On how defining and measuring a channel bed elevation impacts key quantities in sediment overloading with supercritical flow

Hasan Eslami1 · Hooshyar Yousefyani1 · Mohsen Yavary Nia1 · Alessio Radice1

Abstract
The manuscript presents the results of an aggradation experiment performed in a laboratory channel with supercritical flow. The channel was fed with a stationary sediment load exceeding the transport capacity of the flow in the initial condition, thus inducing sediment aggradation and an increase of the bed slope. The experiment is part of a laboratory campaign mimicking sediment overloading in mountain rivers, a process that can determine increased hydraulic risk levels at key spots. A crucial issue in measuring sediment aggradation is the definition and determination of the bed elevation, this issue being quite relevant in experiments with a relatively large transport capacity, where a thick bed-load layer exists and hinders the possibility to determine with confidence a reference bed elevation. The determination of the bed elevation, in turn, impacts the quantification of a number of properties, including the initial sediment transport capacity of the flow, temporal scales of the aggradation process, water depth and Froude number. The manuscript presents a sensitivity analysis of the results to two extreme definitions for the bed elevation: the first one locates the bed at the upper edge of the bed-load layer, while the second one at the lower edge of the bed-load layer where the particles do not move. The presentation of the two alternatives is focused on the experimental methods they use, consistently with the intent of the special issue. Furthermore, it is demonstrated that the definition of the bed elevation also has a major impact on numerical models of the process. The experimental results have been reproduced numerically, demonstrating that the calibration parameters returning a best fit are also impacted significantly by how the bed is defined. The preferred definition for analyzing an experimental campaign is locating the bed below the bed-load layer.

Keywords
Bed-load transport · Channel aggradation · Bed definition · Image-based measurements · Sediment transport capacity · Aggrading front celerity · Equivalent roughness

Introduction
In general, nature aims at maintaining equilibrium, so it responds to any disturbance tending to a new stable state. In this context, a river is governed by some parameters such as path slope, flow discharge, sediment characteristics, and sediment yield; any natural or artificial disturbance such as heavy rains, floods, landslides, or hydraulic structures can thus alter the river morphology (e.g., Chanson 2004).

Therefore, it is important to study river morphologic phenomena and their related parameters. Experimental studies aim at phenomenological interpretation, at quantitative depiction and at providing enough data for calibration and validation of numerical models that are mostly used in engineering practice to analyze real situations. In this work, we are concerned with channel aggradation induced by sediment overloading, a process that can increase hydraulic risk during flash floods (e.g., Zanchi and Radice 2021).

The present manuscript is a follow-up of an earlier experimental campaign carried out at the Politecnico di Milano (Radice and Zanchi 2018; Zanchi et al. 2019; Zanchi and Radice 2021) where sediment aggradation was studied in subcritical flow, providing simple predictors for the celerity of propagation and the height of an aggrading front and numerically reproducing some benchmark experimental results. Furthermore, in the prior campaign, ad hoc
image-based measurement methods were devised for measuring the relevant parameters. With the current campaign, the aim is to investigate the aggradation process in supercritical flows. In mountain rivers, in fact, due to higher slope, the flow is mostly supercritical and has the ability to carry a significant amount of coarse sediment. Furthermore, in these conditions a thick bed-load layer develops, hindering the determination of a bed elevation. The specific thrust for the present manuscript is to study how several key quantities representing the process can be affected by using different definitions for the position of the bed and corresponding image processing methods for bed detection.

The determination of the reference bed is crucial in a number of applications, even without sediment transport. The determination of a law of the wall in turbulent flows requires the knowledge of the wall position, an issue that may be obvious if the bed is smooth but is instead tricky if the bed is rough (e.g., Wilcock 1996; Smart 1999) and becomes further complicated if the sediment bed is moving under the action of the flow (e.g., Dey et al. 2012; Ferreira et al. 2012). Some studies (e.g., Bareš et al. 2016; Berzi et al. 2019; Capart and Fraccarollo 2011; Kaczmarek et al. 2019; Matoušek et al. 2015, 2019) have considered the sediment concentration and velocity profiles under intense sediment transport and have defined the motion of the sediment layer; the transport layer of the flow has been subdivided into an upper collisional sublayer and a lower dense sublayer which is above the stationary deposit. In the dense part, the velocity of the grains is significantly lower than that in the collisional part, and the maximum concentration of sediment is very similar to that in the stationary deposit, challenging the identification of the interface between the flow and bed. The issue is connected to different approaches to the so-called active layer. For example, Church and Haschenburger (2017) reported two different definitions of the active layer in fluvial sediment transport: first, the mobile surface layer, which is the topmost layer of the sediment, actively moving in bed load transport; second, the one based on the scour fill concept, which is the full depth of the material prone to be moved. However, considering that, on the other hand, the recognition of a water surface can be less troubling, the uncertainty in the determination of the bed elevation has an obvious impact on the quantification of a flow depth. The definition of relevant interfaces is important also in parameterizing and modeling other processes than bed-load transport (e.g., Venuleo et al. 2021).

Definitions of interfaces call for corresponding methods to measure their elevations. Different methods have been used in the literature to measure the bed and water elevation. Jumain et al. (2013) measured the bed and water surface elevation by using a digital point gauge. In some other studies, acoustic sensors have been employed (e.g., Kinzel et al. 2010; Vesipa et al. 2018; Wren et al. 2020, 2021). Image-processing methods have been also applied for the same purpose. For example, Lafaye de Micheaux et al. (2015) used watershed transformation and background extraction methods for the detection of the bed and water surface; also, Viriyakijja et al. (2015) used Canny edge detector to detect the water surface.

