# Supply-Limited Fluvial Dunes

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ABSTRACT: Among the parameters affecting the morphology of fluvial dunes is the volume of mobile sediment. Fluvial dunes have an important practical relevance since they give a substantial contribution to flow resistance by inducing a hydraulic roughness which depends on their shape and dimensions. Although supply-limited dunes present similarities with typical fluvial dunes, the scaling of their wavelength and their three-dimensional evolution differs from that of alluvial dunes observed where the volume of mobile sediment is not limited. The present investigation is intended to be a contribution to the theory of sand dune stability which comprises the effect of supply limitation on the formation of fluvial dunes.

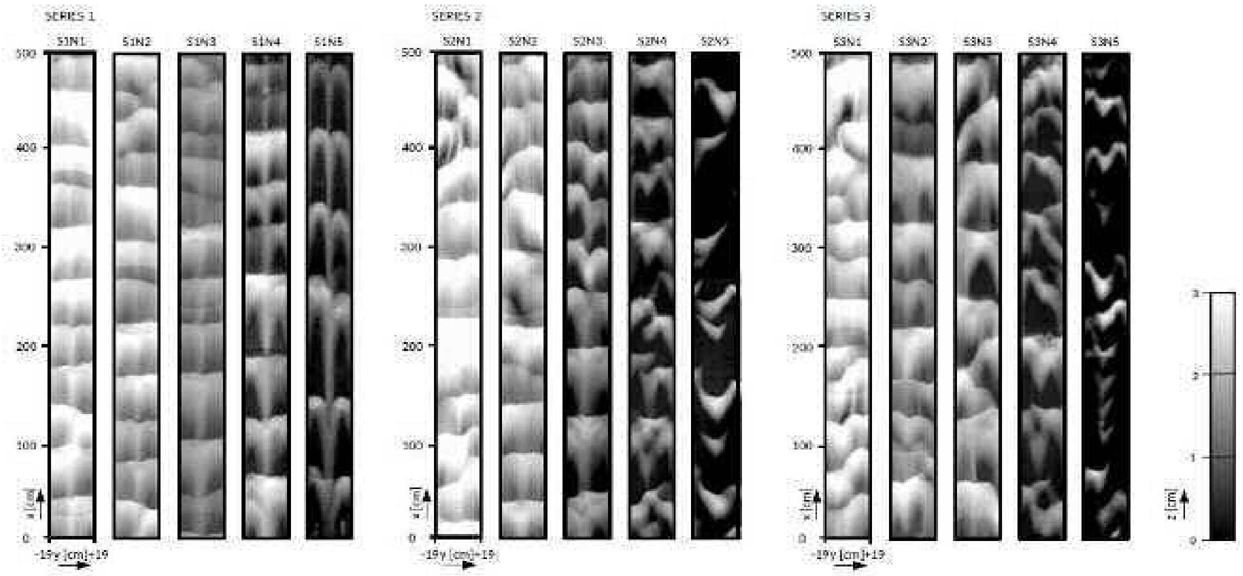
## 1 INTRODUCTION

The motion of natural fluids interacts with the erodible surface of the Earth by sediment transport. When the bottom shear stress exceeds its threshold value for sediment entrainment, sediment particles begin to move. In response to this movement, sedimentary patterns might appear. Among the various morphological patterns, the present study focus on transverse fluvial dunes, the crests of which are usually perpendicular with the main direction of the river stream. Formation and migration of fluvial dunes are very important because they give a substantial contribution to flow resistance, they affect the sediment transport and they have significant interactions with human activities. Fluvial dunes are a primary source of roughness and therefore a major factor in determining river stages. Moreover, their practical interest arises also in connection with fluvial structures the safety of which could be endangered by their dynamics. The appearance of sand dunes and their characteristics have been dealt with in great details by various researchers over the years. Investigations on the morphology and dynamics of fluvial dunes include both theoretical and physical modelling. The knowledge of dune dynamics is in constant progress thanks to the development of new techniques for laboratory and field observations and the improvement of its theoretical modelling. Field surveys clearly show that these patterns are repetitive both in time and space, so that typical wavelengths, amplitudes and migration speeds can be assigned to them. Although no theoretical models have yet been able to reproduce all the characteristics of sand dunes correctly, idealised models exist which are capable of predicting their spacing. By describing their appearance as a free instability of cohesion-less river beds forced by steady currents, these models, based on a linear stability analysis, predict dune wavelengths in fair agreement with both laboratory and field observations. One of the main limitation of stability-based models is the assumption of full mobility conditions, i.e. unlimited sediment supply. Under supply-limited conditions, i.e., limited sediment supply, they are not valid. How fluvial dunes react to a limitation in the sediment supply is the main research question this study tries to address. The investigation described below consists of a first part in which a physical modelling of the formation of fluvial dunes is presented. Then in a second part a numerical modelling is described that is intended to be a contribution to the theory of sand dune stability which accounts for sediment supply limitation.

