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Dynamical Evolution of Channel Bed: Applications of Sediment Pick-Up Function

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Abstract

Rivers are characterized by a continuum of morphological diversity due to several factors such as the climate, topography and geomorphology of rivers. The combination of these parameters regulates the capacity of the river and characterizes its dynamics. This contribution focuses mainly on the modeling of sediment transport and its effects on the rivers morphological changes. A laboratory experiments were carried out in the rectangular channel built at the National Agronomic Institute of Tunisia (INAT). The aim is to visualize the morphological evolution of the channel bottom consisting of fine sand under the effect of steady flow. In parallel with these developments, several numerical simulations were performed. Various sediment pick-up functions have been tested to analyze more deeply the morphological evolution of water courses. A 2D hydro-sedimentary model was set up via TELEMAC 2D and SISYPHE. Our approach is based on two objectives. First, we aim to predicting properly the erosion rate of the sand particles carried by the water flow, and then deduct the corresponding morphological changes. The analysis of the results shows a good agreement between simulations and experiments. The numerical models represent accurately the reality.

1. Introduction

The floods contribute to significant changes in river dynamics. It is so important to quantify the impacts of flood on the geometry of stream channels [1]. The numerical modeling of sediment transport may limit this risk. In fact, the sediment transport rate depends on the flow characteristics and sediment properties, such as bed shear stress, grain size distribution [2].

This contribution focuses on the study of the channel bottom morphologic evolution basing on an experimental study in a rectangular channel. Our approach is based on two main objectives. First, we study the evolution of the erosion rate of sand particles in the channel. Second, we determine the geomorphological evolution of the sandy bottom along the channel [3]. Furthermore, numerical simulations tests were performed basing on several models designed for quantifying the bed load transport. One the bed load rate is determined we can calculate the amount of changes in the channel bottom [4]. Finally, a comparative analysis between the calculated results and the experimental data is performed.

2. Experimental Set-up

An experimental study was conducted at the Laboratory of Water Science and Technology (LSTE) of the National Agronomic Institute of Tunisia (INAT). The aim is to visualize the morphological evolution of the channel bottom consisting of fine sand under the effect of a steady flow. The experiments were carried out in the rectangular inclinable flume of length L = 5 m and width B = 7.5 cm. The side walls are made of glass to permit observation of the flow.

Figure 1: Experimental set-up and equipment (INAT)

A layer of fine sand of diameter D = 250 μm was placed in the middle of the channel over a length of 2 m. To maintain the sand layer, two thresholds were installed of long 12.5 cm and wide 7.5 cm (Figure 1). Once the bed was ready, clear water was injected by a pump at the upstream flume inlet with constant discharge (no injection of sediment) [5].

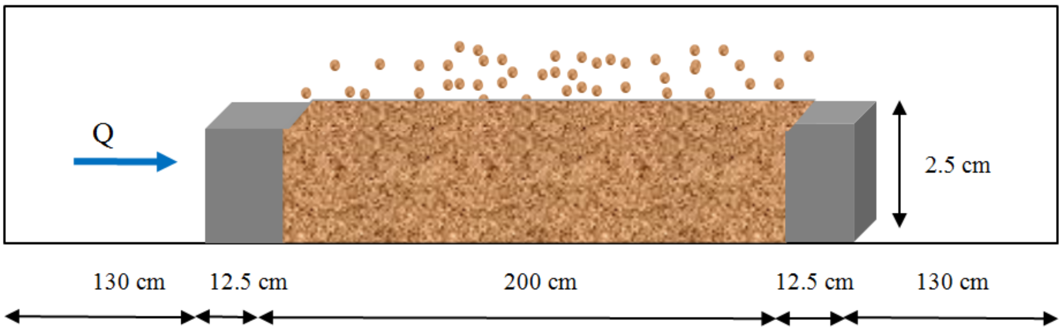

Figure 2: Schema of the equipment set-up and experimental design (INAT)

Flow rates measurements were carried out at the channel outlet at different time steps. Regarding measurements of the solid discharges, several sediment samples at different moments were performed. Finally, for the morphological evolution of the channel bottom, a high-speed camera is proposed which is based on image sequence. The treatment of these images determines the morphological evolution of the bottom along the canal over time, through a comparison between images at different times (image processing).

