2D numerical modelling of sediment transport with non uniform material

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Foreword

This report is the master thesis required to obtain the MSc. in Hydropower Development, at the Department of Hydraulic and Environmental Engineering. It was carried out during the last semester of the Hydropower Development Master Programme, under the supervision of Associate Professor Nils Rüther.

I was very interested in numerical modelling and sediment transport, so the combination of both topics motivated my work. Selecting the topic and the software was made together with my supervisor. Acquired knowledge of numerical modelling and of the software was intended to be used in applied cases during my engineering work.

The learning of the software and this final report are products of my own work.

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June, 2013

Acknowledgements

Abstract

Numerical modelling is nowadays an important tool for predicting river flows and sediment transport. Two dimensional (2D) models give more detailed information than the often used one dimensional (1D) models, and 2D models have the advantage over three dimensional (3D) models that the simulation times are reduced, and therefore could be more attractive to use in many applied cases, where 3D flow effects are not so important. When using numerical models in predicting sediment transport, the non-uniformity of the bed material has to be considered, especially in natural environments, where it is very likely to have different particle sizes. Sediment transport is highly dependent on the grain size distribution of the sediment mixture of the river bed. The main goal for this thesis was to see if the 2D model CCHE2D could assess accurately the sediment transport in a case with non-uniform material. A physical model study carried out by S. Lanzoni in 2000 was selected for this purpose. In the laboratory, a straight flume with a bimodal sediment mixture was used. Experiments on sediment transport were conducted in the flume, where bed load was the dominating transport mode, alternate bars developed during the experiment and equilibrium conditions were reached. The data from the physical model was the input for the numerical model used in this thesis.

CCHE2D was capable of replicating the bed load transport rate in the flume, with only a 1.5 % difference between the measured average value and the simulated value. From the numerical modelling study, it was concluded that the modified Ackers and White formula for calculating sediment transport capacity gave the best results compared to the other available formulae in CCHE2D. This formula includes the hiding and exposure effects, which are important for a sediment mixture like the one used in the studied case. During the study, the main parameters that influenced the sediment transport process were identified. The numerical simulations proved to be very sensitive to the roughness height, the adaptation length and the mixing layer thickness. The study showed that the bed load transport rate calculation is also strongly dependent on the boundary conditions. Uncertainties on parameters and boundary conditions were solved by calibration and sensitivity analyses.

The CCHE2D model could be applicable to cases where depth averaged values are accurate enough for the prediction of the physical processes that are being modeled, especially, in cases where helical flows have minor influence on the results. The time required for the simulations and the computational resources were adequate for carrying out this study. However, an applied case with a more complex geometry would require much more computational resources. Additionally, assessment of the parameters requires measured data and calibration.

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1 Introduction

1.1 Background

In natural environments it is very likely to have non-uniform sediment transport. River beds are often composed by a mixture of particles between gravel and sand, and sometimes even cobbles and boulders. In this type of mixtures, due to size differences, some particles will be exposed to the flow and some of them will be hidden by other particles, total or partially. The lift and drag forces on the particles, and hence their movement along the river, will vary depending on the degree of hiding or exposure. On the other hand, how sediment move will have an effect on the bed changes, which in turn will influence sediment transport twofold. First, bed changes will affect the flow field and second, they will influence sediment transport itself, by means of gravity.

In other words, sediment transport is highly dependent on the grain size distribution of the sediment mixture of the river bed.

Numerical modelling is nowadays an important tool for predicting river flows and sediment transport. Developments in computers, occurred in the past years, have made it more accessible for different users in the engineering field. The models may be classified in one dimensional (1D), two dimensional (2D) or three dimensional (3D) models. One dimensional models require few data and are simple to use, but they give overall values for every cross section. On the other hand, 3D models are more precise and comprehensive, but they need more computational time to handle more sophisticated algorithms. In the middle of them, 2D models have the advantage that the simulation times are reduced, and therefore could be more attractive to use in many applied cases. They could be applied successfully when 3D processes are not so important, i.e. in straight channels, and when the width is much larger than the depth.

CCHE2D is a model developed by the National Center for Computational Hydroscience and Engineering, at the University of Mississippi, for two-dimensional simulation and analysis of river flows. CCHE2D latest version can simulate non-uniform sediment mixtures, since it calculates the probabilities of the particles to be exposed or hidden, depending on the sediment size classes or gradation. Other incorporated features are the use of movable bed roughness and non-equilibrium conditions.

Some laboratory cases have been used in the past to test the CCHE2D model, as described in Wu (2001) and Jia and Wang (2001b). As example, Wang and Ribberink's (1986) experiment of net deposition in a flume with non-uniform sediment feeding was simulated, but the assumption of uniform sediment was made for the numerical simulations (d_{50} equal to 0.095 mm). Seal et al (1995) tests in the laboratory flume

were also simulated, but in this study the particle sizes in the weakly bimodal mixture that was fed at the inlet were taken into account (particle sizes from 0.125 mm to 64 mm were used in the tests). Ashida and Michiue's (1971) flume study was used to simulate the scour and armoring processes downstream of a dam, with non-uniform sediment (median size equal to 1.5 mm) used in the numerical model.

In this Master thesis, CCHE2D will be tested in order to determine its applicability for assessing sediment transport in water flows. It will be applied on a data set from a physical model. The selected case is a straight flume with graded sediment, where the main sediment transport mode was bed load and alternate bars were the predominant bed forms.

1.2 Objectives

The main purpose of the study is to find out if the CCHE2D model can assess accurately the sediment transport in a case with non-uniform material.

Since the formation of bed forms is mainly a three dimensional process, it is not an objective of this study to try to replicate the bed forms with the two dimensional model. The goal is to replicate sediment transport rates with the two dimensional depth averaged model CCHE2D.

In order to do so, the following objectives have to be met.

- Generate the grid

- Set up the model and run the simulation

- Compute the bed load transport rates

- Compare the numerical results with the results from the physical model

- Prepare the figures to show the results

- Assess uncertainties in the CCHE2D model, by varying algorithms, parameters and input data.

2 Sediment transport

In this section, concepts that are relevant for the present study are described. First, some definitions for bed forms are stated. Then, several formulae for roughness calculation and for sediment transport are presented. There exist a vast number of formulae, but only the ones available for the CCHE2D model, and which are used in this thesis, are described in the following paragraphs.

2.1 Bed forms

When non-cohesive sediment particles start moving in a riverbed, undulating forms will develop. The type, size and shape of the forms will depend on the shear stress and the particle size (Lysne et al., 2003).

Starting with a flat bed, the bed will first evolve in ripples. Their dimensions are related to the grain size d of the bed material, normally 50-100 d high and 100 d long (Wu, 2008).

With increasing stress, dunes will form. Similarly to ripples, sediment will deposit in the downstream side of the bed form and erode from the upstream side, moving in the direction of flow (Olsen, 2011). Their dimensions are related to the flow depth h, meaning 0.1 to 0.5 h high and 5-10 h long (Wu, 2008).

Other bed forms that would appear with increasing stress are anti dunes, chutes and pools (upper flow regime).

Larger scale bed forms are bars, which have lengths in the order of the channel width and heights in the order of flow depths. There are two types of bars, point bars and alternate bars. The former develop in the inner side of bends and they do not move (Chang, 2008).

Alternate bars can show up in straight channels were sediment deposits change from right to left (Julien, 2002). The height of alternate bars can reach the flow depth. The wavelength is proportional to the channel width by a factor of 2 times π or approximately 6 (Yalin and Da Silva, 2001). Alternate bars move, in contrast with point bars, slowly downstream (Chang, 2008).

There are several approaches to predict bed forms, in Section 2.2.1, van Rijn's approach (1984) is described.

The bed forms have in general a strong effect on the flow field. They will also affect the sediment movement, since gravity will lead particles to move in a certain direction. Consequently, the bed load transport rates depend also on the bed forms.

2.2 Bed roughness

Roughness is an essential parameter for bed shear stress calculation, hence also for sediment transport processes. The vertical velocity profile is strongly dependant on the roughness height, as it is shown in the following formula (Schlichting, 1979).

$$\frac{U}{u_*} = \frac{1}{\kappa} \cdot \ln\left(\frac{30y}{k_s}\right)$$

Where

U : average flow velocity

u_* : shear velocity

y : distance from the bed

k_s : roughness height

κ : empirical constant equal to 0.4

When using a depth-integrated logarithmic law, the velocity, the shear velocity and the roughness height are related with the following equation (Jia and Wang, 2001a).

$$\frac{U}{u_*} = \frac{1}{z} \cdot \left[\frac{z_0}{h} - 1 + \ln\left(\frac{y}{k_s}\right)\right]$$

$$U = \sqrt{U_x^2 + U_y^2}$$

Where

U_x : velocity in x direction

U_y : velocity in y direction

z_0 depends on flow conditions and can be calculated from:

Smooth: $z_0 = 0.11 \cdot \frac{\nu}{u_*}$ $\frac{u_* \cdot k_s}{\nu} \leq 5$

Rough: $z_0 = \frac{k_s}{30}$ $\frac{u_* \cdot k_s}{\nu} \geq 70$

Transition:
$$z_0 = 0.11 \cdot \frac{v}{u_*} + \frac{k_S}{30} \qquad 5 < \frac{u_* \cdot k_S}{v} < 70$$

Where

v : kinematic viscosity of water

There are different methods for calculating the roughness height. Some of them only depend on the grain size distribution of the bed material. Then the roughness is calculated with a formula structured as:

$$k_s = n \cdot d_n$$

Where

n : number depending on the author of the formula

d_n : characteristic diameter that depends on the grain size distribution

Very known formulae assume the roughness height to be 2 times d_{90} (Kamphius, 1974) or 3 times d_{90} (van Rijn, 1982).

When bed forms develop, flow resistance increases, as shown in Figure 1, which was developed for sand beds. "For a channel bed with sand grains and bed forms (such as ripples and dunes), the bed shear stress, τ_b, may be divided into the grain (skin or frictional) shear stress, τ_b' and the form shear stress, τ_b''"(Wu, 2008).
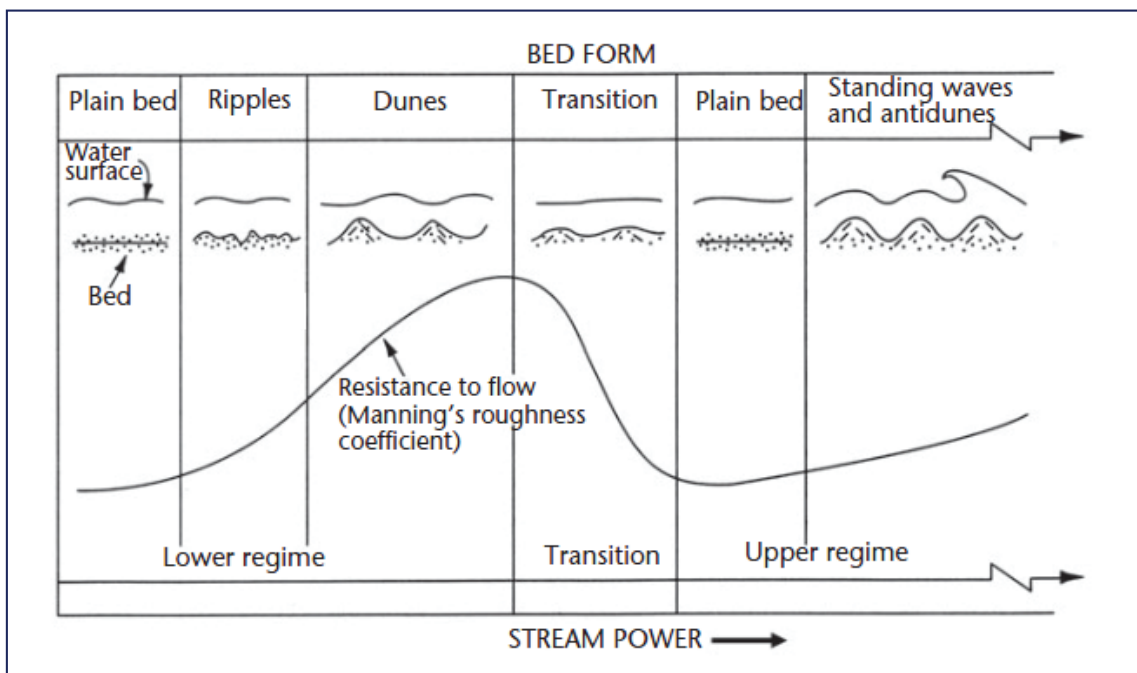
Figure 1. Variation of roughness with bed formations, Dingman (2009).

There are several formulae for roughness calculation that take into account both grain resistance and bed forms effect. The two bed roughness formulae used in the study are presented in the next paragraphs.

2.2.1 Van Rijn's formula

The roughness is computed from

$$k_s = 3 \cdot d_{90} + 1.1 \cdot \left(1 - e^{\frac{25\Delta}{\lambda}}\right)$$

Where

Δ : bed form height

λ : bed form length equal to 7.3 times the water depth

The first term on the right side of the equation is the grain roughness and the second one is the roughness due to the bed forms.

The bed form height is calculated using

$$\frac{\Delta}{h} = 0.11 \cdot \left(\frac{d_{50}}{h}\right)^{0.3} \cdot (1 - e^{-0.5T}) \cdot (25 - T)$$

$$T = \left(\frac{U'_*}{U_{*cr}}\right)^2 - 1$$

$$U'_* = \frac{U \cdot g^{0.5}}{18 \cdot \log\left(\frac{4 \cdot h}{d_{90}}\right)}$$

Where

h : flow depth

T : non-dimensional excess bed shear stress

U'_* : effective bed shear velocity relating to the grain

U_{*cr} : critical bed shear velocity for sediment motion given by Shields diagram

Van Rijn's approach (1984) for predicting bed forms is empirical and as can be seen from the formula above, depends mainly on the particle size and on the parameter T, which represents the grain shear stress in relation to the critical shear stress, from the Shield's diagram (Shields, 1936).

2.2.2   Wu and Wang's formula

Wu and Wang (1999) suggest that the total roughness is calculated with only one formula.

$$n = \frac{d^{1/6}}{A}$$

Where

$d : d_{50}$, for non-uniform bed material

A : empirical roughness parameter that depends on if it is a flat bed or a movable bed

For a flat bed: $A = 20$

For a movable bed with sand waves:

$$\log \frac{A}{g^{1/2} \cdot F_r^{1/3}} = 0.911 - 0.273 \cdot \log T - 0.05 \cdot (\log T)^2$$

$$T = \frac{\tau'_b}{\tau_c} - 1$$

$$\tau'_b = \left(\frac{n'}{n}\right)^{3/2} \cdot \tau_b$$

Where

Fr : Froude number

τ'_b : grain shear stress

τ_c : critical shear stress

τ_b : bed shear stress

n : Manning's roughness coefficient for the channel bed

n': Manning's coefficient corresponding to the grain roughness

Other authors have suggested other values for d and A, different from the ones proposed by Wu and Wang (1999). As example, for Meyer-Peter and Müller (1948), d is rather d_{90} and A equals 26.

2.3 Bed load sediment transport formulae

Many formulae for calculating bed load transport have been developed. Four of them, which are available in the CCHE2D model, are presented here. All of them take the hiding and exposure effect into account.

2.3.1 Wu, Wang and Jia´s formula (Wu et al. formula)

The transport rate is calculated with (Wu et al., 2000)

$$q_{bk} = \emptyset_{bk} \cdot \left(p_{bk} \sqrt{\left(\frac{\gamma_s}{\gamma} - 1\right) \cdot g \cdot d_k^3} \right)$$

$$\emptyset_{bk} = 0.0053 \cdot \left[\left(\frac{n´}{n} \cdot \frac{\tau_b}{\tau_{ck}} - 1 \right) \right]^{2.2}$$

Where

q_{bk} : equilibrium transport rate of the kth size class of bed load per unit width

Φ_{bk} : non dimensional bed load transport capacity

p_{bk} : bed material gradation

d_k : diameter of size class k

τ_{ck} : critical shear stress, which accounts for hiding and exposure effects.

The critical shear stress in the formula above is calculated using:

$$\tau_{ck} = 0.03 \cdot (\gamma_s - \gamma) \cdot d_k \cdot \left(\frac{p_{hk}}{p_{ek}} \right)^{0.6}$$

$$p_{hk} = \sum_{j=1}^{N} p_{bj} \cdot \frac{d_j}{d_k + d_j}$$

$$p_{ek} = \sum_{j=1}^{N} p_{bj} \cdot \frac{d_k}{d_k + d_j}$$

Where

p_{hk} and p_{ek}: hiding and exposure probabilities for the kth size class of bed material

The equation was calibrated with laboratory data and field data. In the laboratory data the grain sizes varied from 0,073 mm and 64 mm (Wu, 2001).

2.3.2 Modified Ackers and White´s formula

This formula was developed for total load with uniform material. The original formula is widely applied and starts with the calculation of a mobility number and a dimensionless grain diameter (Ackers and White, 1973).

Mobility number

$$F_{gr} = \frac{U_*^n}{\left[\left(\frac{\gamma_s}{\gamma} - 1\right) \cdot g \cdot d\right]^{1/2}} \cdot \left[\frac{U}{\sqrt{32} \cdot \log\left(\frac{10 \cdot h}{d}\right)}\right]^{1-n}$$

Dimensionless grain diameter

$$D_* = d \cdot \left[\left(\frac{\gamma_s}{\gamma} - 1\right) \cdot \frac{g}{v^2}\right]^{1/3}$$

The bed material load is then calculated by

$$g_s = \frac{G_{gr} \cdot d}{h} \cdot \frac{\gamma_s}{\gamma}\left(\frac{U}{u_*}\right)^n$$

With

$$G_{gr} = C \cdot \left(\frac{F_{gr}}{A} - 1\right)^m$$

In the above formulae,

m, A, n, C depend on the dimensionless diameter, according to Table 1

g_s : sediment concentration by weight

Table 1. Coefficients in Ackers and White formula (Chang, 2008).

Coefficient	$D_* > 60$	$1 < D_* \leq 60$
C	0.025	$\log c = 2.791(\log D_*)^2 - 3.46$
n	0	$1 - 0.56\log D_*$
A	0.17	$0.23/D_* + 0.14$
m	1.78	$6.83/D_* + 1.67$

The values come from best-fit curves of sets of laboratory data.

Chang (2008) describes the mobility number, the first term represents the suspended load that is associated with the turbulence and the second term reflects the bed load. When *n* equals zero the coarse sediment move only in bed load transport mode.

Proffit and Sutherland (1983) modified the original formula to predict bed load transport rates while taking non uniformity of sediment into account. Instead of taking an equivalent sediment diameter, the method uses the bed material grain size distribution. Experiments in a flume were conducted and the measured sediment transport rates were compared with the ones calculated from the formula. "One finds for each size fraction the correction necessary to force the chosen transport formula to give the same transport rate for each size fraction as was obtained in the experiments."(Proffit and Sutherland, 1983).

The modification includes:

- Multiplying the mobility number by a hiding and exposure correction factor (to match the measured transport rates in the experiment)

$$F_{gr} = n_k \cdot \frac{U_*^n}{\left[\left(\frac{\gamma_s}{\gamma} - 1\right) \cdot g \cdot d\right]^{1/2}} \cdot \left[\frac{U}{\sqrt{32} \cdot \log\left(\frac{10 \cdot h}{d}\right)}\right]^{1-n}$$

The correction factor according to Proffit and Sutherland´s experiments takes the following values

$$n_k = 1.3 \qquad\qquad \text{for} \qquad 3.7 < \frac{d_k}{d_u}$$

$$n_k = 0.53 \log\left(\frac{d_k}{d_u}\right) + 1 \qquad\qquad \text{for} \qquad 0.075 < \frac{d_k}{d_u} < 3.7$$

$$n_k = 0.4 \qquad\qquad \text{for} \qquad \frac{d_k}{d_u} < 0.075$$

Where d_u is called the scaling size and can be determined from a figure. For armoured beds and small transport rates d_u is close to d_{50} and for unarmoured beds with larger transport rates d_u is smaller than d_{50}. In any case, it depends on a dimensionless shear stress (Proffit and Sutherland, 1983).

Another way of calculating n_k is by using the following equations (Wu, 2008)

$$n_k = \frac{1}{0.4 \cdot \left(\frac{d_k}{d_a}\right)^{-0.5} + 0.6}$$

$$\frac{d_a}{d_{50}} = 1.6 \cdot \left(\frac{d_{84}}{d_{16}}\right)^{-0.28}$$

- Calculating the bed load fraction by the same formula used for the uniform material case, but using the diameter and the concentration of each size class, as follows:

$$g_{sk} = \frac{G_{grk} \cdot p_{bk} \cdot d_k}{h} \cdot \frac{\gamma_s}{\gamma} \left(\frac{U}{U_*}\right)^n$$

Where G_{gr} and F_{gr} are calculated using the diameter for each fraction.

Wu and Wang (2001) also tested the modified Ackers-White formula and found it should not be used for very fine sediment, less than 0.2 mm (Wu, 2008).

2.3.3 SEDTRA Module

The SEDTRA module (Garbrecht et al., 1995) includes three different formulae that are applied, according to the size classes, as follows:

-   From 0.010 mm to 0.25 mm, Lauren´s formula (1958)
-   From 0.25 mm to 2.00 mm, Yang´s formula (1973, 1984)
-   From 2.00 mm to 50 mm, Meyer-Peter and Müller´s formula (1948)

The total concentration in parts per million of weight is calculated with:

$$C_{*t} = \sum p_k \cdot C_{*k}$$

Where

p_k : percentage of the kth size class of sediment

C_{*k} : sediment transport capacity for the kth size class of sediment

When calculating the critical shear stress, the diameter of each size should be corrected in order to take the hiding and exposure effect into account, using the following equation:

$$d_{ek} = d_k \cdot \left(\frac{d_k}{d_m}\right)^{-x} = d_k \cdot \left(\frac{d_k}{d_m}\right)^{-1/B}$$

Where

d_{ek} : sediment size to calculate critical stress

d_m : mean sediment size of the bed material

B : bimodality parameter

$$B = \left(\frac{d_c}{d_f}\right)^{1/2} \cdot \sum p_m$$

Where

d_c: sediment size of coarse mode

d_f: sediment size of fine mode

p_m : portion of the sediment mixture contained in the coarse and fine modes.

The three formulae used in the SEDTRA module are listed below. All of them are taken from Wu (2008).

Lauren´s formula

$$C_{t*} = 0.01\gamma \sum_{k=1}^{N} p_k \left(\frac{d_k}{h}\right)^{7/6} \left(\frac{\tau'_b}{\tau_{ck}} - 1\right) f\left(\frac{U_*}{\omega_{sk}}\right)$$

$$\tau'_b = \frac{\rho U^2}{58} \left(\frac{d_{50}}{h}\right)^{1/3}$$

Where

C_{t*} : sediment concentration by weight per unit volume

p_k : percentage of the kth size class of sediment

N : total number of size classes

τ_{ck} : critical shear stress for the incipient motion of sediment size d_k, given by Shields diagram

$f(U*/\omega_{sk})$: is taken from a figure.

Yang´s formula

$$\log C_{t*} = M + N \log\left(\frac{US_f}{\omega_s} - \frac{U_c S_f}{\omega_s}\right)$$

$$\frac{U_c}{\omega_s} = 0.66 + \frac{2.5}{\left[\log\left(\frac{U_* d}{v}\right) - 0.06\right]} \qquad\qquad \text{for } 1.2 < \frac{U_* d}{v} < 70$$

$$\frac{U_c}{\omega_s} = 2.05 \qquad\qquad \text{for } 70 \leq \frac{U_* d}{v}$$

Where

C_{t*} : sediment concentration in parts per million by weight

ω_s : settling velocity.

M and N are coefficients that are calculated differently if the diameter is smaller than 2 mm or between 2 mm and 10 mm.

Meyer-Peter and Müller´s formula

$$\frac{q_{b*}}{\gamma_s\left(\gamma_s/\gamma - 1\right)g d_m^3} = 8 \cdot \left[\frac{\left(n'/n\right)^{3/2}\gamma R S_f}{(\gamma_s - \gamma)d_m} - 0.047\right]^{3/2}$$

Where

q_{b*} : bed load transport rate by weight per unit time and unit width

d_m : is the arithmetic mean diameter of the bed sediment mixture

n': Manning coefficient due to grain roughness $\qquad\qquad n' = \dfrac{d_{90}^{1/6}}{26}$

R : hydraulic radius.

