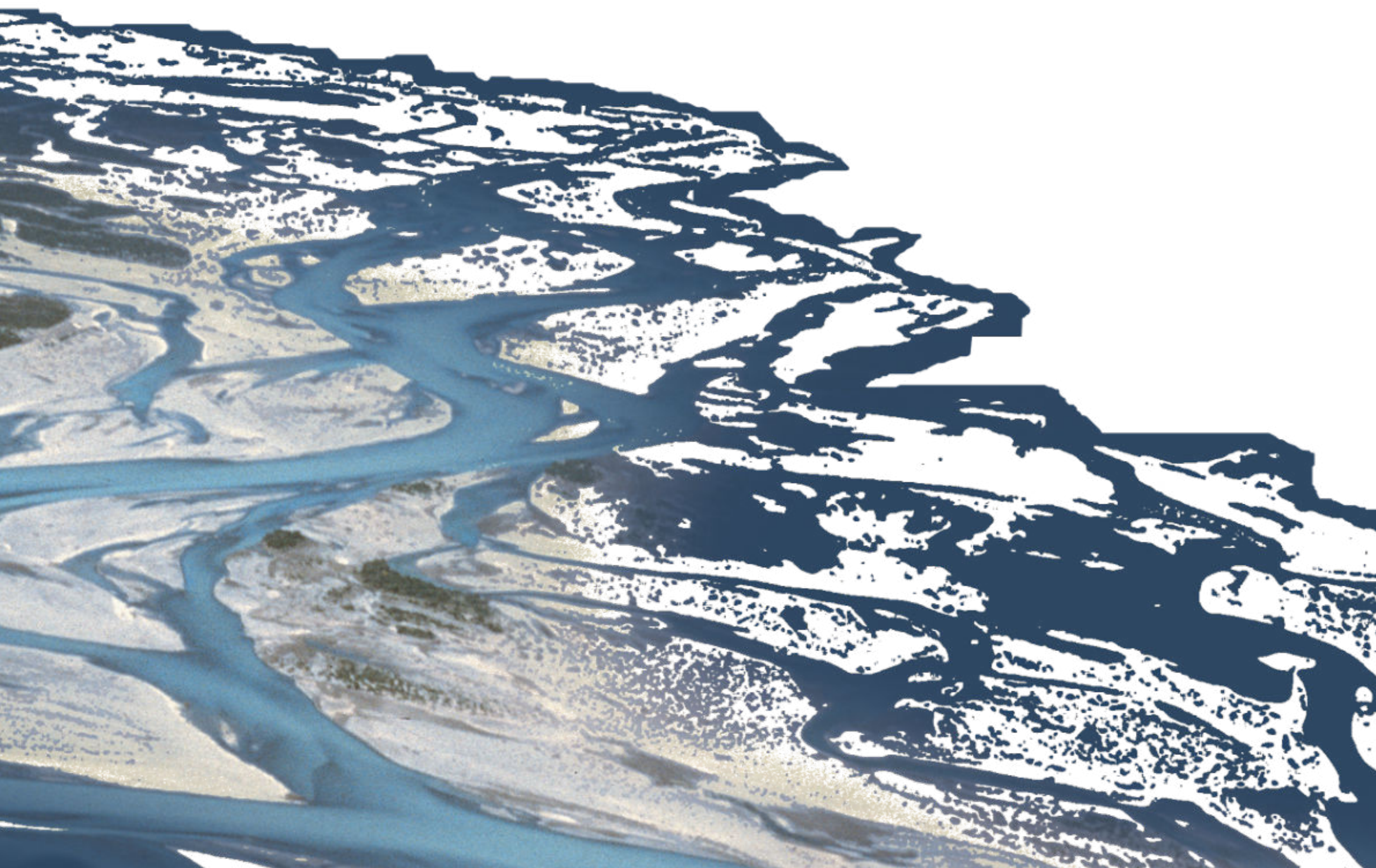
BASEMENT

BASIC SIMULATION ENVIRONMENT
FOR MODELLING OF ENVIRONMENTAL
FLOWS AND NATURAL HAZARDS

SYSTEM MANUALS

VERSION 4.1.0
JUNE 2024



Preamble

VERSION 4.1.0

June 2024

Credits

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Over the years, many enthusiastic engineers and developers have contributed to the development, testing and documentation of BASEMENT. An up-to-date overview of the current development team, along with current and former contributors, can be found on our website:

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For Software:

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BASIC SIMULATION ENVIRONMENT
FOR MODELLING OF ENVIRONMENTAL
FLOWS AND NATURAL HAZARDS

REFERENCE MANUAL BASEHPC

VERSION 4.1.0
JUNE 2024

Contents

1

Mathematical Models

1.1 Hydrodynamics

1.1.1 Introduction

Mathematical models of the so-called *shallow water* type govern a wide variety of physical phenomena. Especially the one-dimensional (1D) de Saint-Venant equations (SVE) or two-dimensional (2D) shallow water equations (SWE) are of practical interest with regard to water flows with a free surface under the influence of gravity. Applications of the models include e.g.:

- River hydrodynamics
- Propagation of flood waves
- Dam break waves
- Flooding and inundation
- Ecological assessment based on flow quantities

The 2D SWE are based on the following set of hypotheses:

- the water is assumed to be incompressible; i.e. the water density ρ is constant
- the vertical acceleration of the water particles are assumed to be small compared to the longitudinal component of the acceleration. As a consequence the pressure distribution is hydrostatic;
- the bottom slope is small enough for the longitudinal coordinate to coincide with the horizontal axis;
- the flow regime is turbulent. As a consequence the head loss, mainly due to friction against the bottom, is proportional to the square of the flow velocity.

1.1.2 Governing Equations

The governing equations are obtained under shallow water conditions imposing mass conservation for the fluid and solid phases and the momentum principle to a flow in an open channel with a fixed bottom.

Introducing a Cartesian reference system (x, y, z) in which the z axis is vertical and the $x - y$ plane is horizontal with respect to gravity g , the system of governing equations can be written as

$$\begin{cases} \frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = S_h \\ \frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_x^2}{h} + \frac{1}{2}gh^2\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{h}\right) + gh\left(S_{bx} + S_{fx}\right) + T_x = 0 \\ \frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_y q_x}{h}\right) + \frac{\partial}{\partial y}\left(\frac{q_y^2}{h} + \frac{1}{2}gh^2\right) + gh(S_{by} + S_{fy}) + T_y = 0\ , \end{cases} \tag{1.1}$$

where:

h	$[m]$	water depth
g	$[m/s^2]$	gravity acceleration
$u\ (v)$	$[m/s]$	depth averaged velocity in x (y) direction
$q_x\ (q_y)$	$[m^2/s]$	discharge per unit width in x (y) direction
S_h	$[m/s]$	lateral inflow/outflow discharge per unit width
$S_{fx}\ (S_{fy})$	$[-]$	friction terms in x (y) direction
$T_x\ (T_y)$	$[-]$	turbulent terms in x (y) direction .

The bed slope source terms

$$S_{bx}, S_{by}$$

are evaluated as follows:

$$S_{bx} = -\frac{\partial z_B}{\partial x} \quad ; \quad S_{by} = -\frac{\partial z_B}{\partial y} \tag{1.2}$$

1.1.3 Closure Relations

In order to solve system (eq. 1.1) we need to specify the closure relations for the friction terms S_{fx}, S_{fy} and the value of lateral inflow/outflow discharge per unit width S_h.

1.1.3.1 Friction Terms

The governing equations (eq. 1.1) have been derived under the hypothesis (H3) of turbulent flow, hence the friction term S_f can be assumed proportional to the square of the depth-averaged velocity and can be written as:

$$S_{fx} = \frac{u|\vec{u}|}{gc_f^2 h} \quad ; \quad S_{fy} = \frac{v|\vec{u}|}{gc_f^2 h} \tag{1.3}$$

where g is the gravity acceleration, u and v are the depth averaged velocities in x and y direction, $|\vec{u}| = \sqrt{u^2 + v^2}$ is the magnitude of the velocity vector and c_f is the dimensionless friction coefficient.

Several formulae are available for the dimensionless friction coefficient c_f. Here it is quantified using both a power or a logarithmic for which are described in the next sections.

1.1.3.1.1 Power Law

The Manning-Strickler power law is widely used in practice and it requires that either the Strickler's k_{str} $[m^{1/3}/s]$ or the Manning's n coefficients ($k_{str} = n^{-1}$) is specified.

In this case the dimensionless friction coefficient c_f is calculated as

$$c_f = \frac{k_{str} h^{1/6}}{\sqrt{g}} \tag{1.4}$$

1.1.3.1.2 Logarithmic Law

The following approaches are implemented to determine the friction coefficient c_f:

Chézy:

$$\begin{aligned} c_f &= 5.75 \log\left(12 \frac{R}{K_s}\right) \qquad \text{for} \qquad R > K_s \\ c_f &= 5.75 \log(12) \qquad \text{for} \qquad R < K_s \ , \end{aligned} \tag{1.5}$$

where K_s $[m]$ is the bed roughness height which is commonly taken to be proportional to a representative sediment size d_x. For rivers, K_s can be assumed $K_s = n_k d_{90}$ where $n_k = 2 \div 3$.

Bezzola:

In this closure relation, proposed by Bezzola (2002), c_f is given as a function of the roughness sublayer height y_R $[m]$ (usually for rivers $y_R \approx 1.0 d_{90}$ is a good approximation). This approach is also valid for small values of the relative submergence h/y_r Bezzola (2002).

$$\begin{cases} c_f = 2.5\sqrt{1 - \frac{y_R}{h}}\ \ln\left(10.9\frac{R}{y_R}\right), & \text{for} \quad \frac{h}{y_R} > 2 \\ c_f = 1.25\sqrt{\frac{h}{y_R}}\ \ln\left(10.9\frac{R}{y_R}\right), & \text{for} \quad 0.5 \leq \frac{h}{y_R} \leq 2 \\ c_f = 1.5, & \text{for} \quad \frac{h}{y_R} < 0.5 \end{cases} \tag{1.6}$$

1.1.3.2 Turbulent Terms

The turbulent and viscous stresses are considered under the eddy viscosity model, following the Boussinesq hypothesis, and can be written as

$$T_{x_i} = \frac{\partial}{\partial_{x_j}} \left((\nu + \nu_t) \frac{\partial}{\partial_{x_j}} h u_{x_i} \right) \tag{1.7}$$

where x_i stands for the x or y direction, ν and ν_t are the laminar and turbulent kinematic viscosities, respectively, u_{x_i} is the flow velocity and T_{x_i} are the commonly denominated Reynolds stresses. The turbulent viscosity is the defining parameter when employing this type of turbulence closure, with several closures being available in fluid mechanics literature. For SWE systems, the most common options for computing the eddy viscosity are the constant, mixing-length and κ-ϵ models.

1.1.3.2.1 Mixing-length model

The mixing-length model was derived by Ludwig Prandtl and is based on a characteristic length concept where a fluid retains some of its original characteristics (namely turbulence) before dispersing them into the surrounding fluid. In this model, the turbulent viscosity is locally derived by a length scale, the strain rate and the friction velocity as follows:

$$\nu_t = l_s^2 \sqrt{2 S_{ij} S_{ij} + \frac{2.34\kappa}{u_f}} \tag{1.8}$$

where l_s is the characteristic length scale, $S_{ij} = \left(\partial_{x_j} u_i + \partial_{x_i} u_j\right)/2$ is the strain rate, κ is the von Karman constant and $u_f = c_f|\vec{u}|$ is the friction velocity. The length scale can be defined as a constant or by using $l_s = 0.267\kappa h$ (ref).

1.1.3.2.2 κ-ϵ model

The κ-ϵ model is one of the most widely adopted models in hydraulics and general fluid mechanics. The turbulent kinetic energy (TKE) κ is introduced by means of an additional conservation equation, given by:

$$\frac{\partial(kh)}{\partial t} + \frac{\partial(khu_i)}{\partial x_i} - \frac{\partial}{\partial x_j}\frac{\nu_t}{\sigma_k}\frac{\partial kh}{\partial x_j} = hP_\kappa - h\epsilon \tag{1.9}$$

where P_k is the TKE production rate and ϵ is its dissipation rate. The P_k term is locally defined, whereas the ϵ term is solved through another conservation equation, as:

$$\frac{\partial(\epsilon h)}{\partial t} + \frac{\partial(\epsilon hu_i)}{\partial x_i} - \frac{\partial}{\partial x_j}\frac{\nu_t}{\sigma_k}\frac{\partial \epsilon h}{\partial x_j} = hS_\epsilon \tag{1.10}$$

where S_ϵ is an aggregate net source of ϵ. In the Standard κ-ϵ model, the source terms for both κ and ϵ are defined as:

$$P_k = 2\nu_t S_{ij} S_{ij} + \frac{u_f^3}{c_f h} \tag{1.11}$$

$$S_\epsilon = 2c_{\epsilon_1}\frac{\epsilon}{\kappa}\nu_t S_{ij} S_{ij} + 3.6\frac{c_{\epsilon_2}\sqrt{c_\mu}u_f^4}{h^2 c_f^{3/4}} - c_{\epsilon_2}\frac{\epsilon^2}{\kappa} \tag{1.12}$$

and the constants of the standard model are $c_\mu = 0.09$, $\sigma_k = 1.00$, $\sigma_\epsilon = 1.30$, $c_{\epsilon_1} = 1.44$ and $c_{\epsilon_2} = 1.92$. The turbulent viscosity is finally obtained, locally, as

$$\nu_t = c_\mu \frac{\kappa^2}{\epsilon} \tag{1.13}$$

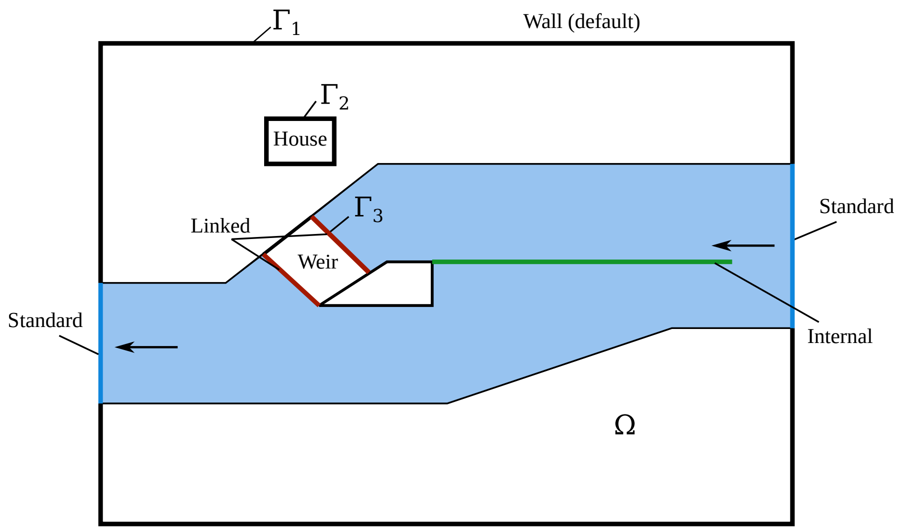

Figure 1.1 *Modeling domain and types of boundary conditions available. The flow is from right to left and a side weir (green line) divides the channel into a lower and an upper channel through the weir.* ***Standard*** *or* ***linked*** *boundary conditions must be provided at* Γ_1*,* Γ_2 *and* Γ_3 *while* ***internal*** *boundary conditions can be specified in any place within* Ω

1.1.3.3 Lateral Inflow/Outflow

S_h is used to represent additional sources of water like rainfall and springs or water abstraction (sink) and are allocated on a set of elements defined by regions. The external source can be specified as total discharge $[m^3/s]$ or distributed over time $[mm/h]$. Different approaches are used to manage the behaviour of the external sources:

- Exact: The specified water volume is added or extracted (non conservative)
- Available: The specified water volume to extract is limited by the available water volume in the elements (conservative)
- Infinity: All available water will be abstracted (conservative)

Addition of water always follows the "Exact" behaviour as there is no upper limit. The abstraction of water could also follow the "Exact" behaviour but the simulation might end abruptly if the available water volume is smaller than the volume prescribed. Therefore, the "Available" behaviour aims to avoid this situation. The "Infinity" behaviour abstracts all available water volume.

1.1.4 Boundary Conditions

After the specification of the *closure relations* there are now three equations and three unknowns, namely h, q_x and q_y. In principle, given initial and boundary conditions, one should be able to solve system (eq. 1.1) for h, q_x and q_y as functions of space x, y, and time t. Given the modeling domain described in Figure 1.1, boundary conditions are required at the domain boundary Γ and optionally can be specified within the interior domain Ω.

Therefore, three different types of boundary conditions can be defined:

- Standard boundary conditions: located at the domain boundary Γ_i
- Linked boundary conditions: located at the domain boundary Γ_i or inside the domain Ω
- Internal boundary conditions: located inside the domain Ω

Standard boundaries (at Γ) represent the limits of the computational domain possibly including also buildings, weirs or structures for water intake (see Figure 1.1).

1.1.4.1 Standard Boundary Conditions

At the standard boundaries, two different types of boundary conditions can be specified: wall or flow boundaries. Flow boundary conditions allow the flow to enter or leave the domain while wall boundary conditions express no mass flux over the boundary. By default, the extneral boundaries of the domain are set as wall boundaries.

1.1.4.1.1 Wall Boundaries

The *Wall* or *reflective* boundary consider the boundary at Γ_i and suppose it physically consists of a fixed, reflective impermeable wall. Then the physical situation is modelled imposing that:

$$\rho\vec{u}\cdot\vec{n} = 0 \quad ; \quad \frac{\partial\vec{u}}{\partial\vec{n}} = 0 \tag{1.14}$$

Where $\vec{n}$ is the outward directed unit vector perpendicular to the wall and $\vec{u} = (u, v)^T$ is the velocity vector. The static pressure is assumed to be zero.

1.1.4.1.2 Flow Boundaries

The *Flow* boundary conditions are defined as *inflow* if they let water entering or as *outflow* if they let water leaving the domain. Flow boundaries are further distinguished into *Standard* and *Linked*. The former are applied on the boundary domain Γ, while the latter establish a *link* between two portions of the domain.

Standard

Inflow boundaries:

This boundary requires the specification of a value for the total volume discharge Q, $[m^3/s]$, which is then divided by the length of the boundary Γ and projected orthogonally to the boundary to obtain the values of q_x and q_y. In case of supercritical flow the following possibilities to specify the value of the water depth h are possible:

- *uniform_in*: h is calculated assuming that local uniform flow conditions. The calculation proceeds as follows:

$$h = \sqrt[3]{\frac{(Q/b)^2}{gc_f^2 s}} \tag{1.15}$$

where c_f is the Chézy coefficient, b is the entire length of the boundary Γ and s is the value of the local bed slope that must be specified.

- *froude_in*: In this case the flow depth h is calculated as follows:

$$h = \sqrt[3]{\frac{(Q/b)^2}{gFr^2}} \tag{1.16}$$

where b is the entire length of the boundary and Fr is the value of the local Froude number that must be specified

- *zhydrograph*: The water surface elevation (wse) at the boundary must be specified by the user. The depth is calculated as:

$$h = wse - z_B \tag{1.17}$$

where z_B is the bottom elevation at the boundary. The flow velocity at the boundary is set to zero.

Outflow boundaries:

At the outflow boundaries a value for the water depth h must be specified. These are the possible options:

- *uniform_out*: the water depth h is calculated using equation (eq. 1.15) specifying a value for the total discharge Q and a local bed slope s. Uniform flow is calculated based on given slope and cell state at boundary (eq. 1.15).
- *weir_out_constant* and *weir_out_dynamic*: These boundary conditions establishe a relation between the approaching discharge q constant and the water depth using the Poleni weir formula:

$$q = \frac{2}{3}\mu\sqrt{2g(h_{up} - w)^3} \tag{1.18}$$

where h_{up} is the water depth of the approaching flow and w is the weir elevation. The Poleni factor μ can be either set as constant ($\mu = 0.75$ by default) or dynamically evaluated as:

$$\mu = \frac{0.611}{a}\frac{0.75}{b}\frac{h_{up} - z_w}{w} \tag{1.19}$$

where a and b must be specified by the user in the case of *weir_out_dynamic* (default values are $a = 0.611$ and $b = 0.075$).

- *hqrelation_out*: The discharge is determined as a function of the water surface elevation, thus a stage-discharge-relation has to be specified.
- *zhydrograph*: Sets a fixed water surface elevation (wse) at the boundary. The wse [m] at the boundary must be specified by the user. The depth is calculated as:

$$h = wse - z_B \tag{1.20}$$

where z_B is the bottom elevation at the boundary. The flow velocity is calculated with the Riemann solver (HLLC).

- *zero_gradient_out* (scientific use only): Transmissive, or transparent boundaries allow the passage of waves without any effect on them. This is mathematically obtained imposing over the entire length of the boundary that:

$$\rho\vec{u}\cdot\vec{n} = \text{const} \quad ; \quad \frac{\partial\vec{u}}{\partial\vec{n}} = 0 \tag{1.21}$$

In this case there is no need to specify further parameters.

Note: This is boundary condition should ***not*** *be used for practical problems and is intended for scientific use only.*

1.1.4.2 Linked Boundary Conditions

This type of boundaries establish a *link* between within a certain region of the domain where equations are not solved. Once this domain portion is identified the two boundaries, between which the link is established, must be specified. Let us call them Γ_{in} and Γ_{out}. Then, one inflow boundary condition must be specified at Γ_{in} and one outflow boundary condition at Γ_{out} while in the remaining boundaries wall conditions are automatically assigned. Not necessarily, Γ_{in} and Γ_{out} must have the same number of elements.

