Dynamics of Turbulent Sediment Transport: Experiments and Modeling

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Abstract

Almost all bedload transport laws proposed in the literature consider implicitely that the sediment flux is a local function of the shear stress [Garcia, 2006 and references therein]. They consequently ignore any relaxation effect, although the latter is recognized to control the development of bedforms. To account for this relaxation effect, Charru [2006] proposed a theoretical erosion-deposition model of bedload transport. In this poster we report the results of an experimental investigation aimed at testing the prediction of this model. We study the motion of bedload particles in the ideal case of a steady and uniform turbulent flow above a flat sediment bed of uniform grain size. Using a high-speed video imaging system, we visualize the trajectories of the entrained grains and measure the particles velocities, the length and durations of their flights and the density of moving particles. As far as we know, this study is the first one to present measurements of all these quantities in the same experimental conditions.

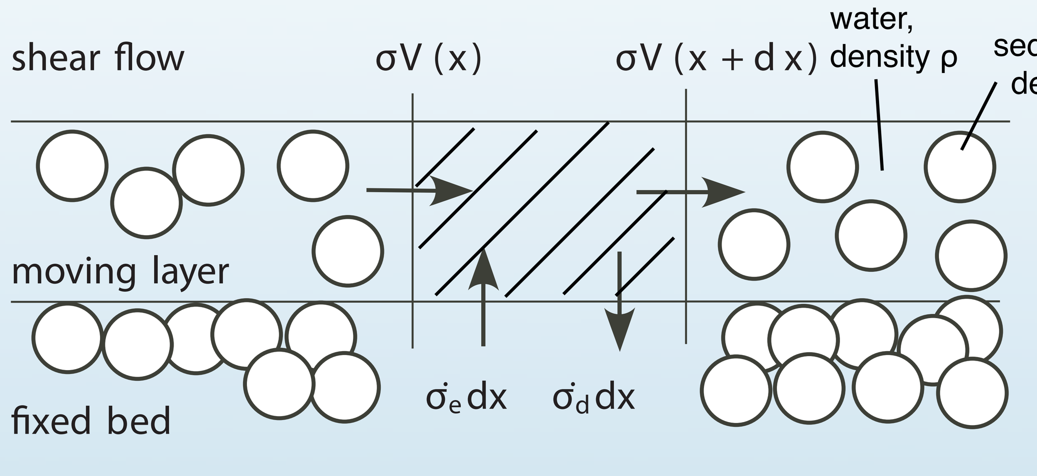
Our observations show that the particles entrained by the flow exhibit intermittent trajectories composed of the succession of periods of motion, hereafter called "flights", and periods of rest. During the same flight, a particle may go through phases of rolling, during which it moves in nearly persistent contact with the rough bed, and phases of saltation, during which it travels sufficiently high above the bed to reach high velocities. The experimental results support the erosion-deposition model of Charru [2006] and allow us to calibrate the values of the different coefficients of the model. The results presented in this paper provide a valuable physical framework to describe bedforms developpement in turbulent flows.

• An erosion-deposition model for bedload transport

• The sediment flux reads

$$q_s = \delta v \; \sigma \; V$$

volume of a particle — average particle velocity — surface density of moving particles



• Mass conservation applied to the hatched zone:

$$\frac{\partial \sigma}{\partial t} = \dot{\sigma}_e - \dot{\sigma}_d - \frac{\partial(\sigma V)}{\partial x}.$$