Referring to the SEDTRA model, Wu (2008) found that "these formulae may not transit smoothly in the case of low sediment transport, because they adopt different criteria for incipient motion".

2.3.4 Modified Engelund and Hansen´s formula

The original Engelund and Hansen´s formula was modified by Wu and Vieira (2002) to be used with non-uniform bed-material load.

$$f' \cdot \emptyset_k = 0.1 \cdot (\varepsilon_k \cdot \tau_{*k})^{5/2}$$

Where

f' : friction factor

$$f' = \frac{2 \cdot g \cdot R \cdot S}{U^2}$$

τ_{*k} : non dimensional bed load transport capacity

U : average flow velocity

S : energy slope

ε_k : correction factor for the hiding and exposure consideration.

$$\varepsilon_k = \left(\frac{p_{ek}}{p_{hk}}\right)^{0.45}$$

$\Phi_{bk,}$ p_{hk} and p_{ek} were all defined in Section 2.3.1.

3 CCHE2D model

In this section, a general overview of the CCHE2D model is presented, together with a summary of the theory behind the model and a brief description of how to setup a case using this software.

3.1 General

CCHE2D is a model developed by the National Center for Computational Hydroscience and Engineering (NCCHE), at the University of Mississippi, for two-dimensional simulation and analysis of river flows. Unsteady turbulent open channel flow and non-uniform sediment transport can be modeled with this software. Processes are solved by the depth integrated Navier-Stokes equations, mass transport equations, sediment sorting equations, bed load equations and bed deformation equations. CCHE2D is freeware and can be downloaded from the web site (www.ncche.olemiss.edu/sw_download). The version used in this thesis was the latest available (version 3.29).

The model uses the Efficient Element Method for discretizing the equations, which is a special type of the finite element method. The continuity equation for surface elevation is solved on a staggered grid. Velocity corrections are applied to solve the system. The model uses an implicit scheme for time marching. It has three options for the eddy-viscosity calculation (Zhang, 2006a).

CCHE2D includes a non-equilibrium transport model for bed load and suspended load. It can simulate non-uniform sediment mixtures, using different size classes. It can also simulate cohesive sediment transport (Wu, 2001).

A graphic user interface (GUI) is provided with CCHE2D. The interface works with a given computational mesh. It was designed to help the user to define initial conditions, to setup flow and sediment parameters, to give boundary conditions, to run the simulations and finally visualize the results.

A mesh generator is also available for users of CCHE2D (CCHE-MESH 2D). Several techniques are used for mesh generating of structured meshes, e.g. algebraic and numerical.

3.2 Theoretical background

3.2.1 Shallow water equations

CCHE2D uses the shallow water equations for computing the hydrodynamic flow field.

The depth-integrated momentum equations are

$$\frac{\partial U_x}{\partial t} + U_x \frac{\partial U_x}{\partial x} + U_y \frac{\partial U_x}{\partial y} = -g \frac{\partial Z_s}{\partial x} + \frac{1}{h}\left(\frac{\partial h\tau_{xx}}{\partial x} + \frac{\partial h\tau_{xy}}{\partial y}\right) - \frac{\tau_{bx}}{\rho h} + f_{cor} v$$

$$\frac{\partial U_y}{\partial t} + U_x \frac{\partial U_y}{\partial x} + U_y \frac{\partial U_y}{\partial y} = -g \frac{\partial Z_s}{\partial y} + \frac{1}{h}\left(\frac{\partial h\tau_{yx}}{\partial x} + \frac{\partial h\tau_{yy}}{\partial y}\right) - \frac{\tau_{by}}{\rho h} - f_{cor} v$$

The depth-integrated continuity equation is

$$\frac{\partial h}{\partial t} + \frac{\partial U_x h}{\partial x} + \frac{\partial U_y h}{\partial x} = 0$$

Assuming the bed does not change during the flow simulation process, this equation becomes

$$\frac{\partial Z_s}{\partial t} + \frac{\partial U_x h}{\partial x} + \frac{\partial U_y h}{\partial x} = 0$$

Where

U_x : depth-integrated velocity component in the x direction

U_y : depth-integrated velocity component in the y direction

Z_s : water surface elevation

h : water depth

f_{cor}: Coriolis parameter

τ_{xx} , τ_{xy} , τ_{yx} , τ_{yy} are depth integrated Reynolds stresses

τ_{bx} , τ_{by} are shear stresses on the bed and on the flow interface.

$$\tau_{xx} = 2v_t \frac{\partial U_x}{\partial x}$$

$$\tau_{xy} = 2v_t \left(\frac{\partial U_x}{\partial y} + \frac{\partial U_y}{\partial x}\right)$$

$$\tau_{yy} = 2v_t \frac{\partial U_y}{\partial y}$$

$$\tau_{yx} = 2\nu_t \left(\frac{\partial U_x}{\partial y} + \frac{\partial U_y}{\partial x} \right)$$

3.2.2 Shear stress calculation

In CCHE2D, there are two methods for calculating the shear stress at the river bed, depending on whether the roughness height k_s or the Manning coefficient n is chosen. If the roughness height is chosen, the shear velocity will be calculated from the depth-integrated logarithmic wall law and the velocity values (see Section 2.2). The shear velocity would then depend on the roughness height, the velocity and the depth, and requires an iterative process. Afterwards, the Darcy-Weisbach coefficient can be calculated and as a consequence the shear stress components found. If the Manning coefficient is given, the stress components are calculated directly and the shear velocity calculated from the total stress. No iterative process is required because the Manning coefficient does not change with the flow conditions. For simulation with experimental data the roughness approach is recommended (Jia & Wang, 2001).

3.2.3 Eddy viscosity models

Three methods are implemented in the CCHE2D model: the depth-integrated parabolic eddy viscosity formula, the depth integrated mixing length eddy viscosity model and the two dimensional k-epsilon model for depth integrated flow. The methods are explained in detail by Jia and Wang (2001).

3.2.4 Sediment transport equations

For non-uniform sediment transport simulations, the sediment mixture is divided into size classes.

The depth-averaged convection-diffusion equation is derived from integrating the three-dimensional equation over the suspended load zone. After applying the boundary conditions and making some simplifications (Wu, 2001), the sediment transport formula for the kth size of sediment is

$$\frac{\partial (hC_k)}{\partial t} + \frac{\partial (U_x hC_k)}{\partial x} + \frac{\partial (U_y hC_k)}{\partial y} = \frac{\partial}{\partial x}\left(\varepsilon_s h \frac{\partial C_k}{\partial x} \right) + \frac{\partial}{\partial y}\left(\varepsilon_s h \frac{\partial C_k}{\partial y} \right) + E_{bk} - D_{bk}$$

Where

C_k : depth-averaged concentration of suspended load

E_{bk} : upward flux of the kth sediment class at the interface between suspended load zone and bed load zone

D_{bk} : downward flux of the kth sediment class at the interface between suspended load zone and bed load zone

ε_s : eddy diffusivity of sediment $\qquad \varepsilon_s = {}^{\nu_t}/_\sigma$

ν_t : eddy viscosity of flow

σ : turbulent Prandtl-Schmidt number, which takes a value from 0.5 to 1

Integrating the three dimensional equation of sediment transport over the bed load zone, gives the depth-average bed load continuity equation, Wu (2001)

$$(1 - p') \frac{\partial z_{bk}}{\partial t} + \frac{\partial (\delta c_{bk})}{\partial t} + \frac{\partial q_{bkx}}{\partial x} + \frac{\partial q_{bky}}{\partial y} = -E_{bk} + D_{bk}$$

Where

P' : porosity of bed material

δ : thickness of the bed load zone

c_{bk} : average concentration of bed load at the bed load zone

q_{bkx} : component of bed load transport rate q_{bk} of the kth size class in x direction

q_{bky} : component of bed load transport rate q_{bk} of the kth size class in y direction

z_{bk} : bed elevation

Bed load movement is assumed to be along the direction of the bed shear stress.

Adding both equations for bed load and suspended load, the total sediment transport formula is obtained.

$$(1 - p') \frac{\partial z_{bk}}{\partial t} + \frac{\partial (hC_{tk})}{\partial t} + \frac{\partial (q_{bkx} + q_{skx})}{\partial x} + \frac{\partial (q_{bky} + q_{sky})}{\partial y} = 0$$

Where

q_{skx} : component of suspended load transport rate q_{sk} of the kth size class in x direction

q_{sky} : component of suspended load transport rate q_{sk} of the kth size class in y direction

$$q_{skx} = U_x hC_k + \varepsilon_s h \frac{\partial C_k}{\partial x}$$

$$q_{sky} = U_y hC_k + \varepsilon_s h \frac{\partial C_k}{\partial y}$$

3.2.5 Adaptation length

If a model assumes local equilibrium when simulating bed load transport, the actual bed load transport rate is set to the transport capacity under equilibrium conditions. In some situations, this may lead to unrealistic predictions of bed deformation, so non-equilibrium transport effects should be taken into account (Wu, 2001).

For bed load transport, the relation between equilibrium transport rate, actual rate and bed deformation is given by the following equation

$$(1 - p') \frac{\partial z_{bk}}{\partial t} = \frac{1}{L_b} \cdot (q_{bk} - q_{b*k})$$

Where

P' : porosity of bed material

q_{bk} : actual bed load transport rate of the kth size class

q_{b*k} : bed load transport rate of the kth size class under equilibrium conditions

z_{bk} : bed elevation

L_b : adaptation length of bed load.

The adaptation length is the distance for sediment to adjust from a non-equilibrium state to an equilibrium state (Wu and Vieira, 2002). "It is the length scale for the river bed to respond the disturbances of environment, such as hydraulic structure constructions, channel geometry changes and incoming sediment variation" (Wu, 2001).

According to Wu (2001), the adaptation length is an important parameter for the numerical stability. Small adaptation lengths require a small grid size and a fairly small time step (Wu and Vieira, 2002).

The adaptation length is related to the sediment movements, bed forms and channel geometry. This is very different for laboratory cases and for rivers (Wu and Vieira, 2002).

It is recommended (Wu, 2001) that the adaptation length for bed load has a value of the length of the predominant bed form. That would mean, for sand dunes 7.3 times the flow depth or for alternate bars 6.3 times the channel width.

The equation for bed load transport becomes:

$$\frac{\partial (\delta c_{bk})}{\partial t} + \frac{\partial q_{bkx}}{\partial x} + \frac{\partial q_{bky}}{\partial y} + \frac{1}{L_b} \cdot (q_{bk} - q_{b*k}) = -E_{bk} + D_{bk}$$

In a similar manner an adaptation length for total load can be defined with (Wu, 2001):

$$(1 - p') \frac{\partial z_{bk}}{\partial t} = \frac{1}{L_t} \cdot (q_{tk} - q_{t*k})$$

Where

q_{tk} : actual total load transport rate of the kth size class

q_{t*k} : transport capacity of the kth size class under equilibrium conditions

L_t : adaptation length of bed material load.

And the total sediment transport formula becomes

$$\frac{\partial (hC_{tk})}{\partial t} + \frac{\partial (q_{bkx} + q_{skx})}{\partial x} + \frac{\partial (q_{bky} + q_{sky})}{\partial y} + \frac{1}{L_t} \cdot (q_{tk} - q_{t*k}) = 0$$

3.2.6 Bed material sorting

CCHE2D takes into account the vertical variation of the bed material gradation. The bed material is divided into three layers; each one may have different sediment properties. The layer on top is called the mixing layer. All three layers form the bed material above the non erodible material.

The variation of the gradation in the mixing layer is calculated using the following formula (Wu, 2001).

$$\frac{\partial (\delta_m p_{bk})}{\partial t} = \frac{\partial z_{bk}}{\partial t} + p_{bk}^* \cdot \left(\frac{\partial \delta_m}{\partial t} - \frac{\partial z_b}{\partial t} \right)$$

Where

p_{bk} : bed material gradation in the mixing layer

δ_m : thickness of the mixing layer

p_{bk}^* : is the bed material gradation in the subsurface layer if the term in brackets in the left side of the equation is positive, or is the bed material gradation p_{bk} in the mixing layer otherwise.

The total bed deformation rate is given by:

$$\frac{\partial z_b}{\partial t} = \sum_{k=1}^{N} \frac{\partial z_{bk}}{\partial t}$$

Where

N : number of size classes

3.2.7 Movable bed roughness

With CCHE2D there are two options for calculating movable bed roughness. They both include the increase of roughness due to bed forms, in addition to the grain roughness. Both are described in Section 2.2.

3.2.8 Bed load transport formulae

When using CCHE2D, one of the four available formulae for bed load sediment transport calculation can be selected. They were selected "by considering the evaluation of many investigators and the capability of accounting for the hiding and exposure effect as well as by testing with many experimental and field data" (Wu, 2001). The formulae were described in Section 2.3.

"… the modified Engelund and Hansen's formula is good in predicting uniform or quasi-uniform sediment transport, but it is not as good as Wu et al.'s (2000) formula and SEDTRA module in the prediction of fractional transport rate of non-uniform sediment mixtures" (Wu, 2001).

Both, Modified Ackers and White´s formula and Modified Engelund and Hansen´s formula are widely used, that is the reason they are implemented in the CCHE2D.

3.2.9 Transport mode

When setting up a model in CCHE2D, there are 3 options for selecting the sediment transport mode. The first one is to select a bed load transport model. When this option is chosen, the sediment simulation refers to bed load or total load without the diffusion of suspended load, depending on which formula for sediment load is used. Modified Ackers and White formula is a total load formula, while Wu et al. is a bed load formula. The equation for total sediment load included in Section 3.2.4 is used for calculating the sediment transport.

The second option is to simulate only suspended load or total load as suspended load. And the third one is to simulate separately bed load and suspended load. In this case, no formula for sediment transport can be applied.

3.3 Model set up

3.3.1 Mesh

The first step to perform a numerical simulation is to generate a mesh. This is done with the CCHE-MESH Structured Mesh Generator, which was developed to create structured meshes (Zhang and Jia, 2009). Much of the success of a numerical simulation depends on the quality of the mesh. Orthogonality, aspect ratio and smoothness are important criteria that must be fulfilled and that are checked by this software.

There are two options for generating the mesh in CCHE-MESH Structured Mesh Generator, the algebraic method and the numerical method. While the former uses less computational effort, the latter gives better results in terms of quality. There are also some tools for improving the mesh quality implemented in the code, when the algebraic method is used (Zhang and Jia, 2009).

When generating algebraic meshes, the two boundary method is used in the CCHE-MESH Structured Mesh Generator. First, outer boundaries should be defined; they are called first boundary and second boundary. These are used to control the geometry of the mesh. Control points are then equally distributed along the two boundaries. Each pair of points, one in each boundary, will form the control lines. The mesh will then be generated following the control lines and respecting the boundaries. The user's manual gives a detailed explanation (Zhang and Jia, 2009).

Once a good mesh quality is obtained and the result saved as a geometry file, the project in CCHE2D can be created. A graphical users' interface has been developed to work with the projects. The set up of a new simulation needs initial conditions, boundary conditions, flow parameters and sediment parameters, all of them described briefly in the following sections. Evidently, more details are found in the Graphical Users interface manual (Zhang, 2006a) and (Zhang, 2006b).

3.3.2 Initial conditions

Initial geometry and initial flow conditions must be specified for every point in the mesh. The initial geometry means initial bed elevations. The initial flow conditions are:

- Initial water surface
- Bed roughness
- Bed erodability
- Maximum deposition thickness
- Maximum erosion thickness

- Layer thickness
- Layer sample

3.3.3 Flow parameters

Numerical modelling is an approximation of the reality that depends upon several parameters. It is very important to choose the best parameters that control the simulation, both for the flow and for the sediment calculation.

The flow parameters that have to be specified in CCHE2D are:

- Simulation time.
- Time step.
- Turbulence model option: as previously mentioned, there are three options available (see Section 3.2.3).
- Wall slipness coefficient: this coeffcient indicates the wall boundary condition at no-flow boundaries (Zhang, 2006a). No slip, partial slip, total slip or log-law conditions are available options.
- Depth to consider dry conditions (dried up areas): this refers to a value for distinguishing between wet and dry nodes.
- Time iteration method: the user can choose between a small, a medium or a large number of iterations per time step. "The value should be based on the time step size, i.e., if the time step size is large, the iteration control flag should be set to a higher value (Zhang, 2006a).
- Bed roughness: the user should choose between the value specified in the initial conditions (.geo file) or the use of a movable bed formula between Wu and Wang (1999) formula or van Rijn formula (1984; refer to Section 2.2). The value specified in the initial conditions can be the roughness height or the Manning number.

3.3.4 Sediment parameters

The sediment parameters required for a simulation are mentioned below.

- Number of bed layers: the default value is 3.
- Minimum mixing layer thickness: numerical parameter to confine the bed erosion process.
- Size classes: the maximum number is 8.
- Transport mode: the options have to be chosen between total load as bed load plus suspended load, total load as bed load model or total load as suspended load model. If total load as bed load model is selected, there are four sediment transport formulae available.

- Sediment simulation mode: there are 2 options, slow bed changes for steady flow or fast bed change for unsteady flow.
- Adaptation length for bed load: the options are average grid length, average dune length or to specify a value.
- Adaptation factor for suspended load: the possible lengths are based on Armanini and di Silvio (1988) or a user specified value.
- Bed roughness: the options are the same as for flow simulation, and the same option has to be chosen for flow and for sediment simulation.
- Sediment specific gravity: the default value is 2.65, but another value can be specified.
- Curvature effects: it can be decided to include them or not.
- Only for steady flow computation:
  - Time steps to adjust flow
  - Erosion/Deposition limit (0.01-0.05 of depth)
- Bank erosion: includes all the parameters for a bank erosion simulation.
- Bed material samples: they are used to characterize the initial bed material composition in vertical and horizontal directions for the domain, as well as the porosity and the fractions for each predefined size class.

3.3.5 Boundary conditions

In CCHE2D, all boundaries in the domain are walls unless specified otherwise. The method for specifying boundary conditions is, first to define which nodes are inlet nodes and which ones are outlet nodes. The second step is to associate the flow and sediment boundary conditions to these nodes.

At the inlet boundary, a constant discharge or a hydrograph (.dhg extension file) can be specified. If the simulation includes sediment transport, one or two sediment rate files have in addition to be attached, depending on if it is a bed load type transport mode (.bbc extension file), a suspended sediment transport mode (.sbc extension file) or a total load simulation (both files should be attached).

There are four available boundary condition types for the outlet boundary, a constant water level, an open boundary condition, a rating curve (stage & discharge curve file with .rcv extension) or a stage hydrograph (time & stage curve with .shg extension file).

3.3.6 Run simulation

CCHE2D has the options for cold start and hot start for both, flow simulation and sediment simulation. Cold start for flow simulation means start the simulation from rest. It uses the initial water surface, from the initial conditions. Hot start for flow

simulation means it will start from an already computed flow field. Cold start for sediment simulation means to use the initial bed elevation and a selected flow field. Finally, hot start for sediment simulation means the simulation will begin with previously calculated bed elevations and flow field.

4 Lanzoni case

In this section, the case study selected for the thesis is described. First, the main characteristics of the physical model are mentioned, followed by relevant results obtained from the testing. Finally, the parameters for the simulation setup for this case are shown.

4.1 Laboratory setup

The purpose of the laboratory experiments carried out by Lanzoni was to "get a better understanding of the effect of sediment heterogeneity on bar morphology" (Lanzoni, 2000b). To study longitudinal and vertical sorting was an additional objective.

The testing was done in a rectangular flume, 50 m long and 1.5 m wide. A set of 16 runs were performed with discharges in the range of 0.030 to 0.055 m^3/s and with durations varying from 3 hours to 93 hours. For every run, a constant discharge flowed in the flume over an initially flat bed.

The sediment was recirculated in the flume. A sediment trap was installed at the downstream end of the flume. The sediment was then pumped to the upstream end, and evenly distributed across the width with a diffuser at the inlet section (Lanzoni, 2000a).

A strongly bimodal sediment mixture was used for the study. An index of bimodality above 1.7 shows the bimodal character of a given mixture (Lanzoni, 2000b). The equation in Section 2.1.5 shows how to calculate this index, which is needed for calculating the bed load transport rate in the SEDTRA method. In the experiment, the sediment had an index of bimodality of 5.7. Depending on the shear stress on the particles and the critical shear stress, different situations may occur with this kind of mixture. Low shear stress will generate no mobilization of particles. Increasing shear stress will first mobilize smaller particles in a higher rate than coarser particles, and then full mobilization will be reached (Lanzoni, 2000b).

The sediment used in the physical model had a density of 2 650 kg/m^3.

Some characteristic diameters for the sediment mixture are shown in Table 2. The grain size distribution is presented in Figure 2.

Table 2. Diameters of sediment mixture (Lanzoni, 2000b). All diameters are in mm.

d_g, geometric mean	0.494
σ_g, geometric standard deviation	3.305
d_{10}	0.157
d_{30}	0.199
d_{50}	0.262
d_{70}	1.280
d_{85}	2.890
d_{90}	3.210
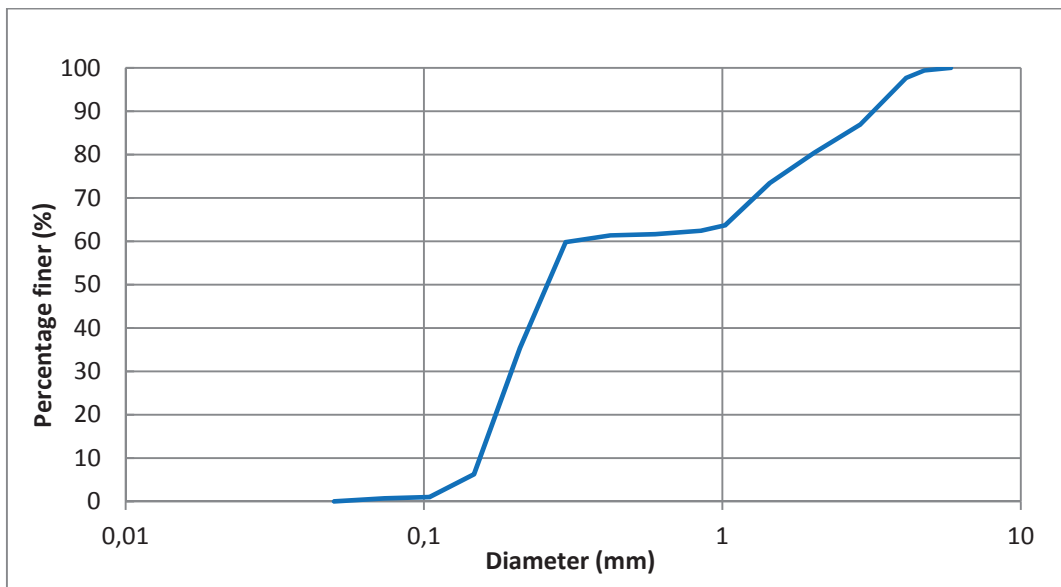
Figure 2. Particle size distribution, Lanzoni case.

From the set of tests, Run P1309 was chosen for the numerical simulation in this thesis. The reason for selecting this run was the availability of measured data, which included average bed load transport rates, grain size distribution for bed load and longitudinal profiles. This information was not available for most other cases.

For run P1309, the discharge was 0.045 m^3/s. The average surface slope was 0.525 %, the average depth flow was 0.05 m and the average velocity was 0.60 m/s.

According to Lanzoni (2000b), the experiments were stopped when equilibrium conditions were reached.