## 2 PHYSICAL MODELLING

In many fluvial environments supply-limited sediment transport is common. When a sediment mixture is subject to a discharge wave or a period of low flow, the bed-level undergoes a transient degradation until it is fully armoured leading to the natural formation of a motionless substratum over which sandy patterns grow and migrate. In sand-gravel mixtures, such transport conditions are common and supply limited dunes have been observed both by field surveys (Carling et al., 2000) and by flume experiments (Tuijnder et al., 2009). While the field surveys by Carling et al. (2000) seem to indicate that a decrease in the sediment availability causes an increase in dune length as well as in the irregularity of their morphology, the experimental data by Tuijnder et al. (2009) show an opposite trend.

In order to provide data on a topic in which measurements are limited and to use this data to shed light on the apparent contradiction found in the literature, a set of laboratory experiments are presented which investigate the relation between dune morphology and sediment availability. An open-channel free-surface flow forcing an erodible hydraulically rough sandy bottom is described for a flow regime in which a continuous intermittent sediment transport occurs. The experience is conducted in a slope varying laboratory flume. The entire flume is mounted on a beam, the slope of which can be easily adjusted. Cohesion-less sand is used as artificial roughness. At the beginning of each experiment the same sediment is uniformly spread on the flume bottom to generate an initial layer of sediment with a constant thickness. Three series of experiments are realised by fixing hydrodynamic and morphodynamic parameters and in particular the duration of the experiments but varying the thickness of the initial layer of mobile sediment and therefore the sediment supply. Each run is stopped after half an hour from the beginning of the experiment allowing sand dunes to develop over the entire length of the channel. Their geometry varied significantly depending on the initial volume of mobile sediment. In the first experiment of each series, the volume of mobile sediment is enough to allow the formation of sand dunes under alluvial conditions. Progressively decreasing the initial sand layer thickness, the formation of supply-




*elevation is shown in shades of grey, lighter colours corresponding to higher values. Rigid bottom level is black. Flow is from bottom to top.*

limited dunes is observed. The physical modelling of the formation of supply-limited dunes indicates that the presence of a motionless substratum strongly affects the morphology of the dunes, the average wavelength of which increases with a decreasing sediment supply.

## 3 NUMERICAL MODELLING

The linear stability analysis by Colombini (2004) has been extended to take into account the effect of supply limitation on the formation of fluvial dunes. A steady turbulent free-surface water flow through a wide straight channel is studied in two-dimensional Cartesian coordinate system with the horizontal axis along the channel axis and the vertical axis over the depth pointing upwards with the origin at the bottom. The presence of two-dimensional dunes with crests orthogonal to the direction of the flow is considered. Assuming that the dune amplitude is much smaller than the local water depth, the flow field can be evaluated by means of a perturbation approach. Such assumption seems reasonable since supply limitation should keep bottom forms low. Regarding the bottom geometry as periodic, the sandy bed can be expressed as superposition of different spatial components, the number of which should be large enough to describe the discontinuity of the supply limited bottom profile. Analogously to the above described physical modelling, the dune profile is thought to be the result of the instability of a thin layer of sand of given thickness which at first is homogeneously lying on a motionless substratum. The hydrodynamic problem can be split into the evaluation of a basic flow field, which describes the steady flow over a flat bottom, and a set of linearly independent differential problems, which describe the perturbation of the flow field owing to the presence of sand dunes. Since fluvial streams are characterized by high values of the Reynolds number, the determination of the flow field requires the introduction of a turbulence model. The two-dimensional Reynolds-Averaged-Navier-Stokes equations are numerically integrated to evaluate the basic flow field, under the shallow water approximation, and the perturbed flow field, which is solved fully two-dimensional. At the free surface, the dynamic boundary condition forces the vanishing of the shear stresses and the kinematic boundary condition is considered as well. Close to the bottom, the velocity vanishes at a distance from the seabed related to the bed roughness. The hydrodynamic problem is closed by introducing a self-similar solution for the kinematic eddy viscosity, and, finally, Reynolds stresses are quantified by the Boussinesq relationship. Directly from the knowledge of the perturbed flow field, information on the net sediment transport can be obtained by the evaluation of the bed shear stress and relative Shields parameter introducing sediment transport predictor formulae. Suspended sediment transport is neglected at this first stage of the modelling. Only bed-load sediment transport is considered, including a correction in the threshold value for sediment motion, in order to account for the role of gravity, which opposes uphill motion and favour downhill motion. The Shields stress is evaluated at the interface between the flowing fluid and the very thin saltation layer, where grains are involved in transport processes. The sediment discharge is computed by the classical Mayer-Peter & Müller formula. The time-development of the sandy bottom can be estimated introducing the sediment continuity equation (Exner equation), which is the heart of the morphodynamic model. Linearising all the morphodynamic formulae and coupling them with the linear hydrodynamics previously described, it is possible to perform a linear stability analysis. Such a linear stability analysis entails few main steps. Small amplitude bottom perturbations and related sediment transport rates are expressed as exponential functions in time and space and investigated one separately from the other. Directly from the linearised sediment continuity equation a dispersion relationship is deduced. The morphodynamic time dependent amplitude of the bottom perturbation turns out to be exponential, and, in turn, its complex argument is able to describe the growth (decay) of the amplitude, with its imaginary part, and the migration of the crest, with its real part. Finally, assuming the most unstable mode to prevail on the other, the main features of the sand dune which is more likely to occur can be predicted depending on the values of the flow and sediment parameters.