Linked boundaries can describe a $h - Q$ relation, a weir, or prescribed water surface elevation, i.e.:

- *weir_linked_constant* and *weir_linked_dynamic*: Similar to the standard weir boundary, the weir height w has to be specified.
- *hqrelation_linked*: The discharge is determined as a function of the water surface elevation, thus a stage-discharge-relation has to be specified.
- *2way_hqrelation_linked*: The internal boundary works as dynamic wall that is controlled by water surface elevation thresholds. If the upper water surface elevation threshold is reached, the internal boundary is removed until the water level reaches the lower water surface elevation, where the wall is re-established.
- *zhydrograph_linked*: Sets a prescribed water surface elevation (WSE) at the upstream boundary. The flux over the upstream boundary is caculated with the Riemann solver and used as inflow in the downstream boundary.

The inflow conditions at the downstream boundary can be controlled via the tag *type_downstream*. Four options are available as downstream inflow condition. For all options, the mass inflow flux is calculated based on outflow at upstream boundary. The difference between the options lies in the calculation of the momentum flux over the boundary:

- *no_momentum*: No momentum flux over the boundary.
- *froude_downstream*: Momentum flux calculated based on Froude number in the elements of the downstream nodestring.

- *froude*: Momentum flux calculated based on the Froude number specified via the parameter *froude_number*.
- *uniform*: Momentum flux calculated based on uniform flow conditions for the slope specified via the parameter *slope*.

In BASEMENT versions without the option *type_downstream*, the various linked boundary conditions differ in how the momentum flux at the downstream boundary was calculated. The following combinations correspond to the implementation of the boundary conditions in previous versions:

type	type_downstream
weir_linked_constant	froude_downstream
weir_linked_dynamic	froude_downstream
hqrelation_linked	no_momentum
2way_hqrelation_linked	no_momentum
zhydrograph_linked	no_momentum
zhydrograph_linked_kinE	froude_downstream

1.1.4.3 Internal Boundary Conditions

The internal boundary condition allows a direct cell-cell relation due to the exact same number of elements on the left and on right side of the boundary. Internal boundary conditions can be used to specify internal walls, dynamic walls or an h-Q relation.

- *wall_internal*: The wall conditions (eq. 1.14) are applied on both sides of the internal boundary.
- *dynamic_wall_internal*: The wall conditions are applied on the internal boundary until reaching a threshold value (time or water depth) after which the wall is removed.
- *hqrelation_internal*: A stage-discharge relation is applied on one side of the internal boundary, while on the other side, wall conditions apply (unidirectional flow).

For the *hqrelation_internal* boundary condition, the inflow conditions at the downstream boundary can be controlled via the tag *type_downstream*. Four options are available as downstream inflow condition. For all options, the mass inflow flux is calculated based on outflow at upstream boundary. The difference between the options lies in the calculation of the momentum flux over the boundary:

- *no_momentum*: No momentum flux over the boundary.
- *froude_downstream*: Momentum flux calculated based on Froude number in the elements of the downstream nodestring.
- *froude*: Momentum flux calculated based on the Froude number specified via the parameter *froude_number*.
- *uniform*: Momentum flux calculated based on uniform flow conditions for the slope specified via the parameter *slope*.

In BASEMENT versions without the option *type_downstream*, the various linked boundary conditions differ in how the momentum flux at the downstream boundary was calculated. The following combinations correspond to the implementation of the boundary conditions in previous versions:

type	type_downstream
hqrelation_internal	no_momentum

1.1.5 Flood Tracking

The flood tracking aims at extracting the flood arrival time, the maximum water depth, flow velocity, specific discharge and bed shear stress along the numerical simulation and over a selected domain area. The flood tracking provides outputs within a tracking time step defined by the user.

1.2 Morphodynamics

1.2.1 Introduction

Morphodynamic models provide scientific frameworks for advancing our understanding of river systems. The research on involved topics is an important and socially relevant undertaking regarding our environment. Nowadays numerical models are used for different purposes, from answering questions about basic morphodynamic research to managing complex river engineering problems. Due to increasing computer power and the development of advanced numerical techniques, morphodynamic models are now more and more used to predict the bed patterns evolution to a broad spectrum of spatial and temporal scales. The development and the success of application of such models are based upon a wide range of disciplines from applied mathematics for the numerical solution of the equations to geomorphology for the physical interpretation of the results.

Applications of morphodynamic models include:

- Damming of river basins
- Morphological changes due to width changes (e.g. River widenings)
- Effects of sediment mining
- River straightening

1.2.2 Bedload Sediment Transport

1.2.2.1 Governing Equations for Uniform Sediment Transport

The governing equations are obtained under shallow water conditions imposing mass conservation for the fluid and solid phases and the momentum principle to a flow in an open channel with a cohesionless bottom.

Introducing a Cartesian reference system $(x; y; z)$ in which the z axis is vertical and the $x - y$ plane is horizontal, the system of governing equations is described by the system of equations (eq. 1.1) for hydrodynamics coupled with one equation for the conservation of the total sediment mass. The conservation of sediment mass is ensured by the Exner equation (eq. 1.22), named after the Austrian sedimentologist Felix M. Exner (Exner, 1925). The Exner equation allows to describe the bed evolution due to erosion or deposition, which results in the elevation change of the actual bed level z_B:

$$(1-p)\frac{\partial z_B}{\partial t} + \frac{\partial q_{B_x}}{\partial x} + \frac{\partial q_{B_y}}{\partial y} - Sl_b = S_s \tag{1.22}$$

where p is the porosity, Sl_b is the source term per unit width specifying local input or output of sediment material (e.g. slope collapse or excavation), and $\vec{q}_B = \begin{pmatrix} q_{B_x} \\ q_{B_y} \end{pmatrix}$ is the specific bedload flux. The term S_s describes the exchange per unit width between the sediment and the suspended material (see Section 1.3). The Exner equation describes the bed evolution due to erosion or deposition processes, which results in changes of the bed level z_B.

The Exner equation is solved in a decoupled way, meaning that the shallow water equations and the Exner equation are solved in sequence. This approach makes the assumption that the bedload flux is much slower than the water flow velocity (Soares-Frazão and Zech, 2011).

1.2.2.2 Governing Equations for Mixed-Size Sediment Transport

1.2.2.2.1 Hirano-Exner Model

The mixed-size sediment transport is based on the Hirano-Exner model Hirano (1971), which extends the Exner equation to sediment mixtures consisting of N discrete grain size classes with grain size diameters d_g. The subscript $_g$ denotes the grain size class. The model is based on the assumption, that the river bed can be distunguished into different vertical layers. Only the sediment in the uppermost layer, also called active layer, is in directly exposed to the forces of the flow and therefore, only sediment from this layer is available for bedload transport. The active layer is the control volume for the mass conservation equation of each grain size class (Eq. eq. 1.23) and has a finite thickness L_a (see Fig. Figure 1.2). The sediment mixture in the active layer is determined by the active layer fractions F_g of each grain class g. The substrate below the active layer may be further distinguished into j sublayers with sublayer fractions $f_{j,g}$. The conservation of mass for each grain size class g in the active layer is then given as

$$(1-p)\frac{\partial (F_g \cdot L_a)}{\partial t} + \frac{\partial q_{B,g_x}}{\partial x} + \frac{\partial q_{B,g_y}}{\partial y} + S_{s,g} - Sl_{b,g} - Sf_g = 0 \qquad \text{for} \qquad g = 1, ..., N, \tag{1.23}$$

where p is the porosity, $S_{s,g}$ is the source term for the exchange of sediment with the water column (suspended sediment transport), $Sl_{b,g}$ is the source term per unit area specifying local input or output of sediment material (e.g. sediment replenishment or excavation), and $\vec{q}_{B,g} = (q_{B,g_x}, q_{B,g_y})$ is the specific bedload flux of grain fraction g. The source term

Sf_g for the flux between the active layer and the uppermost sublayer due to changes in the bed level z_B or in the active layer thickness L_a is given as

$$Sf_g = -(1-p) f_{I,g} \frac{\partial (z_B - L_a)}{\partial t}, \tag{1.24}$$

where the fraction $f_{I,g}$ depends on whether the lower edge of the active layer defined at $z = z_B - L_a$ moves up- or downwards as:

$$f_{I,g} = \begin{cases} f_{1,g} & \text{if} \quad \frac{\partial (z_B - L_a)}{\partial t} < 0, \\ F_g & \text{if} \quad \frac{\partial (z_B - L_a)}{\partial t} > 0. \end{cases} \tag{1.25}$$

Here, $f_{1,g}$ denotes the fraction of grain class g of the uppermost sublayer (index 1).

The conservation of the sediment fractions in the active layer for each sublayer j are given as:

$$\sum_{g=1}^{N} F_g = 1 \qquad \text{and} \qquad \sum_{g=1}^{N} f_{j,g} = 1 \qquad \text{for} \qquad j = 1, ...$$

The global conservation of sediment mass is defined by the extension of the Exner equation:

$$(1-p)\frac{\partial z_B}{\partial t} + \sum_{g=1}^{N} \left(\frac{\partial q_{B,g_x}}{\partial x} + \frac{\partial q_{B,g_y}}{\partial y} + S_{s,g} - Sl_{b,g} \right) = 0 \qquad \text{for} \qquad g = 1, ..., N. \tag{1.26}$$

Finally, we require closure relations for the sediment transport rate $\vec{q}_{B,g}$, which are obtained from a sediment transport formula (see Section Section 1.2.2.4).

1.2.2.2.2 Active layer thickness

The thickness of the active layer (bed load control volume) L_a is an important calibration parameter. This parameter influences significantly the grain sorting process. The active layer thickness can be specified in the ACTIVE_LAYER block within the PARAMETER block. The *active_layer_type* can either be set to:

- constant: The active layer thickness is constant and defined via the parameter *active_layer_thickness*
- d90: The active layer thickness is a calculated at each time step as $L_a = kd_{90}$, where k is the user specified *active_layer_factor* and d_{90} is the characteristic grain diameter for which 90% of the sediment in the active layer is smaller than d_{90}.

1.2.2.2.3 Limitations

For compuational performance reasons, the maximum available grain classes is limited to 10. Similarly, the number of sublayers available is limited to 2. Coupling of bedload and suspended load transport is not yet implemented ($S_{s,g}$ for $g > 1$), i.e. suspended load transport only works for uniform sediment transport models.

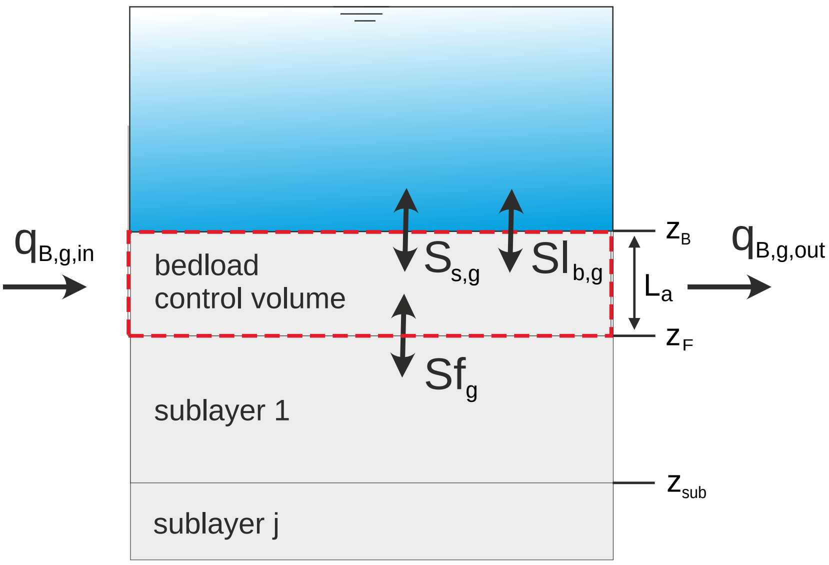

Figure 1.2 *Definition sketch of overall control volume (red) of bed material sorting equation*

1.2.2.3 Threshold Conditions for Sediment Movement

The key dimensionless parameter quantifying sediment mobility is the Shields parameter defined as:

$$\theta = \frac{|\vec{\tau_b}|}{(\rho_s - \rho)gd} \tag{1.27}$$

where $vec\tau_b$ is the bed shear stress (drag force acting on the particle), d is the sediment diameter, ρ and ρ_s are the water and sediment density, respectively. The Shields parameter can be interpreted as the ratio scaling the impelling force of flow drag acting on a particle to the Coulomb force resisting motion acting on the same particle.

The bed shear stress $\vec{\tau_b} = \begin{pmatrix} \tau_{bx} \\ \tau_{by} \end{pmatrix}$ is usually estimated by a closure condition using an empirical or semi-empirical formula. Here we use the quadratic friction law which relates the depth-averaged velocities to the bed shear stress as follows:

$$\tau_{bx} = \rho \frac{|\vec{u}|u}{c_f^2} \quad ; \quad \tau_{by} = \rho \frac{|\vec{u}|v}{c_f^2} \tag{1.28}$$

where $\vec{u} = \begin{pmatrix} u \\ v \end{pmatrix}$ is the flow velocity vector, ρ is the density of water and c_f is the dimensionless Chézy friction coefficient as defined in Section 1.1.3.1.

When a granular bed is subjected to a turbulent flow, it is found that virtually no motion of the grains is observed below a critical value (θ_{cr}) of the Shields parameter. According to the Shields' theory Shields (1936), θ_{cr} can be expressed as a function of the Reynolds number $Re^* = \frac{du_*}{\nu}$. Alternatively, the diagram of incipient motion (see Figure 1.3) can be

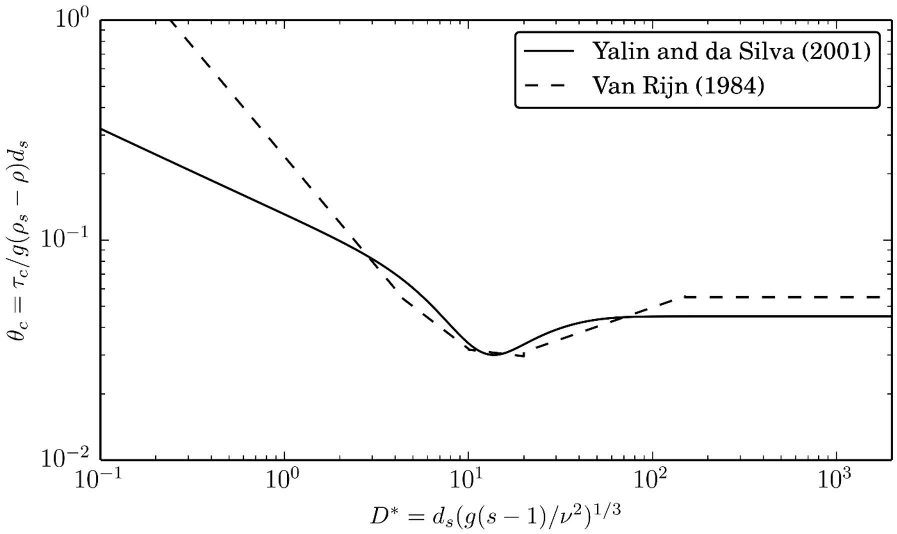

Figure 1.3 *Modified Shields diagram for initiation of sediment motion*

plotted as a function of the dimensionless grain diameter D^* ($\theta_{cr} = f(D^*)$), where

$$D^* = d\left[\frac{g(s-1)}{\nu^2}\right]^{1/3}$$

.

The curve representing the particle incipient motion ($\theta = \theta_{cr}$) can be divided into three parts in the log-log graph:

- for $D^* \leq 3$, can be approximated by a linear segment;
- for $3 \leq D^* \leq 100$ this is represented by a curve with a relative minimum;
- for \$D^* > 100 \$ by a constant trend. “

An explicit formulation of the Shields curve was proposed by Yalin and Silva (2001). It reads

$$\theta_{cr} = 0.13 D^{*-0.392} \exp(-0.015 D^*) + 0.045 \left(1 - \exp(-0.068 D^*)\right) \tag{1.29}$$

Two approaches for determining the dimensionless critical Shields parameter are available (theta_critical_approach):

- *constant*: The default dimensionless critical Shields parameter is constant and equal to the user-specified value *theta_critical* (default)

- *yalin*: The critical Shields parameter is determined with the approach of Yalin and Silva (2001) (Eq. eq. 1.29). D^* is calculated based on the arithmetic mean grain diameter of the active layer.

1.2.2.3.1 Influence of Local Slope on Incipient Motion

The threshold condition for incipient motion of grains developed by Shields is valid for almost horizontal bed. In case of sloped bed in flow direction or transverse to it, the stability of grains is either increased or reduced due to the gravity. The critical shear stress value can be adapted consequently to account for the influence of local slopes. One approach is to multiply the critical shear stress for almost horizontal bed θ_{cr} with the correction factors k_l and k_t for the local bed slope in the longitudinal and transversal flow direction. In the following, the critical Shields stress corrected for arbitrary bed slope δ is referred to as $\theta_{c,\delta}$, defined as:

$$\frac{\theta_{c,\delta}}{\theta_{cr}} = k_l k_t = k \tag{1.30}$$

The correction factor k_l and k_t are calculated as suggested by van Rijn (1989):

$$k_l = \cos\delta_l \left(1 - \frac{\tan\delta_l}{\tan\gamma}\right) \tag{1.31}$$

$$k_t = \cos\delta_t \sqrt{1 - \frac{\tan^2\delta_t}{\tan^2\gamma}} \tag{1.32}$$

where δ_l is the angle between the horizontal and the bed along flow direction, δ_t is the slope angle transversal to the flow direction and γ is the angle of repose of the sediment material.

Other formulations are also available, as for example the one proposed by Chen et al. (2010):

$$k = \frac{1}{\tan\gamma}\left(\cos^2\left(\frac{\pi}{2} - \delta_l\right) - 1 + \frac{1 + \tan^2\gamma}{(1 + \tan^2\delta_l + \tan^2\delta_t)}\right)^{0.5} + \cos\left(\frac{\pi}{2} - \delta_l\right) \tag{1.33}$$

1.2.2.4 Closure Relations for Bedload Transport

In order to solve system (eq. 1.1) and equation (eq. 1.22) we need to specify the closure relations. For the friction terms S_{fx}, S_{fy} and the value of lateral inflow/outflow discharge per unit width S_h we can use the relations already introduced in the Hydrodynamic part (Section 1.1.3). For the Exner equation we need relations quantifying the bedload discharge. Let us now introduce the dimensionless bedload transport rate Φ also known as the Einstein bedload number, first introduced by Hans Albert Einstein in 1950, and given by

$$\Phi = \frac{q_B}{\sqrt{(s-1)gd^3}} \tag{1.34}$$

where $s = \rho_s/\rho$.

It is common practice to quantify bedload transport empirically relating Φ with either the Shields stress θ or the excess of the Shields stress θ above some appropriately defined "critical" Shields stress $(\theta - \theta_{cr})$. The critical Shields stress θ_{cr} is defined so as to fit experimental or field data and provide a threshold for which the bedload transport rate is too low to be of interest. The Shields parameter, takes the following form

$$\theta = \frac{h\sqrt{S_{fx}^2 + S_{fy}^2}}{(s-1)d} \tag{1.35}$$

where h is the water depth, S_{fx} and S_{fy} the friction slope in x- and y-direction respectively, $s = \rho_s/\rho_w$, and d is the grain size diameter. Note that Eq. 1.27 and Eq. 1.35 are equivalent.

In what follows, we describe the bedload transport formulas that are implemented to calculate the transport capacity $q_B = |\vec{q_B}|$, where the specific bedload flux vector $\vec{q_B} = (q_{B_x}, q_{B_y})$ generally has the same direction as the water flow.

For practical purposes, the bedload transport formula can be calibrated by an additional pre-factor (*factor*). The bedload transport capacity is obtained from the closure relation scaled by this pre-factor.

1.2.2.4.1 Meyer-Peter and Müller (1948)

The bedload transport formula of Meyer-Peter and Müller (Meyer-Peter and Müller, 1948) defines the specific bedload transport rate q_B as:

$$q_B = \alpha(\theta - \theta_{cr})^m \sqrt{(s-1)gd^3} \tag{1.36}$$

Herein, α denotes the bedload coefficient (originally $\alpha = 8$), m the bedload exponent (originally $m = 1.5$), θ is the dimensionless bed shear stress (Shields parameter), θ_{cr} is the critical dimensionless bed shear stress, d is the grain diameter, $s = \rho_s/\rho$ and g stands for the gravitational acceleration. Meyer-Peter and Müller observed in their experiments that the first grains moved already for $\theta_{cr} = 0.03$. But as their experiments took place with steady conditions they used a value for which already 50% of the grains where moving. They proposed the value of $\theta_{cr} = 0.047$. The formula of Meyer-Peter and Müller is applicable in particular for coarse sand and gravel with grain diameters larger than 1 mm (Malcherek, 2001).

The bedload coefficient α, the exponent m and the critical Shields parameter θ_{cr} can be adapted by the user in the MPM-like formula.