With reference to the experimental campaign that is now ongoing at the Politecnico di Milano, the aim of the present study is investigating the sensitivity of some key parameters (Froude number, initial transport capacity of the flow, front propagation celerity) to the definition and measurement of the bed surface. Furthermore, the experimental results have been also reproduced numerically determining best-fit values of calibration parameters (a bed-load coefficient and an equivalent roughness coefficient), since experimental data can be typically used as benchmarks for numerical simulations that are instead most used in practice. The aim of the manuscript also included analyzing how numerical parameters are affected by the definition of a bed surface. In this regard, two extreme definitions of the bed are presented. One corresponds the upper bound of the bed-load layer and has been measured with the detection method already used in the subcritical campaign (“edge-based” in the following), while the other one corresponds to the lower boundary of the bed-load layer, and its measurement required developing a new method (that will be named “motion-based” henceforth). The manuscript is structured as follows: first, the experimental setup and procedures are provided; then, the experimental data acquisition methods and their analyses are explained in detail; finally, the results are presented and discussed, and the conclusions are derived.

**Laboratory facility**

**Experimental setup**

The aggradation experiment presented in this manuscript has been run at the Mountain Hydraulics Laboratory of the Politecnico di Milano, Lecco campus (Italy). The configuration of the flume can be seen in Fig. 1. The used rectangular channel has a length of 5.2 m, width of 0.3 m, and bank height of 0.45 m. The channel has Plexiglas walls and its stream-wise slope can be adjusted acting on a jack. The water is pumped from an underground container into an upstream tank that creates the upstream head for the channel flow. The water discharge, $Q$, can be regulated using a guillotine valve and is measured by an electromagnetic flowmeter. The erodible channel bed, which is bordered by a sill at the downstream end of the flume, is 15 cm thick and is made of polyvinyl chloride (PVC) sediment particles. In the first 0.75 m of the channel, the bed is not erodible (plates with the sediment particles glued are placed ensuring
a continuity of the bed elevation), to avoid the local scour caused by the inlet flow and a sediment feeding system. The latter is a vibrating channel placed below a hopper where the sediment to be fed is stored. At the downstream of the channel, there are two collectors; the first one is for monitoring the amount of sediment transported through the channel and the second one is for preventing the particles from entering the underground container.

The sediment characteristics were determined by Unigarro Villota (2017) as follows: the particle equivalent diameter \(d\) is 3.8 mm with a uniformity coefficient \(f\) 1.04, the density \(\rho_s\) is 1443 kg/m\(^3\), and the porosity \(p\) is 0.45. The Manning roughness coefficient of the sediment particles is \(n_s = 0.015\) s/m\(^{1/3}\) as determined during preliminary tests by Zanchi and Radice (2021).

The key measurements are performed by image analysis. In fact, due to the swiftness of the aggradation process, it is needed to measure different parameters in different times and locations, and it is almost impossible to measure them manually with relatively high spatial and temporal resolutions. There is a camera positioned over the vibration channel of the sediment feeding; two cameras are positioned beside the channel and one is positioned beside the collector (Fig. 1).

**Experimental procedure**

Before an experiment: (1) the slope of the channel is set to the desired value (in this study 1.2%); (2) the hopper is filled with sediment particles and the vibration intensity of the feeder is set to a desired value; (3) the sediment particles in the channel are scraped to create an even layer, and the bed surface is sprayed with nebulized water to avoid particle movement due to the surface tension of water when the initial flow of water reaches them; (4) the cameras are positioned in their proper places for image acquisition.

An aggradation experiment is run as follows: (1) the water pumping system is switched on, and the water discharge is set to a low value (<0.0005 m\(^3\)/s) to avoid any disturbance to the mobile bed at water entrance into the channel; (2) when the bed is completely saturated and the water surface reaches the bed surface, the cameras are turned on; (3) the water discharge is set to the test value (that is larger than the threshold water discharge for sediment transport); (4) the hopper is switched on, and the time at which this happens is considered as the initial time of the experiment; (5) during the experiment the flow and sediment feeding rate are maintained constant and the hopper is refilled manually; (6) the experiment ends when no more sediment particles are available.

After a run, the sediment material is taken out from the collectors and flume, let dry for some days, then weighted for a global balance of sediment mass involved in the experiment.

**Parameters of the present aggradation experiment**

For the purposes of this study, an aggradation experiment has been performed with the control parameters listed in Table 1 (\(T\) is the experiment duration, \(S_0\) the initial channel slope, \(Q\) the flow rate, and \(Q_{s_{in}}\) the sediment feeding rate).

**Table 1** Parameters of the aggradation experiment performed in the present study

| \(T\) (s) | \(S_0\) (%) | \(Q\) (m\(^3\)/s) | \(Q_{s_{in}}\) (m\(^3\)/s) |
|----------|------------|------------------|-----------------------------|
| 260      | 1.2        | 0.007            | \(2.28 \times 10^{-4}\)     |
Methods/1: measurement methods

Measurement of the sediment feeding rate

The method used to determine the sediment feeding rate and check its stationarity during an experiment is the same one developed by Radice and Zanchi (2018), that is based on the assumption that a relationship exists between the sediment feeding rate and the velocity of the particles travelling along the vibrating channel. This relationship is quantitatively determined during preliminary runs and is depicted in Fig. 2a. During an experiment, the particle velocity is measured continuously by applying Particle Image Velocimetry (PIV) to the movie captured by the camera above the vibrating channel. In this way, a continuous time series of the sediment feeding rate can be obtained (Fig. 2b). This method is not described in more detail in this manuscript, since it is not an original contribution of the present study.