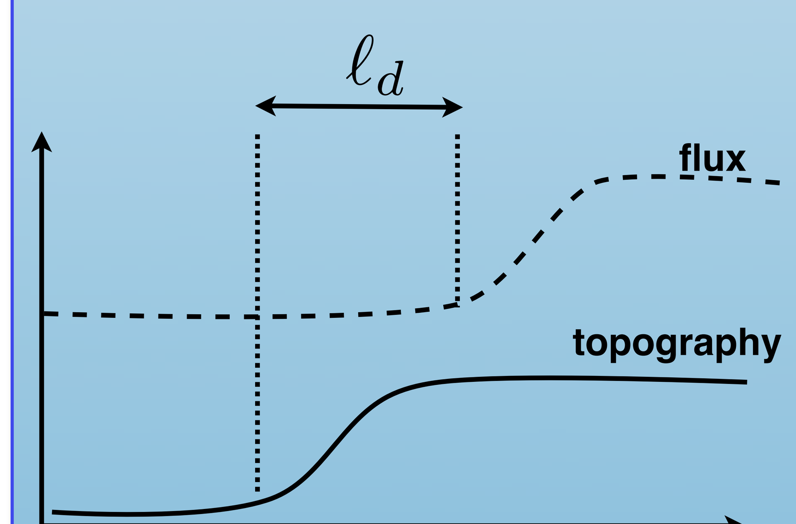
erosion rate — deposition rate

• The number of moving particles per unit bed area σ is related to exchanges with the fixed bed, through the erosion rate $\dot{\sigma}_e$ and the deposition rate $\dot{\sigma}_d$, and to the divergence of the bedload flux.

• Bedforms develop on timescales much larger than the characteristic scale of sediment transport so that this latter is commonly assumed to adapt instantaneously to the bed topography. In this case of steady sediment transport over a varying topography, mass conservation reduces to

$$\ell_d \frac{\partial q_s}{\partial x} = q_{sat} - q_s,$$

length necessary for the flux to adapt to a change of bed topography — **saturated sediment flux above a flat topography**



• Physical and dimensional resoning leads to :

$$\begin{aligned} q_{sat} &= \delta v \sigma_{sat} V \\ \ell_d &= \frac{1}{c_d}\frac{V}{\sqrt{RgD}} D \\ \sigma_{sat} &= \frac{c_e}{c_d}\frac{\tau^* - \tau_c^*}{D^2} \\ \frac{V - V_c}{\sqrt{RgD}} &= a\left(\tau^{*1/2} - \tau_c^{*1/2}\right) \end{aligned}$$

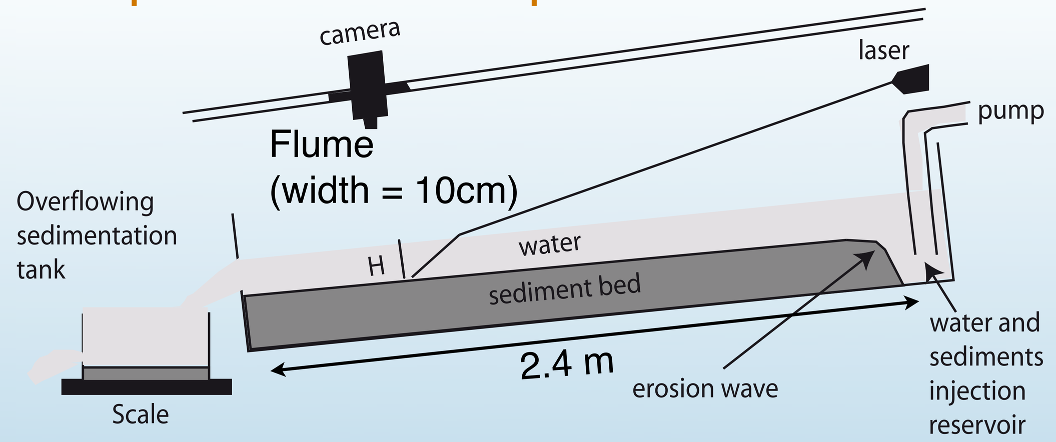
with $R = \frac{\rho_s - \rho}{\rho}$

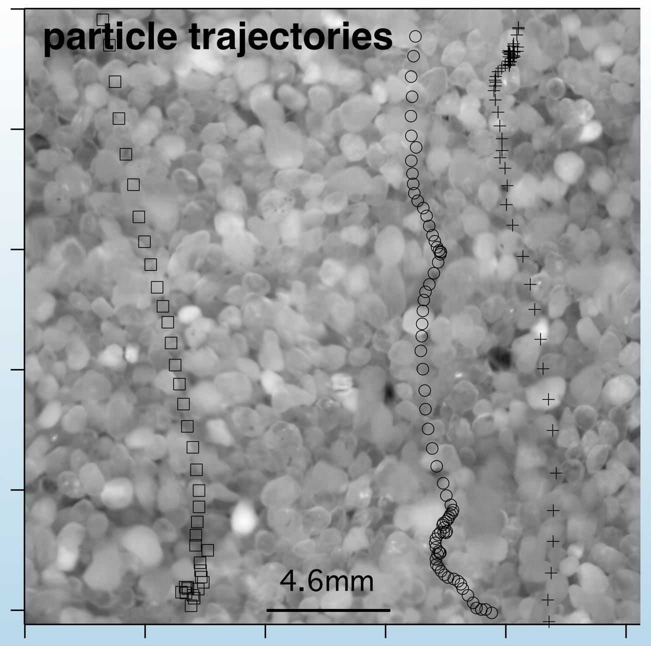
a is a constant to be calibrated.