1.2.2.4.2 Meyer-Peter and Müller (1948) with hiding and exposition effects after Ashida and Michiue (1971)

This closure relation for bedload transport of sediment mixtures extends the formula of Meyer-Peter and Müller (Meyer-Peter and Müller, 1948) by consideration of hiding and exposition effects according to the approach Ashida and Michiue (Ashida and Michiue, 1971). It is defines the specific bedload transport rate q_B as

$$q_{B,g} = \alpha(\theta - \theta_{cr,g})^m \sqrt{(s-1)gd_m^3}, \tag{1.37}$$

where d_m is the geometric mean diameter of the sediment mixture in the active layer, and $\theta_{cr,g}$ is the dimensionless citical shear for grain class g calculated as:

$$\theta_{cr,g} = \theta_{cr,ref}\xi_g. \tag{1.38}$$

The reference dimensionless critical shear stress $\theta_{cr,ref}$ is usually defined with a fixed value (e.g. $\theta_{cr,ref} = 0.047$) and the hiding factor ξ_g is defined as Ashida and Michiue (1971):

$$\xi_g = \begin{cases} [\log(19)/\log(19 d_g/d_m)]^2 & d_g/d_m \geq 0.4 \\ 0.843 d_m/d_g & d_g/d_m < 0.4 \end{cases} \tag{1.39}$$

d_g and d_m denote the grain size diameter of grain class g and the geometric mean diameter of the sediment mixture in the active layer, respectively.

The bedload coefficient α, the exponent m and the critical Shields parameter θ_{cr} can be adapted by the user in the MPM-like formula.

1.2.2.4.3 Grass Formula

The Grass formula (Grass, 1981) proposes a simple bedload transport formula, where q_b is a function of the flow velocity u and a dimensional constant α and does not require the evaluation of the Shields stress:

$$q_B = \alpha(u - u_c)^m \cdot \sqrt{(s-1)gd^3} \tag{1.40}$$

where $\alpha \in [0, 1]$ is a dimensional constant that encompasses the effects of grain size and kinematic viscosity and is usually determined from experimental data, u_c is the critical velocity and the exponent m is usually set to $m = 3$. The threshold condition for incipient motion of grains is typically set to zero, meaning that the bedload transport and the fluid motion start simultaneously. The coefficient α characterizes the interaction between the bed and the fluid. If $\alpha = 0$, no sediment transport occurs. If $\alpha = 1$ the interaction between the bed and fluid is the largest.

1.2.2.4.4 Engelund and Hansen (1972)

Engelund and Hansen (1972) proposed a transport formula for uniform bed material taking into account at the same time the presence of both bed- and suspended-load. This formula is commonly used as a bulk load formula and reads

$$q_B = 0.05\sqrt{(s-1)gd^3} \cdot c_f^2 \theta^{2.5} \tag{1.41}$$

where d denotes the median sediment size of the bed material, c_f the dimensionless Chézy friction coefficient and θ is the dimensionless bed shear stress (see eq. 1.35). The Engelund and Hansen formula for bedload transport does not consider the critical shear stress as threshold condition for incipient motion.

1.2.2.4.5 Smart & Jäggi (1983)

Smart and Jaeggi (1983) developed a bedload transport formula for steep channels using their own experimental results and the results of Meyer-Peter and Müller (Meyer-Peter and Müller, 1948). The specific bedload transport rate q_B is defined as:

$$q_B = \frac{\alpha}{(s-1)} \left(\frac{d_{90}}{d_{30}}\right)^{0.2} J^{0.6} |\vec{q}| (J - J_{cr}) \tag{1.42}$$

where s is the sediment density coefficient ($s = \rho_s/\rho$), $|\vec{q}|$ is the magnitude of the specific discharge and d_{30} and d_{90} are the characteristic grain size diameters, i.e. 30 % resp. 90 % (by weight) of the bed material are smaller. The energy slope J and the critical slope for the initiation of the bedload transport J_{cr} calculated as

$$J = \frac{\theta(s-1)d_m}{h} \tag{1.43}$$

$$J_{cr} = \frac{\theta_{cr}(s-1)d_m}{h} \tag{1.44}$$

where θ is the dimensionless bed shear stress (see eq. 1.35), θ_{cr} the critical dimensionless bed shear stress, d_m the mean grain size diameter and h the water depth. Smart and Jaeggi (1983) recommend values of $\alpha = 4$ and $\theta_{cr} = 0.05$. The scope of applictation is for bed slopes 0.005 ≤ J ≤ 0.2 (Smart and Jaeggi, 1983).

1.2.2.5 Wilcock and Crowe (2003)

Wilcock and Crowe developed a sediment transport model for sand/gravel mixtures (Wilcock and Crowe, 2003), similar to Parker's model (Parker, 1990), and it was developed with a large experimental results dataset. It references fractional transport rates to the size distribution of the bed surface, rather than the subsurface, making the model explicit and capable of predicting transient conditions. The hiding function incorporated in the model resolves discrepancies obvserved among earlier hiding functions implemented in other transport models, such as the Oak Creek and the Cambridge ones (Parker and Sutherland, 1990). The Wilcock and Crowe model (Wilcock and Crowe, 2003) uses the full grain size distribution of the bed surface, including sand, incorporating a non-linear effect of sand content on gravel transport rate. The specific bedload transport rate $q_{B,g}$ for grain class g is defined as:

$$q_{B,g} = \frac{F_g u_*^3}{(s-1)g} W_g^*, \tag{1.45}$$

where F_g is the active layer fraction of grain size class g, u_* is the shear velocity ($u_* = (\tau/\rho)^{0.5}$, s is the sediment density coefficient ($s = \rho_s/\rho$) with the sediment density ρ_s and water density ρ, and g the gravitational acceleration. The dimensionless bedload transport rate W_g^* is defined as "

$$W_g^*(\phi_g) = \begin{cases} 0.002\phi_g^{7.5} & \phi_g < 1.35 \\ 14\left(1 - \dfrac{0.894}{\phi_g^{0.5}}\right)^{4.5} & \phi_g \geq 1.35 \end{cases} \tag{1.46}$$

with $\phi_g = \tau/\tau_{r,g}$. The reference shear stress $\tau_{r,g}$ of grain class g (a surrogate for a critical Shields number) is defined as:

$$\tau_{r,g} = \tau_{r,g}^*(s-1)\rho g d_g \tag{1.47}$$

where d_g is the grain diameter if grain size class g, and the dimensionless reference shear stress $\tau_{r,g}^*$ of grain class g as:

$$\tau_{r,g}^* = \tau_{r,m}^* \left(\frac{d_g}{d_m}\right)^{b-1} \quad ; \qquad \text{with} \quad b = \frac{0.67}{1 + \exp\left(1.5 - \frac{d_g}{d_m}\right)} \tag{1.48}$$

and the dimensionless reference shear stress of the mean grain diameter if the surface (geometric) $\tau_{r,m}^*$ is:

$$\tau_{r,m}^* = 0.021 + 0.015\exp\left(-20F_s\right). \tag{1.49}$$

The non-linear effect of sand content F_s on gravel transport is taken into account in $\tau_{r,m}^*$. Wilcock and Crowe (Wilcock and Crowe, 2003) have shown that increasing sand content in the bed active layer of a gravel-bed stream increases the surface gravel mobility. This effect is captured in their relationship between $\tau_{r,m}^*$ (a surrogate for a critical Shields number) and the fraction sand in the active layer F_s. Note that $\tau_{r,m}^*$ decreases as F_s increases, causing an increase of ϕ_g and in turn of the fraction bedload $q_{B,g}$.

1.2.2.5.1 Hunziker and Jaeggi (2002)

Hunziker and Jaeggi (Hunziker and Jaeggi, 2002) proposed a bed load formula for fractional bed load transport of graded sediment (also in (Hunziker, 1995)):

$$q_{Bg} = 5\beta_g[\xi_g(\theta'_{dms} - \theta_{cdms})]^{3/2}\sqrt{(s-1)gd_{ms}^3} \tag{1.50}$$

where θ'_{dms} denotes the Shields parameter of the mean grain size of the surface bed material d_{ms} according to eq. 1.51, ξ_g denotes the hiding function applied on the excess shear stress $(\theta'_{dms} - \theta_{cdms})$.

$$\theta'_{dms} = \frac{\tau'_b}{\rho_w\left(s-1\right)d_{ms}} \tag{1.51}$$

Note that due to the correction of the excess shear stress $(\theta'_{dms} - \theta_{cdms})$, the transport formula is based on the concept of "equal mobility", i.e. all grain classes start to move at same flow condition. The critical Shields parameter θ_{cdms} of the mean grain size diameter is determined according to

$$\theta_{cdms} = \theta_{ce}\left(\frac{d_{mo}}{d_{ms}}\right)^{0.33} \tag{1.52}$$

where θ_{ce} denotes the critical Shields parameter for incipient motion for uniform bed material. Two sediment layers are distinguished: the upper mixing layer which is in interaction with the flow and a subsurface layer below. Here, d_{ms} denotes the mean grain size diameter of surface bed material and d_{mo} denotes the mean grain size diameter of subsurface bed material. This relation (d_{ms}/d_{mo}) can be approximated as a function of the Shields parameter of the mean grain size of the surface bed material as

$$\frac{d_{ms}}{d_{mo}} = 0.0163\theta'^{-1.45}_{dms} + 0.6 \tag{1.53}$$

Finally, the hiding function is determined as

$$\xi_g = \left(\frac{d_g}{d_{ms}}\right)^{-\alpha} \tag{1.54}$$

where α is an empirical parameter depending on the Shields parameter (see also Hunziker and Jaeggi (2002)) according to eq. 1.55, which is limited to a range between -0.4 and 2.0.

$$\alpha = 0.011\theta'^{-1.5}_{dms} - 0.3 \tag{1.55}$$

1.2.2.6 Correction of Bedload Direction

The 2D projection of the solid discharge along x and y is obtained through standard procedures, that are mostly based on empirical basis and which account for the downward effect of gravity on sediment particles due to local bed slope and the presence of spiral flow motion in curved reaches.

1.2.2.6.1 Lateral Bed Slope Effect

Empirical bedload formulas were originally derived for situations where bed slope equals flow direction. However, in case of lateral bed slope with respect to flow direction, the bedload direction differs from the flow direction due to gravity acting on the bed material. Figure 1.4 illustrates the deviation of the bedload transport direction due to lateral bed slope in a Cartesian coordinate system.

The bedload direction is corrected for lateral bed slope based on the following approach (e.g. see Ikeda (1982) and Talmon et al. (1995)):

$$\tan\varphi_b = -f(\theta)\cdot\ \vec{s}\cdot\ \vec{n}_q \quad \text{for} \quad \vec{s}\cdot\vec{n}_q < 0 \tag{1.56}$$

$$f(\theta) = N_l\left(\frac{\theta_{cr}}{\theta}\right)^{M_l} \tag{1.57}$$

where φ_b = bedload direction with respect to the flow vector $\vec{q}$, N_l = lateral transport factor ($0.75 \le N_l \le 2.63$), M_l = lateral transport exponent (typically $M_l = 0.5$), $\vec{s} = \left(\frac{\partial z_B}{\partial x}, \frac{\partial z_B}{\partial y}\right)$ bed slope (positive uphill, negative downhill), $\vec{n}_q$ = unit vector perpendicular to $\vec{q}$ pointing in downhill direction ($\vec{s}\cdot\vec{n}_q < 0$) , θ = effective dimensionless shear stress and θ_{cr} = critical dimensionless shear stress of sediment.

The direction of the bedload transport under the influence of lateral bed slope is written as:

$$\frac{q_{B_y}}{q_{B_x}} = \tan(\varphi_b + \varphi_q) \tag{1.58}$$

1.2.2.6.2 Curvature Effect

Curvature in rivers may cause deviation of the bedload direction from the depth averaged flow direction. Due to three dimensional spiral flow motion, the bedload direction tends to

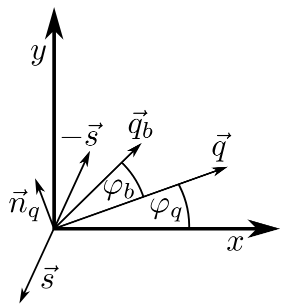

Figure 1.4 *Bed load transport deviation angle φ_b from the flow direction $\vec{q}$ due to the lateral bed slope $\vec{s}$ (Vonwiller, 2017)*

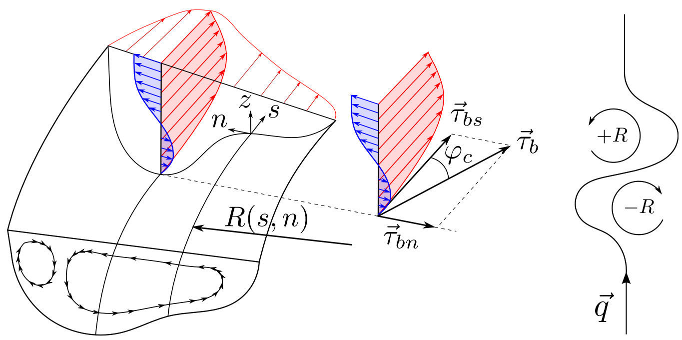

Figure 1.5 *Effect of spiral motion in river bend on bed shear stress $\vec{\tau}_b$ with deviation angle from main flow direction φ_c (Vonwiller, 2017)*

point towards the inner side of the curve, while the flow direction points towards the outer side (Figure 1.5). This curvature effect is taken into account according to an approach proposed by Engelund (1974) , where the deviation angle φ_c of the bottom shear stress $\vec{\tau}_b$ (positive counterclockwise and vice versa) from the main flow direction is determined as

$$\tan \varphi_c = \frac{|\vec{\tau}_{bn}|}{|\vec{\tau}_{bs}|} = -N_* \frac{h}{R} \tag{1.59}$$

where $\vec{\tau}_{bn}$ and $\vec{\tau}_{bs}$ are the bed shear stress normal to and in the flow direction respectively, h denotes the water depth, N_* is a curvature factor, and R denotes the radius of the river bend (positive for curvature in counterclockwise direction and vice versa).

Note that the curvature factor N_* mainly depends on bed roughness. Therefore, $N_* \approx 7$ for natural streams (Engelund, 1974), and values up $N_* \approx 11$ for laboratory channels (Rozovskii, 1961).

1.2.2.7 Bed Material and Fixed Bed Concept

With the feature of the bedload transport for sediment mixtures, the concept of soil layers, as it is implemented in the BASEMD module, was adopted for BASEHPC. Soils consisting of different vertical layers can be defined via the SOILDEF block to characterize the bed subtrate. Soils can subsequently be assigned to different regions of the computational

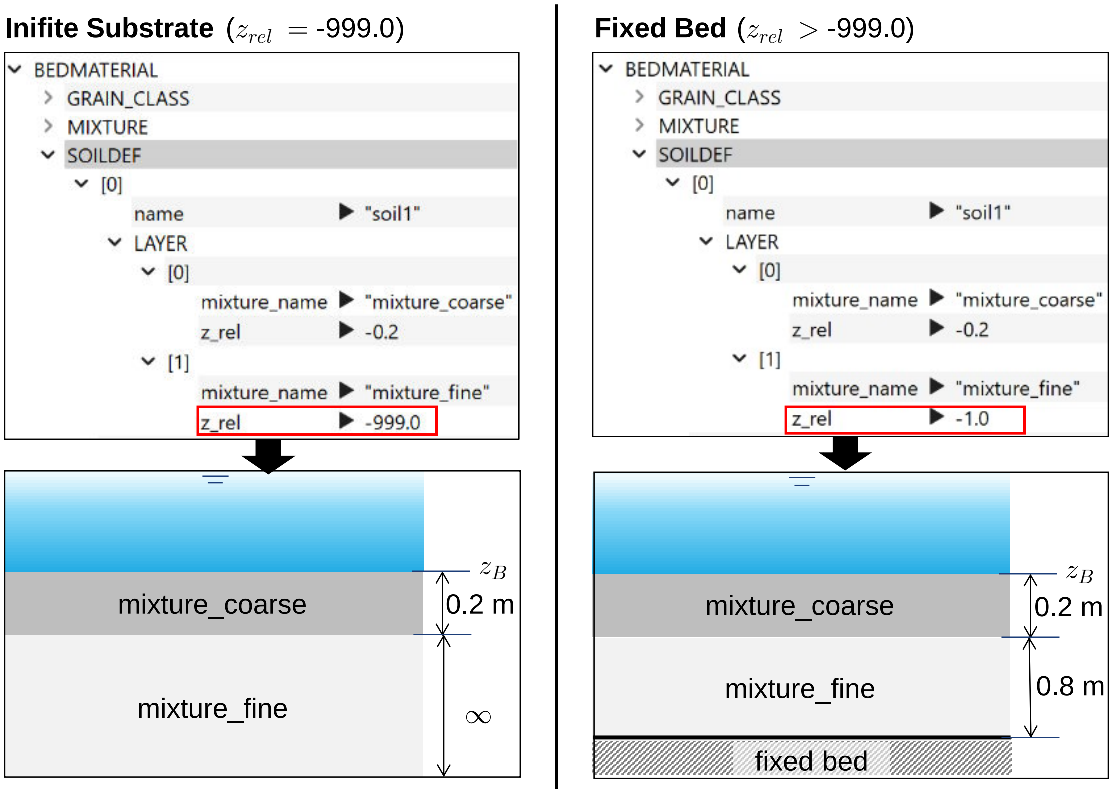

Figure 1.6 *Definition of an infinite substrate by using default value of z_{rel} = -999.0 for the lowest soil layer or definition of a fixed bed by using a value z_{rel} > -999.0*

domain within the SOIL_ASSIGNMENT block. Currently, the number of layers per soil is limited to 2 for reasons of computational efficiency. Each layer is defined through a sediment mixture and an elevation relative to the bed elevation ($z_{rel} \leq 0$), which defines the lower edge of the layer. When a new layer is created in the graphical user interface (GUI), the default relative elevation for is -999.0 meters. Setting a z_{rel} value for the lowest layer of a soil other than the default value of -999.0, is equivalent to defining a fixed bed elevation at this relative elevation, as illustrated in Fig. Figure 1.6.

The soil definition in combination with the active layer thickness detmines the intitialization of the vertical bed substrate. An example is given in Figure Figure 1.7. In the example, the soil is characterized by two layers: a upper layer with coarse sediment of 0.2 m thickness and a lower layer with finer sediment with infinite thickness. The choice of the active layer thickness L_a either smaller, equal or larger than the upper soil layer affects the number of initialized sublayers, as well as the composition of the active layer at the start of the simulation.

For restart or re-run simulations, the composition of bed material, including the active layer and sublayer composition can be provided from a result H5-file via the INITIAL block inside the BEDMATERIAL block.

Morphodynamic simulations generate deposition and erosion patterns of the riverbed. Erosion processes, if not limited, can proceed indefinitely in the vertical direction. This limit can be imposed by defining a non-erodible fixed bed elevation z_{rel}, below which the river bed is considered as *fixed*. This threshold also determines the amount of sediment available for transport (see Figure 1.8). There are three ways to define a fixed bed elevation:

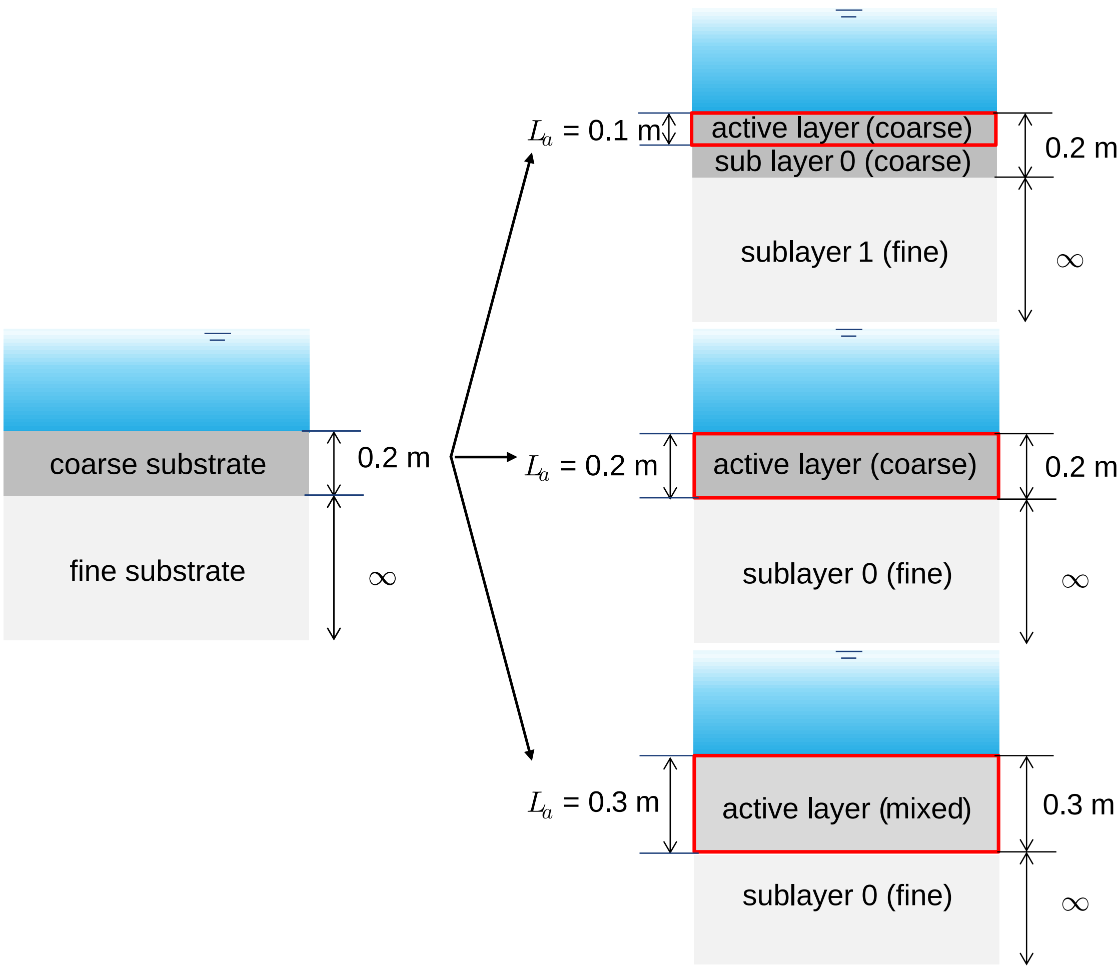

Figure 1.7 *The initialization of the active layer and sublayers is determined by the soil layers and the active layer thickness*

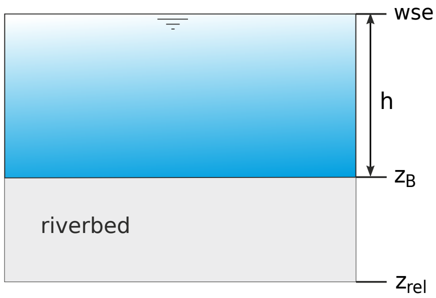

Figure 1.8 *Fixed bed concept and definition*

(1) via regions in the FIXED_BED block, or (2) via a separate .2dm mesh file in the FIXED_BED block, or (3) via layers in the SOILDEF block, as mentioned above. If fixed bed elevations are defined both in the FIXED_BED and SOILDEF blocks, definitions in FIXED_BED block overwrite fixed bed information from the SOILDEF block.