Measurement of the bed and water elevation

As mentioned above, the definition and measurement of the bed elevation is the key issue treated in this manuscript. Our starting point is again a method proposed by Radice and Zanchi (2018); however, the present experiments required a modification of the prior method. As mentioned above, Radice and Zanchi (2018) developed their “edge-based” method for aggradation experiments in subcritical flow. The sediment surface elevation was determined by a succession of steps: (1) an edge detection technique (in that case, by a Sobel operator) was applied to one frame of the movies taken by the cameras beside the flume, recognizing all the edges present in the image and, in particular, the contours of the sediment particles; (2) a binary image was produced with all the edges, obtaining a much larger concentration of edges within the sediment layer than in the water layer; (3) the image was scrolled vertically using a rectangular search window, and vertical profiles of edge concentration were produced; (4) the bed elevation was located at a sharp change of edge concentration. The application of this method to a frame taken during the present experiment is shown in Fig. 3. The accuracy of the method mostly depends on the type of the camera and the distance at which the camera is placed; for this specific work, it is around 0.5 cm. It needs to be mentioned that, since the cameras used in this study have short lenses causing the so-called “fisheye effect”, a proper
transformation was applied to the movie frames to obtain rectified images for subsequent processing.

In the present experiment, run with supercritical flow, a thick bed-load layer existed and, as mentioned, stimulated a reconsideration of how the bed elevation could be defined. Basically, the red line of Fig. 3b corresponds to the top of the bed-load layer. An alternative option is to place the bed atop the still sediment layer over which the bed-load layer is developing. Since this definition of the bed elevation is based on recognizing the moving sediment in the bed-load layer, one must use two frames to detect this motion and this method to determine the bed elevation is called the “motion-based” one. Starting from two subsequent frames, their absolute difference is calculated by subtracting the first from the second and taking the absolute value. Then, a binary image (Fig. 4a) is produced using a threshold, that in this study was equal to 5% of the maximum pixel intensity (0.05 × 255). Wherever the absolute difference image has an intensity larger than the threshold, a movement is considered to have occurred in the image and it is represented by black color in the binary image, and vice-versa. Therefore, in the binary image the black layer represents a motion layer including bed-load particles and water. In fact, since the water is carrying isolated particles and the threshold is very low, the water layer’s movement is also detected. The lower edge of this black layer is the border between the stationary bed and the bed-load layer, and the upper edge represents the water surface. Therefore, the measuring principle is that, by detecting the lower edge, one can detect the surface of the stationary bed. To do so, a moving window with a specific size (4 × 10 pixel² = 0.46 × 1.14 cm²) is used along vertical lines like that in Fig. 4a. In any position of the search window, its average pixel intensity is computed, so for each vertical line a profile like that in Fig. 4b is produced. The profile shows abruptly decreasing values as it approaches the black layer from above, and a sharp increase of values reaching the stationary bed. In this study, the locations of the changes in the signal have been detected using the function findchangepts in MATLAB. The lowest point corresponds to the still bed. A correction of half the vertical size of the search window needs to be applied using this method, since the mean intensity value starts changing as the first edge of the search window crosses the ideal boundary of the still bed. Repeating the procedure for all possible vertical lines, a bed profile can be obtained (Fig. 4c). Finally, as it can be seen from the figure, in some parts the bed is not detected correctly due to either errors tape rulers attached to the channel wall. To correct these errors, the MATLAB function filloutliers is used (this function considers each datum as an outlier if it deviates more than a prescribed number of times the standard deviation from the mean of the data in the neighborhood), obtaining a fixed profile (Fig. 4d).

Since the whole channel is monitored by two cameras, the above procedure is applied to the frames recorded by each camera and then the data are merged; furthermore, the measuring units are changed from pixel to cm by applying an appropriate conversion. This conversion is made by simply dividing the length of the channel in cm by the corresponding number of pixels. Finally, the measured bed profile is smoothed by applying the Savitzky–Golay filter (Fig. 5).

The difference between consecutive frames and the corresponding binary image also serves as a basis for the measurement of the profile of the water surface. As it was mentioned before, the upper edge of the black layer seen in Fig. 4a represents the free surface; therefore, finding the other change of value in the vertical profile of mean intensity (Fig. 4b), the water profile can be produced similarly to the bed profile. A measured profile of the free surface is depicted in Fig. 6.
Fig. 4 Measuring the bed elevation by the motion-based method: 
(a) binary image obtained from the difference between two consecutive frames showing the side view of the flume, with a vertical line used for the profile of panel (b); (b) vertical profile of mean intensity in a moving search window; (c) bed elevation profile before correction; (d) bed elevation profile after correction

Fig. 5 Smoothing applied to a measured bed profile

Fig. 6 Water surface profile measured based on the second change of value in profiles like that in Fig. 4b
Figure 7, as a summary, depicts the water profile and the bed profile detected by two methods over a movie frame. Since the edge-based method detects the surface of the moving sediments as the bed surface and the motion-based method developed in this study detects the surface of the still sediment as the bed surface, the bed detected by the former is always higher than that detected by the latter.

**Measurement of the amount of sediment transported into the collector**

The amount of sediment into the collector needs to be measured as it can be converted into a sediment discharge out of the flume. Starting from a movie frame, different points on the edge of the sediment in the collector are chosen to extract their coordinates in the pixel scale. The points must be chosen in a way that the polygon created by them represents the shape of sediment accumulated into the collector (Fig. 8). After selection of the points, their coordinates must be changed from pixel scale into the metric scale. Then, the area of the polygon can be calculated using the shoelace formula and then multiplied by the width of the collector to compute the volume occupied by the sediment stored at the bottom of the latter.