where c_e and c_d are constants (to be calibrated) related to the erosion and deposition rates:

$$\dot{\sigma}_e = \frac{c_e}{D^2}\sqrt{\frac{Rg}{D}}\,(\tau^* - \tau_c^*) \qquad \dot{\sigma}_d = c_d \sigma \sqrt{\frac{Rg}{D}}$$

• Experimental Setup





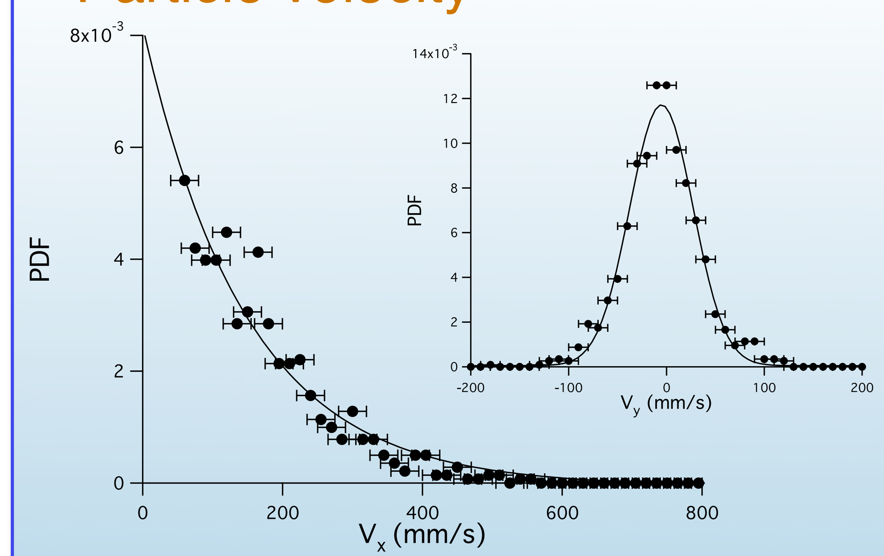
We used a high-speed video camera (500 ips) to track the trajectories of sediments (quartz grains) entrained by a turbulent flow in a rectangular flume over a flat sediment bed of uniform grain size.

We varied the slope S (0.2 to 6°), the flow discharge (2 to 32 L/min) and the grain size (D = 1.15, 2.24 and 5.5 mm).

The vertical flow velocity profile measured using PIV is logarithmic as expected for the range of Re.

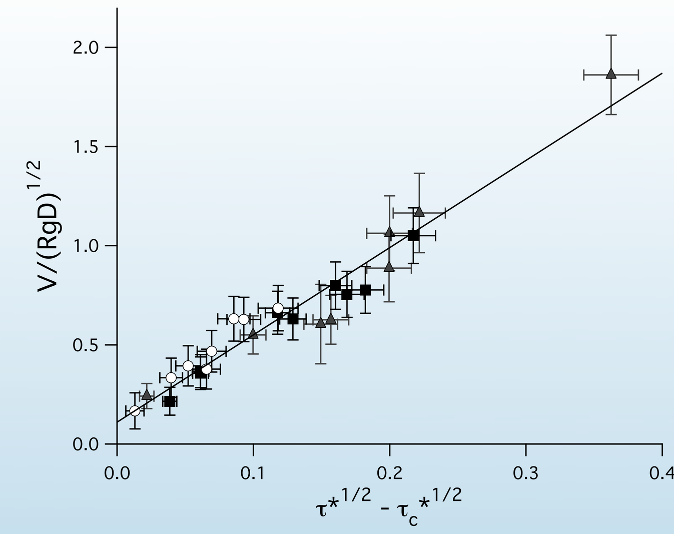
- **H/D = 2-10**
- **Shields number τ^* = 0.06 - 0.25**
- **Reynolds number Re = 1500-6000**
- **Particles Reynolds number Re* = 12-500**
- **Settling Reynolds number Re_s = 150, 430 and 1650**

• Particle velocity



• Streamwise velocity PDFs are exponential. Transverse velocity PDFs are gaussian.