"In some of the runs… the transported sediment was sampled during the equilibrium phase by collecting into a bucket the sediment flowing over the diffuser" (Lanzoni, 2000b). The samples were sieved and new grain size distributions were plotted. From

the total transport rate and the size fraction, a transport rate for each sediment size was calculated. The following equation was used:

$$q_{sk} = q_s \cdot f_{ak}$$

Where

q_{sk} : fractional transport rate

q_s : measured total transport rate per unit width

f_{ak} : proportion of the kth fraction in the transport

Figure 3 shows the mean fractional transport rates for run P1309, scaled by the proportion of each fraction in the substrate f_{sk}. Figure 4 shows the grain size distribution at the end of the run.
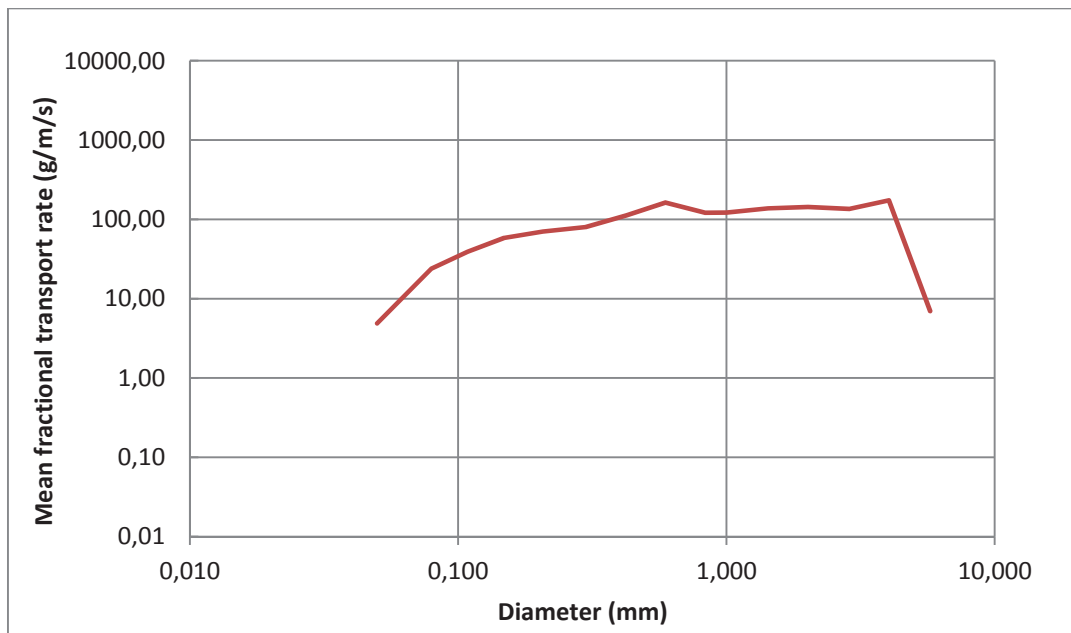
Figure 3. Mean fractional rates, Lanzoni case.

4.2 Results from the physical model

During the experiments, in the full mobilized cases, alternate bars developed. "A regular sequence of well-formed alternate bars … was observed only in the early stages of a given run. These initially formed bars gradually migrated out of the flume, and later on only irregularly shaped alternate bars were observed to grow rather sporadically in the final reach of the flume."(Lanzoni, 2000b).

Lanzoni (2000b) concluded that sediment heterogeneity inhibits the formation of bed forms, when compared to a uniform sediment case. As a consequence, the flow resistance decreases and is dominated by friction (Lanzoni, 2000b).

As a result of the runs, both longitudinal and vertical sorting occurred in the bed material. The gradation of the sediment samples, taken at the equilibrium phase of the test (end of the run), were very different from the initial sediment mixture. In these samples there is a lack of finer and coarser sediment sizes, which indicates that complete full mobility was never attained (Lanzoni, 2000b). In relation to sediment sorting, it was also reported "an intense longitudinal sorting which accreted the coarser particles on bar crests" (Lanzoni, 2000b).

In all experiments, the sediment transport mode was mainly bed load.

An important conclusion of the experiments regarding the present study is that "… a reasonable prediction of the actual flow resistance is provided by assuming k_s to be

equal to the value of the coarse mode of the mixture (corresponding approximately to d_{85} = 2.89 mm)" (Lanzoni, 2000b).

4.3 Setup of the case with CCHE2D

4.3.1 Grid generation

A straight flume is a simple geometry for grid generation, needing no adjusting of smoothness and orthogonality. Two straight boundaries were defined and an algebraic mesh was generated, with a cell size of 0.10 m x 0.10 m. So, Reaching adequate aspect ratio and expansion ratio, which could be difficult in many other cases, was not an issue in the present case.

The cell size was selected looking for balance between accuracy and the computational time. Many cases with similar geometries and similar flow conditions, presented in Wu (2001) and Jia and Wang (2001b) report larger cell sizes. The boundaries and the mesh used for the Lanzoni case are shown in Figure 5.

4.3.2 Flow parameters

The simulation time was 29 hours for all the sediment runs, to be consistent to the P1309 experiment in the Lanzoni case. A time step of 1 second was used. CCHE2D uses an implicit method for discretization, so it was not compulsory to meet the Courant criteria.

Among the three options for turbulence models available in CCHE2D, the more advanced k-epsilon model was selected for the simulations.

The chosen output parameters made results available for every ten minutes in the history file.

The wall slipness coefficient was set to 0.5, meaning an intermediate value between no slip and full slip conditions at the wall was chosen.

The depth to differentiate between dry and wet nodes was set to 0.0005, which was considered adequate in relation to the average flow depths in the flume.

Method 1 for time iterations was selected. This means small number of iterations, and it is recommended when time steps and cell sizes are also small.

The default values for Coriolis force coefficient, gravity, von Karman constant and fluid kinematic viscosity were used.

The bed roughness was an important parameter for the simulations and the different available options were tested in order to get an accurate solution. Constant values for the roughness height and the two available formulae were compared (Section 2.2).
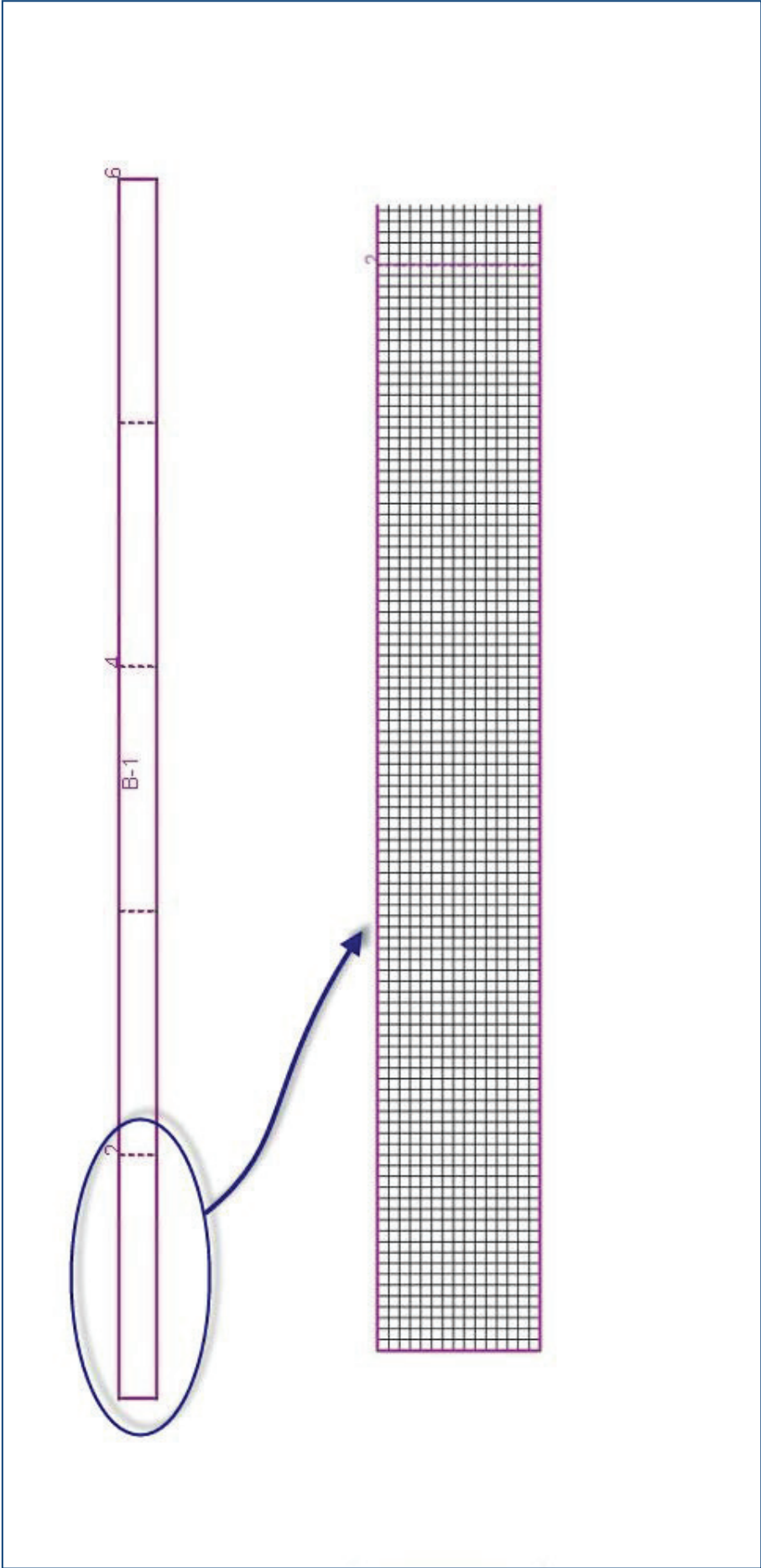
Figure 5. Boundaries and grid for the model.

4.3.3 Sediment parameters

The default value for the number of layers (3) was used. In this case it was not a relevant parameter since in the physical model, only one layer with the same bed material was used.

The minimum mixing layer thickness is an important parameter that was evaluated during the simulations. It is related to the flow and the sediment conditions, like the shear stress and the sand wave height (Wu, 2001). Values like $2d_{50}$, d_{90} and $2d_{90}$ were tested.

The maximum number of size classes was selected, means 8 size classes, to try to represent the grain size distribution curve as accurate as possible. Figure 6 shows the different size classes used in the simulations. The bimodal character of the sediment mixture can be observed.
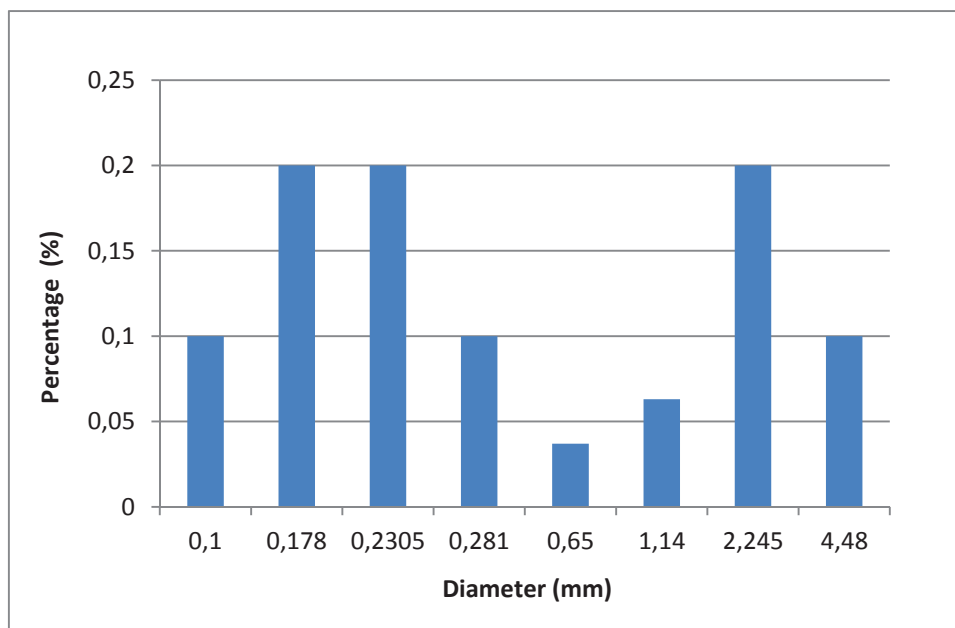
Figure 6. Size classes used in the simulations.

In the experiments, primarily bed load transport mode was reported (Lanzoni, 2000b). So this option was chosen for all the simulations. This also had the advantage of being able to choose among the different formulae for sediment transport in the CCHE2D model.

In the sediment simulation mode box, the fast bed change for unsteady flow was selected. While the discharge was kept constant during the laboratory experiment, the sediment feeding changed over time.

Initially, a constant adaptation length was used, set to 5 times the channel width. Later, it was set to equal to the theoretical bar length and finally larger changes were simulated to test the sensitivity of this parameter in the bed load rate (see Section 5.3.3).

The adaptation factor for suspended load was not used, since the sediment simulations were based on bed load and not on suspended load.

For all cases, the bed roughness for sediment transport was the same as the roughness for flow simulation. So, different values and formulae were tested, as well.

The default value for the sediment specific gravity was used, means 2.65. This was specifically reported for the laboratory test (Lanzoni, 2000b).

The curvature effects were included in all calculations.

The bed material samples define the initial bed material composition in vertical and horizontal directions. The porosity was set to 0.4, although a porosity of 0.5 was also tested. The fractions for each size class are also shown in Figure 6.

4.3.4 Initial conditions

The initial bed elevation for the flume was used for the simulations, including the slope reported by Lanzoni (2000b), for the P1309 Run. This was the same for the steady flow simulations and the sediment simulations.

A nearly uniform flow condition was used as the initial water surface for the steady simulation. The resulting flow field and water surfaces were then the initial conditions for the sediment runs. In other words, a cold start for both flow simulations and sediment simulations was used.

Both methods for assessing the bed roughness were tested. For some simulations, every point in the grid had a corresponding roughness height equal to d_{85}, d_{90}, $2d_{90}$, and so on. For other simulations, either the Wu and Wang formula (1999) or the van Rijn formula (1984) was used.

For the whole domain, the bed was chosen to be "erodible", with maximum deposition thickness and minimum deposition thickness set large enough to not limit the deposition process.

Like it was mentioned before, 3 layers were defined for the bed material sorting calculations. The first layer has to be equal to the mixing layer thickness, and has to be specified in the initial conditions and in the sediment parameters. The sum of all of them should be enough for including the erosion processes during the simulations.

One layer sample has to be assigned to each of the bed layers. For the Lanzoni case, all of the layers have initially the same composition, which is shown in Figure 6.

4.3.5   Boundary conditions

Boundary conditions for the inlet and the outlet of the flume had to be defined. For the steady flow simulations, a constant discharge at the inlet boundary was used. For the time dependant simulations, a discharge hydrograph was selected, but a constant discharge was represented, because the discharge was kept constant in the physical model. A bed load boundary condition was also specified, attaching a file to the inlet boundary (extension .bbc). This type of files can be created using the editor available in the CCHE2D interface. In the file, the bed load transport rate over time is specified, in kg/m/s as well as the fractions for each sediment size class for the incoming sediment. For all the simulations, the gradation for the sediment input was the same as the bed material gradation. This does not represent exactly what happened with the flume in the laboratory, because as mentioned before, the sediment was recirculated and the sediment size distribution varied over time. For this study this simplification was made, but the variation of bed load over time was considered to be a parameter for the simulations, so different files were used for each of the cases that were analyzed.

A constant water surface level was specified in the outlet boundary. This value depended of the roughness used for flow calculation and was determined after some short testing.

5 Simulations and results

5.1 General

The main objective of the simulations was to replicate the average bed load transport rate in the flume for the Lanzoni case with CCHE2D.

Accordingly, comparisons between simulations and experimental data were done by calculating the sediment transport rate in kg/m/s and comparing with the measured value. Although other data was compared, this value was the most important for evaluating the accuracy of the simulation, in this thesis.

Lanzoni (2000b) reported measured average volumetric solid discharges, including pores, for each of the runs. In run P1309, he measured 471 l/hr, in average. Sediment porosity can take values between 0.36 and 0.4 (Chanson, 2004). A value of 0.4 was chosen for calculating the sediment rate in kg/m/s. The corresponding sediment transport rate is 0.139 kg/m/s. A porosity of 0.5 was also used for testing the sensitivity of this parameter.

The simulations carried out for the Lanzoni case can be divided in two groups, each one with a different purpose. In the first group of simulations, the goal was to find out about the sediment transport capacities of the model using the different available bed load transport formulae. In a first step, the sediment transport formulae were tested without sediment input in the flume. The resulting bed load transport rate from the first step was, in a second step, used as a feedback for the sediment feeding in the flume and another simulation was run. The sediment input and hence the final transport rates depended entirely on the transport capacities of the formulae used in the model. It was important to reach sediment transport rates similar to the measured average rates. In addition a parameter sensitivity analysis was conducted in order to study the effects of the main parameters.

In the second group of simulations, the real transport rate, meaning the measured transport rate in the physical model was the input for the computations. In this case, reaching equilibrium conditions was the main objective. In the following two sections, each group of simulations is described correspondingly.

5.2 Simulations with calculated sediment input

5.2.1 General procedure

Initially, all the available sediment transport formulae in the model were tested. Roughness is a main parameter for flow resistance and for sediment transport. So, it was the first parameter to be evaluated in the study, and different roughness heights were used. Roughness height was chosen over the Manning´s roughness number, as suggested by Jia and Wang (2001). Other parameters, such as adaptation length, mixing layer thickness and porosity, were kept constant in order to compare between the different transport formulae.

For all cases the same procedure was followed and it consisted of three simulations as described below.

- A steady flow simulation which would be the initial flow conditions for the sediment simulation.
- A sediment simulation for a short period, over one hour, in order to calculate the sediment transport at the end of the period. This would be the sediment input for the long term simulation.
- A sediment simulation for the entire period, 29 hours so to represent the test P1309.

5.2.2 Bed load transport models

a) Wu et al.

As the first case, Wu et al. formula for sediment transport was used together with Wu and Wang´s formula for roughness calculation. Both formulae were supposed to work well together by complementing each other. The roughness formula includes both, grain roughness and roughness from the bed forms and the sediment transport formula takes into account the hiding and exposure effect, so the combination is thought to have a more complete physical approach.

After the one hour simulation, the sediment transport rate at the end of the flume was 0.025 kg/m/s. So this value was chosen as sediment input for the 29 hours simulation, as shown in Figure 7. A linear variation in the first hour and a constant sediment load afterwards was the inlet boundary condition for the long term simulation.
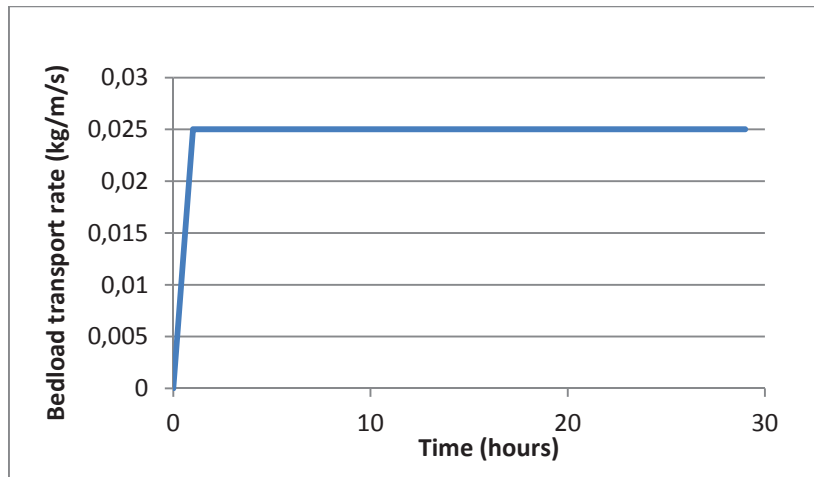
Figure 7. Sediment input for Wu et al. simulation.

This assumption was considered to be accurate enough for the first simulations, although it may not completely be exact. The sediment was recirculated in the laboratory, which means that the sediment output for the flume should be the sediment input in the next moment, with a continuous variation with time. However, CCHE2D cannot handle this kind of situation, so the simplified boundary conditions described above were assumed. Variations of the time for reaching the maximum value were also done, and are described in Section 5.3.4.

Figure 8 shows the simulated transport rate and the average measured transport rate along the flume. Variations along the flume were very small and the sediment output was slightly higher than the sediment input, which indicates that the equilibrium condition was almost, but not completely reached. In the laboratory, reaching equilibrium was an indication for ending the runs. However, Wu et al.´s formula is far from predicting the actual bed load transport rate, as it can be seen in the figure. It under predicts the bed load by a factor of almost 5.
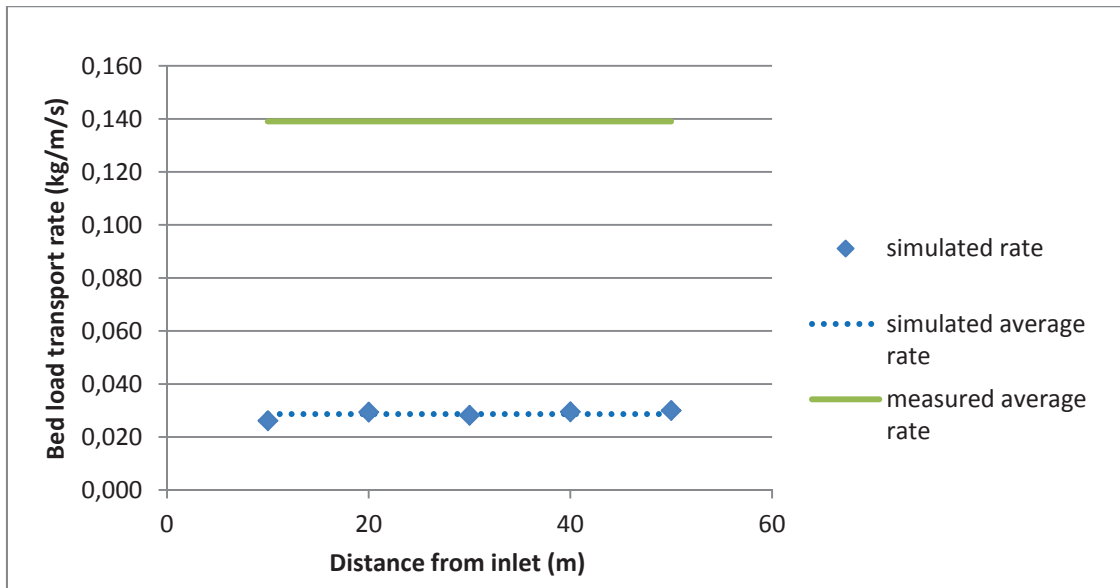
Figure 8. Bed load transport rate for Wu et al. sediment transport formula.

Some parameters were changed and new simulations were run to measure their influence and find out if the sediment transport predictions could be increased for the Wu et al. formulation, as described in the following paragraphs.

Change in porosity

In the CCHE2D model, the porosity has to be specified in the bed sample parameters. The porosity has also an effect when calculating the measured sediment transport rate in kg/m/s, from the physical model.

A porosity of 0.5 was tested and compared against a porosity of 0.4. Figure 9 shows the results, the presented data was extracted from two cross sections in the flume, one located 15 m from the inlet and the other one at the downstream end. No significant changes were observed in the sediment transport rate.