**Methods/2: analysis of data**

**Spatial and temporal evolution of bed and water elevation**

Spatial evolution profiles show the bed and water surface elevation along the channel at specific time instants, while temporal evolution profiles indicate the elevation of the bed and water surface during the experiment at specific locations along the channel. The profiles are obtained using the two methods explained in the previous part, with a temporal resolution of 1 second. Figure 9a depicts the spatial evolution of bed and water elevation at two experimental times of 40 s and 220 s. Since the channel is monitored by the cameras from the $x$ coordinate equal to 136 cm (distance from the upstream), the experimental profiles are provided from this coordinate until the downstream part. Figure 9b presents instead the temporal evolution of bed and water elevation at 1.7 m and 3.65 m from the flume inlet. As expected, the bed elevation detected by the edge-based method is, in each section and time instant, higher than that detected by the motion-based method, and may not start from the initial level at initial time due to the development of a bed-load layer. Strictly speaking, these are the first results one obtains from the experiment; we chose to present them in a “method” section since these raw results serve as a basis for describing the other methods used in the analysis.
Estimation of the initial sediment transport capacity of the channel

An aggradation experiment is designed in such a way that the sediment feeding rate exceeds the sediment transport capacity of the channel in the initial state. Furthermore, the propagation of an aggradation front may depend on a load ratio, intended as the ratio of the feeding rate to the initial transport capacity (e.g., Soni 1981; Yen et al. 1992; Alves and Cardoso 1999; Zanchi and Radice 2021). Therefore, one needs to estimate the sediment transport capacity $Q_s$ of the experimental channel in the initial condition where the bed is not affected yet by the aggradation phenomenon. Two methods are used in this work to estimate the initial sediment transport capacity of the channel: the “collector” method and the “continuity” method.

The “collector” method is based on the fact that almost all the sediment particles leaving the channel at its outlet are trapped in the downstream collector; as a result, the time variation of the amount of sediment in the collector represents the sediment transport capacity of the terminal part of the channel. Indeed, the method is based on measuring the volume of the accumulated sediment in the downstream collector at different times. If the volume occupied by sediment stored in the collector ($V_{\text{measured}_{\text{collector}}}$) is measured with the method mentioned above at different times, then the sediment transport capacity $Q_{s,\text{collector}}$ is computed as:

$$Q_{s,\text{collector}} = \frac{V(t)_{\text{measured}_{\text{collector}}} \times (1 - p)}{t},$$

where $t$ is the time at which the volume accumulated in the collector is measured and $p$ is the porosity of the sediment.

Fig. 9  a Spatial and b temporal profiles of bed and water elevation during the experiment
These calculations are done every 5 s for the initial part of the experiments (until 130 s), and then every 10 s or more. The initial sediment transport capacity of the channel ($Q_{s0,\text{collector}}$) is the average of sediment transport capacities obtained from the above equation at the initial time instants, where the values of $Q_{s,\text{collector}}$ are almost constant and the bed is not affected significantly by the aggradation phenomenon; in fact, in later times the values obtained with (1) are no longer of the initial sediment transport capacity because the sediment transport capacity of the last part of the channel increases due to an increase in slope, in turn due to aggradation. The calculated $V_{\text{sediment \_ collector}} = V_{\text{measured \_ collector}} \times (1-p)$ and $Q_{s,\text{collector}}$ at different times are shown in Fig. 10. The initial sediment transport capacity of the channel, $Q_{s0,\text{collector}}$, is the average of the calculated $Q_{s,\text{collector}}$ between times $t_1$ and $t_2$ (red rectangle), where the values of the $Q_{s,\text{collector}}$ are almost constant. The times before $t_1$ are not considered in the calculations because, at the beginning of the experiment, the amount of sediment in the collector is not enough to be measured correctly.

The “continuity” method is based on the mass conservation law and is an evolution of the method used by Zanchi and Radice (2021). In an aggradation experiment, some sediment material is fed into the channel, some is deposited in the channel and some leaves it through the outlet. At any time ($t$), one can first compute the volume of the deposited material in the channel ($V_{\text{measured \_ bed}}$) as:

$$V(t)_{\text{measured \_ bed}} = A(t)_{\text{bed}} \times B,$$

where $A(t)_{\text{bed}}$ is the side area of a depositional wedge, $t$ is time and $B$ is the width of the channel. These calculations are done every 5 s from the beginning of the experiment. Unfortunately, the sediment is fed at 25 cm from the channel inlet, while the bed profiles are monitored starting at $x = 136$ cm; consequently, the sediment volume deposited between $x = 25$ cm and $x = 136$ cm cannot be calculated. To solve this problem, two scenarios are considered to simulate the non-monitored upstream bed: a “constant upstream” (CU) scenario where it is assumed that the bed elevation in the missing reach is constant and equal to the bed elevation at $x = 136$ cm; and an “inclined upstream” (IU) scenario where it is assumed that the bed elevation in the missing reach linearly increases, based on a slope computed considering the following reach between $x = 136$ cm and $x = 247$ cm (using, for slope estimation, a length equal to that of the missing reach). However, by knowing $V(t)_{\text{measured \_ bed}}$

\[ \text{Fig. 10} \] Temporal evolution of: a the sediment volume in the collector, and b the corresponding sediment transport rate
at different times and the sediment feeding rate, a sediment transport capacity is estimated using as:

\[ Q_{\text{in}}, \text{continuity} = Q_{s, \text{in}} - m \times (1 - p) \]  

(3)

where:

\[ m = \frac{dV_{\text{measured bed}}}{dt}. \]  

(4)

In this equation, \( m \) represents the slope of a linear function which is fitted to the values of \( V(t)_{\text{measured bed}} \) in time. In this regard, time is a crucial issue, because again only the values of \( V(t)_{\text{measured bed}} \) corresponding to the initial times of the experiment should be considered in the calculations. Based on this concept, two different scenarios to obtain \( m \) and evaluate the initial sediment transport capacity of the channel are considered: a 0–\( t_1 \) and evaluate the initial sediment transport capacity of the experiment should be considered in the calculations. In this regard, time is a crucial issue, because again only the values of \( V(t)_{\text{measured bed}} \) corresponding to the initial times of the experiment should be considered in the calculations. Based on this concept, two different scenarios to obtain \( m \) and evaluate the initial sediment transport capacity of the channel are considered: a 0–\( t_1 \) and \( t_1–t_2 \) range, where \( t_1 \) and \( t_2 \) are the bounds of the time interval selected for the collector method. Finally, another important issue for the application of (3) refers to the porosity in the depositional layer, that is not necessarily the porosity measured for the sediment in preliminary tests in a bucket. Moreover, the depositional layer (when the bed elevation is measured with the edge-based method) is compound of still sediment and bed-load sediment, that reasonably have different porosity. Different scenarios for porosity are considered in the following, in a sensitivity analysis to this parameter.