• Identical results were obtained by Charru et al. [2004] for a purely viscous flow. PDFs are more likely to reflect the nature of the interaction of the particles with the bed than to result from the laminar or turbulent nature of the flow.



• The average particle velocity is consistant with the model prediction:

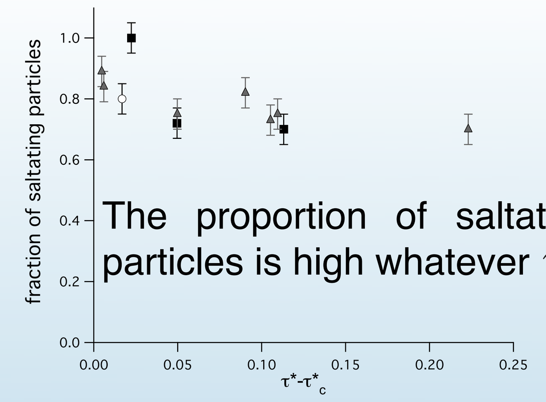
$$\frac{V}{\sqrt{RgD}} = \frac{V_c}{\sqrt{RgD}} + a\left(\tau^{*1/2} - \tau_c^{*1/2}\right)$$

0.11 +/- 0.3   4.4 +/- 0.2

• Non zero velocity at the threshold of sediment transport!!

• Phenomenology

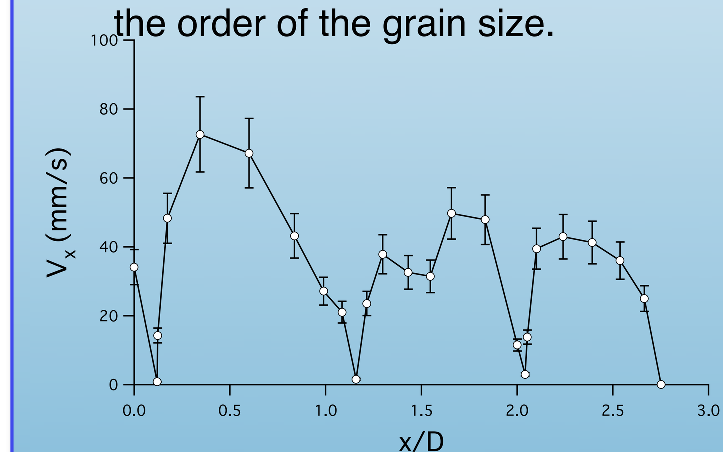
Particles entrained by the flow exhibit intermittent trajectories composed of the succession of periods of motion, hereafter called "flights", and periods of rest.



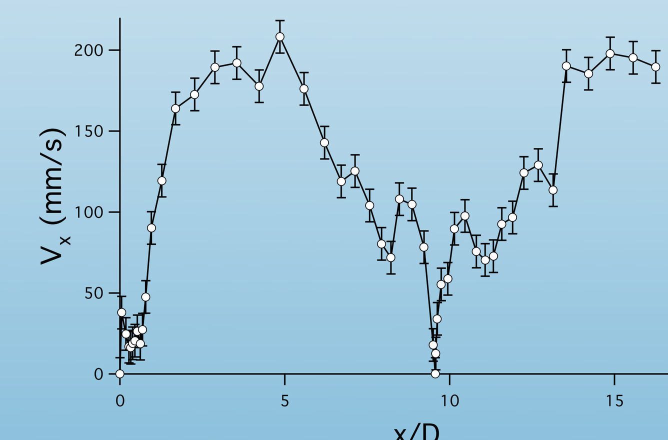
The proportion of saltating particles is high whatever τ^*

Two different kind of trajectories can be distinguished :

Rolling
strong interaction with the bed
velocity oscillates with a periodicity on the order of the grain size.