For the next simulations, the 0.4 porosity was kept constant, since this value is within the normal range, as mentioned in Section 5.1.
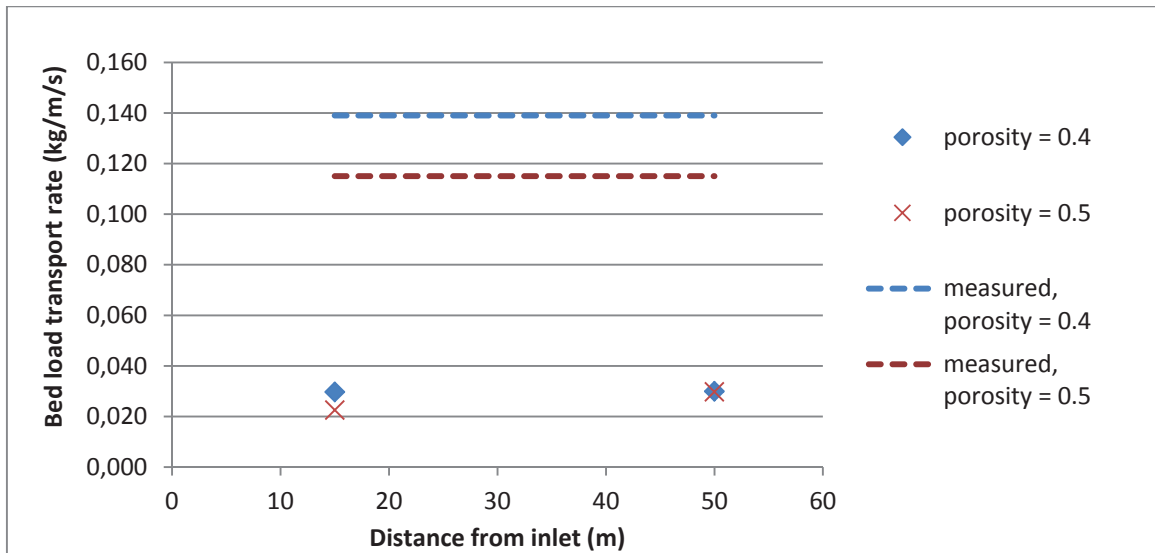
Figure 9. Influence of porosity in bed load transport rate, Wu et al. sediment transport formula.

Changes in calibration factor

A calibration factor is available in the CCHE2D model, for the case when a bed roughness formula in the simulation is used. "If you choose roughness formula for flow, the selected formula will be also used in the bed roughness calculation for sediment. You also need to specify the formula parameters, such as D16, D50, D90 and Calibration Factor. The Calibration Factor is within the range of [0.2, 5.0] and its default value is 1.0" (Zang, 2006a). There is no further explanation in the user´s guides about how this calibration factor is applied, so using this parameter would not be suitable (black box).

Nevertheless, the calibration factor was modified, so that the average flow depth reported in the laboratory matched the average depth flow calculated during the steady flow calculation. The result was a calibration factor of 0.8. Figure 10 shows a resulting increase of sediment transport rate, but not a significant one.
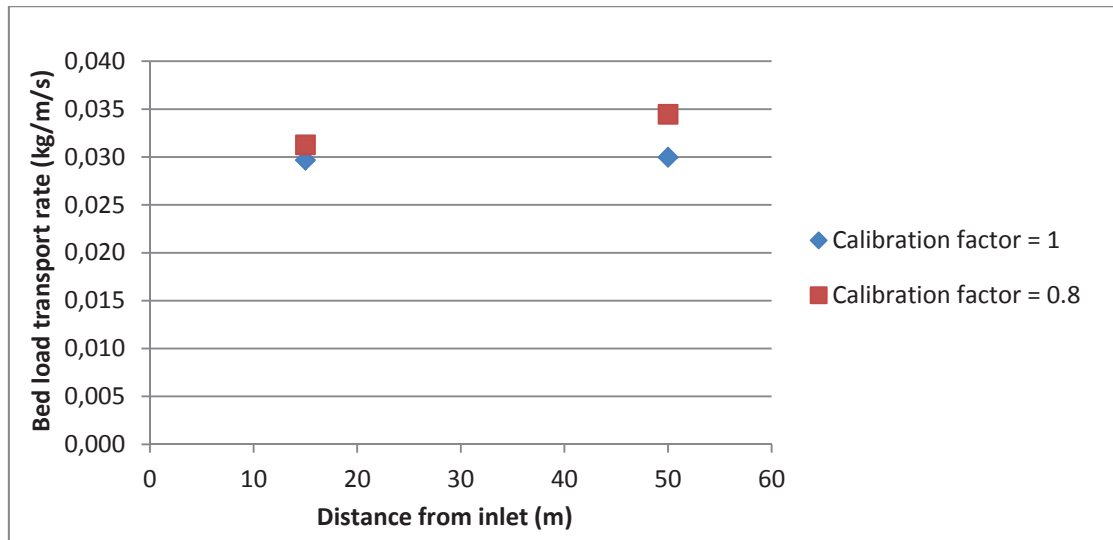
Figure 10. Effect of calibration factor in sediment transport rate, Wu et al. sediment transport formula.

Changes in mixing layer thickness

The mixing layer thickness was changed from $2d_{50}$ to d_{90}, in an attempt to observe an impact on the sediment transport rate. There was a small increase in the bed load transport rate, but not a significant one. A thickness of d_{90} was then kept for the next simulations.

A more detailed analysis of the mixing layer thickness is presented in Section 5.3.5.

Changes in adaptation length

The adaptation length was changed from 7.5 m to 9.45 m, to adjust it to the predominant bed form. A detailed explanation is presented in Paragraph b) of this section.

Figure 11 shows the results for the bed changes and bed load transport rates. In this figure, the mixing layer thickness is d_{90}.

It can be observed that the bed load transport rates do not increase significantly. The bed changes are very small. There is erosion in most part of the flume, in an order of 0.001 mm.

(a) Bed changes (m)

(b) Bed load transport rates (kg/m/s)
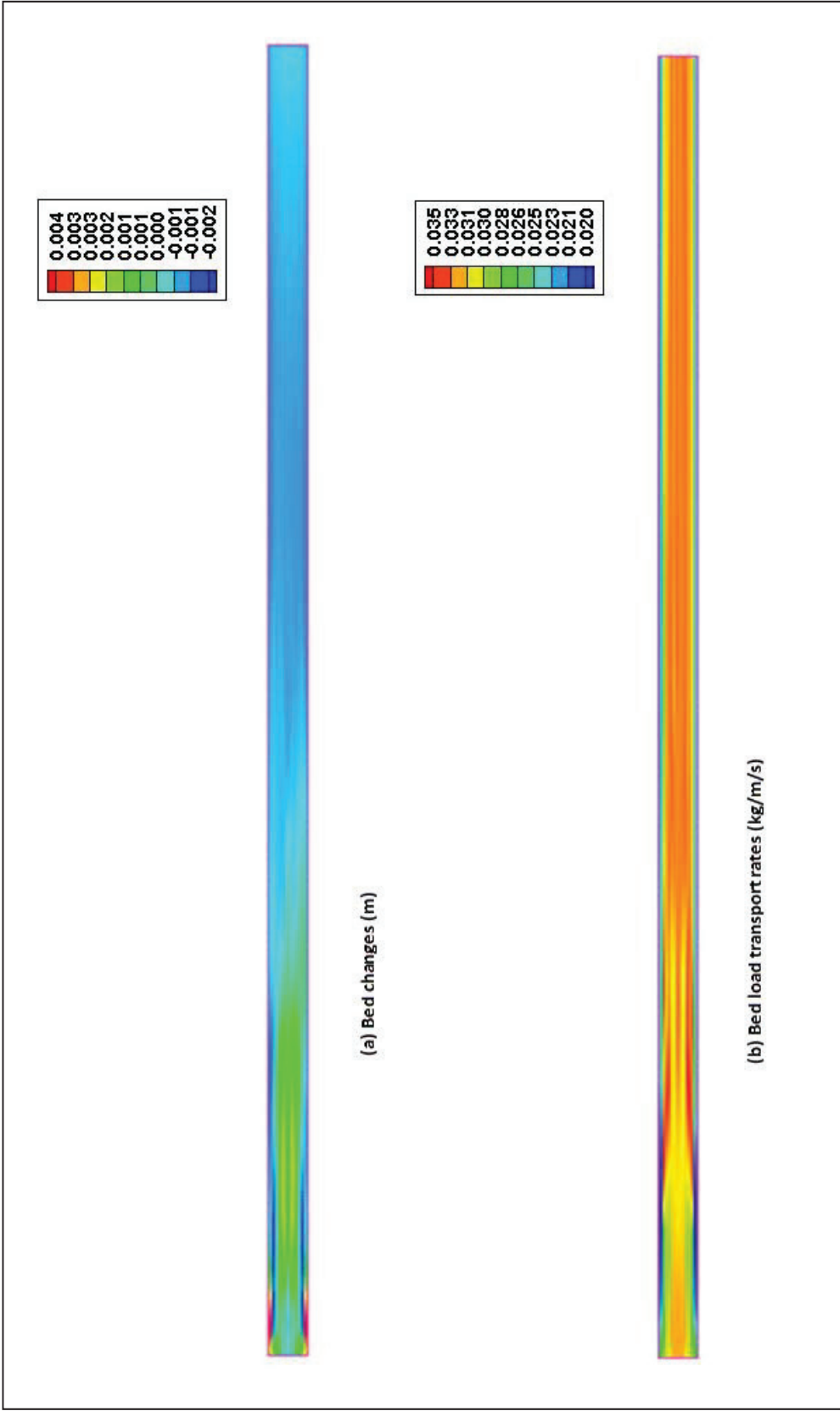
Figure 11. Results from sediment simulation, Wu et al sediment transport formula, mixing layer equal to d_{90}.

b) Modified Ackers and White

As described in Section 2.1.4, the modified Ackers and White sediment transport formula is another available formula in the CCHE2D model (Wu, 2001). Different roughness values were tested in combination with this formula. The modified Ackers and White formula is used for total sediment transport calculation, while Wu et al. is a bed load formula.

The sediment input was calculated in the same way that with the Wu et al. case. The computation is roughness dependant, so it was repeated for each of the chosen roughness. Figure 12 shows the bed load boundary condition at the inlet when a roughness height equal to d_{85} is used. In this case, the bed load rate in one hour was 0.121 kg/m/s.
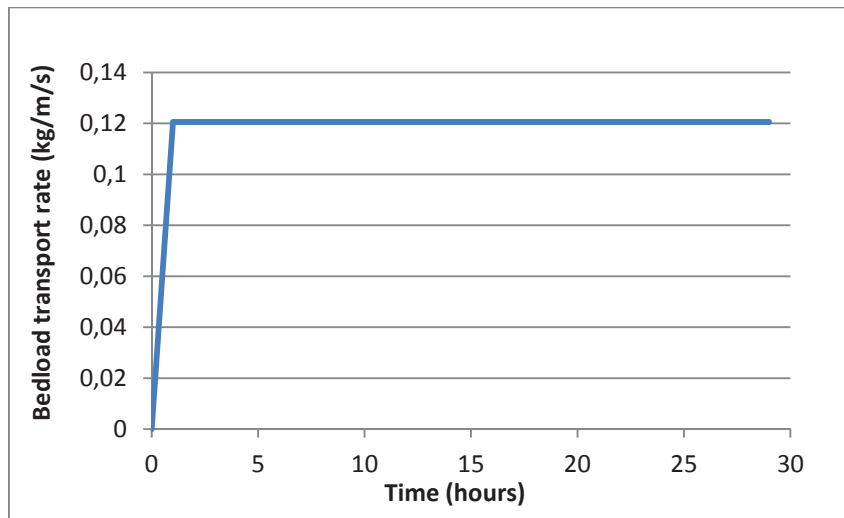
Figure 12. Sediment input for modified Ackers and White simulation, roughness height equal to d_{85}.

The variation of sediment transport rate over time was checked by running the simulation for 3 hours and looking on the transport rate at the end of the flume in this period. This is shown in Figure 13. As expected, the sediment transport rate decreases over time, if there is no sediment input. A period of one hour was the initial assumption, since it was supposed that by this time the sediment would move and would be transported towards the downstream end of the flume. Since a slow variation over time can be observed from the figure, changes in the value of sediment input due to small differences over time should not be significant in this case. However, when the sediment feeding was set equal to the average measured one in the physical model, this parameter was further tested, as described in Section 5.3.4.
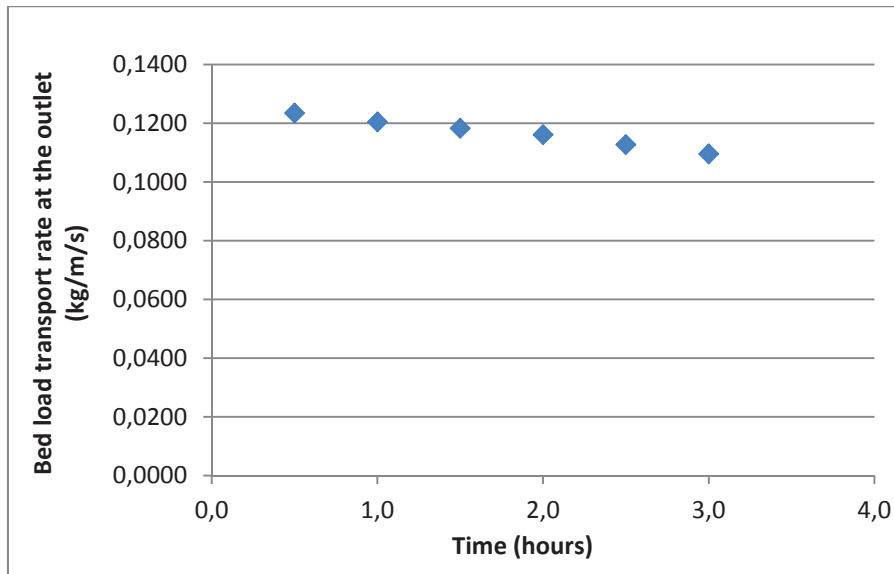
The bed load transport rates simulated with the modified Ackers and White formula are shown in Figure 14. The section locations are the same as in the Wu et al. case. The bed load transport rates from the numerical model, proved to be very sensitive to the bed roughness.

If the roughness is set to be constant and related to a typical grain size, like d_{85}, d_{90} or $2d_{90}$, the lower the roughness height, the higher the transport rate. When using a formula for the roughness, which combines bed form and grain size contributions to roughness, van Rijn gives a much lower transport rate than the Wu and Wang formula.
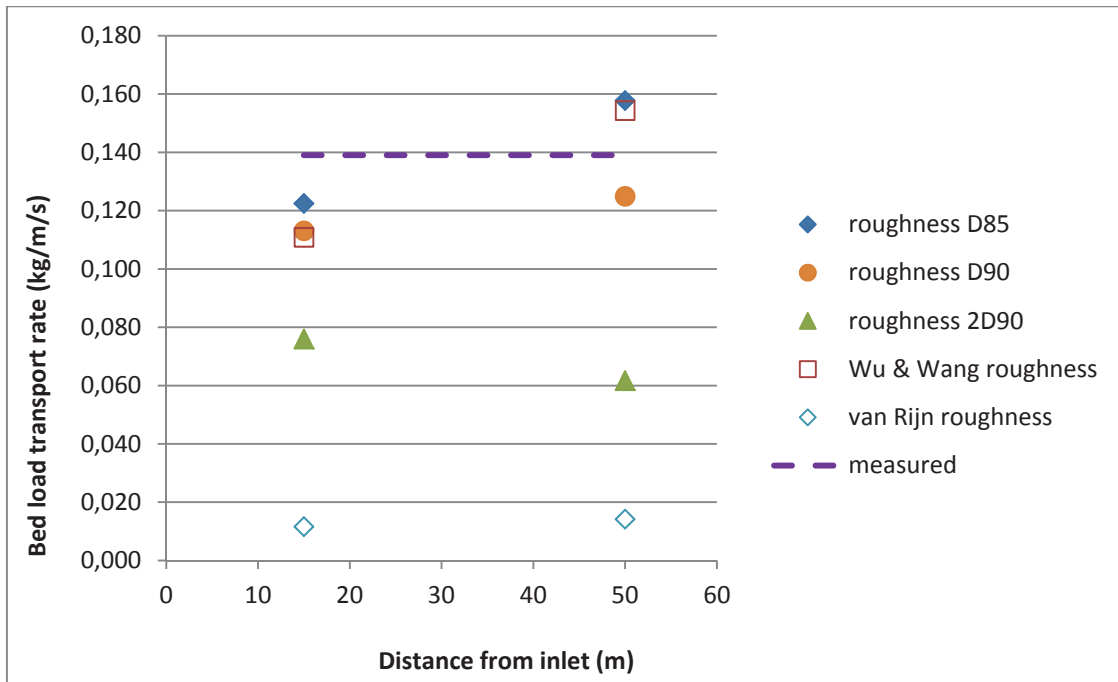
Figure 14. Sensitivity of bed roughness for modified Ackers and White sediment transport formula.

Modified Ackers and White formula with d_{85} roughness height and Wu & Wang roughness predict a similar average sediment transport rate, closer to the measured average rate than any other chosen roughness. It may be assumed that both methods give almost similar roughness values. However, variation along the distance, presented in Figure 15 and also bed profiles are quite different for each case. Modified Ackers and White formula with d_{85} roughness height gives a smoother variation within the flume compared to the roughness calculated by Wu and Wang.
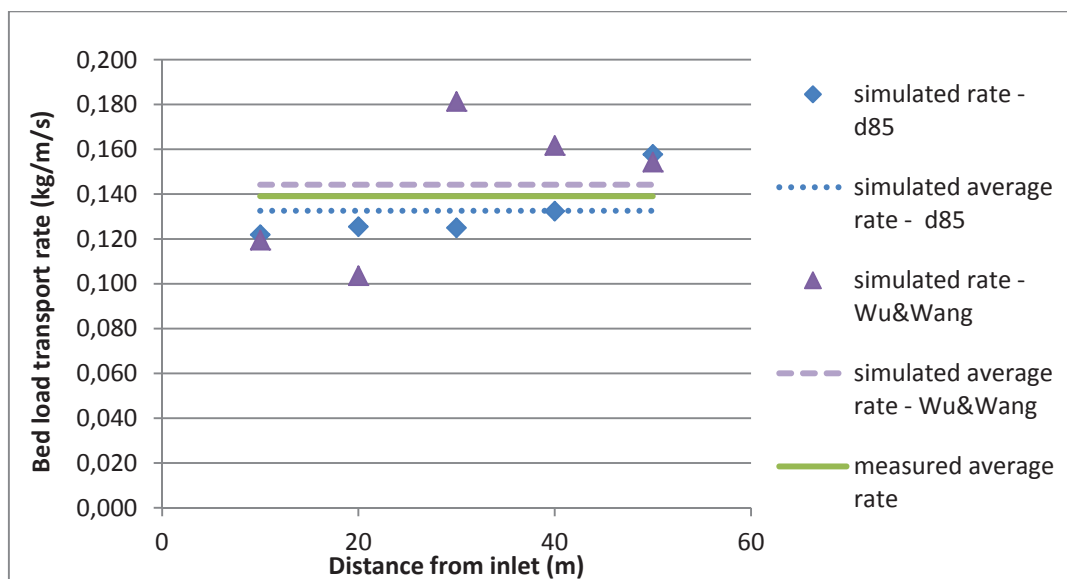
Figure 15. Bed load transport rates (Modified Ackers and White formula) with d_{85} roughness and Wu and Wang roughness.

A roughness equal to d_{85} was reported to give a reasonable prediction of the actual flow resistance in the physical model (Lanzoni, 2000b). For the sediment mixture used in the experiments, d_{85} was equal to 2.89 mm. This fact confirmed the findings with the computational model, and it strengthened the decision to use d_{85} as roughness height for the next simulations.

A more detailed look on the bed load rate variation was done for this roughness. Figure 16 shows the bed load variation over time, for the last 9 hours of the simulation. Some variations can be observed, especially at the downstream end, where a very high transport rate takes place. A high variation in the downstream end indicates that it could be caused by the chosen boundary conditions. Average rates calculated without taking into account this outliner should then give a better indicator of what is happening in the flume. As a result, 0.126 kg/m/s average rate is calculated. This is slightly higher than the sediment input, which means that erosion is occurring within the flume and equilibrium conditions were not reached, so far.
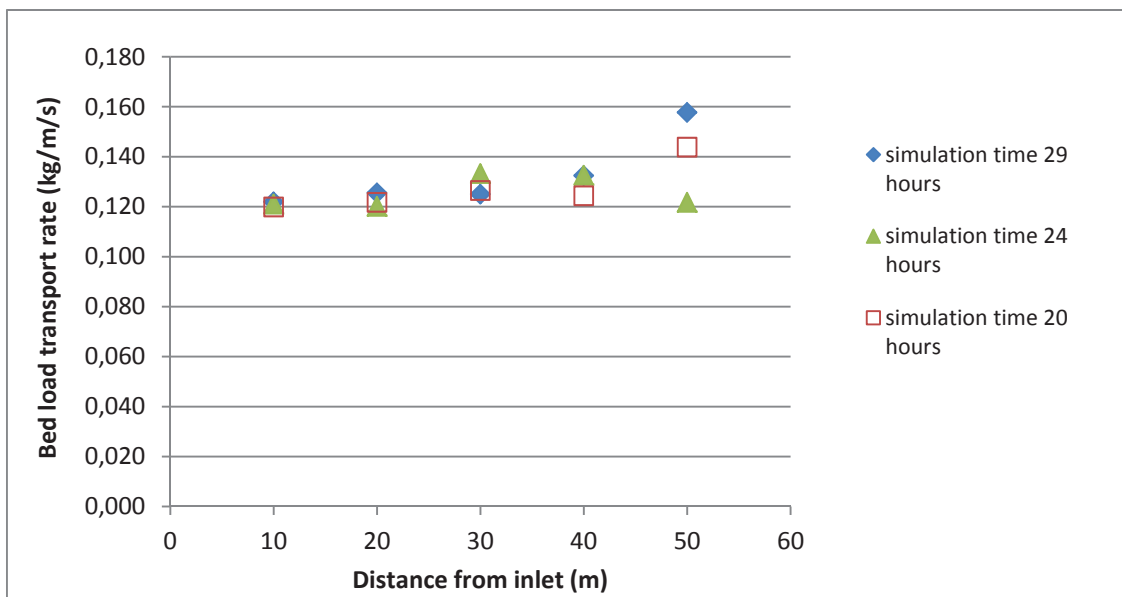
Figure 16. Time variation of bed load transport rate, modified Ackers and White transport formula.

Additional simulations were conducted to test other parameters and their influence on the results.

Adaptation length

An important parameter in the sediment transport calculation is the adaptation length. An initial value of 5 times the width of the flume was selected, which was used initially for all simulations and comparisons. Later the adaptation length was set accordingly to

the predominant type of bed forms that occur in the flume (Wu, 2001). Wu (2001) suggests the use of an adaptation length of 6.3 times the width of the flume when alternate bars predominate. This is the length of the bar, as it was described in Section 2.1. Lanzoni (2000b) reports the development of alternate bars, regular at the beginning of the run and sporadic and irregular in shape later on. "The development of small scale (ripples) and mesoscale (dunes) sediment waves tended to be inhibited thus allowing a decrease in resistance" (Lanzoni, 2000b). The adaptation length was adjusted from 7.5 m to 9.45 m.

In Figure 17, the results obtained after changing the adaptation length from the initial value to the length of the bar, are presented. Although there is some variation at the downstream end of the flume, the average without these outliners, is practically the same. A value of 0.127 kg/m/s in average is obtained. The sediment feeding in this case is 0.120 kg/m/s, so there is some erosion taking place after 29 hours, and equilibrium is not reached in the simulation. However, in the physical model, Run 1309, equilibrium was reached and an average value of 139 kg/m/s was measured. Section 5.3 refers to the simulations using this value as the sediment input at the end.
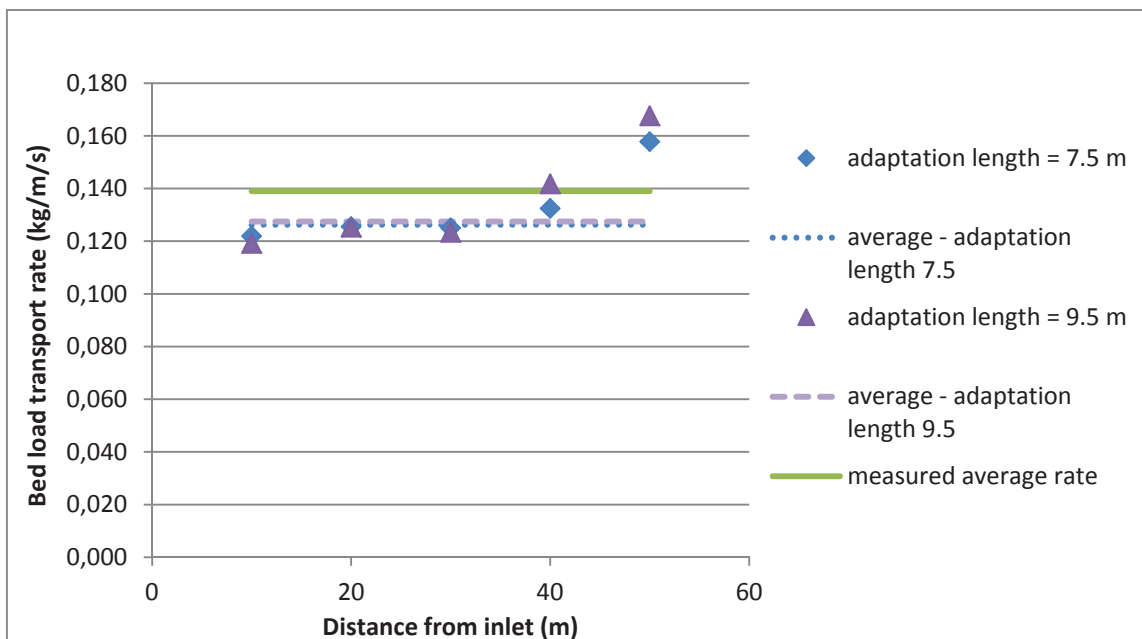
Figure 17. Bed load transport rate for different adaptation lengths, modified Ackers and White sediment transport formula.