**Propagation celerity of an aggradation front**

In the aggradation process, the deposition happens with a sediment front moving along the channel. We here use the term “celerity” for the sediment front velocity of migration. In flows with lower velocities (mostly in subcritical flows), the sediment front is of a translating type, and an abrupt change of bed elevation is evident; on the other hand, in flows with higher velocities (mostly in supercritical flows), the sediment front is dispersive and depositional wedge becomes thinner and thinner, tending to a zero aggradation downstream. When dealing with a translating sediment front, one can trace the front in different time instants to find its celerity; by contrast, when the aggradation happens in a dispersive manner, a sediment front cannot be identified easily.

The definition of a most appropriate manner to determine the celerity of propagation of an aggradation front in supercritical flows is beyond the scope of the present manuscript but, on the other hand, we intend to prove that the way in which one defines and measures a bed elevation will affect also the propagation properties of the process. The following analyses are based on a simplified definition of celerity that is as follows. Color gradient graphs (Fig. 11) are produced for the spatial and temporal evolution of the bed elevation. These graphs correspond to matrices where the rows represent the time and the columns represent the location. A color plot is convenient for finding the celerity of aggradation fronts since the slope of the borders between the colors is the inverse of a velocity.

Given the difficulty in seeing a front, an aggradation height is chosen, and a celerity is found for it. The \( x \) coordinates where the aggradation height is equal to the chosen one at any certain time are extracted from the matrices used for the color gradient graphs. These data are then plotted in a time–space plot (Fig. 12) and a linear interpolation is used to find the celerity of the chosen aggradation height. These lines are fitted to just the initial times, because the space–time distribution of the aggradation heights (see again Fig. 11) clearly show that the celerity also changes with space and time.

**Methods/3: numerical analysis**

**Hydro-morphologic model and numerical solver used**

The hydro-morphologic evolution of bed and water elevation in one-dimensional conditions is depicted by a system of partial differential equations, including two Saint–Venant equations (SVEs), describing water motion, and one Exner equation, representing the sediment continuity:

\[
\begin{align*}
\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} &= 0 \\
\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( q^2 + gh \left( \frac{\partial h}{\partial x} + \frac{\partial z}{\partial x} \right) \right) + gh \left( \frac{\partial h}{\partial x} + \frac{\partial z}{\partial x} \right) &= -ghS_f, \\
(1 - p) \frac{\partial z}{\partial t} + \frac{\partial q}{\partial x} &= 0,
\end{align*}
\]  

(5)

where \( h \) is the water depth, \( q = u \times h \) is unit flow discharge (\( u \) is the depth-averaged velocity), \( g \) is the gravitational acceleration, \( z_b \) shows the bed elevation, \( S_f \) represents the friction slope, and \( q_s \) represents the solid discharge per unit width.

In addition, in order to estimate the sediment discharge, a closure equation should be used; in this study, among different equations, the Meyer–Peter and Müller (1948) formula (which is generally assumed valid for coarse sediment) is chosen:

\[ \Phi = 8 \left( \tau^* - \tau_{c}^* \right)^{1.5}, \]  

(6)

where \( \Phi \) is the non-dimensional solid discharge per unit width, and \( \tau^* \) and \( \tau_{c}^* \) are the Shields parameter and its
Fig. 11  Color gradient maps of bed elevation for: (a) the edge-based method, and (b) the motion-based method

threshold value, respectively. The Shields parameter can be computed as: 

\[
\tau^* = \frac{\tau}{(\rho_s - \rho)gd},
\]  

(7)
where $\rho_s$ represents the solid density, $\rho$ represents the fluid density, $d$ shows the sediment diameter and $\tau$ is the bed shear stress and is calculated as follows:

$$\tau = \rho g R_H S_f,$$  

(8)

where $R_H$ shows the hydraulic radius. In order to obtain the friction slope, the Manning–Strickler equation is used:

$$S_f = \frac{n^2 \times U^2}{R_H^3/3}.$$  

(9)

In this formula, $U$ is the velocity of the flow and $n$ is the Manning coefficient. The critical Shields parameter, $\tau_c^*$, is the other important parameter in the Meyer–Peter and Müller formula (1948) which can be determined either directly from the Shields diagram as a function of the shear Reynolds number or from a transformed Shields diagram as a function of the dimensionless grain diameter $D^*$ ($\tau_c^* = f(D^*)$); in this regard, there are different approaches to transform the Shields diagram and estimate $\tau_c^*$ as a function of $D^*$. In the presented study, the Van Rijn approach (1984) is used to calculate $\tau_c^*$:

$$\tau_c^* = 0.24 D^*^{1.3} \text{ for } 1 \leq D^* \leq 4$$

$$\tau_c^* = 0.14 D^*^{0.64} \text{ for } 4 < D^* \leq 10$$

$$\tau_c^* = 0.04 D^*^{1.1} \text{ for } 10 < D^* \leq 20$$

$$\tau_c^* = 0.013 D^*^{0.29} \text{ for } 20 < D^* \leq 150$$

$$\tau_c^* = 0.055 \text{ for } D^* > 150$$

(10)

where $D^*$ is the dimensionless grain diameter and is calculated as:

$$D^* = d \left(\frac{(\rho_s - \rho) g}{\rho n^2}\right)^{1/3}.$$  

(11)

Considering $d = 0.0038 \text{ m}$, $\rho_s = 1443 \text{ kg/m}^3$, $\rho = 1000 \text{ kg/m}^3$, and the water kinematic viscosity $\nu = 1 \times 10^{-6} \text{ m}^2/\text{s}$, in this study, $D^*$ and $\tau_c^*$ are obtained equal to 62 and 0.043, respectively.