3. Materials and Methods

The morphological changes in rivers are the result of continuous interaction of several processes. The mechanisms of erosion and deposition of particles are among the factors that explain the morphological evolution of the rivers [6]. In this context, a full analysis of several pick-up functions for predicting the erosion rate (n_e) was performed. In general, the erosion capacity derived from the variation of the bed shear stress. Many researchers have been interested on the study of the erosion process basing on laboratory experiments.

Einstein [7] provides a formula for calculating the erosion rate. Per Einstein, a particle will be eroded when the instantaneous lift force exceeds the weight of submerged particles. Fernandez-Luque [8] offers another deterministic function. However, Yalin [9] was based on a stochastic approach and assumes that the erosion time scale is proportional to the ratio between the particles diameter and the shear velocity, and proposes a new formula. Van Rijn [10] has conducted experiments to determine the erosion rate of particle size ranging between 130 to 1500 μm [11]. The analysis of experimental data has led to new empirical law. Finally, a new law calculating the erosion rate was proposed by Charru [12] basing on laboratory experiments. Charru et al. [13] assume that the erosion of a particle depends on the hydrodynamic force acting on it such as on the velocity of the water, the bed shear stress, etc. In fact, the erosion rate can be expected to be proportional to the excess shear rate. Table 1 below summarizes the most used models for calculating the capacity of erosion [14].

Table 1: Most commonly used pick-up functions

Author	Formulas	Notations
Einstein [7]	$n_e = \alpha\rho_s (RgD)^{0.5} \left(\frac{\tau^* - \tau_c^*}{0.2668}\right)$	α = 0.02 – 0.016 σ : angle of repose σ = 1.32
Fernandez Luque [8]	$n_e = \alpha\rho_s (RgD)^{0.5} \left(\tau^* - \tau_c^*\right)^{3/2}$	
Van Rijn [10]	$n_e = 0.00033\, \rho_s (RgD_{50})^{0.5}\, D_*^{0.3} \left(\frac{\tau^*}{\tau_c^*} - 1\right)^{1.5}$	
Charru et al. [13]	$n_e = 0.0306\, \rho V_s \left(\tau^* - \tau_c^*\right)$	

* The models listed in Table 1, is not exhaustive and other pick-up function can be found in the work by Van Rijn [10].

Where τ^* is the Shields number; τ_c^* is the critical Shields number; R is the relative density; g is the gravitational acceleration; ρ is the density of water usually 1000 kg m^{-3}; ρ_s is the sediment density usually 2650 kgm^{-3}; V_s is the settling velocity, D* is the dimensionless particle diameter.

4. Numerical model implementation

Therefore, SISYPHE and TELEMAC 2D is chosen here to simulate the morphological evolution of the channel bottom. A 2D hydro-sedimentary model was developed to simulate the morphological evolution of the sandy layer (non-cohesive) in the channel. Several models were tested in this study to better understand and interpret the morphological evolution of rivers [15].

TELEMAC 2D is an ideal modeling framework for rivers due to its finite element grids which allow graded mesh resolution [16]. In fact, areas that require high bathymetric accuracy such as meandering can be well resolved by TELEMAC 2D. This model performs 2D hydraulic calculations; it solves Saint Venant equations of momentum and continuity, derived from the Navier Stokes equations by taking the vertical average. The main results give the water depth and the average vertical velocity at each point of the resolution mesh [17].

SISYPHE is the state of the art sediment transport and bed evolution module of the TELEMAC modeling system. SISYPHE can be used to model complex morphodynamic processes in diverse environments, such as coastal, rivers, lakes and estuaries, for different flow rates, sediment size classes and sediment transport modes [18]. In SISYPHE, sediment transport processes are grouped as bed load, suspended load or total load, with an extensive library of bed load transport relations. SISYPHE is open source software; it is a horizontal two dimensional. The area of study is a rectangular channel of length L = 5 m and width B = 7.5 cm. A flat sand layer is installed at the center channel consists of fine sand uniform, diameter D = 250 µm. A triangular mesh of 15000 mesh is selected, leading to finer mesh of 2 mm in the sand layer and a mesh of 5 mm elsewhere. At the initial time, the bottom is attached to the side z = 0. Regarding the roughness of the channel, a coefficient of Strickler of 65 $m^{1/3}/s$ was selected. Roughness has a major impact on the water depth evolution in the channel. The channel roughness is quite high given the presence of the sand layer (fine particles).

