Chapter 1: Introduction

Sediment transport is a fundamental aspect of fluvial hydraulics. Indeed, river beds always tend to an asymptotic equilibrium strongly affected by the two transported phases: water and sediments. The river morphology may be altered by natural (floods) or, mainly, man-induced (river training works) perturbations. These perturbations may lead to significant morphological changes in the bed profile. For example, consequently to the construction of a dam or a sill, the sediments are trapped in the upstream reach where there is a deposition, while the lack of sediment supply downstream implies an erosion at the toe of the dam. The alluvial river responds to the new hydraulic regime by changing its slope through erosion and deposition processes. When a sill is broken, as it was the case on the Var in 1994 (Rossi, 2002) or when a meander is cut in order to improve the navigation (Rhine, Rhône, Mississippi, etc), major alterations may occur in rather short time. Human activities may cause significant modifications in the morphologic characteristics of a river. As the effects are coupled, it is not easy to foresee the consequences of a river engineering project. Erosion and deposition depend a lot on new flow conditions, which, in turn, depend on new morphological conditions.

The present work aims at modelling this mutual interaction by means of a two-layer model relying on shallow-water assumptions. This model is then validated against some simplified experimental situations. Some limitations are imposed: only one-dimensional cases considering an infinitely wide channel are taken into account and the sediment grain-size distribution is assumed to be uniform. Conversely, the model is designed to address some difficult situations like changes in flow regime (transcritical flows) or sudden transitions in the nature of the bed (erodible bed downstream of a fixed structure) and to introduce properly the boundary conditions.

In order to predict the bed evolution and the change in water regime when such unsteady flows occur, physical and mathematical models are proposed in literature. The physical models are particularly used to calculate local scouring phenomena, such as the local erosion around a bridge pier or the scour hole due to a jet issued from an underflow gate. However, when problems with larger space or time scales have to be solved, the use of a mathematical model is generally required. In some particular and simplified cases, the governing equations of the mathematical model can be solved analytically (de Vries, 1965), for example in the case of a bed aggradation due to an excess of sediment supply (Capart et al., 1998). For more general problems, a numerical resolution of the mathematical model has to be adopted.

In fluvial hydraulics, different sets of equations are used to model the interaction between water and sediment, depending on the modelling assumptions.

The most common are the Saint-Venant – Exner equations (see for example Cunge et al., 1980 and Graf and Altinakar, 1998), where a transport layer is not explicitly considered and where friction head loss and solid transport are estimated by closure equations. In this frame, some modellers adopt an uncoupled approach solving the water and bed reactions in two different stages (for example: Vreugdenhil and de Vries, 1967; Cunge and Perdreau, 1973), while others adopt a coupled resolution: water and sediment are treated together (for example: Rahuel, 1988; Correia et al., 1991, Correia, 1992). The expected advantage of a coupled approach is a closer interaction between water and sediment movement.

Even in a coupled form, the disadvantage of those models is that the equations do not take into account non-equilibrium sediment transport. To face this problem, some authors have proposed to add an empirical bed-load loading law (Bell and Sutherland, 1988; Phillips and Sutherland, 1989 and 1990). A second drawback is the following: as the solid discharge is calculated with a closure relation, it does not belong to the main unknowns of the system, which does not help to impose the solid transport as a boundary condition. Indeed, according to the classical eigenvalue analysis of the Saint-Venant – Exner equations (Vreugdenhil and de Vries, 1967; Cunge et al., 1980; Lyn and Altinakar, 2002), three characteristics describe the celerity of perturbations, two of them with positive slope in the plane (x, t), one with negative slope. Three boundary conditions (typically a water discharge, a water level and a bottom level) have to be imposed, two at the upstream, one at the downstream boundary, forcing to impose the solid discharge externally without clear logic in the choice of the concerned boundary.

To face these drawbacks, some modellers added a fourth equation, in which the time- and space-derivatives of the solid discharge explicitly appear (Armanini and Di Silvio, 1988; Leopardi, 2001; Di Cristo et al., 2002).

Another type of model relies on two-layer descriptions of the two-phase flow based on the shallow-water assumptions. Capart (2000) has introduced a coupled model based on a two-layer approach, one layer is clear water and the other is the water-sediment mixture constituting the bed-load transport layer. Erosion and deposition result from mass exchange between the fixed bed and the transport layer. This model assuming the same velocity in the two layers gives good results on dam-break cases (Fraccarollo and Capart, 2002). An extension of the model (Capart and Young, 2002) allows the velocity in each layer to be different, which is more appropriate for fluvial flows. More recently, Spinewine (2005) adapted the equations to take into account that the sediment concentration is lower in the bed-load layer than in the bed. As the sediment transport is now explicitly considered, a loading law is not required anymore to model non-equilibrium solid transport. Also, the interaction between the two layers is now explicitly expressed, leading to a real coupling between water and sediments. Moreover, the solid discharge now belongs to the unknowns, which allows introducing it in the boundary conditions by means of additional characteristic.

Other two-layer models were developed with some variations in the description of how the flow is stratified. For example, Leal et al. (2003), assume that the velocity profiles in the water and the bed-load transport layer are linked, depending on some physical parameters. Contrarily to the model developed by Capart (2000) and Spinewine (2005), the sediment concentration in the transport layer is one of the main unknowns.