When the fixed bed elevation is specified via regions or via layers, the fixed bed elevation must be provided relative to the initial bottom elevation z_B with $z_{rel} \leq 0$. When the fixed bed elevation is specified via a mesh, the elevation in the separate .2dm mesh file must correspond to the absolute fixed bed elevation z_{fix} [m]. Moreover, the fixed bed mesh file must have the exact same topology as the original computational mesh. In case the specified mesh only has elevation information on the nodes, the elevation is interpolated with the same method as specified in the INTERPOLATION block (default: mean). If the fixed bed elevation of the fixed bed mesh exceeds the bottom elevation of the computational mesh, the fixed bed elevation is defined at the elevation of the computational mesh.

The accuracy of the fixed bed correction is guaranteed by defining the maximal overshoot below the fix bed elevation and the maximal number of iterations required for the correction.

Warning: Defining a fixed bed elevation can slow down computations compared to simulations with a mobile bed.

1.2.2.8 Gravitational Transport

Gravitational induced riverbank or sidewall failures are significant aspects concerning erosion and transport modelling. Such processes may play an important role in many situations, such as meandering streams, river widenings or failures of erodible embankment structures due to overtopping waters. Such slope failure processes take place mostly discontinuous and can deliver significant contributions to the total sum of transported material. The modes of slope failures can differ largely (falls, topples, slides, etc.) and depend on the soil material, the degree of soil compaction and the pore pressures within the soil matrix. Here, a simplified, geometric approach is applied to be able to consider some aspects of this purely gravitational induced transport. The main idea of the implemented geometrical approach is to assume that a slope failure takes place if the local bed slope γ becomes steeper than a critical slope γ_{cr} (Figure 1.9).

$$q_{B,grav} = \begin{cases} 0 & \text{if}\,(\gamma \leq \gamma_{cr}) \\ f(\gamma, \gamma_{cr}) & \text{if}\,(\gamma > \gamma_{cr}) \end{cases} \tag{1.60}$$

The sliding material is moved from the sediment element with higher elevation to the lower

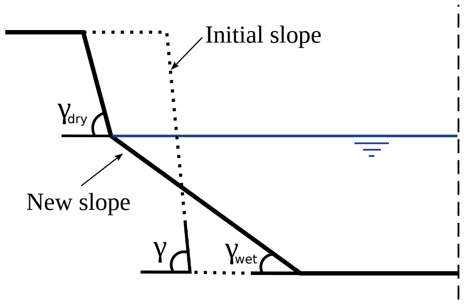

Figure 1.9 *Critical failure angles for slope collapse*

situated element until the stable condition: $\gamma \leq \gamma_{cr}$ is reached. Two characteristic critical slope angles are defined in this approach to have some flexibility in modelling the complex geotechnical aspects. The critical angles can be characterized as:

- critical angle for dry or partially saturated bank material γ_{dry}, which may greatly exceed the material's angle of repose (up to nearly vertical walls) due to negative pore pressures,
- critical angle for fully saturated and over flown material γ_{wet} which is in the range of the material's angle of repose

1.2.2.8.1 Calculation Proceedure

The flux due to gravitational transport $q_{B,grav}$ is calculated with the following proceedure, by looping over each element of the computational grid:

1. In a first steep, the local bed slope γ_i is calculated with respect to each neighbouring element i, where z is the bed elevation of the main element, z_i is the bed elevation of the neighbour element i and d_i is the distance between the element centers.

$$\gamma_i = textarctan\left(\frac{z - z_i}{d_i}\right) \tag{1.61}$$

2. For local bed slopes γ_i exceeding the critical slope γ_{cr}, the new bed elevations z_{new} and $z_{i,new}$ are determined such that the stable condition $\gamma_i = \gamma_{cr}$ is reached for all neighbouring cells i. The critical angle γ_{cr} is selected according to eq. 1.62, where h is the water depth in the main element and h_{min} is the user-specified minimum water depth.

$$\gamma_{cr} = \begin{cases} \gamma_{wet} & \text{if}\, h \geq h_{min} \\ \gamma_{dry} & \text{if}\, h < h_{min} \end{cases} \tag{1.62}$$

3. If the calculated bed elevation change of the main element $\delta_z = z - z_{new}$ is smaller than the user-specified parameter *min_bed_change* (default: 0.001 m) $\delta_{z,min}$, no gravitational transport occurs to avoid oscillatory behaviour and to reduce the

computational effort. If the minimum bed elevation change $\delta_{z,min}$ is exceeded, the specific gravitational flux $q_{B,grav,i}$ [m^2/s] to each neighbour element i is calculated from the bed elevation change in element i according to eq. 1.63, where A_i is the area of element i, and l_i is the length of the edge connecting the main element to its i^{th} neighbour element. If the calculated bed elevation change of the main element $\delta_z = z - z_{new}$ is larger than the user-defined maximum bed elevation change $\delta_{z,max}$, the gravitational flux is limited, such that $\delta_z = \delta_{z,max}$. The maximum bed elevation change $\delta_{z,max}$ is calculated by eq. 1.64, where $r_{b,max}$ is the user-specified parameter *max_bed_change_rate* and Δt is the current update time step.

$$q_{B,grav,i} = \begin{cases} 0 & \text{if } \delta_z < \delta_{z,min} \\ \frac{(z_{i,new} - z_i) \cdot A_i}{l_i} & \text{if } \delta_z \geq \delta_{z,min} \\ \frac{(z_{i,new} - z_i) \cdot A_i}{l_i} \cdot \frac{\delta_{z,max}}{\delta_z} & \text{if } \delta_z \geq \delta_{z,max} \end{cases} \tag{1.63}$$

$$\delta_{z,max} = r_{b,max} \cdot \Delta t \tag{1.64}$$

4. If a non-erodbile fixed bed elevation z_{fix} is specified, the gravitational transport flux is corrected the same way as the bedload transport flux (see Section 1.2.2.7).

5. Finally, the balancing of the gravitational fluxes and the determination of the new bed elevations z is achieved by solving the Exner equation using the same numerical approaches as outlined for the bed load transport. This procedure ensures that fixed bed elevations are taken into account and the mass continuity is fulfilled.

1.2.2.8.2 Time Scale of the Gravitational Transport Process

Since the sediment movement due to gravitational transport during one update time step is limited to adjacent elements, it may take many update time steps to reach a stable condition on a larger scale, e.g. a bank slope spanning over multiple elements. The time scale until a globally stable condition is reached, is influenced by the update time step (update_time), the maximum bed change rate (max_bed_change_rate) and the grid resolution. The parameter *update_time* (default: 0.0 s) determines at which frequency the gravitational transport proceedure (steps 1-5 above) is executed. Generally, a smaller update time step reduces the time scale until a globally stable condition is reached. The default behaviour is to set the update time step value to 0.0 seconds, which results in the gravitational transport proceedure being executed at the same time step as determined from the hydraulic CFL-criterium (see Section 2.3.4).

Furthermore, the speed of the gravitational transport process can be limited with the parameter *max_bed_change_rate* (default: 1.0 m/s). This parameter represents a maximum rate at which the bed elevation of a cell can be lowered due to gravitational transport and determines the maximum bed elevation change during one update time step. Generally, a smaller value may increase the time scale until a globally stable condition is reached.

Since sediment movement due to gravitational transport is limited to adjacent elements, also the grid resolution effects the time scale until a globally stable condition is reached. A finer grid resolution (smaller elements) increases the necessary number of update cycles the reach a stable slope over a specific length. However, a finer grid resolution may also

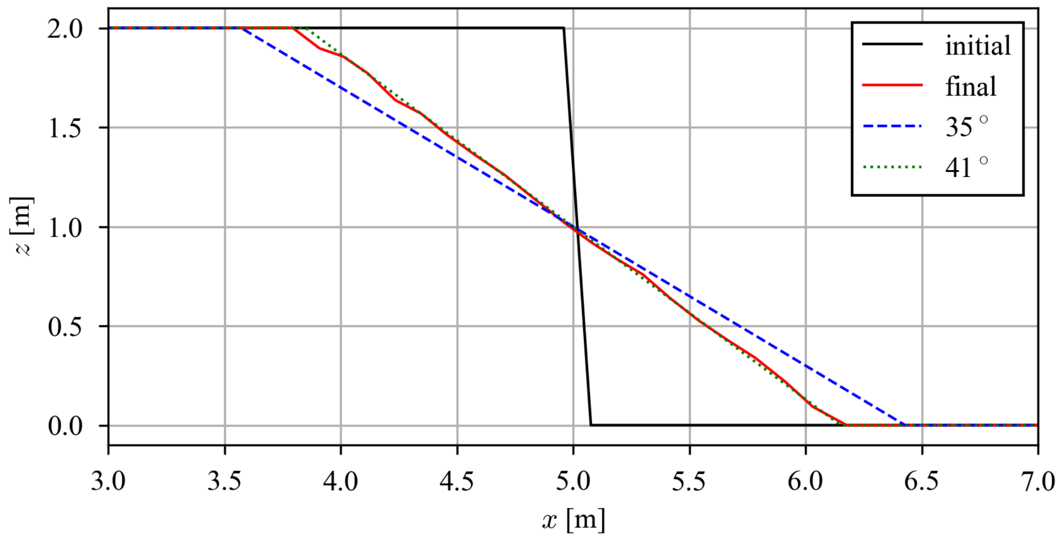

Figure 1.10 *Initial and final bed elevation profiles along the centerline are compared to profiles with angles of 35° and 41°. The slope of the bed profile at stable conditions (final) exceeds the critical angle of γ_{dry} = 35°.*

decrease the hydraulic time step and therefore may the increase frequency at which the gravitational transport procedure is executed.

1.2.2.8.3 Bed slope at Stable Condition

The implemented approach for modelling gravitational transport processes ensures that the local bed slope does not exceed the user-specified critical angle. Due to the spatial discretization with constant bed elevations within an element, the local bed slope is calculated between two element centers. On a larger scale (e.g. a bank slope spanning over multiple elements), the bed slope may deviate from the user-specified critical angle after reaching stable conditions. The stable bed slope over multiple elements, generally exceeds the critical bed slope.

To illustrate this effect, a simple test case was simulated. The rectangular computational domain is initially split into two parts: the left side with a bed elevation of 2 meters and the right side with a bed elevation of 0 meters. The domain is completely dry and the critical angle for dry material is set to $\gamma_{dry} = 35°$. The simulation only considers only gravitational tranport and is stopped after a stable condition is reached. The initial and final bed elevation profile along the centerline are illustrated in Figure 1.10. The initial profile exhibits the nearly vertical bed step. The final profile at stable conditions exhibits a slope of approximately 41°, which exceeds the critical angle of $\gamma_{dry} = 35°$. The reason for this deviation on a larger scale is that the distance which is considered for the calculation of the slope is not a straight line, but a line connecting the element centers. This is illustrated in Figure Figure 1.11. Calculating the large scale slope considering the length of the green line results in a slope of approximately 41°, while considering the length of the red line results in a slope of approx. 35°.

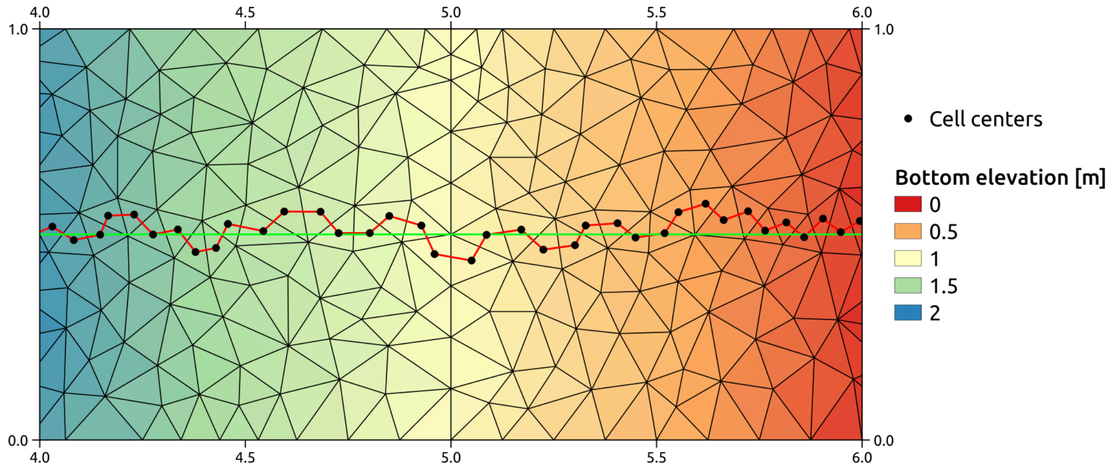

Figure 1.11 *The red line connects the element centers and represents the distance, which is taken into account for the* ***local slope*** *calculation and thus for the gravitational transport. The green line represents the direct distance, which is taken into account for the* ***large scale slope****. The slope along the red line corresponds to 35°, while the slope along the green line corresponds to 41°.*

1.2.2.9 External Sources Terms

The source term Sl_b represents additional sediment mass input or output (sink) that occurs locally on the computational domain on a set of elements defined by regions. The source can be specified as total volume flux including porosity $[m^3/s]$. Different approaches are used to manage the behaviour of the external sources in case of a negative flux (sink):

- Exact: The specified sediment volume is added or extracted (non conservative)
- Available: The specified sediment volume to extract is limited by the defined fixed bed elevation of the elements (conservative)
- Infinity: All available sediment will be abstracted (conservative)

Addition of sediment always follows the “Exact” behaviour as there is no upper limit. The abstraction of sediment could also follow the “Exact” behaviour but the simulation might end abruptly if the available sediment volume is smaller than the volume abstracted. Therefore, the “Available” behaviour aims to avoid this situation. The “Infinity” behaviour abstracts all available sediment volume.

1.2.2.10 Boundary Conditions

After the specification of the *closure relations* for the sediment transport, the system of governing equations (eq. 1.1) and (eq. 1.22) can be solved within the modeling domain described in Figure 1.1, provided boundary conditions (morphologic boundary conditions) are specified at the domain boundary Γ. For the sediment transport only *external boundaries* that allow sediment flowing into or out of the domain can be specified. A morphologic boundary condition can be co-located with a hydraulic boundary condition. In case no hydraulic boundary condition is specified, the boundary will behave as a wall and sediment transport will not occur.

1.2.2.11 Upstream Boundary Condition

- *equilibrium_in*: After erosion or deposition up to a user specified reference bed elevation (*reference_bed_elevation*) this upstream boundary condition grants a equilibrium condition, i.e. the same amount of sediment leaving the first computational cell in flow direction enters the cell from the upstream boundary. This leads to a constant bed elevation at the boundary condition.
- *sedimentograph*: based on a sediment hydrograph describing the bedload inflow as function of time (constant or variable). The bedload is defined as a volumetric flow rate $Q_b = \dfrac{\mu_s}{\rho_s}$ $[m^3/s]$, where μ_s is the sediment mass flow rate $[kg/s]$ and ρ_s the sediment density $[kg/m^3]$. Notice that the porosity is not considered in the bedload input and is specified separately as own parameter value. The volumetric flow rate is either distributed using a geometrical weighting (*sedimentograph*), using wetted area weighting (*sedimentograph_warea*) or using wetted conveyance weighting (*sedimentograph_conveyance*). **Note:** When using the pre-factor (*factor*) described in Section 1.2.2.4, it is automatically applied to the volumetric flow rate at the boundary for these types of boundary conditions, i.e. the sediment hydrograph is scaled by the pre-factor.

- *transport_capacity*: the sediment inflow is defined by calculating the equilibrium transport capacity according to the hydraulic state at the boundary. The bedload is defined as a compact volumetric flow rate (without porosity) Q_b $[m^3/s]$. The volumetric flow rate is either distributed using a geometrical weighting (*transport_capacity*), using wetted wetted area weighting (*transport_capacity_warea*) or using wetted conveyance weighting (*transport_capacity_conveyance*). **Note:** When using the pre-factor (*factor*) described in Section 1.2.2.4, the pre-factor is implicitly included in the volumetric flow rate at the boundary for this type of boundary condition, i.e. the transport capacity at the boundary is scaled by the pre-factor. Additionally, an independent scaling factor can be specified (*boundary_factor*), only applying to these types of the boundaries.

For the sediment discharge and transport capacity boundary condition types, the specific sediment discharge q_b is distinguished by three weighting schemes:

1. Geometrical weighting with respect to the total nodestring length L_n.

$$q_b = \frac{Q_b}{L_n} \qquad \left[\frac{m^3}{s \cdot m}\right] \tag{1.65}$$

2. Wetted area weighting

$$q_b = \frac{Q_b}{A_{w,tot}} \cdot h \qquad \left[\frac{m^3}{s \cdot m^2}\right] \tag{1.66}$$

3. Conveyance weighting

$$q_b = \frac{Q_b}{K_{tot}} h\sqrt{c_f h} \qquad \left[\frac{m^3}{s \cdot m}\right] \tag{1.67}$$

with $K_{tot} = A_{w,tot}\sqrt{c_f h}$ the total conveyance and c_f the friction coefficient.

1.2.2.12 Downstream Boundary Condition

One downstream boundary condition is available:

- *equilibrium_out*: After erosion or deposition up to a user specified reference bed elevation (*reference_bed_elevation*) this downstream boundary condition grants a equilibrium condition, i.e. all sediment entering the last computational cell will leave the cell over the downstream boundary. This leads to a constant bed elevation at the boundary condition.

1.2.2.13 Linked Boundary Condition

One linked boundary condition is available:

- *equilibrium_linked*: At the upsteam boundary, erosion or deposition is possible up to a user specified reference bed elevation (*reference_bed_elevation*). After reaching the reference elevation, this boundary condition grants a equilibrium condition, i.e. all sediment leaving the computational cells on the upstream side is entering at the downstream boundary with a lag of one timestep. This leads to a constant bed elevation at the upstream boundary.

1.3 Suspended Sediment Transport

1.3.1 Governing Equations for Uniform Suspended Sediment Transport

Similarly to bedload, the governing equations are also derived under shallow water conditions ensuring mass conservation extends to the suspended sediment phase. In a Cartesian reference system $(x; y; z)$ in which the z axis is vertical and the $x - y$ plane is horizontal, the conservation of suspended sediment mass is ensured by an advection-diffusion equation with source terms, describing the bed interaction and elevation changes arising from resuspension and deposition.

$$\frac{\partial}{\partial t} C_s h + \frac{\partial}{\partial x_i} \left(C_s h u_i - h D_{s_{ij}} \frac{\partial C_g}{\partial x_j} \right) = S_s + Sl_s \tag{1.68}$$

where C_s is the concentration of suspended sediment, $D_{s_{ij}}$ is its diffusivity (tensor), Sl_s are local sources and S_s aggregates the source terms that parameterize vertical exchanges with the bed.

1.3.2 Closures for Suspended Transport

For suspended sediment transport, the source term S_s represents the exchange with the bed and is calculated through the difference between the deposition rate q_d and the resuspension rate q_e.

$$S_s = q_e - q_d \tag{1.69}$$

1.3.2.1 Deposition rate

The deposition rate is expressed as the a sink flux:

$$q_d = w_s \alpha_s C_s \tag{1.70}$$

where w_s is the settling velocity and α_s is an adaptation coefficient. The adaptation coefficient can be determined through two distinct approaches, the first being provided by Lin (1984) as

$$\alpha_s = m\left(3.25 + 0.55\ln\left(\frac{w_s}{\kappa u_*}\right)\right) \tag{1.71}$$

where κ is the von Karman constant and m is a tuning parameter (default value 1.0). The the second is based on the critical shear stress approach of Xu (1998)

$$\alpha_s = \begin{cases} \left(1 - \frac{\tau}{\tau_{c,d}}\right) & \tau < \tau_{c,d} \\ 0 & \tau \geq \tau_{c,d} \end{cases} \tag{1.72}$$

with

$$\tau_{c,d} = \frac{\rho_s - \rho}{\rho_s}\frac{ghw_s}{mU} \tag{1.73}$$

and where m is a calibration parameter which has been suggested to take a value of 0.0018.