For the 2D implementation via TELEMAC 2D, a constant flow Q = 2 l/s is imposed on the channel input, and a free fall on the downstream site (experimental conditions). In SISYPHE, we insert also the physical properties of sediments and fulfill the boundary conditions of the model. Regarding the calculation methods, SISYPHE offers several empirical laws for the estimation of the bed load transport rates. Four bed load transport formulas: Einstein [7], Fernandez Luque [8], Van Rijn [10], and Lajeunesse et al. [19] were tested. Finally, to determine the morphological evolution of the bottom, SISYPHE solves the Exner equation given by:

$$(1-p)\frac{\partial z_b}{\partial t} + \frac{\partial (q_b)}{\partial x} = n_e - n_d \quad (1)$$

Where Z_b is the bed elevation; p is the bed porosity (p~0.4 for non-cohesive sediment); q_b is the bed load rate, layer; $\dot{n}_e$ and $\dot{n}_d$ are the width averaged sediment entrainment and deposition fluxes at the interface between the suspended load and bed load zones.

The Exner equation is a statement of conservation of mass that applies to sediment in a fluvial system. This equation allows us to have a spatiotemporal description of changes in the sand layer. SISYPHE is internally coupled with TELEMAC 2D, to take in account, the evolution of the bottom in calculating hydraulic parameters (data will be exchanged directly between the two programs).

5. Results and discussion

A first analysis of the results shows that both processes of erosion and deposition are responsible for the evolution of bottom elevations in the channel. The first part of this work concerns the presentation of simulation results for predicting the erosion rate (n_e). Second, we performed a comparison between simulated results and experimental data for simulating the geomorphological evolution of the channel bottom.

5.1. Evolution of the erosion rate

Several simulations were performed using the most prevalent laws for predicting the erosion rate (Table 1) [10]. Our choice is mainly based on two criteria: the first is the order of magnitude of the Shields number ($0.03 < \tau^* < 0.3$), the second criterion is the particle size ($130\ \mu m < D < 1500\ \mu m$) [20]. The aim is to visualize the effectiveness of these formulas in the prediction of the erosion rate. The results of the simulation of the erosion capacity calculated by the models are summarized in Figure 3.

