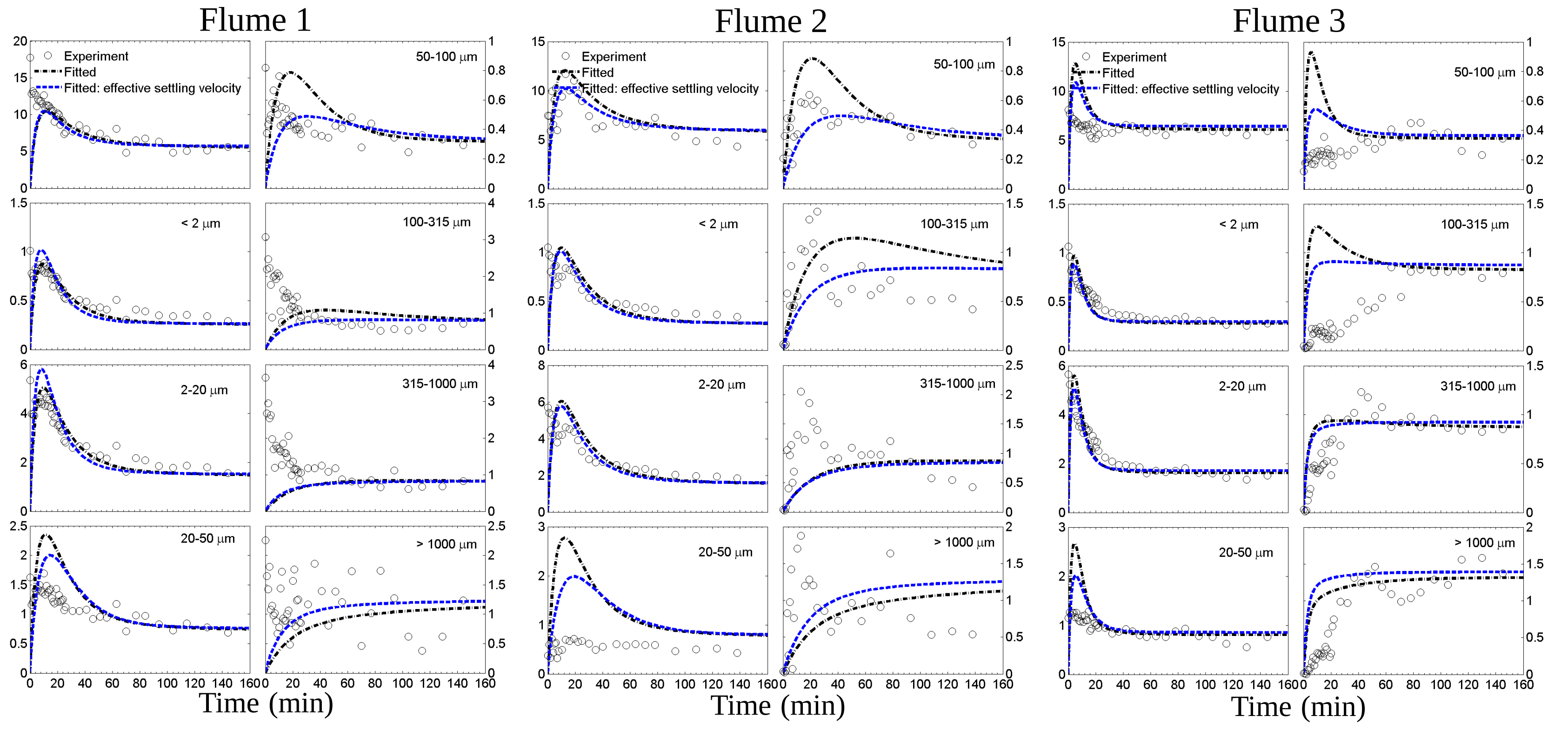


Fig. 5. Sediment concentration (g/l) as a function of time

Table 1. Best-fit parameters for the flumes

Parameters	a (kg/m^3)	a_d (kg/m^3)	m_{dt}^* (kg/m^2)	a (kg/m^3)	a_d (kg/m^3)	m_{dt}^* (kg/m^2)
	Fitted with settling velocity			Fitted with effective settling velocity		
Flume 1	30	**8700**	0.30	30	**1400**	0.30
Flume 2	35	**8800**	0.40	35	**1500**	0.40
Flume 3	70	**8700**	0.10	70	**1500**	0.10
Flume 4	40	**8000**	0.15	40	**2000**	0.15

❑ The estimated parameters are consistent between the flumes 1 and 2. However, for flume 3, a_d and m_{dt}^* are different to the values obtained in flumes 1 and 2. On the other hand, the parameters of flume 4 are completely different to the other flumes. This could be explained by the drainage collector's location for this flume.

7. Discussion

The finer particles were consistent and independent of the initial and the downstream boundary conditions. However, when the fraction size increases the variability in the measured concentrations increases and the concentrations of the larger particles were highly sensitive to the spatial scale and boundary conditions.

The experimental results indicate that raindrop splash dominated in the flumes having the larger widths (1 m and 0.5 m). This process generated a short time peak for all individual size classes. However, the effect of raindrop splash was less present in observed sediment concentrations of the collected data from the smaller width flumes (0.25 m). For these flumes, the detached sediment was controlled by the transversal width of the flume. An amount of detached sediment adhered to the barriers instead of being removed in the overland flow.

Even though a new settling velocity calculation was used taking the effect of raindrop splash on the deposition force of particles into accounts, the numerical approximations could not predict the consistent short time peak of the larger particles appeared in flumes 1 and 2.

8. Conclusion

The experimental data, numerical approximations and accompanying analyses showed that:

- ❑ Raindrop splash can have a dominant effect on short-time erosion behavior in situations where the rainfall drop energy is relatively high;
- ❑ The analytical results agreed well with the total sediment concentrations but not the measured sediment concentrations of all individual size classes although when the effective settling velocity was used;
- ❑ The H-R model does not include sufficient mechanistic detail to account for high-energy raindrops;
- ❑ There is a minimum transverse length scale over which the H-R model is likely applicable, and this minimum scale is controlled by the characteristic splash length scale;
- ❑ The boundary condition-inducted asymmetry markedly reduces the applicability of the H-R model.

9. References

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