1.3.2.2 Erosion rate

The erosion (or resuspension) rate, q_e, is given by

$$q_e = w_s \beta_s C_r \tag{1.74}$$

where w_s is the settling velocity of particles (see Section 1.3.2.3), β_s is a calibration constant and C_r is a reference concentration which can be determined by multiple options available in the literature. According to van Rijn (1984), the reference concentration can be calculated as

$$C_r = a\frac{d_g}{b}\frac{T_g(\theta_c)^c}{D^{*d}} \tag{1.75}$$

where:

T_g is the dimensionless characteristic number for the bottom shear stress, b is the reference height above the mean bed bottom, D^* is the dimensionless diameter and a, c and d are calibration constants with default values $(a, b, c, d) = (0.015, 0.05, 1.5, 0.3)$. Another approach is the one of Zyserman and Fredsøe (1994), calculated as

$$C_r = \frac{a(\theta_s - \theta_c)^c}{1 + b(\theta_s - \theta_c)^d} \tag{1.76}$$

where a, b, c and d are calibration constants with default values $(a, b, c, d) = (0.331, 0.72, 1.75, 1.75)$.

1.3.2.3 Settling Velocities of Particles

The settling velocity w_s of sediment particles is an important parameter when determining suspended load. Many different empirical or semi-empirical formulas have been suggested in literature, with the following being implemented:

1.3.2.3.1 van Rijn

The sink rate can be determined according to the grain diameter after van Rijn (1984):

$$w_s = \frac{(s-1)gd^2}{18\nu} \;\text{ for }\; 0.001 < d \le 0.1mm \tag{1.77}$$

$$w_s = \frac{10\nu}{d}\left(\sqrt{1+\frac{0.01(s-1)gd^3}{\nu^3}}-1\right) \;\text{ for }\; 0.1 < d \le 1mm$$

$$w_s = 1.1\sqrt{(s-1)gd} \;\text{ for }\; d \ge 1mm$$

where d is the diameter of the grain, ν is the kinematic viscosity and $s = \rho_S/\rho$ is the specific density.

1.3.2.3.2 Wu and Wang

Another approach for the computation of the sink velocity is the one of Wu et al. (2000):

$$w = \frac{M\nu}{Nd}\left[\sqrt{\frac{1}{4}+\left(\frac{4N}{3M^2}(D^*)^3\right)^{1/n}}-\frac{1}{2}\right]^n \tag{1.78}$$

where:

$M = 53.5e^{-0.65S_p}$
$N = 5.65e^{-2.5S_p}$ {#eq:30_mm_SuspLoad_Wu2}
$n = 0.7 + 0.9S_p$

S_p is the Corey shape factor, with a value for natural sediments of about 0.7 (0.3 - 0.9).

1.3.2.3.3 Zhang

The Zhang formula (Zhang, 1961) is based on many laboratory data and was developed for naturally worn sediment particles. It can be used in a wide range of sediment sizes in the laminar as well turbulent settling regions:

$$w_s = \sqrt{\left(13.95\frac{\nu}{d}\right)^2 + 1.09(s-1)gd} - 13.95\frac{\nu}{d} \tag{1.79}$$

1.3.3 External Source Terms

The source term Sl_s represents additional sediment mass input or output (sink) that occurs locally on the computational domain on a set of elements defined by regions. The source can be specified as total volume flux including porosity $[m^3/s]$ or by an imposed concentration [-]. Different approaches are used to manage the behaviour of the external sources in case of a negative flux (sink):

- Exact: The specified sediment volume is added or extracted (non conservative)

- Available: The specified sediment volume to extract is limited by the defined fixed bed elevation of the elements (conservative)
- Infinity: All available sediment will be abstracted (conservative)
- Concentration: This sink type allows to impose a specified concentration.

Addition of sediment follows the “Exact” behaviour as there is no upper limit. The abstraction of sediment could also follow the “Exact” behaviour but the simulation might end abruptly if the available sediment volume is smaller than the volume abstracted. Therefore, the “Available” behaviour aims to avoid this situation. The “Infinity” behaviour abstracts all available sediment volume.

1.3.4 Boundary Conditions

For the suspended sediment transport only external boundaries that allow sediment flowing into or out of the domain can be specified. Boundary conditions of suspended transport type can be co-located with hydraulic or bedload boundary conditions.

1.3.4.1 Upstream Boundary Condition

Two upstream boundary conditions are available:

- *discharge_in* and *discharge_in_warea*: based on a suspended sediment discharge inflow, either as a constant or a function of time, the prescribed volumetric flow rate $[m^3/s]$ is imposed at the boundary. The volumetric flow rate is either distributed using a geometrical weighting or a wet-area weighting.
- *concentration_in*: the suspended sediment inflow is defined by forcing a target concentration. The suspende sediment input rate is thus given by the target concentration paired with the total hydrodynamic mass flux.

1.3.4.2 Downstream Boundary Condition

- *zero_gradient_out*: this downstream boundary allows the free outflow of any tracer quantities in the flow. **Note:** If this condition is not prescribed, a wall condition is assumed and the tracer quantities will be retained (no outflow).

1.4 Passive tracers

1.4.1 Introduction

A multitude of dissolved species are present in environmental flows. In the context of hydraulic and environmental engineering, numerical modelling of scalar transport becomes a relevant tool mostly because of its versatility. In terms of advective phenomena, the most common applications include

- Pollutant fate and transport
- Accumulation or depletion of nutrients
- Calculation of water residence times
- Flow visualization

1.4.2 Transport of passive species

1.4.2.1 Governing Equations for passive specie transport

The governing equations are obtained under the shallow water framework and impose mass conservation for both fluid and dissolved phases.

In a Cartesian frame of reference $(x; y; z)$ in which the z axis is vertical and the horizontal lies in the $x - y$ plane, the system of governing equations is formed by (eq. 1.1) for hydrodynamics and is coupled with multiple equations for the conservation of the total tracer masses. The conservation of each tracer mass is ensured by the scalar continuity equation (eq. 1.80), which is tightly coupled to the shallow water equations. This equation allows to describe the evolution of the specie concentration as:

$$\frac{\partial}{\partial t} C_k h + \frac{\partial}{\partial x_i} \left(C_k h u_i - h D_{k_{ij}} \frac{\partial C_k}{\partial x_j} \right) = Sl_k \tag{1.80}$$

where C_k is the concentration of specie k, $D_{k_{ij}}$ is it's diffusion tensor and Sl_k is the local source term, specifying additional sources or sinks of the specie k.

1.4.2.2 External Sources Terms

The source term Sl_k conveys an input or output (sink) that occurs locally on the computational domain over elements limited by regions. It can be specified as total volumetric flux $[m^3/s]$ or by an imposed concentration [-]. Different approaches define the behaviour of external sources if it imposes negative fluxes (sink):

- Exact: The specified volume is added or extracted (non conservative)
- Available: The specified volume to extract is limited by the available tracer volume (conservative)
- Infinity: All available tracer volume will be extracted (conservative)
- Concentration: This sink type allows to impose a specified tracer concentration.

Additionally, there is the option of forcing a target concentration C_k^f homogeneously across all cells defined by the region.

1.4.2.3 Boundary Conditions

The system of governing equations (eq. 1.1) and (eq. 1.80) can be solved within the modeling domain described in Figure 1.1, provided that boundary conditions (hydrodynamical and tracer boundary conditions) are specified at the domain boundary Γ. For the tracer transport only *external boundaries* that allow tracer flowing into or out of the domain can be specified. A tracer boundary condition should be co-located with a hydraulic boundary condition. Otherwise, the boundary will behave as a wall and tracer transport will not occur.

1.4.2.4 Upstream Boundary Condition

Two upstream boundary conditions are available:

- *discharge_in* and *discharge_in_warea*: based on a tracer discharge inflow, either as a constant or a function of time, the prescribed volumetric flow rate Q_k $[m^3/s]$ is imposed at the boundary. The volumetric flow rate is either distributed using a geometrical weighting or a wet-area weighting, and the specific tracer discharge q_k is thus given by:

1. Geometrical weighting with respect to the total nodestring length L_n.

$$q_k = \frac{Q_k}{L_n} \qquad \left[\frac{m^3}{s \cdot m}\right]$$

2. Wetted-area weighting

$$q_k = \frac{Q_k}{A_{w,tot}} \cdot h \qquad \left[\frac{m^3}{s \cdot m}\right]$$

- *concentration_in*: the tracer inflow is defined by forcing a target tracer concentration C_k^f. The volumetric flow rate is thus given by the target concentration paired with the total hydrodynamic mass flux q through that boundary as $q_k = q\phi_k^f$.

Note: If the hydrodynamical mass flow at the boundary is not inward directed then no tracer flux is imposed.

1.4.2.5 Downstream Boundary Condition

One downstream boundary condition is available:

- *zero_gradient_out*: this downstream boundary allows the free outflow of any tracer quantities in the flow. **Note:** If this condition is not prescribed, a wall condition is assumed and the tracer quantities will be retained (no outflow).

1.5 Riparian vegetation

1.5.1 Introduction

Riparian vegetation is known to play an important role in mediating river morphodynamic processes at various spatial and temporal scales. Predicting river morphology has to account for the feedbacks between plants, flow, and sediment transport. On one hand, vegetation can modify the flow resistance and the shear stresses acting on the riverbed, thus influencing the overall flow pattern and rate of sediment transport. On the other hand, erosion and deposition processes may cause plant mortality through uprooting and burial during floods. Including vegetation into river morphodynamic simulations has potential applications for

- estimating sedimentation and erosion processes
- restoration projects
- riparian forests dynamics
- flood hazard mapping

1.5.2 Description of Vegetation

Vegetation is described by a dimensionless aboveground biomass density, B_c (subscript c stands for canopy), belowground density, B_r (subscript r stands for roots) and a rooting depth, D_r (see Figure 1.12). The sum of B_c and B_r should ideally be 1 at maximum, while there is no specific limit for the rooting depth. The model accounts also for the vegetation height, H, which is derived as $H = aB_c^b$, where a and b are constant parameters. B_c and B_r are considered to distribute linearly along the main vertical axis of the plant. The uprooting depth, D_{upr}, namely the depth at which uprooting occurs, is defined as $\beta_{upr} D_r$, with β_{upr} a constant input parameter that decreases the maximum erosion that vegetation can withstand. The burial height, H_{bur}, represents the effective plant height when the plant is submerged (due to bending) and is defined as $H_{bur} = \beta_{bur} H$, with β_{bur} a constant parameter (see Section 1.5.5).

1.5.3 Effect of Vegetation on Water Flow

The aboveground vegetation is assumed to change the bed roughness. This is included by modifying the Strickler's coefficient k_{str} $[m^{1/3}/s]$ (Bertoldi et al., 2014), such as

$$k_{str}(t) = k_{s,g} + (k_{s,v} - k_{s,g})B_c(t) \tag{1.81}$$

where $k_{s,g}$ represents the roughness of the bare bed, which depends on the sediment grain size, while $k_{s,v}$ ($< k_{s,g}$) is the roughness of a completely vegetated bed assumed to vary with species-specific canopy characteristics. The Strickler's coefficient can change during the simulation as B_c changes (see Section 1.5.5) (Caponi et al., 2020).

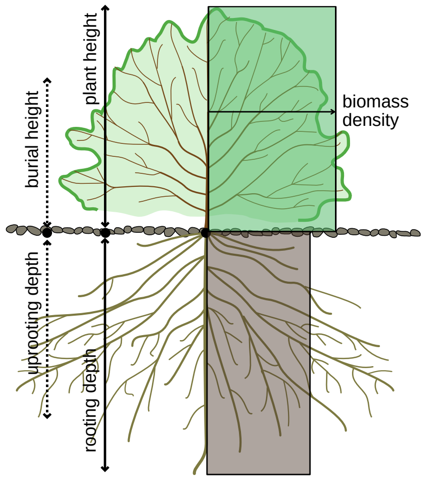

Figure 1.12 *Schematic representation of vegetation in the model. The vegetation state is described by an aboveground, belowground biomass, and a rooting depth. The other variables (uprooting depth, burial height, and plant height) are derived thought specific functions and input parameters. Adapted from Caponi et al. (2020)*

1.5.4 Effects of Vegetation on Bedload Transport

1.5.4.1 Bottom Shear Stress

The presence of vegetation is also known to affect the shear stresses acting on the bed surface and responsible for sediment transport. The reduction of bed shear stress is included in the model by multiplying the total shear stress by a factor $\gamma < 1$ and computing the sediment flux using a reduced dimensionless bed shear stress (Shields parameter), $\gamma\theta$. The parameter γ ranges between 0 and 1 and it is chosen according to $\gamma = k_{str}(t)/k_{s,g}$, with k_{str} evaluated as in eq. 1.81, (Caponi and Siviglia, 2018).

1.5.4.2 Critical Shear Stress

The role of root-enhanced riverbed cohesion is taken into account by increasing the critical Shields parameter (Bertoldi et al., 2014). Assuming an MPM-like formula (eq. 1.36), the critical Shields parameter θ_{cr} is defined as

$$\theta_{cr}(t) = \theta_{cr,g} + (\theta_{cr,v} - \theta_{cr,g})B_r(t) \tag{1.82}$$

in which $\theta_{cr,g}$ and $\theta_{cr,v}$ ($> \theta_{cr,g}$) represent the values used for bare bed and completely vegetated riverbed, respectively (Caponi and Siviglia, 2018).

1.5.5 Effects of Bed Changes on Vegetation

Bed level change causes three effects on vegetation in the model: uprooting, burial, and biomass redistribution.

1.5.5.1 Biomass Redistribution

As soon the bed level changes, the portion of vegetation above and below ground changes as well. The model assumes that the total biomass remains constant during a simulation, unless uprooting occurs. This means that in case of a positive bed level change, $\Delta z_B > 0$ (deposition), B_c will decrease by $\Delta z_B(B_c/H_{bur})$ and B_r will increase by the same amount, where H_{bur} is a fraction of the plant height. On the contrary, in case of bed level erosion, B_c will increase by $\Delta z_B(B_r/D_r)$ and B_r will decrease by the same amount (Caponi et al., 2020). Changes in B_c and B_r during the simulation will change the effects on flow and sediment transport associated with these values following eq. 1.82 and eq. 1.81.

1.5.5.2 Plant Burial

Plant burial is the mechanism by which a plant get covered by sediments, that is, when the bed level increases in a cell until reaching the burial plant height H_{bur}. This value takes into account the bending of the plant when submerged, which reduces the effective height of the plant. In case the bed level change reaches H_{bur}, B_c will go to zero, causing the k_{str} value to equal $k_{s,g}$. In case the bed level decreases again during the simulation, B_c can increase as well (Caponi et al., 2020). Plants can in fact resist well sedimentation processes, thanks to the high flexibility of the stems that prevents breakage.

1.5.5.3 Plant Uprooting

Plant uprooting occurs when the pulling forces applied on the plant by the water flow equal the resisting forces of the plant, which are given by the root system anchoring. We consider that this can occur only when part of the plant roots are already exposed to the flow, that is, when the bed level has decreased during the simulation (type II of uprooting, following the conceptual model of Edmaier et al. (2011)). Therefore, the uprooting is modelled by defining a critical depth at which the plant is removed. This depth is currently defined as a percentage of the rooting depth as $D_{cr} = \beta_{upr} D_r$, where β_{upr} is a parameter that modulates the resistance of the plant and depends on soil characteristics and plant species. When uprooting occurs, B_c and B_r are set to zero and vegetation cannot influnce flow and sediment transport anymore during the simulation.

1.6 Water temperature

1.6.1 Introduction

River water temperature is a fundamental physical property of flowing water, having a key role in many ecological processes (Caissie, 2006). Its magnitude, fluctuations and seasonality have a critical impact on biota behaviour, metabolism and distribution. River temperature shows also spatial heterogeneity, i.e. thermal landscapes, resulting from complex interplay between atmospheric conditions with landscape and reach morphological characteristics.

In this context a modelling solution that account for 2D (bi-dimensional, depth averaged) hydro-thermal dynamics to quantify and simulate thermal dynamics is desirable yet challenging. It requires a good amount and quality of field data (e.g. atmospheric,

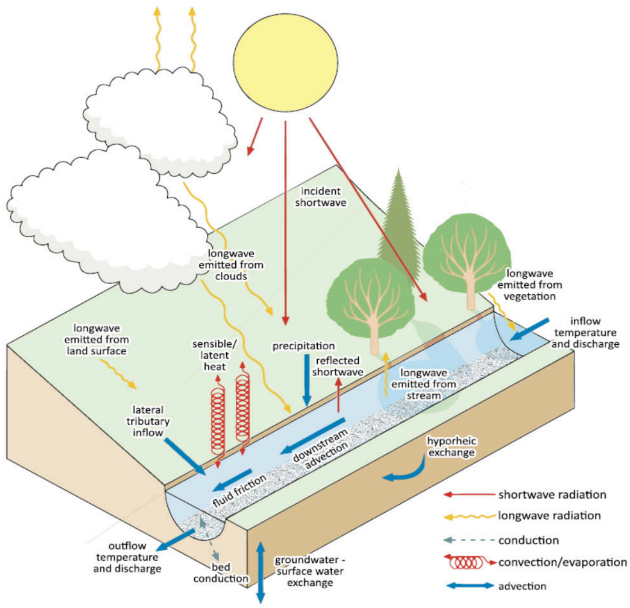

Figure 1.13 Schematic representation of energy and hydrological exchanges determining river water temperature. From Dugdale et al. (2017)

groundwater level, topography, etc.), and a solid model for hydro-thermodynamic simulation at adequate spatial and temporal scale.

1.6.2 Thermodynamics: governing equations

River water temperature can be modelled assuming the passive advection and diffusion of a scalar quantity, in the form of dissolved or particulated particles (Vanzo et al., 2016). The transport of the water temperature can be described by the following advection-diffusion-reaction equation:

$$\partial_t q_T + \partial_x \left[\frac{q_x q_T}{h} - h \left(K_{xx} \partial_x T + K_{xy} \partial_y T \right) \right] + \partial_y \left[\frac{q_y q_T}{h} - h \left(K_{yx} \partial_x T + K_{yy} \partial_y T \right) \right] = \frac{H_{atm}}{c_w \rho_w} + \frac{H_b}{c_w \rho_w}, \quad (1.83)$$

where the equation unknown is the specific thermal mass $q_T = hT$ $[m°C]$, with T the water temperature and h the water depth. The terms K_{ij} $[m^2/s]$ are the components of the 2D diffusion tensor. The right-hand side terms of eq. (eq. 1.83) are the "reaction" terms, hence represent the variation of water temperature due to external forcings, such as atmospheric ones. In particular, H_{atm} $[W/m^2]$ is the total net energy flux exchanged with the water column from the surface, i.e. with the atmosphere, whilst H_b collects the energy fluxes related with the river bed. Finally, ρ_w and c_w are the water density $[Kg/m^3]$ and specific heat $(4186 JKg^{-1}K^{-1})$, respectively.

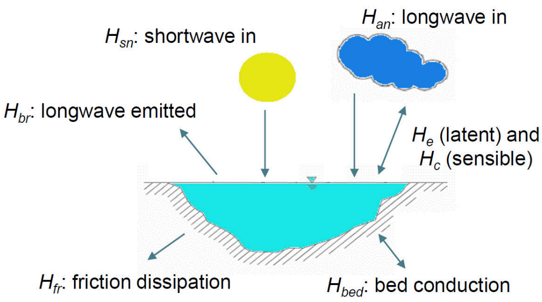

Figure 1.14 *Schematic representation of thermal fluxes that can be simulated*

1.6.3 Temperature closure relationships

The atmospheric net heat exchange H_{atm} $[W/m^2]$ to or from the water column (positive for incoming fluxes) is the sum of different factors:

$$H_{atm} = H_{sn} + H_{an} + H_{br} + H_e + H_c. \tag{1.84}$$

The incoming net short-wave radiation flux H_{sn} is expressed as

$$H_{sn} = 0.97H_{si}(1.0 - SF), \tag{1.85}$$

where the user-provided total incoming radiation H_{si} $[W/m^2]$ is corrected with albedo (3%) and a user-provided shade factor SF [0 to 1]. Incoming long wave radiation is H_{an} and reads:

$$H_{an} = \sigma\left(T_a + 273.15\right)^4 \left(Ca + 0.084900481\sqrt{e_a}\right)(1 - R_l), \tag{1.86}$$

where σ=5.67$e^{-8}W.m^{-2}K^{-4}$ is the Stefan-Boltzman constant, T_a $[degC]$ is the air temperature, e_a [kPa] is the air vapor pressure and the two coefficients Ca=0.6 (Brundt's coefficient) and R_l=0.03 (reflective coefficient) are assumed constant. The air vapor pressure e_a is calculated from the user-provided relative humidity RH [%] and the saturation of vapor pressure e_v [kPa] as:

$$e_a = 0.01RH \cdot e_v. \tag{1.87}$$

The saturation of vapor pressure e_v [kPa] is evaluated via Tetens equation, as function of the air temperature:

$$e_v = \left(0.61078 \cdot e^{\dfrac{17.27 \cdot T_a}{T_a + 237.3}}\right). \tag{1.88}$$

The emitted long wave radiation H_{br} is a function of the river water temperature T, and is calculated as:

$$H_{br} = -\sigma\epsilon\left(T + 273.15\right)^4, \tag{1.89}$$

with same symbols as before, and emissivity ϵ=0.97.