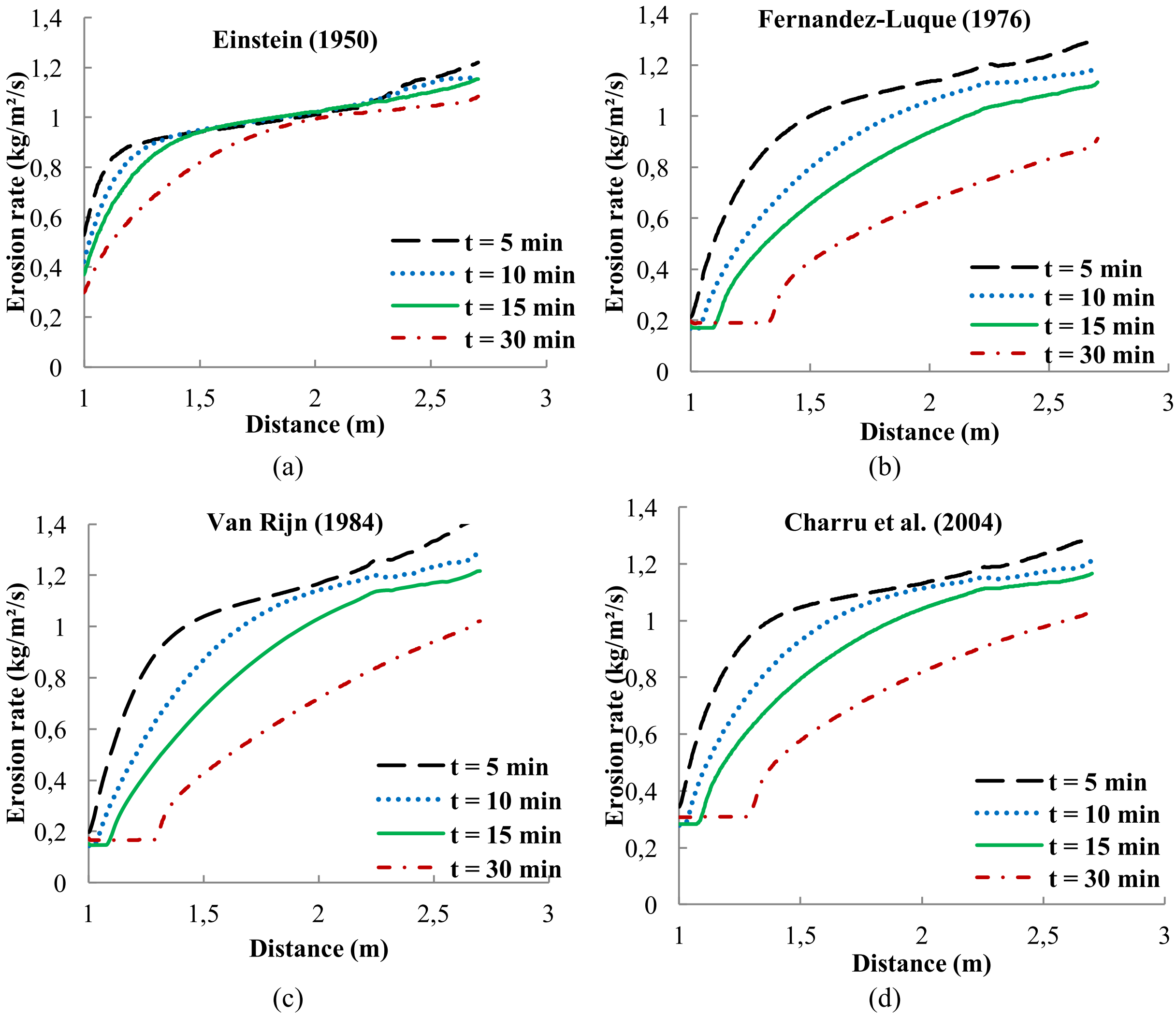

Figure 3: Erosion evolution along the channel calculated by 4 models: Einstein [7], Fernandez-Luque [8], Van Rijn [10], and Charru et al. [13]

The results calculated by the different models have the same shape of the curve and the difference between the models estimations is relatively low. For all models, the erosion capacity decreases over time along the channel. For different tests, the erosion rate of the fine sand particles increases from upstream to downstream. The rate of

eroded sand particles is very important, it varies in average between 0.2 kg/m²/s up to 1.2 kg/m²/s at the channel outlet.
To better visualize the difference between predictions of tested models a comparative analysis was performed between the values simulated by the models at the end of the experimental tests (at the same time t= 15 min). The simulation results are summarized in Figure 4.