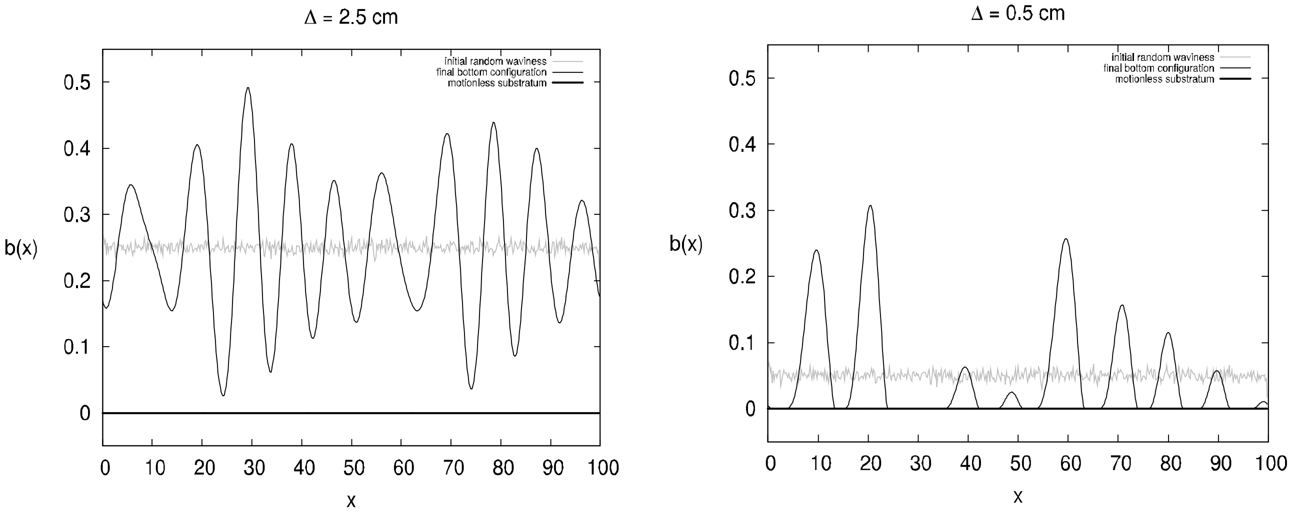



*Illustration 2: Time development of an initial random bottom waviness for a conductance coefficient C = 15, a Froude number F r = 0.5 and an angle of repose of the sand Ψ = 50°. The bottom profile is plotted in the horizontal direction at the beginning (grey lines) and at the end of each numerical simulation (black thin lines). The motionless substratum is represented by the thick black lines.*

The numerical approach described by Blondeaux et al. (2016) is adopted to take into account the effect of supply limitation on the sediment transport. When local entrainment of sediment is prevented by the presence of a motionless substratum, and, therefore, the amount of sediment in motion is smaller than the local transport capacity, the sediment flux is evaluated by numerical means. Where locally no sand is available, the sediment transport depends on the bed shear stress and its spatial derivative. If the shear decreases in the direction of the main flow, the sediment transport rate is provided by the sediment transport predictor formulas and some deposition occurs accordingly with the sediment continuity equation. Conversely, if the shear stress increases in the flow direction, the sediment transport rate cannot increase because locally no further sediment is available, and, therefore, its local value should be equal to the upstream value.

Numerical simulations of the bottom time-development starting from an initial random small-amplitude perturbation are presented. The length of the computational domain, the initial thickness of the sand layer and the simulation time-window are free parameters. The bottom time-development is computed for a simulation time-window of the same order of the duration of the laboratory experiments. Flow and sediment parameters has been chosen so that they fall in the range of values typical of the above described flume experiments. The main outcome of the model is the lengthening of the supply-limited dunes owing to the decrease of the volume of mobile sediment. This finding is qualitatively and quantitatively in fair agreement with the experimental measurements.

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