The evaporation (latent) heat flux H_e is evaluated as:

$$H_e = -\left(9.2 + 0.46 v_w^2\right) \cdot (e_v - e_a), \tag{1.90}$$

where v_w $[m/s]$ is the 2m-above-soil wind speed. Similarly, the convective (sensible) heat flux H_c reads:

$$H_c = -0.47\left(9.2 + 0.46 v_w^2\right) \cdot (T - T_a). \tag{1.91}$$

Detailed references for the formulation of the atmospheric heat fluxes H_{atm} are given in (Siviglia and Toro, 2009).

The heat exchanges with the river bed H_b $[W/m^2]$ are evaluated in the form of two contributions,

$$H_b = H_{bed} + H_{fr}. \tag{1.92}$$

The first right-hand side term H_{bed} represents the convective heat exchange with the bed and it is (at this stage) a crude simplification of the relation proposed in (Caissie and Luce, 2017) (Eq. 3):

$$H_{bed} = -k_b \frac{\partial T}{\partial z} \approx -k_b \frac{T - T_b}{L_b}, \tag{1.93}$$

where T_b is the user-provided reference bed temperature at the sediment depth L_b [m]. The bed thermal conductivity k_b $[W/m/K]$ has default value of 1.5. The second term of the bed fluxes H_{fr} can be used to simulate the water heat dissipation by friction, and it is proposed similarly to (Beltaos, 2013):

$$H_{fr} = -f_{fr} \rho_w \frac{u^3}{c_f^2}, \tag{1.94}$$

where u is the magnitude of the flow, c_f the friction term (see (Vanzo et al., 2021)). The pre-factor f_{fr} [-] (default value 0, ranging 0 to 1) can be used to tune the contribution of such term. It is worth mentioning that the formulation was proposed in the framework of modelling ice formation in rivers and it should be carefully applied/tuned.

The terms K_{ij} of the diffusion tensor vary considerably with respect to the physical nature of the transported species. Diffusive transport is modelled in terms of both molecular diffusion K^m and turbulent dispersion K_{ij}^t, such that $K_{ij} = K^m I_{ij} + K_{ij}^t$, with I_{ij} the identity matrix. The molecular diffusion is assumed as an isotropic Fickian process with constant coefficient K^m. Turbulent dispersion is anisotropic (K_{ij}^t) and scales with the friction velocity $u_* = \|\mathbf{u}\|/c_f$ and water depth via a longitudinal α_L and transversal α_T non-dimensional coefficients. Suitable values for open channel flows in natural environments are α_L=13 and α_T=1.2 (Vanzo et al., 2016).

1.6.4 Initial conditions

The user is requested to define the initial conditions of the simulation. Different types of initial conditions are available, similarly to the other modules:

- **zero**: temperature is set to 0 in all the computational cells (default);
- **region defined**: user explicitly defines the initial values of the water temperature. Different values can be assigned to different region of the computational domain;
- **continue**: values are taken from the result file of previous simulations at the provided time t.
- **assigned from file** (experimental): water temperature initial conditions are read from a text file (single column of values) where the row numbers matches the computational cell ID from the mesh file.

1.6.5 Boundary conditions

In the current version of the water temperature module, only *standard* BCs are implemented for river temperature simulations, with three types: i) temperature inflow as a constant value or ii) as a time-series (`passive_in`) and (iii) Neumann BC outflow (`passive_out`). User can set a multiplication factor (default value=1) to scale the input timeseries.

1.6.6 Setup parameters

The parameters needed in the equations of section Section 1.6.3 are to be found in the sub-blocks PARAMETERS and DIFFUSION of the temperature module. They all have default values. A brief explanation follows.

Block PARAMETER * “fluid_specific_heat”[J/Kg/K]: Water specific heat. Default value = 4186 J/Kg/K; * “temperature_start” [s]: possibility to delay the beginning of temperature calculation. Default value = 0s, i.e. starts from the beginning; * “source_update_time” [s]: interval for updating the source terms. Default = 0s (i.e. at every computational timestep). Larger values lead to faster simulations, but convergence needs to be tested; * “friction_heating_factor” [-]: to calibrate the heat dissipation by friction with the river bed. Default=0, i.e. deactivated; * “bed_thermal_thickness”[m]: vertical thickness to reach constant soil temperature. Default = 1m; * “bed_thermal_conductivity”[$W/m/K$]: it depends on soil type. Default value = 1.5 $W/m/K$. Hint: Set to 0.0 to exclude this contribution from the simulation.

Block DIFFUSION

- “type”:
  - none (equivalent to removing the block)
  - constant: fixed diffusion coefficients
  - dynamic: diffusion coefficients depend on flow conditions
- “molecular diffusion” [m2/s]: in water. Default value = 1e-9 m2/s,
- “longitudinal_diffusion_coeff”:

  - constant value in [m2/s] if type=constant
  - non-dimensional factor (suggested 13) if type=dynamic
  - default value = 0

- "transversal_diffusion_coeff":

  - constant value in [m2/s] if type=constant
  - non-dimensional factor (suggested 1.2) if type=dynamic
  - default value = 0

- "maximum_relaxation_parameter"[-]: related with the numerical solver (Vanzo et al., 2016). Default value = 0.1.

2

Numerical Models

2.1 General View

The governing equations of hydro- and morphodynamics are conservation laws expressing conservation of mass and momentum. The aim of the numerical simulation is to solve these equations over the computational domain and for a given time. The computational domain is discretized by a computational mesh consisting of elements and conservation equations are applied on each domain element. In order to numerically solve the conservation equations, the mathematical model is approximated by numerical schemes, i.e. the numerical approximation consists of the spatial and temporal discretization of the conservation equations including an algorithm that solves the discretized equations.

For BASEHPC::BASEplane, the spatial discretisation of the domain is based on an unstructured mesh made of triangular elements (Figure 2.1). For the conservation equations, the spatial discretisation follows the finite volume scheme, while for the temporal discretisation an explicit first order Euler scheme is used. The software processes the different modules (e.g. hydraulic, morphology, tracers) in a decoupled way (Figure 2.2).

The discretization and the solution method for the hydro- and morphodynamic equations will be presented in the following sections.

2.2 Discretization

The problem is discretised adopting a finite volume approach over unstructured triangular meshes. A conforming triangulation T_Ω of the computational domain $\Omega \subset \mathbb{R}^2$ by elements Ω_i such that $T_\Omega = \bigcup \Omega_i$, is assumed. Hereafter we will use the following notation: given a finite volume Ω_i, $j = 1, 2, 3$ is the set of indexes such that Ω_j is a neighbour of Ω_i; Γ_{ij} is the common edge of two neighbour cells Ω_i and Ω_j, and l_{ij} its length. $\mathbf{n}_{ij} = (n_{ij,x}, n_{ij,y})$ is the unit vector which is normal to the edge Γ_{ij} and points toward the cell Ω_j (see Figure 2.3). Data are represented by cell averages $\boldsymbol{U}_i^n$ and the numerical solution sought at time $t^{n+1} = t^n + \Delta t$, is denoted by $\boldsymbol{U}_i^{n+1}$.

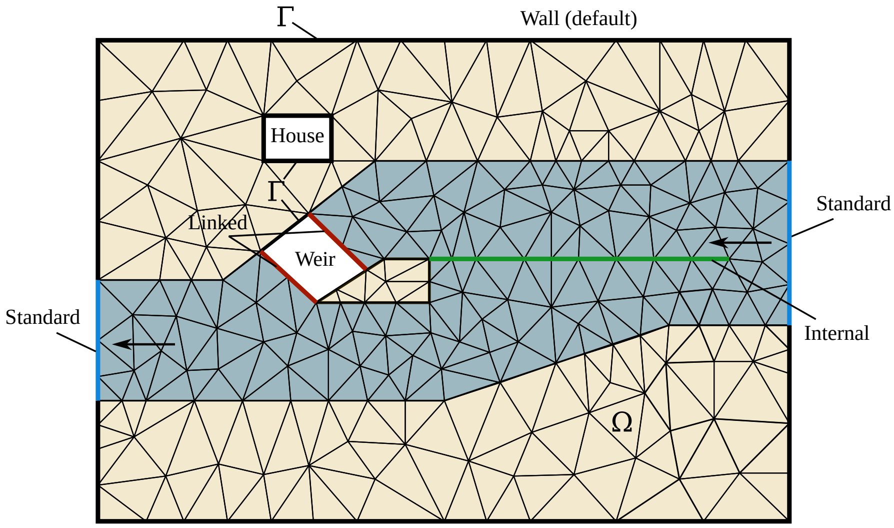

Figure 2.1 *Modeling domain, types of boundary conditions and computational mesh. The flow is from right to left and a side weir (green line) divides the channel into a lower and an upper channel through the weir.* External *boundary conditions must be provided at* Γ_1, Γ_2 *and* Γ_3 *while* internal *boundary conditions can be specified in any place within* Ω

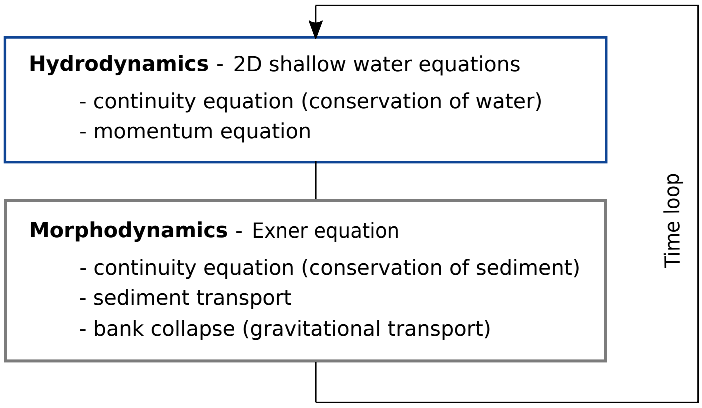

Figure 2.2 *Overview of the numerical model*

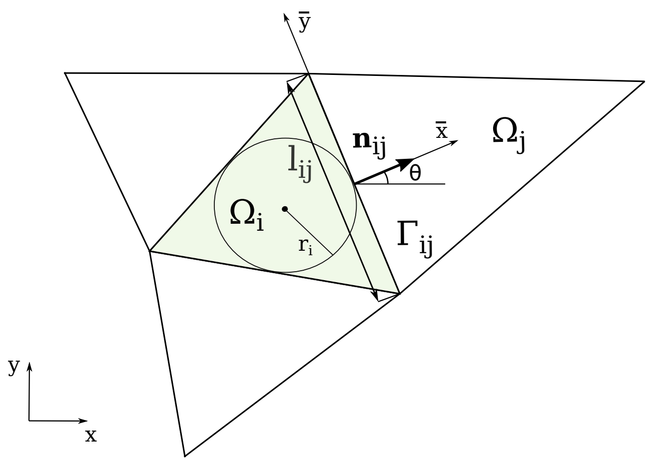

Figure 2.3 *Element (shaded triangle) of unstructured triangular mesh and used notation.*

2.3 Numerical solution of Hydrodynamics

2.3.1 Vectorial Form of the Governing Equations

For numerical convenience, the system of governing equations (eq. 1.1) is rewritten in vectorial form in terms of the water surface elevation $H = h + z_B$. It now reads:

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}_x}{\partial x} + \frac{\partial \boldsymbol{F}_y}{\partial y} = \boldsymbol{S} \tag{2.1}$$

where the vector of unknowns is

$$\boldsymbol{U} = \begin{pmatrix} H \\ q_x \\ q_y \end{pmatrix} \tag{2.2}$$

the vector fluxes are

$$\boldsymbol{F}_x = \begin{pmatrix} q_x \\ uq_x + \frac{1}{2}g(H^2 - 2Hz_b) \\ uq_y \end{pmatrix} \quad ; \quad \boldsymbol{F}_y = \begin{pmatrix} q_y \\ vq_x \\ vq_y + \frac{1}{2}g(H^2 - 2Hz_b) \end{pmatrix} \tag{2.3}$$

and the vector of source terms is

$$\boldsymbol{S} = \begin{pmatrix} S_h \\ gHS_x \\ gHS_y \end{pmatrix} \quad . \tag{2.4}$$

The motivation of using H instead of h lies in the fact that it is easier to develop numerical schemes which preserve depth positivity and satisfy the well-balanced property.

2.3.2 Spatial Discretisation

In order to discretise the system of governing equations, the domain is meshed by a set of triangular elements. The spatial discretization of the conservation equations is carried out by the finite volume method, where the differential equations are integrated over the single elements, i.e. control volumes. The water surface elevation is defined at the element center and is equally distributed over the element.

By integrating the governing system of equations eq. 2.1 in the control volume $V = [\Omega_i] \times [t^n, t^{n+1}]$, we obtain

$$\boldsymbol{U}_i^{n+1} = \boldsymbol{U}_i^n - \frac{\Delta t}{|\Omega_i|} \sum_{j=1}^{3} l_{ij} \left[\boldsymbol{F}_{ij}\right] + \Delta t \boldsymbol{S}_i \ . \tag{2.5}$$

2.3.3 Flux Estimation

2.3.3.1 Rotational Invariance of the Shallow Water Equations

The flux $\boldsymbol{F}_{ij}$ are evaluated taking advantage of the rotational invariance property of the shallow water equations. According to this property the two-dimensional homogeneous shallow water equations satisfy the following equality (Toro, 2009):

$$\boldsymbol{n}_{ij} \cdot [\boldsymbol{F}_x(\boldsymbol{U}), \boldsymbol{F}_y(\boldsymbol{U})] = \boldsymbol{T}^{-1}(\theta)\boldsymbol{F}_x[\boldsymbol{T}(\theta)\boldsymbol{U}] \tag{2.6}$$

where θ is the angle between the vector $\boldsymbol{n}_{ij}$ and x-axis, measured counter clockwise from the x-axis (see Figure 2.3) and

$$\boldsymbol{T}(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \tag{2.7}$$

being

$\boldsymbol{T}^{-1}(\theta) =$ inverse of $\boldsymbol{T}(\theta)$.

2.3.3.2 Computation of the Flux

The flux $\boldsymbol{F}_{ij}$ is obtained at every edge of the finite volume mesh, as the solution of the one-dimensional projected Riemann problem along the normal direction of the two conservation laws eq. 2.1. The computational steps can be summarized as follows:

- First, the vector of conserved variables $\boldsymbol{U}$ is transformed into the local coordinate system ($\bar{x}$, $\bar{y}$) (see Figure 2.3) at the edge with the operation $\boldsymbol{T}(\theta)\boldsymbol{U}$.
- A one-dimensional, local Riemann problem is formulated and solved in the normal direction of the edge. From this calculation the new flux vector over the edge $\boldsymbol{F}[\boldsymbol{T}(\theta)\boldsymbol{U}]$ is defined.
- The flux vector, formulated in the local coordinate system is transformed back to the global coordinates (Cartesian) with $\boldsymbol{T}^{-1}\boldsymbol{F}[\boldsymbol{T}(\theta)\boldsymbol{U}]$. The sum of the fluxes of all edges of an element gives the total fluxes in the x- and y directions.

The fluxes are calculated in the normal direction of the element edges. The normal direction of the edge is defined positive from element i (L) to element j regarding the edge direction.

2.3.3.3 The HLLC approximated Rieman Solver

The HLLC approximate Riemann solver (Toro, 1994) is a modified HLL (Harten, Lax and van Leer) approximate Riemann solver that includes the shear wave.

The numerical flux at the cell interface is computed as follows:

$$\boldsymbol{F}_{ij}^{HLLC} = \begin{cases} \boldsymbol{F}_i & if \quad 0 \leq S_i, \\ \boldsymbol{F}_{*i} = \boldsymbol{F}_i + S_i(\boldsymbol{U}_{*L} - \boldsymbol{U}_i) & if \quad S_i \leq 0 \leq S_*, \\ \boldsymbol{F}_{*j} = \boldsymbol{F}_j + S_j(\boldsymbol{U}_{*R} - \boldsymbol{U}_j) & if \quad S_* \leq 0 \leq S_j, \\ \boldsymbol{F}_j & if \quad 0 \geq S_j. \end{cases} \tag{2.8}$$

The wave speed velocities are estimated as:

$$S_i = u_i - \sqrt{gh_i}\xi_i \ ; \ S_j = u_j + \sqrt{gh_j}\xi_j \tag{2.9}$$

where $\xi_{K=(i,j)}$ is defined as:

$$\xi_K = \begin{cases} \sqrt{\frac{1}{2}\left[\frac{(h_*+h_K)h_*}{h_K^2}\right]} & if \quad h_* > h_K, \\ 1 & if \quad h_* \leq h_K. \end{cases} \tag{2.10}$$

with h_*, an estimate for the exact solution of the water depth in the star region obtained using the depth positivity condition. It reads as

$$h_* = \frac{1}{2}(h_L + h_R) - \frac{1}{4}(u_R - u_L)(h_L - h_R)/(\sqrt{gh_L} + \sqrt{gh_R}) \tag{2.11}$$

In case of dry-bed conditions, the wave speeds are estimated as the exact dry front speed, i.e.:

$$S_i = \begin{cases} u_i - 2\sqrt{gh_i} & if \quad h_i = 0, \\ \text{usual estimate} & if \quad h_i > 0, \end{cases}$$
$$S_j = \begin{cases} u_j + 2\sqrt{gh_j} & if \quad h_j = 0, \\ \text{usual estimate} & if \quad h_j > 0. \end{cases} \tag{2.12}$$

And the middle estimated wave speed S_* corresponds to the front wave speed in case of dry-bed problem.

The expression of the states $\boldsymbol{U}_{*i}, \boldsymbol{U}_{*j}$ and the middle wave speed S_* can be found in the book of Toro (2009).

2.3.4 Numerical Stability

Numerical stability is assured by choosing the time step Δt for time integration such that it obeys the Courant-Friedrichs-Lewy (CFL) condition. In 2-D the Courant number (CFL) can be defined as follows:

$$CFL = \frac{(\sqrt{u^2 + v^2} + c)\Delta t}{r_i} \tag{2.13}$$

where r_i is the radius of the inscribed circle that defines the element center (Figure 2.3), u, v are the corresponding velocities of the element and $c = \sqrt{gh}$. The HLLC scheme is stable for

$$0 < CFL \leq 1 \tag{2.14}$$

2.3.5 Discretisation of Source terms

2.3.5.1 Bed Slope Source Term

The bed slope source term (eq. 1.2) is discretized using the robust modified-state approach proposed by Duran et al. (2013). The discretization presents a motionless steady states-preserving scheme:

$$\boldsymbol{S}_{b,i} = \sum_{j=1}^{m} l_{ij} \boldsymbol{S}_{b,ij} = \sum_{j=1}^{m} l_{ij} \begin{pmatrix} 0 \\ g H_{ij}^{*} (z_i - \bar{z}_{ij}) \vec{\boldsymbol{n}}_{ij} \end{pmatrix} \tag{2.15}$$

where $\bar{z}_{ij} = \check{z}_{ij} - \Delta_{ij}$ with $\check{z}_{ij} = \max(z_{bi}, z_{bj})$ the maximum bed elevation between cells i and j and $\Delta_{ij} = \max(0, \check{z}_{ij} - H_i)$. H_{ij}^{*} is the approximated value of the water surface elevation H at the cell interface Γ_{ij}.

2.3.5.2 Friction Source Term

We handle the inhomogeneous character of system eq. 1.1 due to the presence of frictional source terms by adopting a robust splitting technique Toro (2001). We initially consider the initial value problem (IVP)

$$\left.\begin{array}{llll} PDE: & \mathcal{A}(\boldsymbol{U}) & = & \mathcal{S}(\boldsymbol{U}) \\ IC: & \boldsymbol{U}(x,y,0) & = & \boldsymbol{U}_i^n \end{array}\right\} \text{IVP} .$$

where $\mathcal{A}$ represents the advective operator

$$\mathcal{A}(\boldsymbol{U}) = \frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}_x}{\partial x} + \frac{\partial \boldsymbol{F}_y}{\partial y} = \boldsymbol{0} ,$$

and $\mathcal{S}$ represents the frictional source term operator.

The numerical solution is then obtained by subsequently integrating *two* initial value problems (IVPs):

$$\left.\begin{array}{llll} ODEs: & \frac{\mathrm{d}\boldsymbol{U}}{\mathrm{d}t} & = & \mathcal{S}(\mathbf{U}) \\ ICs: & \boldsymbol{U}(x,y,0) & = & \boldsymbol{U}_i^n \end{array}\right\} \xRightarrow{\Delta t} \overline{\boldsymbol{U}}_i \quad \text{IVP1} ,$$

$$\left.\begin{array}{llll} PDEs: & \mathcal{A}(\mathbf{U}) & = & 0 \\ ICs: & \boldsymbol{U}(x,y,0) & = & \overline{\boldsymbol{U}}_i \end{array}\right\} \xRightarrow{\Delta t} \boldsymbol{U}_i^{n+1} \quad \text{IVP2} ,$$

The initial condition (IC) for IVP1 is $\mathbf{U}_i^n$, corresponding to the initial condition of the full problem IVP. The solution of IVP1 is obtained solving a system of ordinary differential equations (ODEs) after integration by a time step Δt and is denoted by $\overline{\boldsymbol{U}}_i$. IVP2 is then integrated by a time step Δt, with initial condition given by the solution of IVP1 $\overline{\boldsymbol{U}}_i$. The solution of IVP2 $\boldsymbol{U}_i^{n+1}$ is obtained solving an hyperbolic homogeneous system of partial differential equations (PDEs) and represents the approximate solution of the full problem

IVP.\ Since we adopt an implicit second-order Runge-Kutta method for solving the ODEs systems IVP1 and an explicit finite volume method for solving IVP2, the integration time step Δt is determined accordingly with the CFL stability condition for IVP2.