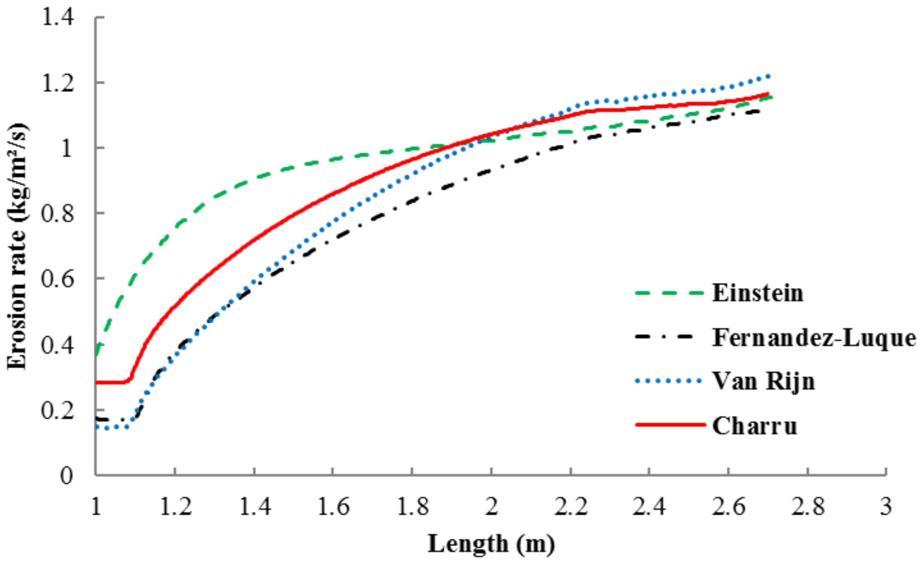

Figure 4: Evolution of the erosion rates simulated by different models at t = 15 min

The analysis of the simulation results shows that the different models correctly reproduce the reality. The erosion phenomena depend basically on the variation of hydraulics parameters, especially the bed shear stress.
The erosion rate increases from the upstream to the downstream channel until a maximum value of 1.2 kg/m²/s. However, we note few differences between the values simulated by the models. These differences may be justified by the fact that these empirical laws are highly dependent on particle size. Moreover, the presence of two barriers to maintain the sand layer contributes to the variation of hydraulic parameters that influence the models calculations.

5.2. Morphological evolution of the channel bottom
The objective of this part is to study the evolution of the sand layer in the channel. Figure 5 shows the evolution of the morphology of the sand layer in response of transported sand particles at t = 15 min.

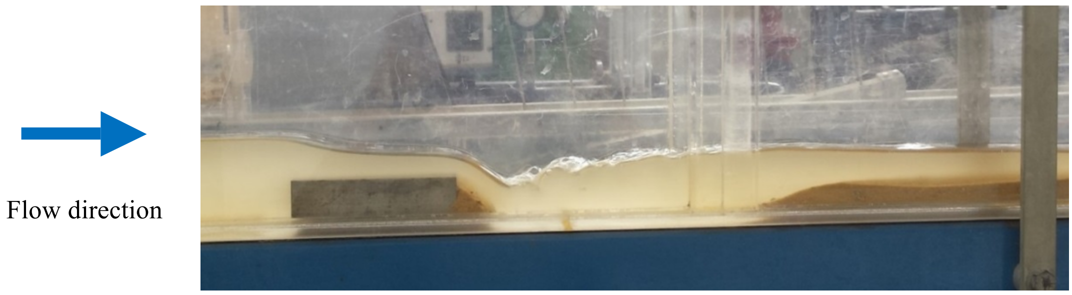

Figure 5: Evolution of the sand layer in the channel

A 2D hydro sedimentary modeling was developed via SISYPHE coupled with TELEMAC 2D. The set-up model converse the amount of sediment carried into volume of sediments to determine the evolution of the corresponding morphological change in the channel bottom, basing on the resolution of the Exner equation. The established model provides a detailed description of the hydraulics parameters variation on the sediment transport rates. It also allows determining accurately the variations in the geometry of the sand layer along the channel. Several simulation tests were carried out with 4 models for quantifying the bed load transport rate.
The results of the coupled approach TELEMAC 2D and SISYPHE show that there is a longitudinal evolution on the channel bottom. From the beginning of the experience, we note the appearance of erosion and deposition

zones. These two zones grow over time (Figure 6). Below is a comparison between measured and simulated results by different models at t = 15 min.