Mixing layer thickness

Another parameter that was changed was the mixing layer thickness. The initial value of $2d_{50}$ was changed to d_{90}. A more detailed explanation of this parameter is shown in Section 5.3.5. The sediment rate at the end of one hour varied from 0.120 kg/m/s to 0.118 kg/m/s and the average rate simulated at the end of the run was 0.131 kg/m/s.

The output from the CCHE2D model for this case is presented in Figure 18 and Figure 19. Flow conditions are almost constant in the first third of the flume, meaning a velocity of about 0.6 m/s and a shear stress of about 2.4 N/m^2 are represented well by the numerical model. In the downstream part of the flume alternate bars show up and bed changes vary about ±0.02 m. As consequence differences in velocities and shear stress show up within cross sections when the bars are formed. Also erosion processes takes place in the downstream part of the flume.

(a) Specific discharge (m2/s)

(b) Velocity magnitude (m/s)

(c) Total shear stress (N/m2)
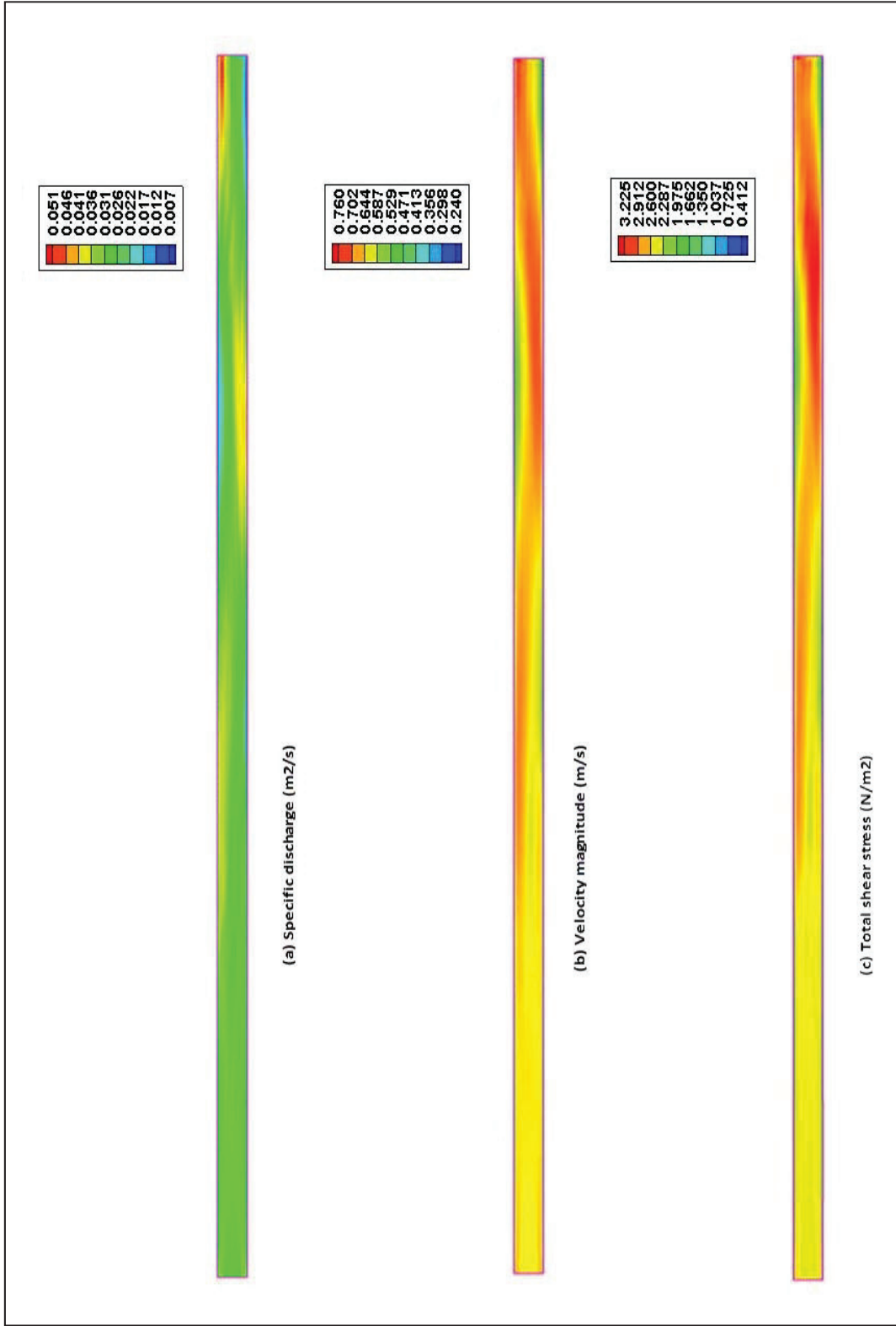
Figure 18. Flow results, modified Ackers and White transport formula and d_{85} roughness height.

(a) Bed changes (m)

(b) Bed load transport rates (kg/m/s)
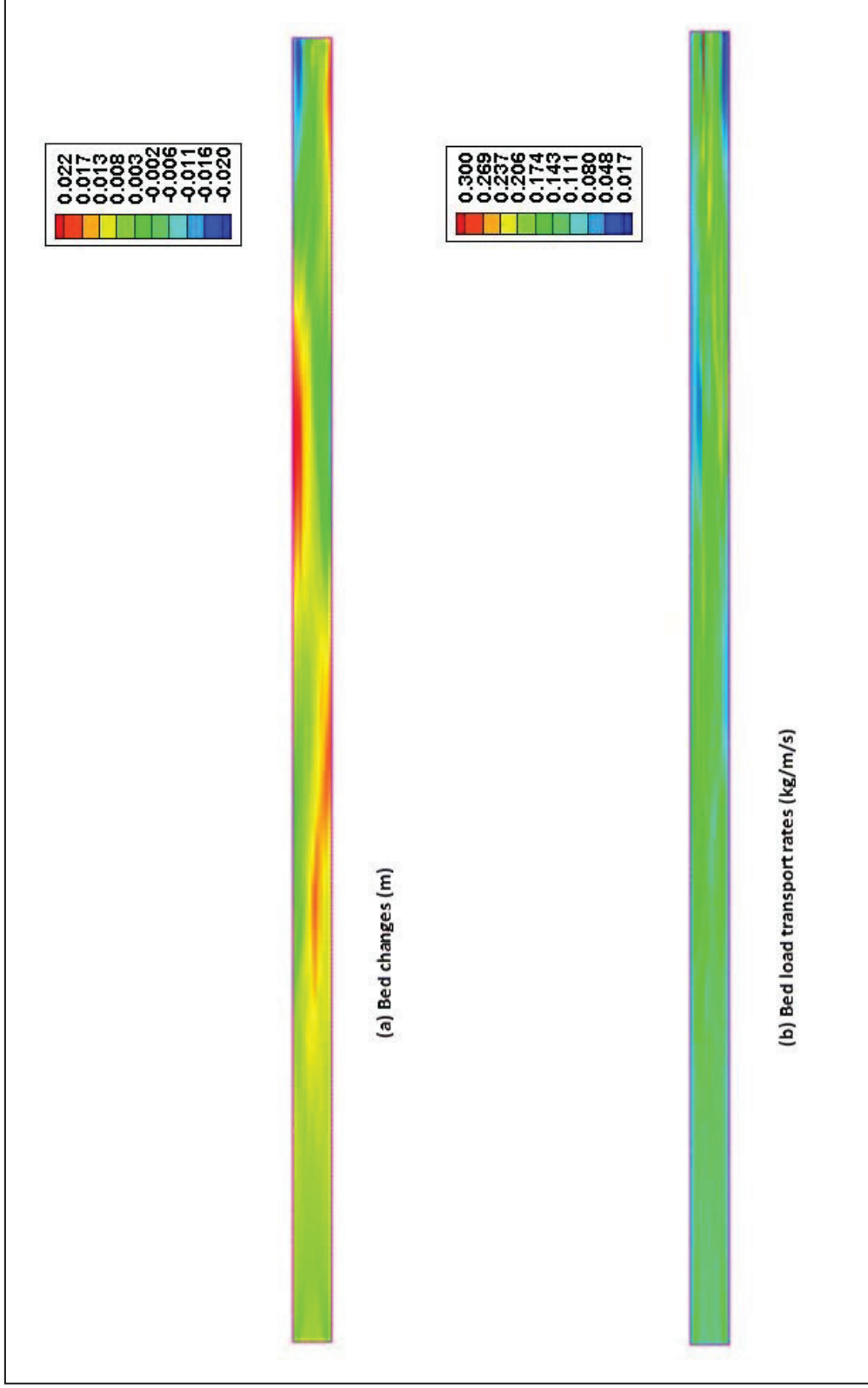
Figure 19. Sediment results, modified Ackers and White transport formula and d_{85} roughness height.

a) SEDTRA Module

With this sediment transport formula, sediment transport rates simulated by the model were almost zero. Consequently, this formula was not considered for further simulations.

b) Modified Engelund and Hansen´s formula

The results of the simulations with the modified Engelund and Hansen´s formula are similar to the ones using the SEDTRA Module; there was almost no sediment transport in this case, so no more simulations were conducted.

5.2.3 Conclusions from the first simulations

The comparison between the available formulae for sediment transport showed that the CCHE2D model with modified Ackers and White sediment transport formula and d_{85} as roughness gave a better prediction of the bed load rate in the flume, when sediment feeding is set according to what the model simulates, in a first step. Wu et al. under predicted the sediment transport rates, but it was not discarded. Additional simulations were carried out in the second part of the study using the Wu et al. formula for sediment transport and Wu and Wang formula for roughness calculation. The SEDTRA module and the modified Engelund and Hansen´s formula were found not applicable in the case of this study, so no further simulations were carried out for these methods.

Among the tested parameters, porosity had no big influence on the results. Since the calibration factor did not give major changes in the results and actually is a black box system, it was not considered any further in the simulations.

The adaptation length and the mixing layer thickness were found to be the more important parameters and were studied more in detail. The additional work and the results are presented in the next section.

5.3 Simulations with sediment input rates from the physical model

5.3.1 General procedure

As in the previous cases, all sediment simulations required initial flow conditions that were obtained running a steady flow simulation.

In all the simulations the maximum value of the sediment input curve was set to the average measured sediment rate, as described in Section 5.1. Time for reaching this sediment rate was a parameter in the analysis, but obviously not the only one tested.

The goal in this part of the study was to equal sediment input rate to average sediment rate within the flume after the 29 hours, as a condition for equilibrium.

Modified Ackers and White formula for sediment transport with a roughness height of d_{85} was, as consequence of the previous tests, chosen as the basic case to compare with, since it gave more similar transport rates than the rate measured in the physical model (see Section 5.2). Sensitivity of different parameters was tested for this basic case. However, additional simulations with Wu et al. formula were also carried out in this part.

5.3.2 Basic case

For the basic case, the following main parameters were used:

- Roughness height equal to d_{85}
- Adaptation length equal to 9.45 m
- Mixing layer equal to d_{90}

As mentioned before, modified Ackers and White formula for the sediment transport calculation was used.

The inlet boundary condition for the bed load was set to 0.139 kg/m/s to be reached in one hour, linearly.

The results are shown in Figure 20 and Figure 21. A strong deposition in the upstream part of the flume can be observed. In this area sediment accumulates in the center part over the width and causes the cells to be dried. Flow concentrations develop on the sides of the deposition zone, which increases specific discharge, velocity and shear stress. The consequence is a very high bed load transport rate in these areas.

At the downstream part of the flume, a similar situation occurs, with high deposition on the right hand side of the flume that causes very high transport rates, locally.

In most part of the flume sediment deposits, erosion takes place only in the downstream area.

In Figure 22, the sediment rate variation within the flume is shown. An average bed load transport rate of 0.169 kg/m/s was obtained, which is a consequence of the high velocities that result from the simulation. Large deviations from the average value can also be seen from Figure 22.

The simulated transport rate was higher than the sediment feeding, so equilibrium was not reached. Different parameters were changed in order to improve the accuracy of the simulation, as described in the next sections.

(a) Specific discharge (m2/s)

(b) Velocity magnitude (m/s)

(c) Total shear stress (N/m2)

Figure 20. Basic case, flow results.

(a) Bed changes (m)

(b) Bed load transport rates (kg/m/s)
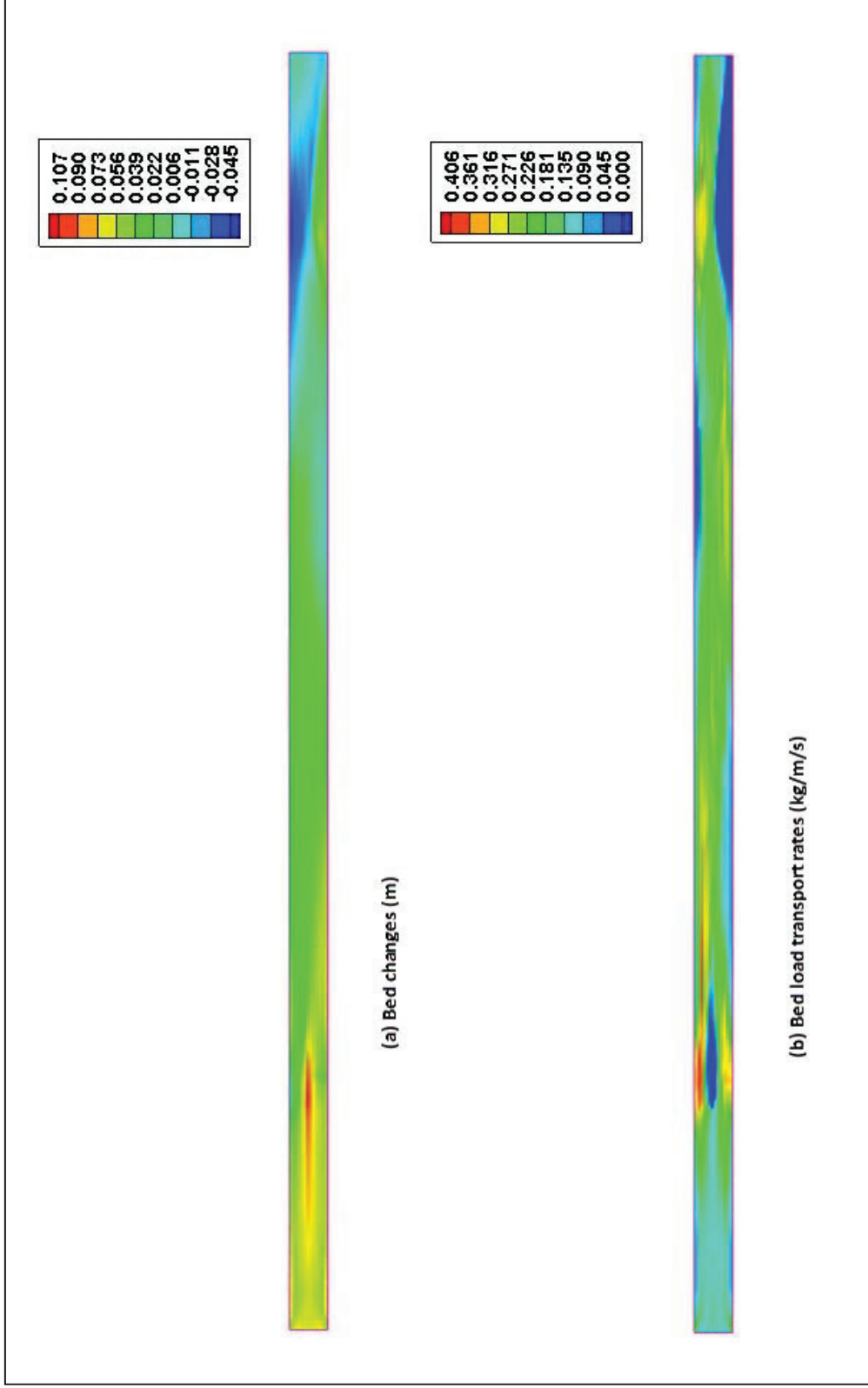
Figure 21. Basic case, sediment results.
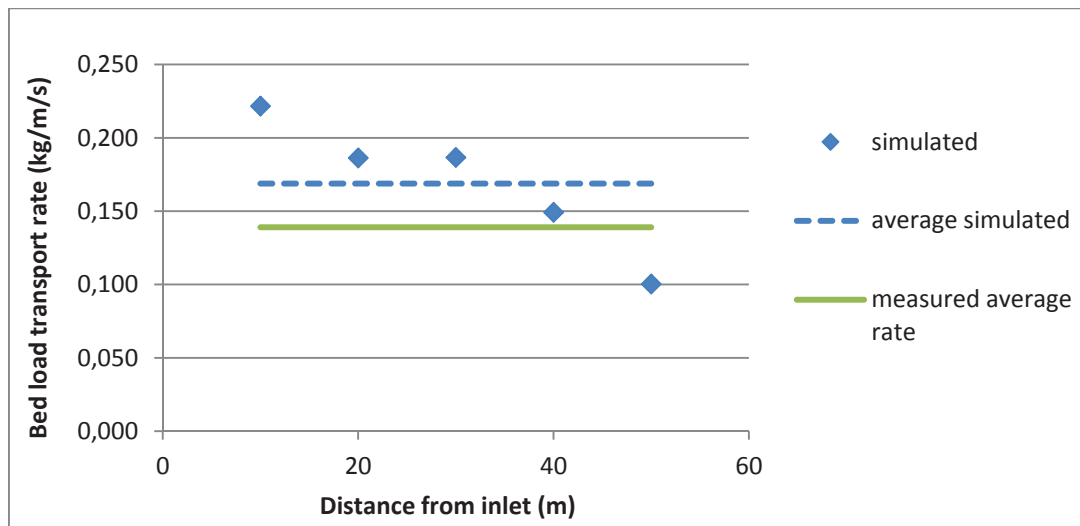
Figure 22. Basic case, bed load variation within the flume

5.3.3 Adaptation length

Adaptation length has been reported to be a very important parameter in models with the non equilibrium sediment transport approach (Vieira and Wu, 2002). Referring to the adaptation length, Wu and Vieira (2002) indicate that "Unfortunately, it has to be prescribed empirically, and considerable uncertainty exists about its prescription, as rather different values have been adopted by different researchers". Some formulae can be used for calculating this length, as described in Section 3.2.5.

As shown in Section 5.2.1 b), the adaptation length is also an important parameter for this case and it was set to the theoretical length of alternate bars, in the previous simulations. Description of sediment movement in Lanzoni (2000b) indicated that these were the predominant bed forms. For the P1309 Run, at the initial stages, regular alternate bars with 10.3 m length and 3.4 m height were formed. In the final equilibrium phase, a length of 11.7 m and a height of 2.3 m were reported. When the final bars developed, they had an irregular pattern and formed rather sporadically, only in the downstream part of the flume (Lanzoni, 2000b).

Keeping the same inlet boundary and the same parameters for all the simulations (basic case), different adaptation lengths were tested, including the length of the alternate bars in the P1309 Run and higher values, from the initial value up to the total length of the flume.

The results are shown in Table 3.

Adaptation length (m)	Average bed load transport rate (kg/m/s)
9.45	0.169
11.7	DNF*
14	0.141
15	0.136
20	0.153
25	0.200
30	0.149
40	0.136
50	0.154

*DNF means "the simulation did not finish normally "

It can be seen that the average bed load transport rate matches the average measured transport rate for an adaptation length of 14 m, with a 1.5 % difference.

Previous runs with changing values for the adaptation length showed that higher adaptation lengths gave smoother bed profiles and less bed changes in the flume. By increasing this parameter, the length of the alternate bars also increased. From these observations and the data from Table 3, it is clear that the adaptation length is a main parameter for the case in this study.

Figure 23 and Figure 24 show the variation of bed changes and bed load transport rates for varying adaptation length, respectively.

It can be observed, from Figure 23, that for an adaptation length of 14 m, the bed changes vary from -0.036 m to 0.053 m. If compared to the bed changes for the basic case, both positive and negative changes are reduced. The same pattern in deposition occurs, with the high deposition in the upstream part of the flume, concentrated in the middle of the transverse direction, and erosion at the downstream end. Alternating zones of higher deposition in the sides of the flume show up. The maximum bed load rate in this case is 0.480 kg/m/s, but the average value is 0.141 kg/m/s, as it was shown in Table 3.

For adaptation lengths in this order of magnitude (14 m), after an initial period of erosion in the entire flume, deposition starts at the upstream end. After some time, alternate bars are formed. In the cross section were the bar is formed, the flow concentrates in the part where there is no deposition, increasing specific discharge, shear stresses and transport rates. In some cases the erosion and deposition processes kept increasing until the differences in bed changes and sediment rates in the same cross section were very large and the simulation could not finish normally.
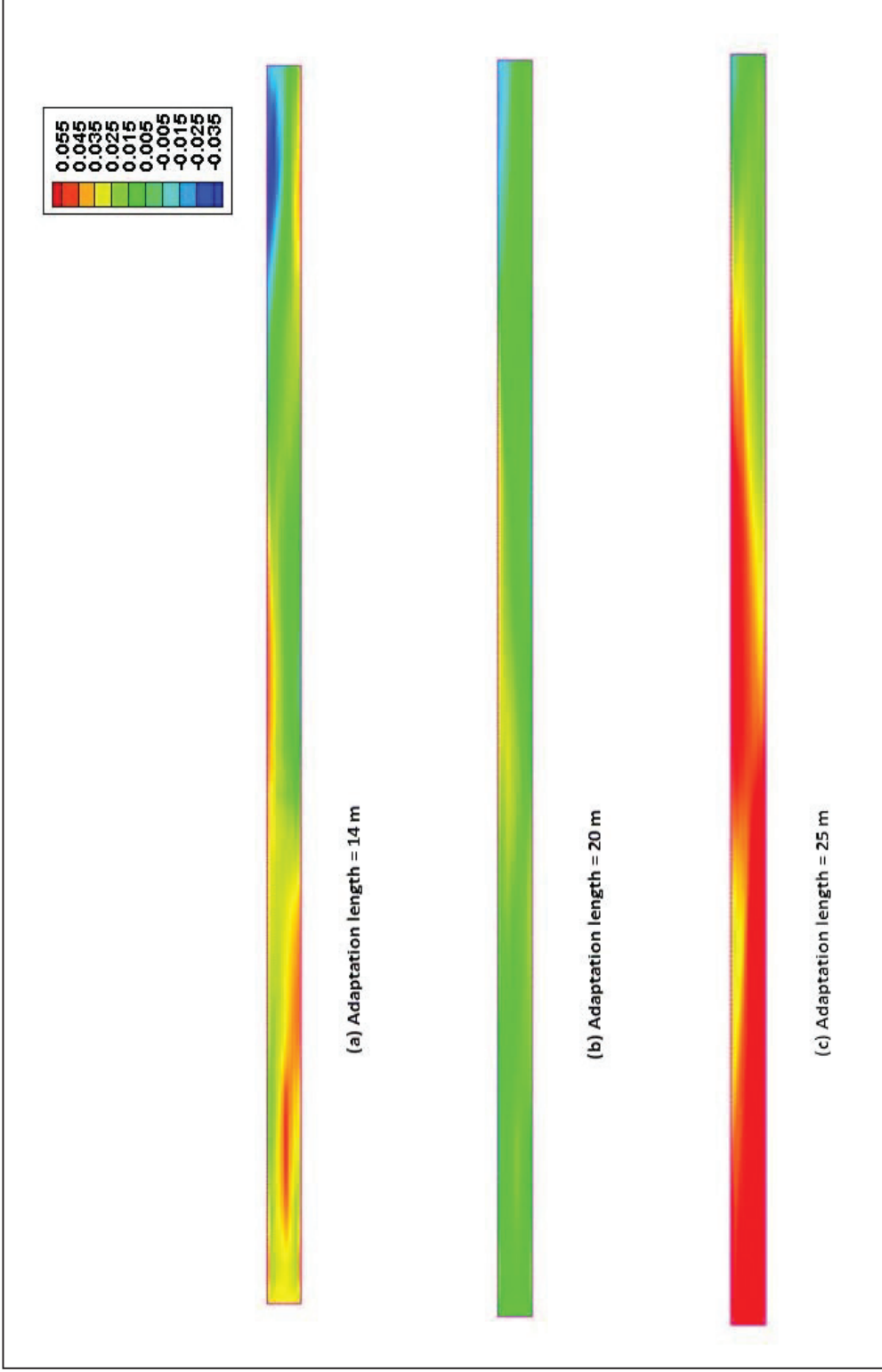
Figure 23. Bed changes for varying adaptation length.