The numerical solver used to solve the system (5) is embedded in the BASEMENT software provided by ETH Zürich / Laboratory of Hydraulics, Glaciology, and Hydrology (VAW). This solver was already used to represent experiments carried on in the present channel by Zanchi et al. (2019).

Model parameterization and calibration

In order to make the model in the BASEMENT, it is essential to define different parameters as the input of the model. The geometrical and sediment parameters applied in the model are the same used in the experimental study. Also, a constant flow and sediment feeding rate are imposed at the inlet ($Q = 0.007 \text{ m}^3/\text{s}$ and $Q_{s,in} = 2.28 \times 10^{-4} \text{ m}^3/\text{s}$) as in the experiment. The numerical run has the same duration of the laboratory run. At the downstream section, a fixed bed elevation is imposed as the boundary condition so that it is assumed that all sediment entering the last computational section leaves the channel through the downstream section.

The numerical model is calibrated to match experimental and numerical profiles by changing a coefficient ($\epsilon_{MPM}$) applied to the MPM equation (to calibrate the transport formula), and a Manning coefficient (to consider a contribution to roughness given by the bed load transport process).

Results

Initial sediment transport capacity of the flow

The initial sediment transport capacity of the flow estimated using the collector method, $Q_{s,0,Collector}$, is equal to $1.2 \times 10^{-4} \text{ m}^3/\text{s}$ using $t_1$ and $t_2$ equal to 30 s and 55 s, respectively. A load ratio (ratio of sediment feeding rate to initial transport capacity) of 1.9 is then obtained based on this estimate.

For the continuity method, twelve different estimates of the initial transport capacity have been obtained, considering: (1) the bed elevation returned by the edge-based method or the motion-based one, (2) a depositional scenario of constant (CU) or linear (IU) upstream aggradation height, and (3) applying (3) in a time range 0–$t_2$ (case 1) or a $t_1$–$t_2$ range (case 2). In addition, the four estimates with the edge-based method have been duplicated considering a porosity of 0.45 or 0.65 (to account for the fact that sediment particles in the active layer are not concentrated as those in the still layer below). Figure 13 presents the temporal evolution of the aggradation volume obtained in the eight scenarios. Furthermore, in Table 2 the results of the estimation of $Q_{s,0,continuity}$ using (3) are presented (and most values are between $1.3 \times 10^{-4} \text{ m}^3/\text{s}$ and $1.7 \times 10^{-4} \text{ m}^3/\text{s}$). A graphical comparison is provided in Fig. 14.

Propagation celerity

Based on the lines of Fig. 12, one finds a propagation celerity of 7.9 cm/s and 0.4 cm/s for the bed detection by the edge-based method and the motion-based method, respectively.
Fig. 13 Temporal evolution of $V_{\text{measured\_bed}}$ in different scenarios (indicated in the plot corners) using, for bed elevation, the edge-based method (left) or the motion-based method (right).
Froude number

Color gradient graphs like those of Fig. 11 can be produced also for the water elevation, then for water depth, bulk flow velocity, and other properties depending on these. We present in Fig. 15 the graphs for the Froude number related to the two methods for bed detection. Also, Table 3 provides the ranges of the Froude number during the experiment. It should be mentioned that the first 30 s of the experiment are not considered in the reporting of the Froude number range due to uncertainties in the detection of the water surface at the beginning of the experiment.

Calibration parameters of the numerical model

The results of the final calibration parameters of the numerical method are presented in Table 4. Also, the table reports the values of the dimensionless shear stress, $\tau^*$, at the beginning of the experiment for the motion-based and edge-based methods; in order to calculate $\tau^*$, Eqs. (7) and (8) are applied together to the Gauckler–Strickler equation, assuming uniform flow in the initial condition of the run. It should be mentioned that this parameter for the condition of a fixed rough bed is calculated as equal to 0.2. In Fig. 16, the comparison between the numerical profiles (after calibration) and experimental ones obtained by motion-based method and edge-based method in time $t = 40$ s and $t = 220$ s are shown. It needs to be mentioned here that it turned to be impossible to reproduce the aggradation profiles measured with the edge-based method, that present some aggradation at the downstream end that conflicts with a downstream boundary condition of fixed elevation imposed in the numerical simulations. For the calibration with this method, therefore, the intent has been that of reproducing the channel slope and water depth (that is the reason why an offset is visible in Fig. 16b for both the bed and water surface). In both cases, however, the transport capacity at the end of the simulation is about $2.2 \times 10^{-4}$ m$^3$/s, thus it tends to the sediment feeding rate as expected.

Discussion and conclusions

As proven by the results above, depending on which method is applied for bed detection, different values are estimated for different key parameters. Interpretation of the findings needs to consider that the method applied for bed detection, on which this manuscript is focused, also clearly reflects a
physical concept, since the edge-based and motion-based methods are related to defining the bed as being, respectively, at top or bottom bound of the bed-load sediment layer. In fact, the bed detected by the edge-based method is always higher than that detected by the motion-based method. Furthermore, the bed elevation returned by the edge-based method may be typically higher than the reference elevation at the beginning of one experiment; while this is understandable from the phenomenological point of view due to sediment loosening when the bed-load layer is formed, detecting some aggradation at the beginning of the experiment conflicts with an expectation of zero aggradation in the initial condition. Conversely, one can note that the motion-based method returns bed degradation in the last part of the channel, due to the release of the sediment from the bottom, while this degradation does not exist in the bed reported by the edge-based method (Fig. 9a).