Saltation
weak interaction with the bed
much longer flights and velocities



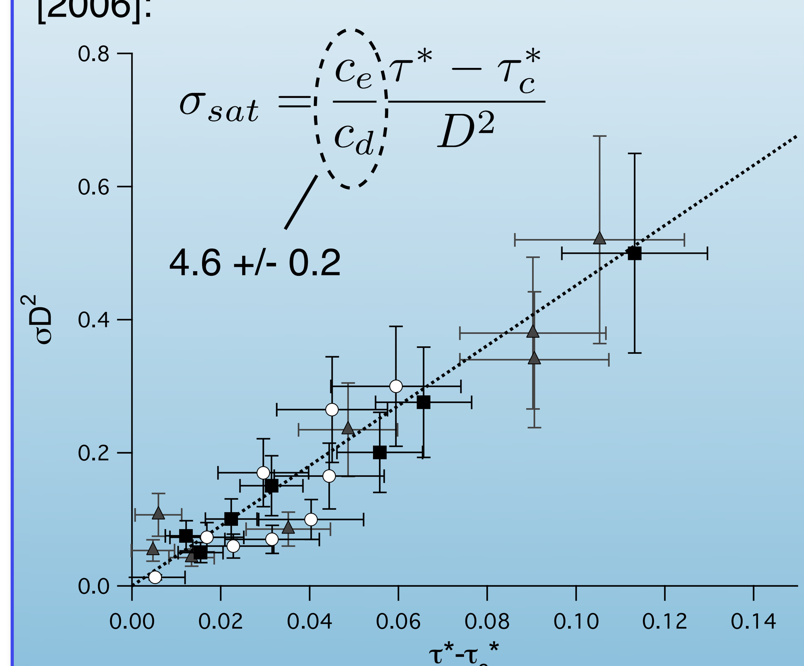
• Surface density of moving particles and flight duration

• σ_{sat} cancels below a finite value of τ^* providing a natural way to define the critical Shields at the onset of sediment transport τ_c^*.

• Above τ^*_c, σ_{sat} verifies the predictions of Charru [2006]:

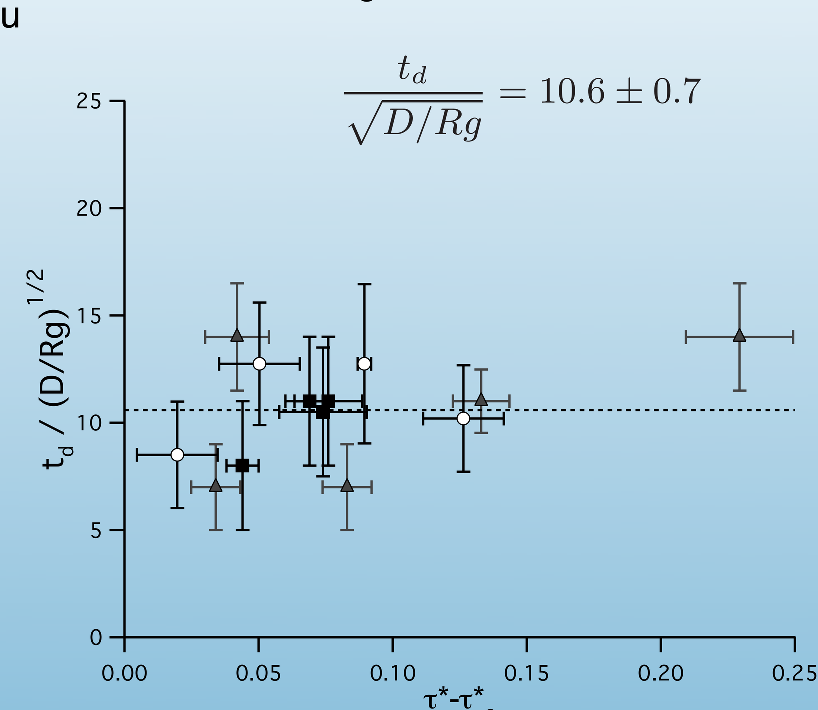
$$\sigma_{sat} = \frac{c_e}{c_d}\frac{\tau^* - \tau_c^*}{D^2}$$