(a) Adaptation length = 14 m

(b) Adaptation length = 20 m

(c) Adaptation length = 25 m

An adaptation length of 20 m smoothes the bed changes even more, which vary from -0.015 m to 0.031 m. In this case, the maximum deposition does not occur in the upstream part of the flume, like with smaller adaptation lengths, but at the left hand side, around the middle of the channel. The maximum bed load rate is 0.360 kg/m/s. So, increasing the adaptation length reduces the maximum local value but increases the average value of the sediment transport rate.

For an adaptation length of 25 m, the bed changes vary from -0.006 m to 0.084 m. Even when most of the flume has high depositions, there are no dried areas. There are 2 zones of maximum deposition, in alternate sides of the flume. The bed load rate varies from 0.060 kg/m/s to 0.426 kg/m/s. The high values coincide with very high shear stresses.

With an adaptation length as high as 40 m (not shown in the figures), the bed change pattern varies dramatically, if compared to lower adaptation lengths. Higher depositions take place at the upstream part of the flume and decrease over the length, from 0.058 m to zero, with the main variation in the longitudinal axis.

Figure 25 shows the variation of bed load transport rates within the flume as a function of the adaptation length.

It can be observed that increasing the adaptation length from the initial value to 14 m or 15 m gives less variation of the bed load rate within the flume and a closer match to the laboratory results. However, increasing the adaptation length further gives very high transport rates which deviate from the measured value. Setting up this length to the order of the flume length tends to make the bed forms disappear and to eliminate high variations of the bed load transport rates within the flume. Also, the average rate is smaller than the sediment input rate, which is explained by the fact that there is deposition in the entire flume.

From all the above, it was confirmed that what happens in the flume is very sensitive to the adaptation length.

(a) Adaptation length = 14 m

(b) Adaptation length = 20 m

(c) Adaptation length = 25 m
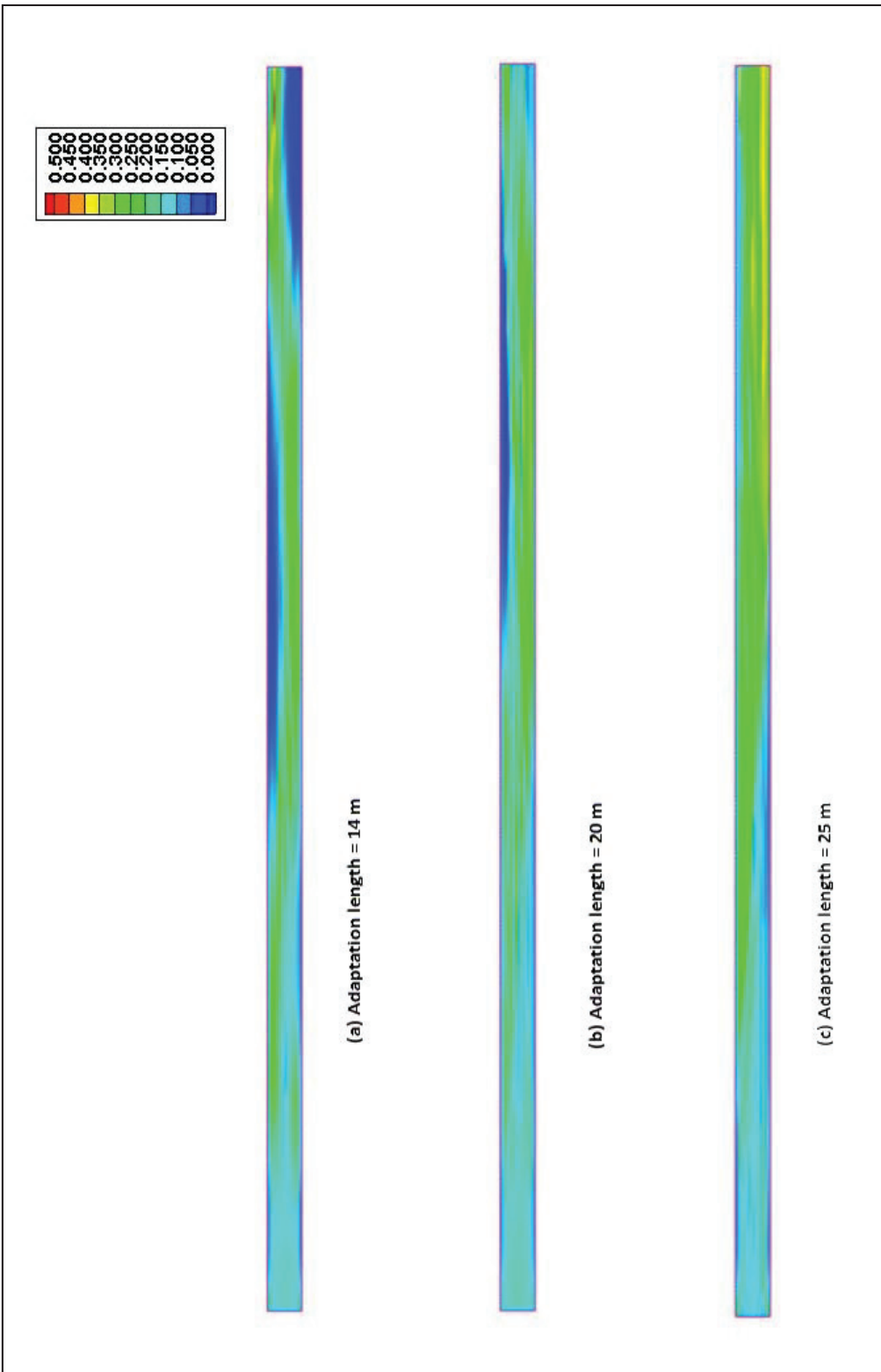
Figure 24. Bed load transport rates with varying adaptation length.
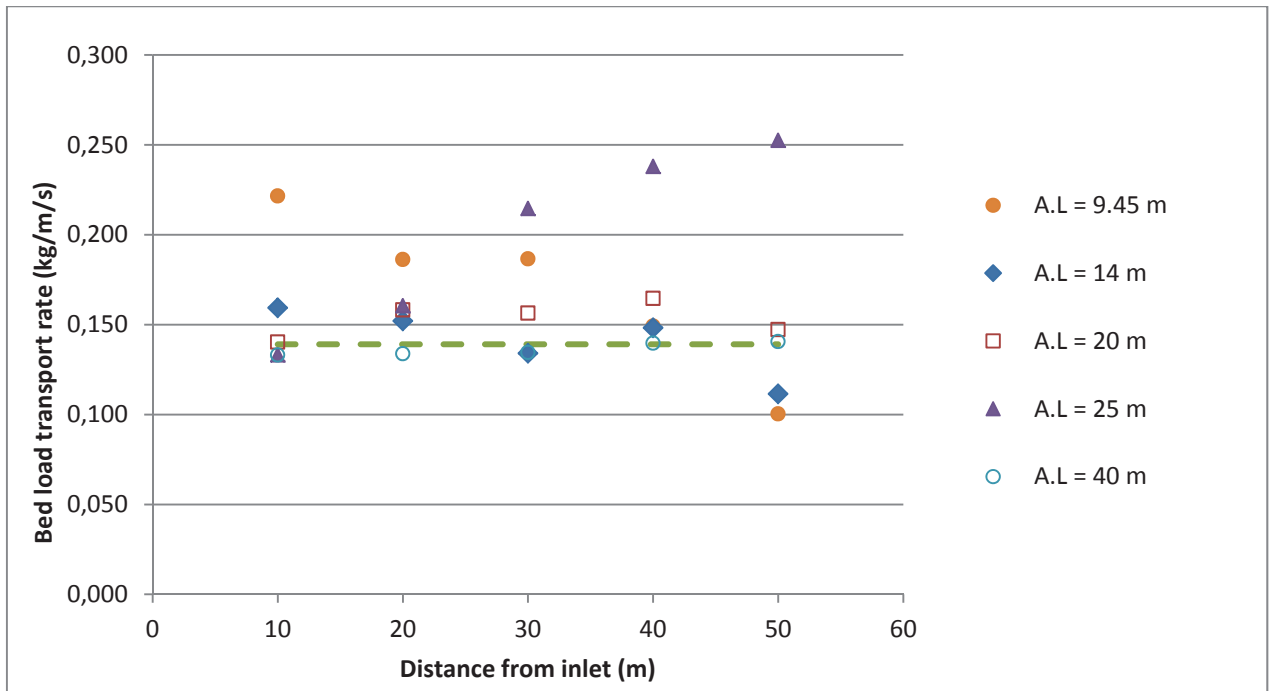
Figure 25. Sediment transport rates along the flume for different adaptation lengths. All cases with 4 hour sediment input time.

5.3.4   Time for reaching sediment input maximum

In the experiment, the sediment input in kg/m/s changed over time. An average measured sediment transport rate was reported, but there is no information available regarding the moment this value was reached. Furthermore, there is no information about maximum values that were reached in the runs. However, to simplify the inlet boundary conditions for the simulations, it was assumed that a maximum value is reached after a certain time, with a linear variation. Changes of the time for reaching the maximum value were made, keeping all the other parameters constant.

An adaptation length of 14 m was used to measure sensitivity of input conditions. The results are shown in Table 4. The difference between the input and the output, in percentage, is also shown in the table.

Table 4. Bed load transport rates for different times in reaching maximum sediment input.

Time (hr)	Average bed load transport rate (kg/m/s)	Difference between simulation and measured rates (%)
1	0.141	1.5
2	0.202	45.3
3	0.164	18.0
4	DNF*	-

*DNF means "the simulation did not finish normally "

From the results can be observed that the sediment transport rates are very sensitive to the sediment feeding in the flume. The one hour period for reaching maximum value is still the best assumption for replicating the experiment in the laboratory.

Figure 26 and Figure 27 show the bed changes and sediment transport rates for different sediment input times.

The general pattern of bed changes did not change, as it can be observed form Figure 26. There was deposition in the upper part and in the left hand side of the middle part of the flume, in all cases. Increasing the sediment input time increased the total area where erosion took place in the flume. However, a 1 hour input gives much higher erosion depths in a local scale, than the 2 hour or the 3 hour case.

For the 2 hour case, deposition in most of the flume and a higher average bed load transport rate occur at the same time. This situation looks unrealistic, which may indicate that the combination of these parameters is not correct.

The 2 hour case showed that, contrarily to the other cases, deposition in most of the flume and a higher average bed load transport rate occur at the same time. This situation looks unrealistic, which may indicate that the combination of these parameters is not correct.

For the 1 hour case, dried areas appear and in consequence, there are zones with bed load transport rates equal to zero. For the other cases, this was not observed.

In general, it was found that the time for reaching sediment input maximum was important information for the sediment simulations.

(a) Time for reaching maximum sediment input = 1 hour

(b) Time for reaching maximum sediment input = 2 hours

(c) Time for reaching maximum sediment input = 3 hours
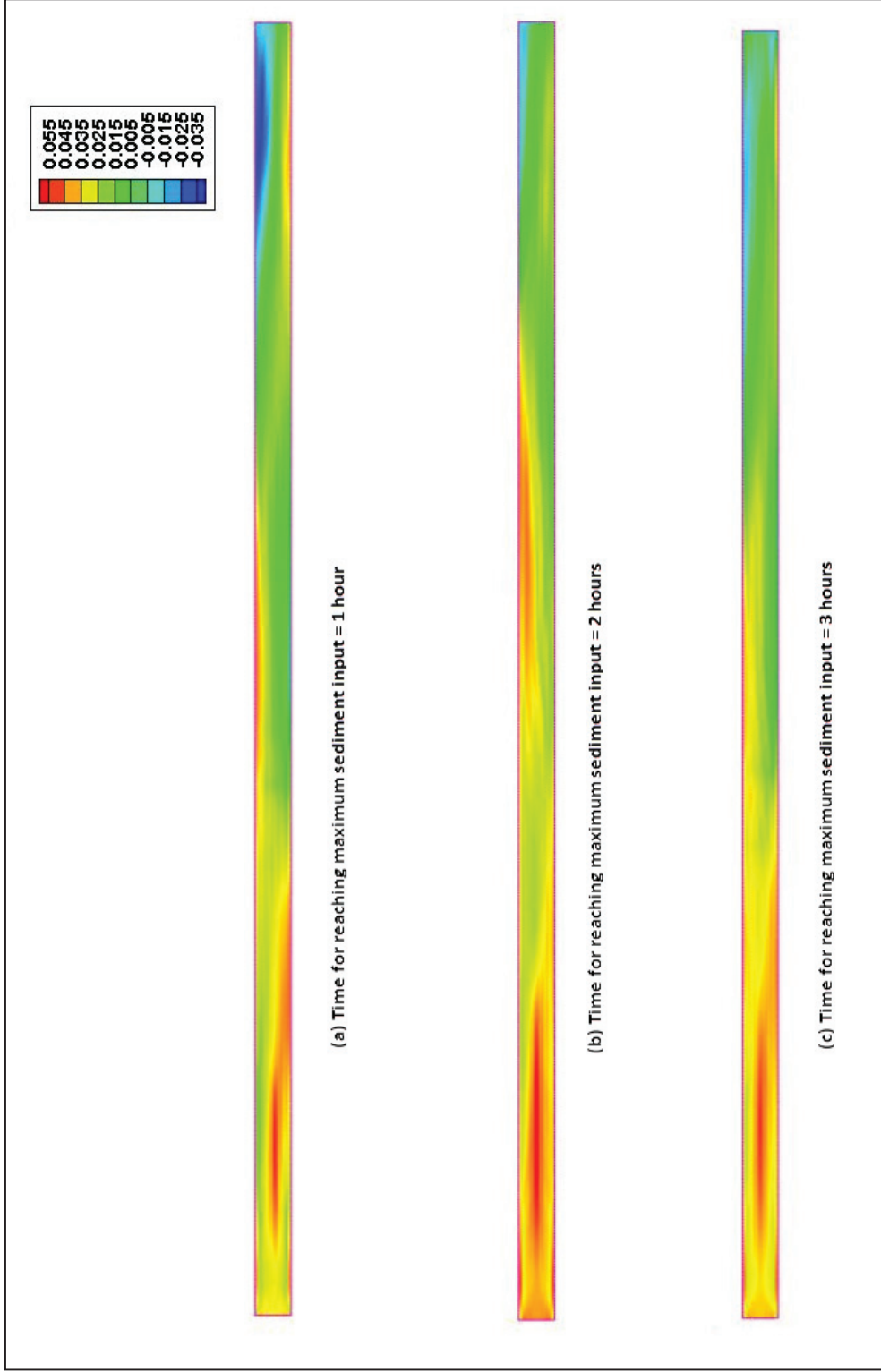
Figure 26. Bed changes for varying input time.

(a) Time for reaching maximum sediment input = 1 hour

(b) Time for reaching maximum sediment input = 2 hours

(c) Time for reaching maximum sediment input = 3 hours
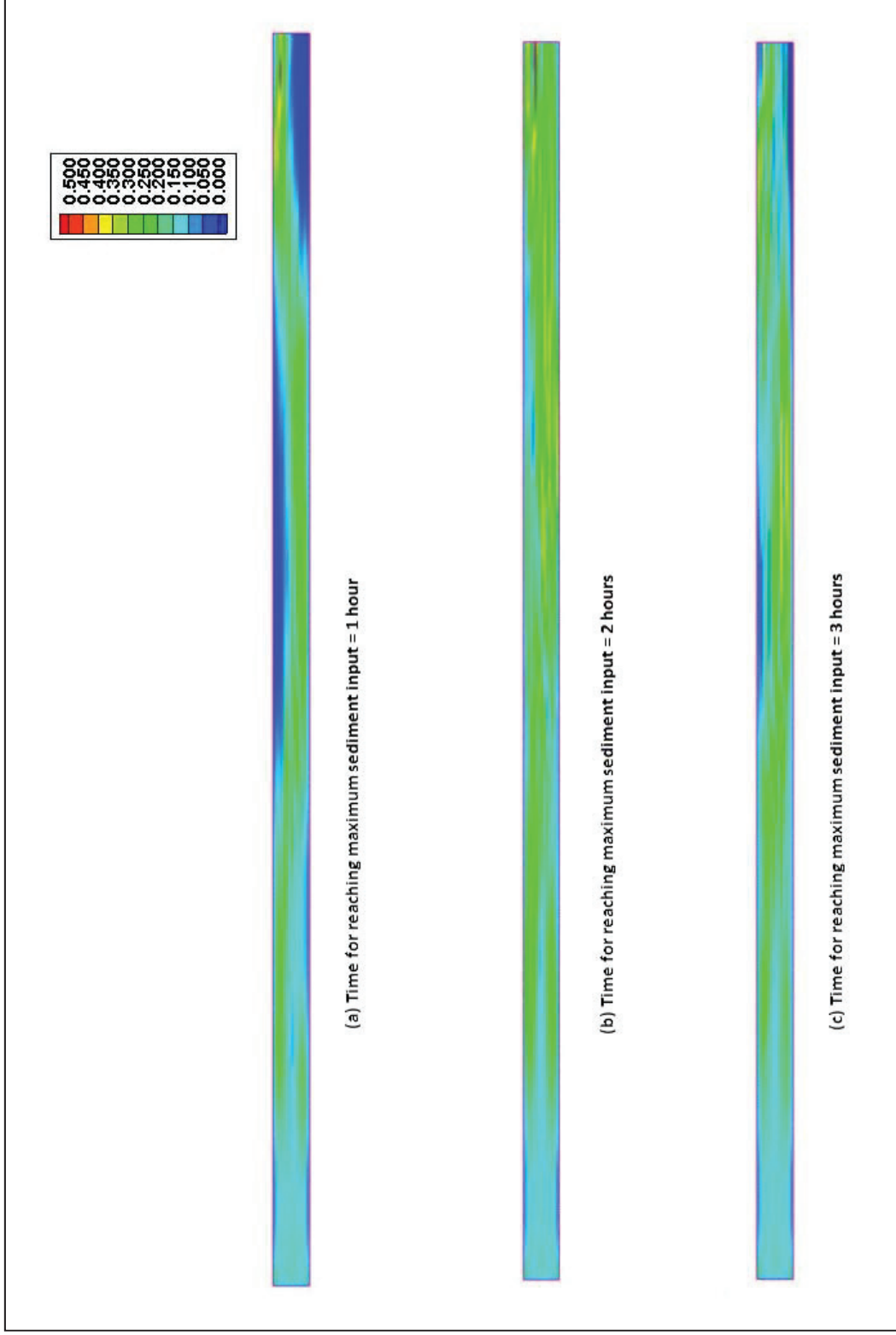
Figure 27. Bed load transport rates for varying input time.

Additional simulations were set up to see the combined effect of sediment input time and adaptation length. Figure 28 shows the results of the simulations.
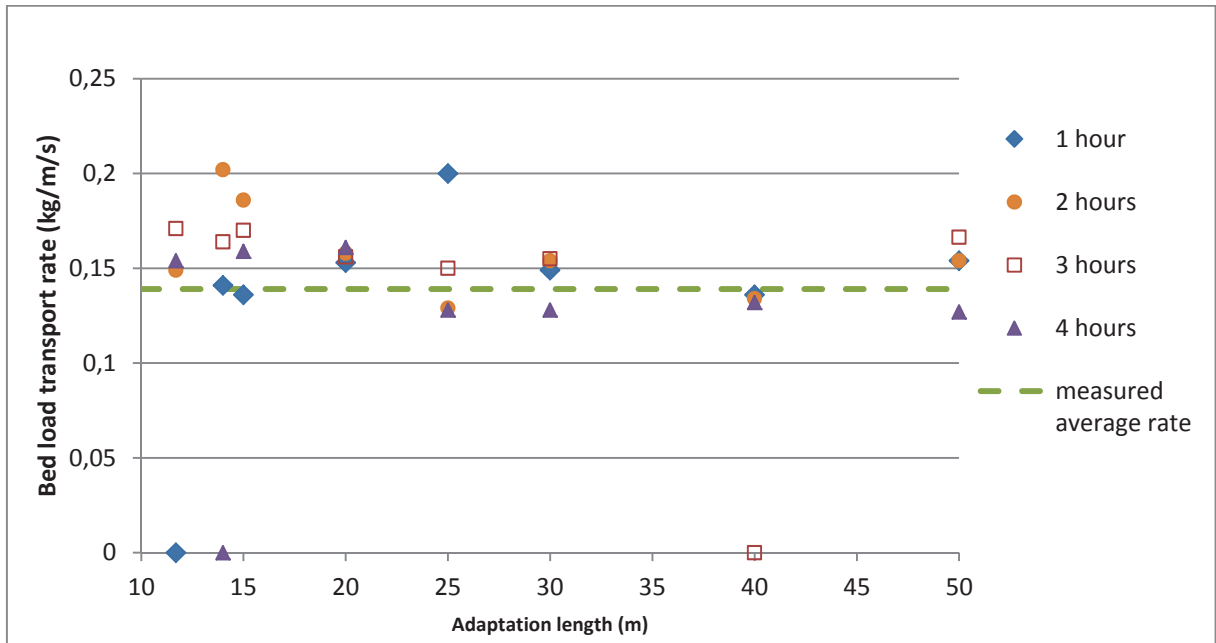
Figure 28. Effect of input time and adaptation lengths on average bed load transport rates.

From this figure it can be observed that there is no general trend for the transport rates, but for 2 and 3 hours, the higher transport rates are obtained for smaller adaptation lengths. Higher bed changes were also seen from the simulations, and consequently more cases with instability. For adaptation lengths of 20 m and 40 m, the bed load transport rates were nearly independent of the time for reaching maximum sediment input.

In general, higher adaptation lengths improved stability, but as described in 5.3.3, high adaptation lengths smooth out the bed levels and may change the pattern dramatically.

5.3.5 Mixing layer

Keeping the adaptation length equal to 14 m and a one hour sediment input time, the mixing layer was changed, in order to assess the sensitivity of this parameter.

According to Wu and Vieira (2002), the mixing layer should be set as the maximum value between $2d_{50}$ and half of the dune height. As mentioned in Section 2.1, the dune height can vary between 0.1 and 0.5 times the flow depth. For the Lanzoni case, it would be in a range between 0.005 m tand 0.025 m. The value of $2d_{50}$ would be for this case 0.000524 m.

These values were tested and the results are shown in Table 5.

Table 5. Sensitivity of the mixing layer thickness.

Thickness of the mixing layer (m)	Average bed load transport rate (kg/m/s)
$2d_{50}$	0.127
0.0025	0.142
d_{90}	0.141
0.0125	0.158

It can be observed that the use of d_{90} in the model gave an average bed load transport rate closer to the average value measured in the physical model, which confirmed the assumption in previous simulations. In this case, d_{90} is very close to the lower limit for the dune height. In general, higher thickness of mixing layer gave higher transport rates.