The initial transport capacity of the flow is an important parameter to be determined since, as mentioned above, the properties of aggrading fronts may depend on a load ratio of which the $Q_{sd}$ is the denominator. While the collector method is independent of the bed detection procedure and thus reports a unique value for the initial sediment layer. In fact, the bed detected by the edge-based method is always higher than that detected by the motion-based method. Furthermore, the bed elevation returned by the edge-based method may be typically higher than the reference elevation at the beginning of one experiment; while this is understandable from the phenomenological point of view due to sediment loosening when the bed-load layer is formed, detecting some aggradation at the beginning of the experiment conflicts with an expectation of zero aggradation in the initial condition. Conversely, one can note that the motion-based method returns bed degradation in the last part of the channel, due to the release of the sediment from the bottom, while this degradation does not exist in the bed reported by the edge-based method (Fig. 9a).

The initial transport capacity of the flow is an important parameter to be determined since, as mentioned above, the properties of aggrading fronts may depend on a load ratio of which the $Q_{sd}$ is the denominator. While the collector method is independent of the bed detection procedure and thus reports a unique value for the initial sediment

---

Table 3: Range of variability of the Froude number based on the different methods to determine the bed elevation

| Bed detection method | Froude number |
|----------------------|--------------|
| Edge-based           | $1.2 \leq Fr \leq 3.4$ |
| Motion-based         | $0.9 \leq Fr \leq 1.6$ |

Table 4: Final values used to calibrate the numerical model and the values of Shields parameter with two bed detection methods

| Bed detection method | Dimensionless shear stress, $\tau^*$ | Modified bedload factor, $\alpha_{MPM}$ | Modified Manning coefficient (s/m$^{1/3}$) |
|----------------------|-------------------------------------|----------------------------------------|--------------------------------------------|
| Edge-based           | 0.16                                 | 2.45                                   | 0.010                                      |
| Motion-based         | 0.21                                 | 1.70                                   | 0.016                                      |
transport capacity of the channel, the $Q_s$ estimated by the continuity method depends significantly on the bed detection method. Considering the same porosity for the two methods, one obtains a lower value for the initial sediment transport capacity of the channel with the edge-based bed detection method (since the volume deposited in the channel is more

Fig. 16 Comparison between special evolution profiles of bed and water obtained from calibrated numerical model and experimental work using: a edge-based method, b motion-based method, at selected times $t=40$ s and $t=220$ s
and \( Q_{s, in} \) is the same). Furthermore, the difference between the two estimates depends on the times used: in the scenarios CU1 and IU1 the values of \( Q_{s, in} \) are much different from each other, while in the scenarios CU2 and IU2 the difference is much less (because the \( n \) values in the range \( t_1-t_2 \) are much more similar than in the range \( 0-t_2 \)). Finally, if one changes the porosity value in Eq. (3) when the edge-based method is used for bed detection, further different results are obviously obtained: increasing the porosity results in an increase of the values of \( Q_{s, in} \), that become more similar to those from the motion-based bed detection method (and even slightly larger than the latter when the time range \( t_1-t_2 \) is used). In summary, in the estimation of the initial sediment transport capacity of the channel using the continuity method, depending on the different scenarios (especially related to the time term and porosity), different results and trends can be obtained. However, the values of \( Q_{s, in} \) estimated using the motion-based bed detection method are generally higher than those coming from the edge-based method.

The way in which the bed elevation is defined and measured can also affect the propagation celerity of the aggrading front. For the aggradation depth chosen above, the celerity estimated using the edge-based bed detection method is more than 19 times that obtained from the motion-based method. This significant difference between the calculated celerities with both methods may be due to the fact that the aggradation height was chosen equal to 1.7 cm; such an aggradation depth for the bed detected by the edge-based happens almost at the beginning of the experiment, when the process is very dynamic and the channel elevation changes rapidly, while for the motion-based method it happens at the end, when the morphological changes are slower. The chosen aggradation depth is the minimum common depth for which the celerity is measurable with both the methods. However, another reason for the celerity estimated with the edge-based method being so higher than the other one could also be that it considers the creation of the bed-load layer at the experiment start as an abrupt downstream movement of the front, while this is instead discarded by the other method.

Since the water surface is placed at the same elevation for both the placements of the bed, the water depth changes dramatically when moving from one bed detection method to the other, in turn causing a change in the bulk flow velocity and in the Froude number. Since the bed elevation from the edge-based bed detection method is higher than that from the motion-based method, one obtains a lower water depth and a higher Froude number. This would be particularly impactful in case the variation of the Froude number that one obtains determines a change of the estimated flow regime, that could be either subcritical or supercritical depending on the method used for bed detection.

Different values are needed for the calibration parameters of a numerical simulation in order to reproduce the experimental results if one uses either of the two bed detection methods. While the modified Manning coefficient for the motion-based bed detection method did not differ significantly from that \( (n_m = 0.015 \text{ s/m}^{1/3}) \) determined by Zanchi and Radice (2021), it reduced when using the edge-based bed detection method, again because a lower water depth needed to be reproduced in the numerical simulation. Conversely, the coefficient applied to the MPM formula \( (\alpha_{MPM}) \) was 1.7 and 2.45 for the motion-based and the edge-based bed detection method, respectively. The increased value of \( \alpha_{MPM} \) for the edge-based method deserves some more explanation, as one would expect it to be lower considering that the water velocity is higher and the system needs to tend to a prescribed sediment transport capacity (equal to the feeding rate); by contrast, the low value of the Manning coefficient that one needs to reproduce the low depth, in turn requires a higher coefficient to be applied to the transport formula. Furthermore, it was observed that changing the bed measurement method results in different values of the Shields parameter: the latter was higher for the motion-based method than for the edge-based method, consistently with the changes of the modified Manning coefficient applying the two methods. Finally, Fig. 16 indicates that with the motion-based bed detection method the calibration of the numerical model has resulted in an appropriate match between experimental and numerical profiles, while with the edge-based bed detection method the calibration needed to be limited to the values of bed slope and water depth due to deposition at the downstream end. It is worth mentioning that the values obtained for the calibration parameters obviously depend on the sediment transport formula one uses; however, the aim of this study was to demonstrate that the calibration of any valid formula depends on the detection method used for the sediment bed.