4.6 +/- 0.2



• As predicted by dimensional analysis, the average flight duration scales as the time necessary to settle from a height of the order of a few grain sizes:

$$\frac{t_d}{\sqrt{D/Rg}} = 10.6 \pm 0.7$$

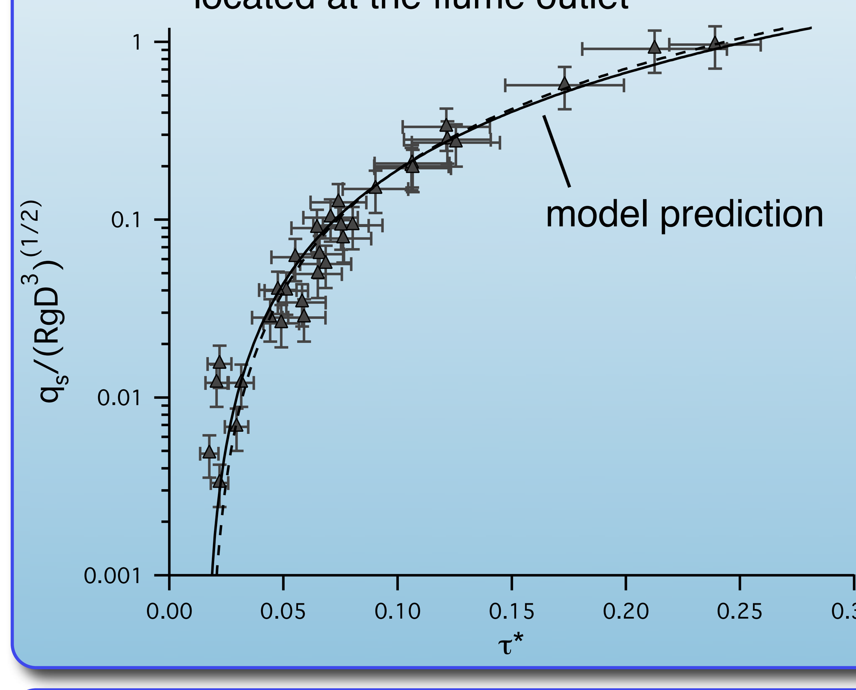


• Comparison between experiments and model

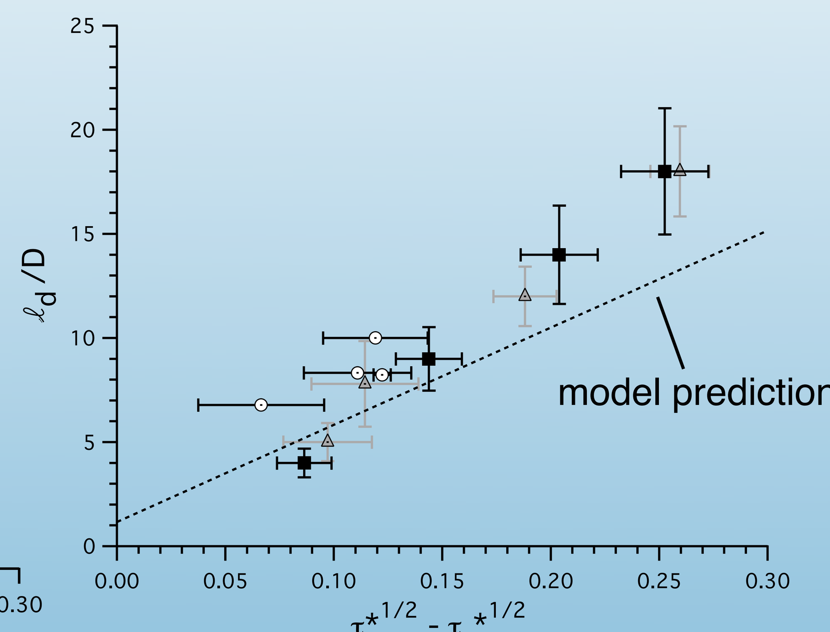
• The experimental results validate the erosion-deposition model of Charru [2006] and allow us to calibrate its coefficients.

• The model prediction are succesfully tested for:

• q_{sat} measured with a scale located at the flume outlet



• The deposition length ℓ_d



• Conclusion

• Our experiments provide a unique set of consistent data (surface density of entrained particles, flight length and duration, velocity distributions, sediment flux,...) that can be used by the community to test bedload transport models.

• They allow us to validate and calibrate an erosion-deposition model which naturally accounts for the relaxation effect which controls the development of bedforms.

• The next steps are:
1. to test experimentally the model predictions against bedforms developpement in turbulent flows,
2. to incorporate the effect of a more complex granulometric composition of the bed in the erosion-deposition model.

• References

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