Figure 29 and Figure 30 show the bed changes and the bed load transport rates, respectively, when changing mixing layers thickness.

For a mixing layer thickness of $2d_{50}$, the bed changes varied from -0.048 m to 0.058 m, which were in the order of the flow depth. Alternate bars were formed. Bed load transport rates varied from zero to 0.386 kg/m/s.

Increasing the mixing layer to the lower limit for dune height (0.0025 m) decreased the bed changes, which were in the range of -0.017 m to 0.050 m. In this case, alternate bars were formed and bed load transport rates varied from almost zero to 0.309 kg/m/s.

Finally, the upper limit of the dune height (0.0125 m) made the bed changes vary between -0.005 m and 0.024 m. Bed load transport rates varied between 0.094 kg/m/s and 0.236 kg/m/s.

It could be seen that with increasing mixing layer thickness the bed changes reduce. Erosion processes are more sensitive to this parameter than deposition processes, since there was almost no erosion when the thickness was highest. Deposition decreased in that case almost by half.

(a) Mixing layer 2d50

(b) Mixing layer 0.0025

(c) Mixing layer 0.0125
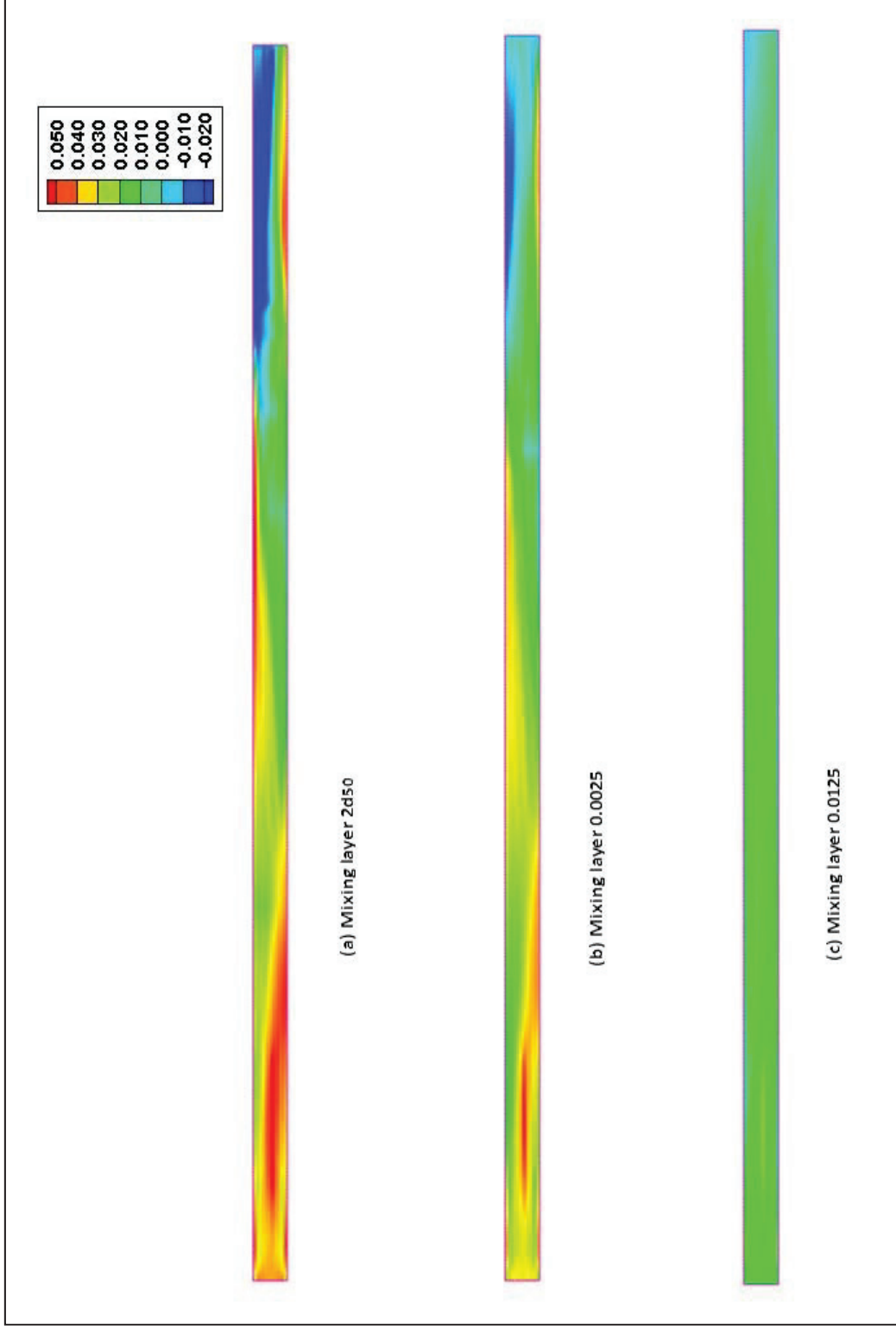
Figure 29. Bed changes for varying mixing layer thickness.
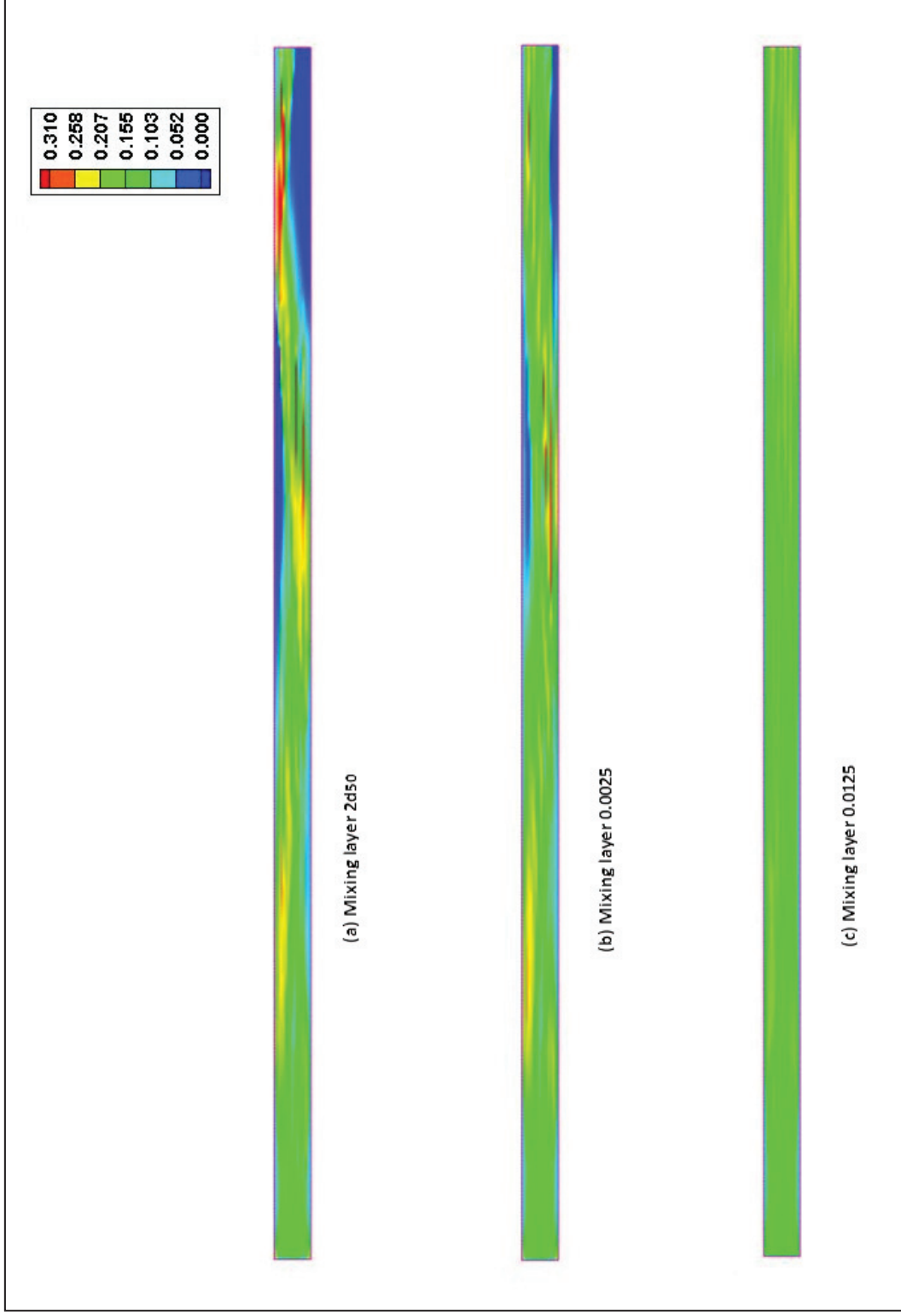
Figure 30. Bed load transport rates for varying mixing layer thickness.

(a) Mixing layer 2d50

(b) Mixing layer 0.0025

(c) Mixing layer 0.0125

For the highest mixing layer thickness that was tested, local differences between bed load rates within the flume decreased, although in average, the rate was higher. This was due to the fact that no dried cells showed up in the downstream part of the flume, so there was no flow concentration with increasing velocities. Local bed load transport rates were higher, the lower the thickness was.

The mixing layer thickness proved to be another important parameter in sediment simulations.

5.3.6 Wu et al. formula

Even though the modified Ackers and White formula was chosen in Section 5.2 as the best equation to represent the bed load transport rate in the Lanzoni case, further simulations with Wu et al. transport formula were conducted, using the measured average sediment rate. In contrast to the basic case with modified Ackers and White, the bed roughness was calculated from Wu and Wang formula (Section 2.2.2). Adaptation length and mixing layer thickness, which proved to be very important parameters, were varied in order to find out if the results with these formulae could be improved. In addition the inlet boundary condition, meaning time for reaching maximum rate of sediment transport was also tested. The results are shown in Tables 6, 7 and 8.

When changing adaptation length, all other parameters were kept constant. An increase in bed load transport rate was obtained when adaptation length was increased. Although there were significant increases, in the range of 11 to 30%, the resulting values of the simulations were very low compared the value from the laboratory.

Table 6. Sensitivity to adaptation length, Wu et al. formula

Adaptation length (m)	Average bed load transport rate (kg/m/s)
9.45	0.061
15	0.069
25	0.079

Table 7. Sensitivity to mixing layer, Wu et al. formula

Mixing layer (m)	Average bed load transport rate (kg/m/s)
$2d_{50}$	DNF
d_{90}	0.061
$2d_{90}$	0.073
0.025	0.068

*DNF means "the simulation did not finish normally "

The mixing layer thickness was varied keeping the adaptation length equal to 9.45 m and reaching a sediment maximum rate in one hour. Higher mixing layer thickness gave higher sediment transport rates, but as seen before, still under predicted the measured values in the physical model.

Table 8. Sensitivity to inlet boundary condition, Wu et al. formula

Time for reaching maximum sediment (hr)	Average bed load transport rate (kg/m/s)
1	0.061
2	0.057
3	0.069

There were also some changes in the bed load transport rate, when changing the time for reaching sediment maximum rate. However, the results were more sensitive to the sediment parameters than to the time for reaching sediment maximum rate, in this case.

Figure 31 and Figure 32 show the results of the simulations for this case. It can be observed that sediments deposit when they enter the flume, reaching almost 0.2 m of height, which seems unrealistic, but it may be explained by the fact that transport capacity with Wu et al. is not sufficient when 0.139 kg/m/s are fed.

(a) Specific discharge (m2/s)

(b) Velocity magnitude (m/s)

(c) Total shear stress (N/m2)
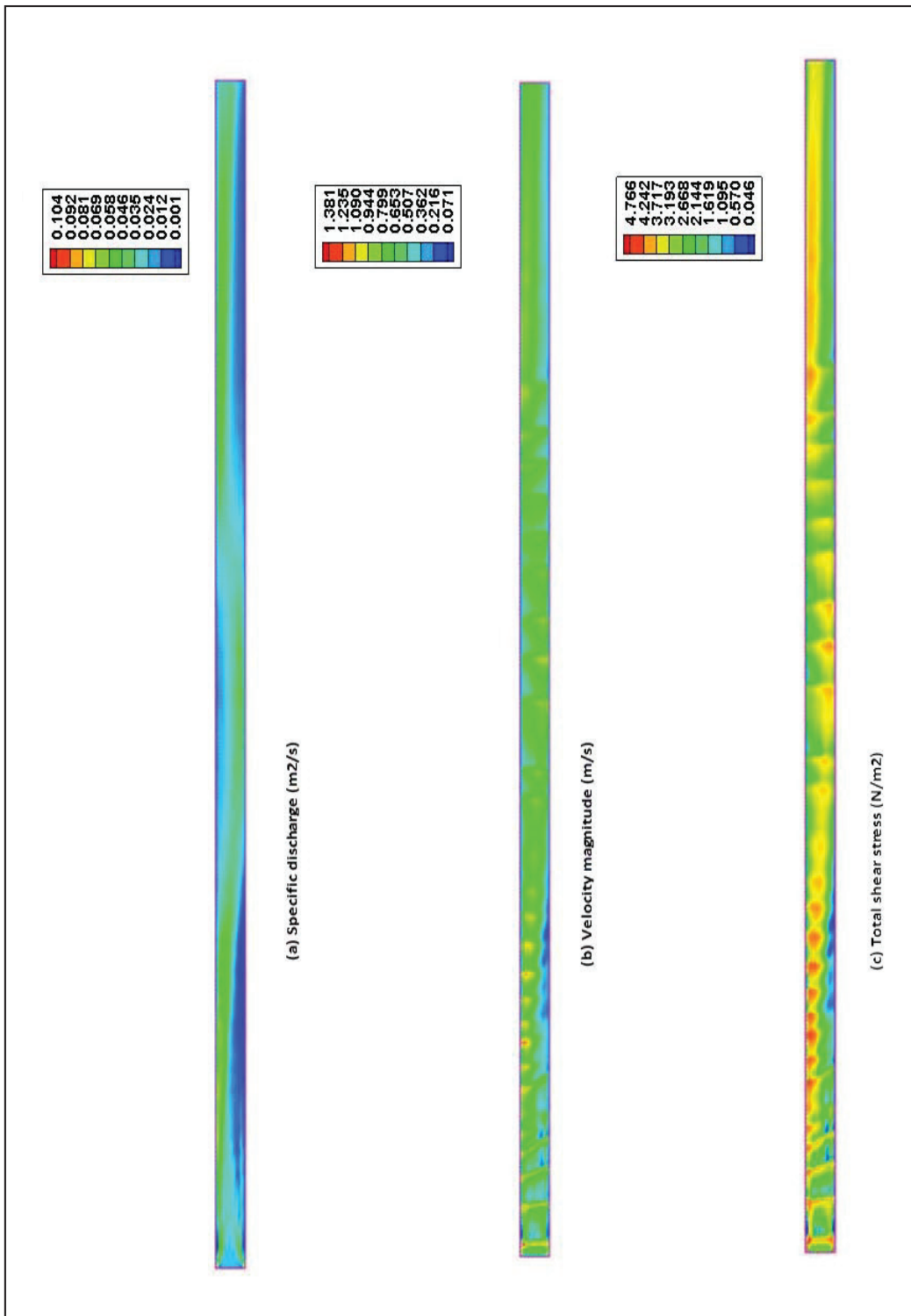
Figure 31. Flow results, Wu et al. formula with 0.139 kg/m/s.

(a) Bed changes (m)

(b) Bed load transport rates (kg/m/s)
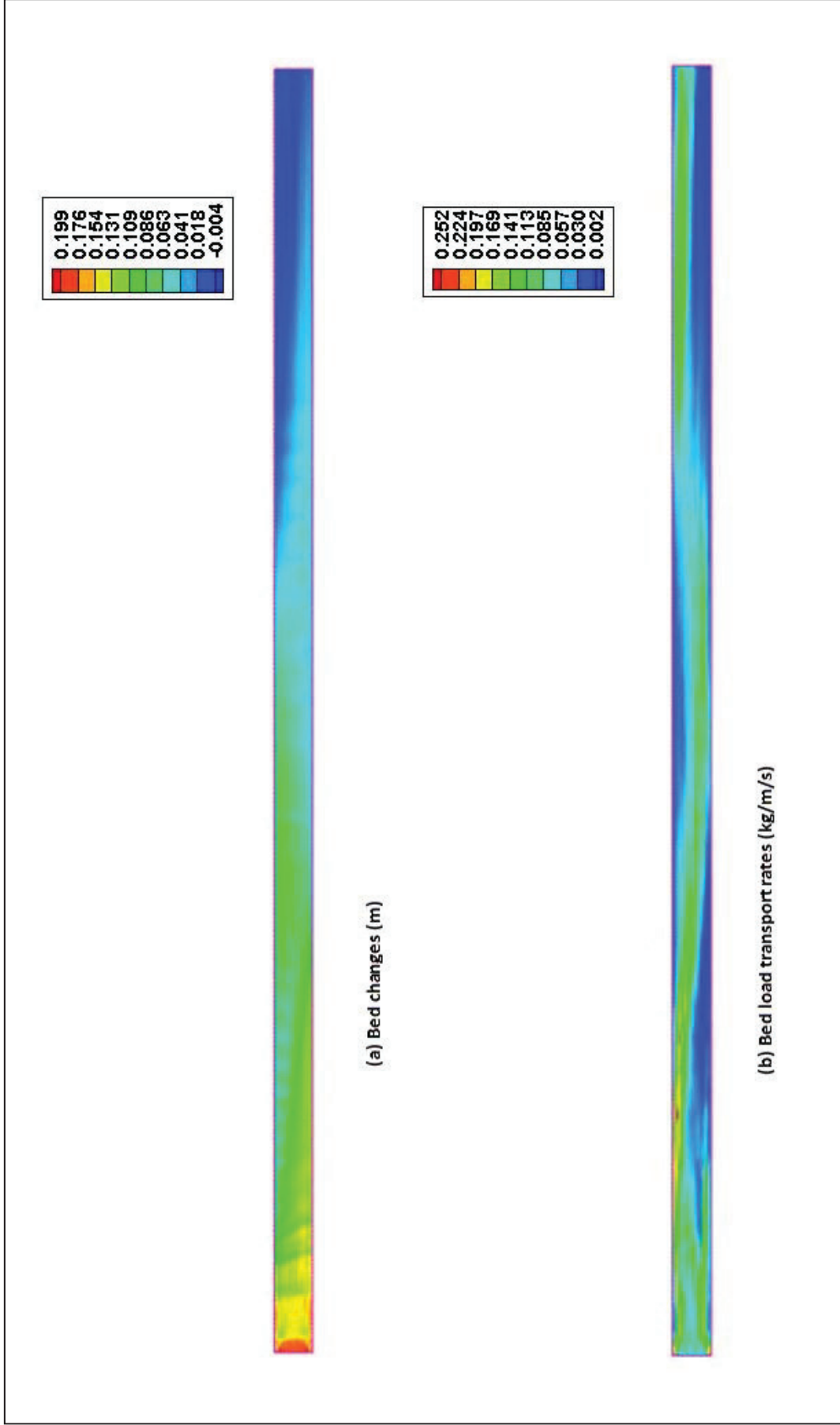
Figure 32. Sediment results, Wu et al. formula with 0.139 kg/m/s.

5.3.7 Longitudinal profiles

Although the goal in this study was not to replicate the occurring bed forms, longitudinal profiles were extracted from the simulation results and are shown in Figure 33. The longitudinal profiles from the numerical simulation were taken at the same location that the ones from the physical model, which means at a distance 0.2 m from the side walls (Lanzoni,2000b).

In the physical model, during the equilibrium phase, at the end of the run, irregular bars were formed, mostly in the downstream part of the flume. The height of the bars tended to increase as the bars migrated downstream and they were lower that the initial bars, formed at the beginning of the experiment.
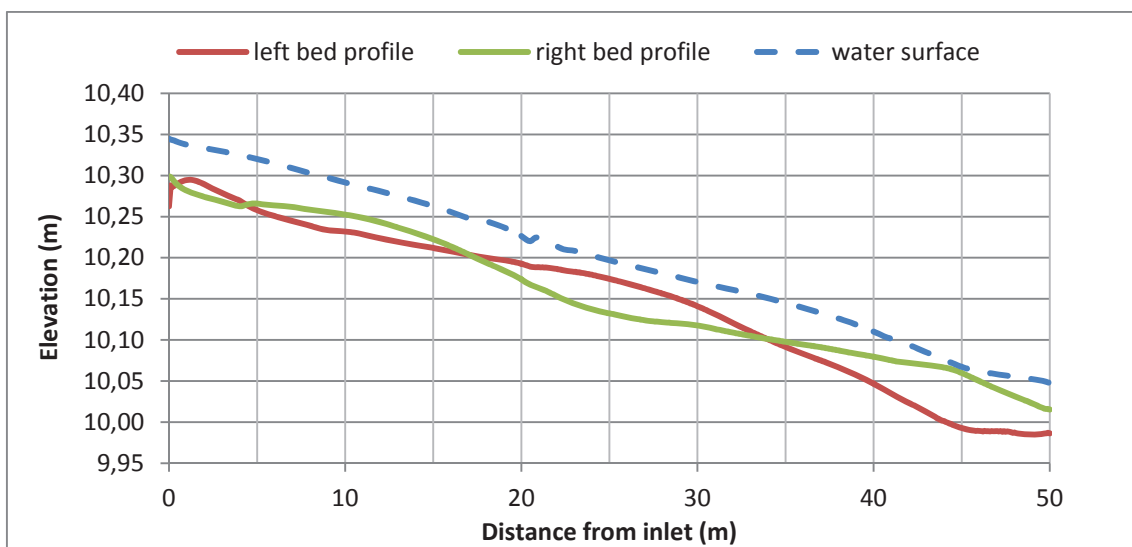
Figure 33. Longitudinal profiles for the optimum case.

In the numerical simulation, alternate bars were formed as well. However, they did not match the pattern obtained in the physical model. On one side, they formed over all the length of the flume whereas in the laboratory, bed forms showed up, as described before, at the end of the flume, during the equilibrium phase. On the other side, the length of the bars do not match neither the theoretical values nor the values measured during the experiment, they are larger. Nevertheless, the bar heights tendency to increase in the downstream direction is also found in the numerical model, as it can be observed in Figure 33, at 10 m, 25 m and 45 m from the inlet.

There is no information about the water surface in the physical model; it is shown in Figure 33 only for illustrative purposes.

Differences between the right profile and the left profile are shown in Figure 34. In the physical model the differences between the right and the left bed levels in the flume were in the order of magnitude of about half of the flow depth, while in the numerical

model, it was in the order of the flow depth. So the simulated values were much higher than the measured values.

From Figure 34 it can also be seen that the simulated length of the bars is much larger than the bars which formed in the laboratory. However, the rising trend in the amplitude of the bed differences observed in the physical model was replicated by the numerical model.
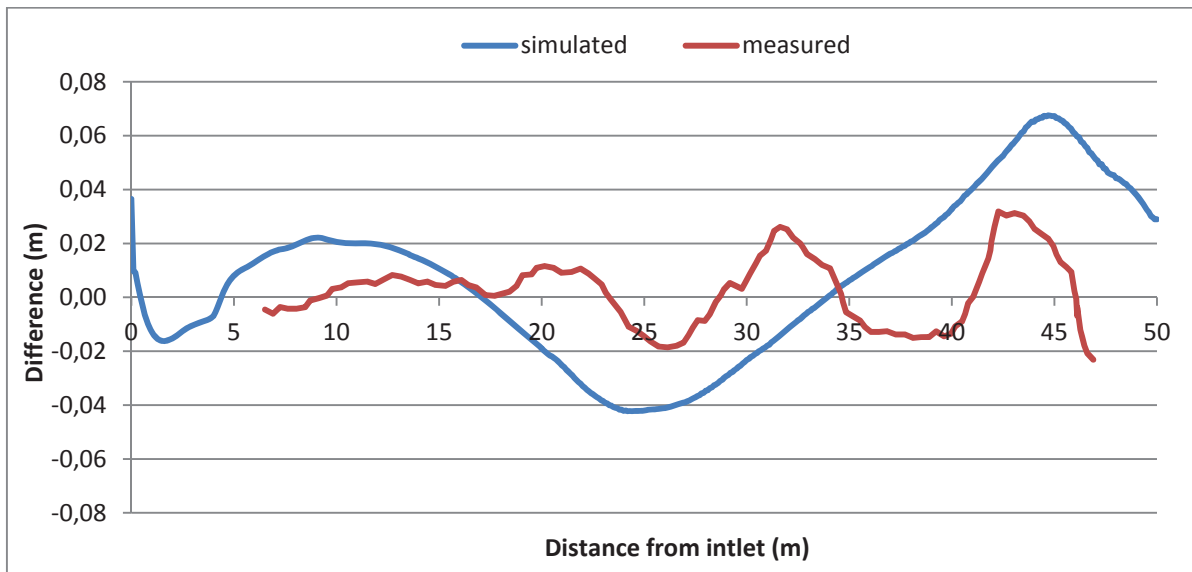
Figure 34. Difference between right profile and left profile, simulated and measured, for the optimum case.