In conclusion, the methods used to define and detect a bed definitely impact the estimation of several key hydro-morphological parameters, as quantitatively demonstrated in this manuscript (moving from the edge-based to the motion-based method, one obtains lower bed elevation, higher depth and lower Froude number, higher transport capacity of the initial flow estimated by sediment continuity, lower celerity of an aggrading front, higher channel roughness). The major intent of this manuscript was to prove this sensitivity rather than to give preference to either method. However, some of the results tentatively indicate the motion-based method as to be better used for the bed detection. Physically, this means considering the bed-load layer as a part of the flow rather than the bed that instead is just compound of still sediment. Considering instead the bed-load layer as a part of the bed leads to at least two problems. First, the celerity of the aggrading front derived by the edge-based method is very high due to large aggradation detected by this method at the beginning of the experiment, but this may actually
mix the two different processes of formation of the bed-load layer and front migration. Second, the attempt to calibrate a numerical model reproducing the experimental results was only partially successful and the interpretation of the calibration parameters was less straightforward than for the other method. However, the results presented in this manuscript may be useful when comparing data from different sources and are of interest for numerical modelers of real situations where an experimental benchmark is not available.

Funding Open access funding provided by Politecnico di Milano within the CRUI-CARE Agreement.

Declarations

Conflict of interests The authors declare no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Alves E, Cardoso AH (1999) Experimental study on aggradation. Int J Sedim Res 14(1):1–15
Bareš V, Zrostlík Š, Picek T, Krupička J, Matoušek V (2016) On local velocity measurement in gravity-driven flows with intense bedload of coarse lightweight particles. Flow Meas Instrum 51:68–78
Berzi D, Jenkins JT, Richard P (2019) Erodible, granular beds are fragile. Soft Matter 15(36):7173–7178
Capart H, Fracarollo L (2011) Transport layer structure in intense bed-load. Geophysical Research Letters 38(20)
Chanson H (2004) Hydraulics of open channel flow. Elsevier
Church M, Haschenburger JK (2017) What is the “active layer”? Water Resour Res 53(1):5–10
Dey S, Das R, Gaudio R, Bose SK (2012) Turbulence in mobile-bed streams. Acta Geophys 60(6):1547–1588. https://doi.org/10.2478/s11600-012-0055-3
Ferreira RML, Franca MJ, Leal JGAB, Cardoso AH (2012) Flow over rough mobile beds: Friction factor and vertical distribution of the longitudinal mean velocity. Water Resour Res. https://doi.org/10.1029/2011WR011126
Jumain M, Ismail Z, Ibrahim Z, Zaini NA (2013) Sediment transport rate and bed formation in straight compound channels. Glob J Environ Res 7(3):40–44
Kaczmarek LM, Biegowski J, Sobczak Ł (2019) Modeling of sediment transport in steady flow over mobile granular bed. J Hydraul Eng 145(4):4019009
Kinzl P, Nelson J, McDonald R, Logan B (2010) Topographic evolution of sandbars: Flume experiment and computational modeling. In: Proceedings of the 4th federal interagency hydrologic modeling conference and of the 9th federal interagency sedimentation conference, Las Vegas
Lafaye de Micheaux H, Dudíl A, Frey P, Ducottet C (2015) Image processing to study the evolution of channel slope and water depth in bimodal sediment mixtures
Matoušek V, Bareš V, Krupička J, Picek T, Zrostlík Š (2015) Experimental investigation of internal structure of open-channel flow with intense transport of sediment. J Hydrol Hydromech 63(4):318–326
Matoušek V, Krupička J, Picek T, Zrostlík Š (2019) Conditions at interfaces of layered flow with intense bed load transport. EPJ Web Conf 213:2056
Radice A, Zanchi B (2018) Multicamera, multimethod measurements for hydromorphologic laboratory experiments. Geosci 8(5):172
Smart GM (1999) Turbulent velocity profiles and boundary shear in gravel bed rivers. J Hydraul Eng 125(2):106–116
Soní JP (1981) Laboratory study of aggradation in alluvial channels. J Hydrol 49(1–2):87–106
Unigarro Villota S (2017) Laboratory study of channel aggradation due to overloading
Venuleo S, Pokrajac D, Toksay T, Constantinescu G, Schleiss AJ, Franca MJ (2021) Parameterization and results of SWE for gravity currents are sensitive to the definition of depth. J Hydraul Eng 147(5):4021016
Vesipa R, Camporeale C, Ridolfi L (2018) Hydraulics of braided river dynamics. Insights from flume experiments. E3S Web of Conferences, 40, 2020
Viriyakijja K, Chinnarasri C (2015) Wave flume measurement using image analysis. Aquat Procedia 4:522–531
Wilcock PR (1996) Estimating local bed shear stress from velocity observations. Water Resour Res 32(11):3361–3366
Wren DG, Kuhnle RA, Langendoen EJ (2020) Sediment transport and bed-form characteristics for a range of step-down flows. J Hydraul Eng 146(2):4019060
Wren D, Kuhnle R, McAlpin T, Abraham D, Jones K (2021) Detailed bed topography and sediment load measurements for two step-down flows in a laboratory flume. International Journal of Sediment Research
Yen C, Chang S, Lee H-Y (1992) Aggradation-degradation process in alluvial channels. J Hydraul Eng 118(12):1651–1669
Zanchi B, Radice A (2021) Celerity and height of aggradation fronts in gravel-bed laboratory channel. J Hydraul Eng 147(10):4021034
Zanchi B, Zucchi M, Radice A (2019) On the relationship between experimental and numerical modelling of gravel-bed channel aggradation. Hydrol 6(1):9