2.3.5.3 External Source Term

An external source is defined as specific mass flux δ (m/s), uniformly distributed over a number of elements of the domain with a specific surface area. The external source can either be specified as discharge (m^3/s) or precipitation intensity (mm/h) for a specific region of the domain. The external source value is divided among the cells composing the region and converted to cell specific mass flux δ_i. The volume allocated is characterized by different behaviors:

$$\begin{array}{llll}
\text{Exact:} & S_{h,i} = \delta_i & & \\
\text{Available:} & S_{h,i} = \delta_i & \text{if} & \delta_i \cdot \Delta t > 0 \\
 & S_{h,i} = \max(\delta_i, -h_i) & \text{if} & \delta_i \cdot \Delta t < 0 \\
\text{Infinity:} & S_{h,i} = \delta_i & \text{if} & \delta_i \cdot \Delta t > 0 \\
 & S_{h,i} = -h_i & \text{if} & \delta_i \cdot \Delta t < 0
\end{array} \tag{2.16}$$

Where h_i is the water depth of the element i. The external source volume is added to the initial water volume.

$$h_i^{t+1} = h_i^t + S_{h,i} \cdot \Delta t \tag{2.17}$$

2.3.6 Solution Procedure

The numerical solution procedure of BASEMENT explains how the discretised shallow water equation (eq. 1.1) is solved inside a defined time step Δt through a sequence of loops over the edges or cells (Figure 2.4).

First, a global minimum time step Δt should be defined. Then, the hydraulic fluxes (liquid mass, x-momentun and y-momentum) are calculated with a HLLC Riemann solver at the element edges according to the initial states of the left and right cells (Section 2.3.3). Subsequently, the hydraulic state variables i.e. cell centered quantities are updated and finally, the friction (source term) is calculated using an implicit scheme, thus looping twice over the cell.

2.4 Numerical solution of Morphodynamics

2.4.1 Numerical solution of the Exner equation

2.4.1.1 Fundamentals

The Exner equation assures that sediment mass is conserved in the bed and is used to model the riverbed time evolution. The rate of sediment transport is determined using a closure equation. The cell centered finite volume approach is used to discretise the Exner equation and in particular the HLL approximate Riemann solver with a wave speed

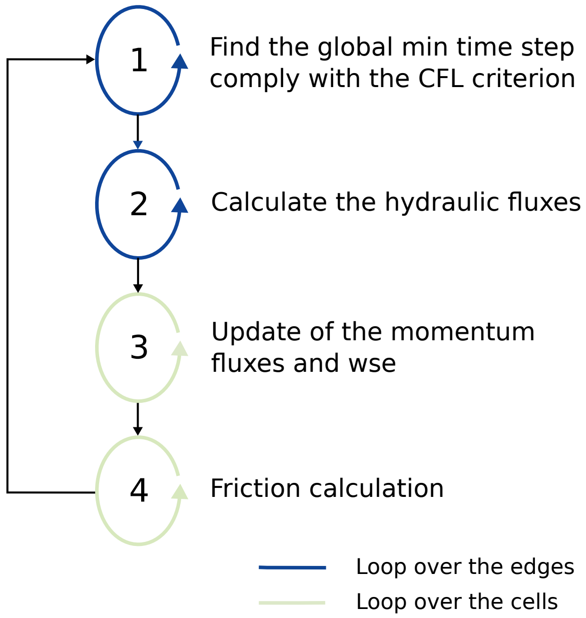

Figure 2.4 *Numerical solution procedure of hydrodynamic simulation for each time step* Δt

estimator defined in Soares-Frazão and Zech (2011) is adopted. The shallow water and the Exner equations create a system of equations that is solved in a decoupled way (Figure 2.2). This approach makes the assumption that the bed load flux is much slower than the water flow velocity (Soares-Frazão and Zech, 2011).

2.4.1.2 Spatial discretization

In order to discretise the the Exner equation, we use the same unstructured mesh adopted for the hydrodynamic part and the same finite volume approach. As a consequence, the bed level z_B is defined at the element center and is equally distributed over the element.

By integrating the Exner equation in the control volume $V = [\Omega_i] \times [t^n, t^{n+1}]$, we obtain

$$z_{Bi}^{n+1} = z_{Bi}^{n} - \frac{\Delta t}{|\Omega_i|} \sum_{j=1}^{3} \left[q_{Bij \cdot l_{ij}} \right] + \Delta t \boldsymbol{S}_i \ . \tag{2.18}$$

The calculation of the sediment flux at the cell interface proceeds as follows:

1. loop over the cells and calculate:

    1. correction terms for the bed-load vector directions (if selected by the user), therefore:

    - calculation of the local bed slope, for the lateral-transport correction (see section Section 1.2.2.6.1)
    - calculation of the local curvature of the flow field, for the spiral flow correction (see section Section 1.2.2.6.2)

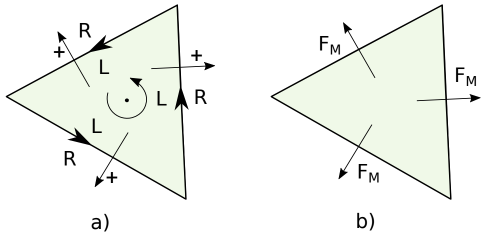

Figure 2.5 *a) Sign convention for the edge direction: counterclockwise b) Positive morphological flux direction at edges: from left (L) to right (R)*

2. loop over the cell interfaces and:

    1. calculate the flux projection along the normal vector ($n_{ij,x}$,$n_{ij,y}$ of edge Γ_{ij}, i.e.: $q_{Bi,n} = q_{Bi,x} \cdot n_{ij,x} + q_{Bi,y} \cdot n_{ij,x}$ and $q_{Bj,n} = q_{Bj,x} \cdot n_{ij,x} + q_{Bj,y} \cdot n_{ij,x}$ with j=1,2,3
    2. compute the flux at the interface using the approximate HLL Riemann solver at the interface

- Evaluate the wave speeds at the interface. this is obtained following the approach proposed by Soares-Frazão and Zech (2011), for which the wave speeds can be calculated as an approximation of the smallest eigenvalue of the system of governing equations, i.e. Shallow water and Exner. They read:

$$\lambda_1 = 1/2(u_n - c - \sqrt{(u_n - c)^2 + 4a_2c^2}) \tag{2.19}$$

$$\lambda_2 = 1/2(u_n - c + \sqrt{(u_n - c)^2 + 4a_2c^2}) \tag{2.20}$$

where $u_n = u \cdot n_{ij,x} + v \cdot n_{ij,y}$, $c = \sqrt{gh}$ and $a_2 = \dfrac{\partial q_{b,n}}{\partial q_n}$ which is the derivative of the bed load discharge in the normal flow direction with respect to the hydraulic flux direction. Then the speeds estimate are

$$S^- = \min(\lambda_{1,L}, \lambda_{1,R}) \tag{2.21}$$

and

$$S^+ = \max(\lambda_{2,L}, \lambda_{2,R}) \tag{2.22}$$

- Flux calculation:

$$q_{Bij}^{HLL} = \begin{cases} q_{Bi,n} & if \quad S^- \geq 0, \\ \dfrac{q_{Bi,n}S^+ - q_{Bj,n}S^- + S^-S^+(z_{Bj} - z_{Bi})}{S^+ - S^-} & if \quad S^- < 0 < S^+, \\ q_{Bj,n} & if \quad S^+ \leq 0. \end{cases} \tag{2.23}$$

The convention for the positive bed load flux direction is the same as for the hydrodynamic flux and is presented on Figure 2.5

2.4.1.3 Discretization of External Source Term

The source term Sl_b describes a local input or removal of sediment mass into a river.

An external source is defined as specific mass flux δ (m/s), uniformly distributed over a number of elements of the domain (region) with a specific surface area. The external source can be specified as the total volume flux (m^3/s) for a specific region of the domain. The external source value is divided among the cells composing the region and converted to cell specific mass flux δ_i. The volume allocated is characterized by different behaviors:

$$\begin{array}{lll} \text{Exact:} & S_{b,i} = \delta_i & \\ \text{Available:} & S_{b,i} = \delta_i & \text{if} \quad \delta_i \cdot \Delta t > 0 \\ & S_{b,i} = \max(\delta_i, -(z_{Fix} - z_i)) & \text{if} \quad \delta_i \cdot \Delta t < 0 \\ \text{Infinity:} & S_{b,i} = \delta_i & \text{if} \quad \delta_i \cdot \Delta t > 0 \\ & S_{b,i} = -(z_{Fix} - z_i) & \text{if} \quad \delta_i \cdot \Delta t < 0 \end{array} \tag{2.24}$$

Where z_i is the bottom elevation and z_{Fix} the fixed bed elevation of the element i. The external source volume is added to the initial bottom elevation of element i.

$$z_i^{t+1} = z_i^t + S_{b,i} \cdot \Delta t \tag{2.25}$$

2.4.2 Solution procedure

The numerical solution procedure of BASEMENT explains how the discretised Exner equation (eq. 1.22) is solved through a sequence of loops over the edges or cells (Figure 2.6).

In the numerical simulation, the hydrodynamic and morphodynamic simulations are performed in a decoupled way. The morphodynamic simulation is executed after the hydrodynamic simulation, using the hydraulic fluxes to calculate the morphological fluxes. This approach assumes that the sediment transport is much slower than the water velocity, which is an accurate assumption for the numerical modelling of slow flood with morphological changes occurring over a long period (Soares-Frazão and Zech, 2011). The numerical solution procedure of Figure 2.6 is performed after the step 4 of Figure 2.4 inside the same time step Δt.

The numerical solution of the Exner equation starts with a loop over the cells in order to find the bedload transport capacity q_b with a potential correction due to a curvature effect or lateral bed slope. Then, the morphological fluxes F_M are calculated at the element edges and finally, the bed elevation z_b is updated over the cells.

2.5 Numerical solution of Advection-Diffusion equation

2.5.1 Numerical solution of the advective part

The scalar advection equation assures that scalar masses are conserved in the flow column when moving with the surrouding fluid. The same cell cell-centered finite volume approach used for the SWE is employed in scalar advection, namely the HLLC approximate Riemann solver. In order to discretize the scalar advection equation, the same unstructured mesh adopted for the hydrodynamic and morphodynamic parts is used, as is the same finite

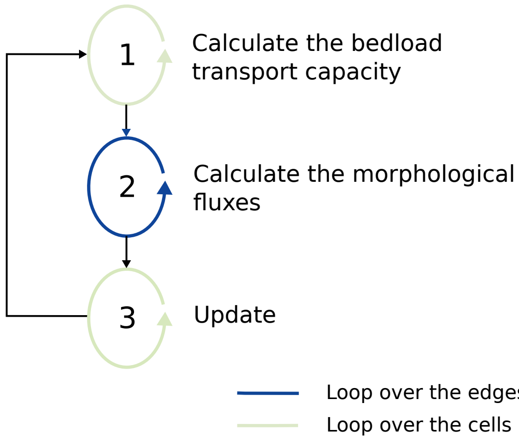

Figure 2.6 *Numerical solution procedure of morphodynamic simulation for each time step* Δt

volume approach. As a consequence, the scalar concentration ϕ_s is defined at the element center and is equally distributed over the element. This numerical approach is applied to turbulent kinetic energy quantities (κ, ϵ), suspended sediment and tracers.

By integrating the scalar advection equation

$$\frac{\partial}{\partial t}\phi_k h + \frac{\partial}{\partial x_i}\left(\phi_k h u_i - h D_{s_{ij}}\frac{\partial \phi_k}{\partial x_j}\right) = S_{\phi_k} \tag{2.26}$$

in the control volume $V_i = [\Omega_i] \times [t^n, t^{n+1}]$ for a generic quantity defined by ϕ_k, we obtain:

$$q^{n+1}_{\phi_k i} = q^n_{\phi_k i} - \frac{\Delta t}{|\Omega_i|}\sum_{j=1}^{3}\left[f_{\phi_{k,ij}} \cdot l_{ij}\right] + \Delta t \boldsymbol{S}_{\phi_{k,i}} \tag{2.27}$$

where f_{Sij} is the intercell scalar advective flux. The scalar advective fluxes at the cell interface are defined by:

$$f_{\phi_{k,ij}} = \frac{q_{\phi_k i}}{h} q_m \;\text{ if }\; q_m > 0 \tag{2.28}$$

$$f_{\phi_{k,ij}} = \frac{q_{\phi_k j}}{h} q_m \;\text{ if }\; q_m < 0 \tag{2.29}$$

where q_m is the hydrodynamic mass flux. This approach significantly reduces the numerical effort involved in the computation of the numerical fluxes for each species, without sacrificing accuracy or stability.

2.5.2 Numerical solution of the diffusive part

The diffusion equation ensures that quantities are conserved in the flow column due when turbulent or molecular exchanges originate some form of mixing. By integrating the scalar diffusion equation

$$\frac{\partial}{\partial t}\phi_k h - \frac{\partial}{\partial x_i}\left(hD_{s_{ij}}\frac{\partial \phi_k}{\partial x_j}\right) = 0 \tag{2.30}$$

in the control volume $V_i = [\Omega_i] \times [t^n, t^{n+1}]$ we obtain:

$$q^{n+1}_{\phi_k i} = q^n_{\phi_k i} - \frac{\Delta t}{|\Omega_i|}\sum_{j=1}^{3}\left[d_{\phi_{k,ij}} \cdot l_{ij}\right] \tag{2.31}$$

where $d_{\phi_{k,ij}}$ is the intercell scalar diffusive flux. To compute the solution of the diffusive terms, the SVT solver Vanzo et al. (2016) is employed. It involves the augmentation of the existing system with a set of new conservation quantities and equations for each diffusive specie ϕ_k. The role of these new variables is to allow a relaxation of the diffusive part, such as

$$\lim_{\zeta\to 0}\psi^{\phi_k}_x = \partial_x\phi_k\,, \qquad \lim_{\zeta\to 0}\psi^{\phi_k}_y = \partial_y\phi_k \tag{2.32}$$

where ψ denotes a relaxation variable, subject to the following relations

$$\partial_t\psi^{\phi_k}_x - \partial_x\frac{\phi_k}{\zeta} = -\frac{\psi^{\phi_k}_x}{\zeta}\,, \quad \partial_t\psi^{\phi_k}_y - \partial_y\frac{\phi_k}{\zeta} = -\frac{\psi^{\phi_k}_y}{\zeta} \tag{2.33}$$

which are formally denoted as the relaxation sub-system. The main purpose of this relaxation is to preserve the hyperbolicity of the numerical scheme, as demonstrated by Vanzo et al. (2016). To construct the diffusive numerical fluxes, the following Riemann problem is considered along some edge normal as

$$\begin{cases} \partial_t\boldsymbol{\Phi_k} + \partial_\xi\boldsymbol{D_{n_{ij}}} = \mathbf{0}\,, \;\; \xi\in\mathbb{R}\,, \;\; t>0\,, \\ \boldsymbol{\Phi_k}(\xi,0) = \begin{cases} \boldsymbol{\Phi_k}^n_i & \text{if} \quad \xi<0\,, \\ \boldsymbol{\Phi_k}^n_j & \text{if} \quad \xi>0\,, \end{cases} \end{cases} \tag{2.34}$$

where $\boldsymbol{\Phi_k}$ is the conserved variables vector and $\boldsymbol{D_n}$ is the diffusive numerical flux vector. The structure of this Riemann problem is composed of three unique waves (from a total of six). One of these is always a stationary contact discontinuity and the two remaining waves are symmetrical, with the same propagation speed in opposite directions. The problem thus becomes characterized by a single intermediate state $\boldsymbol{\Phi^*_k}$ where the fluxes are directly evaluated. The exact expression for the intermediate state $\boldsymbol{\Phi^*_k}$ and numerical $\boldsymbol{D(\Phi^*_k)_n}$ can be found in Vanzo et al. (2016).

2.5.3 Discretization of external source terms

The source term S_{ϕ_k} describes a local input or removal of scalar mass into a river. An external source is defined as specific mass flux δ (m/s), uniformly distributed over a number of elements of the domain (region) with a specific surface area. The external source can be specified as the total volume flux (m^3/s) for a specific region of the domain. The external source value is divided among the cells composing the region and converted to cell specific mass flux δ_i. The volume allocated is characterized by different behaviors:

$$\begin{array}{lll} \text{Exact:} & S_{\phi_{k,i}} = \delta_i & \\ \text{Available:} & S_{\phi_{k,i}} = \delta_i & \text{if} \quad \delta_{\phi_k} \cdot \Delta t > 0 \\ & S_{\phi_{k,i}} = \max(\delta_i, -q_{\phi_{k,i}}) & \text{if} \quad \delta_i \cdot \Delta t < 0 \\ \text{Infinity:} & S_{\phi_{k,i}} = \delta_i & \text{if} \quad \delta_i \cdot \Delta t > 0 \\ & S_{\phi_{k,i}} = -q_{\phi_{k,i}} & \text{if} \quad \delta_i \cdot \Delta t < 0 \end{array} \tag{2.35}$$

The external source volume is then added to the initial value of element i through a first-order Euler approach.

$$q^{t+1}_{\phi_{k,i}} = q^{t}_{\phi_{k,i}} + S_{\phi_{k,i}} \cdot \Delta t \tag{2.36}$$

2.5.4 Solution procedure

The numerical solution for all modules involving scalar advection and diffusive terms – turbulence, suspended sediment and tracers – is obtained as follows:

1. Loop over the cell interfaces and compute the advective flux at each interface:

- Retrieve the hydrodynamic fluxes $\boldsymbol{F}_{ij}$ at the interface between cells i and j and extract the fist component of the flux vector (mass fluxes) to the variable q_m.
- For each specie, perform the advective flux calculation through the simplified HLLC solver described above

2. Loop over the cell interfaces and compute the diffusive flux at each interface:

- Retrieve the hydrodynamic and scalar quantities $\boldsymbol{Q}_h$ and $\boldsymbol{\Phi_k}$ at the interface between cells i and j perform the flux calculation using the SVT solver

3. Define the diffusion specific timestep and update the global minimum time step Δt
4. Loop over the cells and update the conserved quantities with the fluxes at each of its interfaces:

- Retrieve and add the advective fluxes $f_{\phi ij}$ and diffusive fluxes $d_{\phi ij}$ at each of the three interfaces.
- For each specie, perform the update as prescribed in Equations 2.27, 2.31, and 2.36.

5. Add the external source terms

2.6 Numerical solution of the thermodynamics equation

The numerical integration of the evolution equation for the thermodynamics (eq. eq. 1.83) is analogous to the numerical strategy of section Section 2.5. Hence, for details of the numerical integration of the advetive and diffusive parts, please cf. sections Section 2.5.1 and Section 2.5.2, respectively.

2.6.1 Discretization of external source terms

The temperature source terms (right-hand side of eq. Section 1.6.2) describes the thermal exchanges of the column of water with the atmosphere an the river bed. The calculated source contributions (i.e. energy fluxes) are added/subtracted exactly from the thermal mass of each computational cell. Then the The external source volume is then added to the initial value of element i through a first-order semi-implicit Euler approach:

$$q_T{}^{t+1} = q_T{}^{t} + \frac{(H_{atm} + H_b)}{(c_w\rho_w - \Delta t \partial_T (H_{atm} + H_b))} \cdot \Delta t \tag{2.37}$$

2.6.2 Solution procedure

The numerical solution is equivalent to the other modules involving scalar advection and diffusive terms and it is obtained as follows:

1. Loop over the cell interfaces and compute the advective flux at each interface:

- Retrieve the hydrodynamic fluxes at the interface between cells i and j and extract the fist component of the flux vector (mass fluxes), then perform the advective flux calculation as in Section 2.5.1.

1. Loop over the cell interfaces and compute the diffusive flux at each interface:

- Retrieve the hydrodynamic and thermal quantities $\boldsymbol{Q}$ and $\boldsymbol{q_T}$ at the interface between cells i and j perform the flux calculation using the SVT solver (Section 2.5.2).

3. Define the diffusion specific timestep and update the global minimum time step Δt
4. Loop over the cells and update the conserved quantities with the fluxes at each of its interfaces:

- Retrieve and add the thermal advective and diffusive fluxes at each of the three interfaces.
- Perform the update of the advective and diffusive thermal fluxes, equivalent to equations eq. 2.27} and eq. 2.31}, respectively.

1. Add the external source terms with eq. eq. 2.37.

3

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File: aclocal.m4 (only for ICU4C)
Section: pkg.m4 - Macros to locate and utilise pkg-config.

(The condition for the exception is fulfilled because
ICU4C includes a configuration script generated by Autoconf,
namely the `configure` script.)

File: config.guess (only for ICU4C)

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File: install-sh (only for ICU4C)


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    table, the facility still operates, and performs whatever part of
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```
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```
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1) Use a suitable shared library mechanism for linking with the Library. A suitable mechanism is one that (a) uses at run time a copy of the Library already present on the user's computer system, and (b) will operate properly with a modified version of the Library that is interface-compatible with the Linked Version.

e) Provide Installation Information, but only if you would otherwise be required to provide such information under section 6 of the GNU GPL, and only to the extent that such information is necessary to install and execute a modified version of the Combined Work produced by recombining or relinking the Application with a modified version of the Linked Version. (If you use option 4d0, the Installation Information must accompany the Minimal Corresponding Source and Corresponding Application Code. If you use option 4d1, you must provide the Installation Information in the manner specified by section 6 of the GNU GPL for conveying Corresponding Source.)