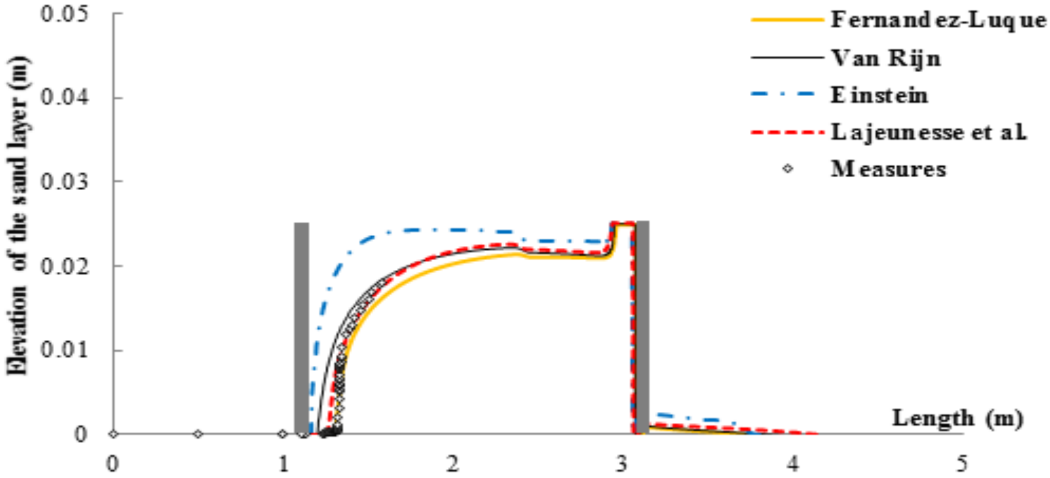

Figure 6: Evolution of the sand layer morphology along the channel

The measurement of the sand layer at t = 15 min are obtained by image processing techniques during the experiments. The comparative analysis of the results shows that both models Lajeunesse et al. [19] and Van Rijn [10] give satisfactory results. Yet, over time the model of Fernandez Luque [8] overestimates eroded sand particles.

Moreover, the presence of the two barriers disrupts the flow and forcing the water level to rise and go over the barrier and shows the appearance hydraulic jump. This causes a significant variation in the water depth in the channel [20]. The hydraulic jump is one of the most complex phenomena in open channel flow which strongly influences the model calculations. However, the numerical models overcome these constraints, and it succeeds to represent correctly what happens. The water level follows the morphological evolution of the sand layer. To make clear the differences between the simulation results, we calculated the evolution of sediment transport volumes [21]. The Table 2 below summarizes the percentage of sediment volumes calculated by the different models.

Table 2: Comparison of eroded sand volumes (%) for the different models

	t = 0	**t = 5 min**	**t = 10 min**	**t = 15 min**	**t = 30 min**
Formulas	Volume of eroded sediment (%)				
Einstein [7]	0	0.6	2.6	4.8	12.2
Fernandez Luque [8]	0	6.2	15.4	24.2	43.6
Van Rijn [10]	0	4.2	11	18.2	34
Charru et al. [13]	0	5	12.2	20.2	40

The analysis of the results shows some differences in the models estimations. The most erosive model is Fernandez-Luque [8] after 30 min about 50% of the sand layer was eroded. However, the two models of Van Rijn [10] and Charru [12] give similar results compared to the sands transported volumes. Finally, the Einstein model does not reproduce the reality, after 30 minutes, 87.8% of the sand layer has not moved. We note that for studies related to the short-term scour the Fernandez-Luque [8] model can give good results. However, of Van Rijn [10] and Charru [12] models are recommended for the study of erosion processes in the long-term rivers.

Conclusions

This current research presents an experimental and theoretical work to understand and predict the evolution of river bed erosion and sediment transport. Two open to simulate flow and sand transport in a rectangular channel containing sand obstacle. An experimental set-up is made to visualize and track the morphological evolution of the sand layer, to this end high speed camera is used. The simulation results show that river morphological evolution depend the hydrodynamics of the river and sediment properties. In fact, the experiments conducted in

the experimental flume lacks many precisions and sophisticated measurements tools to accurately track flux of sediment transport and morphological evolution of the sandy bottom.
Also, the presence of two barriers and the appearance of the hydraulic jump influenced the numerical calculations. However, numerical simulation via TELEMAC 2D coupled with SISYPHE give generally satisfactory results. The analysis of simulations shows that changes in channel geometry depend heavily on sediment grain size, hydraulic parameters. Both models Van Rijn [10] and Charru et al. [13] are recommended for the study of the process of long-term erosion, while for studies related to the short-term scour model Fernandez-Luque [8] can give good results.

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