Several numerical methods are available to solve these sets of equations, the most commonly used are the finite-volume (explicit) and the finite-difference (explicit or implicit) schemes. As far as the Saint-Venant-Exner coupled model are concerned, the most often used method is the implicit Preismann finite difference scheme (Preissmann, 1961; Cunge and Perdreau, 1973), used by Holly and Rahuel (1990) and by Correia (1992). An implicit scheme allows high Courant number and large time step, which is useful to model real river flow during several years. However, the main problem is that such a method, applied on the Saint-Venant-Exner equations, is not able to model transcritical flows (Meselhe and Holly, 1997). Indeed, it does not allow imposing conflicting boundary conditions (e.g. to impose the water depth upstream and downstream at the same time).

At the opposite, the explicit finite-volume method requires a Courant number lower than one, implying very small time step. It allows to model flows on a short time (several hours or days) but the long computational time makes it impossible to run long duration simulations extending over several years. With such short time steps, the difference between the coupled and uncoupled resolution of the Saint-Venant-Exner equations is negligible. An advantage of the explicit finite-volume scheme is the flexibility in imposing the boundary conditions and the fact that the method is shock capturing (e.g. allowing to model a hydraulic jump).

In order to simulate unsteady flows, two models are presented and compared in this thesis: (1) the common Saint-Venant-Exner model, and (2) a two-layer model inspired by the model initially developed by Capart (2000) under various assumptions.

In chapter 2, the governing equations are demonstrated with considerable details in order to clearly identify and underline the differences and the similarities between the models. Under its more complete formulation (Spinewine 2005), the two-layer model is derived without restrictive assumptions on the velocity or the sediment concentration in the sediment transport layer. However, in order to better understand the implications of the various assumptions, it is important to also consider two-layer models with simplified assumptions. In the second part of this chapter the eigenstructure of each model is analysed and a common example is treated in order to have a comparison point.

Chapter 3 describes the numerical method used to solve the equations. Both the Saint-Venant – Exner and the two-layer models are solved with a finite-volume method in order to be able to reproduce transcritical flows. The systems to solve are split in two parts, first the hyperbolic part of the equations (without the source terms) is solved with the HLL (Harten et al., 1983) hyperbolic solver. Some extensions of this HLL solver are also presented. Then the source terms are solved, also using a splitting strategy for the two-layer model.

Till now, the two-layer approach was mainly applied to dam-break induced flows, which do not require a boundary condition treatment. For normal flows, boundary conditions have to be imposed: a treatment of such boundary conditions is proposed in chapter 4. The method, based on the characteristics (Abbott, 1979) and the associated compatibility relations, is exemplified on the simple case of the Saint-Venant equations. Then it is extended to the Saint-Venant – Exner equations, and to the two-layer model. Under its more complete formulation, no analytical solution exists, the solution of the eigenvalue system then requires a numerical resolution.

Chapter 5 is a short description of the experimental set up of the Civil and Environmental Engineering Laboratory of the Université catholique de Louvain, where the experiments, on which the numerical models are tested, were performed.

Before dealing with unsteady flows, the two-layer model is confronted with uniform flow conditions in chapter 6. The two-layer model accounts for the solid discharge as a main variable, while the friction is represented by the various shear stresses at each layer interface. The solid discharge is influenced by the friction coefficients associated to those shear stresses. In uniform flow conditions, the solid discharge calculated by the two-layer model or by the common empirical formulae (for example Meyer-Peter and Müller, 1948) should be the same, allowing to calibrate the friction coefficients required by the two-layer model. Once calibrated for one situation (e.g.: a given bottom slope), using either experimental or theoretical data, the two-layer model is able to generate the water depth and the solid discharge for any situation (e.g.: other bottom slopes), without use of any transport formula. In that sense the method offers an alternative to common transport formulae. The comparison between common transport formulae and several versions of the two-layer model is tested for a wide range of Froude numbers and grain diameters.

Once validated under uniform flow conditions, the two-layer model is confronted with transcritical flows over mobile bed in chapter 7. In such cases, the change in flow regime induces a sudden variation in the shear stress applied on the bed and then in the sediment transport. First, an experiment carried out by Mourad Bellal (Bellal et al, 2004) representing a regressive erosion due to the transition from a mild to a steep slope is modeled. The migration of the control section located at the slope transition, also called the knickpoint, is numerically studied. Then, in the second part, the numerical models are compared with the experimental case of a hydraulic jump over a mobile bed (experiment carried out by Bellal et al., 2003). This transcritical flow, resulting from conflicting boundary conditions (water level imposed upstream and downstream), is challenging for numerical modeling. Indeed a sudden change in the downstream boundary conditions forces a flow discontinuity in the channel, which is only possible to manage if boundary conditions are well posed and if the internal solver is shock-capturing. For both cases, the calibration, the boundary condition treatment and comparisons between different models (various versions of the two-layer model and Saint-Venant-Exner) are proposed.

Chapter 8 concerns another kind of unsteady flow, which is induced by the transition from a non-erodible to an erodible bed. A distance of adaptation after the transition is needed to obtain the equilibrium solid discharge, predicted by common solid transport formulae. Usually bed-load loading laws, based on empirical results, are introduced in models. As the transport layer is physically taken into account in the two-layer approach, the hope is that such a model would be able to deal with this spatial and temporal lags without adding empirical laws. First the experiments carried out in collaboration with Michele Iervolino from the University of Naples in the framework of this thesis are described. Significant experimental results, like the maximum scour depth, are compared with empirical laws selected from literature. Then, the numerical results computed with the two-layer model are compared with experimental data. A second test case, which reproduces the erosion at the toe of a sill, highlights the limitations of the two-layer model as formulated in this thesis.