5. Combined Libraries.

You may place library facilities that are a work based on the Library side by side in a single library together with other library facilities that are not Applications and are not covered by this License, and convey such a combined library under terms of your choice, if you do both of the following:

a) Accompany the combined library with a copy of the same work based on the Library, uncombined with any other library facilities, conveyed under the terms of this License.

b) Give prominent notice with the combined library that part of it is a work based on the Library, and explaining where to find the accompanying uncombined form of the same work.

6. Revised Versions of the GNU Lesser General Public License.

The Free Software Foundation may publish revised and/or new versions of the GNU Lesser General Public License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns.

Each version is given a distinguishing version number. If the Library as you received it specifies that a certain numbered version of the GNU Lesser General Public License "or any later version" applies to it, you have the option of following the terms and conditions either of that published version or of any later version published by the Free Software Foundation. If the Library as you received it does not specify a version number of the GNU Lesser General Public License, you may choose any version of the GNU Lesser General Public License ever published by the Free Software Foundation.

Qwt

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can use it too, but we suggest you first think carefully about whether
this license or the ordinary General Public License is the better
strategy to use in any particular case, based on the explanations below.

  When we speak of free software, we are referring to freedom of use,
not price.  Our General Public Licenses are designed to make sure that
you have the freedom to distribute copies of free software (and charge
for this service if you wish); that you receive source code or can get
it if you want it; that you can change the software and use pieces of
it in new free programs; and that you are informed that you can do
these things.

  To protect your rights, we need to make restrictions that forbid
distributors to deny you these rights or to ask you to surrender these
rights.  These restrictions translate to certain responsibilities for
you if you distribute copies of the library or if you modify it.

  For example, if you distribute copies of the library, whether gratis
or for a fee, you must give the recipients all the rights that we gave
you.  You must make sure that they, too, receive or can get the source
code.  If you link other code with the library, you must provide
complete object files to the recipients, so that they can relink them
with the library after making changes to the library and recompiling
it.  And you must show them these terms so they know their rights.

  We protect your rights with a two-step method: (1) we copyright the
library, and (2) we offer you this license, which gives you legal
permission to copy, distribute and/or modify the library.

  To protect each distributor, we want to make it very clear that
there is no warranty for the free library.  Also, if the library is
modified by someone else and passed on, the recipients should know
that what they have is not the original version, so that the original
author's reputation will not be affected by problems that might be
introduced by others.

  Finally, software patents pose a constant threat to the existence of
any free program.  We wish to make sure that a company cannot
effectively restrict the users of a free program by obtaining a
restrictive license from a patent holder.  Therefore, we insist that
any patent license obtained for a version of the library must be
consistent with the full freedom of use specified in this license.

  Most GNU software, including some libraries, is covered by the
ordinary GNU General Public License.  This license, the GNU Lesser
General Public License, applies to certain designated libraries, and
is quite different from the ordinary General Public License.  We use
this license for certain libraries in order to permit linking those
libraries into non-free programs.

  When a program is linked with a library, whether statically or using
a shared library, the combination of the two is legally speaking a
combined work, a derivative of the original library.  The ordinary
General Public License therefore permits such linking only if the
entire combination fits its criteria of freedom.  The Lesser General
Public License permits more lax criteria for linking other code with
the library.

  We call this license the "Lesser" General Public License because it
does Less to protect the user's freedom than the ordinary General
Public License.  It also provides other free software developers Less
of an advantage over competing non-free programs.  These disadvantages
are the reason we use the ordinary General Public License for many
libraries.  However, the Lesser license provides advantages in certain
special circumstances.

  For example, on rare occasions, there may be a special need to
encourage the widest possible use of a certain library, so that it becomes
a de-facto standard.  To achieve this, non-free programs must be
allowed to use the library.  A more frequent case is that a free
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library does the same job as widely used non-free libraries.  In this
case, there is little to gain by limiting the free library to free
software only, so we use the Lesser General Public License.

  In other cases, permission to use a particular library in non-free
programs enables a greater number of people to use a large body of
free software.  For example, permission to use the GNU C Library in
non-free programs enables many more people to use the whole GNU
operating system, as well as its variant, the GNU/Linux operating
system.

  Although the Lesser General Public License is Less protective of the
users' freedom, it does ensure that the user of a program that is
linked with the Library has the freedom and the wherewithal to run
that program using a modified version of the Library.

  The precise terms and conditions for copying, distribution and
modification follow.  Pay close attention to the difference between a
"work based on the library" and a "work that uses the library".  The
former contains code derived from the library, whereas the latter must
be combined with the library in order to run.

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  0. This License Agreement applies to any software library or other
program which contains a notice placed by the copyright holder or
other authorized party saying it may be distributed under the terms of
this Lesser General Public License (also called "this License").
Each licensee is addressed as "you".

  A "library" means a collection of software functions and/or data
prepared so as to be conveniently linked with application programs
(which use some of those functions and data) to form executables.

  The "Library", below, refers to any such software library or work
which has been distributed under these terms.  A "work based on the
Library" means either the Library or any derivative work under
copyright law: that is to say, a work containing the Library or a
portion of it, either verbatim or with modifications and/or translated
straightforwardly into another language.  (Hereinafter, translation is
included without limitation in the term "modification".)

  "Source code" for a work means the preferred form of the work for
making modifications to it.  For a library, complete source code means
all the source code for all modules it contains, plus any associated
interface definition files, plus the scripts used to control compilation
and installation of the library.

  Activities other than copying, distribution and modification are not
covered by this License; they are outside its scope.  The act of
running a program using the Library is not restricted, and output from
such a program is covered only if its contents constitute a work based
on the Library (independent of the use of the Library in a tool for
writing it).  Whether that is true depends on what the Library does
and what the program that uses the Library does.

  1. You may copy and distribute verbatim copies of the Library's
complete source code as you receive it, in any medium, provided that
you conspicuously and appropriately publish on each copy an
appropriate copyright notice and disclaimer of warranty; keep intact
all the notices that refer to this License and to the absence of any
warranty; and distribute a copy of this License along with the
Library.

  You may charge a fee for the physical act of transferring a copy,
and you may at your option offer warranty protection in exchange for a
fee.

  2. You may modify your copy or copies of the Library or any portion
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of it, thus forming a work based on the Library, and copy and
distribute such modifications or work under the terms of Section 1
above, provided that you also meet all of these conditions:

    a) The modified work must itself be a software library.

    b) You must cause the files modified to carry prominent notices
    stating that you changed the files and the date of any change.

    c) You must cause the whole of the work to be licensed at no
    charge to all third parties under the terms of this License.

    d) If a facility in the modified Library refers to a function or a
    table of data to be supplied by an application program that uses
    the facility, other than as an argument passed when the facility
    is invoked, then you must make a good faith effort to ensure that,
    in the event an application does not supply such function or
    table, the facility still operates, and performs whatever part of
    its purpose remains meaningful.

    (For example, a function in a library to compute square roots has
    a purpose that is entirely well-defined independent of the
    application.  Therefore, Subsection 2d requires that any
    application-supplied function or table used by this function must
    be optional: if the application does not supply it, the square
    root function must still compute square roots.)

These requirements apply to the modified work as a whole.  If
identifiable sections of that work are not derived from the Library,
and can be reasonably considered independent and separate works in
themselves, then this License, and its terms, do not apply to those
sections when you distribute them as separate works.  But when you
distribute the same sections as part of a whole which is a work based
on the Library, the distribution of the whole must be on the terms of
this License, whose permissions for other licensees extend to the
entire whole, and thus to each and every part regardless of who wrote
it.

Thus, it is not the intent of this section to claim rights or contest
your rights to work written entirely by you; rather, the intent is to
exercise the right to control the distribution of derivative or
collective works based on the Library.

In addition, mere aggregation of another work not based on the Library
with the Library (or with a work based on the Library) on a volume of
a storage or distribution medium does not bring the other work under
the scope of this License.

  3. You may opt to apply the terms of the ordinary GNU General Public
License instead of this License to a given copy of the Library.  To do
this, you must alter all the notices that refer to this License, so
that they refer to the ordinary GNU General Public License, version 2,
instead of to this License.  (If a newer version than version 2 of the
ordinary GNU General Public License has appeared, then you can specify
that version instead if you wish.)  Do not make any other change in
these notices.

  Once this change is made in a given copy, it is irreversible for
that copy, so the ordinary GNU General Public License applies to all
subsequent copies and derivative works made from that copy.

  This option is useful when you wish to copy part of the code of
the Library into a program that is not a library.

  4. You may copy and distribute the Library (or a portion or
derivative of it, under Section 2) in object code or executable form
under the terms of Sections 1 and 2 above provided that you accompany
it with the complete corresponding machine-readable source code, which
must be distributed under the terms of Sections 1 and 2 above on a
medium customarily used for software interchange.
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  If distribution of object code is made by offering access to copy
from a designated place, then offering equivalent access to copy the
source code from the same place satisfies the requirement to
distribute the source code, even though third parties are not
compelled to copy the source along with the object code.

  5. A program that contains no derivative of any portion of the
Library, but is designed to work with the Library by being compiled or
linked with it, is called a "work that uses the Library".  Such a
work, in isolation, is not a derivative work of the Library, and
therefore falls outside the scope of this License.

  However, linking a "work that uses the Library" with the Library
creates an executable that is a derivative of the Library (because it
contains portions of the Library), rather than a "work that uses the
library".  The executable is therefore covered by this License.
Section 6 states terms for distribution of such executables.

  When a "work that uses the Library" uses material from a header file
that is part of the Library, the object code for the work may be a
derivative work of the Library even though the source code is not.
Whether this is true is especially significant if the work can be
linked without the Library, or if the work is itself a library.  The
threshold for this to be true is not precisely defined by law.

  If such an object file uses only numerical parameters, data
structure layouts and accessors, and small macros and small inline
functions (ten lines or less in length), then the use of the object
file is unrestricted, regardless of whether it is legally a derivative
work.  (Executables containing this object code plus portions of the
Library will still fall under Section 6.)

  Otherwise, if the work is a derivative of the Library, you may
distribute the object code for the work under the terms of Section 6.
Any executables containing that work also fall under Section 6,
whether or not they are linked directly with the Library itself.

  6. As an exception to the Sections above, you may also combine or
link a "work that uses the Library" with the Library to produce a
work containing portions of the Library, and distribute that work
under terms of your choice, provided that the terms permit
modification of the work for the customer's own use and reverse
engineering for debugging such modifications.

  You must give prominent notice with each copy of the work that the
Library is used in it and that the Library and its use are covered by
this License.  You must supply a copy of this License.  If the work
during execution displays copyright notices, you must include the
copyright notice for the Library among them, as well as a reference
directing the user to the copy of this License.  Also, you must do one
of these things:

    a) Accompany the work with the complete corresponding
    machine-readable source code for the Library including whatever
    changes were used in the work (which must be distributed under
    Sections 1 and 2 above); and, if the work is an executable linked
    with the Library, with the complete machine-readable "work that
    uses the Library", as object code and/or source code, so that the
    user can modify the Library and then relink to produce a modified
    executable containing the modified Library.  (It is understood
    that the user who changes the contents of definitions files in the
    Library will not necessarily be able to recompile the application
    to use the modified definitions.)

    b) Use a suitable shared library mechanism for linking with the
    Library.  A suitable mechanism is one that (1) uses at run time a
    copy of the library already present on the user's computer system,
    rather than copying library functions into the executable, and (2)
    will operate properly with a modified version of the library, if
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    the user installs one, as long as the modified version is
    interface-compatible with the version that the work was made with.

    c) Accompany the work with a written offer, valid for at
    least three years, to give the same user the materials
    specified in Subsection 6a, above, for a charge no more
    than the cost of performing this distribution.

    d) If distribution of the work is made by offering access to copy
    from a designated place, offer equivalent access to copy the above
    specified materials from the same place.

    e) Verify that the user has already received a copy of these
    materials or that you have already sent this user a copy.

  For an executable, the required form of the "work that uses the
Library" must include any data and utility programs needed for
reproducing the executable from it.  However, as a special exception,
the materials to be distributed need not include anything that is
normally distributed (in either source or binary form) with the major
components (compiler, kernel, and so on) of the operating system on
which the executable runs, unless that component itself accompanies
the executable.

  It may happen that this requirement contradicts the license
restrictions of other proprietary libraries that do not normally
accompany the operating system.  Such a contradiction means you cannot
use both them and the Library together in an executable that you
distribute.

  7. You may place library facilities that are a work based on the
Library side-by-side in a single library together with other library
facilities not covered by this License, and distribute such a combined
library, provided that the separate distribution of the work based on
the Library and of the other library facilities is otherwise
permitted, and provided that you do these two things:

    a) Accompany the combined library with a copy of the same work
    based on the Library, uncombined with any other library
    facilities.  This must be distributed under the terms of the
    Sections above.

    b) Give prominent notice with the combined library of the fact
    that part of it is a work based on the Library, and explaining
    where to find the accompanying uncombined form of the same work.

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             END OF TERMS AND CONDITIONS

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possible use to the public, we recommend making it free software that
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redistribution under these terms (or, alternatively, under the terms of the
ordinary General Public License).

  To apply these terms, attach the following notices to the library.  It is
safest to attach them to the start of each source file to most effectively
convey the exclusion of warranty; and each file should have at least the
"copyright" line and a pointer to where the full notice is found.

    <one line to give the library's name and a brief idea of what it does.>
    Copyright (C) <year>  <name of author>

    This library is free software; you can redistribute it and/or
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Also add information on how to contact you by electronic and paper mail.

You should also get your employer (if you work as a programmer) or your
school, if any, to sign a "copyright disclaimer" for the library, if
necessary.  Here is a sample; alter the names:

  Yoyodyne, Inc., hereby disclaims all copyright interest in the
  library `Frob' (a library for tweaking knobs) written by James Random Hacker.

  <signature of Ty Coon>, 1 April 1990
  Ty Coon, President of Vice

That's all there is to it!
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Shapelib

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           Version 2, June 1991

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 of this license document, but changing it is not allowed.

[This is the first released version of the library GPL.  It is
 numbered 2 because it goes with version 2 of the ordinary GPL.]

          Preamble

  The licenses for most software are designed to take away your
freedom to share and change it.  By contrast, the GNU General Public
Licenses are intended to guarantee your freedom to share and change
free software--to make sure the software is free for all its users.

  This license, the Library General Public License, applies to some
specially designated Free Software Foundation software, and to any
other libraries whose authors decide to use it.  You can use it for
your libraries, too.

  When we speak of free software, we are referring to freedom, not
price.  Our General Public Licenses are designed to make sure that you
have the freedom to distribute copies of free software (and charge for
this service if you wish), that you receive source code or can get it
if you want it, that you can change the software or use pieces of it
in new free programs; and that you know you can do these things.

  To protect your rights, we need to make restrictions that forbid
anyone to deny you these rights or to ask you to surrender the rights.
These restrictions translate to certain responsibilities for you if
you distribute copies of the library, or if you modify it.

  For example, if you distribute copies of the library, whether gratis
or for a fee, you must give the recipients all the rights that we gave
you.  You must make sure that they, too, receive or can get the source
code.  If you link a program with the library, you must provide
complete object files to the recipients so that they can relink them
with the library, after making changes to the library and recompiling
it.  And you must show them these terms so they know their rights.

  Our method of protecting your rights has two steps: (1) copyright
the library, and (2) offer you this license which gives you legal
permission to copy, distribute and/or modify the library.

  Also, for each distributor's protection, we want to make certain
that everyone understands that there is no warranty for this free
library.  If the library is modified by someone else and passed on, we
want its recipients to know that what they have is not the original
version, so that any problems introduced by others will not reflect on
the original authors' reputations.

  Finally, any free program is threatened constantly by software
patents.  We wish to avoid the danger that companies distributing free
software will individually obtain patent licenses, thus in effect
transforming the program into proprietary software.  To prevent this,
we have made it clear that any patent must be licensed for everyone's
free use or not licensed at all.

  Most GNU software, including some libraries, is covered by the ordinary
GNU General Public License, which was designed for utility programs.  This
license, the GNU Library General Public License, applies to certain
designated libraries.  This license is quite different from the ordinary
one; be sure to read it in full, and don't assume that anything in it is
the same as in the ordinary license.

  The reason we have a separate public license for some libraries is that
they blur the distinction we usually make between modifying or adding to a
program and simply using it.  Linking a program with a library, without
changing the library, is in some sense simply using the library, and is
analogous to running a utility program or application program.  However, in
a textual and legal sense, the linked executable is a combined work, a
derivative of the original library, and the ordinary General Public License
treats it as such.
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  Because of this blurred distinction, using the ordinary General
Public License for libraries did not effectively promote software
sharing, because most developers did not use the libraries.  We
concluded that weaker conditions might promote sharing better.

  However, unrestricted linking of non-free programs would deprive the
users of those programs of all benefit from the free status of the
libraries themselves.  This Library General Public License is intended to
permit developers of non-free programs to use free libraries, while
preserving your freedom as a user of such programs to change the free
libraries that are incorporated in them.  (We have not seen how to achieve
this as regards changes in header files, but we have achieved it as regards
changes in the actual functions of the Library.)  The hope is that this
will lead to faster development of free libraries.

  The precise terms and conditions for copying, distribution and
modification follow.  Pay close attention to the difference between a
"work based on the library" and a "work that uses the library".  The
former contains code derived from the library, while the latter only
works together with the library.

  Note that it is possible for a library to be covered by the ordinary
General Public License rather than by this special one.

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addressed as "you".

  A "library" means a collection of software functions and/or data
prepared so as to be conveniently linked with application programs
(which use some of those functions and data) to form executables.

  The "Library", below, refers to any such software library or work
which has been distributed under these terms.  A "work based on the
Library" means either the Library or any derivative work under
copyright law: that is to say, a work containing the Library or a
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Vtk

```
/*=========================================================================

  Program:   Visualization Toolkit
  Module:    Copyright.txt

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VtkexodusII

Zlib

```
ZLIB DATA COMPRESSION LIBRARY

zlib 1.2.12 is a general purpose data compression library.  All the code is
thread safe.  The data format used by the zlib library is described by RFCs
(Request for Comments) 1950 to 1952 in the files
http://tools.ietf.org/html/rfc1950 (zlib format), rfc1951 (deflate format) and
rfc1952 (gzip format).

All functions of the compression library are documented in the file zlib.h
(volunteer to write man pages welcome, contact zlib@gzip.org).  A usage example
of the library is given in the file test/example.c which also tests that
the library is working correctly.  Another example is given in the file
test/minigzip.c.  The compression library itself is composed of all source
files in the root directory.

To compile all files and run the test program, follow the instructions given at
the top of Makefile.in.  In short "./configure; make test", and if that goes
well, "make install" should work for most flavors of Unix.  For Windows, use
```

one of the special makefiles in win32/ or contrib/vstudio/ . For VMS, use
make_vms.com.

Questions about zlib should be sent to <zlib@gzip.org>, or to Gilles Vollant
<info@winimage.com> for the Windows DLL version. The zlib home page is
http://zlib.net/ . Before reporting a problem, please check this site to
verify that you have the latest version of zlib; otherwise get the latest
version and check whether the problem still exists or not.

PLEASE read the zlib FAQ http://zlib.net/zlib_faq.html before asking for help.

Mark Nelson <markn@ieee.org> wrote an article about zlib for the Jan. 1997
issue of Dr. Dobb's Journal; a copy of the article is available at
http://marknelson.us/1997/01/01/zlib-engine/ .

The changes made in version 1.2.12 are documented in the file ChangeLog.

Unsupported third party contributions are provided in directory contrib/ .

zlib is available in Java using the java.util.zip package, documented at
http://java.sun.com/developer/technicalArticles/Programming/compression/ .

A Perl interface to zlib written by Paul Marquess <pmqs@cpan.org> is available
at CPAN (Comprehensive Perl Archive Network) sites, including
http://search.cpan.org/~pmqs/IO-Compress-Zlib/ .

A Python interface to zlib written by A.M. Kuchling <amk@amk.ca> is
available in Python 1.5 and later versions, see
http://docs.python.org/library/zlib.html .

zlib is built into tcl: http://wiki.tcl.tk/4610 .

An experimental package to read and write files in .zip format, written on top
of zlib by Gilles Vollant <info@winimage.com>, is available in the
contrib/minizip directory of zlib.

Notes for some targets:

- For Windows DLL versions, please see win32/DLL_FAQ.txt

- For 64-bit Irix, deflate.c must be compiled without any optimization. With
  -O, one libpng test fails. The test works in 32 bit mode (with the -n32
  compiler flag). The compiler bug has been reported to SGI.

- zlib doesn't work with gcc 2.6.3 on a DEC 3000/300LX under OSF/1 2.1 it works
  when compiled with cc.

- On Digital Unix 4.0D (formely OSF/1) on AlphaServer, the cc option -std1 is
  necessary to get gzprintf working correctly. This is done by configure.

- zlib doesn't work on HP-UX 9.05 with some versions of /bin/cc. It works with
  other compilers. Use "make test" to check your compiler.

- gzdopen is not supported on RISCOS or BEOS.

- For PalmOs, see http://palmzlib.sourceforge.net/

Acknowledgments:

The deflate format used by zlib was defined by Phil Katz. The deflate and
zlib specifications were written by L. Peter Deutsch. Thanks to all the
people who reported problems and suggested various improvements in zlib; they
are too numerous to cite here.

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  Jean-loup Gailly        Mark Adler
  jloup@gzip.org          madler@alumni.caltech.edu

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