6 Discussion

In this section, a discussion about the numerical modelling process and its results is presented. First, a discussion about how applicable the different sediment transport equations available in the CCHE2D model are to the studied case is described. Next, the parameter sensitivity analyses are presented, followed by a discussion on the boundary conditions. Additionally, comments on the longitudinal profiles are presented. Finally, the uncertainties in the modelling (setting up the model and the model itself) are listed, together with how they were handled in this study.

Sediment transport equations

From the four sediment transport formulae available in the CCHE2D, the modified Ackers and White was the best formula for replicating the average measured sediment transport rate in the Lanzoni case.

Large differences between the results from each formula were found. The Wu et al. formula gave from 20 to 50 % of the measured average bed load transport rate. The SEDTRA module and the Engelund and Hansen formula were not able to represent the sediment transport within the flume at all, since the calculated sediment transport rates were almost zero. However, such variations in the transport rates were not unexpected, since high differences between different formulae have been reported before (U.S. Bureau of Reclamation, 2006).

Particle sizes in the sediment mixture of the Lanzoni case were in the range of 0.079 mm to 5.8 mm (d_{50}=0.262 mm and d_{90}=3.21 mm). The Ackers and White formula was modified based on laboratory experiments with non-uniform bed material, with d_{50} at the beginning of the experiment in the range of 1.8 mm to 4.0 mm and standard deviations from 1.71 to 2.30 (Proffit and Sutherland, 1983). The mean velocity in the flume, for developing the modified Ackers and White formula, varied from 0.65 m/s to 1.04 m/s and the slope was 0.003. Although these flow conditions may be similar to the Lanzoni case, the bed material for coming up with the formula modification was coarser. However, in this study the modified Ackers and White formula predicted the bed load transport rate accurately.

There is a good agreement between the results obtained by the numerical model by using the modified Ackers and White formula and the measured transport rates. Brownlie (1981) concluded in the same way in his study. This author tested different formulae over a large data base from flume experiments and field measurements. Among the other tested equations in Brownlie´s study were Engelund and Hansen, Laursen and Yang. He found that Ackers and White performed best for the laboratory

data, whereas Engelund and Hansen performed better for the field data. However, the modifications for including non-uniform sediment in the formulae were not incorporated in the study conducted by Brownlie (1981).

The particle size range for the Lanzoni case is among the range for applicability of the SEDTRA module formulae (0.01 mm to 50 mm). With this method, the sizes are corrected with an equation that depends on the bimodality parameter B, for taking the hiding and exposure effects into account. In previous versions of CCHE2D, the parameter B was a user-specified parameter (the recommended values were between 1 and 1.43), but in the latest version which was used for this thesis, B is not an input parameter anymore (Wu, 2001). However for the sediment mixture used in the physical model in the Lanzoni case, B was equal to 5.7, which differs highly from the recommended values and probably from the one used in CCHE2D. Consequently, the corrections on the sizes used to calculate critical shear stress would give higher or lower values, depending of the ratio between the diameter of a size class and the mean diameter. This could be a reason why the sediment transport simulations did not work. Additionally, according to Wu (2008), each formula has different criteria for motion, so the use of non-uniform material leads to sharp transitions between the results for each diameter. Therefore, SEDTRA module may work better with uniform material.

Although Wu et al. equation was calibrated with laboratory data and field data, with grain sizes between 0.073 mm and 64 mm (Wu, 2001), they do not seem applicable for this case. Wu et al. formula under predicted transport rates in all the simulations. In the first case, with sediment input calculated with the model for one hour, it gave only about 20 % of the measured transport rate. When the sediment input was increased to 0.139 kg/m/s, the simulated transport rate also increased, but still 50 % under the measured value.

When using the Wu et al. sediment transport formula, the Wu and Wang roughness formula and the sediment input equal to 0.139 kg/m/s, the sediment built up at the upstream part of the flume, up to 0.20 m, which indicates that the calculated transport capacity was not enough for the flow conditions occurring in the physical model.

The modified Ackers and White formula is a bed material load equation (total load equation), while Wu et al. is a bed load equation. Since bed material load is the sum of bed load and suspended load, and in the Lanzoni case the main transport mode was bed load, comparing results from both formulae is possible.

Parameter sensitivity analyses

The first parameter that was tested was the roughness height. This is a very important parameter because it affects the flow field and the sediment transport as well.

Simulations with roughness heights related to a typical grain size, like d_{85}, d_{90} or $2d_{90}$ were conducted and it was found that the lower the roughness height, the higher the transport rate. This could be explained by the fact that the roughness affects the flow field, which in turn affects the sediment simulation. For example, smaller roughness heights produced less flow depths, higher velocities and higher bed shear stresses in the steady flow calculation and hence in the initial conditions for the sediment simulation. Higher bed shear stresses increase the sediment transport.

When a formula which combines bed form and grain size contributions was used for roughness calculation, van Rijn gave a much lower transport rate than the Wu and Wang formula. Van Rijn´s bed roughness calculation is based on dune formation, and this type of bed from did not develop in the physical model. Actually, Lanzoni (2000b) reported that the non-uniform sediment mixture inhibited the development of ripples and dunes in the flume, which allowed the bed resistance to be lower. This may be the reason why van Rijn´s formula was not suitable for the case used in this study. On the other hand, Wu and Wang´s formula gave more comparable results than the ones with a roughness height equal to d_{85} or d_{90}.

A roughness height equal to d_{85} was finally chosen as to better represent the bed load transport rate in the flume. This agrees with the observations from the physical model, where flow resistance was accurately predicted by using the value of the coarse mode sediment mixture as roughness height, in this case it corresponded to d_{85}. It also agrees with the conclusions of numerical simulations made by Francalanci et. al (2012), where the overall flow resistance was slightly affected by the presence of alternate bars.

Among the other parameters that were tested, the adaptation length and the mixing layer thickness were found to be relevant for this case. Results were very sensitive to these parameters.

In general, with the modified Ackers and White formula used for the simulations, there was not an evident trend in variations of the average bed load transport rate in the flume, with the adaptation length. Trends were more easily observed in the bed changes or the bed profiles. Higher adaptation lengths smoothed the bed profiles and increased the alternate bar lengths, when they showed up. Differences in the bed changes were observed depending on the order of magnitude of the adaptation length. When this parameter was in the order of the length of the flume, the bed forms disappeared and differences in the bed load transport within the flume were fairly small, with no local variations. In the simulations with adaptation lengths in the order of the predominant bed from, as recommended by Wu (2008), alternate bars developed. In this case, local variations of bed load rates, together with the magnitude of the bed changes were very sensitive to the adaptation length. Single simulations did

not finish normally more often for smaller adaptation lengths, so increasing the adaptation length increased the stability in the model.

When Wu et al.'s formula was used in the simulations, a trend was observed, the higher the adaptation length, the higher the average bed load transport rate. However, less parameter values were tested compared to the number of modified Ackers and White simulations, due to the fact that Wu et al.'s formula extremely under predicted the sediment transport rate.

Finally, an adaptation length equal to 14 m was selected as the best value for this parameter in the simulation of the Lanzoni case.

The bed load transport rates were also very sensitive to the thickness of the mixing layer. Smaller thickness gave less average bed load transport rates. Bed changes were very sensitive to this parameter as well. The thicker the mixing layer, the smaller the bed changes, with erosion processes proven to be more sensitive than deposition processes.

A mixing layer thickness equal to d_{90} was chosen as the final value for this parameter.

Adaptation length and mixing layer thickness were found to be two main parameters in this case. But this is not always the situation, sensitivity depends on the sediment transport process that is being studied (Wu, 2008). Sensitivity analysis for a degradation study and an aggradation study, were carried out by Wu and Vieira (2002). While the former showed that degradation was not sensitive to adaptation length but it was to mixing layer, the aggradation study concluded that neither one of them was important in the simulation. In the degradation study, two of the values of adaptation length that were tested were time dependent. Moreover, Huang (2007) compared the different transport formulae in a degradation case, and found that the adaptation length is completely different for each formula and also changes with steady or unsteady flow boundaries. This shows that choosing a correct value of the adaptation length is not straightforward.

Boundary conditions

Boundary conditions are very important in a numerical simulation for achieving accurate results. For the Lanzoni case, there was limited information of bed load transport rates during the testing. Only one average value was reported for Run 1309. A simplification, where a maximum transport rate was reached after one hour, was made in order to model the experiment with CCHE2D, but many other options were possible as well. As example, Proffit and Sutherland (1983), reported that, in the physical model were they developed the modification for the Ackers and White formula, during the first hour the transport rate was very high, and later in the experiment, the transport rate decreased to less than 5% of the initial rates, due to

bed armoring processes. However, data limitations from the case and obviously the sediment feeding simulation capabilities of the numerical model were handled by making the simplification previously mentioned and making a sensitivity analysis for the time for reaching the maximum value.

It was found that for adaptation lengths in the order of the chosen value (14 m), the bed load transport rates are very sensitive to the time for reaching maximum sediment transport, in other words, very sensitive to the inlet boundary conditions. For higher adaptation lengths, in the order of the length of the flume, the transport rates were nearly independent.

The best fit between simulated and measured transport rates was obtained with a one hour input time.

A drawback of simulating sediment transport in recirculating systems without detailed information regarding the entrained sediment is that variations of sediment gradation during the run are not taken into account. The fractions of each sediment size of the bed load entering the inlet in the numerical model are kept constant, whereas in the physical model this may not be the case. Consequently, on one side, it is difficult to compare simulated and measured bed material gradations, and on the other side this brings uncertainty to the results.

Longitudinal profiles

Even though it was not an aim of this study to replicate bed forms and longitudinal profiles in the flume, some observations were made in this sense and the main results for the selected case were presented as part of this study.

In the numerical model, alternate bars developed in the flume. Although the type of the bed form is predicted, the characteristics of the bars are far from the ones developed in the physical model. Neither the length nor the heights of the bars were represented well by the model. In the simulation, the bars were formed in the entire flume, while in the experiment they formed only in the downstream reach.

This is explained by the fact that alternate bars are 3D bed forms and the model used for the simulations is 2D. When alternate bars develop, secondary currents in a channel may not be negligible. Often 2D models have special algorithms included to take helical flows into consideration. However, in cases with a challenging flow field also models with additional included algorithms may not be able to predict the secondary flow accurately.

Francalanci et. al (2012) describe that "… alternate bars can strongly enhance bed load transport at low Shield stress". The reasoning behind is that sediment transport is related to local velocities in a non-linear way, and velocities depend on variations of

depth and in bed inclination in both streamwise and transverse direction. The non-linearity is explained by "doubling of Shields number produces more than doubling of the load" (Francalanci et. al, 2012). This was also observed in the numerical simulations carried out in this thesis, where local variations in velocity and shear stress caused by the alternate bars strongly increased the sediment transport rates.

Uncertainties in the modelling process

The different sources of uncertainties of modelling the case in this study with CCHE2D are mainly linked to the data, to the boundary conditions and to the parameters and empirical formulae used by the numerical model.

Information about the initial geometry and the flow discharge were the basic data. Although there might be uncertainties in the measurements from the physical model, they can be considered quite precise. The physical properties of sediment, like density and particle size distribution were reported by Lanzoni (2000b). Porosity was not given but its influence on the calculations was tested and proved to have little influence on the results. Default values for water density and water kinematic viscosity were used.

The number of size classes chosen for the simulations could be a source of error too, when the maximum value is not enough to represent the sediment gradation. This could be more significant when a bimodal sediment mixture is used, like in the present case. Additionally, discretizing the particle size distribution in classes may lead to inaccuracies. Although a sensitive analysis was not carried out for this parameter, it may be assumed that the eight size classes that were selected were representative of the grain size distribution used in the physical model.

Other numerical parameters, like grid spacing and the time step, proved to be adequate for the stability of the simulations in most of the cases. Instabilities occurred mainly in cases where the adaptation length was small.

As explained before, in this study, some assumptions were made in the boundary conditions and so, there is a reason for uncertainty. At the inlet, the discharge was known but the bed load input rate and the composition of the sediments (gradation) changed over time. A sensitivity analysis of this variation was conducted during the study. At the outlet, a constant water level was used, but this might not be exact if the bed changes in the downstream area are important.

The different empirical formulae used by CCHE2D for sediment transport calculations were tested in order to find the one that represented better the physical process in the laboratory. Sensitivity analysis for the most important parameters, i.e. roughness, adaptation length and mixing layer thickness, were conducted to resolve uncertainties.

7   Conclusions

The main goal for this thesis was to see if the CCHE2D model could assess accurately the sediment transport in a case with non-uniform material. A physical model study carried out by Lanzoni (2000b) was selected for this purpose. In the laboratory, a straight flume with a bimodal sediment mixture was used (d_{50}=0.262 mm and d_{90}=3.21 mm). Experiments on sediment transport were conducted in the flume, where bed load was the dominating transport mode. Alternate bars developed during the experiment and equilibrium conditions were reached. The data from the physical model was used as input for the numerical model that was the subject of this thesis.

CCHE2D was capable of replicating the bed load transport rate in the flume, with only a 1.5 % difference between the measured average value and the simulated value. So, the main goal of this study was reached.

Every part of the assignment, which was specified at the beginning of the study, was achieved. The generation of the grid was a basic task, due to the simple geometry of the flume and the capabilities of the available software for generating meshes developed with CCHE2D. Setting up the model and running the simulations were made with the use of the graphical user interface, provided with the software. After the CCHE2D learning process was accomplished, it was possible to obtain the results and to compare them with the data from the physical model. Finally, uncertainties were evaluated for the study and the sensitivity of certain parameters was tested.

From the numerical modelling study, it was concluded that the modified Ackers and White formula for calculating sediment transport capacity gave the best result compared to the other available formulae in CCHE2D. This formula includes the hiding and exposure effects, which are important for a sediment mixture like the one used in the studied case.

During the study, the main parameters that influenced the sediment transport process were identified. The numerical simulations proved to be very sensitive to the roughness height, the adaptation length and the mixing layer thickness. The optimum simulation was found using a roughness height of d_{85}, an adaptation length of 14 m and a mixing layer of d_{90}.

It can also be concluded that selecting the correct parameters is vital for numerical modelling. Results are extremely dependant on the values used for the parameters. Also, empirical formulae and approaches are used, which may bring further uncertainty in the calculations. Calibration and sensitivity analyses, especially for the roughness coefficient and the mixing layer thickness, are in general extremely important. In CCHE2D, the non-equilibrium approach leads to an additional parameter,

the adaptation length, that has to be assessed and this could be difficult without measured data.

The simulations were also sensitive to the boundary conditions. In this particular case, the inlet boundary conditions were uncertain, since the available data from the physical model was limited. It is very important to have detailed information for setting up a numerical model. In the case used for this study, continuous measurement of sediment transport rates for the runs in the physical model could have been valuable for the simulations.

Even though the aim of the study was to simulate the actual bed load transport rates and not to replicate the bed forms in the flume, for each simulation, following up bed changes was part of the procedure to get a better insight of what was happening in the flume. With the modified Ackers and White formula, average sediment transport rate fit the laboratory data, but as expected, the longitudinal profiles with a correct forming of the alternate bars were not replicated. Alternate bars are highly 3D processes, which cannot be modeled accurately by a 2D model.

Nevertheless, in many applied cases, predicting only the sediment transport would be sufficiently useful.

The CCHE2D model could be applicable to model cases where depth averaged values are accurate enough for the prediction of the physical processes that develop, especially, in cases where helical flows have minor influence on the results. With the selected grid size and time step, the time required for the simulations and the computational resources were adequate for carrying out this study. However, for this case the geometry was simple and the number of nodes was not high. An applied case, for example a river simulation, would require a much more complex mesh and more computational resources.

8 Further research

The physical model study carried out by Lanzoni brought valuable information on sediment transport and bar formation with non-uniform sediment to the research community. A lot of data was collected and reported for this case. However, when trying to set up the numerical simulation, data which turned out to be important for the numerical simulations was missing. However, the Lanzoni case is not the only case where a large quantity of data is obtained in a laboratory but it may be not the complete data that is required for a numerical simulation. If additional information were available, more modelling studies and more accurate results could be obtained, which would as consequence allow a further development of the numerical models. In this sense, it would be valuable to make research on sediment transport with non-uniform material using physical models, and next to it, collect detailed data for setting up and calibrating a numerical model.

In relation to CCHE2D and the case that was studied in this thesis, it would be interesting to develop two topics. First, compare the results of this study with a case with uniform sediment, i.e. model the first series of runs that Lanzoni conducted in the laboratory (Lanzoni, 2000a). Second, to simulate other runs from the same case (non-uniform sediment), using the parameters that proved to be best for simulating the bed load transport rate in this study.

It would also be interesting, for further research, to test the same case with different 2D models and even with a 3D model, in order to compare results and conclude about which 2D software handles better sediment transport with non-uniform material and how much the 3D effects influence the quality of the results. The common case could be the one used in this thesis, or another one with a data set obtained for numerical modelling purposes.

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Appendix

List of major simulations

Folder name: P1309-3

Objective: Evaluate calibration factor, porosity, adaptation length, mixing layer thickness and sediment input

Fixed parameters:

Sediment transport formula	Wu et al.
Roughness	Wu and Wang

Case	Run	Calibration factor	Porosity	Adaptation length (m)	Mixing layer thickness (m)	Sediment input (kg/m/s)	Input time (hr)
2	2	1	0.4	7.5	$2d_{50}$	0	-
2	3	1	0.4	7.5	$2d_{50}$	0.025	1
6	2	0.8	0.4	7.5	$2d_{50}$	0	-
6	3	0.8	0.4	7.5	$2d_{50}$	0.029	1
7	4	1	0.5	7.5	$2d_{50}$	0	-
7	5	1	0.5	7.5	$2d_{50}$	0.024	1
8	2	1	0.4	9.45	d_{90}	0	-
8	3	1	0.4	9.45	d_{90}	0.029	1
9	3	1	0.4	9.45	d_{90}	0.139	1
10	2	1	0.4	9.45	$2d_{90}$	0.139	1
11	2	1	0.4	9.45	0.0125	0.139	1
12	2	1	0.4	9.45	0.025	0.139	1
13	2	1	0.4	9.45	d_{90}	0.139	2
14	2	1	0.4	9.45	d_{90}	0.139	3
15	2	1	0.4	15	d_{90}	0.139	1
16	2	1	0.4	25	d_{90}	0.139	1

Folder name: P1309-4

Objective: Evaluate time step dependency, mixing layer thickness and sediment input

Fixed parameters

Sediment transport formula	Modified Ackers and White
Roughness	d_{85}
Porosity	0.4

Case	Run	Adaptation length (m)	Time step (s)	Mixing layer thickness (m)	Sediment input (kg/m/s)	Input time (hr)
4	2	7.5	0.5	$2d_{50}$	0	-
4	3	7.5	0.5	$2d_{50}$	0.120	1
5	2	9.45	0.5	$2d_{50}$	0	-
5	3	9.45	0.5	$2d_{50}$	0.119	1
6	2	9.45	1.5	$2d_{50}$	0	-
6	3	9.45	1.5	$2d_{50}$	0.119	1
7	4	9.45	1	d_{90}	0	-
7	5	9.45	1	d_{90}	0.118	1
8	3	9.45	1	$2d_{50}$	0.139	1
9	2	9.45	1	d_{90}	0.139	1
10	2	9.45	1	$2d_{90}$	0.139	1
11	2	9.45	1	d_{90}	0.139	2
12	2	9.45	1	d_{90}	0.139	3
13	2	9.45	1	d_{90}	0.139	5

Folder name: P1309-5

Objective: Evaluate changes in sediment input

Fixed parameters

Sediment transport formula	Modified Ackers and White
Roughness	d_{85}
Porosity	0.4
Adaptation length	9.45

Case	Run	Mixing layer thickness (m)	Sediment input (kg/m/s)	Time for max. sediment input (hr)
6	2	$2d_{50}$	0.126	1
7	3	$2d_{50}$	0.122	1
8	2	d_{90}	0.139	10
9	2	d_{90}	0.139	5
12	2	d_{90}	0.139	15
13	2	d_{90}	0.139	2
14	2	d_{90}	0.139	4
15	2	d_{90}	0.139	3
16	2	d_{90}	0.139	6
17	2	d_{90}	0.139	12
18	2	d_{90}	0.139	20
19	2	d_{90}	0.139	4.5
20	2	d_{90}	0.139	4.2
21	2	d_{90}	0.139	4.1

Folder name: P1309-6

Objective: Evaluate changes in adaptation length and sediment input

Fixed parameters

	Modified Ackers and White
Sediment transport formula	
Roughness	
Sediment input (kg/m/s)	d_{85} 0.139
Mixing layer thickness (m)	d_{90} 0.4
Porosity	

Case	Run	Adaptation length (m)	Time for max. sediment input (hr)
8	2	30	4
9	2	50	4
10	2	50	5
11	2	30	4
12	2	50	4
13	2	50	5
14	2	9.45	4
15	2	20	4
16	2	40	4
17	2	50	6
18	2	40	1
19	2	40	2
20	2	50	7
21	2	40	7
22	2	40	10
23	3	25	4
24	4	15	4

Folder name: P1309-6 (cont.)

Objective: Evaluate changes in adaptation length and sediment input

Fixed parameters

	Sediment transport formula	Modified Ackers and White
	Roughness	d_{85}
	Sediment input (kg/m/s)	0.139
	Mixing layer thickness (m)	d_{90}
	Porosity	0.4

Case	Run	Adaptation length (m)	Time for max. sediment input (hr)
25	5	25	1
26	6	25	2
27	7	25	3
28	8	25	1.5
29	9	25	2.5

Folder name: P1309-7

Objective: Evaluate changes in adaptation length, mixing layer and sediment input

Fixed parameters

Sediment transport formula	Modified Ackers and White
	d_{85}
Roughness	
Sediment input (kg/m/s)	0.139
Porosity	0.4

Case	Run	Adaptation length (m)	Mixing layer thickness (m)	Time for max. sediment input (hr)
11	2	15	d_{90}	2
12	2	15	d_{90}	1
13	3	15	d_{90}	3
14	2	20	d_{90}	1
15	2	20	d_{90}	2
16	2	20	d_{90}	3
17	2	30	d_{90}	1
18	2	30	d_{90}	2
19	2	30	d_{90}	3
20	2	11.7	d_{90}	1
21	2	11.7	d_{90}	2
22	2	11.7	d_{90}	3
23	2	11.7	d_{90}	4
24	2	14	d_{90}	1
25	2	14	d_{90}	2

Folder name: P1309-7 (cont.)

Objective: Evaluate changes in adaptation length, mixing layer and sediment input

Fixed parameters

Sediment transport formula	Modified Ackers and White
Roughness	d_{85}
Sediment input (kg/m/s)	0.139
Porosity	0.4

Case	Run	Adaptation length (m)	Mixing layer thickness (m)	Time for max. sediment input (hr)
26	2	14	d_{90}	3
27	2	14	d_{90}	4
28	2	50	d_{90}	1
29	2	50	d_{90}	2
30	2	50	d_{90}	3
31	3	14	$2d_{50}$	1
32		14	0.0025	1
33		14	0.0125	1